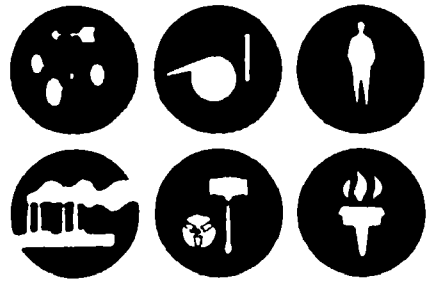
Office of Air and Water Programs
Air Pollution Training Institute

Combustion Evaluation— Sources and Control Devices



Manual: Training Course 427

Combustion Evaluation - Sources and Control Devices

Conducted by
CONTROL PROGRAMS DEVELOPMENT DIVISION
Air Pollution Training Institute
Research Triangle Park, North Carolina 27711
April, 1973

The Combustion Evaluation manual has been prepared specifically for the trainees attending the course and should not be included in reading lists or periodicals as generally available.

AIR POLLUTION TRAINING INSTITUTE
CONTROL PROGRAMS DEVELOPMENT DIVISION
OFFICE OF AIR AND WATER PROGRAMS

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Francis J. King, Chief
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FUNDAMENTALS IN COMBUSTION

Basic Combustion Concepts
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BASIC COMBUSTION CONCEPTS

Darryl J. von Lehmden*

I INTRODUCTION

Combustion is a chemical reaction. Complete combustion consists of the rapid oxidation of a combustible substance to innocuous carbon dioxide and water accompanied by the release of energy (heat and light).

II PRINCIPLES OF COMBUSTION

To achieve complete combustion, i.e., the combination of the combustible elements with all the oxygen which they can utilize, sufficient space, time, turbulence, and a temperature high enough to ignite the constituents must be provided.

The "three T's" of combustion -- time, temperature, turbulence -- govern the speed and completeness of the combustion reaction. For complete combustion, the oxygen must come into intimate contact with the combustible molecule at sufficient temperature, and for a sufficient length of time, in order that the reaction be completed. Incomplete reactions may result in the generation of aldehydes, organic acids, carbon and carbon monoxide.

The factors influencing completeness of combustion are evaluated in more detail below:

A Temperature

Every combustible substance has a minimum ignition temperature, which must be attained or exceeded, in the presence of oxygen, if combustion is to ensue under the given conditions. This ignition temperature may be defined as the temperature at which more heat is generated by the reaction than is lost to the surroundings.

The ignition temperature for flame combustion of combustible substances cover a large range, as indicated in Table 1.[1]

The ignition temperatures of the gases volatilized from coal vary considerably and are appreciably higher than the ignition temperatures of the fixed carbon in the coal. The gaseous constituents in the coal are usually distilled off, but not ignited, before the ignition temperature of the fixed carbon is attained. Therefore if complete combustion of the gases is to be achieved it is necessary that the temperature of the effluent gases be raised to the ignition temperature of the gases.

The same principle applies to the complete combustion of any mixture of combustible substances. A sufficiently high temperature must be achieved which will burn all the combustible compounds. To achieve such a temperature it may be necessary to add auxilliary heat to the combustible-laden gas stream (e.g., via a gas fired burner).

Since the reaction rate increases with temperature, temperatures considerably above the ignition temperatures of the combustible may be necessary to accomplish complete combustion in a reasonable amount of time.

B Oxygen

Oxygen is necessary for combustion to occur. The end products of combustion depend on the supply of oxygen. When methane, for instance, is burned with too little oxygen, solid carbon results thus:

$$CH_4 + O_2 = C + 2H_2O + Q \text{ (heat of reaction)}$$

The solid carbon agglomerates forming particles of soot and smoke. If enough oxygen is supplied, the carbon is burned to carbon dioxide, thus:

$$CH_4 + 2O_2 = CO_2 + H_2O + Q$$

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Table 1. FLAME IGNITION TEMPERATURE IN AIR*
(At Pressure of One Atmosphere)

Combustible	Formula	Temperature, °F
Sulfur	S	470
Charcoal	C	650
Fixed carbon (bituminous coal)	C	765
Fixed carbon (semibituminous coal)	C	870
Fixed carbon (anthracite)	C	840 - 1115
Acetylene	C_2H_2	580 - 825
Ethane	C_2H_6	880 - 1165
Ethylene	C_2H_4	900 - 1020
Hydrogen	H_2	1065 - 1095
Methane	CH_4	1170 - 1380
Carbon monoxide	CO	1130 - 1215
Kerosene	-	490 - 560
Gasoline	-	500 - 800

* Rounded-out values and ranges from various sources; a guide only.

Here, then it is completely burned, no solid is set free, and hence there is no smoke.

When carbon is burned with an insufficient supply of oxygen, carbon monoxide results:

$$2C + O_2 = 2CO + Q$$

If enough oxygen is available, then carbon dioxide results:

$$C + O_2 = CO_2 + Q$$

The chemical reactions which occur during the combustion of many compounds are shown in Table 2. (1)

To achieve complete combustion of a combustible compound with air, a Stoichiometric (theoretical) quantity of oxygen must be available. The quantity of air which must be furnished to obtain theoretical complete combustion for many combustible compounds is shown in Table 3. (1)

It is necessary, however, to use more than the theoretical air required to assure sufficient oxygen for complete combustion. Excess air would not be required if it were possible to have every oxygen molecule combine with the combustibles. The amount of excess air added to insure complete combustion must be held at a practical minimum to reduce the stack heat losses. Realistic values of excess air necessary to burn various fuel are given in Table 4. (1)

C Time

A fundamental factor in the design and performance of combustion equipment

Table 2. COMMON CHEMICAL REACTIONS OF COMBUSTION

Combustible	Reaction
Carbon (to CO)	$2C + O_2 = 2CO + Q$
Carbon (to CO_2)	$C + O_2 = CO_2 + Q$
Carbon monoxide	$2CO + O_2 = 2CO_2 + Q$
Hydrogen	$2H_2 + O_2 = 2H_2O + Q$
Sulfur (to SO_2)	$S + O_2 = SO_2 + Q$
Sulfur (to SO_3)	$2S + 3O_2 = 2SO_3 + Q$
Methane	$CH_4 + 2O_2 = CO_2 + 2H_2O + Q$
Acetylene	$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O + Q$
Ethylene	$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O + Q$
Ethane	$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O + Q$
Hydrogen sulfide	$2H_2S + 3O_2 = 2SO_2 + 2H_2O + Q$
where Q = the heat of reaction	

is the time required for combustion of a particle in relation to the residence time in the equipment at combustion conditions. The residence time (at conditions conducive for complete combustion) should be greater than the time required for combustion of the particle.

The time of residence depends primarily on aerodynamic factors including size which are arbitrarly set in the design of the unit. The time of combustion is controlled by the temperatures and aerodynamic factors. The time of residence, then, becomes a question of economy; namely size versus temperature. The smaller the unit, the higher the temperature must be to oxidize the material in the time of contact.

D Turbulence

Not only must the oxygen be supplied, but it must be intimately mixed with the material being burned so that it is available to the combustion substance at all times. When burning solids, without turbulence, the initial products of combustion act as a screen for the incoming oxygen and thereby slow down the rate of surface reaction. The burning of gases requires a thorough mixing of them with air: otherwise separate zones between the gases and air will form and they will escape unchanged or incompletely burned.

Through the proper regulation and control of these four factors, complete combustion can be attained.

Table 3. COMBUSTION CONSTANTS

No.	Substance	Formula	Molecular Weight	Lb per Cu Ft	Cu Ft per Lb	Sp Gr Air 1.0000	Heat of Combustion: Btu per Cu Ft Gross (High)	Heat of Combustion: Btu per Cu Ft Net (Low)	Heat of Combustion: Btu per Lb Gross (High)	Heat of Combustion: Btu per Lb Net (Low)	For 100% Total Air, Moles per mole of Combustible or Cu Ft per Cu Ft of Combustible: Required for Combustion O_2	Required for Combustion N_2	Required for Combustion Air	Flue Products CO_2	Flue Products H_2O	Flue Products N_2	For 100% Total Air, Lb per Lb of Combustible: Required for Combustion O_2	Required for Combustion N_2	Required for Combustion Air	Flue Products CO_2	Flue Products H_2O	Flue Products N_2
1	Carbon*	C	12.01	.....	.....	.....	...	...	14,093	14,093	1.0	3.76	4.76	1.0	...	3.76	2.66	8.86	11.53	3.66	...	8.86
2	Hydrogen	H_2	2.016	0.0053	187.723	0.0696	325	275	61,100	51,623	0.5	1.88	2.38	...	1.0	1.88	7.94	26.41	34.34	....	8.94	26.41
3	Oxygen	O_2	32.000	0.0846	11.819	1.1053	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	....
4	Nitrogen (atm)	N_2	28.016	0.0744	13.443	0.9718	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	....
5	Carbon monoxide	CO	28.01	0.0740	13.506	0.9672	322	322	4,347	4,347	0.5	1.88	2.38	1.0	...	1.88	0.57	1.90	2.47	1.57	...	1.90
6	Carbon dioxide	CO_2	44.01	0.1170	8.548	1.5282	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	....
Paraffin series																						
7	Methane	CH_4	16.041	0.0424	23.565	0.5543	1013	913	23,879	21,520	2.0	7.53	9.53	1.0	2.0	7.53	3.99	13.28	17.27	2.74	2.25	13.28
8	Ethane	C_2H_6	30.067	0.0803	12.455	1.0488	1792	1641	22,320	20,432	3.5	13.18	16.68	2.0	3.0	13.18	3.73	12.39	16.12	2.93	1.80	12.39
9	Propane	C_3H_8	44.092	0.1196	8.365	1.5617	2590	2385	21,661	19,944	5.0	18.82	23.82	3.0	4.0	18.82	3.63	12.07	15.70	2.99	1.63	12.07
10	n-Butane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3370	3113	21,308	19,680	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
11	Isobutane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3363	3105	21,257	19,629	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
12	n-Pentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	4016	3709	21,091	19,517	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
13	Isopentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	4008	3716	21,052	19,478	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
14	Neopentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	3993	3693	20,970	19,396	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
15	n-Hexane	C_6H_{14}	86.169	0.2274	4.398	2.9704	4762	4412	20,940	19,403	9.5	35.76	45.26	6.0	7.0	35.76	3.53	11.74	15.27	3.06	1.46	11.74
Olefin series																						
16	Ethylene	C_2H_4	28.051	0.0746	13.412	0.9740	1614	1513	21,644	20,295	3.0	11.29	14.29	2.0	2.0	11.29	3.42	11.39	14.81	3.14	1.29	11.39
17	Propylene	C_3H_6	42.077	0.1110	9.007	1.4504	2336	2186	21,041	19,691	4.5	16.94	21.44	3.0	3.0	16.94	3.42	11.39	14.81	3.14	1.29	11.39
18	n-Butene	C_4H_8	56.102	0.1480	6.756	1.9336	3084	2885	20,840	19,496	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
19	Isobutene	C_4H_8	56.102	0.1480	6.756	1.9336	3068	2869	20,730	19,382	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
20	n-Pentene	C_5H_{10}	70.128	0.1852	5.400	2.4190	3836	3586	20,712	19,363	7.5	28.23	35.73	5.0	5.0	28.23	3.42	11.39	14.81	3.14	1.29	11.39
Aromatic series																						
21	Benzene	C_6H_6	78.107	0.2060	4.852	2.6920	3751	3601	18,210	17,480	7.5	28.23	35.73	6.0	3.0	28.23	3.07	10.22	13.30	3.38	0.69	10.22
22	Toluene	C_7H_8	92.132	0.2431	4.113	3.1760	4484	4284	18,440	17,620	9.0	33.88	42.88	7.0	4.0	33.88	3.13	10.40	13.53	3.34	0.78	10.40
23	Xylene	C_8H_{10}	106.158	0.2803	3.567	3.6618	5230	4980	18,650	17,760	10.5	39.52	50.02	8.0	5.0	39.52	3.17	10.53	13.70	3.32	0.85	10.53
Miscellaneous gases																						
24	Acetylene	C_2H_2	26.036	0.0697	14.344	0.9107	1499	1448	21,500	20,776	2.5	9.41	11.91	2.0	1.0	9.41	3.07	10.22	13.30	3.38	0.69	10.22
25	Naphthalene	$C_{10}H_8$	128.162	0.3384	2.955	4.4208	5854	5654	17,298	16,708	12.0	45.17	57.17	10.0	4.0	45.17	3.00	9.97	12.96	3.43	0.56	9.97
26	Methyl alcohol	CH_3OH	32.041	0.0846	11.820	1.1052	868	768	10,259	9,078	1.5	5.65	7.15	1.0	2.0	5.65	1.50	4.98	6.48	1.37	1.13	4.98
27	Ethyl alcohol	C_2H_5OH	46.067	0.1216	8.221	1.5890	1600	1451	13,161	11,929	3.0	11.29	14.29	2.0	3.0	11.29	2.08	6.93	9.01	1.92	1.17	6.93
28	Ammonia	NH_3	17.031	0.0456	21.914	0.5961	441	365	9,668	8,001	0.75	2.82	3.57	...	1.5	3.32	1.41	4.69	6.10	....	1.59	5.51
														SO_2						SO_2		
29	Sulfur*	S	32.06	.....	.....	...	...	...	3,983	3,983	1.0	3.76	4.76	1.0	...	3.76	1.00	3.29	4.29	2.00	...	3.29
30	Hydrogen sulfide	H_2S	34.076	0.0911	10.979	1.1898	647	596	7,100	6,545	1.5	5.65	7.15	1.0	1.0	5.65	1.41	4.69	6.10	1.88	0.53	4.69
31	Sulfur dioxide	SO_2	64.06	0.1733	5.770	2.2640	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	.....
32	Water vapor	H_2O	18.016	0.0476	21.017	0.6215	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	.....
33	Air		28.9	0.0766	13.063	1.0000	...	...	.....	.....	...	....	....	....	....	....	....	....	....	....	....	....

*Carbon and sulfur are considered as gases for molal calculations only.

Note: This table is reprinted from *Fuel Flue Gases*, 1941 Edition, courtesy of American Gas Association.

All gas volumes corrected to 60 F and 30 in. Hg dry.

Table 4. USUAL AMOUNT EXCESS AIR SUPPLIED TO FUEL-BURNING EQUIPMENT

Fuel	Type of furnace or burners	Excess Air, % by wt.
Pulverized coal	Completely water-cooled furnace for slag-tap or dry-ash-removal	15-20
	Partially water-cooled furnace for dry-ash-removal	15-40
Crushed coal	Cyclone furnace - pressure or suction	10-15
Coal	Stoker-fired, forced-draft, B&W chain-grate	15-50
	Stoker-fired, forced-draft, underfeed	20-50
	Stoker-fired, natural-draft	50-65
Fuel-oil	Oil burners, register-type	5-10
	Multifuel burners and flat-flame	10-20
Acid sludge	Cone- and flat-flame-type burners, steam-atomized	10-15
Natural, Coke-oven, & Refinery gas	Register-type burners	5-10
	Multifuel burners	7-12
Blast-furnace gas	Intertube nozzle-type burners	15-18
Wood	Dutch-oven (10-23% through grates) and Hofft-type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for kraft and soda-pulping processes	5-7

E Heat of Combustion

The rapid oxidation of combustible compounds results in the exothermic reaction (evolution of heat). The heat evolved (Q) is known as the "heat of reaction" or more specifically the "heat of combustion."

The principles involved in the development of heat by combustion, generally accepted as authoritative, were propounded by Berthelot. His "second law," as applied to combustion in furnace practice, is of particular interest and may be stated as follows[1]: In a furnace (where no mechanical work is done) the heat energy evolved from the union of combustible elements with oxygen depends upon the ultimate products of combustion and not upon any intermediate combinations that may occur in reaching the final result.

The heat of combustion for a number of substances is shown in Table 3.

III TYPES OF FLAME COMBUSTION

A Yellow flame

A luminous (yellow) flame results when air and fuel flowing through separate ports are ignited at the burner nozzle. Combustion occurs over an extended area in the combustion chamber, producing a highly radiant flame. The expansion of the gases as the flame progresses provides the necessary turbulence, while a large combustion chamber assures the necessary time at the combustion temperature to complete the reaction.

According to the carbonic theory[2] (yellow flame combustion), the hydrocarbon molecules decompose upon exposure to the high temperature in the combustion zone into it's constitutent elements, carbon and hydrogen, and these then burn independently, each combining separately with a part of the oxygen present. Carbonic combustion is characterized by a yellow flame, caused primarily from the incandescent carbon. Under conditions of incomplete combustion yellow flame combustion will deposit quantities of soot but will not give offensive odors.

B Blue Flame

A burner utilizing the same fuel, but arranged to premix the air and fuel prior to delivery to the burner nozzle, will produce a short, intense, blue flame, permitting complete oxidation within a confined space.

According to the hydroxylation theory[2] (blue flame combustion) the hydrocarbon molecules upon entering the combustion zone absorb oxygen in successive stages, each stage resulting in the formation of hydroxyl (OH) groups. The intermediate products of the absorption of oxygen by a hydrocarbon (hydroxylation) are thus alcohols and aldehydes. Under the influence of further heat and temperature the alcohols and aldehydes burn to carbon monoxide and hydrogen, and finally to carbon dioxide and water.

Hydroxylative combustion is characterized by a blue flame, resulting from the formation of aldehydes and then the burning of these aldehydes. Under conditions of incomplete combustion, blue flame combustion gives a strong aldehydic odor, but will not deposit soot in the combustion chamber or gas passages.

In any fuel-fired burner, whether it is of the luminous (yellow flame) or permixed (blue flame) type, sustained combustion depends upon maintaining the air-gas supply to the burner within the flammable range.

REFERENCES

1 Babcock and Wilcox Co. Stream -- Its Generation and Use. 37th Edition, Chapter 4. 1963.

2 Faust, F.H., et.al. Handbook of Oil Burning. p. 173.

FUNDAMENTALS IN COMBUSTION CALCULATIONS

Darryl J. von Lehmden

I COMBUSTION TERMINOLOGY

A Numerous terms are used in combustion calculations. Occasionally more than one term will have generally the same meaning. In order to avoid ambiguities in terms used in combustion calculations, the terms commonly used must be understood. Therefore, definitions of terms commonly used in combustion calculations are listed below.

B Definitions

1 Heat of Combustion: The heat released by the complete combustion of a specific quantity of fuel, etc.* with molecular oxygen. Heats of combustion are normally reported in BTU per cubic foot or BTU per pound of fuel.

2 Gross Heating Value: The total heat obtained from the complete combustion of a fuel which is at 60°F when combustion starts, and the combustion products of which are cooled to 60°F before the quantity of heat released is measured. Constant pressure, normally 1 atmosphere (29.92 in. Hg), is maintained throughout the entire combustion process. Gross heating values are also referred to as total or higher heating values.

3 Net Heating Value: The gross heating value minus the latent heat of vaporization of the water formed by the combustion of the hydrogen in the fuel. For a fuel containing no hydrogen, the net and gross heating values are the same.

4 Latent Heat of Vaporization: Heat given off by a vapor condensing to a liquid or gained by a liquid evaporating to a vapor, without a change in temperature. The latent heat of vaporization of water at 212°F is 970.3 BTU per pound.

5 Sensible Heat: Heat, the addition or removal of which results in a change in temperature, as opposed to latent heat of vaporization.

6 Available Heat: The gross quantity of heat released within a combustion chamber minus (1) the sensible heat carried away by the dry flue gases and (2) the latent heat and sensible heat carried away in water vapor contained in the flue gases. The available heat represents the net quantity of heat remaining for useful heating. Figure 2 and 3 shows the available heat from the complete combustion (No excess air) of various fuels at various flue gas temperatures.

Figure 4 is a generalization for all fuels giving percent available heat with various flue gas temperatures and various amounts of excess air.

7 Heat Content: The sum total of the latent and sensible heat present in a substance (gas, liquid, or solid) minus that contained at an arbitrary set of conditions chosen as the base or zero point. Heat content is usually expressed in units of BTU per pound. For gases, the heat content may be expressed in BTU per cubic foot if the conditions of pressure and temperature under which these volumes are measured are specified.

The heat content of various gases in BTU per pound is given in Table 1. Figure 1 is a graphical representation showing the inter-relationship of the terms previously defined.

*Includes combustible waste solids, waste liquids and waste gases resulting from man's activities. Hereafter referred to in the definition of combustion terms under the title; fuel(s).

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TABLE 1

Combustion Constants

No.	Substance	Formula	Molecular Weight	Lb per Cu Ft	Cu Ft per Lb	Sp Gr Air = 1.0000	Heat of Combustion Btu per Cu Ft Gross (High)	Heat of Combustion Btu per Cu Ft Net (Low)	Heat of Combustion Btu per Lb Gross (High)	Heat of Combustion Btu per Lb Net (Low)	For 100% Total Air Moles per mole of Combustible or Cu Ft per Cu Ft of Combustible Required for Combustion O_2	N_2	Air	Flue Products CO_2	H_2O	N_2	For 100% Total Air Lb per Lb of Combustible Required for Combustion O_2	N_2	Air	Flue Products CO_2	H_2O	N_2
1	Carbon*	C	12.01	.....	.....	.....	...	...	14,093	14,093	1.0	3.76	4.76	1.0	...	3.76	2.66	8.86	11.53	3.66	...	8.86
2	Hydrogen	H_2	2.016	0.0053	187.723	0.0696	325	275	61,100	51,623	0.5	1.88	2.38	...	1.0	1.88	7.94	26.41	34.34	....	8.94	26.41
3	Oxygen	O_2	32.000	0.0846	11.819	1.1053	...	...	.....	.....	...	....	....	...	...	....	....	....	....	....	...	....
4	Nitrogen (atm)	N_2	28.016	0.0744	13.443	0.9718	...	...	.....	.....	...	....	....	...	...	....	....	....	....	....	...	....
5	Carbon monoxide	CO	28.01	0.0740	13.506	0.9672	322	322	4,347	4,347	0.5	1.88	2.38	1.0	...	1.88	0.57	1.90	2.47	1.57	...	1.90
6	Carbon dioxide	CO_2	44.01	0.1170	8.548	1.5282	...	...	.....	.....	...	....	....	...	...	....	....	....	....	....	...	....
Paraffin series																						
7	Methane	CH_4	16.041	0.0424	23.565	0.5543	1013	913	23,879	21,520	2.0	7.53	9.53	1.0	2.0	7.53	3.99	13.28	17.27	2.74	2.25	13.28
8	Ethane	C_2H_6	30.067	0.0803	12.455	1.0488	1792	1641	22,320	20,432	3.5	13.18	16.68	2.0	3.0	13.18	3.73	12.39	16.12	2.93	1.80	12.39
9	Propane	C_3H_8	44.092	0.1196	8.365	1.5617	2590	2385	21,661	19,944	5.0	18.82	23.82	3.0	4.0	18.82	3.63	12.07	15.70	2.99	1.63	12.07
10	n-Butane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3370	3113	21,308	19,680	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
11	Isobutane	C_4H_{10}	58.118	0.1582	6.321	2.0665	3363	3105	21,257	19,629	6.5	24.47	30.97	4.0	5.0	24.47	3.58	11.91	15.49	3.03	1.55	11.91
12	n-Pentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	4016	3709	21,091	19,517	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
13	Isopentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	4008	3716	21,052	19,478	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
14	Neopentane	C_5H_{12}	72.144	0.1904	5.252	2.4872	3993	3693	20,970	19,396	8.0	30.11	38.11	5.0	6.0	30.11	3.55	11.81	15.35	3.05	1.50	11.81
15	n-Hexane	C_6H_{14}	86.169	0.2274	4.398	2.9704	4762	4412	20,940	19,403	9.5	35.76	45.26	6.0	7.0	35.76	3.53	11.74	15.27	3.06	1.46	11.74
Olefin series																						
16	Ethylene	C_2H_4	28.051	0.0746	13.412	0.9740	1614	1513	21,644	20,295	3.0	11.29	14.29	2.0	2.0	11.29	3.42	11.39	14.81	3.14	1.29	11.39
17	Propylene	C_3H_6	42.077	0.1110	9.007	1.4504	2336	2186	21,041	19,691	4.5	16.94	21.44	3.0	3.0	16.94	3.42	11.39	14.81	3.14	1.29	11.39
18	n-Butene	C_4H_8	56.102	0.1480	6.756	1.9336	3084	2885	20,840	19,496	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
19	Isobutene	C_4H_8	56.102	0.1480	6.756	1.9336	3068	2869	20,730	19,382	6.0	22.59	28.59	4.0	4.0	22.59	3.42	11.39	14.81	3.14	1.29	11.39
20	n-Pentene	C_5H_{10}	70.128	0.1852	5.400	2.4190	3836	3586	20,712	19,363	7.5	28.23	35.73	5.0	5.0	28.23	3.42	11.39	14.81	3.14	1.29	11.39
Aromatic series																						
21	Benzene	C_6H_6	78.107	0.2060	4.852	2.6920	3751	3601	18,210	17,480	7.5	28.23	35.73	6.0	3.0	28.23	3.07	10.22	13.30	3.38	0.69	10.22
22	Toluene	C_7H_8	92.132	0.2431	4.113	3.1760	4484	4284	18,440	17,620	9.0	33.88	42.88	7.0	4.0	33.88	3.13	10.40	13.53	3.34	0.78	10.40
23	Xylene	C_8H_{10}	106.158	0.2803	3.567	3.6618	5230	4980	18,650	17,760	10.5	39.52	50.02	8.0	5.0	39.52	3.17	10.53	13.70	3.32	0.85	10.53
Miscellaneous gases																						
24	Acetylene	C_2H_2	26.036	0.0697	14.344	0.9107	1499	1448	21,500	20,776	2.5	9.41	11.91	2.0	1.0	9.41	3.07	10.22	13.30	3.38	0.69	10.22
25	Naphthalene	$C_{10}H_8$	128.162	0.3384	2.955	4.4208	5854	5654	17,298	16,708	12.0	45.17	57.17	10.0	4.0	45.17	3.00	9.97	12.96	3.43	0.56	9.97
26	Methyl alcohol	CH_3OH	32.041	0.0846	11.820	1.1052	868	768	10,259	9,078	1.5	5.65	7.15	1.0	2.0	5.65	1.50	4.98	6.48	1.37	1.13	4.98
27	Ethyl alcohol	C_2H_5OH	46.067	0.1216	8.221	1.5890	1600	1451	13,161	11,929	3.0	11.29	14.29	2.0	3.0	11.29	2.08	6.93	9.02	1.92	1.17	6.93
28	Ammonia	NH_3	17.031	0.0456	21.914	0.5961	441	365	9,668	8,001	0.75	2.82	3.57	...	1.5	3.32	1.41	4.69	6.10	....	1.59	5.51
														SO_2						SO_2		
29	Sulfur*	S	32.06	.....	.....	.....	...	...	3,983	3,983	1.0	3.76	4.76	1.0	...	3.76	1.00	3.29	4.29	2.00	...	3.29
30	Hydrogen sulfide	H_2S	34.076	0.0911	10.979	1.1898	647	596	7,100	6,545	1.5	5.65	7.15	1.0	1.0	5.65	1.41	4.69	6.10	1.88	0.53	4.69
31	Sulfur dioxide	SO_2	64.06	0.1733	5.770	2.2640	...	...	.....	.....	...	....	....	...	...	....	....	....	....	....	...	....
32	Water vapor	H_2O	18.016	0.0476	21.017	0.6215	....	...	.....	.....	...	....	....	...	...	....	....	....	....	....	...	.....
33	Air	.....	28.9	0.0766	13.063	1.0000	...	...	.....	.....	...	....	....	...	...	....	.....	....	....	....	...	....

*Carbon and sulfur are considered as gases for molal calculations only.

Note: This table is reprinted from *Fuel Flue Gases*, courtesy of American Gas Association.

All gas volumes corrected to 60 F and 30 in. Hg dry.

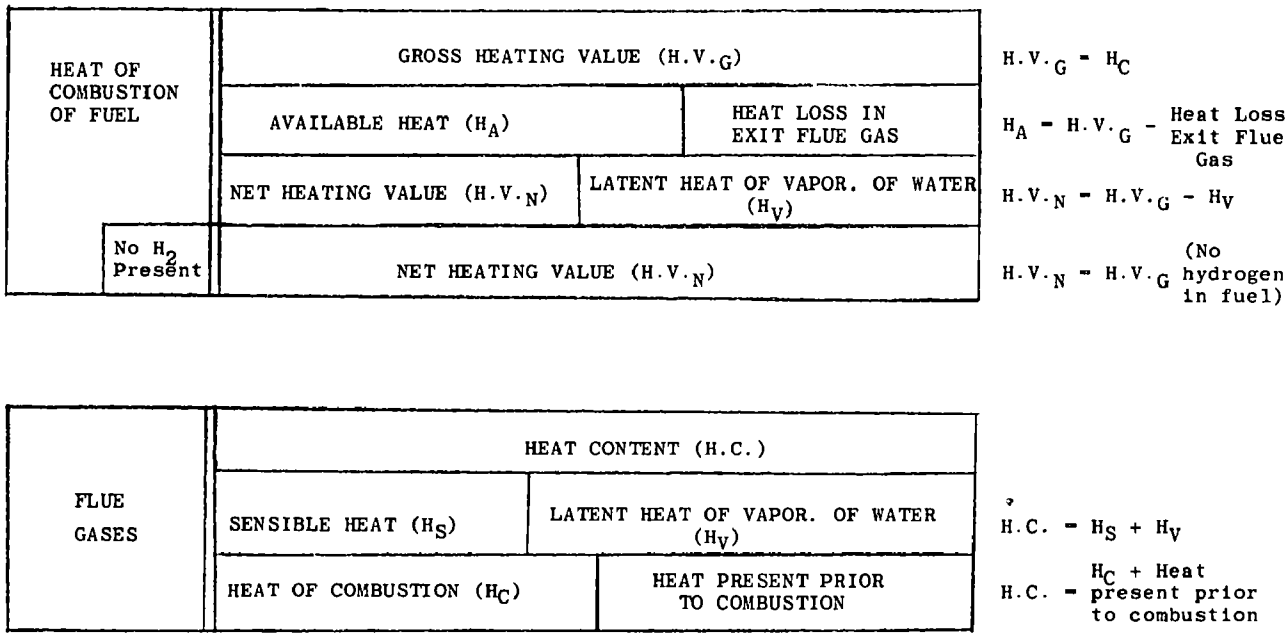


FIGURE 1. INTER-RELATIONSHIP OF TERMS USED IN COMBUSTION CALCULATIONS

C Tables Useful in Combustion Calculations

1 Gross heating value, net heating value, theoretical combustion air and specific gas volumes.

Heating values for the complete combustion of various fuels are shown in Table 1. Theoretical air requirements, for complete combustion are shown also in Table 1.

The volume occupied by one pound of gas under any specified condition of temperature and pressure is called the specific volume. The specific volume for various gases (including fuels) at 60°F and 1 atmosphere are also given in Table 1.

Since most combustion processes take place at constant pressure (normally 1 atmosphere) the specific volume of gases at elevated temperatures may be calculated from Charles' Law.

Charles Law states that the volume varies in direct proportion to the absolute temperature under constant pressure.

$$\text{Charles Law: } \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

2 Available heat (complete combustion, no excess air)

a General type fuels

The curves in Figure 2 show the available heat when the hydrogen to carbon ratio in the fuel is known. The available heat is for complete combustion of the fuel using the theoretical amount of air required for combustion.

The curves serve as a generalized comparison of the available heat from pure hydrocarbon fuels. In order to use the curves properly a fuel must be chemically analyzed to determine the carbon/hydrogen ratio.

When available heat curves for specific fuels are accessible (e.g. Figure 3), such curves should be used in preference to the curves in Figure 2.

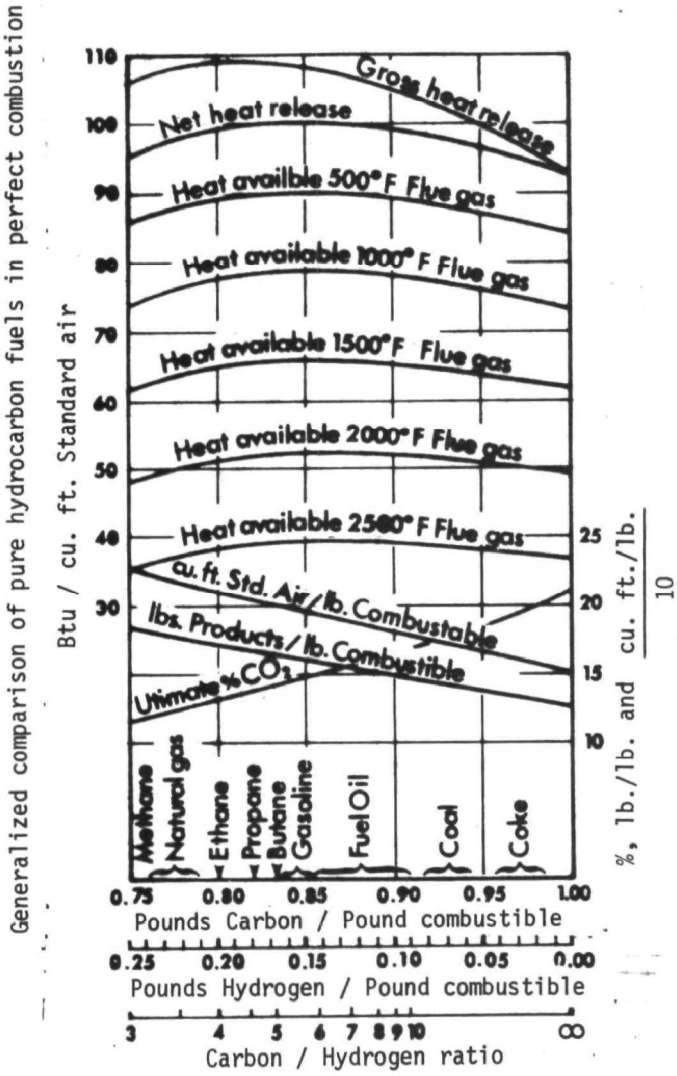


Figure 2. GENERALIZED COMPARISON OF AVAILABLE HEATS FOR PURE HYDROCARBON FUELS(1) (Refer to 60°F)

b Typical fuels

Figure 3 shows the available heats for some typical fuels. All available heat values are based upon complete combustion (theoretical air) and a fuel input temperature of 60°F.

The gross heating values for the fuels are indicated next to the name of the fuel. The scale on the left side of Figure 3 is for the solid curves. The scale on the right side is for propane and butane (dashed curves).

The available heat for fuels not shown in Figure 3 may be calculated from the following ratio (See Part B of the example calculation for more detail).

$$\frac{H_A}{H.V._G} \text{ (Specific fuel)} = \frac{H_A}{H.V._G} \text{ (Fig. 3)}$$

Table 2 shows a number of gross heating values for some specific gaseous fuels.

3 Available Heat (Complete Combustion; Excess Air Present)

Figure 4 is a generalization for all fuels giving the available heat as a percent of the gross heating value at various flue gas temperatures and various amounts of excess combustion

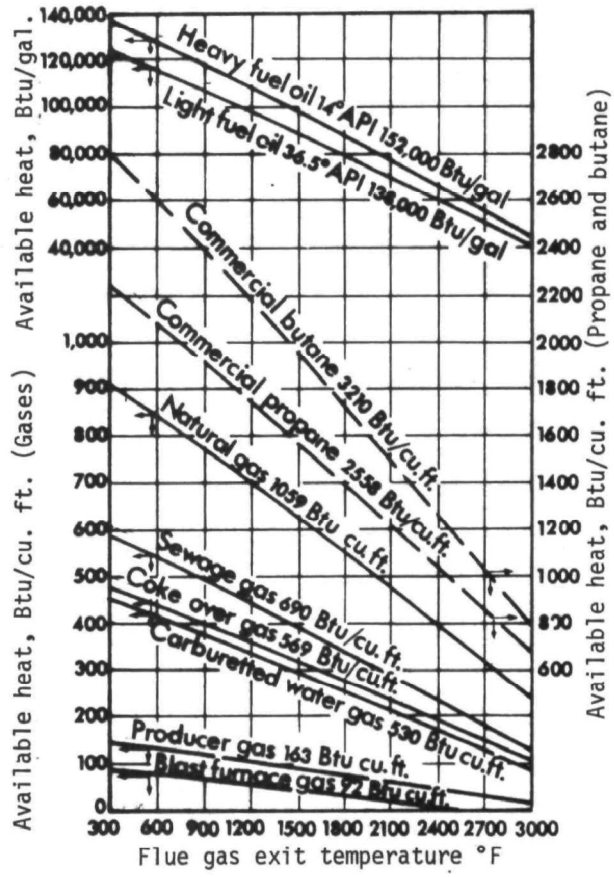


Figure 3. AVAILABLE HEATS FOR SOME TYPICAL FUELS(1) (Refer to 60°F)

air. This chart is approximate since it is based upon the assumption that the combustion air required per gross BTU is the same for all fuels.

The curves in the chart assumes that combustion of the fuel is complete.

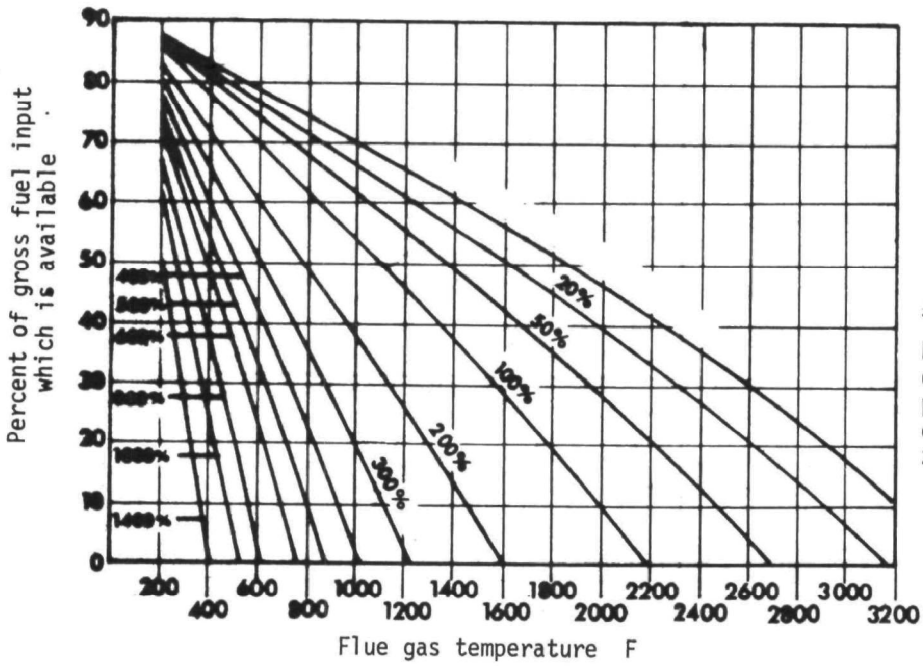
4 Heat Content of Gases

The heat contents for several gases at various temperatures are given in Table 3.

The heat contents in Table 3 are expressed in units of BTU per pound of gas. To convert the heat contents in Table 3 from BTU per pound to BTU per cubic foot, multiply by the specific volume of the gas at the temperature desired.

Table 2. GROSS HEATING VALUES FOR SPECIFIC GASEOUS FUELS[1]

Type of fuel	Gross heating value BTU per cu.ft.(60°F)
Natural Gas:	
Birmingham, Ala.	1002
Cleveland, Ohio	1059 (See Fig. 3)
Kansas City, Mo.	974
Pittsburgh, Pa.	1129
Commercial Propane:	
Natural Gas	2558 (See Fig. 3)
Refinery Gas	2504
Commercial Butane:	
Natural Gas	3210 (See Fig. 3)
Refinery Gas	3184



This chart is only applicable to cases in which there is no unburned fuel in the products of combustion.

The average temperature of the hot mixture just beyond the end of the flame may be read at the point where the appropriate % excess air curve intersects the zero available heat line.

Figure 4. GENERALIZED AVAILABLE HEAT CHART FOR ALL FUELS AT VARIOUS FLUE GAS TEMPERATURES AND VARIOUS EXCESS COMBUSTION AIR[1] (Refer to 60°F)

Table 3. HEAT CONTENTS OF VARIOUS GASES[1]

Temp °F	Relative heat content in Btu per pound (at atmospheric pressure)								
	O_2	N_2	Air	CO	CO_2	SO_2	H_2	CH_4	H_2O
60	0	0	0	0	0	0	0	0	0
100	8.8	9.9	9.6	10.0	8.0	5.9	137	21.0	...
200	30.9	34.8	33.6	34.9	29.3	21.4	484	76.1	
300	53.3	59.9	57.7	59.9	52.0	37.5	832	136.4	1165
400	76.2	85.0	81.8	85.0	75.3	54.4	1182	202.1	1212
500	99.4	110.3	106.0	110.6	99.8	71.8	1532	272.6	1259
600	123.1	136.1	130.2	136.3	125.1	89.8	1882	347.8	1307
700	147.2	161.7	154.5	162.4	149.6	108.2	2233	427.4	1355
800	171.7	187.7	178.9	188.7	177.8	127.0	2584	511.2	1404
900	196.6	213.9	203.4	215.6	205.6	146.1	2935	599.2	1454
1000	221.7	240.7	235.0	242.7	233.6	165.5	3291	691.1	1505
1200	272.5	294.7	288.5	297.8	290.9	205.1	4007	886.2	1609
1400	324.3	350.8	343.0	354.3	349.7	245.4	4729	1094.1	1717
1600	377.3	407.3	398.0	407.5	416.3	286.4	5460	1313.0	1829
1800	430.7	465.0	455.0	465.3	470.9	327.8	6198	1542.6	...
2000	484.0	523.8	513.0	523.8	532.8	369.1	6952	...	...
2200	539.3	583.2	570.7	583.3	596.1	411.1	7717	...	...
2400	594.4	642.3	628.5	643.0	659.2	452.7	8490	...	...
2600	649.0	702.8	687.3	703.2	723.2	495.2	9272	...	...
2800	702.8	763.1	746.6	771.3	787.4	537.5	10060	...	...
3000	758.6	824.1	806.3	832.6	852.0	580.0	10870	...	...
3200	816.4	885.8	866.0	894.0	916.7	622.5	11680	...	...
3400	873.4	947.6	925.9	956.0	981.6	665.0	12510	...	...
3600	931.0	1010.3	986.1	1018.3	1047.3	707.5	13330	...	...

II EXAMPLE CALCULATION ILLUSTRATING THE USE OF THE COMBUSTION TABLES (Based on Reference 1, Example 15, Page 54)

A boiler burns 10,000 cubic feet per hour of Pittsburgh natural gas.

DETERMINE:

A The gross heating value per hour for complete combustion.

B The available heat if the flue gases leave the heat exchanger at 500°F and complete combustion is achieved with theoretical combustion air.

SOLUTION:

A The gross heating value for Pittsburgh natural gas is 1129 BTU per cubic foot (Table 2). The gross heating value for the boiler equals 11,290,000 BTU per hour.

B The available heat for Pittsburgh natural gas at 500°F and theoretical combustion is calculated from the following ratio:

$$\frac{H_A}{H.V._G}\ (\text{specific fuel}) = \frac{H_A}{H.V._G}\ (\text{Fig. 3})$$

$$H_A\ (\text{specific fuel}) = \frac{H_A}{H.V._G}\ (\text{Fig. 3}) \times H.V._G\ (\text{specific fuel})$$

$$H_A\ (\text{Pitt. natural gas}) = \frac{H_A}{H.V._G}\left(\begin{matrix}\text{Natural}\\ \text{gas in}\\ \text{Fig. 3}\end{matrix}\right) \times H.V._G\left(\begin{matrix}\text{Pitt.}\\ \text{natural}\\ \text{gas}\end{matrix}\right)$$

$$H_A\left(\begin{matrix}\text{Pitt.}\\ \text{natural}\\ \text{gas}\end{matrix}\right) = \left(\frac{860}{1059} \times 1129\right)\ \text{BTU per cubic foot}$$

The available heat (H_A) for Pittsburgh natural gas is 915 BTU per cubic foot. The available heat for the boiler at 500°F and theoretical combustion equals 9,150,000 BTU per hour.

If 20 percent excess combustion air was used, the available heat at 500°F would be decreased to about 79 percent of the gross heating value for natural gas (calculated from Figure 4).

REFERENCES

1 Anon. North American Combustion Handbook, 1st Ed., Copywrite 1952 by North American Manufacturing Company, Cleveland, Ohio.

2 Hougen, O.A. Chemical Process Principles Part I, 2nd Ed., Copywrite 1954 by John Wiley and Sons, Inc.

Section 2

BURNING OF FOSSIL FUELS

Facts About Fuels

Natural Gas Burning

Gas Burning Equipment
Natural Gas Fired Installations-Design Considerations

Fuel Oil Burning

Oil Burning Equipment
Fuel Oil Burning-Design Parameters
Fuel Oil Burning-Good Operation Practices

Coal Burning

Coal Burning Equipment
Coal Burning-Design Parameters
Coal Burning-Good Operation Practices

Selected Publications

Underfeed Stokers
Spreader Stokers
Another Look at the Traveling Grate Stoker
Corroision and Deposits from Combustion Gases

FACTS ABOUT FUELS

L. N. Rowley, J. C. McCabe and B. G. A. Skrotzki*

I GAS

Of many gaseous fuels, only natural gas has any commercial importance in steam generation because manufactured gases run too high in cost. Usually byproduct gases have low heating values and are produced in relatively minor quantities. So they are ordinarily used at the production point and not distributed.

Natural Gas. The origin is not known but it is often found associated with oil, and the two fuels are believed to have a common source. Natural gas is produced in more than 30 states and widespread pipeline networks make it available in some part of nearly every state.

Natural gas is colorless and odorless. Composition varies with source, but methane (CH_4) is always the major constituent. Most natural gas contains some ethane (C_2H_6) and a small amount of nitrogen. Gas from some areas often called "sour" gas, contains hydrogen sulphide and organic sulphur vapors. Heating value averages about 1000 Btu per cu ft (20,000 Btu per lb) but may run considerably higher. Natural gas is usually sold by the cu. ft. but may be sold by the therm, which is 1,000,000 BTU.

II OIL

Petroleum and its byproducts furnish practically all commerically used liquid fuels. Geologists believe decomposition of minute marine growths or possibly, at times, of vegetable matter formed the oil that lies trapped in pools between layers of the earth's crust. This crude oil consists of 83-87% carbon and 10-14% hydrogen, plus traces of oxygen, nitrogen and sulphur. The hydrogen and carbon are combined as hydrocarbons.

Crude oil moves from well to refinery mainly by pipeline and tanker. Although virtually every state boasts some refining capacity, ten have almost 90% of the nation's total. Fuel oils move from refineries to nearby markets by truck, tank car and barge, with tankers serving seaboard areas.

Refining Processes. Since practically all liquid fuels are either products or byproducts of refining, the way they are made has more to do with their fuel qualities than the source of the crude. Refining consists of separating and, usually, recombining the hydrocarbons of the fuel oil into specialized products like gasoline, fuel oil, etc. Basic process is simple distillation, which separates the hydrocarbons into groups or "fractions" having the same range of boiling points. From light to heavy, typical fractions are: (1) naphtha (2) gasoline (3) kerosene, and (4) gas oil. These are the distillates; the remainder, or residual, is a heavy fuel oil. Products of simple distillation are called straight-run.

Simple distillation is sometimes the whole story, but in modern refining it is only the beginning. To secure greater gasoline yields, fractions heavier than gasoline are usually cracked, that is, decomposed by heat and pressure, with or without a catalyst. Of the new hydrocarbons resulting, some are lighter and some heavier; these are likewise separated according to boiling range. Cracking, unlike simple distillation, actually changes the hydrocarbon structure so crude oil yields more valuable lighter hydrocarbons (gasoline) and proportionately less heavy ones.

Commercial Fuel Oils. Fuel oils used commercially may be either distillates or residuals, and either straight run or cracked. Straight-run products become increasingly less common as refinery practice leans more

*"Fuels and Firing Power" pp. 77-83 (December, 1948.

heavily on cracking, and are, in general, premium grades. Thus the great bulk of commercial fuel oils are cracked products; distillates form the source for lighter grades used in domestic and some commercial and industrial burners, whereas residuals supply the heavy oils for larger commercial and industrial units.

Refinery wastes, which have little or no commercial value, are usually burned at the refinery or in adjacent plants. They include acid sludge, tars and tank cleanings or "bottoms."

Specific Gravity. Since hydrogen has a much higher heating value and lower atomic weight than the other principal element in fuel oil, it's easy to see that the proportions of carbon and hydrogen affect both specific gravity and heating value. Because of this, specific gravity forms a reliable guide to an oil's heating value.

Specific gravity in degrees API (American Petroleum Institute) is found by dividing specific gravity with respect to water (at 60°F)into 141.5 and subtracting 131.5 from the answer. Gravity in degrees Baume is found in the same way except the numbers are 140 and 130, respectively. For practical engineering work, the two gravity scales may be considered the same.

Viscosity. The relative ease or difficulty with which an oil flows is its viscosity. It is measured by the time in seconds a standard amount of oil takes to flow through a standard orifice in a device called a viscosimeter. The usual standard in this country is the Saybolt Universal, or the Saybolt Furol, for oils of high viscosity. Since viscosity changes with temperature, tests must be made at a standard temperature, usually 100°F for Saybolt Universal and 122° F for Furol.

Viscosity indicates how oil behaves when pumped and, more particularly, shows when preheating is required and what temperature must be held.

Flash and Pour. Flashpoint represents the temperature at which an oil gives off enough vapor to make an inflammable mixture with air. Results of a flashpoint test depend on the apparatus, so this is specified as well as temperature. Flashpoint measures oil's volatility and indicates maximum temperature for safe handling.

Pour point represent lowest temperature at which an oil flows under standard conditions. Including pour point in a specification insures that an oil will not give handling trouble at expected low temperature.

By centrifuging a sample of oil, amount of water and sediment can be found. These are impurities and while it is not economical to eliminate them, they should not occur in excessive quantities (not more than 2%). Incombustible impurities in oil, from natural salts, from chemicals in refining operations, or from rust and scale picked up in transit, show up as ash. Some ash-producing impurities cause rapid wear of refractories and some are abrasive to pumps, valves and burner parts. In the furnace, they may form slag coatings.

All tests above are covered by ASTM standards, which should be consulted for details of apparatus and methods (ASTM Standards on Petroleum Products and Lubricants, American Society for Testing Materials, 1916 Race St, Philadelphia 3, Pa.).

Fuel oils have a tendency to deposit sludge in storage; this may be aggravated by mixing oils of different character as when deliveries from two sources go into the same tank. These simple rules avoid trouble when oils are mixed: (1) Straight-run residuals can be mixed with any straight-run product, and cracked residuals with straight-run residual (2) cracked distillate can be added as a third constituent, but (3) cracked residual cannot be added to straight-run distillate.

III COAL

Three-hundred-million years ago, in swamp forests of the Carboniferous Age, the foundation of our present reserves was laid. For 50 million years, giant trees and ferns grew and fell, to decay and form rich peat bogs. Floods buried the bogs under layers of sediment, only to subside and permit the growth-and-decay cycle to begin again. As millions of years passed, pressure, heat and time worked to drive off some volatile matter, to harden the mass, and to turn it into the carbon-substance we call coal.

Different kinds contain different amounts of carbon substance depending on the age of the deposit and the conditions under which it formed. Next to the original peat, the "youngest" form is lignite, high in moisture and low in fixed carbon. Older coals, higher in "rank," contain more fixed carbon.

Analyses. Various tests and methods of analysis express coal qualities in figures instead of words. Principal characteristics are expressed in what is known as a proximate analysis, as distinguished from an ultimate analysis, which shows the exact chemical composition of a fuel, without paying any attention to the physical form in which the compounds appear. As we have seen, this gives data needed for combustion calculations.

For a better picture of coal's behavior in a furnace, the proximate analysis determines the percentage of (1) moisture (2) ash (3) volatile matter and (4) fixed carbon. These percentages add up to 100. In addition, it is customary to determine: (1) total amount of sulphur, as a separate percentage (2) ash-fusion temperature, and (3) heating value.

Reporting Analyses. There are five ways to report an analysis, although only the first three are likely to be met in power-plant work: (1) as received (2) air dried (3) moisture free (4) moisture and ash free, and (5) moisture and mineral free. As the name implies, the as-received analysis reports the condition of coal as delivered to the laboratory. This comes closest to giving the conditions as shipped or as fired, the values desired in practical work. Loss or gain of moisture between time of sampling and analysis depends on the kind of coal, size, weather conditions, and method of handling sample.

Following paragraphs discuss the various characteristics of coal (those reported in proximate analyses and others) and how they affect the value of coal in power-plant operation. For details on equipment and procedures for testing coal, consult ASTM Standards on Coal and Coke (1948).

Moisture. All coal contains some natural moisture (1 to 5% in Eastern coals and up to 40% in some lignites). This inherent moisture lies in the pores and forms a true part of the coal, being retained when it is air dried. Surface moisture depends on conditions in the mine, and during transit.

Moisture must be transported, handled and stored; its presence in large amounts increases cost and difficulty of these operations. Looked at another way, moisture replaces an equal amount of combustible material and thus decreases the heat content per lb. In addition, some heat liberated in the furnace goes to evaporating moisture in the fuel and superheating the vapor.

A Mineral Impurities

Ash. This incombustible mineral matter, left behind when coal burns completely, differs from "ashes," as the power-plant man knows them, because ashes taken from a furnace always contain some unburned coal.

Like moisture, ash is an impurity that increases shipping and handling costs. It must be removed from the furnace and the plant, usually requiring additional equipment and expense. Recent research shows that amount and character of ash constitutes the biggest single factor in fuel-bed and furnace problems like clinkering and slagging. An increase in ash content usually means an increase in carbon carried to the ashpit.

Volatile Matter. In a way not yet clearly known, coal holds combustible gases such as methane and other hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen. Heat releases these gases.

Percentage of volatile matter indicates the amount of gaseous fuel present and thus bears a direct relationship to firing mechanics. It affects furnace volume and arrangement of heating surfaces.

Fixed Carbon. When the volatile matter distills off, a solid fuel is left, consisting, in the main, of carbon, but containing some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases. Subtracting percentage of moisture, ash and volatile matter from 100% yields a percentage called fixed carbon.

Sulphur. Although it burns, sulphur in coal is an undesirable element for powerplant use. It plays a part in clinkering and slagging, in corrosion of air heaters, economizers, breeching and stacks, and in spontaneous combustion of stored coal. It occurs mainly as iron sulphide (commonly known as pyrites), as organic sulphur, and in small amounts as sulphates. Only total sulphur is measured, although it is known that iron combined with the sulphur shares the blame for troubles laid to sulphur.

Ash Fusion. Temperature at which ash fuses is measured by heating cones of ash in a furnace arranged to produce a reducing atmosphere. Temperature at which the cone fuses down to a round lump is called softening or ash-fusion temperature. Other temperatures sometimes observed include that at which (1) cone tip starts to bend (initial deformation temperature) and (2) cone spreads out in a flat layer (fluid).

Ash-fusion temperature (and sometimes the spread between initial and softening, or softening and fluid temperatures) serves as the best single indicator of clinkering and slagging tendencies under given fuel-bed and furnace conditions.

Heating Value. If a coal sample is burned in a "bomb" calorimeter filled with oxygen under pressure, the higher heating value is measured. The consumer buys energy units when he buys fuel, and so the heating value plays a basic part in judging fuel values. Sometimes heating value of fuel may affect maximum capacity of a plant.

B Pulverizing Qualities

Grindability. Wide use of pulverized-fuel firing brought a need for tests to show the relative ease or difficulty of grinding different kinds of coal. ASTM tentatively approves two methods, ball-mill and Hardgrove. The first measures relative amounts of energy needed to pulverize different coals by finding the number of ball-mill revolutions needed to grind a sample so 80% passes a 200-mesh sieve (74 microns). The ball-mill grindability index, in percent, is found by dividing number of revolutions into 50,000.

In the Hardgrove test, a prepared sample receives a definite amount of grinding energy in a miniature pulverizer; results are measured by weighing amount passing a 200-mesh sieve. Multiplying weight passing the sieve by 6.93 and adding 13 to the product gives Hardgrove grindability.

Grindability values do not give a direct comparison of pulverizer capacity or power requirements. The latter are affected by size and type of pulverizer, and by feed size, moisture and fineness. The operator should check behavior of coals in his pulverizer against standard indices to establish a relation between pulverizer performance and grindability.

Caking, Coking. Considerable confusion exists regarding proper use of these two terms. Heating coal drives off volatile matter, leaving behind practically pure carbon. This is coke. It may take the form of small powdery particles or may fuse into lumps of varying size and strength. Swelling may occur. In commercial coke-making, "coke" generally refers to lumps of marketable size; coking coals make them.

Coke formation, in one shape or another, represents an intermediate combustion stage in any fuel bed; the difference lies in whether a plastic stage occurs and lumps of coke form. Coals that become plastic and form lumps or masses of coke are called caking coals while those that show little or no fusing action are free-burning.

Caking properties of a coal and the nature of the coke masses formed (size, strength, etc.) are valuable indicators of behavior in fuel beds. A recently adopted test measures free-swelling index and a proposed test determines agglutinating value, and approximate measure of that material in coal that fuses and becomes plastic.

C Sizing of Coal

Size stability. Ability of coal to resist breakage is size stability; its opposite is friability, the tendency to break or crumble into smaller pieces. Where plant conditions make size an important factor, friability must be considered to get a rough idea of the difference likely to exist between size as shipped and as fired. ASTM has two tentative tests for these complementary properties: (1) drop-shatter test indicates resistance to breakage from ordinary handling (2) tumbler test, the effect of rougher handling in mechanical conveyors, feeders, etc.

Anthracite Sizes. Standard sizes are: broken, passing a 4 3/8-in. retained on 3 1/4 in.; egg, 3 1/14 to 2 7/16; stove, 2 7/16 to 1 5/8; chestnut, 1 5/8 to 13/16; pea, 13/16 to 9/16; No. 1 buckwheat, 9/16 to 5/16; No. 2 buckwheat (barley), 3/16 to 3/32. Culm or river coal is refuse from screening anthracite into prepared sizes. It is now often dredged from rivers into which it was originally dumped.

Bituminous Sizes. There is little standardization of either screen openings or names given to sizes. Run of mine is unscreened coal as it comes from the mine; a steadily decreasing amount is shipped today because of demand for prepared sizes for domestic stokers, etc. Screen openings usually designate sizes. A "2-in. nut-and-slack" normally means all coal passing a 2-in. screen; amount of different sizes present may vary widely. Occasionally a limitation is placed on percentage of fines. So-called between-screen sizes (everything passing one screen and retained on another) give a closer idea unless spread between screens is large. Coal size affects fuel-bed nature, draft required, density of coke formed, amount of unburned-carbon loss.

D Preparation, Storage

Coal Preparation. Many producers now offer cleaned or washed coals as products having a higher value to users. Cleaning or washing removes impurities and so lowers ash content; it also tends to reduce sulphur in the form of pyrites and raise ash fusion.

Treating coal with refined petroleum oils of 100-600 ssu, or blends of petroleum products, allays dust nuisance in handling by eliminating most of the fine dust and much of the coarse. Treatment remains effective more than a year, even in outdoor storage. Experience seems to show that oil treatment reduces both moisture absorption of coal and freezing troubles. Tests show it does not increase spontaneous heating, nor appreciably affect burning.

Storing. Coal exposed to atmosphere combines with oxygen, liberating heat. Such slow oxidation is called weathering. It dulls the appearance of coal, causes reduction in size, impairs firing and coking qualities, and lowers heating value. These changes are practically unnoticeable for anthracite, and slight for most bituminous coals. Low-rank bituminous coals and lignite suffer more markedly. Loss of heating value over a 5-year period might run 1-3% for West Virginia and Pennsylvania coals, 4-6% for Illinois.

If heat liberated by oxidation is confined to a small area, temperature rises, increasing reaction rate. This cycle of rising temperature and faster oxidation continues until "hot spots" form and spontaneous combustion occurs.

To guard against such troubles: (1) Remember that small sizes pack tighter and present more surface, making them likelier to heat. (2) Avoid piling coal in hot weather or in a heated space. (3) Don't crush before piling, and watch pile closely during first three months since fresh surfaces oxidize more readily. (4) Avoid segregation of sizes by building the pile up in layers, leveling off and compacting each. (5) Check pile regularly, especially 5 to 8 ft below the surface of the flanks - temperature over 140-150 F means danger point is reached at which coal must be withdrawn. For storage details, see POWER, Sept. 1942, p 643.

Sampling. Coal composition varies within a given seam or mine and even between points several feet apart on the face. Although shipped from one point, coal composition varies from car to car and from one part of a car to another. Understanding the nature of all these variations makes it possible to use laboratory tests intelligently.

To begin with, a laboratory analysis, according to approved standards, represents within an extremely small margin of error characteristics of the sample on which it is made. How well the analysis represents the lot of coal involved depends on sampling methods. Until recently, size of gross sample was thought to be of major importance for accurate sampling.

Recent research shows accuracy of sample depends on number and size of increments composing it rather than on its weight. Proof of this point makes possible use of much smaller samples and simplifies reduction of gross sample to laboratory dimensions.

E Sampling Procedure

New ASTM standard distinguishes between "commercial" and "special-purpose" sampling and bases sample size and number of increments on coal size and expected ash content. Note that increment refers to quantity of coal obtained by a single sweep of the sampling instrument; where possible coal should be sampled while in motion.

The standard provides for mechanical sample preparation and subdivision by large and small riffle samplers like those used in the laboratory. Commercial procedure is designed so 95% of test results fall within plus or minus 10% of ash content of coal sampled. Correct determination of ash value indicates accuracy of other results.

Knowing how closely a given analysis represents a given sample and lot of coal, we need also to know how reliable one test may be in predicting the average for a series of shipments, or, if average quality is known, what variation might be expected in individual shipments. Recent research shows that for bituminous coals of less than 9% ash, one-half of ash determinations depart from the average by no more than 0.5%; for coals of more than 10% ash, deviation is about twice as much.

Common sense indicates that one test from one sample from one shipment is a poor guide. Statistical studies show that an average of ten shipments is three times as accurate as a single test while an average of 20 tests is 4.5 times as accurate. Beyond 20 tests, gain in accuracy is small.

GAS BURNING EQUIPMENT

On the face of it burning gas is simple, because the fuel is ready for combustion and requires no preparation in the strict sense of the word. Nevertheless, the remaining parts of the job - proportioning, mixing and burning - can be handled in a variety of ways and their characteristics need to be known for sound selection of equipment and successful operation.

I ATMOSPHERIC BURNERS

Gas burners differ mainly in the way air and fuel mix. Perhaps most familiar is the so-called atmospheric burner. One form appears quite generally in the ordinary house-hold gas range. In it the momentum of the incoming low-pressure gas stream is used to draw in, or aspirate, part of the air needed for combustion. A shutter or similar device regulates amount of air so induced. Gas and air together pass through a tube leading to the burner ports, mixing in the process. The mixture burns at the ports of openings in the burner head (with a blue, nonluminous flame. Secondary air is drawn into the flame from the surrounding atmosphere. Larger counterparts of this general burner type, having ring or sectional burner heads with many ports, are used to fire small boilers and industrial equipment.

A single-port atmospheric burner is shown in Figure 1. Needle valve controls gas flow through the spud; air is drawn in around the shutter at the end. The resulting mixture passes through the tube and burns at its end. Single-port burners may be grouped, several banks high and wide, to serve larger furnaces.

Although physically simple, such a burner must be proportioned with considerable skill to conserve the relatively small amount of energy in the low-pressure gas stream. It is this energy which entrains the primary air. How well this is done depends on primary-air percentage, gas-orifice size, ratio of mixer throat to burner port area and, in boilers especially, furnace draft.

II PREMIX PERCENTAGE

With burner-port size and shape fixed, nature of burning depends largely on amount of primary air, or premix. With premix low, flame is long and pale blue. It may have a yellow tip, indicating some cracking and presence of free carbon. Increasing primary air shortens the flame as burning becomes more rapid, and greenish inner cone appears. When speed of burning, or flame propagation, exceeds that of gas issuing from the port, flame flashes back into mixing tube.

Operation is generally satisfactory with 30 to 70% premix; in some special designs 100% primary air is used. This premix range gives a turn down, or capacity range, of about 4 to 1. Usually premix and capacity ranges are somewhat narrower.

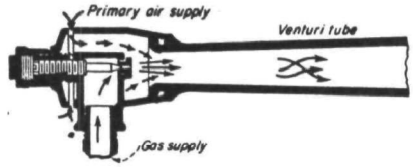
Secondary air is usually drawn in around the burner and the amount thus depends on the area of the opening and the draft. Control may be effected by varying draft or, sometimes, by adjusting opening area by shutters.

The so-called atmospheric burner is one example of a general class, in which the energy of one fluid is used to aspirate the other and in which part or all primary air mixes with the fuel in the burner body. The "high-pressure" burner uses gas at about 20 to 30 psig and air at atmospheric pressure. Another type uses compressed air, and the gas is at atmospheric pressure. The burner of Figure 6 expands high-pressure gas through two venturi-sections in series to obtain thorough mixing in a short distance.

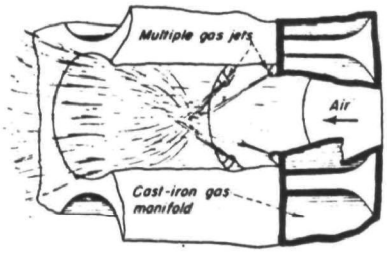
III REFRACTORY BURNERS

For boiler firing, a somewhat different type of burner finds wide use. It depends on natural or fan draft to draw in all air required for combustion; hence draft conditions are most important. Design of Figure 2 employs

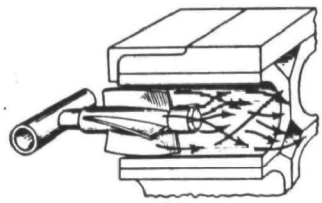
*Based on the publication by: Rowley, L. N., McCabe, J. C., and Skrotzki, B. G. A. Fuels and Firing. Power, pp 84-85. December 1948.



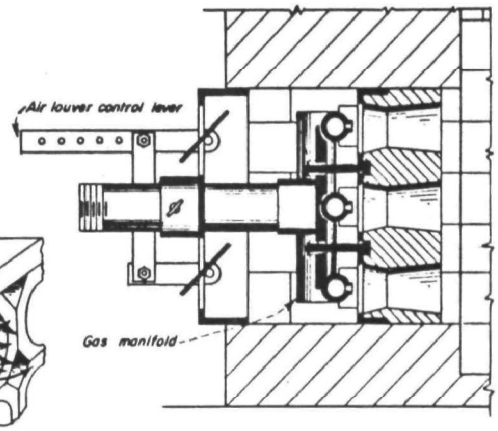
1 Atmospheric gas burners pull in their primary air for combustion by the action of a stream of low-pressure gas expanding through an orifice



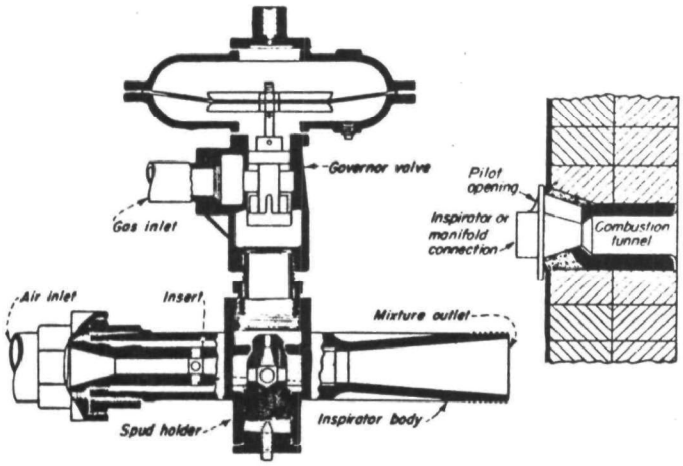
2 Premixing of fuel gas and air needed for combustion takes place in a mixing chamber outside the furnace proper



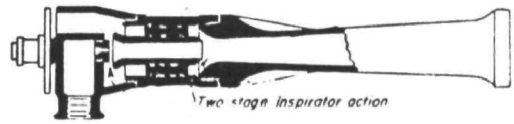
3 Vanes placed in the path of incoming air to this tunnel burner act to impart swirling motion to stream



4 Gas issues from a number of spuds connecting to vertical and horizontal manifolds. Primary air enters around the spuds

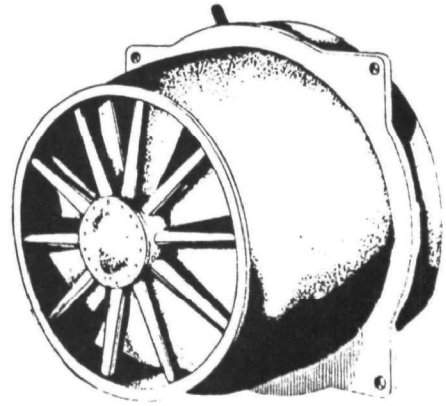


5 So called low-pressure gas-burner systems work with air under pressure and gas at atmospheric conditions. An inspirator governor, left above, delivers gas-air mixture at proper pressure to burner blocks, right above



6 Two-stage burner operates on high-pressure gas; passes it through two venturi sections in series. Primary air enters shutter, at left, under induction

7 High-pressure gas issues from jets in the spider and reaction spins the spider to rotate the fan. Resulting turbulence gives prompt, thorough mixing



multiple gas jets, which discharge into the air stream in such a way that violent agitation results in a short mixing tube or tunnel of refractory. In the burner of Figure 3, turbulence vanes impart a swirling motion to the air entering the tunnel. Each of the small jets of gas issuing from the multiple-jet orifice entrains with the air and impinges it outward against the tunnel walls. This action gives turbulent, thorough mixing.

In the burner shown completely assembled, Figure 4, vertical manifolds connect horizontal tubes, which contain individual gas orifices for the 15 tunnel blocks forming the complete burner (3 high, 5 wide). Louvers in front of the burner assembly control air admission. Each orifice discharges into a refractory mixing tube or tunnel.

In burners of this type the refractory tunnel aids in heating the mixture for ignition and protects metal burner parts from high temperature. The flame can be made relatively luminous, for high radiant-heat transfer.

Large steam-generating units often employ a high-pressure (2 to 25 psi) gas burner of the gas-ring, Figure 8, center-diffusion tube, or turbulent, Figure 7, design. The gas-ring, Figure 8, has an annular manifold located between air register and furnace wall surrounding burner opening. Orifices drilled in this ring spray gas angularly across an incoming air stream controlled in quantity, velocity and rotation by the registers.

IV FAN-MIX BURNER

In the burner of Figure 7, gas issues from jets drilled at an angle in a rotating spider. Resulting reaction spins the spider and with it the connected fan. A shutter controls air drawn in, to maintain desired fuel-air ratio. Thorough mixing of gas and air result from the turbulent interaction of jets and air stream; combustion is completed close to the burner.

Thus far designs in which fuel and air mix in or at the individual burner have been discussed. Higher burner head pressure to overcome variable furnace draft, high overload capacity, uniform air-gas mix at all loads, and single-valve control may be had in a system in which mixture is made at one point and supplied to several burners. Such a system is shown in Figure 5. This is the low-pressure type; gas is at atmospheric pressure while air is at 1 to 2 psi.

V INSPIRATOR GOVERNOR

Heart of the system is the inspirator governor, left, Figure 5. Air passes through the venturi tube at high velocity to create a low-pressure region at the end of the straight run where gas ports are located. This pulls atmospheric-pressure gas through the ports into the throat and produces mixing. As the mixture expands through the inspirator body its velocity is converted to pressure.

Gas enters the governor under pressure and flows through the governor valve. A passage through the governor valve keeps pressure at governor outlet and on the under side of the diaphragm the same. With atmospheric pressure on the other side of the diaphragm, governor delivers gas at atmospheric pressure.

The mixture leaving the inspirator governor contains all air needed for combustion. An air valve controls the burning rate. The complete gas-air mixture goes from the inspirator-governor to a number of individual burners, usually the tunnel type shown at the right in Figure 5. This principle of supplying a complete mixture to a number of burner units is also found in systems operating with high-pressure gas and atmospheric air.

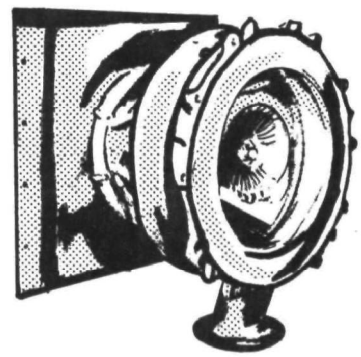


Figure 8. Center-Diffusion Tube Gas Burner Design. Combination gas and oil burner uses either fuel or both together; same register regulates primary air supplied

NATURAL GAS FIRED INSTALLATIONS-
DESIGN CONSIDERATIONS

Kurt S. Jaeger*

I INTRODUCTION

The following will consider the major design parameters for natural gas fired heat generating installations and the fundamental requirements for proper operation of the combustion equipment which is normal to such installations.

The two major factors which control all other system design considerations are:

1 The heat exchanger or vessel which is to be fired;

2 The characteristics and conditions of the gas to be burned.

A third factor which must be considered with these two is:

3 The exhaust system for handling the products of combustion.

While this factor is usually dependent upon Factor 1, it in turn will have an ultimate effect on equipment selection and performance.

Let us represent in block form these three factors from which all other design considerations will arise (Figure 1). This diagram will provide the basis for looking into each factor separately and observing how their individual characteristics correlate and interlock to provide design information for the entire installation.

We will enlarge on this basic diagram one factor at a time, and as we go we will clarify terms and assign meaningful values to some of these terms.

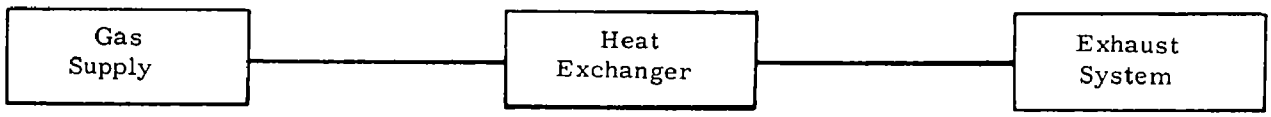


FIGURE 1

*Chief Burner Engineer, Forney Engineering Company, Dallas, Texas.

II Factor 1. THE HEAT EXCHANGER

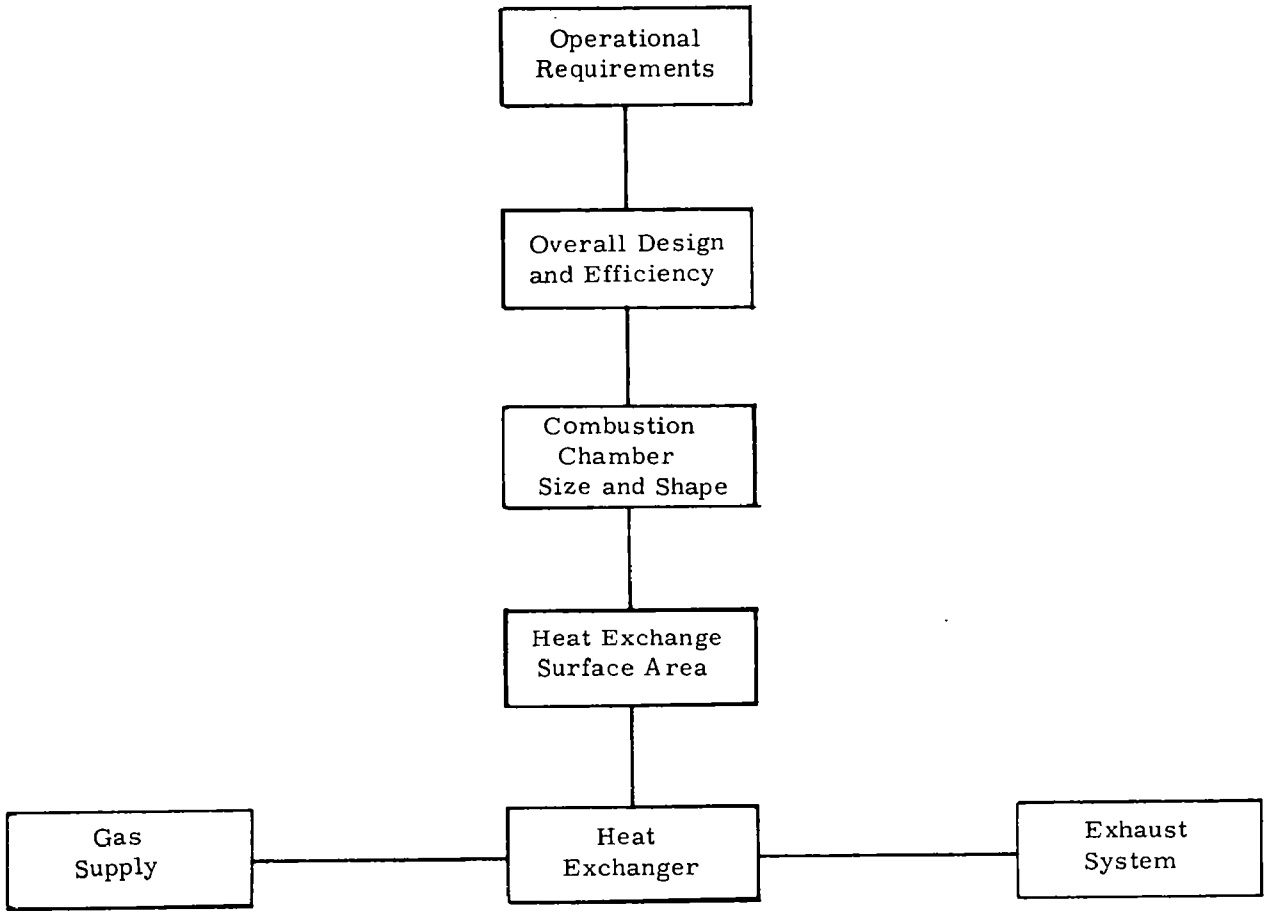


FIGURE 2

Here we see the characteristics of the heat exchanger which constitute its parameters:

A The total surface area of the heat exchanger (which is exposed on one side of its surface to hot gases and on the other side to the medium to be heated) is a major design consideration in that this is what basically determines the heat input required.

In commercial or industrial boiler installations, boilers are rated based on their square feet of heating surface.

Packaged boilers today are commonly rated on the basis that 5 sq. ft. of heating surface will produce 1 boiler horsepower, or 33,500 btu of useful heat, and some claim even less surface required per BHP.

This, then, is our first consideration - size.

B At the same time we are considering size and determining heat input requirements, we must know something of the overall design of the unit and thereby its overall efficiency. A heat exchanger with only one pass of the combustion products through it may not be nearly as efficient as one in which the hot gases make several passes; or, a boiler with large diameter flue tubes may not be as efficient as one with smaller tubes; so, design largely determines heat transfer efficiency and must be considered. This information is usually available from the manufacturer, and, generally speaking, will be in the neighborhood of 80% overall efficiency.

Our second consideration then is - efficiency.

C While we are looking at overall design we must closely examine the size and shape of the combustion chamber because, as we will see shortly, this characteristic will not only affect burner selection, but will also establish what our heat release in the combustion chamber will be, which in turn determines furnace temperatures. Normally, heat releases range from 30,000 to 70,000 btu per hour per cubic foot of combustion space, and furnace temperatures may range from 1300°F to 1900°F.

So, we are thirdly concerned about and governed by - combustion chamber size and shape.

D Last but not least, we must know what medium we are heating, and its end use, so we can determine the true heat input requirements, and properly select controls.

III Factor 2 - THE GAS FUEL

Figure 3 adds to our second major parameter the details which must be known in order to continue with our system analysis.

A The chemical analysis of the gas is the basis from which we determine how much air will be necessary for complete combustion, what we can expect in the way of combustion products, what the flame characteristics will be, etc. We can also determine if the gas contains any significant amount of troublesome elements (such as sulfur) which might require special attention.

Natural gas constituents normally include methane (CH_4), ethane (C_2H_6) in widely varying proportions, and lesser amounts of nitrogen (N_2) and carbon dioxide (CO_2).

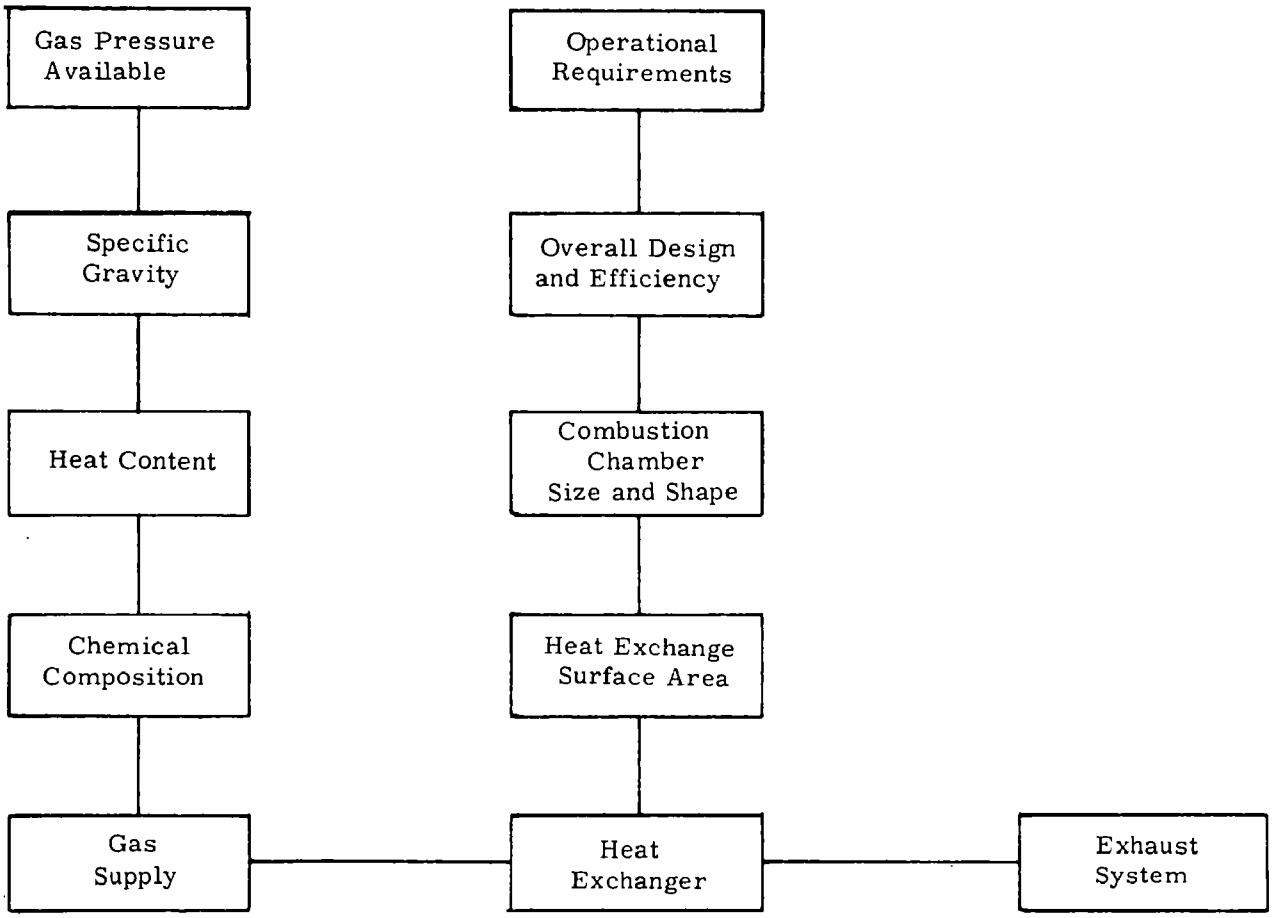


FIGURE 3

From the gas analysis, the heat content and the specific gravity of the gas can be calculated.

Generally speaking we can assign the following approximate values to these characteristics of natural gas:

Heat content - 1000 btu/cu. ft.
Specific gravity - 0.65
Air required for combustion - 10 cu. ft./cu. ft. gas (this does not allow for any excess air).

B The pressure at which the gas will be delivered at the installation is most important, and the point of delivery must be defined. All too often it is discovered too late that the pressure actually available in the boiler room is much lower than had been expected, simply because this point had not be clarified. Burner sizing is a function of available gas pressure, so a burner which is selected to provide a given input at a specified pressure will be too small at some lower pressure.

While these designations vary from one area to another, we normally specify gas pressure ranges as follows:

"LOW PRESSURE" - up to 8 osi (1/2 psig)
"MEDIUM PRESSURE" - 8 osi to 3.0 psig
"HIGH PRESSURE" - 3.0 psig and up

Before we develop Factor 3, and while we have Factor's 1 and 2 in mind, let us see what design considerations can be derived from the parameters we have established thus far (Figure 4).

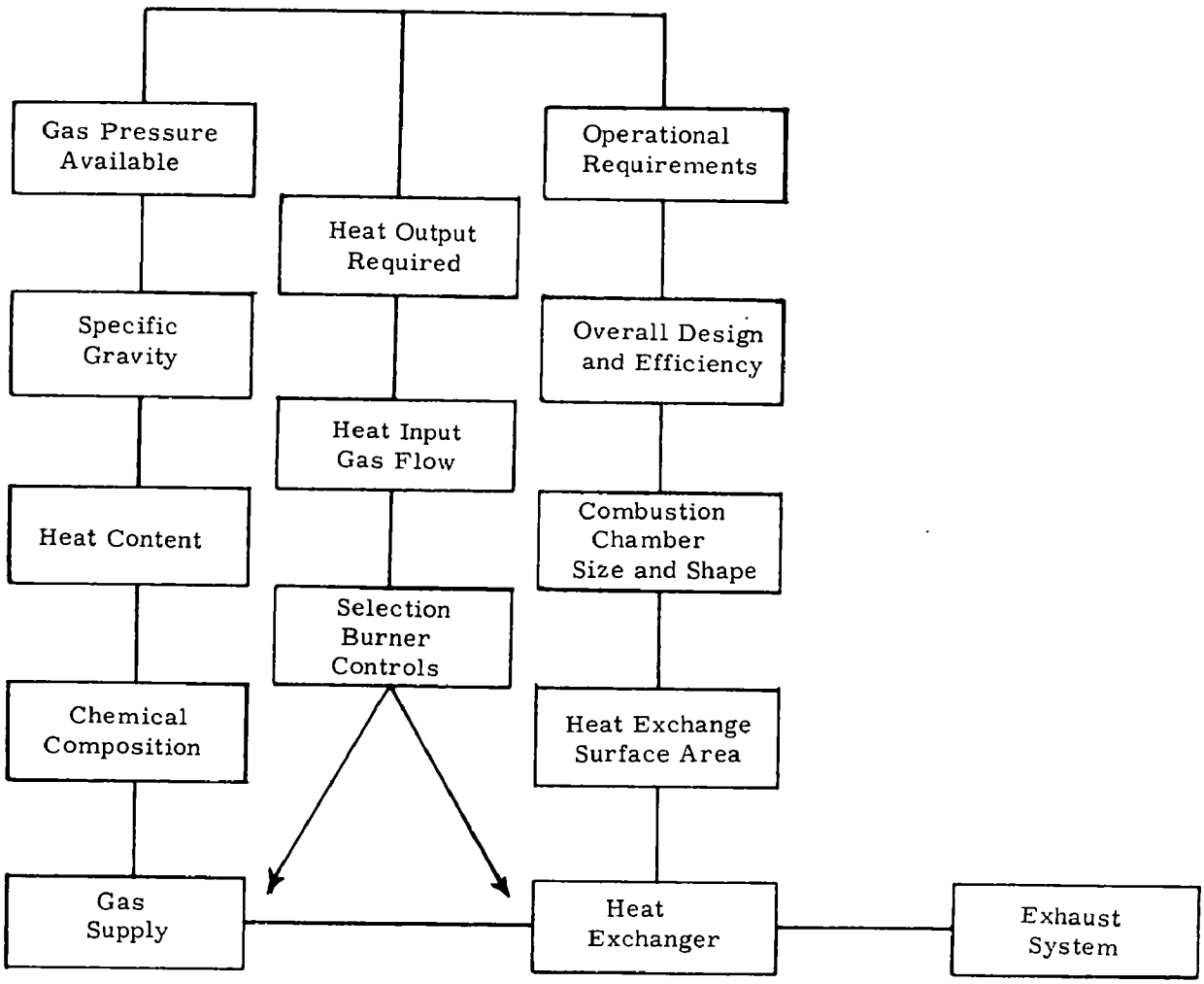


FIGURE 4

C Heat output - this really is a basic parameter which controls the size of the heat exchanger itself, but quite often we have the heat exchanger to start with, and our problem is to determine its heat output. This is a function of heat exchange area and the limits to which we can fire it.

D Knowing the heat output required, and the overall efficiency of the unit, we can determine heat input required and can check the feasibility of this required input against the combustion chamber size. If heat release per unit of combustion volume is too high, we must limit the input to a more reasonable value; this in turn reduces our available heat output.

E Having determined heat input, the volume of gas required to furnish that input can readily be determined by dividing the total input requirement (btu per hour) by the heat content of the gas (btu per cubic foot), with the quotient being expressed in cubic feet per hour.

F We now have gathered sufficient information from which to size and select the appropriate burner and control equipment; this selection involves not only consideration of all of the sub-parameters we have developed, but also some judgement regarding the several possible selections which will present themselves. So that you may appreciate this, we will review here various burner classifications in some detail.

IV BURNER CLASSIFICATION AND SELECTION

The two broad and general classifications into which all burners fall are "atmospheric" and "mechanical draft", which terms are descriptive of the means by which the burner obtains the air which it will mix with the gas preparatory to the combustion process.

The atmospheric burner depends entirely on the negative pressure within the furnace to draw combustion air through the burner assembly; or, it could be said that the difference between atmospheric pressure and furnace pressure results in air flow through the burner, hence the term "atmospheric".

In contrast, the mechanical draft burner includes as one of its components a blower which supplies all the combustion air to the burner, and therefore is not dependent on furnace pressure. The term "forced draft" is often applied to such burners, though it is usually restricted to burners which are designed to work against positive furnace pressures.

It would be well to note here that there are some burner designs which may be used either as atmospheric burners or forced draft burners. For instance, Figure 4a shows a burner which has been enclosed in a plenum, or windbox containing combustion air under a pressure higher than the furnace pressure. This same burner could have been used without the windbox if the negative pressure in the furnace had been sufficient to overcome the draft loss of the burner register. The point here is that the manner in which the burner is finally applied determines how it is classified in that particular instance.

Within these two broad classifications of atmospheric and mechanical draft, gas burners can be further subdivided into type and styles which can be defined as follows:

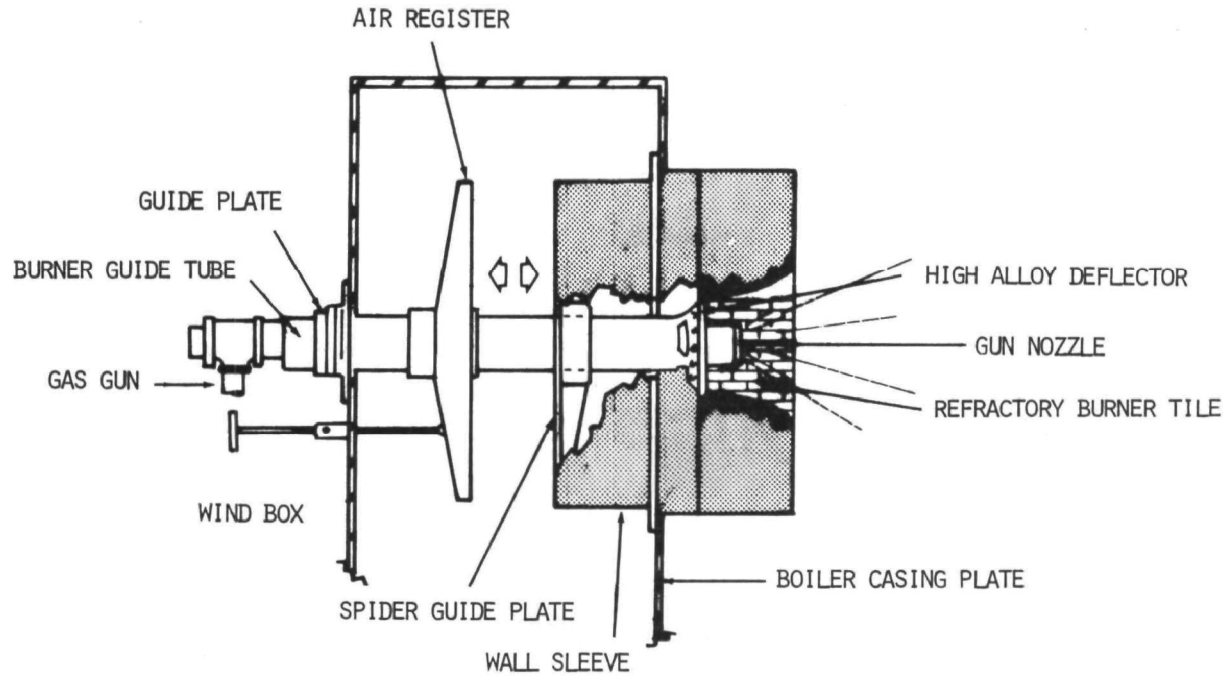


FIGURE 4A

A Premix - some or all combustion air is mixed with the fuel prior to reaching the burner nozzle; in atmospheric burners, this is usually accomplished with venturi shaped mixing tubes, and is limited to mixing primary air only. Secondary air flows around the venturi tubes and mixes beyond the burner nozzle (Figure 4b).

Some mechanical draft burner designs can also be classed as premix burners, but most are not. Premix burners are subject to "flash-back" - the burning of the fuel/air mixture within the venturi or mixing chamber.

Atmospheric premix burners can be arranged to fire either horizontally (inshot) or vertically (upshot) and are commonly used in conversion of existing boilers to gas, where chimney heights are sufficient to provide the proper draft. These burners are designed to operate on low and/or intermediate gas pressures.

B The post-mix or non premix burner has no facility for fuel/air mixing prior to the burner nozzle; this mixing takes place in the burner throat and is rapid enough to permit ignition in the burner throat. Post-mix burners are not subject to flash-back, but quite often show signs of instability if the fuel/air ratio is upset. These burners are usually mechanical draft because the turbulence required to obtain good and rapid mixing must be achieved by air pressures higher than are normally

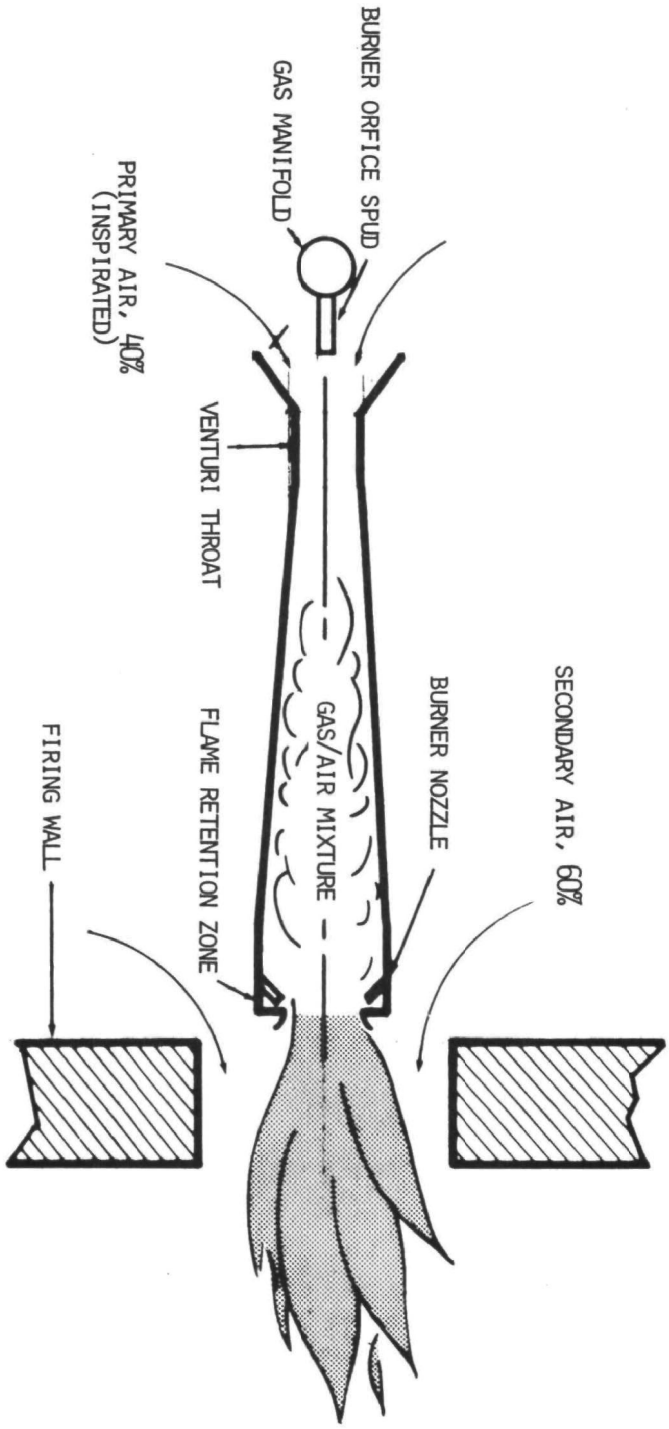

BURNER ORFICE SPUD
GAS MANIFOLD
PRIMARY AIR, 40%
(INSPIRATED)
VENTURI THROAT
FLAME RETENTION ZONE
GAS/AIR MIXTURE
BURNER NOZZLE
SECONDARY AIR, 60%
FIRING WALL

FIGURE 4B

available from negative furnace pressures. Post-mix burners are used in low, intermediate and high gas pressure ranges. Gun type burners and ring burners are two popular examples of post-mix burners, and are usually fired horizontally.

Post-mix burners usually offer a fairly wide turndown range (the ratio of maximum input to minimum input) because they are not subject to flash-back, though, as mentioned earlier, they may become unstable at one end of the range or the other.

The subject of turn-down is one which has often been debated, abused and the term mis-used. When we speak of turn-down as it applies to gas burners, we are talking about volume or burner capacity limits. Since a burner behaves essentially as an orifice, its input varies directly as the square root of the pressure applied to the burner manifold; therefore, if the pressure is increased 4 times, the input will increase the square root of 4, or 2 times. People have been known to describe burner turn-down ratios in terms of pressure rather than volume, and you can see how misleading this can be; the table below shows several pressure versus capacity relationships:

if pressure is increased by a factor of	burner capacity increases by a factor of
2.00	1.414
4.00	2.00
9.00	3.00
16.00	4.00
25.00	5.00
100.00	10.00

It is also well to remember that burner turn-down characteristics are only as important as the need for that turn-down exists. Some jobs run at reasonably constant loads, and do not require wide turn-down burners. Other jobs have widely varying loads and need burners which can match these loads and still maintain stable, efficient fires.

If we had for example, a load which went from its peak down to 1/4 its peak, we would like to have a burner which could give us a turn-down ratio of 4 to 1, but note that this means a pressure variation of 16 to 1. If our burner provided peak capacity at a manifold pressure of, say 1.0 psig, then at low fire the manifold pressure would be only 1/16 psig or 1 ounce. The question we need to satisfy ourselves on is "Can this burner operate in a stable and efficient manner at these two extremes?"

Burner selection also involves deciding on how many burners, as well as selecting the type. Some heat exchangers are designed with combustion chamber shapes which cannot be properly satisfied with only one burner; heat distribution is important to good heat transfer. A very wide furnace, for instance, could not be properly fired with one larger burner; or a very short furnace may require several small burners to prevent flame from impinging on the rear wall. These things are more a matter of judgement than they are a matter of hard and fast rules.

The final major consideration in burner selection has to do with the furnace pressure against which the burner must operate. In the case of the atmospheric burner, we must compare the draft loss of the burner selected against the available furnace draft; failure to do this often leads to inadequate burner input capability. Forced draft burners, on the other hand must have blowers which have both the capacity and static capability required to overcome the draft loss thru the boiler and breeching. The information regarding these burner characteristics should be available from the burner manufacturer, and should be checked against the system requirements.

V Factor 3 - THE EXHAUST SYSTEM

The exhaust system is the third parameter of our system, and we have already seen that its characteristics can affect burner selection.

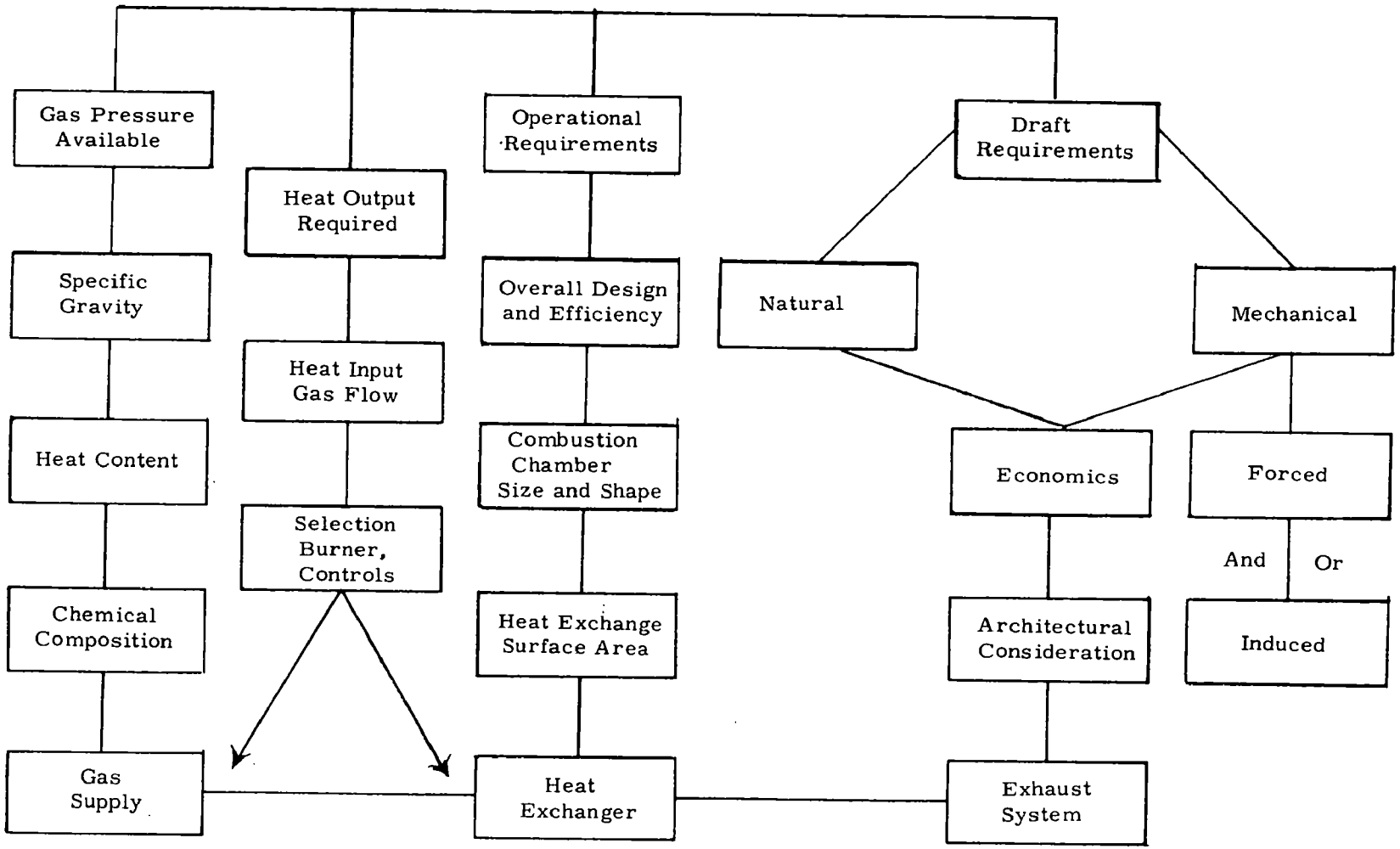

Gas Pressure Available
Specific Gravity
Heat Content
Chemical Composition
Gas Supply
Heat Output Required
Heat Input Gas Flow
Selection Burner, Controls
Operational Requirements
Overall Design and Efficiency
Combustion Chamber Size and Shape
Heat Exchange Surface Area
Heat Exchanger
Draft Requirements
Natural
Mechanical
Economics
Forced
And
Or
Induced
Architectural Consideration
Exhaust System

FIGURE 5

While the exhaust system is purely the means by which the products of combustion are removed from the heat exchanger, the design of it is as important to system operation as any other factor.

In considering the design of a new installation, such factors as architectural considerations, economics of installation and operation, and the type of boiler being considered all combine to dictate whether natural draft or mechanical draft is most desirable. If, for instance, we have a low profile, one story building and a pressure fired boiler (with forced draft burner equipment included), a short "stub" stack may be all that is needed to vent the system. On the other hand, if we have an existing stack which will deliver the necessary draft under all operating conditions, we could eliminate the initial cost and operating expense of mechanical draft fans, and consider the use of atmospheric burner equipment.

In between these two extremes we find cases where we can use an induced draft fan to provide negative furnace pressures, and still meet architectural requirements for low profiles. It is not uncommon to find installations on which both forced and induced draft fans are used.

Modern practices have been forcing the industry more and more toward mechanical draft equipment in order to satisfy the requirements for packaging, single responsibility, purging, and to provide more positive control over air flow characteristics. Since natural draft available from a stack depends on temperature differences inside and outside the stack, it is difficult to specify a definite purge period which would always meet with approval body requirements, because stack conditions can vary so widely. With mechanical draft equipment, you always have a known amount of air flow for purging, so you can assign a definite purge period.

A Stack draft determination

When considering natural draft stacks and their draft capabilities, we have found that the following approach provides satisfactory results:

$$\text{Theoretical draft (inch. wc at sea level)} = 7.6 \frac{(Ts - Ta)}{(Ts \times Ta)} H$$

where: Ts = Absolute gas temperature into stack, ^{o}F
Ta = Absolute air temperature, ^{o}F
H = Height of stack, in feet
Wc = Water Column

Actual draft = 0.80 theoretical draft (this allows for temperature drop and friction in the stack).

The table below is based on the above temperature variations on a 100 foot stack:

ACTUAL DRAFT AVAILABLE, IN. WC

Outside air temp., ^{o}F	Stack Temperature, ^{o}F			
	300	500	600	700
10	0.495	0.663	0.722	0.776
60	0.370	0.538	0.598	0.647
100	0.286	0.454	0.514	0.563

The draft available, whatever means is used to produce it, must be sufficient to overcome the total draft loss of the burner, the boiler and the breeching connecting the boiler to the stack or induced draft fan, with these draft losses being calculated at maximum firing rates.

To allow for losses in breeching runs, we usually allow 0.01 in. wc loss for each 10 feet of straight breeching and 0.05 in. wc for each 90^{o} turn in the breeching. Required breeching sizes are often specified by the boiler manufacturer (as are stack diameters and heights), but when they are not, sizing within these limits will prove adequate.

Breeching construction also seems to be subject to architectural requirements - sometimes with unhappy results. Wide, flat breechings often lead to pulsations which are usually attributed to the burner equipment; if breechings must be other than round in cross-section, they should

be adequately braced internally or externally so as to prevent "drumming" of wide metal panels. Breechings should also be insulated to minimize overheating of the boiler room area and to keep stack temperatures up, particularly if natural draft is involved.

The terminating elevation of natural draft stacks is usually sufficient to preclude objectionable discharges in the vicinity of occupied space. Stub stack and induced draft fan vent outlets, because they are so short, often terminate at or below window or air intake levels and can pose a problem. Due consideration should be given to the consequences of such termination elevations, keeping in mind that the possibility of control mal-adjustment could cause noxious products to issue from the stack.

The normal products of combustion of a natural gas fired appliance are not objectionable products and therefore do not constitute pollutants. This is not to say that natural gas fired installations are incapable of contributing to air pollution, but rather that so long as these installations are properly controlled and adequately checked by reliable instrumentation, they do not present an air pollution problem.

B Control and instruments

Finally, then, let us consider what constitues normal and adequate control and instrumentation.

Time does not permit discussion of the safety control aspects of installations such as we are concerned with, and since we are centering our attention on the control of combustion products, suffice it to say that safety controls are a major consideration, and that the requirements for them are well documented by approval body agencies such as Factory Mutual, Factory Insurance Association, etc.

VI PROPER OPERATION

The proper operation of a gas fired installation will include:

A Keeping the fuel supply in proper relation to the demand;

B Keeping the air supply in proper relation to the fuel supply.

This can be done either by a man who watches gauges and flame appearance and adjusts valves manually according to judgement, or it can be done automatically; in either case, the things which must be done are:

1 Regulate incoming gas supply to provide a constant gas pressure ahead of the control valve. It is good practice to use a regulator for each boiler so that the gas flow to one boiler is not disturbed as the other one turns on or off.

2 Control the gas flow to the burner through a gas control valve which receives information regarding the output of the heat exchanger, and adjusts in direct proportion to that output. On small installations, say under 100 HP, this is often done with just an on-off valve; on larger installations a control system with a modulating valve is usually economically justifiable.

3 Control of the combustion air flow is accomplished by the manipulation of dampers either at the outlet of the heat exchanger, or at the inlet of the burner, or at both points. On small, on-off installations this may be accomplished simply by linking the on-off valve lever to the burner louver, in conjunction with a barometric damper in the flue outlet, or a draft controller which measures furnace draft and positions the boiler uptake damper to control the draft.

The more elaborate systems, such as are found on installations of 500 HP and up, actually meter the fuel flow and air flow and adjust automatically to compensate for flow changes.

Failure to maintain proper air/fuel ratios can lead to or be detected by the following:

a High excess air - evidences of which are:

1) Flame extremely blue and "hard" (lean)

2) Excessive combustion roar

3) Burner vibration, pulsation or flash back

4) Sharp, acrid odor of "aldehydes"

5) High stack temperatures (normal boiler temperatures will run about 125-150°F above steam temperatures, or from 350° to 550°F).

6) Flame front blowing off burner nozzle

7) Flame extinction

8) Excessive gas consumption

b Insufficient air - evidences of which are:

1) Flame extremely rich; will have orange-red appearance and seem to roll in furnace.

2) Smoke issuing from stack

3) Soot deposits on heat exchanger surfaces

4) Burner pulsation

5) Production of carbon monoxide (toxic and odorless) - incomplete combustion

6) Flame front leaving burner nozzle

7) Excessive gas consumption

This is an appropriate point to mention one of the most common causes of insufficient combustion air, and the one most often and easily overlooked - inadequate fresh air openings into the boiler room. It is not enough simply to have the boiler room door open to another room, or to count on windows being open to the outside. There must be some permanent provision to assure that fresh air will always be supplied to the combustion equipment.

One of the first indications of inadequate air supply is a hot, stuffy feeling in the boiler room. It must also be kept in mind that combustion air flow through an opening into the boiler room requires a difference in pressure across the opening, so the draft system must be able to overcome this pressure drop as well as the drops through the rest of the system. For instance, openings which provide 0.50 square feet for each million btu/hr. of gas burned will result in a pressure drop across the opening of approximately 0.012 in. wc; less opening per unit input will increase pressure drop by the square of the reduction ratio.

Some of the above effects are recognized by the senses of sight, hearing and/or smell, while others are best determined by instrumentation.

Flue gas quality is measured by a chemical or electrical analyzer which periodically pulls a sample of flue products into an analyzing chamber and measures its characteristics in terms of CO_2, O_2 and CO.

Normal flue gas products will contain from 9% to 11% CO_2, and 6% to 3% O_2 and no CO; normally, the higher the CO_2, the lower the O_2 content in a flue gas sample. It is possible,

however, to be misled by taking a sample of CO_2 only; referring to Figure 5a, it can be seen that the % CO_2 in a flue gas is at its peak, or "ultimate CO_2" when the % excess air is zero. Therefore, with either an increase or decrease of combustion air, the % CO_2 will go down. Note how it is possible, for instance to have, say, 8% CO_2 and still have an air deficiency. If you had an instrument which would record % CO_2 only, you could easily determine which side of the peak you are on by taking a second reading after having increased the air; you then know your first reading was on the wrong side of the peak.

Associated with flue gas analysis is the stack temperature reading; using the CO_2 reading, you can determine approximate combustion efficiency, or "flue loss". The higher the stack temperature for a given CO_2, the lower the combustion efficiency. Figure 5b provides a nomograph which can be quite useful in approximating combustion quality.

Particularly in the case of atmospheric equipment, another very useful instrument is a furnace draft gauge, which will indicate the pressure within the combustion chamber. This reading can be helpful in avoiding accidental positive furnace pressures and can give us forewarning when some unknown occurrence has affected our available draft.

There are other instruments to be sure, but these plus visual observation are sufficient to help keep any installation in balance.

VII CONCLUSION

This has been a rather broad coverage of design parameters for industrial gas burning installations, with little detail in any one area. Looking again at the completed block diagram, Figure 6, we realize that the heat exchanger and its characteristics, the gas supply and its peculiarities, the exhaust system and its control system are all interrelated and must be considered concurrently in evaluating the overall installation. With this observation, we shall have gained an insight that seems to have escaped many engineers for many years.

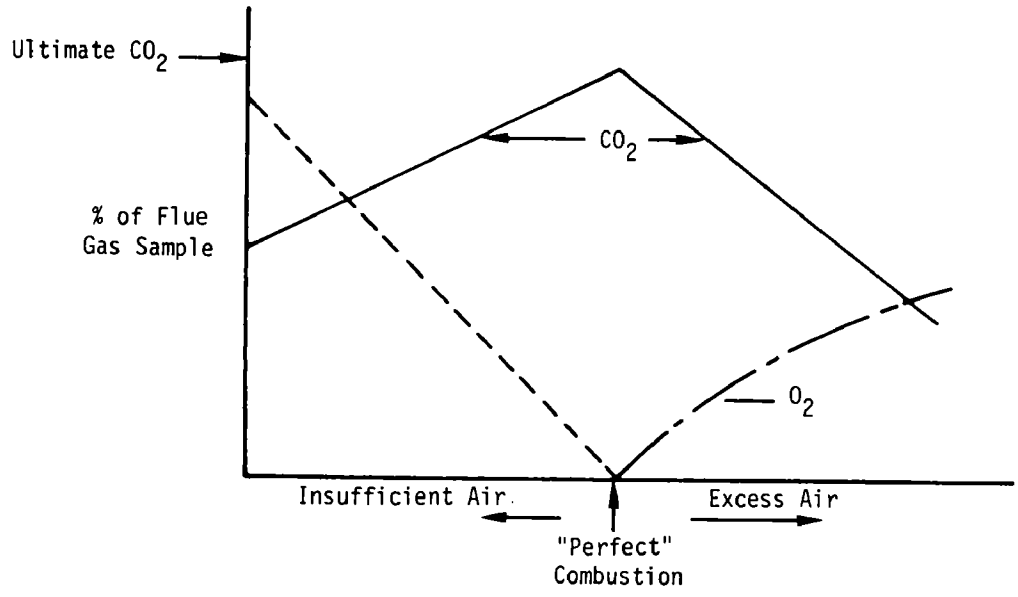


Figure 5A

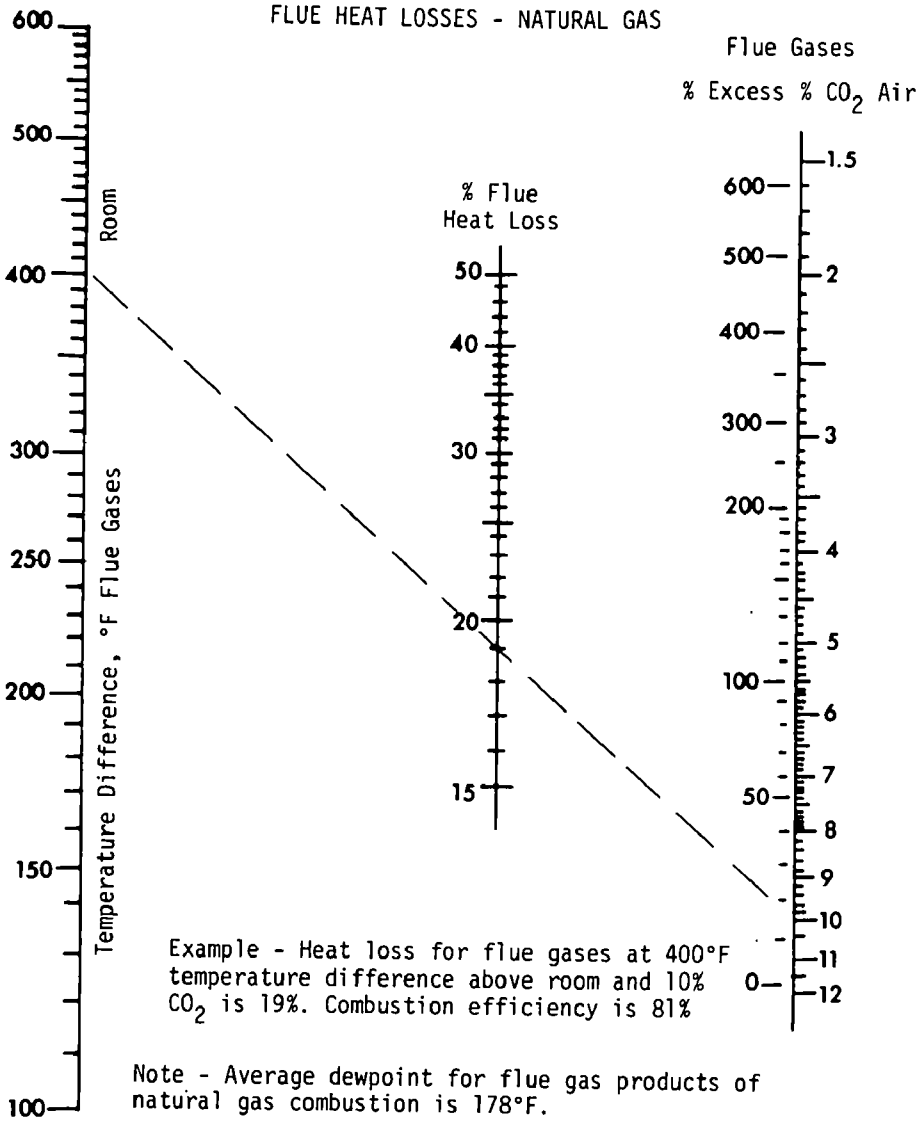

FLUE HEAT LOSSES - NATURAL GAS
Flue Gases
% Excess % CO_2 Air
Temperature Difference, °F Flue Gases
Room
600
500
400
300
250
200
150
100
% Flue
Heat Loss
50
40
30
20
15
600
500
400
300
200
100
50
0
1.5
2
3
4
5
6
7
8
9
10
11
12
Example - Heat loss for flue gases at 400°F temperature difference above room and 10% CO_2 is 19%. Combustion efficiency is 81%
Note - Average dewpoint for flue gas products of natural gas combustion is 178°F.

Figure 5B

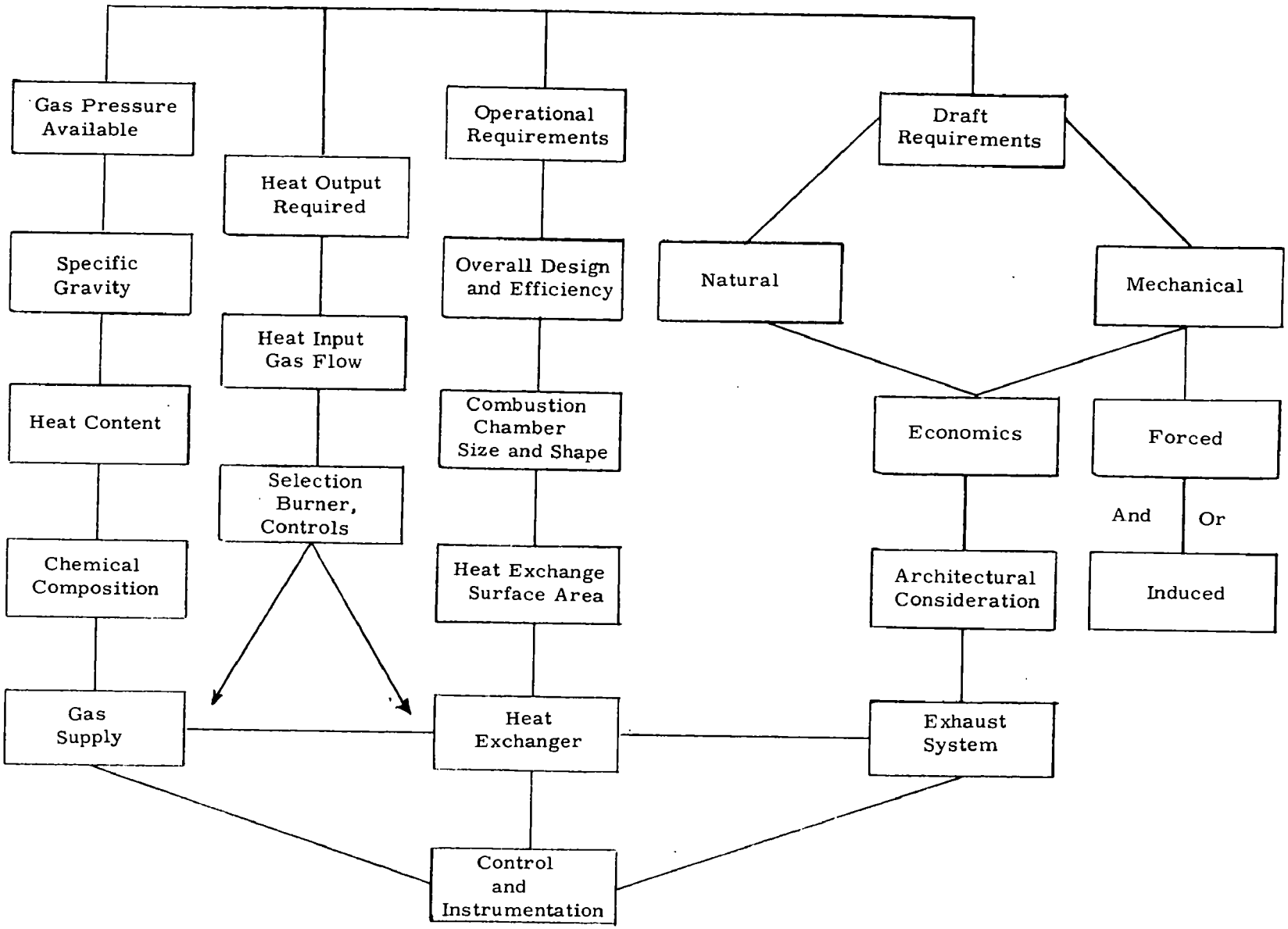

Gas Pressure Available
Specific Gravity
Heat Content
Chemical Composition
Gas Supply
Heat Output Required
Heat Input Gas Flow
Selection Burner, Controls
Operational Requirements
Overall Design and Efficiency
Combustion Chamber Size and Shape
Heat Exchange Surface Area
Heat Exchanger
Control and Instrumentation
Draft Requirements
Natural
Mechanical
Economics
Forced
And
Or
Induced
Architectural Consideration
Exhaust System

FIGURE 6

OIL BURNING EQUIPMENT

In addition to proportioning fuel and air, and mixing them, oil burners must prepare the fuel for combustion. There are two ways of doing this, with many variations of each: (1) The oil may be vaporized or gasified by heating within the burner, or (2) it may be atomized by the burner so vaporization can occur in the combustion space.

Designs of the first group, usually called vaporizing burners, are necessarily limited in the range of fuels they can handle and find little power use.

If oil is to be vaporized in the combustion space in the instant of time available, it must be broken up into many small particles to expose as much surface as possible to the heat. This atomization may be effected in three basic ways by: (1) using steam or air under pressure to break the oil into droplets (2) forcing oil under pressure through a suitable nozzle, and (3) tearing an oil film into drops by centrifugal force. All three methods find use in practical burners.

Turbulence Necessary. In addition to breaking the oil into small particles for fast vaporization, the burner must provide motion between oil droplets and air, so vapor "coats" are stripped off as fast as they form and fresh surfaces exposed. This calls for penetration of the oil particles in the proper direction and for a high degree of turbulence in the air. Such relative motion of oil and air helps to produce more uniform mixture conditions over the combustion zone.

Hydrocarbons burn by hydroxylation and by cracking. In practice, both forms are present, although the usual oil-burner flame is predominantly the latter type. This characteristic short yellow flame has good radiating characteristics and fits usual combustion spaces well. It carries, however, solid carbon particles, which, if their burning is stopped by any chilling action, form soot. Depending on the nature of the chilling, the soot may deposit on heating surfaces or may be carried out the stack as a major constituent of smoke.

Pure hydroxylative burning, while free from soot and smoke possibilities, yields a less radiative flame and can be produced only in certain types of burners. Thus, as in many engineering matters, we compromise and strive to introduce enough hydroxylation into a predominantly cracking process to keep the flame clean and reduce smoking tendencies. Hydroxylation is encouraged by thorough atomization, suitable preheating of both oil and air, and exposing the mixture to a gradually increasing temperature over not too short a time.

A Steam-Atomizing Burners. Let's look now at practical oil-burning equipment. Oldest form is the steam- or air-atomizing burner. Installation is relatively inexpensive and simple, especially where no attempt is made to control steam and oil supply simultaneously. Steam-atomizing burners, as a class, possess ability to burn almost any fuel oil, of any viscosity, at almost any temperature. Air is less extensively used as an atomizing medium because its operating cost is apt to be high.

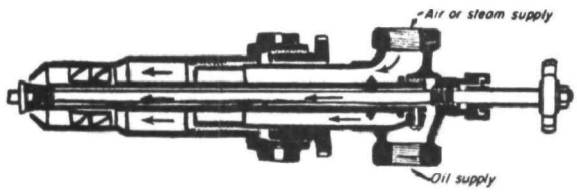
These burners can be divided into two types: (1) internal-mixing or premixing - oil and steam or air mix inside the body or tip of the burner before being sprayed into the furnace, Figs. 2, 4, and (2) external-mixing - oil emerging from the burner is caught by a jet of steam or air, Figs. 1, 3.

Steam consumption for atomizing runs from 1 to 5% of steam produced, usually averaging around 2%. Pressure required varies from about 75 to 150 psi, and steam can be taken from: (1) a low-pressure line (2) a desuperheater with a pressure reducer, or (3) a drum vent, through an orifice and regulating valve. Oil pressure need only be enough (usually 10 to 15 psi) to carry oil to the burner tip.

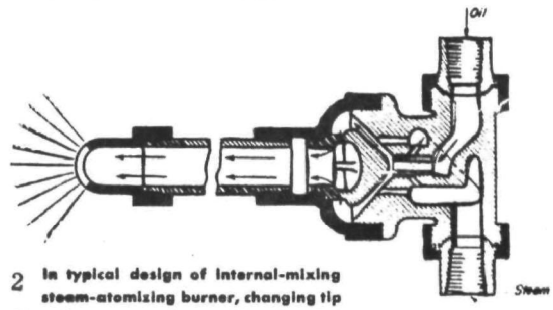
External Mixing. In the burner of Fig. 1, oil reaches the tip through a central passage, flow being regulated by the screw

*Based on the publication by: Rowley, L.N., McCabe, J.C. and Skrotzki, B.G.A., "Fuels and Firing", Power, pp 85-88 (December, 1948).

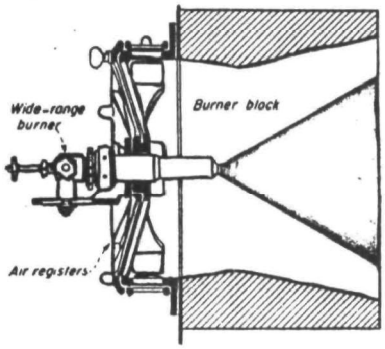
STEAM OR AIR ATOMIZING OIL BURNERS

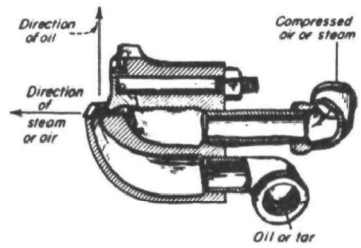


1 Steam-atomizing burner of external-mixing type, above, brings oil and atomizing medium, steam, together at the burner tip. Register, below, has damper vanes to regulate the air supplied

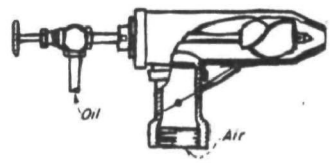


2 In typical design of internal-mixing steam-atomizing burner, changing tip alters the range of capacities handled





3 In this external-mix oil burner a steam jet hits the emerging oil at right angles as the oil leaves the burner; gives turbulent mixing action



4 Low-pressure air serves as atomizing medium for this burner, meeting oil at the tip and breaking it up. Air atomization finds relatively little use because cost is often high

spindle, right. Oil whirls out against a sprayer plate to break up at right angles to the stream of steam, or air, coming out behind it. The atomizing stream surrounds the oil chamber and receives a whirling motion from vanes in its path. When air is used as the atomizing medium in this burner, it should be at 10 psi for lighter oils and 20 psi for heavier. Combustion air enters through a register, shown below in Fig. 1. Vanes or shutters are adjustable to give control of excess air. Fig. 3 shows another external-mixing design. Oil and steam discharge through separate nozzles at right angles to each other, the steam breaking up the oil stream.

Internal Mixing. Figs. 2 and 4 give examples of the premixing principle. In Fig. 2, steam and oil meet and mix well within the burner body. Energy in the steam serves to force the steam-oil mixture through the nozzle for atomization. Burner of Fig. 4 brings oil and air under pressure together at the burner tip for **mixing** before discharge into the furnace.

B Mechanical Atomizing. Now let's look at another major burner class, mechanical atomizers, Figs. 5 to 8. Good atomization results when oil under high pressure (75 to 200 psi or higher) is discharged through a small orifice, often aided by a slotted disk. The disk gives the oil a whirling motion before it passes on through a hole drilled in the nozzle, where atomization occurs. For a given nozzle opening, atomization depends on pressure and, since pressure and flow are related, best atomization occurs over a fairly narrow range of burner capacities (about 40%).

To follow a fluctuating boiler load, a number of burners may be installed and turned on or off as steam demand varies; or burner tips with different nozzle openings can be applied to a single burner body.

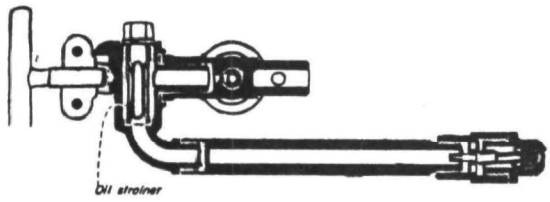
Wide-Range Designs. Oil-burner manufacturers have developed many designs to extend the usual 1.4 to 1 capacity range of the mechanical-atomizing nozzle. One,

for example, features a plunger that opens additional tangential holes in the nozzle as oil pressure increases. This gives a 4 to 1 range. Another design, Fig. 6, employs a movable control rod, which, through a regulating pin, varies the area of tangential slots in the sprayer plate and the volume of oil passing the orifice.

Still another variable-capacity design, Fig. 7, delivers oil at high pressure (350 psi) at a constant rate, but discharges through the nozzle only the quantity needed to meet steam demand. The remainder recirculates.

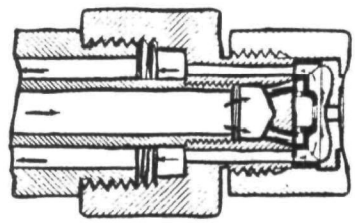
Fig. 8 shows a wide-range mechanical atomizer which, when combined with either of the pumping systems shown in Fig. 9, will give a capacity range of about 15 to 1, and considerably higher if needed. By use of either a constant-differential valve or pump, as shown, difference in pressure between supply and return is held constant. This maintains a uniform pressure drop across the tangential slots in the burner tip and creates a constant atomizing force. The valve system is simple to install and maintain, but the pump system offers advantages in many plants: (1) No hot oil is returned to storage tank or pump suction. (2) Fuel enters the closed circuit at the same rate it is burned, simplifying fuel metering and combustion control. (3) Pump may be used to boost pressure on existing oil-burner systems.

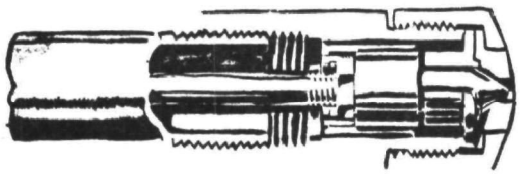
MECHANICAL ATOMIZING OIL BURNERS



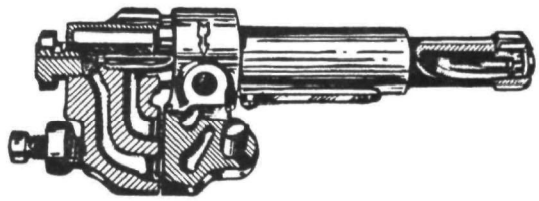
5 **Mechanical-atomizing burner receives the oil under pressure, about 225 to 300 psi, and at an optimum viscosity of about 150 ssu. Orifice atomizes the fuel**

6 **With fixed orifice size, best atomization occurs in narrow flow range. Design at right obtains wide capacity range by supplying oil to burner tip at a constant rate in excess of demand. Oil burned varies with the load, rest is returned**



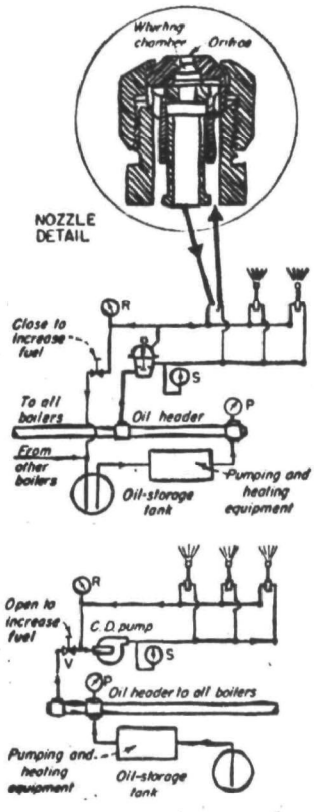


7 **Movable control rod, center, through a regulating pin, varies the area of tangential slots in sprayer plate and volume of oil passing through orifice, right. With oil kept at 300 psi and 200 ssu, range is 10 to 1**



8 **Wide-range burner above operates on constant-differential systems**

Figure 9. How One Wide-Range Mechanical Atomizing Oil Burner System Operates



• Regulation of output from the wide-range burner whose atomizing and whirling end shows above, can come from either constant-differential valve or a constant-differential pump to hold pressure across supply and return

C Rotary-Cup Burners. Third major class of oil burners, the horizontal rotary cup, atomizes fuel oil by literally tearing it into tiny droplets. A conical or cylindrical cup rotates at high speed (usually about 3500 rpm if motor-driven). Oil moving along this cup reaches the rim where centrifugal force flings it into an air stream, Fig. 10.

This system of atomizing requires no oil pressure beyond that needed to bring oil to the cup, and proves attractive in installations where only low-pressure steam is available. High oil preheat temperatures must be avoided since gasification may develop. The rotary cup can satisfactorily atomize oils of high viscosity (300 ssu), however, and has a wide range, about 16 to 1.

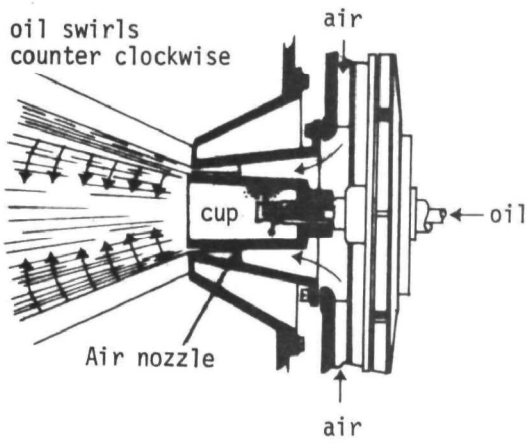
Fig. 11 shows a burner with a built-in driving motor, while Fig. 12 shows one with a belt drive. It also indicates provision for swinging the burner out of the furnace.

Gas and oil burners are often combined. Designs of such combinations vary widely, both in nature of oil unit and gas unit. Their ability to handle either of the two fuels, or both at once, proves desirable in locations where both are available.

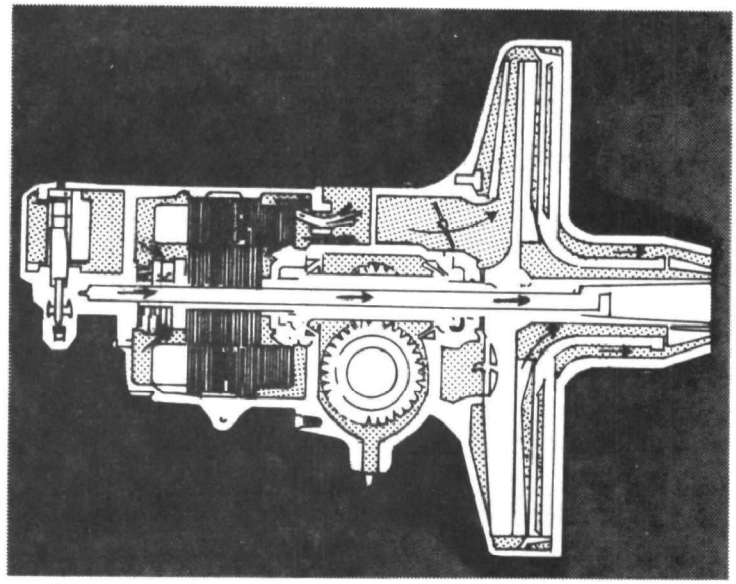
Burner Maintenance. Properly maintained, modern oil burner give highly satisfactory service. For peak performance, make sure that the burner gets uniformly free-flowing oil, clear of sediment that clogs burner nozzles. This means avoiding sludge build-up in storage tanks and keeping strainers in good condition. Preheat temperature must be right for fuel and burner type, and must be uniform.

Keep burners in good condition by watching for wear caused by abrasion of ash in fuel, and for carbon buildup. In rotary-cup burners, worn rims cause poor atomization. If cups are not properly protected after being turned off, carbon forms on the rim. When burner is shut down always take out the cup and insert a flame shield. Worn or carbonized mechanical-atomizing nozzles play hob; replace worn nozzles and keep them clean.

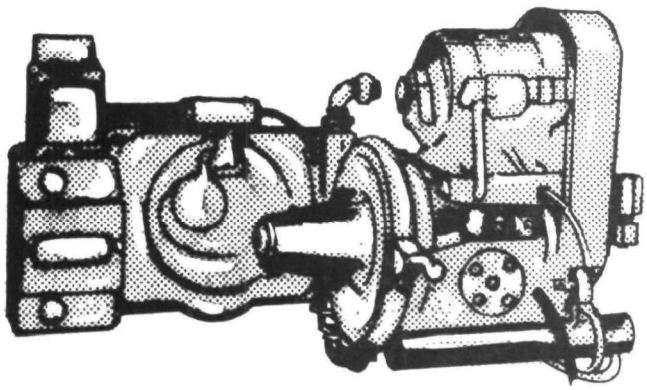
ROTARY CUP ATOMIZING OIL BURNING



10 Cup revolving counterclockwise breaks up all film at rim by centrifugal force and discharges into a clockwise air stream



11 Built-in fan rotating at motor-speed supplies primary air just behind the atomizing oil cup. Air catches up fine oil spray leaving at cup edge



12 Belt driven rotary-cup burner carries a fuel-oil reservoir to insure positve feed, and a submerged electric heater to hold oil at correct temperature. Gas pilot mounted overhead, together with low-voltage system, serves to ignite the oil

FUEL OIL BURNING-DESIGN PARAMETERS

J. Percival*

I. INTRODUCTION

A. Pollutant Information

1. Potential pollutants

Table 1. Potential Pollutants

Emitted Regardless of Design	Reduced By Design	Eliminated by Design
SO_2	NO_x	CO
Ash	SO_3	Smoke Soot

2. Pollutant Emission Rates

For 20,000 lbs steam/hour (1500 lbs oil/hour) the pollutant emission rates are listed in Table 2.

3. Local Nuisance

Acid smuts caused by condensation of soot plus SO_3 may cause local nuisance.

B. Design Parameters

1. Overall Purpose

The overall purpose is to generate hot combustion gases by:

a. Burning fuel completely.

b. Using minimum quantity of air.

c. Discarding flue gas at low temperature.

2. Requirements for Complete Combustion

a. Fine atomization.

b. Good mixing with air - high turbulence.

c. Source of continuous ignition.

d. Room to burn - time to burn.

e. No quenching until combustion complete.

Table 2. Pollutant Emission Rates

	Pollutants						
	SO_2	Ash	NO_x	SO_3	CO	Smoke	Soot
lb/hr	60	1	10	0.3	0.1	-	0.5-6
ppm (vol.)	1300	-	400	35	50	-	-
grains/ft^3	-	.023	-	-	-	-	.01-.14

*ESSO Research and Engineering Company
Linden, New Jersey, February 17-21, 1969

II. FUEL OIL HANDLING

A. Fuel Oil Storage

1. Bunkering

Things can happen in the tank which may affect combustion. Burners may become plugged by sludge. Keep sludge suspended in fuel by CONTROLLED BUNKERING. Controlled bunkering is the process of keeping the stored oil in suspension as illustrated in Figure 1. The incoming fill scours the floor and resuspends the sludge.

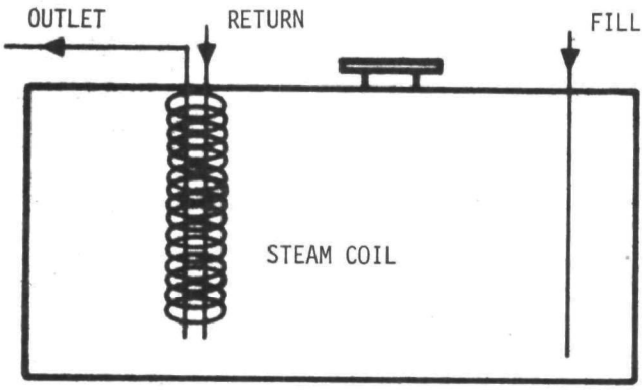


Figure 1. Controlled Bunkering

2. Heating

Stored fuel should be heated to pumpable viscosity.

	Easily Pumpable 5000 SU*	Just Pumpable 25,000 SU*
#6 Oil	90-100°F	70-80°F
#5 Oil	60-70°F	50°F

*Saybolt Universal - Viscosity as measured by a standard orifice

3. Pour Point

Pour point can be important, but the smaller installations will always use 60°F pour fuel. Pour point is the lowest temperature at which an oil flows under standard conditions.

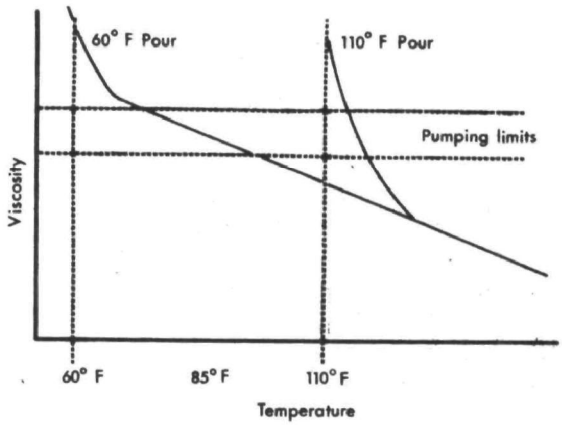


Figure 2. Pour points of two oils of same grade.

B. Pumping and Heating

1. Pumps

Two pumps may be required if:

a. distance from tank to burner is over 100 feet,

b. several burners are fed by common line.

2. Heaters

a. Steam or hot water heat exchangers.

b. Electrical heaters for final heating.

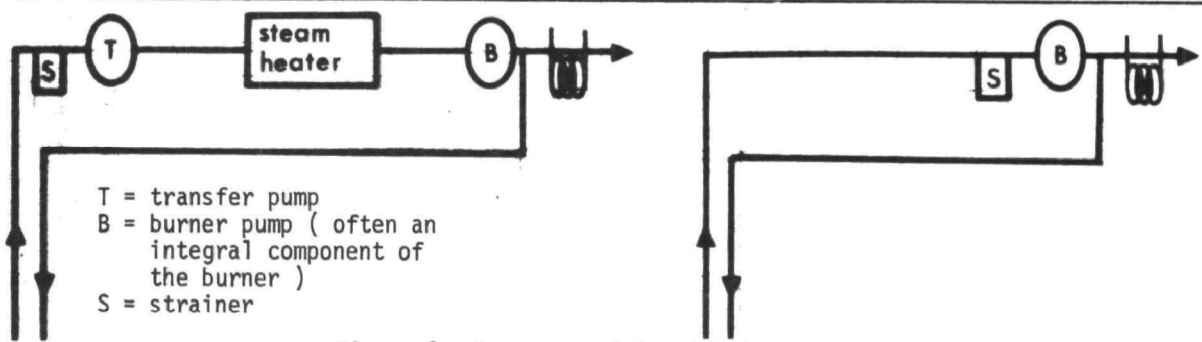


Figure 3. Pumping and Heating Systems

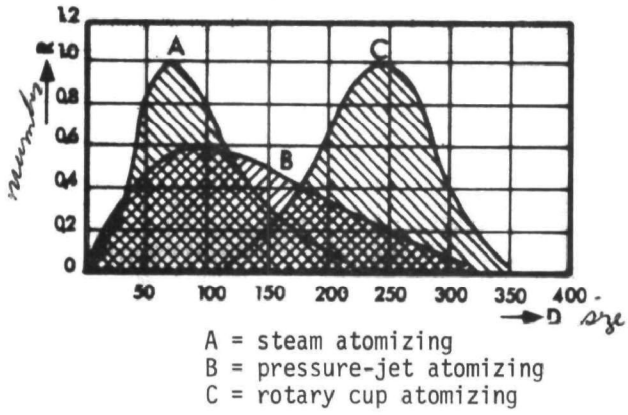


Figure 4. Atomizing characteristics of different burners - distribution of droplet size

III. BURNERS

A. Atomization

Fuel oil must be vaporized to burn. Idea is to provide a large surface. Size of droplet is function of viscosity, fuel oil rate and energy input, e.g., a formula applying to pressure atomizing burners is:

$$SMD = 160 \frac{M^{.16} V^{.22}}{P^{.42}}$$

where: SMD = Sauter mean diameter, micron

Micron = 0.001 mm.
M = fuel rate, lb/hr.
V = viscosity, SUS (Saybolt Universal Seconds).
P = gauge pressure, psig.

Viscosity is controlled by preheat. Energy input may come from oil pressure, a second fluid moving at high velocity, or a centrifugal force.

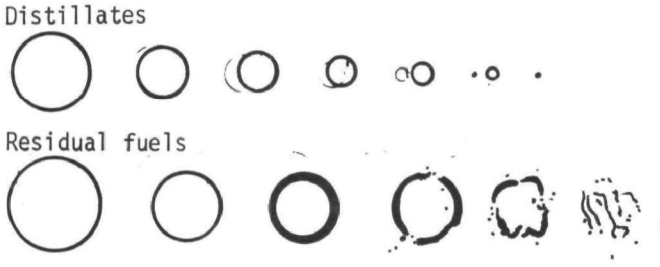


Figure 5. Mode of Combustion of fuel oil droplets

1. Smoke

Submicron particles of graphitic carbon formed from the gas phase and preserved either:

a. By overall lack of oxygen.

b. By premature chilling of flue gas.

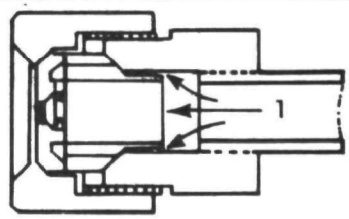
2. Soot

a. Originates as carbonaceous cenospheres, ash plus carbon.

b. Will burn out to ash given time and temperature.

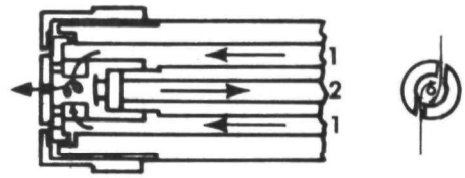
c. Size 10-40 microns plus some much larger if atomization is poor.

B. Burners - Atomizers



1. oil inlet

Figure 6. Simple pressure-jet atomizer



1. oil inlet
2. spill return

Figure 7. Spill pressure-jet atomizer

1. Pressure Atomized Gun Burners

a. Atomizing energy comes from pump pressure.

b. Output increases with square of pressure (simple type).

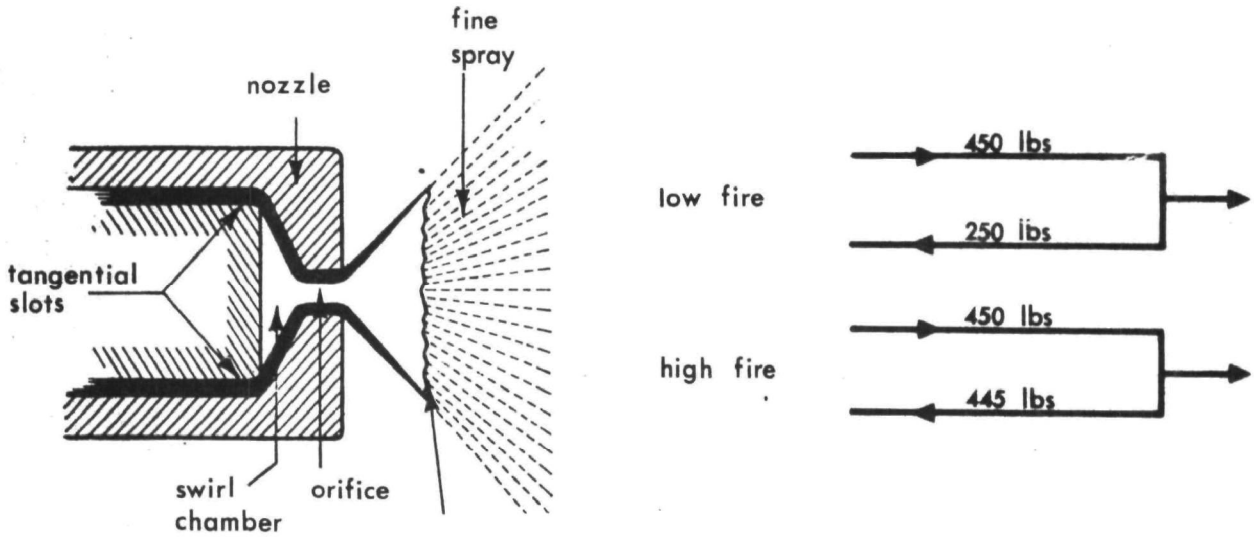


Figure 8. Piping arrangement for spill-back pressure atomizer

c. Output increases with increase of back pressure (spill type).

d. "Anomalous" effect of viscosity - increased viscosity causes increased throughput until the air core chokes.

2. Steam Atomized Burners

a. Large turn-down without sacrifice of atomization.

b. Only moderate pump pressure required on oil.

c. Less vulnerable to dirt in oil than other types.

d. Good atomizers on clean fuel use only 0.1 lbs of steam/lb of oil but consumption may rise to 1 lbs/lb if poorly adjusted.

e. Steam used at burners represents heat lost.

f. Steam effects a final preheat within the burner.

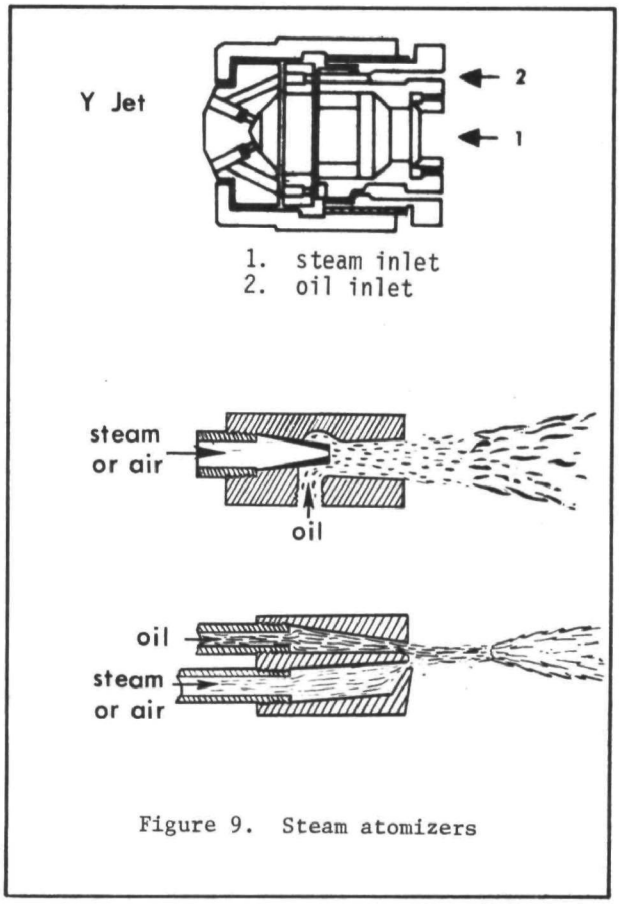


Figure 9. Steam atomizers

3. Air Atomized Burners

Similar in principle to steam atomizers but a large volume of low pressure 0.5-2.0 psig air is used.

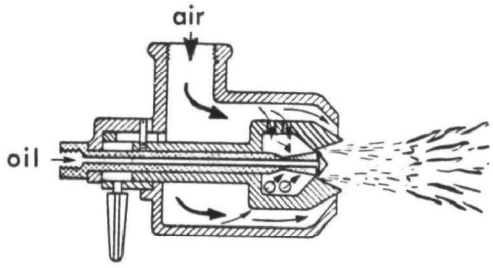


Figure 10. Air atomizer

The amount of air used for atomizing is only a fraction of the total air required for combustion, e.g.,

Total Air To Burn 1 Gallon	Air to Atomize 1 Gallon
1700 SCF	80 SCF

Nevertheless, combustion begins sooner and finishes more rapidly than with any other type of burner - shorter flame.

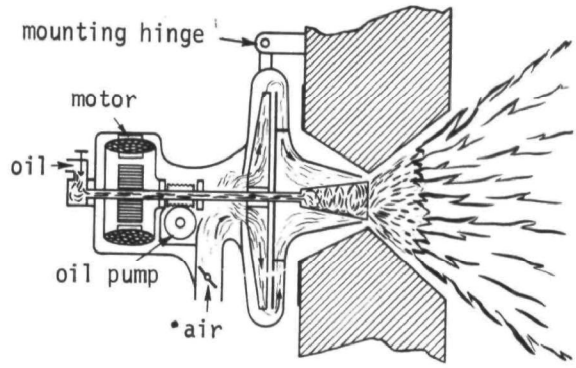


Figure 11. Rotary cup burner

4. Rotary Cup Burners - Centrifugal Burners

a. Cup revolves at 3600 rpm. Throws a sheet of oil from its periphery which is shaped into a cone by the primary air nozzle.

b. Sizes range from 3 gph - 300 gph.

c. Oil flow controlled by metering rate.

d. Principle fault from air pollution point of view concerns vulnerability of edge of cup to accidental notching. Compare with action of a weir. Local high flow at the notch produces some very course droplets.

Table 3. Comparison of Operating Conditions

Burner Type	Viscosity at Burner		Pressure PSIG		
	SU	°F for No. 6	Oil	Steam	Air
Pressure Atomizing	150	210	200 to 1000	-	-
Steam Atomizing	180 to 400	200 to 170	10 to 150	40 to 175	-
Air Atomizing	80	240	30	-	1.5

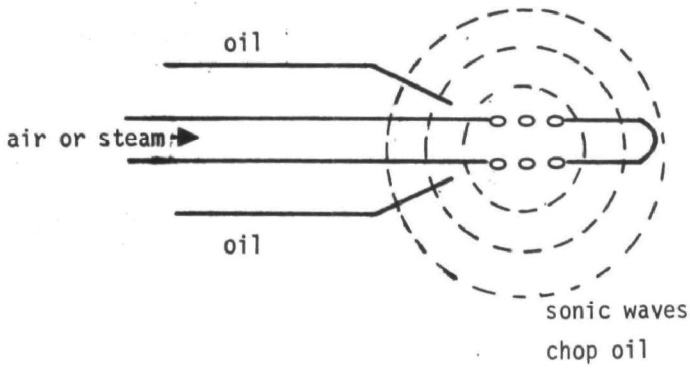


Figure 12. Sonic Atomizer

5. Sonic Atomizers

   a. Sound frequency 10-20,000 cps.

   b. Sizes range from 10 gph - 1000 gph.

   c. Almost any gas can be used to drive the sound generator - air, steam, oxygen, propane, etc.

   d. About 1 pound of air will atomize 5 pounds of oil.

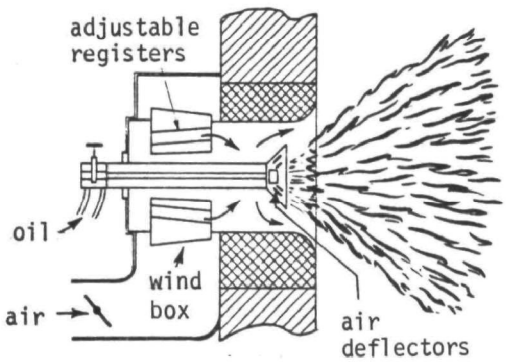
   e. Burner is self-cleaning.

IV. AIR/FUEL MIXING

A. Mixing Air with Atomized Oil

1. Energy for mixing comes from the pressure drop across the burner register.

   a. Forced Draft: ΔP = P (Windbox) - P (furnace)



   b. Natural Draft or induced draft:

      ΔP = P (Atmosphere) - P (furnace)

2. High pressure drops are used with narrow throats. Low pressure drops are used with wide throats.

3. Design maximizes relative velocity of air and fuel - potential energy of ΔP is converted to swirl and turbulent flow. High mixing energy results in a short flame and saves size of combustion space, but costs fan power.

4. At low firing rate the velocity of the air will be reduced in proportion with the fuel rate. Mixing is optimum at high fire. At low fire it is usual to compensate by using more excess air.

B. FUEL/AIR RATIO CONTROL

The purpose of fuel to air ratio control is to insure sufficient combustion air at all imput rates of fuel.

1. Continuously Modulating (e.g., "Steam Flow/Air Flow")

   a. Change in steam flow signals for corresponding change in air flow. Fan louvers adjust or fans change speed.

   b. Change in steam pressure which accompanies the change in flow actuates change in fuel input. Weakness of this system is that oil change is accomplished faster than air change.

   (1). On a falling load a period of high air and low fuel input occurs.

   (2). On a rising load a period of high fuel input and low air rate occurs.

The system must be adjusted not to smoke during the latter (2) mode. In general, this calls for more air than is necessary at the steady mode.

A better system (but more expensive) is one which signals and controls fuel flow and air flow together, with an overriding control on the fuel signal-

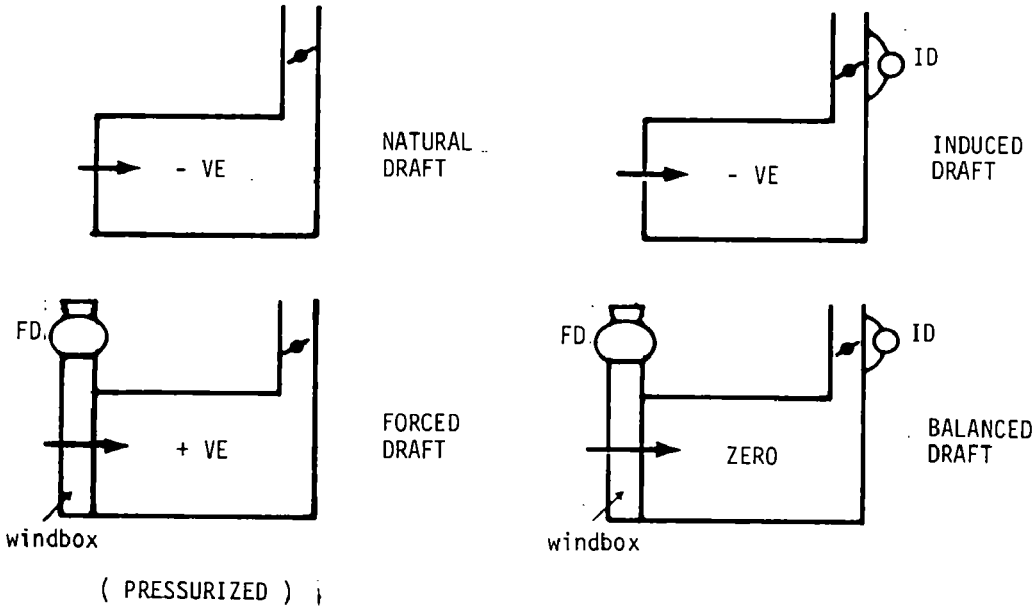


Figure 13. Air handling systems

led by a continuous oxygen analyser. A fast system of flue gas sampling and analysis (by paramagnetic oxygen meter) is required with this system. Most oxygen meter systems have a slow response rate.

2. STEPWISE MODULATION

Stepwise modulation is more common on commercial burners - e.g., apartment houses, small boilers, etc. Oil input is controlled by pressure which can assume any of two or three preset levels. Air shutter is positively connected to the oil control and assumes corresponding positions instantly.

Overall master signal may originate from thermostats, steam pressure signals, etc. Start up sequence will move automatically through low fire, medium fire and high fire positions. The preset modulation is set up on:

a. A clean burner of given throughput.

b. A given grade of oil at a given preheat.

c. A clean set of air shutters.

These conditions must be maintained for satisfactory operation. Major changes (e.g. of oil type) call for readjustment.

C. AIR HANDLING SYSTEMS

V. IGNITION

High intensity flames would blow off the burner if a source of continuous ignition were not present. Three principal sources of continuous ignition are: (1) hot refractory burner block, (2) "diffuser" bluff body creates stagnant pockets of hot gas near point of atomization, and (3) return flow of hot gas. See Figures 14 and 15.

VI. HEAT EXCHANGE

In the larger power station boilers about half the heat in the fuel is given up in the RADIANT section; the other half in the CONVENTION section.

A. FURNACE AND SUPERHEATER

The temperature to the inlet of the furnace is the theoretical flame temperature, which is never attained in

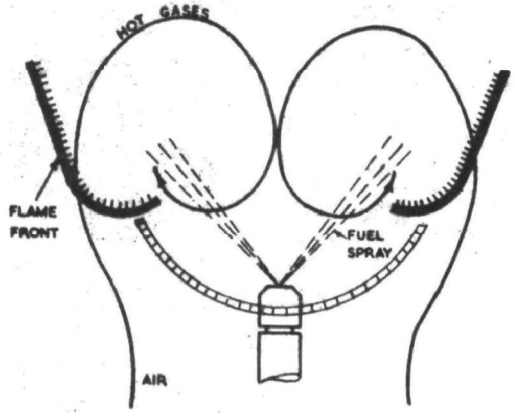


Figure 14. Dish stabilizer

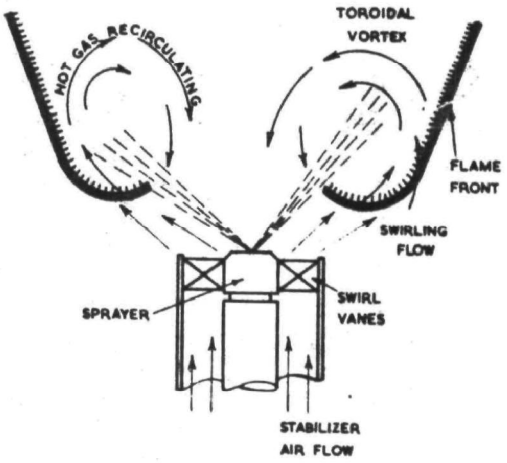


Figure 15. Swirl flow stabilizer

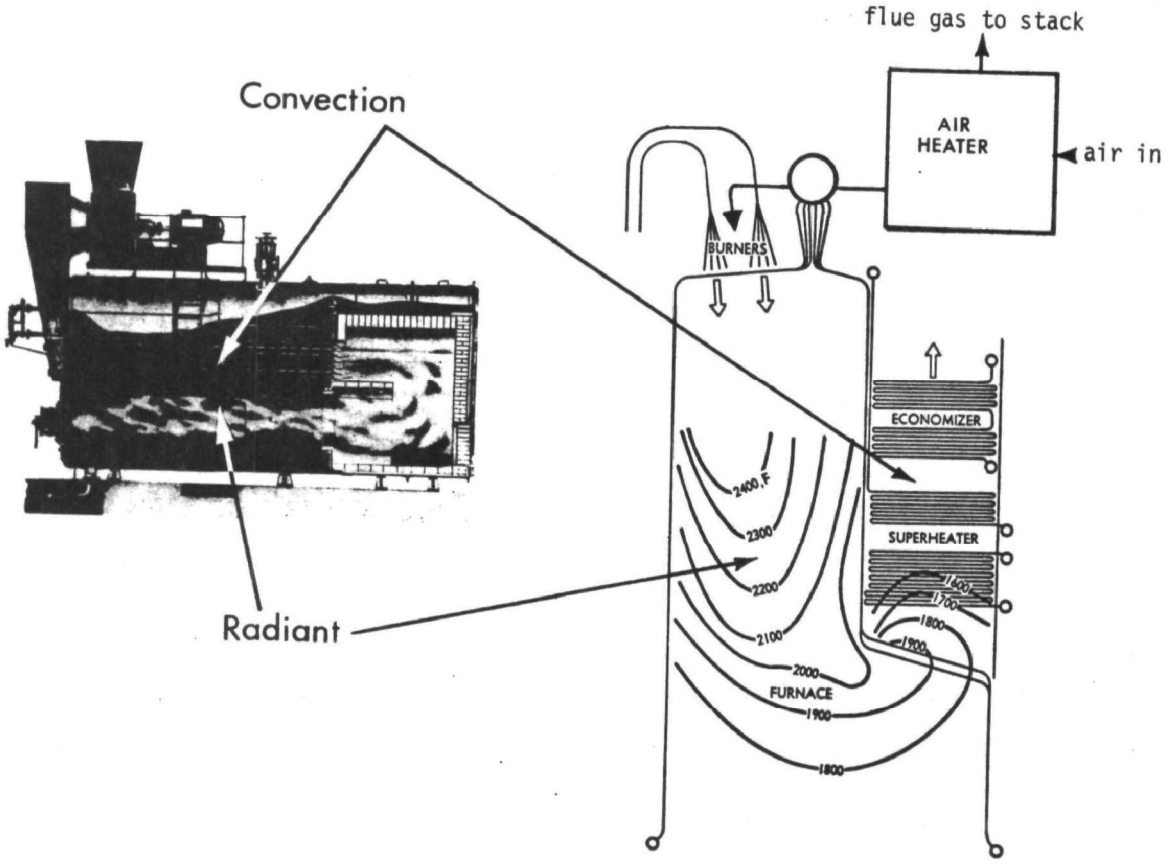


Figure 16. Boiler showing radiant and convection sections

Table 4. Temperatures in Boilers

Section	Temp. In	Temp. Out	ΔT
Furnace (Radiant Section)	3600°F	2000°F	1600
Superheater	2000°F		
Economizer (Convection Section)	900°F	600°F	1650
Air Heater	600°F	350°F	

fact for two reasons: (1) the flame begins to radiate heat away to the furnace walls before combustion is complete and (2) combustion will not go to completion at very high temperatures because of dissociation,

$$2CO_2 \rightleftharpoons 2CO + O_2$$

In general, the smaller boilers have proportionately less radiant section and more convection. For this reason the temperature of combustion gases leaving the furnace of a smaller boiler may be considerably higher than 2000°F.

Furnace temperatures are also a function of the amount of excess air employed, the rate of firing, the proportion of the furnace wall which is covered by water tubes as shown in Figure 17 which applies to a marine boiler.

In a boiler making superheated steam, furnace exit temperatures must be known accurately in order to design the convection section. The combination of flue gas temperature available and steam temperature required governs the selection of tube materials for the superheater.

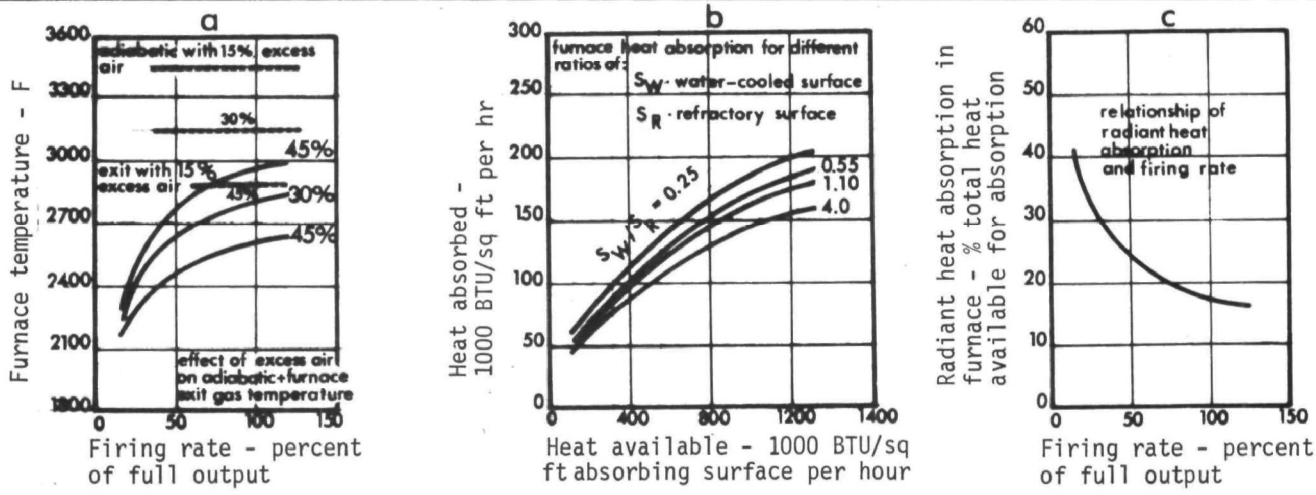


Figure 17. General effect of excess air (diagram a), ratio of heat absorbing to refractory surface (diagram b), and firing rate (diagram c) on furnace heat absorption and temperature. Based on 18,500 BTU fuel oil.

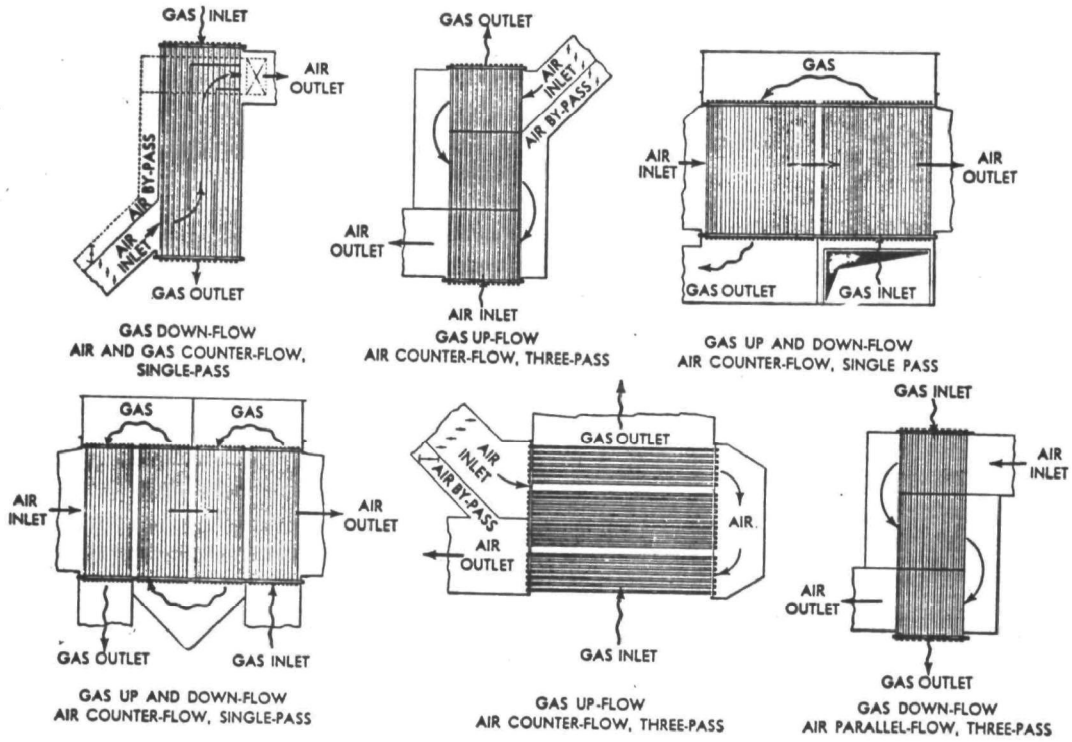


Figure 18. Some arrangements of tubular air heaters to suit various directions of gas and air flow

A knowledge of furnace temperature is less important in boilers which make saturated steam in which all of the heat exchanger surface is backed by water or water/steam emulsion.

B. ECONOMIZERS AND AIR HEATERS

In low pressure boilers with an economical amount of heat transfer surface, flue gas can be cooled to 400°F or less as it makes its final pass over the steam generating surface.

In high pressure boilers, particularly when the steam is superheated, the temperature of the flue gas is still high when it leaves the last bank of steam generating or superheating tubes.

It is usually economical to build additional heat absorbing surfaces to take out some of this heat by using: (1) economizers to heat up boiler feed water and (2) air heaters to heat air which is routed to the windbox by a F.D. fan. Either or both can be used to extract heat from the final flue gas.

Major point of concern with these pieces of Cold End Equipment is the potential problem of sulfuric acid condensation on surfaces cooler than the Acid Dew Point. This causes (1) corrosion and (2) accumulation of soot and ash particles. Available heat in flue gas is less at low loads. Some air may have to bypass the air heater to avoid chilling the metal below the dew point.

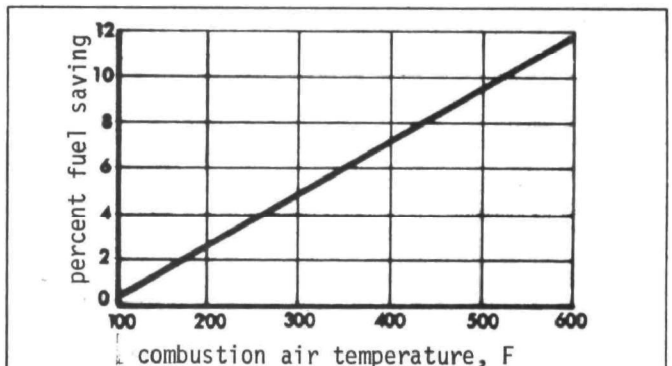


Figure 19. Order of improvement in efficiency when heated combustion air is used in boiler units

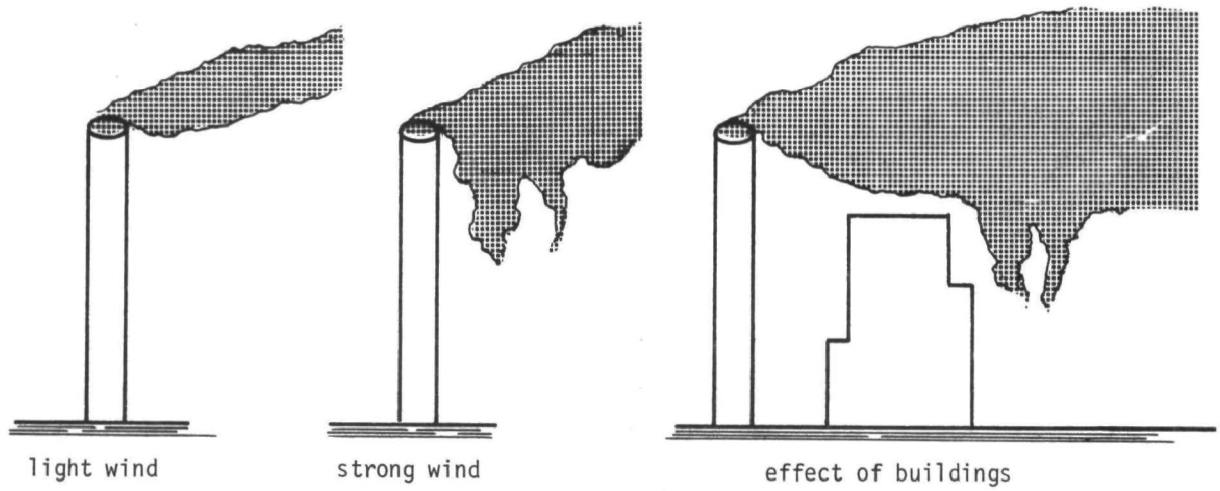


Figure 20. Plume rise

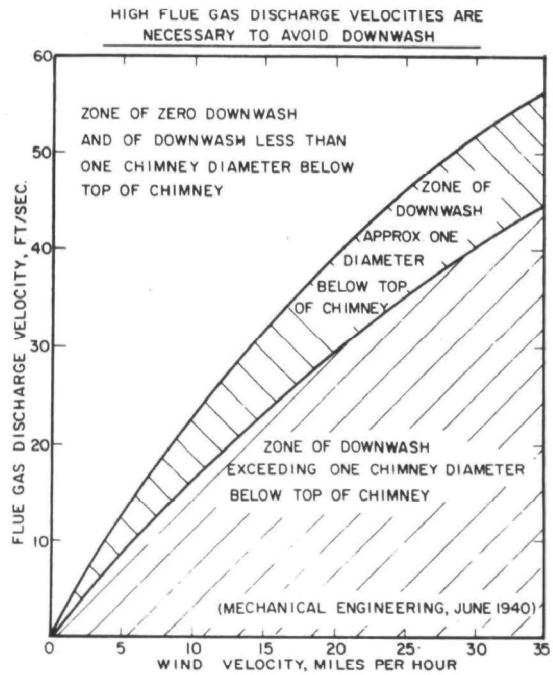
VII. OTHER CONSIDERATIONS

A. Breeching and Stack

Problems with final ductwork and stacks are similar to those encountered in air heaters. They are all connected with the potential deposition of sulfuric acid and its corrosive and "fly-paper" properties. Ideal design requires that (1) the temperature of all inner surfaces of the ducts be above the acid dew point at all loads, (2) the exit velocity be sufficiently high to promote plume rise in all winds, and (3) the height be sufficient to disperse the flue gases efficiently, particularly that it be high enough to avoid downdrafts caused by neighboring buildings.

Modern design exit velocities are of the order 40-60'/sec. at full firing rate.

A good rule of thumb for stacks in the vicinity of buildings is that they should be 2-½ times as high as the buildings. Several mathematical formulae have been developed to predict what height of stack is required to guarantee a safe maximum concentration of SO_2 at ground level. Some of these are compared in Figure 22 which relates to 3% sulfur in fuel and a required maximum ground level concentration (GLC) of 0.2 ppm SO_2.



High flue gas discharge velocities are necessary to avoid downwash

Figure 21.

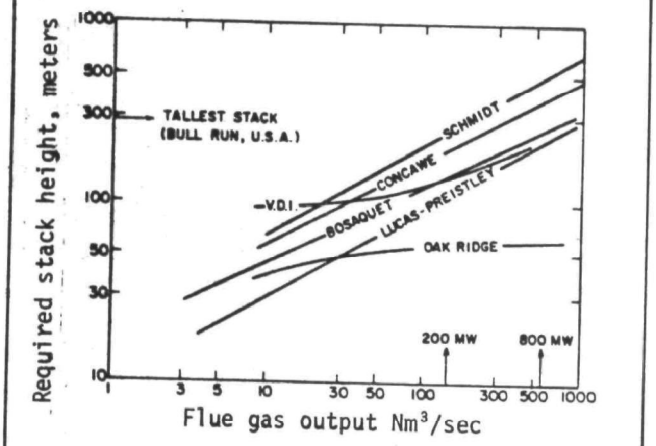


Figure 22. Predicted stack height requirements

Once a plant is built, fairly major changes are required to alter either the gas velocity or the gas temperature in the ductwork and stack.

B. MATERIALS OF CONSTRUCTION

1. Firebox Refractory. High alumina firebox to withstand attack from oil ash.

2. Steam Generating Tubes. Usually low carbon or medium carbon steel.

3. Superheater Tubes. Stainless. Chromium alloys or nickel chrome depending upon temperature.

4. Economizer. Originally cast iron to resist conversion from O_2 in boiler water. Now low carbon steel with de-aeration of feedwater.

5. Air Heaters. Mostly low carbon steel but low temperature parts may be stainless; ceramic and even glass has been employed.

6. Stacks. Masonry lined with acid resistant brick and mortar, masonry liner supported within a concrete outer stack with a heat insulating cavity between, steel liner welded and supported within a concrete outer stack (recommended for stacks which are under positive pressure).

C. INSTRUMENTATION REQUIREMENTS

1. Draft controls.

2. Low water cut off.

3. Light up sequence controls.

   a. purge with air
   b. light and prove pilot
   c. light and prove burner

4. Flame failure control.

5. Air/fuel ratio controls.

6. Steam temperature control.

7. Oxygen analyser. (Sometimes CO/H_2 analyser).

8. Smoke recorder. (Only instrument which is connected directly with air pollution control).

D. INFLUENCE OF FUEL OIL TYPE ON DESIGN PARAMETERS

1. Distillate Fuels

   a. Require somewhat less combustion space to burn completely than do residuals.

   b. May be burned at small burners down to 0.5 gallons/hour.

   c. Generally need no preheat.

2. Low Sulfur Fuels

   a. Permit design of lower cold end temperatures.

   b. May permit some savings on superheater materials.

3. Low Ash Fuels

   a. Permit closer spacing of tubes in convection section.

Table 5. Safe Maximum Temperatures (Oxidation Resistance Basis)

Material	ASME Specification	Maximum* Metal Temp F
Carbon steel	SA-210	950
Carbon-Moly.	SA-209 grade T1a	975
Croloy 1/2	SA-213	975
Croloy 1 1/4	SA-213 grade T11	1050
Croloy 2	SA-213 grade T14	1080
Croloy 2 1/4	SA-213 grade T22	1100
Croloy 3M	SA-213 grade T21	1125
Croloy 9M	SA-213 grade T9	1200
Croloy 18-8 Ti	SA-213 grade TP321	1400**
Croloy 18-8 Cb	SA-213 grade TP347	1400**

* Of surface in contact with flue gases.

** Temperature limit may be modified depending on character of fuel and other circumstances. It can be 100 to 200F higher in low pressure process steam superheaters fired with low sulfur fuel.

PAGE NOT

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DIGITALLY

FUEL OIL BURNING
GOOD OPERATION PRACTICES

J. Percival *

I. INTRODUCTION

Ideal operation occurs when (1) all carbon in the fuel is burned to CO_2. (2) a minimum quantity of the sulfur in the fuel is burned to SO_3, and temperatures are arranged so that only a minimum amount of sulfuric acid is deposited in the cold end, and (3) a minimum quantity of nitric oxide is formed. All of these are affected by the amount of combustion air employed.

Production of SO_3 and NO are reduced at low excess air. Smoke is generally reduced by using higher excess air. Soot is complicated but there is usually an optimum amount of excess air for minimum soot.

II. OPTIMUM COMBUSTION AIR

The theoretical quantity of air needed to convert fuel oil to CO_2 and H_2O is given by the following:

lbs Air/lb Fuel = 11.52 x wt. fraction carbon

+ 34.56 x wt. fraction hydrogen

+ 4.30 x wt. fraction sulfur

Alternatively:

% H_2 = 26 - 15 x specific gravity, and
% C = 100 - (% hydrogen + % sulfur + water + sediment).

A common type of #6 fuel oil has the following analysis:

% Carbon	86.4
% H_2	11.3
% S	2.0
% Water	0.2
% Sediment	0.1

Total theoretical air requirement of such an oil is:

11.52 x .864 = 9.95
34.56 x .113 = 3.90
4.30 x .020 = .09
13.94

13.94 lbs air/lb oil.

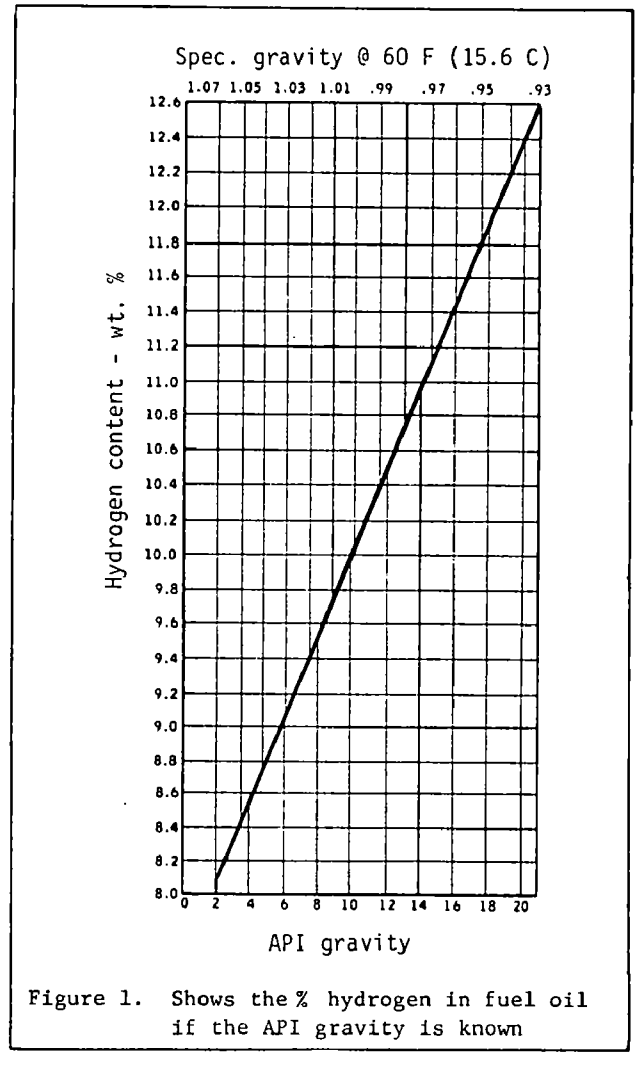


Figure 1. Shows the % hydrogen in fuel oil if the API gravity is known

*ESSO Research and Engineering Company
Linden, New Jersey, February 17 - 21, 1969

If, in fact, 17 lbs of air is employed in a real combustion process, the amount of excess air is:

$$\frac{17-13.94}{13.94} = 22\%$$

There is, of course, no need to measure rates of air flow to know how much excess air is being used.

An analysis of the flue gas for either CO_2 or O_2 can be correlated with the excess air.

Thus, for the type of fuel oil under discussion:

Flue Gas Analysis		Excess Air
CO_2%	O_2%	%
16.2	0.0	0.0
15.7	0.6	3.0
15.3	1.0	5.0
14.7	2.2	10.0
13.5	3.7	20.0
10.7	7.2	50.0
7.8	10.7	100.0
0.0	21.0	Infinite

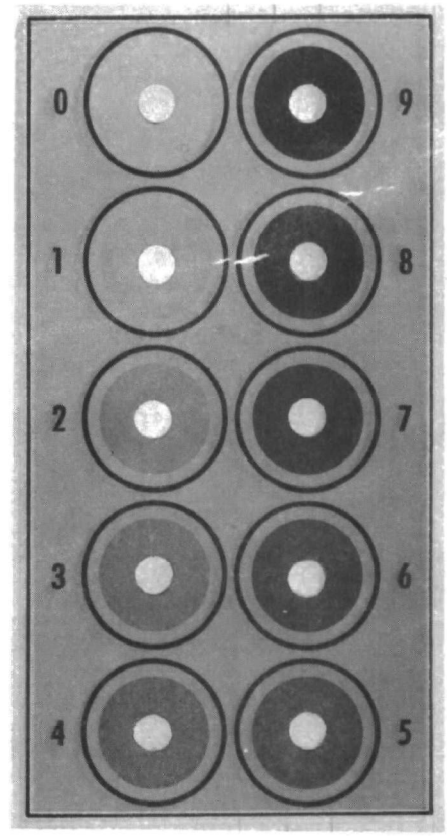


Figure 2. Bacharach Oil Burner Smoke Scale

III. SMOKE

A. Formation of Smoke

Smoke consists of sub-micron particles of carbon formed by:

1. An overall lack of oxygen - e.g. by using less than the theoretical requirement of air.
2. Insufficient mixing of air and fuel even though the air is theoretically sufficient.
3. Prematurely chilling a partially burned mixture.
4. Burning with too much air.

Notes (2), (3) and (4) are respectively examples of insufficient turbulence, time and temperature.

B. Smoke Measuring Instrument

Standard instrument for measuring smoke is Bacharach Smoke Tester.

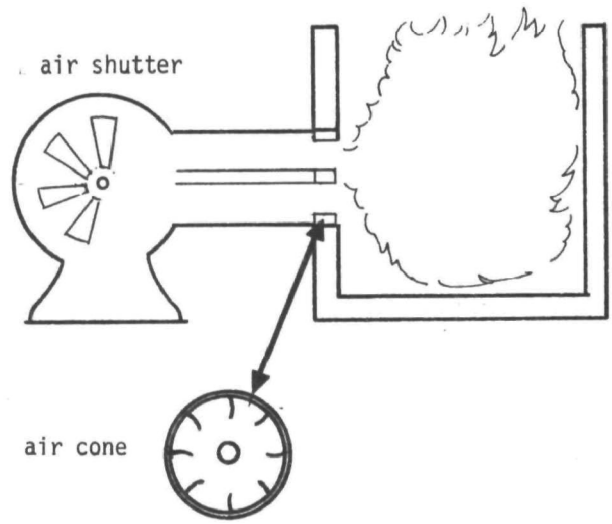


Figure 3. Small furnace burning distillate fuel

Table 1. Typical smoke/CO_2 correlation for a domestic burner

CO_2	% Excess Air	Smoke No.	Stack Appearance	Flame Appearance
14	10	9+	Smoke Visible	Long and Dark
11	40	6	Not Visible	Long and Dark
10	50	2	Not Visible	Long and Clear
9	60	0	Not Visible	Shorter
6	140	Yellow	Thin Vapor Visible	Very Short and Noisy

Table 2. Some typical excess air levels in various types of equipment (at zero or minimum smoke)

Type	Heat Input to Furnace 10^6 Btu/hr	Excess Air %	CO_2%
Home Heat	0.18	40	11
Apartment House Boiler	2.2	27	13
Ship's Boiler	80	15	14
60 MW Power Station	600	3	15.7

Table 3. Volumetric heat release rates

Tape	Volumetric heat release rates BTU input/ft^3 combustion space/hour	Residence time seconds
Home	340,000	0.13
Apartment	100,000	0.50
Ship	70,000	0.80
Power Station	20,000 to 40,000	2.2 to 1.1

C. Smoke Control in a Small Furnace Burning Distillate Fuel

A domestic burner may have smoke and CO_2 readings shown in Table 1.

The performance of such a burner might be improved by using a smaller air cone which would employ the available fan pressure to promote better mixing.

Since these burners are practically unattended and since lint accumulation can build up on the air shutter ports in the course of a season, they should not be set for maximum thermal efficiency.

Some give-away of CO_2 must be allowed. The formation of SO_3 and NO is quite small regardless of excess air level.

D. Smoke Control in Larger Units

Some typical excess air levels in various type of equipment at minimum smoke are given in Table 2.

It would seem that the larger the unit the less excess air is needed. Compare the volumetric heat release rates of the different types of units (see) Table 3.)

Note that the residence time (the time available for combustion within the high temperature

environment) is longer when the heat input rate/ft^3/hr is smaller.

Why are the larger units designed to have more residence time (large volume/unit of fuel rate)?

1. Possible to accomodate a second fuel, e. g. pulverized coal.

2. Directionally because heat input is limited by the ability of the combustion chamber walls (steam generating tubes) to absorb heat. Usual rate is 50-100,000 Btu/sq. ft/hr

For similar shapes, large furnaces have proportionately less wall area per unit volume. Some designers place curtain walls between columns of burners to get increased area.

IV. LOW EXCESS AIR

A. Resume of Factors Affecting Ability to Operate at Low Excess Air

In general the fuel/air mixture must be fully combusted before it leaves the furnace zone, because once it leaves that zone its composition is virtually frozen. For the same reason, the flame must not impinge on the furnace walls.

Thus the optimum conditions are those which fill the furnace with flame at high fire, so that the tips of the flame extinguish just short of the exit (screen tubes). If this condition cannot be met, one or more of the following steps must be taken:

1. Increasing excess air shortens the flame.

2. Lowering the firing rate shortens the flame.

3. Adjusting the position of the burner within the throat of the air register may shorten the flame but beware of impingement on the burner block.

4. Changing to a wider angle nozzle may shorten the flame, but again beware of impingement.

5. Increasing the windbox/furnace differential pressure shortens the flame if the increased energy can be converted into turbulence. (This means narrowing the throat or introducing a swirl impeller).

(1) and (2) above are available to the operator within the limits of design and the demands on the unit. (3) and (4) represent minor changes of design which should only be tried in consultation with the boiler supplier. (5) represents a major upgrading of the design which must be accompanied by suitable modification of the air register to convert the pressure energy to mixing energy.

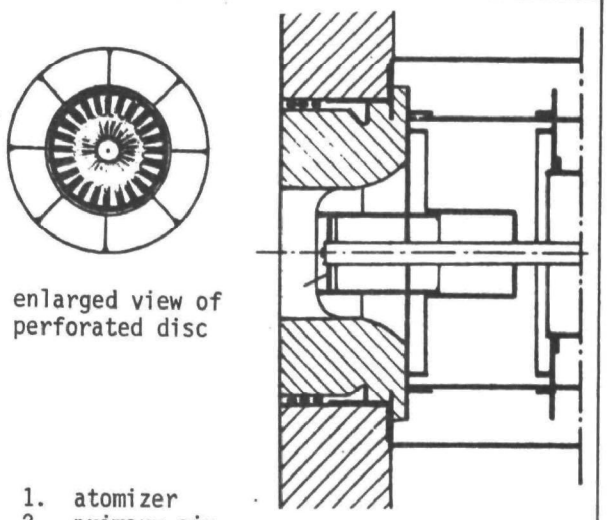


Figure 4. Oil burner with steam atomizer

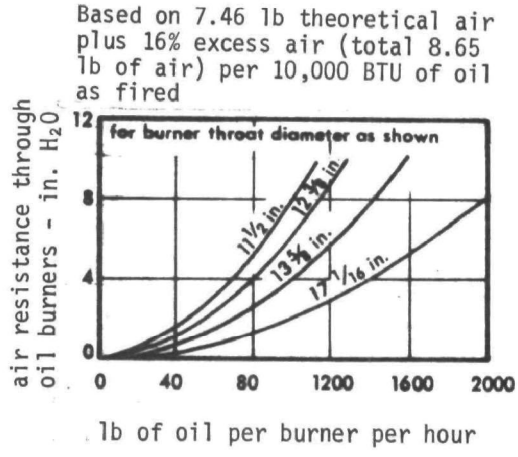


Figure 5. Air resistance for typical marine oil burners

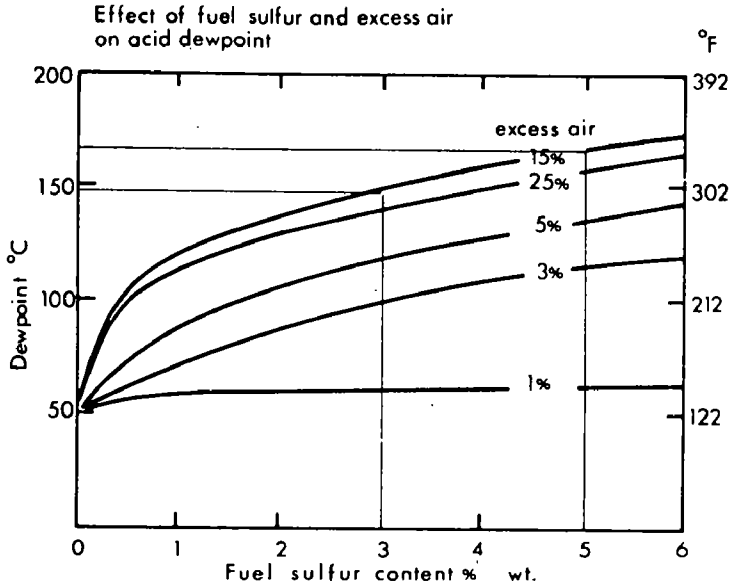


Figure 6. Effect of fuel sulfur and excess air on acid dewpoint

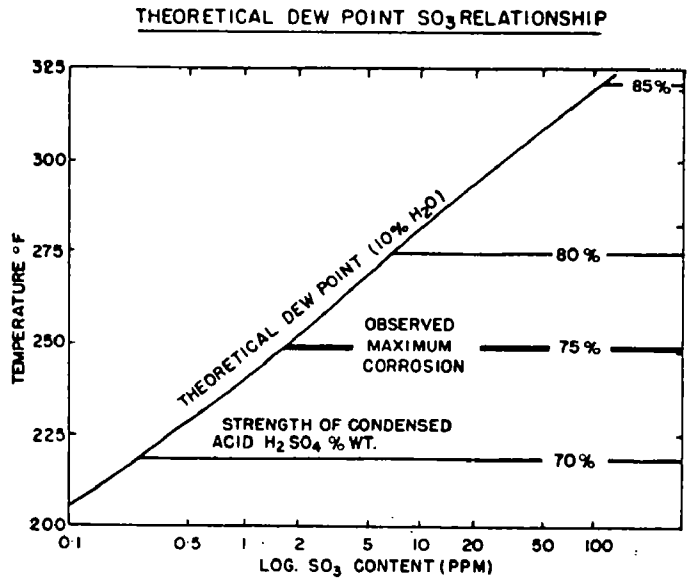


Figure 7. Theoretical dewpoint SO_3 relationship

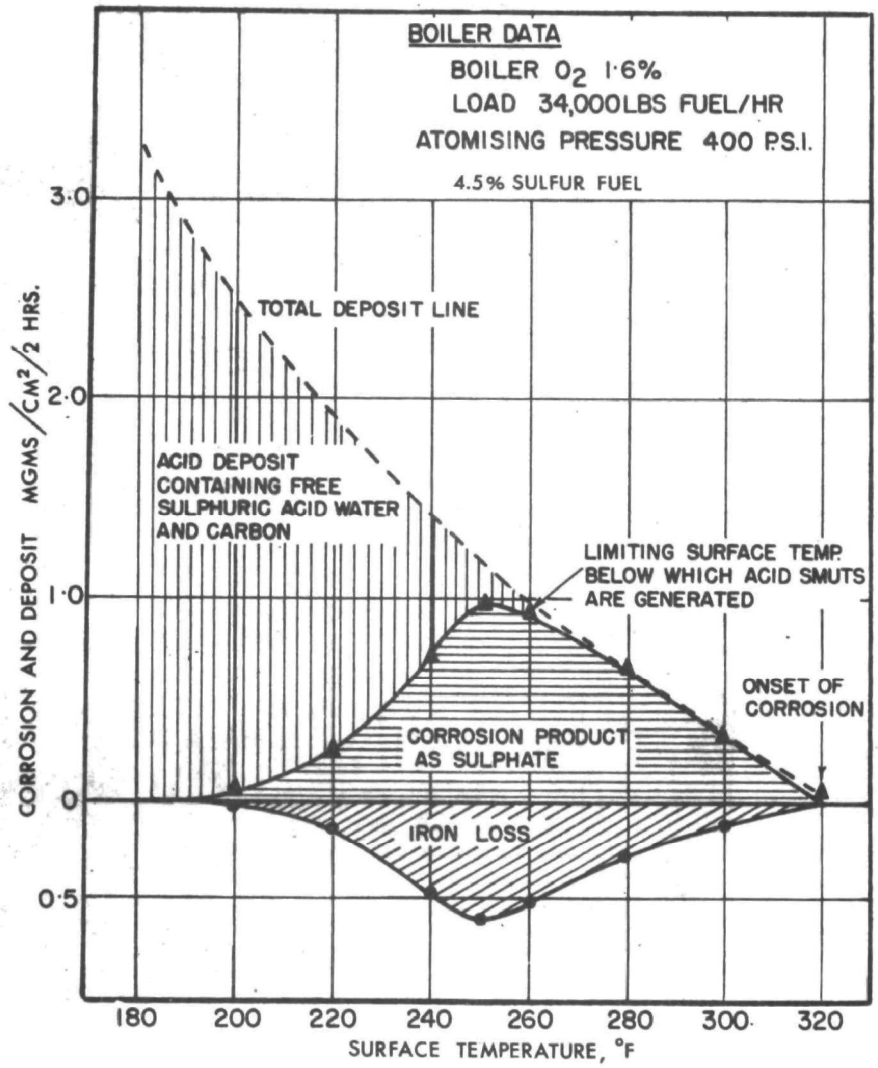


Figure 8. Surface temperature and boiler oxygen control the formation of moist deposits

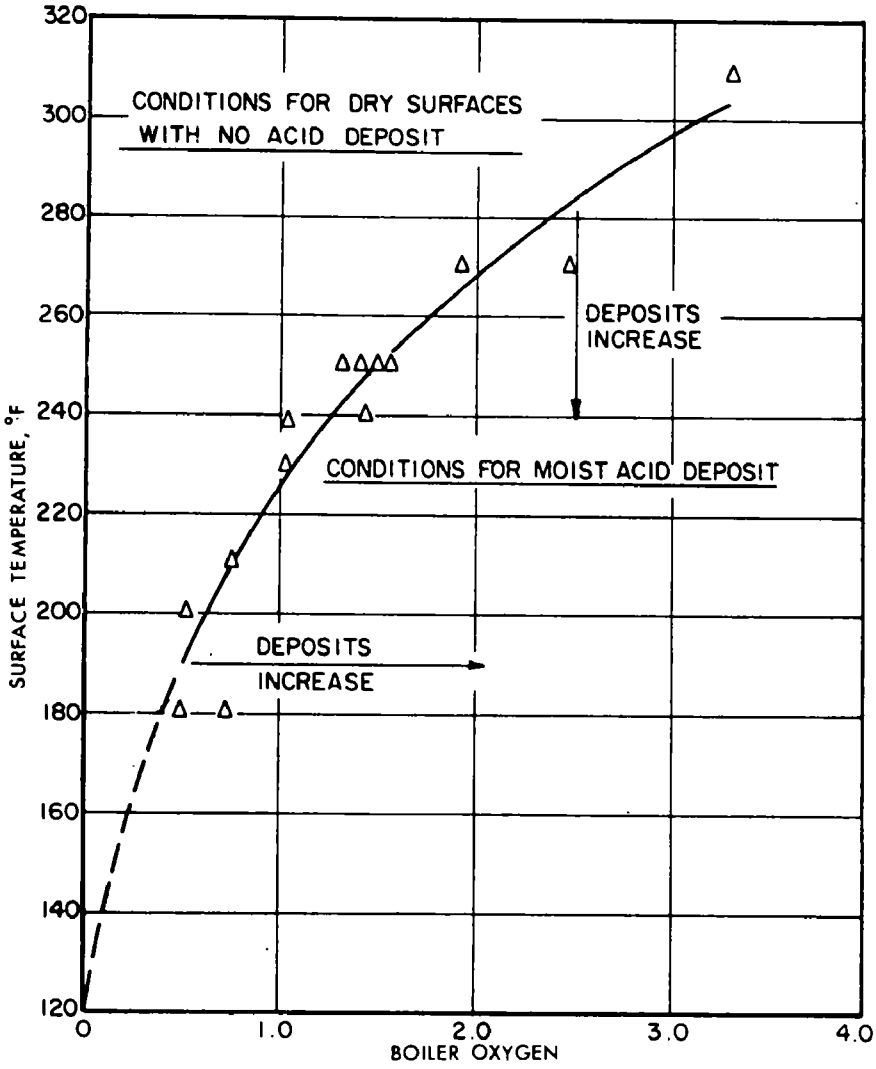


Figure 9. Relation between surface temperature and acid deposit formation

B. Benefits of Low Excess Air Operation

1. Increased thermal efficiency.
2. Lower acid dew point.
3. Lower rates of corrosion of superheaters.
4. Less opacity of stack plume if caused by SO_3.

V. ROLE AND RATE OF SULFUR IN FUEL

Most of the sulfur burns to SO_2 which exits at the stack. A small percentage (0-3%) burns to SO_3. The amount depends on the level of sulfur in the fuel but more upon the amount of excess air used. The following diagrams explain the situation (see figures 6,7,8, and 9).

Good operation requires that minimum condensation of sulfuric acid occurs on any surface, because: (1) the material will be corroded and (2) the moist surface will act like a fly-paper and will collect solids. The sulfuric acid problem may be handled by (1) burning a very low sulfur fuel (less than 0.5% S) (2) burning with very little excess air (preferably less than 3%). (3) keeping all critical surfaces at a temperature above the acid dew point, (4) neutralizing the SO_3 with additives.

VI. COLD END TEMPERATURE CONTROL

A. Economizer

Minimum surface temperature is a function of the boiler feedwater temperature - usually above the acid dew point in power boilers.

B. Air Heater

Average surface temperature is approximately the mean between the flue gas temperature and the air temperature. Efficiency of heat exchange must be sacrificed to insure low corrosion rates and cleanliness of the coldest parts of the exchanger:

1. Part of the cold air may be by-passed.
2. Parallel flow may be used in place of the more efficient counter flow.
3. A steam heater may be used to preheat the air before it contacts the air heater proper.

The last method is often acceptable where LP steam is available from a turbine. The loss of efficiency at the boiler is very nearly compensated by the increase in efficiency of the turbine.

C. Breeching and Stack

Whatever heat remains in the flue gas as it leaves the final heat exchange surface should be preserved as the gas travels to the top of the stack.

1. Insulate
2. Avoid leaks and (check CO_2 level along breeching and in stack, and search out and seal leaks if CO_2 is not constant).

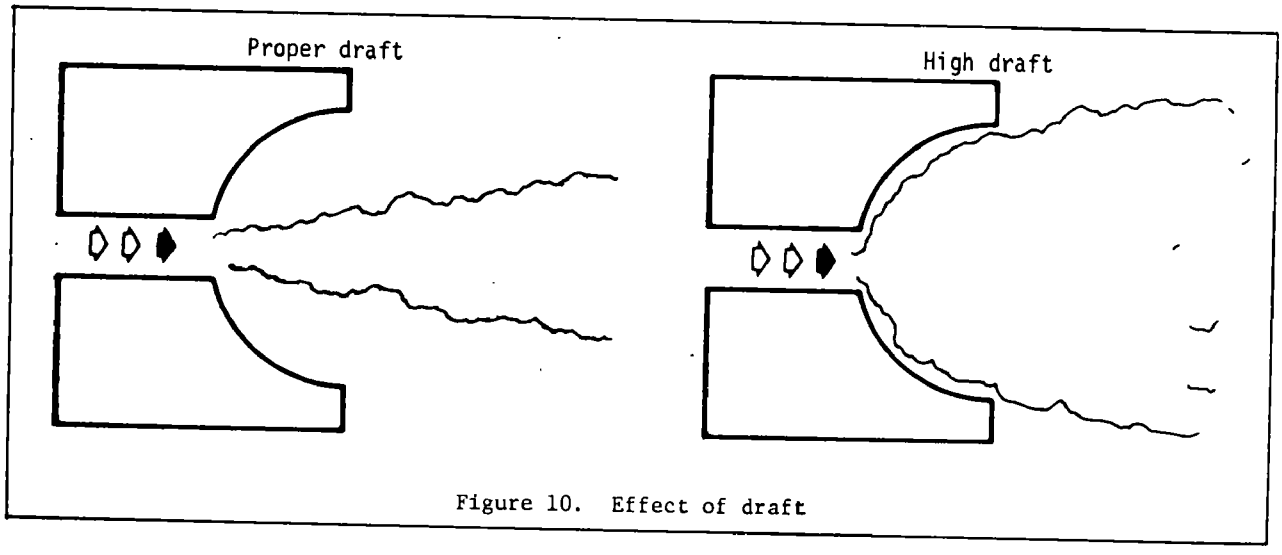


Figure 10. Effect of draft

VII. ACID SMUTS

A. Formation of Acid Smuts

1. Checking atomization - grade of fuel, preheat, condition of atomizer (particularly spinning cup).

2. Checking draft.

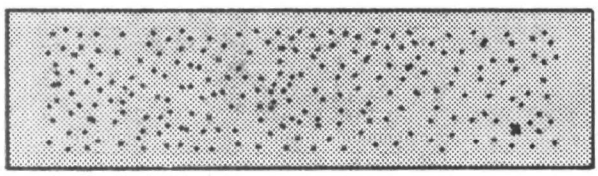
   One of the most common faults of boilers in high-rise apartments is too high a draft.

High draft effectively reduces the available combustion space, and draws the flame away from the refractory. Check for reduction of soot formation with sticky slide (contact adhesive attached to steel holder) at breeching or roof level.

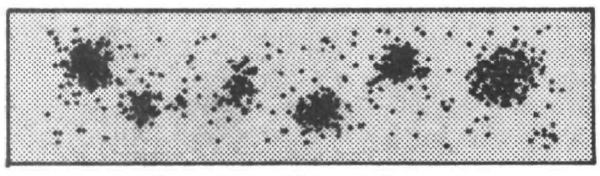
Acid smuts are the product of soot particles which have adhered to and agglomerated on moist acidic surfaces, and which have subsequently lifted off that surface and become airborne. The black agglomerates so formed tend to fall to ground within a few stack lengths. The local nuisance caused thereby is particularly noticeable when a boiler is started up after shut-down.

If the temperature of cold end surfaces is above the acid dew point, smuts cannot form. In that case the soot particles will remain separate and will diffuse widely with the effluent plume.

Alternatively, if the fuel is burned completely to ash, smuts will not form.



representation of slide with soot



representation of a slide with smut

Figure 11. Study paper slides of soot and smut

The following actions may all help a smut problem:

1. Insulate the stack - particularly useful on bare steel stacks - aluminum shrouds have been employed.

2. Seal air leakage at the breeching.

3. Operate at very low excess air.

4. Employ an additive (such as MgO or dolomite).

5. Improve the combustion to minimize the production of soot particles.

6. Burn distillate fuel which makes practically no soot.

Note that (3) and (5) may be mutually exclusive, but not always so (see next section).

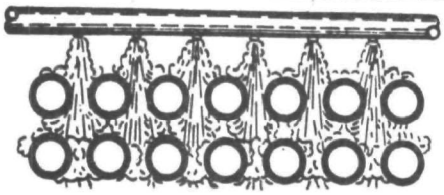
B. Particular Case of Boilers Fired Intermittently e.g. apartment houses small industries

In cases where boilers are fired intermittently it may be quite impossible to prevent the deposition of some acid in the stack. Some draft regulators operate by dumping cold air to the breeching, and chimneys, which handle intermittent firing, oscillate in temperature above and below the dew point. Best approach is to reduce formation of soot particles (cenospheres) to a minimum by:

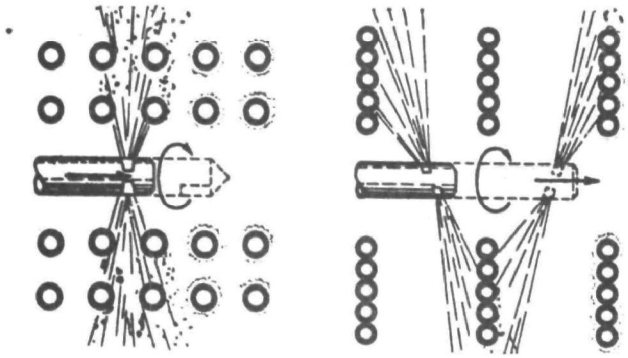
Correcting the draft to manufacturer's specifications usually allows operation at lower excess air.

Table 4. Case history of a 20 gph fire tube hot water boiler

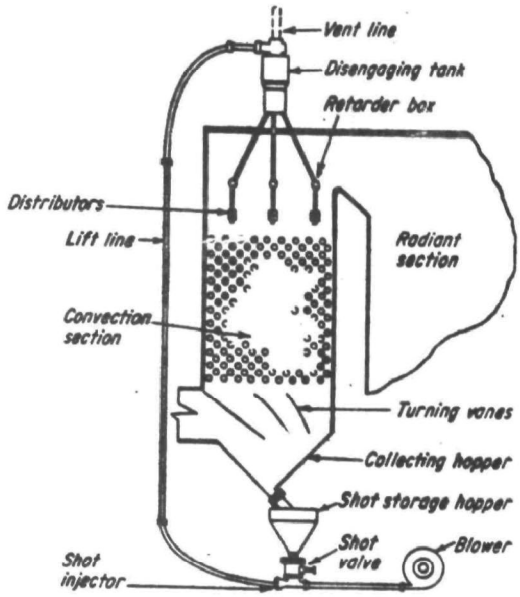
	draft	CO_2	Smoke #	soot
As found	0.22"	10.5	6	much
Reset to specifications	0.06"	13.0	2	trace



Stationary soot blowers employing straight nozzles clean banks of in-line tubes. With staggered tubes, the nozzles are offset for improved penetration



Retractable blower lance, driven by two motors, traverses boiler at one speed, retracts at twice that speed. Result: about a 25% saving in cleaning time and in blowing medium. Speed of lance rotation is held throughout the cycle



Shot cleaning technique calls for cascading metal balls on to heating surfaces. The cycle is automatic, utilizing pneumatic lift

Figure 12. Methods of soot blowing

VIII. SOOT REMOVAL

Large vacuum cleaners are employed to remove soot from small boilers. This does not get into the atmosphere.

Large equipment employs soot blowers, usually steam operated or sometimes by compressed air. Shot cleaning has been employed in certain types of air heaters.

Solids from soot blowing operations end up in the atmosphere. The amount is usually a small percentage of the total solids which are voided in the course of a day but "since it is concentrated in a short span of time it is very noticeable to the public".

Permitted levels of particulates emission from stacks are becoming tighter. Table 5 gives some examples which were in force in 1965.

(Typical particulate loadings for large oil fired boilers are shown in Figure 13.)

The old ASME figure 0.85/lbs/1000 lbs of flue gas and the New York figure of 0.33 lbs/million Btu input are compared below:

	% Fuel Unburned	Grains scf
ASME	1.60	0.46
New York	0.57	0.17

No difficulty should be experienced in meeting these requirements with normal, well adjusted oil fired equipment. These levels may be exceeded for short periods of time (less than one minute) during soot blowing.

Table 5. Particulate emission standards in combustion flue gases

City or Organization	Pounds of particulate matter per 1,000 pounds of flue gas (corrected to 50% excess air, or 12% Carbon Dioxide)
American Society of Mechanical Engineers (1949 Model Smoke Code)	0.85
ASME proposed draft of Nov. 1962	
Sparsely settled areas	0.80
General city usage	0.65
Cities where better conditions are feasible and required by residents	0.50
Provincial and City By-Laws	
Metropolitan Toronto	0.85
Alberta	0.85
Manitoba	0.68
Chicago	0.60
Los Angeles County	0.52
New York	
(a) Refuse burning equipment	0.65 (top limit of 250 lbs. per hr.)
	lbs./million BTU, Input
(b) Fuel burning equipment Capacity rating, BTU,	
10 million or less	0.5
50 million	0.38
100 million	0.33
500 million	0.25
1,000 million	0.22
10,000 million or more	0.15

IX. OPERATION AT VERY LOW LOADS

A. Effects of operation at very low loads

In general combustion conditions are optimum at the rated design loads, and some deterioration of conditions has to be accepted at lower loads when:

1. Temperature in the furnace zone is lowered.

2. Quality of air/fuel mixing deteriorates due to lower windbox/furnace differential pressure, and consequently lower air velocities at the throat.

3. Atomization deteriorates:

   a. Especially with simple pressure jets.

   b. Less so with spill jets, steam or air atomizers.

4. Percent excess air usually has to be raised:

   a. To compensate for poor air/fuel mixing.

   b. To maintain steam temperature (if superheated).

5. Air in-leakage at breechings, etc. becomes proportionately increased.

B. Results

As a result of above factors, thermal efficiency is reduced and production of soot and acid smuts (per pound of fuel consumed) is likely to be greater at low load. Where there is a choice:

1. Shut down some burners in a multi-burner unit and fire the remainder near full throughput.

2. Where there are several boilers to carry a load, work two boilers at half load rather than four at quarter load - better still, one at full load (but generally the operator will require some spare capacity to be instantly available).

X. CARBON MONOXIDE

Carbon monoxide in fuel gas is a sign of incomplete combustion, and a waste of fuel,

e.g. $C + \frac{1}{2} O_2 \rightarrow CO + 4000$ Btu
$C + O_2 \rightarrow CO_2 + 14000$ Btu

As air is reduced most units will smoke before they produce CO. Large power station boilers (having greater residence time) may be capable of producing CO before the onset of smoke. However, their operators do not allow this to happen for fear of explosions in the superheater zone.

XI. NITROGEN OXIDES

The facts about NO_x levels in boilers are not as well known as those on SO_2, SO_3 and CO. NO is produced from the oxygen and nitrogen in the combustion air. Nitrogen in the fuel is insignificant.

Studies of full scale equipment are not far advanced. NO production is promoted by (1) high flame temperatures and (2) high excess air. The flame temperature effect is probably the more important.

If controls are found to be necessary for the future, they will probably have to be designed into the unit. Flue gas recirculation and two stage combustion are possible routes toward combustion at low flame temperature. Smaller units appear to make less NO_x per pound of fuel than larger units.

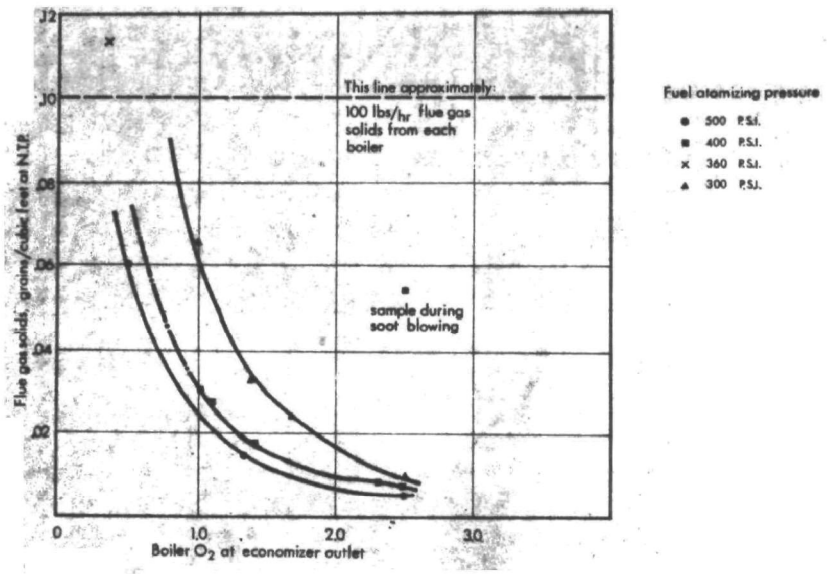


Figure 13. Effect of excess air and fuel atomizing pressure on flue gas solids burden

I UNDERFEED STOKERS, SINGLE-RETORT, RESIDENTIAL

In the residential underfeed stoker, the coal is fed from a hopper or directly from the coal storage bin to the retort by a continuous, rotating screw (see Figure 1). Coal rises into the firing zone from underneath, thus the term "underfeed firing." Air is delivered to the firing zone through tuyeres (grate openings), also from underneath the actively burning bed. The coal and primary air control is "all on" or "all off." Ash is removed as a clinker from a refractory hearth through the furnace firing door. Burning rates range from 1 to 60 pounds of coal per hour.

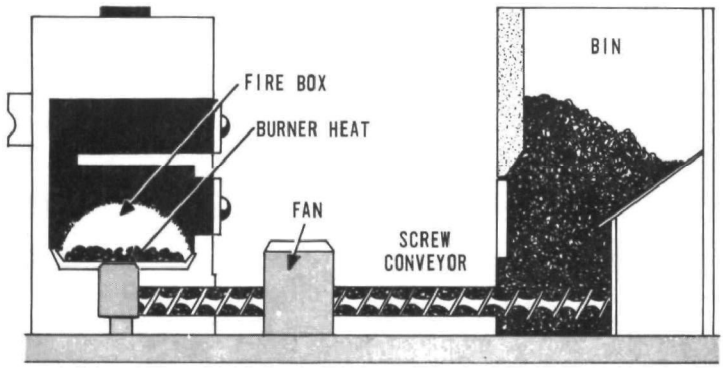


Figure 1. Residential underfeed stoker

II UNDERFEED STOKERS, COMMERCIAL, INSTITUTIONAL, AND SMALL INDUSTRIAL

The general arrangement is as described in the previous paragraph, with "dead" plates replacing the refractory hearth (Figure 2). As sizes become larger, screw feeders are replaced by a mechanical ram, which feeds coal to pusher blocks that distribute the coal in the fire box. Ash is discharged by side-dump grates. Modulating combustion controls, i.e., variable control of both fuel and air rates, are often used. Forced draft is automatically regulated, and separate over fire-air systems are used, particularly when on-off controls are used. A bridge wall retains the coal over the stoker grates. The size ranges for screw-feed stokers are 60 to 1,200 pounds of coal per hour and for ram-feed stokers, from 300 to 3,500 pounds per hour.

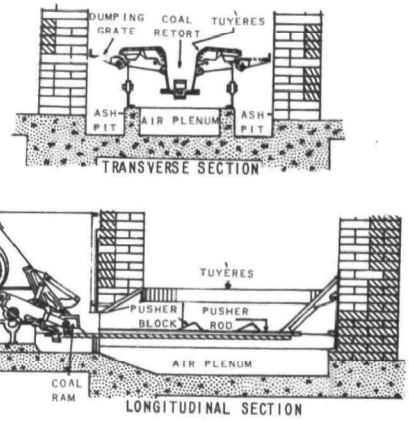


Figure 2. Single-retort underfeed stoker.

III MULTIPLE-RETORT UNDERFEED STOKERS

As the name implies, these units usually consist of several inclined retorts side by side, with rows of tuyeres in between each retort (Figure 3). Coal is worked from the front hopper to the rear ash-discharge mechanism by pushers. The forced-air system is zoned beneath the grates by means of air dampers, and the combustion control is a fully modulating system. In the larger furnaces the walls are water-cooled, as are the grate surfaces in some units. Multiple-retort underfeed stokers are losing their popularity, giving way to spreaders and traveling-grate units. Sizes range from 20,000 to 500,000 pounds of steam per hour with burning rates up to 600,000 Btu per square foot of grate per hour.

IV TRAVELING-GRATE AND CHAIN-GRATE STOKERS

Traveling-grate and chain-grate units (Figure 4) are essentially moving grate sections,

*Based on the publication by: Smith, W.S., and Gruber, C.W. Atmospheric Emissions from Coal Combustion - An Inventory Guide. Public Health Service Publication No. 999-AP-24, April, 1966.

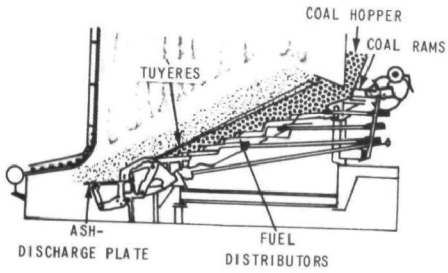


Figure 3. Multiple-retort underfeed stoker.

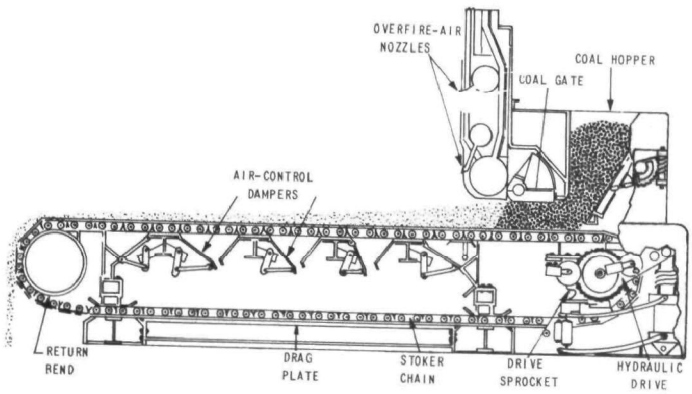


Figure -4. B & W jet-ignition chain-grate stoker.

moving from the front to the rear and carrying coal from the hopper in front through a gate into the combustion zone. The fuel bed burns progressively to the rear, where the ash is continuously discharged. Older units with natural draft are fast disappearing; modern units have zone-controlled forced draft. Complete combustion-control systems are utilized, and overfire air, especially in the front wall, is an aid to burning the volatiles in the fuel. Units range in size from 20 to 300 $\times$ 10^6 Btu per hour input.

V VIBRATING-GRATE STOKER

This unit consists of a water-cooled grate structure on which the coal moves from the hopper at the front of the boiler through the burning zone by means of a high-speed vibrating mechanism automatically operated on a time-cycling control (Figure 5). As in the traveling grate, the fuel bed progresses to the rear, where the ash is continuously discharged. Forced air is zone-controlled and regulated, along with the complete coal and air system, through an automatic combustion-control regulator. Grate heat release may range from 350,000 to 500,000 Btu per square foot per hour. The size range for this unit is from 5,000 to 100,000 pounds of steam per hour.

VI BCR* AUTOMATIC "PACKAGED" BOILER

This unit is a complete steam or hot water generating system, incorporating a water-cooled vibrating grate as the firing mechanism (Figure 6). Coal is delivered from the storage bin to a hopper from which it travels on the vibrating grate to the fuel bed. Ash is discharged automatically with a screw conveyor. The unit has completely automatic conbustion controls so that coal feed to the hopper from the bin and ash discharge is coordinated with load conditions. Forced and induced draft fans are used. The size range is from 3 to 20 million Btu per hour input.

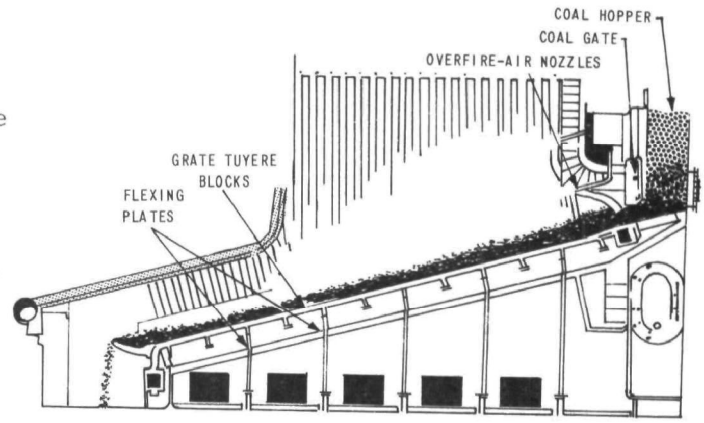


Figure -5. Vibrating-grate stoker furnace.

VII SPREADER STOKER

The spreader stoker combines suspension and fuel bed firing by the stoker mechanism feeding from the hopper onto a rotating flipper mechanism, which throws the fuel into the furnace (Figure 7). Because fuel is burned partly in suspension and partly on the grate, the fuel bed is thin, and response to fluctuations in load is rapid. The grates are either

*Bituminous Coal Research, Inc.

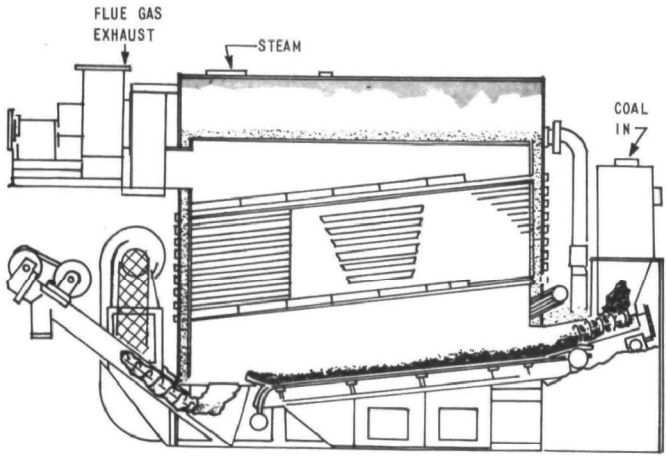


Figure -6. Bituminous Coal Research, Inc., packaged boiler

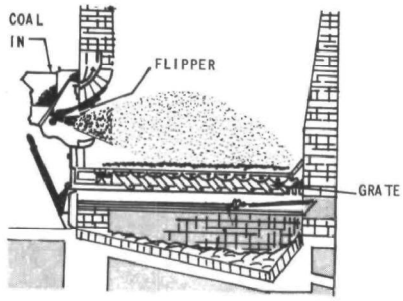


Figure -7. Spreader stoker-fired furnace.

stationary or continuously moving from the rear to the front. Vibrating, oscillating, traveling, and chain grates are designed for moving the fuel toward the ash receiving pit.

Zoned undergrate air is important, as is the careful application of a responsive combustion control system. Overfire air is necessary. Fly-ash carry-over is stronglyinfluenced by high burning rates, whereas smoke emission is increased at low burning rates. In large units, cinders are often returned to the grate from the fly-ash collector to reduce unburned carbon losses. Spreader stokers range in size from 6 to 500×10^6 Btu per hour input or from 5,000 to 400,000 pounds of steam per hour output.

VIII PULVERIZED-FUEL FIRING UNITS

In this sytem, coal is pulverized to particles, at least 70 percent of which pass through a 200-mesh sieve, and is fired in burners similar to those used for liquid fuel (Figure 8). In direct-firing systems; raw coal is dried and pulverized simultaneously in a mill and is fed to the burners as required by the furnace load. The control system regulating the flow of both coal and primary air is so designed that a predetermined air-coal ratio is maintained for any given load. The in-directly fed unit utilizes storage bins and feeders between the pulverizers and the burners. Some bin-and-feeder systems are in use, but the majority of plants use direct-firing units.

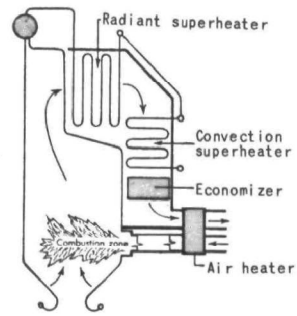


Figure -8. Pulverized-coal-fired unit.

Burners are characterized by their firing position, i.e., horizontal, vertical, or tangential (see Figure 9). Arrangements for the introduction of primary, secondary, and, in some cases, tiertiary air vary with burner manufacturers. One manufacturer uses an adjustable burner, which is tilted upward or downward to control the furnace outlet temperature, so that steam temperature can be regulated over a wide range of capacities.

Pulverized-coal-fired units are usually one of two basic types, wet bottom or dry bottom. The temperature in a wet-bottom furnace is maintained above the ash fusion temperature, thus the slag is melted so that it can be removed from the bottom as a liquid. The dry-bottom furnace maintains a temperature below this point so that the ash will not fuse.

Pulverized-fuel-fired boilers range in capacity from 200,000 to several million pounds of steam per hour.

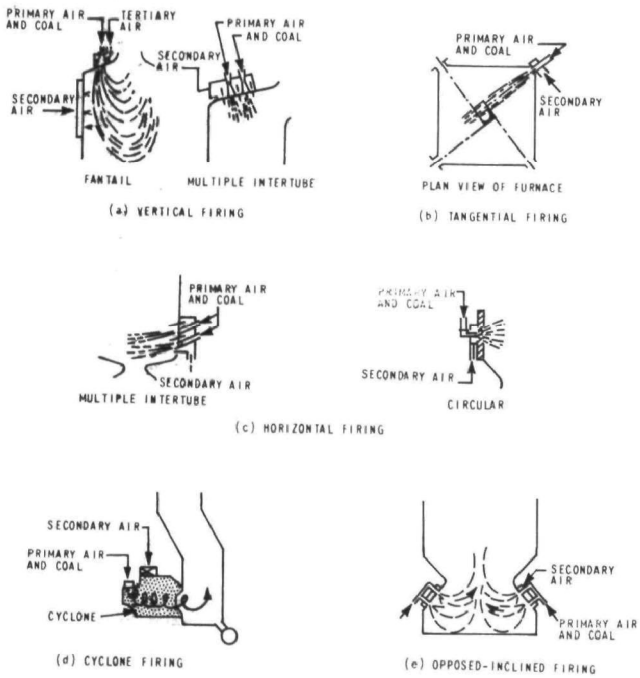


Figure 9. Various methods of firing coal in suspension

IX CYCLONE FURNACE

The cyclone furnace is a water-cooled horizontal cylinder, in which the fuel is fired and heat is released at an extremely high rate for the given volume (Figure 10). Coal is crushed so that approximately 95 percent passes through a 4-mesh screen. Coal is introduced into the burner end of the cyclone, and air for combustion is admitted tangentially. Combustion occurs at heat-release rates of 500,000 to 900,000 Btu per cubic foot per hour at gas temperatures sufficiently high to melt a high percentage of the ash into a liquid slag, which is discharged from the bottom of the furnace through a slag tap opening. The size range of boilers fired are comparable to those with pulverized-fuel units.

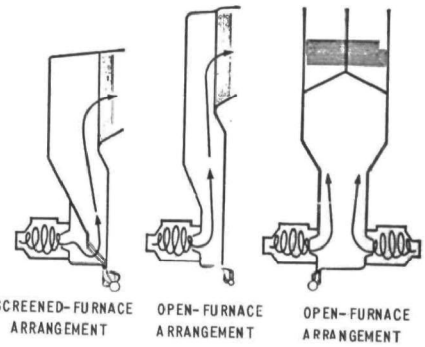


Figure 10. Types of cyclone furnaces

REFERENCES

1 de Lorenzi, O. Combustion Engineering. 1st ed. Combustion Engineering-Superheater, Inc. New York. 1952.

2 Steam - Its Generation and Use. 37th ed. The Babcock and Wilcox Co. New York. 1963.

3 Shields, C. D. Boilers, Types, Characteristics and Functions. F. W. Dodge Corp. New York. 1961.

4 Perry, J. H. Chemical Engineers' Handbook. 4th ed. McGraw-Hill, Inc. New York. 1963.

COAL BURNING-DESIGN PARAMETERS

U.B. Yeager*, P.E.

I INTRODUCTION - A FEW BASIC FACTS

A I think of the three "t's" as forming a mathematical equation for any given unit and for an operating condition of that unit: f $T_{(time)}$ + f $T_{(Temperature)}$ + f $T_{(Turbulence)}$ = $C_{(Constant)}$. But turbulence brings to mind a mixing of a mass within a space or volume or distance cubed ($length^3$) and a degree of mixing also involves time. Moreover, heat transfer by conduction and convection involve the first power of the temperatures involved while radiant heat energy transfer makes use of the fourth power of the temperatures involved. Hence, f $T^x_{(Time)}$ + f $T^y_{(Temperature)}$ + f $M_{(Mass)}$ + f $D^3_{(Distance)}$ = $C_{(Constant)}$.

To me the last equation points more directly to the corresponding change that must be made in one or more of the remaining functions after one of the other functions has been changed.

B Another fact to bear in mind is that all fuels or combustible materials regardless of their form, whether gas, liquid or solid are burned as a gas. All combustion is first of all a surface reaction.

But the surface must be active and available for reaction - and not simply a potential surface. Consider, for example, that a cube of coal one foot on each side has 864 square inches of surface. Break up this cube into one inch cubes and the 1728 cubes now have 10368 square inches. Broken down into 1/300 inch cubes and the whole potential surface becomes 3,110,400 square inches. But, if in use, the fine coal particles were packed, the total potential reactive surface in effect reverts to the initial available surface. With various stoker fired equipment, an attempt is made by means of "Selective Application" to control the size consist (physical make-up by sizes) of the coal and to create a maximum available effective surface by means of fuel bed agitation resulting from the stoker movement to fit the operating needs.

For this reason gas is an ideal fuel. Gas offers the greatest available reactive surface per unit of mass and per unit of heat. Oil, by its degree of atomization and its temperature, as fired, has its liquid form converted into tiny liquid droplets from which it is readily converted into a vapor or gaseous state. Coal, as shown, may have its reactive surface immensely increased by a control of particle size to meet the conditions of its burning. This is true whether the burning is done on grates or fuel bed or by suspension burning.

C From the foregoing discussion it can be stated that any coal fired unit, from the simple pot bellied stove on through to the huge utility power units, is first of all a gas producer. The basic principles involved between any one of these units and the conventional gas producers are the same. The only difference is the element of time between the zone or point of gas production and the final combustion of the gas. With the conventional gas producer and the consumption of its gas, the elements of time and space are more apparent. The time involved may be the matter of several seconds and the distance between gasification and final combustion may be many feet. With the household stove, iron melting furnace or the power unit, the time may be reduced to small fractional parts of a second and the distance or the zones of the two reactions approach being concurrent.

D For the final of the few basic concepts of combustion this statement is offered: Primary air determines the rate of combustion reaction and secondary air determines the efficiency of its reaction. This is true whether the combustion takes place

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on grates or as individual particles in suspension burning. It can be stated that the thickness of the fuel bed does not control the burning rate. Rather, the thickness controls the amount of carbon monoxide that will be produced by the passage of the primary air through the fuel bed.

II COAL BURNING METHODS

A Handfiring

Eary types of handfiring coal made use of four different firing methods:

1 Spreading or Scatter. This method fired the coal lightly, evenly and often over the entire fuel bed.

2 Spot. This method fired the coal mainly over the areas where the coal had been more completely burned. In some respects it was a modification of number one.

3 Strip. This method fired the coal in alternate strips or areas, front to back. This, too, was a modification of number one. Each strip was fired a little heavier at each cycle or firing than was true of number one.

4 Coking. This method first cleaned off part of the ash; the glowing fuel bed was pushed back on the grates; and, the fresh or green coal was fired at the front. This method was considered best to lessen smoke because the distilled volatile gases were carried back and over the incandescent fuel bed. Combustion efficiency likewise was increased.

All methods of handfiring were of the overfeed type. That is, immediately over the grates is a covering of ash. Then above the ash is the glowing fuel bed. The green or fresh coal is fired on top of this incandescent fuel bed.

Mechanical methods of firing coal were initiated in the early 1800's. These methods or stokers really came into their own during the period of 1885 to 1900.

B Overfeed Stokers

Early stokers were simply mechanical adaptations of handfiring. Two of these stokers were the (1) Westinghouse (Roney) and (2) Murphy "V" types. The firing principle was much the same as the "coking" method of handfiring. Later, rotating or chain grates were built. These fired the coal continuously at one end and deposited the ash into a pit at the opposite end. Refractory arches promoted the ignition and efficiency of burning. All of these overfeed units made use of natural draft. Then capabilities as to flexibility of load conditions and output capacity were determined accordingly. Some of the chain grate units were: (1) Combustion Engineering (Green and Coxe); (2) Babcock and Wilcox; (3) Riley Stoker Co. (Harrington), and (4) Johnson and Jennings (Stowe).

A later modification of the chain grate was called the link grate traveling stoker. Basically, this was a different arrangement of the stoker linkage. These may or may not have been the first stokers to make use of forced draft or underfire air under positive pressure. Subsequently, the air was divided into zones or areas from front to back. This brought about a more positive, more proper and more complete combustion at the desired point. Various makes of the overfeed stokers had some limited expansion even up to the late 1920's.

C Underfeed Stokers

The underfeed stokers especially of the larger size were developed before 1900 and had rather large usage prior to World War One and some limited acceptance

through to the mid 1930's. These stokers operated on the principle of feeding the fresh or green coal from below the incandescent fuel bed. The ashes were pushed, gradually, upwards and away from the top of the fuel bed. An advantage of this type of burning is that the volatile hydrocarbons distilled from the green coal must pass upwards through the glowing fuel bed where they may be more readily consumed before leaving the combustion zone. With a proper adjustment of the coal and the air ratios, these stokers can fire with a smokeless type of combustion. The larger underfeed stokers made use of a ram or reciprocating plunger type of coal feed. They, also made use of forced draft. The smaller underfeed stokers for domestic, commercial, small institutional and small industrial usage had worm or screw-type coal feeds. These stokers all had one retort.

These screw feed stokers were especially active in application in the later 1920's to the later 1940's. At one time well over one hundred makes of small screw feed stokers were on the market. Ram type stokers were of the single and multiple retort design with the latter reaching twelve or more retorts. The single retort ram type stoker, normally, has side ash dump grates. The multiple retort units has end dump grates for periodic dumping and for continuous discharge of the ash and clinkers. With one exception the smaller screw feed stokers required that the ash periodically be lifted out manually in clinker form. One make known as "The Original Pocohontas" had a mechanical type of ash removal as an integral part of the stoker. Very few of the single retort stokers had any type of mechanical agitation for the fuel bed to maintain porosity. As a result "coke trees" become something of a problem in many cases. The good that was achieved was the result of good coal application, suitable burning characteristics and the proper size consist combined with improved firing techniques. The multiple retort units with alternate plunger feed action and in some cases stokers with a controlled grate adjustment, for an undulating movement of the fuel bed from the furnace front towards the rear, did maintain a more reactive or breathing fuel bed. These units consequently were able to produce very high rates of combustion per square foot of grate area. Some of the leading American Manufacturers of the large underfeed stokers were: (1) Detroit Stoker Company; (2) Westinghouse Electric Manufacturing Company; (3) American Engineering Company (Taylor); (4) Combustion Engineering Company (Frederick, CE, and E); (5) Riley Stoker Company (Jones); (6) Auburn Foundry Company, and (7) Canton Stoker Company. Some of the manufacturers of the smaller screw feed stokers included: (1) Auburn Foundry Company; (2) Brownell Company; (3) Canton Stoker Company; (4) Eddy Stoker Company; (5) Iron Fireman Manufacturing Company; (6) Illinois Iron and Bolt Company; (7) Fairbanks, Morse & Company; (8) Steward - Warner Corporation; (9) Holcomb and Hoke Manufacturing Company, and (10) Will-Burt Company.

D Spreader Stoker

The spreader stoker was invented in the early 1800's but had only a limited acceptance by the 1920's. Its growth accelerated during the 1930's and its greatest acceptance came after World War II. This growth likely was the result of changes in industrial growth and coal mining methods. The spreader stoker works on the principle of both suspension and grate burning. In some respects it was patterned after the spreading or scatter method of hand-firing. The grates may be of many types: fixed, dumping (power or hand), undulating, vibrating, reciprocating and rotating (traveling). Feeding of the coal is done mainly by rotors or revolving feeder paddle wheels. The "throw" of these feeders may be from six to approximately twenty feet. Furnace turbulence and fly ash carry-over both are increased as the throw increases. One type feeds the coal pneumatically to its feeder plate. Spreader

stokers permit great flexibility as to load changes and capacities by ready response. These stokers permit a rather wide range as to coal grade (quality) and types. Normally, a high volatile type of coal is preferred. The make of the stoker dictates the upper limit as to the size that may be used with best satisfaction. Generally, coal preparations of 3/4 inch to 1 1/4 inch top size (round hole screen equivalent) give most satisfactory results. The coal preparation has a great bearing on the performance of spreader stokers. If the consist of the coal is too coarse, very little suspension burning takes place and the response of the unit to load conditions is very sluggish. If the consist of the coal is too fine, the firing at or near unit rating may cause minor explosive pulsations in the furnace during each throw of the coal feed. Under such a circumstance, the grate burning is nil. The explosive hazard is rather minor but the periodic "puffs" cause excessive fly-ash carryover. Moreover, these puffs cause an excessively dusty boiler room and more attention must be given to maintain good housekeeping. A proper Selective Application determines a consist between the two extremes depending upon the unit design and load conditions.

Various American Manufacturers of spreader stokers include: (1) Detroit Stoker Company (Roto, Rotograte, CC, Vibra Grate); (2) Combustion Engineering Company (C-E); (3) Hoffman Combustion Engineering Company (Firite); (4) Riley Stoker Company; (5) William Bros. Boiler and Manufacturing Company; (6) Erie City Iron Works; (7) American Coal Burner Company (Furnace Feeder); (8) Iron Fireman Manufacturing Company (Pneumatic), and (9) Standard Stoker Company. Earlier, both Westinghouse Electric Company and American Engineering Company made spreader stokers.

E Pulverized Coal Firing

The firing of pulverized coal was invented about 1895. Prior to World War I it had only limited acceptance, and that being in metallurgical applications. The first power plant facility designed especially for pulverized coal was the Lakeside Station of the Wisconsin Electric Company in 1921. This plant made use of a storage type operation. That is the coal was crushed to suitable size, heat dried, pulverized and then the pulverized particles were carried pneumatically to overhead storage bins or bunkers from which the coal was fed to the furnaces. The great success of this station brought about the enthusiasm which resulted in the phenomenal growth of pulverized coal firing. In some respects this method may be considered suspension firing in its purest and best form.

When using high volatile coal, the particle size of the coal, as fired, is about as follows: 65 to 75 percent under 200 mesh; 80 to 88 percent under 100 mesh and no more than 2 to 3 percent plus 60 mesh. When firing low or medium volatile coals, the particle size, as fired, is about: 78 to 85 per cent under 200 mesh; 90 to 96 percent under 100 mesh; and, no more than 2 percent plus 60 mesh. Satisfactory and successful firing is more a function of a minimum of oversize than an excessive amount of ultra fine particles. Coals with ash contents above 8 percent will likely increase maintenance because of excessive erosion to pulverizing surfaces. However, 8 percent is not limiting and much coal with over 8 per cent ash has been consumed. Free ash in the coal is much more abrasive than is the coal itself. Also, it will be found that the excessive ash increases erosion problems with all equipment whose surfaces come into contact with the combustion gases. Manufacturers of pulverized coal fired equipment include: (1) Babcock and Wilcox Company; (2) Combustion Engineering Company; (3) Riley Stoker Company; (4) Foster Wheeler Corporation; (5) Strong-Scott Manufacturing Company; (6) Whiting Corporation; (7) Kennedy - Van Saun Manufacturing and Engineering Corporation; (8) Pennsylvania Crusher Division, Bath Iron Works Corporation; (9) Williams Patent Crusher and Pulverizer Company, and (10) Sturtevant Mill Company.

Most pulverized coal fired installations use the direct firing method. That is the coal is fed directly from the pulverizer mills to the burners at the furnace. There are two basic classes of pulverized coal fired furnaces: (1) The dry bottom furnaces, and (2) The wet bottom furnaces. In the first class the furnace ash is removed from the furnace in a solid dry form. In the wet bottom or slag tap furnace the ash is removed from the furnace in molten form.

Surface moisture in the coal above 4 per cent may cause problems in transporting the coal to the pulverizer and an irregular flow of coal to the steam generating unit. However, after the coal reaches the pulverizer, the hot primary air from the air preheater normally dries the coal sufficiently to avoid further trouble. The temperature of the coal and air mixture at the burner is usually in the range of 150 to 170 degrees Fahrenheit.

F Cyclone Firing

The Cyclone Method of firing is a development of the Babcock and Wilcox Company and came into use shortly after World War II. Firing coal with a cyclone type burner is largely suspension burning with some surface combustion from a fluid fuel bed. A cyclone furnace consists of a cylindrical, water-walled burner about eight feet in diameter and about ten to twelve feet long, set horizontally into the wall of the primary furnace. One or more cyclone units may be used per unit depending upon the design and operating needs. The particle size of the coal as fired is all under 1/4 inch (round hole equivalent). Coal received at the plant of larger size should be crushed to the proper burning size. It is felt that any coal that can be handled and fed to the burner can be burned. That is, the moisture content as fired has less bearing upon a satisfactory performance than with the previously discussed methods of burning. Obviously, as the moisture content increases the "as-fired" heat content per unit of mass must decrease. Moreover, there is a corresponding decrease in the heat release both by unit input and by heat loss by chilling as the moisture is converted into superheated steam within the furnace. It has been estimated that about 80 to 85 per cent of the total ash in the coal is discharged from the cyclone and primary furnace in molten form. The molten ash is chilled in a stream of water causing pellets of slag having a smooth, glazed, glass like particle, black or dark brown in color.

Because of the short time involved in this type of burning, the temperature and turbulence are both high. Heat release within the cyclone ranges between 400,000 and 700,000 BTU per cubic foot per hour.

Ash content of the coal used is less critical than with pulverized coal firing because the coal particles are not reduced to such a small size as fired. Coals having an ash softening temperature of 1900 to 2400 degrees Fahrenheit are most acceptable. Coals within the range of 2400 to 2600 degrees Fahrenheit for ash softening temperature are marginal depending upon the composition of the ash. Few, if any coals having an ash softening temperature above 2600 degrees Fahrenheit are acceptable in current practice, although, if the need were urgent enough, proper design for their use could likely be made.

III HEAT UTILIZATION

A furnace is a structural reaction chamber wherein a combustion process can be initiated or ignited, controlled and contained, and the heat energy in another material. Therefore, any furnace is simply a type of heat exchanger. The use determines the design and the design determines the results. This is well shown in various iron foundries where the purpose of the furnace is to melt the iron or to maintain the iron already molten at a suitable pouring temperature. The furnace is so designed that the heat

energy is reflected from the refractory arches in such manner that the desired temperatures are reached at a given point or zone and this energy absorbed according to the desired needs.

In steam generating units, the purpose is to convert the heat energy of the fuel by combustion into heat energy of the water and steam. Within a steam generating unit, the furnace proper, the boiler, the economizer, the superheater, and the air preheater are all heat exchangers. All steam generating units must have the first two items just mentioned and they may have none, all or any combination of the last three items. Over the years there have been many designs to accomplish that purpose. To show something of the results that have been accomplished, we might consider the following:

Initially boilers were given a manufacturers' rating by which ten square feet of heating surface were considered equal to one boiler horse power. A boiler horse power equals the evaporation of 34.5 pounds of water per hour into steam at sea level (from and at 212 degrees Fahrenheit and one atmospheric pressure). Since the latent heat of evaporation equals 970.3 BTU per pound of steam, the total boiler horse power equals 33475 BTU. Or each square foot of heating surface was supposed to transmit about 3348 BTU in one hour. Now, it is estimated that the direct radiant heat energy per square foot of heating surface within a large modern power unit is 70,000 to 140,000 BTU per square foot per hour depending upon the cleanness of the absorbing surface, with 80,000 to 110,000 BTU per square foot per hour as being normal in practice.

Since the air preheater is the last heat recovery item in a power unit system, the amount of heat remaining in the flue gases at this point and available for recovery must depend upon what recovery equipment has been installed between the exit of the boiler furnace proper and the preheater. The design of the air preheater will, also be influenced by the temperature at which it is desired that the flue gases leave the preheater.

There are two basic types of air preheaters depending upon the method of heat transfer: (1) Recuperative and (2) Regenerative. To some extent, the sulfur content of the coal burned has a bearing upon the temperature of the exit gases from the preheater: "It is desired that the temperature be above the dew point of the sulfurous and sulfuric acids that might be condensed out of the flue gases."

IV COMBUSTION CHAMBERS

Any thought of the act of burning must be related to volume or the three dimensions. A furnace simply gives fixed boundaries to the act. Heat release is the amount of heat liberated within a unit of volume in a unit of time. Normally, heat release is stated as "BTU per cubic foot per hour." If the burning takes place on a stoker a combustion rate may be used as "the weight of fuel burned per square foot per hour". Due to variations in the quantity of heat per unit weight the above expression is not fully acceptable. A more accurate definition is, "the heat released per square foot of grate surface per hour" or "BTU per square foot per hour".

Different uses of the heat require different rates of heat release. Consequently, the furnace must be constructed in such manner both as to design and materials as to achieve that goal. For instance in the melting of iron, the heat release must be quite high, and the design of the walls and arches of such refractory materials capable of withstanding the heat and directing it to the proper zone or area.

Power plant furnaces have been subject to a wide variation in design and in materials of construction. Now, there appears to be more of a standard for the different types of burning. Obviously, the individual requirements must determine the basic needs and different people or groups have different approaches to those needs.

In order to hold down construction costs, many of the larger power units are built with what is known as semi-outdoor design. Here all of the major heat recovery equipment is

well insulated against heat loss but has no other protection from the elements except in some cases, just a roof. Most industrial power plants are of the enclosed type. Possibly these are not so well insulated. At least during bad weather such heat as may be lost can apply towards the comfort of the operators.

Some American Manufacturers of refractory materials are:

1 American Refractories and Crucible Company

2 Armstrong Cork Company

3 Babcock and Wilcox Company

4 Carborundum Company

5 Combustion Engineering Company

6 Philip Carey Manufacturing Company

7 Denver Fire Clay Company

8 Eagle-Picher Company

9 Green, A.P., Fire Brick Company

10 Johns-Manville

11 Kaiser Refractories Div., Kaiser Aluminum & Chemical Corporation

12 Norton Company, Refractories Div.

13 Plibrico Company

14 Porter, H.K. & Son

15 Union Carbide Corporation

16 North American Refractories Company

17 Harbison-Walker Refractories Company

18 Corhart Refractories Company

V DRAFT - NATURAL, FORCED AND INDUCED

Draft is the resultant force that causes the flow of gases in an enclosure and is brought about by the differences in pressures at two critical points. These differences in pressure may be caused by temperature difference of the gases within and without the enclosure or may be caused mechanically. In general power plant use, one atmosphere is the standard or base from which drafts are measured. Negative and positive pressures involved in drafts are measured in inches of water because for the range involved this is the most accurate method.

In normal power plant usage there are three kinds of draft:

(1) Natural

(2) Forced

(3) Induced

In principle, both natural and induced drafts are akin in that they both function from the exhaust or discharge end of the furnace system. Forced draft functions from the opposite or feed end of the system.

Natural draft works on the principle of a rising and expanding column of hot gases leaving behind a negative pressure. This causes fresh or primary air to be drawn through the grates, into the fuel bed and on through the furnace system to balance out the pressure. Gases have no tensile strength, no pulling power in themselves but by compression they do have a pushing property. The natural draft system is characterized by simplicity and is dependent upon the temperatures of the inside flue gases and the outside air, upon the height and diameter of the chimney and upon the velocity of the gases moving within the chimney as well as the resistance offered by the chimney, breeching and other features to the flow of the gases. Therefore, each such unit has limitations as to capacity and flexibility of operations.

The forced draft fan supplies the primary air for combustion. This may be by forcing the air through the grates and into the fuel bed. It may be the means of picking up the coal in a pulverizer and bringing both the pulverized coal and the air to the furnace. As noted earlier, this system operates under positive pressure. It is characterized by increasing the flexibility and the output capacity of the furnace system. Primary air determines the rate of combustion. A forced draft system and a natural draft operate well together, for each assists the other.

The extended use of heat recovery equipment between the zone of combustion and the final emission of the flue gases from the system adds to the draft loss or in other words increases the resistance to the flow of the gases. Moreover, the equipment between the furnace and the chimney is such that heat transfer must be made by scrubbing action of the gases with the heat transfer surfaces. This equipment includes air preheaters, economizers, boiler tubes, superheater tubes, breeching, numerous baffles and dampers and various equipment to lessen the emission of solid particles from the flue gases. Under such circumstances the induced draft fan causes the unit to become more readily responsive to load conditions. This is especially important for rapidly changing process load operations. The induced draft fan simply draws the hot gases from the breeching or other related equipment and forces them into and up the chimney. This fan supplements both the forced draft and the natural draft.

Since World War II, many industrial plants having process loads, have installed induced draft fans for use with the relatively short steel venturi type smoke stacks.

VI CHIMNEYS AND BREECHING

A chimney or smoke stack is intended to discharge the products of combustion into the atmosphere. A chimney's effectiveness is determined by: (1) the temperature of the flue gases within and the temperature of the surrounding air; (2) the height of the chimney; (3) the cross sectional area; (4) the shape of the cross section; (5) the velocity of the hot flue gases; (6) the relative humidity of the air, and (7) the materials of construction. Any one of several chimneys may satisfy the needs for a particular unit. Since the relative costs of chimneys increase with height, economy may dictate a shorter chimney of larger diameter over a taller chimney of smaller diameter.

The temperatures involved with the particular chimney determine to a great extent the refractory needs both as to chemical composition and the extent of the use of special refractory to meet the conditions. In general power plant use, the temperatures of the flue gases may range from a low of about 275 degrees Fahrenheit to possibly as high as 750 degrees Fahrenheit with about 500 to 550 degrees Fahrenheit being a fair average of flue gas temperature to the chimney. Naturally the amount of heat recovery equipment between the furnace and the chimney will determine the specific temperature for the specific units.

Initially the breeching was the connecting link between the furnace and the chimney. Currently one may expect to find one or more of the following between the same two points: (1) economizer; (2) air preheater; (3) fly ash collector (mechanical and/or electrical), and (4) induced draft fan. In effect, the breeching thus becomes a series of short duct work connectors. In some respects the early breeching did serve as a modified type of fly ash settling or collecting chamber. As such and depending upon local conditions they did need to be cleaned periodically. The breeching may be circular or rectangular in cross section but its effective area must be in keeping with the needs of the furnace and the size of the chimney.

Gas velocities within the breeching and the chimney will depend upon the unit design and the operating conditions. The velocities will vary but a velocity of 20 to 25 feet per second has some degree of merit.

VII COAL HANDLING SYSTEM (Storage Area to Furnace)

A Coal Thawing

The first phase of coal handling at the plant, at least during extremely cold weather is the thawing of the coal so that it may be unloaded. This is accomplished in many ways:

1 Steam may be introduced into the pockets of the hopper coal cars by means of a nozzle, at the partially opened car doors. This is effective but it does add moisture to the coal which may cause added freezing problems if the coal is unloaded into an unprotected bunker or silo where freezing may reoccur.

2 Coal cars may be heated with a "flame thrower" type of oil burner.

3 Coal cars may be placed over oil, gas or coal fired thawing pits.

4 Coal cars may be heated by infra-red electric heaters.

When possible it is wise to have items 1, 3, and 4 performed in a closed or protected shed or covering.

Some American manufacturers of this equipment are:

a Aitken Products Company (Infra-red)

b Fostoria Corporation

c J. C. Corrigan Company Incorporation

d Hanck Manufacturing Company

B Unloading Point

The coal may be unloaded readily from an overhead trestle or over a track hopper. It is well to have a grill work covering over the hopper or over the opening under the trestle. This steel grill work covering should have openings 5" × 5", 6" × 6" or 7" × 7", preferably. If the openings are smaller, they tend to clog and slow the discharge of coal from the car. If the openings are larger they tend to become less safe for the workmen and they fail to catch or hold back foreign materials that should be kept from the coal being handled into the plant.

C Unloading Devices

Coal cars may be unloaded by (1) overhead clam shell buckets (2) car shakers or (3) car turnovers.

The first has limited application. The third is suited primarily for consumers of large tonnage (50 or more cars per day). The second type of unloader is of importance primarily to the industrial and utility plants using two to fifty cars per day.

Some American manufacturers of this equipment are:

1 Allis Chalmers Manufacturing Company

2 American Engineering Company

3 Hewitt-Robins Incorporation

4 Heyl and Patterson, Incorporation

5 Industrial Brownhoist Company

6 Link Belt Company

7 National Conveyor and Supply Company

8 Silent Hoist and Crane Company Incorporation

9 Stephens-Adamson Manufacturing Company

10 Webster Manufacturing Company

11 McDowell-Wellman Engineering Company

D Feeder

Normally the coal flows from the track hopper on to a short conveyor called a feeder. There are several types of feeders including: (1) Belt; (2) Apron; (3) Screw; (4) Flight, and (5) Reciprocating.

Manufacturers of this equipment will be shown under conveyors.

E Magnetic Separation

It is well to have some sort of magnetic device at or near the discharge end of the feeder to remove any tramp iron or steel material that might become a potential hazard to further intra plant handling. These devices may be magnetic pulleys over which the coal passes or electro-magnets suspended above the coal flow on the feeder.

Some American manufacturers of this equipment are:

1 Bauer Brothers Company

2 Cutler-Hammer, Incorporation

3 Dings Magnetic Separator Company

4 Eriez Manufacturing Company

5 Homer Manufacturing Company

6 Patterson Foundry and Machine Company

7 Robinson Manufacturing Company

8 Stearns Magnetic Manufacturing Company

F Crushers

If the plant uses two or more cars of coal per day it might well have a crusher for use when emergency conditions requires the purchase of coal of a larger top size than is technically proper and suitable for the burning equipment. Such equipment might well be placed at the discharge point of the feeder.

Some manufacturers of this equipment are:

1 Allis Chalmers Manufacturing Company

2 American Pulverizer and Crusher Company

3 C. O. Bartlett and Snow Company

4 Bauer Brothers Company

5 Gruendler Crusher and Pulverizer Company

6 T. J. Gundlach Machine Company

7 Hardinge Company Incorporation

8 Jeffrey Manufacturing Company

9 Link Belt Company

10 McNally Pittsburgh Manufacturing Corporation

11 Pennsylvania Crusher, Div of Bath Iron Works

12 Smith Engineering Company

13 Sprout, Waldron and Company

14 Traylor Engineering and Manufacturing Company

G Automatic Samples

The large users of coal (industrial, institutional and utility) should be concerned with the quality of the coal shipped to them. Periodic and regular samples should be taken. These samples must be representative of the coal received or they are worse than no sample at all. All samples should be so constructed such that in use the sampling device cuts the full stream of coal. Samplers are well located after the crusher.

Some American manufacturers of this equipment are:

1 Denver Equipment Company

2 Fuller Company

3 Galigher Company

4 Hardinge Company Incorporation

5 Heyle and Patterson, Incorporation

6 Stephens-Adamson Manufacturing Company

H Elevators

If the coal is to be elevated to an overhead bunker, bin or a silo, elevating equipment such as the following may be used:

1 Bucket Elevator

a Swinging bucket

b Centrifugal discharge

c Continuous discharge

d Gravity discharge

2 Bulk Flow

3 Skip Hoist

4 Pneumatic

Some American manufacturers of this equipment are:

1 Barber Greene Company

2 C.O. Bartlett and Snow Company

3 Beaumont Birch Company

4 Fairfield Engineering Company

5 A.B. Farquhar Company

6 Gifford-Wood Company

7 Joy Manufacturing Company

8 Sauerman Brothers, Incorporation

9 Link Belt Company

10 La Del Conveyor and Manufacturing Company

11 Many large rubber companies

I Conveyors

Lateral movement may be necessary either before or after the elevators. This movement may be done by the following conveyors:

1 Belt

2 Flight (scraper, drag)

3 Apron

4 Screw

5 Bulk flow

Some American manufacturers of this equipment are:

1 Allis Chalmers Manufacturing Company

2 American Hoist and Derrick Company

3 John Austin, Inc.

4 Beaumont-Birch Company

5 Blaw-Knox Company

6 Bucyrus Erie Company

7 Gifford-Wood Company

8 Heyle-Patterson, Inc.

9 Frank Hough Company

10 Link-Belt Company

11 Oliver Corporation

12 Sauerman Brothers Inc.

13 Wellman Engineering Company

14 Goodyear Tire and Rubber Company

15 B. F. Goodrich Company

16 U.S. Rubber Company

17 International Harvester Company

18 J. I. Case Company

19 Caterpillar Tractor Company

20 Le Tourneau-Westinghouse Company

J Scales

An accurate determination of power plant operations requires some reasonable knowledge of the amount of coal used over a given period of time. A number of methods are used:

1 Car weights and stock inventory

2 Stroke counters on various using equipment. This gives bulk or volume flow from which the weight can be calculated.

3 Bulk flow devices within spouts

4 Overhead weigh lorries

5 Automatic, belt flow

6 Automatic, mass trip

7 Platform scales. Where relatively small tonnage of coal are consumed the coal may be weighed in wheeled vehicles or track carriers enroute between the point of storage and the point of use.

Some manufacturers of this equipment are:

1 Yale and Towne Manufacturing Company

2 Toledo Scale Company

3 Syntron Company

4 Howe Scale Company

5 Stock Equipment Company

6 Richardson Scale Company

7 Merrick Scale Manufacturing Company

8 Fairbanks, Morse and Company

9 Buffalo Scale Company Inc.

10 Jeffrey Manufacturing Company

K Ash Removal System

There are two kinds of ash of concern from power plant operations: (1) Fly ash and (2) Bottom ash.

Fly ash is collected by several different methods of separating the solid particles, soot, etc., from the gases of combustion:

1 Mechanical (Dry)

a Settling chambers (unit or series arrangement)

b Centrifugal (single large or many small)

c Baffle trap

d Filtration (Bag filters)

2 Electric Precipitators

3 Gas Scrubber (wet)

4 Sonic or Ultra-Sonic Waves

Mechanical separation is a function of the physical characteristics of the fly ash particles. In effect, the particles are dropped from the gases in the settling chambers because the expansion into the chambers gives the slower-moving gas

less "carry-power." Centrifugal force and the inertia of the solid particles to change direction as readily as the gases makes the separation from centrifugal and baffle units. The filtration simply separates the solids from the gases be cause the gases can pass through the openings in the bag filters while most of the solids can not.

The electrical precipitator functions on the basis that the particles acquire static charges when ionized by an electrostatic field.

Gas scrubbers make use of the mass and force of the relative movement of the liquid and gas streams to each other combined possibly with the surface tension of the water or solution to wash the solids from the gas.

The sonic or ultra-sonic system simply filters the solids from the gases by wave motion and the solids inertia characteristics to movement.

The bottom ash is made of loose ash or masses of clinker that are collected in the bottom of the furnace by gravity or in an ash pit at the bottom of the furnace where the stoker movement has discharged such solid material. Such ash generally is moved to outside storage tanks or to other final deposition locations as follows:

1 Manually by wheelbarrow or other wheeled cart

2 By one of the various types of conveyors noted earlier

3 By pneumatic handling system

4 By hydraulic handling system

Some American manufacturers of ash removal equipment are:

(1) Allen-Sherman-Hoff Company

(2) American Blower Corporation

(3) Buell Engineering Company Inc.

(4) Dracco Corporation

(5) Fly Ash Arrestor Corporation

(6) Green Fuel Economizer Company

(7) Koppers Company, Inc.

(8) Aerodyne Development Company

(9) Pangborn Corporation

(10) Prat-Daniel Corporation

(11) Research Corporation

(12) Thermix Corporation

(13) Westinghouse Electric Corporation

(14) Western Precipitation Corporation

(15) American Air Filter Corporation

L Ash

Ash in the coal is found in two types: (1) Intrinsic or inherent ash which is the mineral matter contained in the original vegetation from solutions of inorganic salts and possible later reaction with the organic matter and from finely divided particles as a suspended colloidal mixture in the water in which the plant life grew and decayed; and (2) The extraneous ash which is the irregular inclusions of inorganic matter from layers of varying thickness of very thin layers, small fractions of an inch, up to many feet in thickness of clay, shale, slate, limestone and other inorganic materials. The intrinsic ash is the mineral which was absorbed by and deposited with the plant life in such finely divided form as to become a structural part of the coal. It, therefore, cannot be separated from the coal by the standard methods of cleaning currently in use. The materials

forming the extraneous ash were deposited by floods or washed in with high water or were the result of alternate elevations and depressions of the earth's surface during the periods of coal formation. Mining methods themselves may be other means of adding to the extraneous ash as produced for use. Much of the extraneous ash may be removed from the coal after mining by various methods of cleaning based upon separation by selective specific gravities.

Of course, one cannot give an accurate figure, for as indicated above, the amounts will vary between mines and even at times within any one mine but for an approximation, one might estimate that for every six tons brought out of a mine, one ton may be discarded as refuse by suitable cleaning. The refuse may range from as much as one in three tons to one in sixteen tons mined.

Ash in the coal has many factors in its utilization, most of which are adverse, as follows:

1 Ash being a non-combustible, reduces the available heat value by an amount proportional to its content.

2 Ash increases the transportation and handling costs of the coal.

3 Ash, especially the extraneous ash, increases costs in mining and preparation.

4 Ash particles in movement in the gas stream of a furnace unit causes tube and/or refractory erosion.

5 Finely divided ash particles emitted from a furnace as fly ash increase the problems of and cause a nuisance in air pollution.

6 Ash lessens heat transfer by deposits on heating surfaces as ash, slag or clinkers.

7 Ash above a unit optimum lessens unit efficiency.

8 Ash above a unit optimum increases maintenance costs.

9 Ash above a unit optimum increases unit outage.

10 Ash above a unit optimum materially increases the costs of its deposition at the using facility.

Of all coal burning equipment currently in use or that used in the past only one type, pulverized coal fired equipment, could use coal without ash. Most grates and stoker fired equipment, depending upon the use and application, seem to have a critical ash content below which satisfactory unit performance cannot be had without excessive outage and maintenance. Or, each unit has an optimum ash content for greatest and most favorable acceptance. Therefore, some ash is not a complete evil in the application of coal.

M Sulfur

Sulfur is found in coal in three forms: (1) as an iron disulfide, FeS_2, called pyritic sulfur or iron pyrites in a golden color in the form of very heavy balls or lenses and in small flakes or crystals or bands as partings. This sometimes is called "Fools Gold". (2) organic sulfur originating with and forming an inherent part of the plant life that formed the coal. (3) combined sulfur generally as a sulfate with calcium or other mineral matter and seen as a gypsum of white surface or as veins in the coal. The sulfides may have been formed from the organic sulfur evolved as hydrogen sulfide during the decay of the vegetable matter. Again the sulfates may have been formed by oxidation of the sulfides.

Generally it is considered that the presence of sulfur in the coal weakens its potential usefulness and limits its application as an industrial product for: (1) the problems of spontaneous combustion in storage are increased; (2) corrosion of various kinds of equipment used in handling the coal, in the combustion of the coal and in the handling of the gaseous and solid products of combustion are increased; (3) slagging and clinkering tendencies of the ash are increased; (4) the presence of sulfur in the coke used in various metallurgical purposes of the iron and steel industry is detrimental to these products and uses, and (5) the combustion products from burning sulfur have been found to produce adverse conditions as an air pollutant.

A fair portion of the pyritic form of sulfur may be removed from the coal during its preparation for use. In general, it can be said that the closer the particle size of the coal approaches the particle size of the pyritic flakes, the greater the separation can be and the freer the final coal product is of sulfur. However, at present no economical means is feasible for the removal of any of the organic and sulfate forms of sulfur from the coal prior to its initial use.

It does not of necessity follow that all poor coals are characterized by high sulfur contents. But by and large, most high sulfur coals are considered relatively poor coals, even though for some certain applications they may give a very satisfactory performance. A contamination of the atmosphere by sulfur dioxide has long been considered to be a public health problem and a nuisance. Whether in dilute concentrations as in the normal flue gas (0.05 to 0.3 per cent by volume) or in heavier concentrations as in roaster gases from smelter plants (5.0 to 10 per cent) sulfur dioxide is an undesirable air pollutant. There is some variation in opinion as to the total amount of sulfur that appears as an oxide in the combustion process and that which remains with the solid residue. However, of that portion that does appear in the flue gas as sulfur dioxide two to five per cent will be oxidized further to sulfur trioxide.

The use of the terms High Sulfur and Low Sulfur is rather meaningless. That which may be considered high by one usage may be considered low by another. The use made of the coal must of necessity determine the limitations of such as may be available for application. A. M. Wandless in an article "The Occurrence of Sulfur in British Coals" gives the following as a tabulation, which seems to make some sense for general power-plant usage as a base even though some slight modifications might be desired for use here:

Under 1.0 Per cent - Very low Sulfur

1.1 to 1.5 Per cent - Low Sulfur

1.6 to 2.5 Per cent - Medium Sulfur

2.6 to 3.5 Per cent - High Sulfur

Plus 3.6 Per cent - Very High Sulfur

It must be obvious that the sulfur content of the coal determines the maximum amount of the sulfur oxides that can be produced per unit weight of coal. Likewise, it must be kept in mind that part of the sulfur remains with the solid residue. With any given amount of sulfur in the fuel as a base, the relative loadings of SO_2 in the atmosphere can be expected to vary in almost direct ratio with the relative ratio of another sulfur content to that standard base.

The amount and concentration of sulfur trioxide (SO_3), which is of critical importance, in the flue gases depends not only upon the amount of sulfur in the coal burned but upon other factors which effect the dew point temperature.

The factors affecting the dew point temperature include:

1 The concentration of the SO_3 present per unit volume of the flue gas.

(2) The concentration of water vapor (H_2O) present per unit volume of the flue gas.

(3) The amount of excess air used in the combustion process. Thus, the excess air, by simple dilution, reduces the concentration of SO_3 and water vapor. Again, the amount of excess air and the conditions of combustion may increase the quantity of sulfur trioxide formed by increasing the ratio of sulfur trioxide to sulfur dioxide.

(4) The fly ash present tends to absorb part of the sulfur trioxide. The amount of absorption is variable depending upon existing conditions of the particular operations. However, the fact that this provision is true, points to the desirability of keeping all surfaces as free of fly ash as possible in order to lessen corrosion problems.

(5) The flame temperature and other conditions in the boiler furnace and the auxiliary equipment may have a great effect upon the ratio of SO_3 to SO_2 in the flue gases.

Even with coals of the same sulfur content the above items may cause a wide variation in the ratio of SO_3 to SO_2 by as much as five times.

Under some conditions it may be felt that the sulfur content is a little too high for best performance. In order to lessen or to prevent a dew point corrosive nuisance with its related maintenance problems, the flue gas temperatures may be elevated by a proper control of excess air. Increasing the flue gas temperature 100 degrees Fahrenheit lowers the normal power plant efficiency by 2.5 to 3 per cent. Usage itself must determine the sulfur content of the coal that may be used with satisfaction.

N Materials of Construction

Furnace construction from the standpoint of furnace walls may be classified as:

1 All refractory

2 All refractory - air cooled

3 Refractory - Part water wall

4 All water wall with refractory facing

5 All water walls with insulated plate metal facing

At any earlier period in power plant usage, refractory in the form of walls, arches, bridge walls, baffles, etc., contained and reflected the heat in order to create very hot zones and areas. The products of combustion were so directed that the flow of gases was parallel to or perpendicular to the direction of the heat absorbing surfaces. A scrubbing action with some turbulence of the gases at the transfer surfaces was sought to lessen film heat resistance and to hasten the heat transfer. Under such conditions most of the heat was by conduction and convection with a relatively small amount by direct radiation. Largely, since World War II, the trend of design is to accomplish a maximum of heat transfer directly by radiant energy with a reduced amount by conduction and convection. With the furnace water walls (boiler and superheater tubes) absorbing the heat directly as cold heat with a minimum of flue gas travel and scouring action, economizers and air preheaters must be expanded in heating surface. Many pulverized coal fired furnaces are of such volume that the indicated heat release at the design unit rating may be only 12,000 to 20,000 BTU per cubic foot per hour with about 17,000 BTU per cubic foot per hour approaching an average. Spreader stoker fired units, generally, average about 10,000 BTU per cubic foot per hour more than pulverizer units or

average about 27,000 BTU per cubic foot per hour at rated operation. The great decrease in the use of the overfeed link grate traveling stokers and of the underfeed stokers makes their data less common. At an earlier time, however, it was considered that the heat release of these latter two types of equipment with relatively smaller furnaces and all refractory construction might show heat releases of 35,000 to 40,000 BTU per cubic foot per hour. In the cyclone units, where the heat release approximates a half to three quarters of a million BTU per cubic foot per hour, it is apparent that a great part of the heat recovery must take place in the primary furnace.

Therefore, the materials of construction are dependent upon the design of the unit and the usage of the heat. Some furnaces may require a refractory capable of withstanding a very high temperature throughout the whole unit while others may require only a relatively small amount at about the grate level. The use of water wall recovery surfaces not only adds to the unit efficiency and output but may be a means of lessening furnace maintenance for industrial power plant usage.

The following figures have been noted as being somewhat typical of the heat transfer in BTU per square foot of heat absorbing surface per hour:

Water walls	50,000 to 140,000
Superheater	7,500 to 15,000
Boiler	2,000 to 6,000
Economizer	3,000 to 4,500
Air Preheater	500 to 800

From the standpoint of the stokers alone the firing rate in BTU per square foot of grate surface per hour approximates as a maximum:

Single retort underfeed stokers - 450,000 to 500,000

Multiple retort underfeed stokers - 500,000 to 675,000

Traveling grate overfeed stokers - 425,000 to 550,000

The lower figure might be taken as one where the stoker maintenance with proper care and attention might not be excessive. But the higher figure likely would be cause for increased maintenance costs.

It has been shown that the materials of construction combined with the unit design does have a bearing upon the costs of operation. Moreover, it is generally agreed that the current stage of the metallurgy of boiler construction is the determining factor as to what can be done in this respect.

O Instruments and Controls Requirements

As load conditions become more variable and the power plant units become more complex, the necessity for a constant readiness to meet those conditions by fuel feed, air adjustments, control of temperatures, control of various drafts and pressures becomes more demanding. Man power can be used to make such changes. But man power can become tired and lax in attention and performance. The modern unit cannot tolerate any lack of instant change to meet the operating conditions and needs. A proper instrumentation of gages, meters and controls to meet the status of performance sought should be considered and used. In effect, then, the instruments take over the details of firing and the operator becomes a type of supervisor. But the instruments cannot think and the operator must be well enough acquainted with their use and meaning along with the fundamentals of good combustion to know when conditions within the unit are proper and satisfactory. Instrumentation must be adequate but should not be carried to an extreme beyond the needs. Otherwise much data

may be collected that for all practical purposes is rather worthless except possibly of some academic interest. Then, briefly, one should consider to each unit its own instrumentation according to the needs.

Meters, gages and controls to show the steam load, steam pressure, water level, coal feed, air adjustments, drafts and dampers for same, and temperatures where needed are primary. Management and operators must determine what instrumentation is necessary, what instrumentation might be desirable but not completely necessary and what instrumentation is a luxury.

In some cases, electric eye equipment may be installed and adjusted so as to warn of an operating condition approaching nuisance proportions. Properly used this equipment may become a means of bringing about an improved firing technique. In some cases, a simple arrangement of mirrors can be, if properly observed, a means of helping an operator to correct faulty firing and lessen a potential nuisance. A fireman can accomplish a great deal in improving the efficiency of his unit and in lessening operating faults by periodically observing his firing conditions and correcting when and where necessary. In many cases the unit and facility already has ample requirements for good results but there is a laxness on the part of the operators to make use of that which is available.

Some American Manufacturers of instrument and control equipment are:

(1) Allen-Bradley Company

(2) Askania Regulator Company

(3) Bailey Meter Company

(4) Brooke Engineering Company, Inc.

(5) General Electric Company

(6) Hagan Corporation

(7) Hays Corporation

(8) Republic Flow Meter Company

(9) Leeds and Northrup Company

(10) Taylor Instrument Company

(11) Minneapolis-Honeywell Regulator Company

(12) Hoskins Manufacturing Company

(13) Ellison Draft Gage Company

(14) Weston Electrical Instrument Corporation

P Considerations to Minimize Air Pollution

There are several factors influencing the selection of particulate control equipment as follows:

1 Whether the plant is in use and is being revamped to meet the needs or whether the plant is in the design stage of construction.

2 The method of burning.

3 The heat content of the coal.

4 The ash content of the coal.

5 The rate of burning or the rate of operation.

6 The physical consist of the coal as fired.

7 The capability of the operating personnel and their civic view point.

8 The good neighbor policy of management and the importance to them of their public image.

9 The location of the facility with respect to the community at large.

In speaking of fly ash emission it should be specified whether these are furnace emission or unit emission. A great deal of fly ash may be emitted from a furnace. But a reasonably high portion of such emission may be removed from the gas stream in the various boiler passes, fly ash collectors, air preheaters, economizers, breeching, induced draft fans and in the stack. When the latter is true the problem largely is internal within the facility and even more so within the unit. Operating costs, handling problems, maintenance costs, erosion, corrosion, unit outage, good housekeeping and unit efficiency may all be problems of direct concern within the plant with little or no problem from the outside.

If the emission is from the unit the problem becomes one of the facility relationship to its neighbors and to the community as well as being a technical problem.

Suspension firing brings with its use a higher amount of furnace emission than does bed or grate firing. The reasons for this are obvious in that the particles of coal as fired generally are (1) smaller and (2) are introduced into the furnace at several inches above the grates. Combined with a higher turbulence of furnace gases it is only natural that the gases leaving the furnace have a higher capability of carrying a relatively great amount of entrained solid particles. Bed firing on the other hand begins with the firing of larger particles and the consist may be relatively coarse. In fact, the whole concept of a breathing, porous fuel bed is that a suitably proportioned range of particle sizes as fired, will give a maximum of desirable available reactive surface. Therefore, with the bed firing starting with coal of larger consist and larger particles, and with these placed on the stoker fuel bed prior to entering the furnace in some cases, there is less active fuel bed and furnace action. Moreover, bed firing was originated largely for steady loads while suspension firing was conceived largely for process or swinging loads. It is granted that each type of equipment can be used for the opposite type of load. That is, with the recognized qualifications, suspension firing can be used with steady loads and bed firing can be used for swing loads. Under these reversed uses it will be found that the emission functions likewise are reversed. However, with bed firing the furnace emission seldom, if ever, reach the status of suspension firing and if the emissions do reach this status it is more or less the result of a temporary condition brought on by some unusual circumstance.

Some types of burning equipment make use of a certain amount of fly ash reinjection. With the conventional overfeed and underfeed stokers this is no problem. This practice has been used extensively with spreader stokers. But reinjection may be open to question in real usefulness. At most only the larger coarser particles should be returned to the furnace. Moreover, this ash should be returned to the stoker by some gravity system and not reinjected pneumatically. In many cases, the net gain, especially when returning all of the fly ash pneumatically, has been much less than anticipated. In most cases, practically all of the fly ash with the possible exception of that collected in the initial fly ash collector, could just as well be run directly to the ash hopper. Whenever fly ash is reinjected pneumatically, the total fly ash from the unit eventually is increased; and the furnace walls; boiler tubes; superheater tubes; and economizer tubes; air preheater surfaces, and induced draft fan blades are all severly eroded. Very often the reinjected fly ash increases clinker and slag formation. In the end the total costs very often exceed the gain.

COAL BURNING-GOOD OPERATION PRACTICES

U. B. Yeager*

I Normal Temperature Range in Combustion Chambers, Particulate Control Equipment, Stack, Etc.

The theoretical flame temperature of a good coal is on the order of 3500°F to 4000°F. Possibly 80 percent of that temperature is more normal in practice. Different conditions of heat release vary according to the load conditions. Moreover, the design of the unit coupled with the relative amounts of refractory and water wall heating surface determine the temperatures within the combustion zone. Temperatures immediately adjacent to the water wall tube surface will approximate the temperature of the water within the tube while a few inches within the furnace the temperature will be many hundreds of degrees higher. Out toward the center of the furnace or near the flame zone, the temperatures may be 2600 to 2900°F. Obviously, depending upon furnace design and the path of the flame travel, there must be zones at temperatures between the two extremes. It is desirable, when possible, to have the combustion gases cooled to the temperature of or slightly below the ash softening temperature of the coal being burned as they enter the first bank of tubes. If such a condition is questionable early enough, the tube spacing may be widened in the superheater and first bank of boiler tubes. Any slag accumulation then will not be excessive or may be removed without too much effort. If the condition cannot be corrected early enough and slag does become a problem it may be necessary to operate at a reduced rating or to use another coal having a higher ash softening temperature.

Except for the relatively small percentage of units so designed and in use with positive furnace pressure most units operate with a negative furnace pressure. This negative pressure or furnace draft is adjusted properly to bring about the greatest heat recovery before the gases enter the chimney. Again, this adjustment must depend upon the furnace design, equipment used, operating conditions and firing technique. If the furnace is of an all refractory construction, a higher condition of draft (read in inches H_2O) should be used than if the furnace has a water wall construction. For instance in the first case, if the stoker were an underfeed or overfeed traveling grate or a spreader feed type the overfire furnace draft at about the fuel bed level should be 0.08 to 0.12 inches H_2O, or more, while if the same unit had water walls the draft at the corresponding point might be only 0.00 to 0.08 inches H_2O.

A unit that is designed to operate at a negative pressure should do so. If not, then, the flow of combustion gases, in effect, become bottled and the furnace pressure will become positive. Very often, within a very short time (minutes) the heat within the furnace can become excessive to the extent that the stoker furnace walls or boiler itself may be damaged even to the extent of causing a shut-down. Also, under such a condition the furnace atmosphere approaches or becomes reducing in character which again hastens slag and clinker formation.

Assuming that we have the gases leaving the primary furnace without too much trouble, the purpose of the rest of the heat recovery equipment is to absorb and recover the greatest amount of the sensible heat available in the gases consistent with good operations before they enter the chimney. Whether a superheater is used depends upon the usage of the steam and the temperature of the steam needed. It may be found either immediately before or after the first bank of boiler tubes and possibly in both places.

Since the purpose of the boiler is to produce steam or hot water, one of the best means of assisting it to reach or maintain adequate capacity is by heat recovery with an economizer. This is simply, a water preheater

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gaining its heat from the flue gases that might be lost or wasted otherwise. It is considered, generally, that an economizer will add two to eight percent (or an average of about five percent) to the units efficiency.

The last heat recovery item within the system is an air preheater. Because of the products involved, flue gas and air, the temperatures must be relatively low, in power plant usage at least. For that reason and to make a good recovery, these units will have a large heat recovery surface. These units may add two to five percent to the unit efficiency. It is desired that the flue gases leave the preheater at a temperature such that they are above the dew point of the gases as they enter the chimney. The nature of the operations and, especially, the sulfur content of the coal influence the exit temperature. When conditions require that the exhaust gases must have the temperature increased by 100°F, a loss in efficiency of 2.5 to 3 percent occurs. Moreover, it is desired that the preheated air be of such temperature that when blended with whatever room or cold air may be necessary, that the air temperature at the point of ignition will be proper for the equipment used. For pulverized coal fired units, the coal-air temperature at the burner should be about 150 to 165°F as an average even though the air may have left the preheater at 375 to 450°F. For stoker fired units it appears that the temperature of the air at the stoker generally should be below 250°F for satisfactory performance even though higher temperatures may be used in some cases with satisfaction. The following maintenance costs have been noted for stokers using preheated air but cannot be said to be universally acceptable:

Air Temperature at Stoker °F	Maintenance Costs (cents per ton coal)
200	3
300	6
400	14
450	23

Fly ash collectors (particulate control equipment) are not considered as heat recovery equipment. They may be a means, however, of maintaining good will and a good public relationship within the community outside the plant site. They, also, may be a means of lessening maintenance costs by the removal of the erosive particles that can damage the economizer, air preheater induced draft fan, dampers, etc. Fly ash collectors, normally, are placed between the economizer and air preheater and between the air preheater and induced draft fan or chimney. In some cases, a fly ash collector may be placed between the last pass of the boiler and the economizer.

Since it has been shown that the range of temperatures is fairly broad, the following are listed as being an approximation:

Furnace (Burning Zone)	1900 to 2900°F
Leaving furnace and entering first bank of boiler or supertubes	1900 to 2600°F
Leaving boiler and entering economizer	450 to 750°F
Leaving economizer and entering air preheater	350 to 550°F
Leaving air preheater and entering stack	250 to 350°F

II EFFECT OF COMBUSTION AIR

If it were possible to get a perfect mixture of the fuel with the air for combustion in proper manner, in proper time and under proper conditions of temperature no excess air would be required. Unfortunately, up until this time at least such an ideal cannot be achieved. It is necessary, therefore, to make use of such excess air as may be required to reach the desired results. Only such excess air should be used as is necessary to complete the combustion process and to maintain the unit in such a condition as to assure maximum unit availability or to lessen outage (period unit out of service); and, to give maximum unit efficiency consistent with lowest operating and maintenance costs. Increasing the excess air beyond a desirable optimum increases the flue gas temperatures and lowers the efficiency.

Lessening the excess air below a desirable optimum may lessen the flue gas temperature and lower the efficiency. For instance, it may be possible to lower the excess air and to raise the percentage of carbon dioxide in the flue gas temperature. Thus the efficiency should be increased. But due to a lack of proper contact of the air with the fuel the carbon monoxide might be increased. Under many operating conditions an increase in the carbon dioxide content by one percent might increase the efficiency by one fourth to one-half percent. An increase though of carbon monoxide by one percent might lower the efficiency by 4.5 percent. That which might start to be a gain might end with a much greater net loss.

With a good adjustment of air to the coal feed, the flame will be yellowish orange in color with no black tips. It will appear soft. And its luminosity will give a maximum of radiant heat energy transfer. If the air is increased the flame will become whiter in color and will appear to be harder, sharper and more erosive. Its radiant heat energy will be lessened. If the air is decreased too much the flame will appear to be blacker and the flame will be lazy and without life. Since a reducing atmosphere is now well indicated, soot may be formed and collect at some point in the system. The smoke will be dark.

With a good air adjustment and proper burning the smoke from the chimney should be just a light haze, either light tan or light gray in color.

III NORMAL COMBUSTION AIR REQUIREMENTS

Regardless of the type of fuel whether it be a gas, liquid or solid, theoretically perfect combustion requires approximately 0.75 pound of air per 1000 BTU. Over the years, I have done work with many fuels (primarily coal of many kinds and grades but also with oil, natural gas, by-product manufactured gas, retort gas, low temperature coal carbonization gas, water gas, carbureted water gas, producer gas and blast furnace gas). In attempting to find some common denominator for the fuels I determined the above fact many years ago. Of course, there are some variations depending upon the analyses of the fuels. Of the very large number of analyses from which determinations were made the range of air requirement varied from about 0.65 to 0.85 pounds of air per 1000 BTU with the overall average about 0.75 pounds per 1000 BTU. I have wondered many times as to just how close this range might have been if all samples could have been taken and analyzed with equal accuracy. Quite often it is not realized that the taking of a good, fair sample of any fuel is most important, and sometimes rather difficult to do. The best of analyst and the best of laboratory equipment and technique are worthless if the sample is not representative.

Now, in practice, excess air is used normally in amounts of 10 to 40 percent. Therefore, for a quick check of the air requirements one may use one pound of air per 1000 BTU. While not given as an accurate figure it still has use of estimations.

One cubic foot of air at a temperature of 70°F weighs approximately 0.075 pounds. Therefore, for all practical purposes, 0.75 pounds of air equal 10 cubic feet of air, or a 1000 BTU of any fuel requires 10 cubic feet of air for perfect combustion (no excess air). Therefore, 1 pound of air would indicate about 1/3 excess air would amount to about 13.3 cubic feet.

An air adjustment resulting in a flue gas analysis of 12.5 to 14 percent carbon dioxide when using coal, generally is very satisfactory. A higher figure may cause a smoke emission. Also, the tendency for slag and clinker formations are increased. A lower figure will result in a lowered efficiency.

IV SOOT REMOVAL FROM HEAT EXCHANGER EQUIPMENT

Soot itself is a volatile hydrocarbon that has been distilled from the fuel bed but which has been chilled and condensed by striking

some cool surface before it has had the opportunity to be burned. It is of such character that it will retain some of the solid residue that may come into contact with it. It will burn under suitable conditions as you have learned from the burning of soot accumulations in your own furnace or chimney.

A clean smooth heating surface is best for proper heat transfer. The surface must be clean on both sides. Here we are dealing solely with the gaseous or fire side surface. Soot, ash and slag are the three main forms of solid that may accumulate on the heating surface. The form involved is a function of the completeness of burning; of the furnace temperatures involved; and of the location of the accumulation. Therefore, a periodic cleaning of the heating surface is necessary.

Unit design and operating conditions determine the amount and kind of cleaning that are necessary. Normally, steam jets mounted on suitable equipment are directed against the heating surfaces. This equipment may be permanently mounted within certain gas passes or may be mounted for retractable operation. In some cases, compressed air or steel bristled brushes may be used. Again, in some cases various chemicals may be added to the fuel bed either alone or with the coal for cleaning. Chemicals that may be used for treating the coal usually are chloride salts of calcium, sodium or zinc. Personally, I am inclined to think that these chemicals may do more harm than good over an extended period by corrosive action at numerous critical points. The surfaces of air preheaters and economizers may be cleaned by the erosive action of falling soot. And, in some cases the heating surfaces may be sand blasted.

Some American manufacturers of soot-removal equipment are:

A Bayer Company

B Diamond Power Specialty Corporation

C Hahn-Pitz Corporation

D Vulcan Soot Blower Division Continental Foundry So. Machine Company.

V Importance of Proper Fuel Bed-Depth And Complete Coverage of The Fuel Bed

The burning of coal in a bed on grates involves bringing the air into contact with coal particles. In their relative relationship the coal particles are still and the air is in movement about them. Since the combustion reaction is a chemical reaction the reactive components must be supplied in a fixed relationship.

If the fuel bed is too thick, the depth may offer excessive resistance to the flow of air and sufficient air may not be able to penetrate in an amount necessary to meet the load conditions or even to sustain combustion. If forced draft is available, an excessive underfire air pressure might be required. A blasting of the fuel bed can be a means of increasing clinker formation with its attendant problems. At any rate the fuel bed would become uneven in depth and coverage.

If the fuel bed is too thin, an excessive amount of air could be drawn through the fuel bed without taking place in the burning reaction. Again, the unit output would be lessened and the efficiency of the reaction greatly decreased. The draft could be so regulated that the reaction of the air through the fuel bed could be more correct and complete but it is possible then that the heat output would not be sufficient to meet the load conditions.

Obviously, the fuel bed must be completely covered. If it were not, the primary or underfire air would simply short circuit through the areas of little or no resistance. The furnace would be chilled and the combustion process could be stopped. This is one reason why the underfire air of the stokers is divided into zones. By having such a control of the air, that portion of the fuel bed that needs the most air can have its due amount. By the same token another area of the stoker that needs less air can have its requirements met equally well. In effect the complete fuel bed gets its proper distribution of air.

VI COMBUSTION AIR DISTRIBUTION

As noted earlier, the primary air controls the rate of combustion and the secondary air controls the efficiency. When the firing equipment is such that the stoker or other means of firing cannot or does not supply sufficient air to complete combustion then overfire air may be necessary. If the overall amount of excess air is somewhat low then as much as 20 to 25 percent may be required as overfire air. However, if the amount of excess air is sufficient but turbulence is lacking then possibly only 2 percent of the total air applied as jets under higher pressure may be sufficient. Possibly, a potential amount of 5 to 10 percent of the total air supplied as overfire air would be sufficient in most cases. The individual requirements will determine the amount necessary.

The burning equipment must furnish sufficient secondary air to meet the requirements initiated by the primary air. It is here that the three "T's" of combustion enter into the process. There must be sufficient temperature over an ample period of time with a suitable mixing or turbulence to bring together the air and combustible gases.

VII COMBUSTION QUALITY CONTROL BY OPERATION

It has been said that an operator has three means of quality control for combustion:

1 Flue Gas Analysis

2 Visual Observation; and

3 Furnace instruments.

But I am going to add another

4 Experience and morale.

Actually, the first three are meaningless without the latter.

A Flue Gas Analysis

These may involve spot tests or may be the result of continuous analyses from suitable instrumentation. The items sought generally are amount of carbon dioxide, oxygen and carbon monoxide. As noted elsewhere, a higher carbon dioxide is sought without the presence of any carbon monoxide.

B Visual Observation

This might be called "Reading the Fire." At least, with experience, an operator can look at the fire and determine from the color and shape of the flame; the contour and coverage of the flue bed, a great deal as to the actual conditions existing within the furnace. With suitable experience, he can determine when the coal feed should be increased or decreased; whether the air adjustment should increase or lessen the air supply; whether clinkers likely exist on the grates under the fuel bed; whether the furnace draft is too much or not enough: and the action that he should take if corrections are necessary.

C Furnace Instruments

These should be present in an amount necessary to help the operator do a good job and to determine with some degree of accuracy just how efficiently the coal is being burned for the use intended. They should not be in excess of the requirements and definitely not to the extent that the collection of the data becomes a demanding chore or that the amount of instrumentation is beyond the capability of the plant personnel to understand; to appreciate and to service or to maintain adequately. An instrument that does not indicate the conditions with some degree of accuracy is worse than no instruments at all.

D Experience and Morale

Combined with the three items noted previously, experience and morale should help the operator do a good job efficiently, economically and safely. Proper training as an integral part of experience should bring about a firing technique suitable for the needs.

VIII Operating at Other Than the Manufacturer's Specifications and Design Rating

The results are dependent upon the extent of the variation from the specifications or rating. If done within reason both as to amount of change from the optimum and to the duration no serious difficulties should arise. In some cases even a great amount of good might be done from the technical knowledge that might be gained. Normally, the efficiency of the unit decreases both above and below the design or optimum rating. However, the results of the change from the optimum can only be learned by trial even though the results might be anticipated.

At an early time, prior to the 1920's the output of the boilers were indicated by a "Manufacturer's Rating." As improvements in furnaces, firing equipment, combustion controls and firing technique were developed and improved it was found that in many cases, especially with the Stirling bent tube type boilers the best performance was obtained at 180 to 225 percent of the Manufacturer's Rating. In some cases, this figure dropped to about 140 percent of rating. In other cases, the output reached 325 percent for short periods of time. Many of the standard HRT boilers seemed to give best operations at about 140 percent of the Manufacturer's Rating, but under some circumstances, 180 to 200 percent of rating could be reached.

Generally, variations from the specifications for stoker equipment is more a function of the quality of the coal and of its consist (physical make up by sizes) to meet the operating conditions. A relatively poor coal of proper consist and preparation to fit the needs of the equipment and conditions of use may out perform an inherently better coal but of normal preparation.

In summary, I believe that a reasonably educated trial is worthwhile.

Some of the leading American boiler manufacturers are:

A Babcock and Wilcox Company

B Bigelow Company

C William Bros. Boiler & Manufacturing Company

D Brownell Company

E Combustion Engineering Company

F Edge Moor Iron Works, Inc.

G Erie City Iron Works

H Foster Wheeler Corporation

I Riley Stoker Corporation

J Union Iron Works

K Henry Vogt Machine Company, Inc.

L Wickes Boiler Company

M E. Keeler Company

N Kewanee Boiler Company

IX INFLUENCE OF COAL COMPOSITION ON OPERATING PRACTICES

Basically, all coals are made up of the same materials. But, the combination of the vegetable matter of their origin together with the pressures and heat involved in their formation caused differences in the relative amounts of their chemical composition as well as in their physical structures.

Briefly the classification of coals by Rank is as follows:

Class	Group	Amount of Fixed Carbon Volatile Matter or BTU
1. Anthracite	1. Meta Anthracite	Dry F.C. 98% or more (Dry V.M. 2% or less)
	2. Anthracite	Dry F.C. 92% or more, and less than 98% (Dry V.M. 8% or less, and more than 2%)
	3. Semi Anthracite	Dry F.C. 86% or more, and less than 92% (Dry V.M. 14% or less, and more than 8%)
2. Bituminous	1. Low Volatile Bituminous	Dry F.C. 78% or more, and less than 86% (Dry V.M. 22% or less, and more than 14%)
	2. Medium Volatile Bituminous	Dry F.C. 69% or more, and less than 78% (Dry V.M. 31% or less and more than 22%)
	3. High Volatile Bituminous A	Dry F.C. less than 69% (Dry V.M. more than 31%) Moist BTU 14,000 or more
	4. High Volatile Bituminous B	Moist BTU 13,000 or more, and less than 14,000
	5. High Volatile Bituminous C	Moist BTU 11,000 or more and less than 13,000
3. Subbituminous	1. Subbituminous A	Moist BTU 11,000 or more, and less than 13,000
	2. Subbituminous B	Moist BTU 9,500 or more, and less than 11,000
	3. Subbituminous C	Moist BTU 8,300 or more, and less than 9,500
4. Lignite	1. Lignite	Moist BTU less than 8,300
	2. Brown Coal	Moist BTU less than 8,300

The factors of chemical composition and physical structure each have a bearing upon the application of coal. Naturally, some coals are better suited for some uses. In many cases the coal can be prepared in such a manner that, in effect, its burning characteristics can be altered or modified. Also, by good engineering in the equipment, in furnace design and in the firing technique the range of application can be broadened. And again, I chose to call this determination Selective Application.

For instance the ash content, the sulfur content, the hardness or grindability of a coal, the fusion temperatures of the coal either alone or together may very well decide for or against the use of a coal for certain applications.

Good engineering may make a coal acceptable at one point where the same coal with poorly engineered equipment or poor firing technique may make it unacceptable at another.

You can burn any coal on or in any coal consuming unit physically capable of handling that coal with some degree of success but the real satisfaction and economy of use is governed by just how well the coal burned fits the equipment and conditions of use. Proper coal sizing and size consist must be considered under a policy of Selective Application, if the full potential heat energy is to be recovered in actual Use Value. The use of coal solely on the basis of "Cost per Million BTU" delivered to the plant, in itself, is not enough. This is only one item in good coal application. A relatively inferior coal may perform much better than a superior coal under some conditions. In some cases, a more costly coal may well enough prove to be more economical in use. An improper selection of coal in any one phase can result in:

A Increased fly ash emission

B Increased soot formation

C Increased smoke emission

D Increased slag and clinker formation

E Increased coal handling costs

F Increased ash handling costs

G Increased power costs

H Increased labor costs

I Increased maintenance costs

J Increased explosion hazards

K Increased fuel bed loss

L Increased erosion of equipment

M Increased storage loss due to windage loss

N Increased storage loss due to spontaneous combustion

O Increased outage of unit

P Increased housekeeping problems

Q Increased personnel problems

R Lessened efficiency

S Lessened unit output capacity

T Lessened reactive rate of coal

From the standpoint of being a good neighbor, a facility on the windward side of a community or center of activity must follow a better firing technique than another similar facility on the leeward side. This must be obvious from the standpoint of air pollution without further comment.

It is not of necessity true that all poor coals have a high sulfur and high ash content. It is true that high sulfur and high ash coals are not extremely high grade. It is true that the poorer the coal the closer to its sources it should be used. Or, the better the coal, the greater distance that it may be transported with economy and satisfaction.

Freight rates are on a tonnage or mass basis and not on a quality basis. This is simply to point out that while all coals have a place in our scheme of living, there are certain limiting conditions that determine where the coals should be used.

The terms coking and caking have been used rather loosely over the years. This is unfortunate because some confusion has resulted. Technically, coke is the solid residue of ash and fixed carbon that remains after the volatile products of moisture and hydrocarbons have been driven off by distillation. In this respect all coals can be coked. But some coals mat or cake together in the distillation process. In effect, these coals melt before the volatile materials have been discharged. In the course of distillation this mass is bound together in a honeycombed cellular residue. On occasion, coals that normally are classed as non-caking or free burning may cake together in irregular masses. Also, by Selective Application and a control of size consists those coals that are classed as strongly caking may be made to behave, within some limitations, as if they had a lesser caking quality.

X NORMAL GRATE STOKING PRACTICE

The technique used in firing must be made to match the equipment, the conditions of use and the coal burned. An optimum ash content for most stokers would be about 5 to 6 percent. A smaller amount of ash may be used with care on some units. Overfeed stokers of the traveling grate type will do better with coal of 7 to 8 percent ash content. Coals with much greater amount of ash may be used but as the amount of ash increases over optimum amounts for the particular usage, the stokers, in effect become less of a burner and more of an ash conveyor. Such burning as does take place is done with somewhat more difficulty.

With these as basic qualifications or optimums, the coal must be fired in such a manner that it is completely burned out at the dump grates or point of discharge from the furnace. A combustible content in the ash of 10 to 15 percent works no great hardship upon the unit for 10 percent of a 5 percent ash coal represents only one-half percent on the initial coal feed.

The firemen must regulate his coal feed to meet the load imposed upon his equipment. The air supply must be in accord to the coal feed. The zoned air adjustments must give the burning reaction within the proper area to give most efficient heat release. This means that the stoker action and feed must be adjusted to give the most desirable contour to the fuel bed. In other words, the fuel bed must be adequately and completely covered and of such depth as to produce the contour imposed upon it by the load conditions. And at all times, the fireman should be so well acquainted with his fuel bed as to know the presence or absence of clinkers that might become a source of trouble.

XI INFLUENCE OF HIGH SULFUR COALS ON OPERATING PRACTICES

High sulfur coal is characterized by the fact that all forms of the sulfur are relatively high and not just the pyritic form alone. Normally, most of the sulfur, even after washing (mechanical cleaning), will be of the pyritic (iron disulfide) form. Very often with high sulfur coal, the pyritic form will be as much or more than the organic and sulfate forms combined. Since the iron is largely in the ferrous form a low melting point can be expected. Part of the combustion process takes place in a reducing atmosphere. This in turn tends to emphasize the lowered melting point.

When using equipment that is already in existence and with the load established, the use of a high sulfur coal very likely will require the use of a greater amount of excess air than would be normal otherwise. This lowers the unit efficiency. All handling costs, all labor costs, all operating costs and all maintenance costs, most likely, will be increased if coal of this grade is used for any extended period.

If, however, the units are or have been designed for such coal, a more satisfactory outcome can be achieved. These units, generally are built in such a way that the furnaces are larger, and at the design rating, the furnace heat release is lower. Consequently, the furnaces are cooler. The spacing between the boiler and superheater tubes encountering the flue gases is increased so that slag formation is lessened. If the capacity of the units is of such size as to merit the consideration, cyclone type units may be installed. Then, a fuller realization of the coal with a high sulfur content may be gained than would be true with some other equipment.

XII PERSONNEL

The operation of a boiler plant is a function of four items:

A Equipment

B Fuel (Coal, in this discussion)

C Conditions

D People

Briefly the people are divided into two classes: 1) Management; and 2) Operators. With a proper relationship between the two, much can be accomplished. Obviously, the function of management is to direct. By their leadership they can create a discipline and a morale whereby a great good can be accomplished by all concerned. The training of the operators so that they can do their job properly, efficiently, safely and with a spirit of happiness is one phase of their direction. The housekeeping that is evident in a boiler room is a reflection of the training of the operators and of the pride in their work.

First, there must be a proper communication between management and the operators with the necessary freedom of communication to both levels from both levels. In other words communication must be a two-way approach. For instance, it is not expected that the firemen and the purchasing agent be equally acquainted with each others problems but with a reasonable interchange of ideas as to their particular problems under given conditions much can be done to lessen each others problems.

The firemen must have some knowledge of a proper firing technique for handling his specific equipment to meet the operating needs. He must be aware of the fact that combustion is first of all a chemical reaction and as such the fuel and air have a definite relationship to each other. They must be taught to read their fires with some knowledge of their correctness and to relate this knowledge to the various meters, gages, controls and other instruments.

They must be made conscious that under certain conditions they may be creating a nuisance. They must be taught to observe the amount of that nuisance and how to lessen or within reasonable limits to overcome and eliminate it. It is my personal belief that any facility or person capable of creating a nuisance is capable of correcting it either desirably by choice or less desirably by force. In many cases, ample facilities either physical or mental are already available and it is simply a question of using that which is at hand.

UNDERFEED STOKERS

Harold E. Johnson*

I SINGLE RETORT STOKERS

The single retort underfeed stoker has been popular since the early 1920's and still has a very definite place in a size range of between 3,000 and 25,000 pounds of steam per hour.

Most single retort stokers, except those for household heating, are ram-fed, and operate with periodic charges of coal from the hopper to the retort. The retort runs the full length of the stoker, and the auxiliary pushers located at the bottom of the retort distribute the coal from front to rear of the stoker, while at the same time causing the coal to rise in the retort and then spread from side to side over the entire grate surface.

As the rising fuel approaches the incandescent fuel bed, heat distills volatile gases which are mixed with air and consumed in the incandescent zone without smoke.

The grate surface is made up of either fixed or undulating moving grates resting atop the retort sides and the plenum chamber enclosure, through which the combustion air flows into the fuel bed. The fuel bed burns and is reduced to ash as it moves toward the dump grates located adjacent to each sidewall of the furnace. The ash is dumped at intervals dictated by the ash content of the fuel.

It is, as a rule, advisable to use some of the better grades of coal to get optimum results with this type of stoker. However, this picture has been changing somewhat over the years, and poorer grade coals can be burned with good results, due mainly to the sizing and cleaning processes now commonly used at the mines.

The coal to be used should determine the size of the stoker or grate area. Burning rates of 30 pounds per sq. ft. per hour are reasonable when burning better grades of bituminous coal, with ash fusion temperature above 2400°F. The burning rates should be reduced somewhat when burning coal with ash fusion temperature below 2400°F.

The burning characteristics of the coal are an important factor to be considered when selecting stoker equipment. It is necessary to maintain a compact fuel bed of uniform porosity if optimum operation is to be obtained. Free burning coals, those with a free swelling index of 6, and below, are best suited to the single retort stoker with fixed grates, as the high coking coals, those with free swelling index above 6, tend to swell, causing the flue bed to arch and rise off the grate. For this reason the high coking coal should be burned on single retort stokers equipped with undulating moving grates. The undulating, or wave like grate motion, breaks up arch formation and keeps the fuel bed porous without manual poking.

If high operating efficiency is to be realized it is necessary to maintain correct coal-air ratio. Since it is difficult to manually maintain the correct fuel and air supply at varying loads, it is advisable to employ an automatic combustion control system. The modern single retort stoker is equipped with an adjustable coal feed device which, together with the control damper of the combustion air fan, can be connected to the combustion control system, maintaining automatic synchronization of fuel and air supply over the entire load range.

II MULTIPLE RETORT STOKERS

The multiple retort stoker, although not as popular today as some of the other firing methods, is still preferred by many plants. This stoker is offered in sizes to generate from approximately 20,000 to 500,000 pounds of steam per hour. The grate surface is made up of a series of retorts separated by

*Cincinnati District Manager, Detroit Stoker Company. Presented at the Industrial Coal Conference, University of Kentucky, Lexington, Kentucky. April 1965.

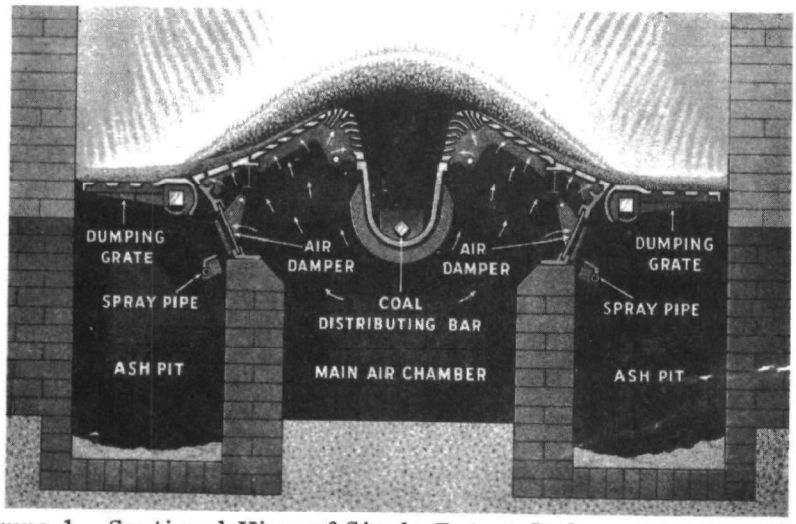


Figure 1. Sectional View of Single Retort Stoker with Fixed Grates

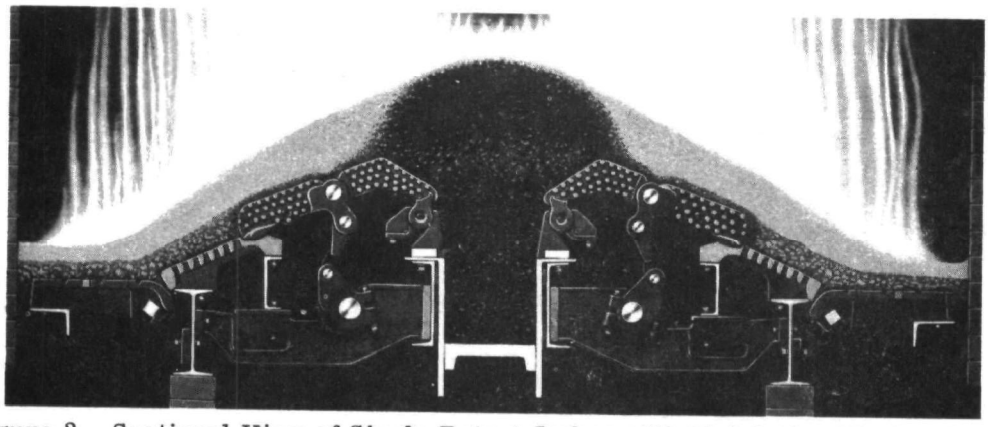


Figure 2. Sectional View of Single Retort Stoker with Undulating Moving Grates

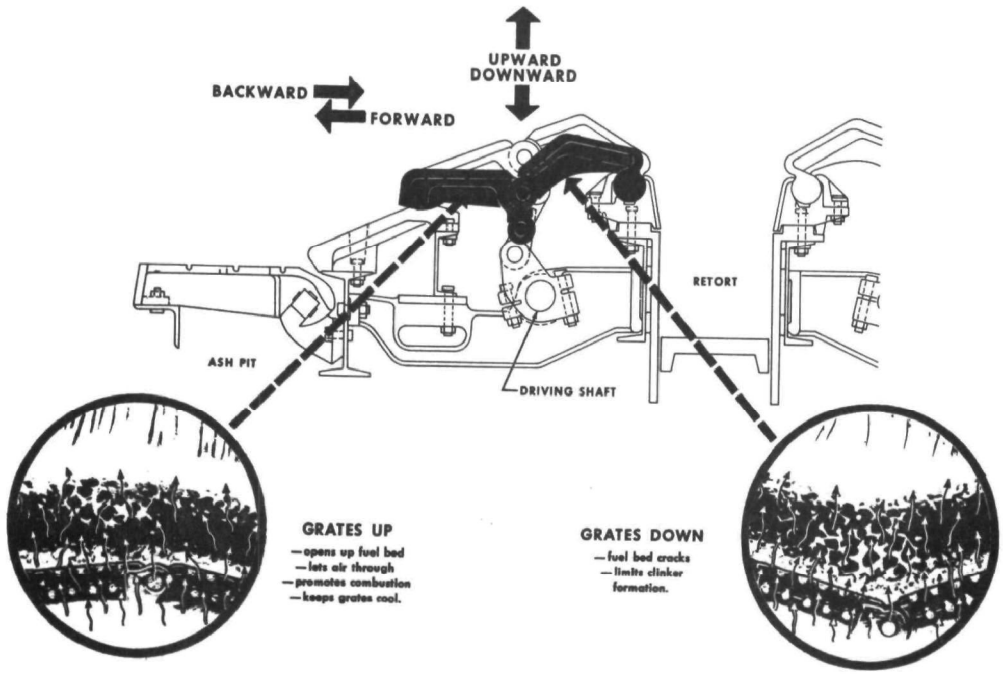


Figure 3. Sectional View Showing Grate Movement of the Undulating Grate Stoker

rows of air tuyeres. Feed rams move coal from the hopper to each retort, secondary pushers then distribute the coal along the length of the stoker. The combustion air flows through the air tuyeres located between each retort to the fuel bed, promoting active burning of the distilled volatile gases and the fuel mass as the coal is moved slowly rearward to the ash discharge section.

Since the same coal burning principles apply to single and multiple retort stokers, the same design criteria apply to both stoker types.

III CONCLUSION

An attempt has been made in the foregoing discussion to outline the design criteria of underfeed stokers, as well as its advantages and disadvantages. The underfeed stoker has for many years played an important role in power and heating, continued usage of these stoker types for many applications in the future is foreseen.

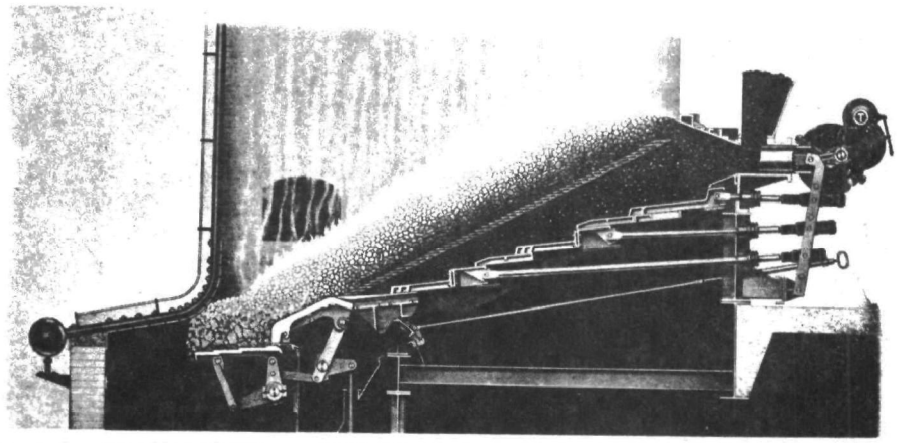


Figure 4. Sectional View of Multiple Retort Stoker - Available in Sizes to 500,000 Pounds of Steam Per Hour

SPREADER STOKERS

John L. Dick*

I INTRODUCTION

In the past twenty-five years spreader stokers have played a prominent role in the production of steam, in the capacity ranges up to 400,000 pounds of steam per hour, both in this country and abroad.

The wide acceptance of spreader stokers can be attributed to the design flexibility and ability to burn a wide range of fuels successfully with low maintenance, high daily efficiency, and simplicity of operation.

Fuels considered not suitable for use on other stoker types can now be burned on spreader stokers with complete assurance of obtaining satisfactory results with a minimum of effort and expense.

It may be beneficial at this time to describe briefly the design principles of spreader stoker operation for a more complete understanding of this method of firing.

II PRINCIPLE OF SPREADER STOKER OPERATION

Basically, the operation consists of metering fuel to the furnace by means of feeders and distributors mounted on the stoker front, over the grate, employing revolving rotors with specially designed blades to insure uniform distribution, both laterally and longitudinally. The fine particles burn in suspension while the coarse coal burns on a protective layer of ash on the grate.

Air is admitted to the fuel bed through a series of closely spaced, venturi shaped, air ports cast in the grate to provide uniform air flow to the entire active grate area.

The fuel introduced into the furnace ignites rapidly, starting to release hydrocarbons the instant the fuel enters the high temperature zone, making it possible to burn both highly coking and low ash fusion coals without special preparation.

III COAL FEEDERS

The number, location, and spacing of coal feeders are important factors to be considered in the initial design. The total feeding area, determined by the length of the rotor blades, should never be permitted to go below 40% of the grate width, otherwise, operation may suffer from mal-distribution.

The feeder spacing should be kept to a minimum to avoid "fishtails" (areas receiving no fuel). Feeders are manufactured in different widths to permit proper spacing and the most desirable relationship between feeder and grate width.

The feeders are directly connected to the combustion control system and the fuel feeding rate responds instantaneously to rapid load changes.

The fuel discharges from the coal hoppers to the rotor blades which are specially designed to insure proper distribution on the grate.

IV TYPES OF SPREADER STOKERS

There are various types of spreader stokers, however, the main difference is in the grate design and operation.

The intermittently cleaned grate type stokers (Figure 1) have either stationary or dumping type grates that are periodically cleaned when the ash accumulation reaches a depth of six to eight inches. The dumping frequency is wholly dependent upon the burning rate and percent of ash in the fuel. These models are constructed in individual sections to provide shutoff of the feeder blast gate and plenum chamber on the particular section

*Special Sales Engineer, Detroit Stoker Company. Presented at the Industrial Coal Conference, University of Kentucky, Lexington, Kentucky. April, 1965.

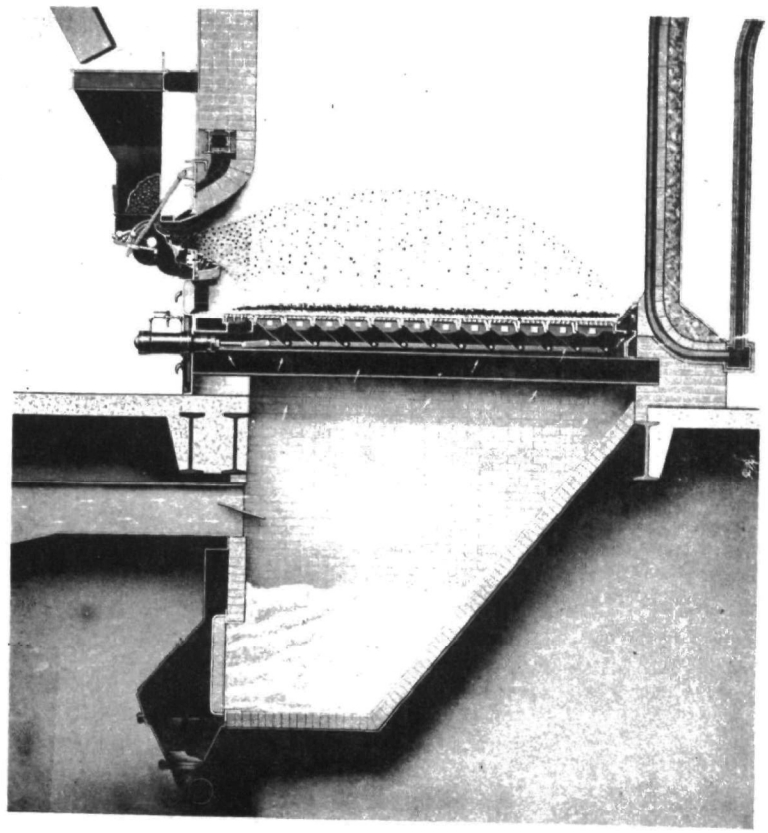


Figure 1

of the grate to be cleaned, while the remaining grate section or sections remain in operation.

There are, for all practical purposes, three types of continuous cleaning grate stokers, namely, Continuously Reciprocating, Intermittently Vibrating, and Traveling Grate.

The reciprocating grate (Figure 2) consists of alternate rows of continuously reciprocating grates imparting forward movement of the ash for automatic discharge at the front.

The vibrating grate stoker employs a vibration generator mounted on the grate frame that is periodically energized to move the ash to the discharge end by means of intermittent vibration.

The front continuous ash discharge traveling grate stoker (Figure 3) is very popular in capacities up to 400,000 pounds of steam per hour. This type consists of an endless chain of grates slowly moving through the furnace permitting the ash to reach a depth of 3 or 4 inches before being automatically discharged into the ash pit.

The grate types described above can be placed in two categories, namely; agitating and non-agitating. The agitating types are the reciprocating and vibrating. The non-agitating are the stationary, intermittent dumping, and the continuously traveling grate.

It is generally recognized that lower ash fusion coals can be burned more successfully on non-agitating grates than can be burned on grates employing agitation.

V THE ADVANTAGES ASSOCIATED WITH SPREADER STOKER OPERATION

A Ease of Operation

The design of the spreader stoker permits adaptation to automatic combustion control systems, permitting synchronization of the fuel-air ratio over the complete load range

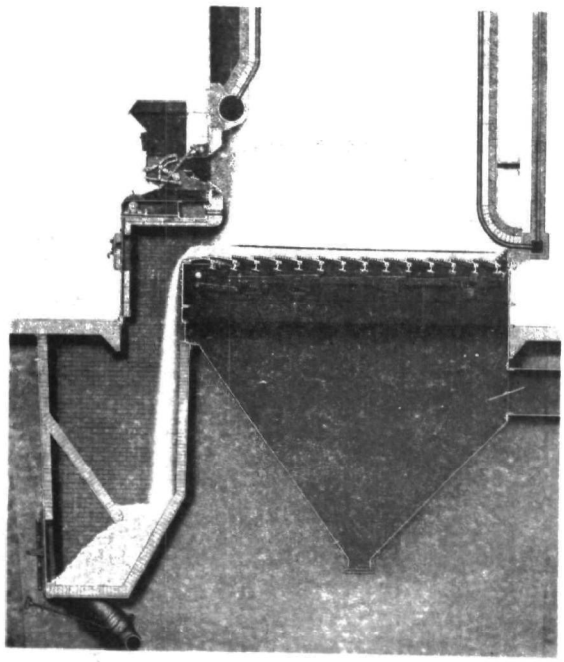


Figure 2

and providing high efficiency while, at the same time, requiring little attention on the part of the operator.

B Low Maintenance

Records indicate that maintenance cost on spreader stokers is exceptionally low.

C Greater Fuel Flexibility

Spreader stokers successfully burn a very wide range of fuels, from the high grade eastern bituminous to the poorer grade sub-bituminous and lignites in the West. In addition, many waste and cellulose fuels, such as, hogged and unhogged bark, wood chips, sawdust, shavings, bagasse, and others, burn separately or in combination with coal.

Spreader stokers proved their flexibility during and following World War II, when it became necessary to burn all types of available fuels with widely varying analyses brought on by fuel rationing. Excellent performance was obtained on spreader stokers during this era and is one of the most popular types of fuel burning equipment in use today.

D Availability

Spreader stokers have a very high availability factor. Surveys and service records indicate many plants operating 24 hours per day, seven days per week, have one scheduled outage per year during the annual inspection period.

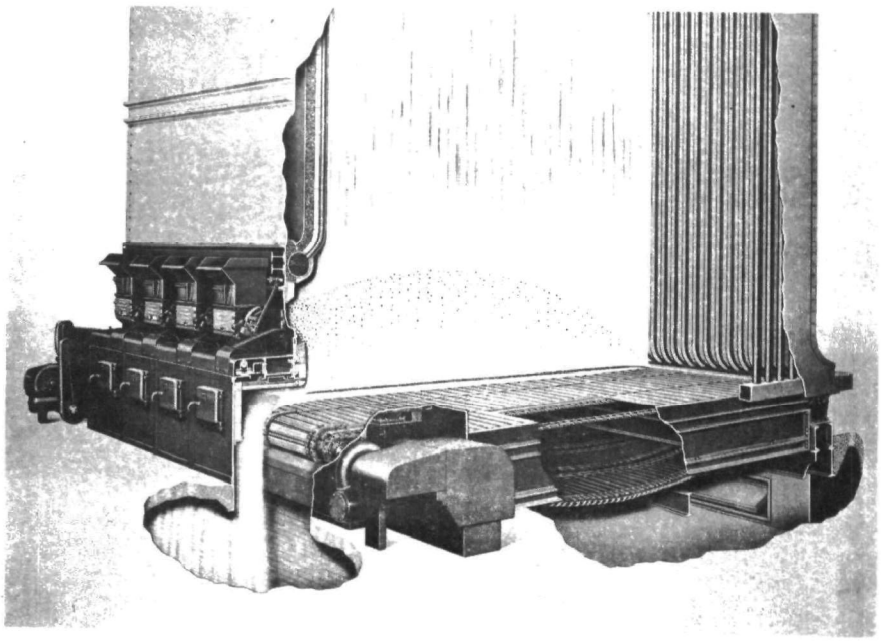


Figure 3

At Central Soya Company, Decatur, Indiana plant, an 80,000 pound per hour boiler served by a Detroit Roto-Grate Stoker has operated more than 13 years, consuming over 475,000 tons of Indiana coal on the original set of grates without a single forced outage. This plant operates around the clock, 355 days per year, allowing 10 days each year for annual inspection and rehabilitation.

Spreader stokers are designed so that maintenance can be performed without having to take the unit out of service.

E Rapid Response to Changing Loads

The fuel input to the furnace is always in direct proportion to the steam demand, and immediately upon sensing a change in load, the combustion control system repositions the fuel feed and air flow rates to satisfy the changing conditions instantaneously. The partial suspension burning responds readily to changing conditions, and severe load swings can be handled without suffering loss of steam pressure, and without over shooting.

F High Daily Efficiency

The control of the fuel-air ratio over the entire operating range results in high operating efficiency.

Effective control of the combustion air through the grates and positive air seals between the stoker and boiler proper make it possible to operate with low excess air over the load range, resulting in high operating efficiency.

It is recognized that more complete combustion is obtained with spreader stoker operation than with other stoker types, resulting in high efficiency.

G Low Initial Cost

The ability of spreader stokers to operate at high burning rates results in the use of more economical boiler shapes.

H Combination Firing of Auxiliary Fuels

The application of spreader stokers to boilers designed with gas and oil firing is quite numerous. The only limitation or restriction is in the location of the burners. Sufficient spacing between the top of the grate and nozzles should be maintained to avoid direct flame impingement on the grate surface. Changing from one fuel to another can normally be accomplished in a 15 to 20 minute interval.

I Safety in Operation

In the many years we have been producing and installing spreader stokers, we have never recorded a single case of gas explosion attributed to the stoker as a result of partial suspension burning.

Fires under the grate are practically nonexistent because the siftings in the sifting hopper contain a very small percentage of unburned carbon.

VI THE DISADVANTAGES ASSOCIATED WITH STOKER FIRING

A Fly-Carbon

Whenever fuel is burned in suspension or when forced draft air is employed to accelerate the burning process, particles of ash and unburned carbon are picked up in the flue gas leaving the furnace. These particles are commonly referred to as fly-ash or fly-carbon.

In spreader stokers, burning fine particles of fuel in suspension, the quantity of carryover is sufficient to warrant collection and returning of these particles to the furnace for burning.

To give you a comprehensive report on fly-carbon reinjection we refer you to a paper recently presented at the 1964 Industrial Coal Conference held at Purdue University, entitled, "Trends in Fly-Carbon Reinjection, (Developments and Improvements)", by Mr. Harold L. Knox,

Assistant Chief Engineer, Detroit Stoker Company, Monroe, Michigan.

B Low Load Operation

The ability of spreader stokers to handle light loads depends on many factors. One of these is the burning rate per square foot of grate per hour. On stationary and intermittent dumping grate types the burning rate is usually established between 350,000 and 550,000 BTU per square foot per hour, depending upon the ash content of the fuel and the number of feeders employed.

On continuous cleaning grate stokers no provisions have to be made for interruptable cleaning periods and much higher burning rates are used ranging between 550,000 and 750,000 BTU per square foot per hour. These figures represent safe, smokeless operation anywhere from 3 to 1 to a 6 to 1 load range, depending on the burning rate at the maximum continuous rating and the stoker type.

During very light load operation the furnace temperatures are too low to sustain complete combustion because of the low burning rates. At these very low loads it is sometimes more advisable to utilize steam jets through the furnace sidewalls rather than overfire air jets to create furnace turbulence.

The distribution of fuel on the grate is an important factor in smoke elimination at reduced ratings. If the fuel bed thickness is not uniform the low pressure air passing through the fuel bed will escape through the shallow sections leaving the thicker sections starved of air.

The proper number and spacing of the cinder return lines can also have a bearing on smokeless operation. If the return lines are not designed properly to evenly spread the returned material, excess loading of fly-ash could produce ridges on the fuel bed, resulting in a smudge pot effect.

VII CONCLUSION

In the foregoing article we have endeavored to present the design features of spreader stoker firing along with its advantages and disadvantages.

There are a great many spreader stoker installations throughout the world representing a substantial portion of the coal burned annually, the continued popularity of this type of firing method is foreseen.

ANOTHER LOOK AT THE TRAVELING GRATE STOKER

Herbert I. Hollander, P.E. *

In light of the greater sensitivity and increasing emphasis being placed on atmospheric contamination, air pollution control engineers and officials are scrutinizing more closely and re-evaluating the performance criteria established for not only coal fired installations but for all gas emitting devices.

This has prompted the reassessment and renewed interest in the "old reliable" mass burning, gate fed type, travelling grate stoker. When properly designed and applied, this stoker type can be operated to provide wide load range performance without objectionable smoke or particulate discharge from the stack.

The two basic types of mass burning, gate fed, traveling grate stokers are the "bar and key" grate and the "chain" grate. As the nomenclature implies, the "bar and key" grate surface is made up of relatively narrow keys or clips mounted on bars or racks, which are pulled or pushed by chain assemblies through the furnace. In general the clips of the chain grate stoker form the chain as well as the grate surface.

Both stoker types draw coal from the stoker hopper with the fuel bed depth controlled by a vertically adjustable gate across the width of the unit. The fuel bed is carried over the several air zones of the stoker for stage burning. The ash is ultimately, discharged into the ash hopper at the rear. Figure 1.

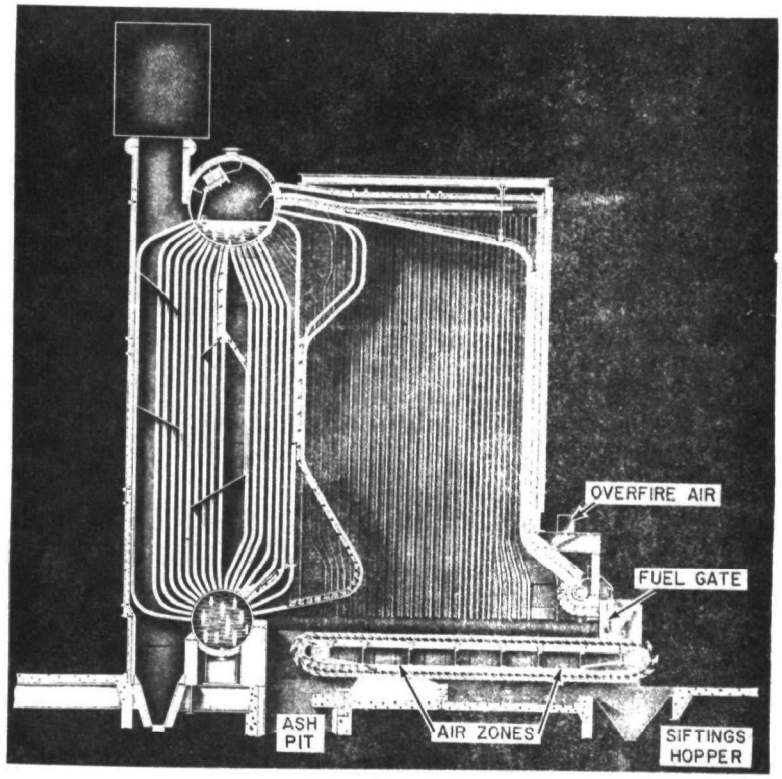


FIGURE 1 TYPICAL RILEY TRAVELING GRATE STOKER

*Riley Stoker Corporation. Presented at the Industrial Coal Conference, University of Kentucky, Lexington, Kentucky. April 1965.

The entire coal feeding and burning action occurs without any agitation of the fuel bed thereby minimizing dust entrainment in the rising gases.

Anthracite, lignite as well as bituminous coals can be burned. Of the bituminous types, the free burning coals are preferred. Coking coals having relatively high free swelling indices can be burned successfully provided the coal sizing is accurately controlled, i.e., 1 - 1/2"× 3/8" with uniform size gradation. The recommended coal sizing for free burning friable coals is 1 - 1/4" × 0" and for non friable coal 3/4" × 0" with not more than 50% passing through 1/4" round mesh screening. Finer size free burning coals, even mine screenings of minus 3/8" can be burned but with some penalty in higher carbon loss, Figure 2. Coals having as much as 30% ash have been, and are being, burned with complete satisfaction on units especially designed for this duty.

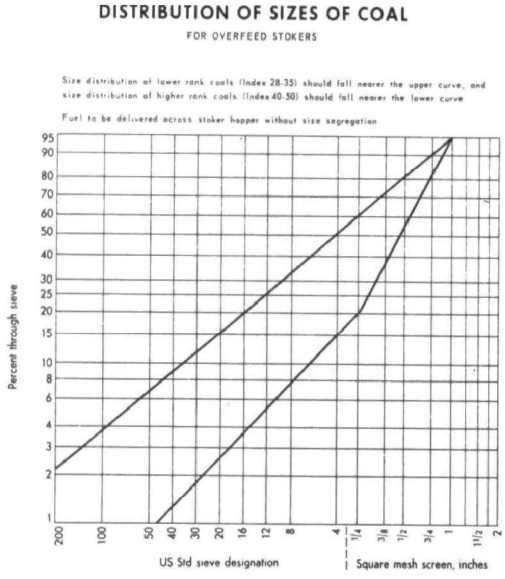


FIGURE 2

It has been found that for most coals these stoker types require some degree of water or steam tempering. The very fine dust in coals are reduced when they are mine washed before shipment, and therefore the percentage of retained moisture from the washing operation, in the coal received at the plant, minimizes or eliminates the need for tempering at the stoker equipment. Tempering, which will increase the moisture in the fuel up to approximately 10%, should be performed as uniformly as possible.

As with all stoker types these machines are also quite sensitive to segregation or poor distribution of coal sizes and moisture content. Unless the fuel consist if uniform across the width of the grate the fuel bed may not burn uniformly and may result in a "tail," and some unburned carbon may end up in the ash hopper.

Stoker and furnace configuration is of prime importance in the performance of any unit. Unless the furnace configuration includes a rear arch, the mass burning traveling grate stoker type will have a thin fire in the burnout zone and therefore high excess air in this area. This can usually be avoided by using a properly designed rear arch similar to that shown in Figure 3 to divert the excess air expeditiously into the rich zone of burning volatiles thereby increasing the CO_2 at the furnace exit.

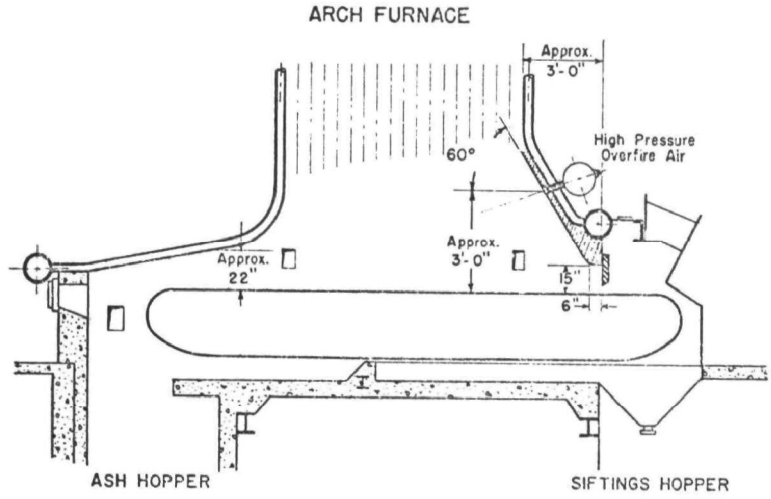


FIGURE 3 ARCH FURNACE

On occasion, to reduce initial cost, some compromized installations are made without rear arches, Figure 4. Mixing of the rising rich and lean furnace gases is attempted by employing overfire air. However, this has been found to be only partially effective and some of these installations still suffer high excess

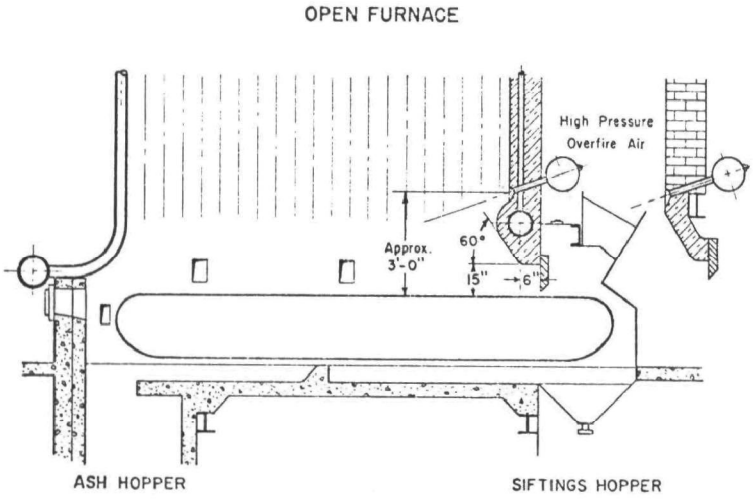


FIGURE 4 OPEN FURNACE

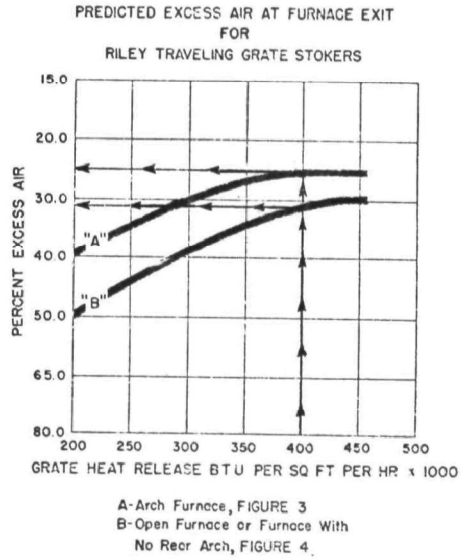
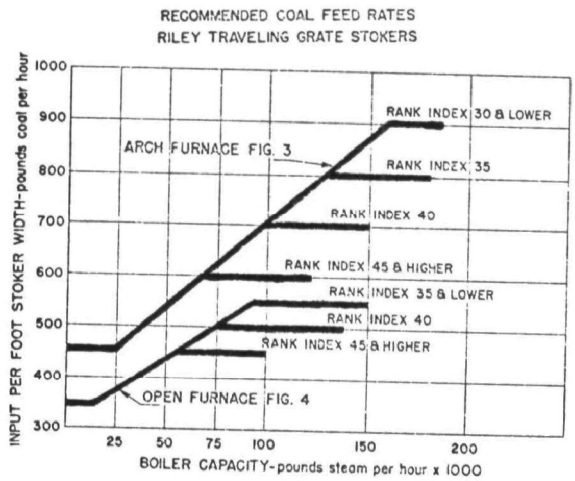


FIGURE 5

air and sometimes even smoke. Optimum performance can be obtained only by using both the rear arch and employing high pressure overfire air.

Figure 5 illustrates excess air quantities at the furnace exit with each of the furnace configurations described at various grate heat release rates.

There are several significant and sometimes conflicting influences in selecting the optimized stoker-furnace configuration. To minimize dust entrainment in the gases, the stoker grate heat release rates should be conservative which will also reduce the ashpit loss. Excessively wide stokers should be avoided so as to reduce the problem of uniform fuel size distribution across the width of the grate, Figure 6.



MAX. RATES FOR RANK INDEX AS SHOWN

$$\text{Rank Index} = \frac{\text{BTU/LB}}{\%\,VM \times 10}$$

FIGURE 6

Some basic design criteria to provide a grate and furnace design for good practical overall performance, are illustrated in Table 1.

Table 1

BASIC DESIGN CRITERIA AT MAXIMUM CONTINUOUS RATING

Ash Softening Temperature (reducing atmosphere) - F	1900	2200 & above
Grate Heat Release Rate - Btu input hour sq ft grate area	300-425,000	450-500,000
Grate Coal Feed Rate - pounds hour foot stoker width	See Figure 6	
Furnace Heat Liberation - Btu input hour cu ft furnace vol	35-40,000	30-35,000
Flame Travel - (distance from grates to furnace exit) feet	Approx. 12	30-40
Excess Air Leaving Furnace - percent	See Figure 5	
Undergrate Air Temperature - °F Free Swelling Index - up thru 7 1 2 - above 7 1 2	80 80	300 80

Mass burning, gate fed, traveling grate stoker applications are best suited for industrial and institutional power plants having steady and sustained load in capacities from 20,000 to 150,000 lbs of steam per hour. There have been some installations made in capacities 200,000 lbs of steam per hour but this is rare and not recommended.

For plants where large rapid load swings are not required this stoker type can operate on full automatic combustion control with rare requirement of readjustment of the air zone dampers.

Many plant operations have reported[1] that their units do comply with the current ASME recommended dust emission codes without the use of dust collectors. However, future codes and/or local critical conditions may ultimately require, that even mass burning traveling grate stoker installations with their inherently low dust emission characteristic, be equipped with efficient dust collectors. Fly carbon reinjection systems are not required since the quantities of collected material and its carbon richness is so low not warranting this complication.

It can be noted from Figure 7 that most bituminous coals used, in conjunction with conservatively designed traveling grate stokers, the total carbon loss would only be approximately 1.5% even without any form of fly carbon recovery equipment.

In regard to maintenance, it has been reported[1] that in general the maintenance of mass burning traveling grate stoker fired steam generators is comparable to that experienced with traveling grate spreader stoker fired installations. Some plant operators have reported that no grate maintenance has been experienced for 10 year periods and longer.

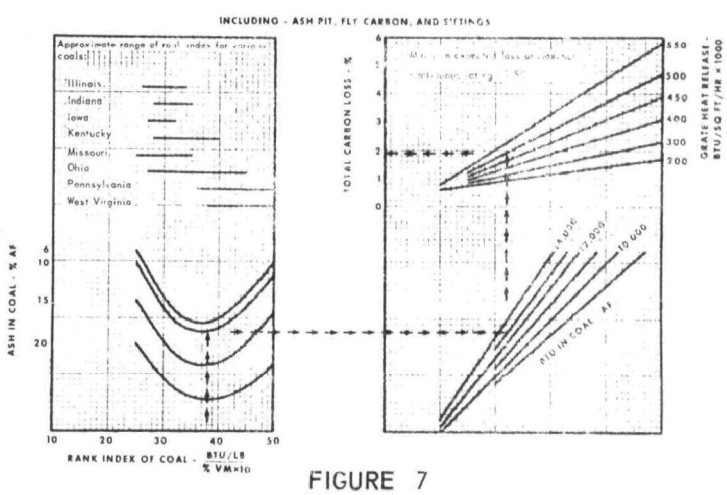


FIGURE 7

We have attempted to describe some of the current design and application aspects of mass burning, grate fed, traveling grate stokers.

Additional reasons for this stoker type receiving more and more favorable consideration in recent years is, the ability to operate with less dust entrainment, improved overfire air systems, more automatic siftings removal systems and the avoidance of complex fly carbon recovery systems.

REFERENCE

1 MacLachlan, J.M. Performance of Chain and Traveling Grate Stokers Burning Coals Mined in the Pittsubrgh District of Pennsylvania. ASME Paper 54-FU-4.

CORROSION AND DEPOSITS FROM COMBUSTION GASES

William T. Reid*

A rough estimate a few years ago by the Corrosion and Deposits Committee of ASME placed the direct out-of-pocket costs of external corrosion and deposits in boiler furnaces at several million dollars a year. It is difficult to pinpoint costs directly, but certainly the unscheduled shut-down of a large steam generator through failure of a superheater element can be an expensive operation. Crossley of CEGB in England estimates that an outage of a 550-megawatt unit for one week costs $300,000. Hence extensive efforts have been made in this country and abroad to learn more about the factors that lead to metal wastage and deposits and how to control them in combustors of all kinds.

Of the fuels being used for central-station power plants, only natural gas is free from the "impurities" that cause these problems. Ash in coal and in fuel oil and the presence of sulfur lead to a wide variety of difficulties. In boilers, deposits form within the furnace, on the superheater and reheater elements, in the economizer, and in the air heater. In gas turbines, combustor problems are not so severe, but deposits on turbine blading can be disastrous.

Although deposits may be objectionable in themselves, as thermal insulators or flow obstructors, usually it is the corrosion conditions accompanying deposits that cause the greatest concern. This has been particularly true in boiler furnaces. Here, deposits interfere with heat transfer and gas movement, but these can be compensated in part by engineering design. On the other hand, corrosion beneath such deposits can cause rapid metal wastage, forcing unscheduled outages for replacement of wall tubes or superheater elements.

With the recent trend to larger and larger steam generators, even up to 1130 megawatts, the importance of eliminating such outages grows in importance. This is the reason mainly, why so much attention has been paid recently to investigating the causes of corrosion and deposits, and to seeking corrective measures.

IMPURITIES IN FUELS

Although natural gas, with its low sulfur content and complete freedom from metallic elements, is the only fuel not causing troubles with corrosion and deposits, its availability and cost limit its use for steam-electric plants to geographical areas where gas is less expensive than other fuels on a Btu basis. Thus, despite its freedom from corrosion and deposits, natural gas is the source of energy for only a fifth of the electricity generated in this country. It is important to realize, then, that although corrosion and deposits are indeed troublesome in the operation of steam-electric plants, it is only one of many factors that play an important role in selecting a fuel or designing a power plant to operate at minimum cost.

Residual fuel, which provides the energy for about 6 percent of our generated electricity, usually contains all the impurities present in the original crude oil. Of these, sodium, vanadium, and sulfur are most troublesome. Typical limits for these impurities are, for sodium, 2 to 300 ppm in residual fuel, or about 0.1 to 30 percent Na_2O in the ash; for vanadium, 0 to about 500 ppm in residual fuel, or 0 to 40 percent V_2O_5 in the ash; and for sulfur, up to 4 percent in residual fuel, with a maximum of 40 percent SO_3 appearing in oil ash depending upon the method of ashing.

*Senior Fellow, Battelle Memorial Institute, Columbus, Ohio. Presented at the Residential Course on Combustion Technology, Pennsylvania State University, 1966.

With coal, which furnishes more than half of the energy converted into electricity, the impurities consist mainly of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, the alkalies, and, of course, sulfur. The range of these ash constituents varies widely, and they may exist in many mineralogical forms in the original coal. Sulfur may be present even up to 6 percent in some commercial coals, but the sulfur content usually is below 4 percent. Sulfur retained in coal ash as SO_3 ranges up to about 35 percent, depending upon the method of ashing and the amount of CaO and MgO in the ash. In coal-ash slags it is seldom more than 0.1 percent. Chlorine is frequently blamed for corrosion with English coals in which it occurs up to 1 percent; it seldom exceeds 0.3 percent in American coals, and it usually is less than 0.1 percent. Because less than 0.3 percent chlorine in coal does not cause problems through corrosion and deposits, chlorine in American coals generally may be neglected as a source of trouble. Phosphorus, which occurs up to about 1 percent as P_2O_5 in coal ash, was a frequent source of deposits when coal was burned on grates. With pulverized-coal firing, however, it is seldom held responsible for fouling.

PROPERTIES OF COAL AND OIL ASHES

Coal Ash

Most of the earlier studies of coal ash were aimed at clinkering problems in fuel beds. Later, studies of ash were concerned with the unique problems involved with slag-tap pulverized-coal-fired boiler furnaces. Ash deposits, collecting on heat-receiving surfaces, cause no end of trouble because they interfere with heat transfer. In the combustion chamber, particularly in pulverized-coal-fired slag-tap furnaces, the layers of slag are fluid and can cover much of the heat-receiving surface.

In dry-bottom furnaces, wall deposits are made up largely of sticky particles that coalesce to cover the tubes in irregular patterns. As the gases cool on passing through superheaters and reheaters in either type of furnace, adherent ash deposits sometimes become so extensive as to block gas flow. In air heaters, ash accumulations again can be troublesome.

The flow properties of coal-ash slags were investigated extensively in this country nearly three decades ago when slag-tap furnaces were still quite new. More recently, those early data have been rechecked and affirmed in England. Although coal ash makes up a 6-component system, it has been found possible to combine compositional variables so as to provide a relatively simple relationship between viscosity, temperature, and composition. It has been found, for example, that slag viscosity above the liquidus temperature can be related uniquely to the "silica percentage" of the slag, where

Silica percentage =

$$\frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} \times 100.$$

Here SiO_2, Fe_2O_3, CaO, and MgO represent the percentage of these materials in the melt. This relationship was found to hold for widely varying ratios of Fe_2O_3 to CaO + MgO and to be almost completely independent of the Al_2O_3 content. The relationship, admittedly an empirical one, can be simplified still further to the form

$$\log (\eta - 1) = 0.066 (SiO_2 \text{ percentage}) - 1.4$$

where η is the viscosity in poises at 2600 F. A much more elaborate treatment of this relationship was one of the useful results of the recent work in England.

The rate of change of viscosity with temperature also is relatively simple, of the form

$$\eta^{-0.1614} = (4.52 \times 10^{-4} t) - B$$

where η is the viscosity in poises at temperature t in degrees F, and B is a constant fixed for each slag. The viscosity at 2600 F can be inserted in this equation to determine B, after which the viscosity of the slag can be calculated for other temperatures. Again, the British have worked out a more elaborate but equally empirical relationship.

At some point when coal-ash are cooled, a solid phase separates which radically affects viscosity by changing the flow from Newtonian to pseudoplastic. Related to the liquidus temperature, this is known as the "temperature of critical viscosity" (T_{cv}) for coal-ash slags. At this point, important changes occur in flow behavior, and the slag may no longer deform under gravitational forces. This, in turn, greatly affects the thickness of slag that can accumulate on the furnace walls, the thickness being greater as T_{cv} is higher and as the Newtonian viscosity is greater, all other factors being constant.

The temperature at which this pseudoplastic behavior begins is related to composition in a most complicated fashion. No such simple relationship as the silica percentage has been found to apply to T_{cv}, which is also affected by such factors as the rate of cooling of fluid slag. For the present, it is enough to know that this is an important factor in fixing the thickness of slag on heat-receiving surfaces, particularly where the temperature of the slag is well below 2600 F. The relationships here between slag accumulation, coal-ash properties, and furnace conditions are extraordinarily complex, at least a dozen parameters being involved. Little use has been made of this analysis, largely because T_{cv} is not related simply to composition and may have to be determined experimentally for each slag composition.

Oil Ash

Possibly because the ash content of residual fuels seldom is greater than 0.1 percent, exceedingly low compared with coal, the properties of oil ash have not been investigated systematically. Silicate minerals in crude oil vary much more widely than in coal ash, and Al_2O_3 and Fe_2O_3 also cover broad limits. Alkalies may be high in residual fuel, often because of contamination in refining the crude oil, or in handling. Seawater, unavoidably present in bunkering, is a common contaminant in residual fuel. Sulfur occurs in oil in a wide variety of forms ranging from elemental sulfur to such complexes as thiophene and its homologues.

The uniqueness of most oil ashes is that they contain, in addition to extraneous materials, metallic complexes of iron, nickel, and vanadium present as oil-soluble organometallic compounds. These are frequently porphyrin-type complexes, so stable that temperatures in excess of 800 F usually are necessary to dissociate them. As a result, they are difficult to remove from fuel oil economically. An undescribed scheme for removing essentially all the nickel and vanadium from residual fuel at a cost as low as 15¢ a barrel was mentioned at the Marchwood Conference in 1963, but the scheme has not been applied commercially as yet. Usually, water-washing and centrifuging are the only procedures economically possible for upgrading low-cost residual fuel.

During combustion, all these complexes are destroyed, probably liberating the metals as oxides. With vanadium, for example, there seems to be a progressive oxidation from V_2O_3 to V_2O_4, and eventually with enough excess air to V_2O_5. The melting point and vapor pressure of these oxides vary widely, with the reduced forms having a higher melting point than the oxidized material. At the high temperatures in flames, there is a further tendency to produce a whole series of vanadates, of which sodium vanadyl vanadate, $Na_2O{\cdot}V_2O_4 \cdot 5V_2O_3$, is typical. Melting points vary widely too, being only 1157 F for this compound.

Hence it is a liquid at the temperature of superheater elements, thereby adding to its aggressiveness in causing corrosion.

The fusion characteristics of oil ash are poorly known. Cone fusion and other arbitrary schemes such as hot-stage microscopes have been used to check on the melting characteristics of oil ashes, but no systematic investigation has been made as with coal ash.

EXTERNAL CORROSION

Tube wastage first posed serious problems in boiler maintenance beginning about 1942, when a sudden rash of wall-tube failures in slag-tap furnaces was traced to external loss of metal. In the worst cases, tubes failed within three months of installation. Measurements of tube wall temperature showed that the tube metal was not overheated, typical maximum wall temperature being 700 F. Heat transfer also was nominal. The only unusual condition was that some flame impingement appeared likely in the affected areas.

It was soon found that an "enamel" was present beneath the slag layer where corrosion had occurred. This material, which was found in thin flakes adhering tightly to the tube wall, resembled a fired-porcelain coating with a greenish blue to pale blue color. These flakes of enamel were moderately soluble in water, giving a solution with a pH as low as 3.0. They also contained large amounts of Na_2O, K_2O, Fe_2O_3, and SO_3, and were obviously a complex sulfate. Following considerable work in the laboratory, the "enamel" was finally identified as $K_3Fe(SO_4)_3$. There is a corresponding sodium salt, as well as a solid solution of these sodium and potassium iron trisulfates.

Alkali ferric trisulfates were formed by reaction of SO_3 with Fe_2O_3 and either K_2SO_4 or Na_2SO_4, or with mixed alkali sulfates. At 1000 F, at least 250 ppm SO_3 is necessary for the trisulfates to form. At this temperature, neither the alkali sulfates nor the Fe_2O_3 alone will react with this concentration of SO_3. Only when both the sulfates and Fe_2O_3 are present will the reaction occur. The trisulfates dissociate rapidly at higher temperatures unless the SO_3 concentration in the surroundings is increased. Quantitative data are few, but it appears that the concentration of SO_3 required to prevent dissociation of the trisulfates at 1200 F to 1300 F, as would be the case on superheater elements, greatly exceeds any observed SO_3 levels in the gas phase. Accordingly, some unique but as yet unexplained action must go on beneath superheater deposits that can provide the equivalent of, perhaps, several thousand ppm of SO_3 in the gas phase. Lacking any better explanation for the time being, "catalysis" is usually blamed.

THE IMPORTANCE OF SO_3

Any discussion of external corrosion and deposits in boilers and gas turbines would be meaningless without reference to the occurrence of SO_3 in combustion gases. Many investigators, both in the laboratory and in the field, have studied the conditions under which SO_3 is formed, on the basis that SO_3 is a major factor both in high-temperature corrosion and in low-temperature corrosion and deposits. These studies have been going on for more than 30 years.

The reasons are not difficult to state. In the hot end of coal-fired equipment - furnace-wall tubes and superheater elements, for example - deposits taken from areas where corrosion has occurred invariably contain appreciable quantities of sulfates, sometimes as much as 50 percent reported as SO_3. Slag layers from the high-temperature zone of oil-fired boilers also contain SO_3, typically from 25 to 45 percent reported as Na_2SO_4. In the 1959 Battelle report to ASME, many examples are given of slag deposits where there was more than 15 percent SO_3 in the deposit.

As has already been noted, the alkali iron trisulfates cannot exist at 1000 F unless at least 250 ppm of SO_3 is present in the

surrounding atmosphere, or the equivalent SO_3 level is provided some other way. At higher temperatures, even more SO_3 must be present if these compounds are to form. In the absence of SO_3, the trisulfates could not be produced and corrosion would not occur.

Bonding of ash to superheater tubes frequently attributed to a layer of alkalies that condenses on the metal wall and serves as the agent to attach the ash to the tube. Further buildup of ash deposits, however, depends on some other mechanism. One explanation with fuels such as some subbituminous coals, lignite, and brown coal containing large quantities of CaO in the ash is that $CaSO_4$ is formed. This substance, well distributed in the ash deposit, is considered by many investigators to be the matrix material that bonds the whole deposit together into a coherent mass. Although $CaSO_4$ might be formed when CaO reacts with SO_2 and O_2, it seems more reasonable to expect that SO_3 is responsible.

At low temperatures, as in air heaters, there is no question but that SO_3 is the major offender. It combines with alkalies to plug air-heater passages, and if the metal temperature is below the dewpoint, H_2SO_4 formed from SO_3 condenses as a liquid film on the metal surfaces to cause serious corrosion. Acid smuts, where carbon particles are saturated with this H_2SO_4, also depend on the presence of SO_3.

These are the reasons why the formation of SO_3 has been given so much attention. In addition to the boiler manufacturers and the fuel suppliers working in their own laboratories and in the field, Battelle has studied the production of SO_3 in flames and by catalysis for the ASME Committee on Corrosion and Deposits. This work has provided a basic understanding of many of the thermochemical reactions leading to corrosion and deposits.

LOW EXCESS AIR

A revolutionary approach has been taken over the past decade in Europe toward eliminating the formation of SO_3 in boiler furnaces fired with oil by limiting the excess air to an absolute minimum. Low excess air seems to have been proposed first in England as a means of decreasing corrosion and deposits when burning residual fuel. In 1960, Glaubitz in Germany reported highly favorable results burning residual fuel with as little as 0.2 percent excess oxygen. By carefully metering fuel oil to each burner and properly adjusting air shutters, he found it possible to reduce excess oxygen to as little as 0.1 percent before incomplete combustion became troublesome. By operating at these low levels of excess air, Glaubitz was able to operate boilers on residual fuel for more than 30,000 hours without any corrosion and with no cleaning being required.

Low excess air in oil-fired equipment also has proven satisfactory in the United States and is being used successfully in many large boiler plants. Precise metering of fuel and air to each burner has proven to be less troublesome than had been expected earlier, and in some instances with high furnace turbulence ordinary controls have been found satisfactory. In other cases, unburned combustibles have made low excess air undesirable. Sound principles guide the use of low excess air, but applying these principles usefully is still largely a matter of judgment by boiler operators. It has been shown repeatedly, however, that SO_3 largely is eliminated, irrespective of the amount of sulfur in the fuel, when the products of combustion contain no more than about 0.2 percent oxygen. At this level, the dewpoint of the flue gas can be as low as 130 F where the dewpoint for the moisture in the flue gas is 105 F.

The important factors whereby low excess air is beneficial include, in addition to a decrease in SO_3, a limitation on the oxidation of vanadium. Low excess air leads to the formation of V_2O_3 and V_2O_4, which have melting points much higher than V_2O_5. Therefore, these reduced forms of vanadium are considered less objectionable from the standpoint of corrosion.

Work done recently in the laboratory shows that the main benefits of low excess air, as would have been expected, result from lack of formation of SO_3. Flame studies have shown that stoichiometric sulfur-bearing flames do not show the usual conversion of part of the sulfur oxides to SO_3 by reaction with oxygen atoms. Competing reactions within the flame simply keep the oxygen-atom level too low. Also, not enough oxygen is present to convert an appreciable amount of SO_2 to SO_3 catalytically on surfaces. The result is an SO_3 level of only a few ppm with a correspondingly low dewpoint, minimizing troubles throughout the boiler, from the superheater through the air heater.

Opinion at present is that corrosion and deposits when burning residual fuel can be essentially eliminated by operating with low excess air. Such procedures presumably will not be possible with coal unless radical changes are made in the combustion system. In the meantime, studies of corrosion and deposits continue in the search for still better ways of eliminating these causes of increased operating expense. Factors involving the formation of SO_3 are now understood fairly well. The next major step will be to develop an equally good knowledge of the mechanism whereby the trisulfates form, the other complex metal sulfates that also can be produced, and the role of vanadium. Meticulous, well-planned research in the laboratory and in the power plant will answer those questions as effectively as it has brought us to our present level of knowledge on the causes of corrosion and deposits.

Section 3

BURNING OF SOLID WASTES

Chemical Analysis of Refuse Components
Terminology Used in Incinerator Technology
Classification of Waste to be Incinerated
Classification of Incinerators

Flue Fed, Industrial, Commercial and Special Type Incinerators

Design Parameters for I.I.A. Incinerator Classes IIA, III, IV, VI and VII

Operation Practices for I.I.A. Incinerator Classes IA, IIA, III, IV and VII

Muncicipal Incinerators (I.I.A. Class V)

Municipal Incinerators - Design Parameters
Design Parameters for Municipal Incinerators
Municipal Incineration: Good Operating Practices
Good Operation Practices for Municipal Incinerators

Selected Publications

I.I.A. Incinerator Standards - 1966
Multiple-Chamber Incinerator Design Standards for Los Angeles County
The Problems of Applying Incinerator Criteria
Discussion of "The Problems of Applying Incinerator Criteria"
Combustion and Heat Calculations for Incinerators
Bibliography on Incineration of Refuse

CHEMICAL ANALYSIS OF REFUSE COMPONENTS

Elmer R. Kaiser*

ABSTRACT

The proximate and ultimate analyses of 20 constituents of municipal and commercial refuse are presented, together with the calorific values. The analyses are useful to incinerator engineers as they are the basis for calculating air requirements, flue-gas volumes, and heat and material balances. The analyses of components of refuse permit the calculation of composite analyses of mixed refuse from known proportions. Future investigations are suggested to obtain more complete refuse data and to determine the variability of municipal refuse.

INTRODUCTION

Millions of tons of solid wastes are burned annually by communities, industries, agriculture, commercial establishments, and residences. At least 4.5 lb of refuse are generated daily per capita in U.S. cities. Incinerators to consume the refuse, range from small batch-fed units to large municipal plants with furnaces, each of which burns over 10 tph, 24 hr/day, by continuous firing on moving grates. The cost of the large plants is upward of $4500 per ton-day (24 hr) of capacity.

Modern engineering design of incinerators begins with a known or assumed analysis and weight of refuse. The refuse determines the quantity of air required, the heat released, the volume of flue gas produced, and hence the size and proportion of ducts, flues, chambers, and stacks. The variability of refuse and the lack of interest in refuse as a fuel for steam generation have caused some delay in scientific studies of refuse. However, interest in refuse analyses has recently increased through the activities of the ASME Incinerator Committee[1] and the investigations in several European cities.

As refuse is usually a mixture of components, the proportions of which will vary appreciably, it was deemed advisable to determine the analyses of the more readily definable and major components. The proportions of the components could then be adjusted by the reader to suit known or assumed conditions of mixture.

Refuse may be thought of as consisting of moisture, dry combustibles, and noncombustibles. The major source of the dry combustible portion originates in plant life. The dry combustible in such items as paper, wool, natural textiles, vegetable wastes, brush, and leaves is largely cellulose ($C_6H_{10}O_5$). Cellulose has a calorific value of 7526 Btu per lb. Proteins, starch, and sugar associated with the cellulose have a minor depressing effect on the calorific value[2] of this combustible but may be included with the cellulose in this grouping.

The second major class of dry combustibles consists of hydrocarbons, fats, oils, waxes, resins, synthetics (plastics and textiles) rubber, linoleum, and the like. They have high calorific values, ranging up to 19,000 Btu per lb and averaging about 16,000 Btu per lb.

The air requirement and the calorific value of the mixture of dry combustibles depend primarily on the proportions of the lean and rich constituents of these two classes. Meat and cheese scraps, for example, are a mixture of the high-Btu fats and lower Btu proteins and carbohydrates.

Moisture contributes no heat units but it absorbs much heat on evaporation in the furnace. Food waste and greens are high in moisture, about 75 per cent when fresh. They lose moisture when exposed to the air or when mixed with dry materials, such as paper. Paper products, wood, and natural textiles

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are hydroscopic and readily absorb moisture until an equilibrium is reached with the surroundings. Hence, special precautions must be taken in sampling these materials to prevent undetermined gain or loss of moisture.

The metals are not considered as combustibles, but it is a fact that they oxidize in the fire to varying degrees and thus produce heat as well as consume oxygen. They also gain weight by oxidation, a fact that may be neglected except for precision work.

The ash remaining after the combustibles have been burned, together with dry mineral oxides in the incinerator charge as in crockery, bricks, glass, and dirt, may be considered as inert.

TWENTY SAMPLES

Samples of 20 of the more important combustible components of municipal refuse were obtained from local sources at the time they were being discarded and before contamination from other refuse could occur. The gross samples ranged between 5 and 25 lb. The samples were dried to equilibrium at 80°C and reduced in size for final chopping in a Wiley No. 3 mill. Samples of 10 to 20 grams for the chemical analysis were taken from the milled product. The particle size was under 2 mm.

The chemical analyses were performed by Fuel Engineering Company of N. Y. in accordance with ASTM Standard D-271-58. The higher heating values were determined by ASTM Standard D-2015-62T. The data from the analytical laboratory were corrected to the initial moisture content. For a discussion on refuse sampling and analysis, the reader is referred to the work of Etzel and Bell.[3]

Table 1 lists the proximate analyses of 20 samples. The calorific values are given on both the "as discarded" and dry bases. The reader can readily convert to the moisture and ash-free basis if desired.

The samples all showed a high loss of volatile matter on heating in a closed crucible, which is indicative of a need for much overfire air and turbulence in the incinerator furnace. The fixed carbon indicates the proportion of the refuse that must be burned out on the grate.

The high moisture content of food and greens is in contrast to the low moisture contents of paper. The high ash content of trade magazines and junk mail is from the clay fillers and sizing used in producing smooth printing papers. A part of the ash content of the leather shoe was from metal parts. The heel and soil composition contained mineral fillers.

The ultimate analyses of the same 20 samples are reported on the dry basis in Table 2. The analyses can be converted readily to any moisture content if desired.

Carbon is the principal fuel element. In cellulose ($C_6H_{10}O_5$) the carbon content is 44.4 per cent, hydrogen 6.2 per cent, and oxygen 49.4 per cent. Oxygen exceeds carbon in weight in some of the samples of paper, which are principally cellulose.

Hydrogen is present in at least the amount necessary to burn all the oxygen in the refuse to water. In other words, the oxygen weight is less than eight times the weight of hydrogen. For convenience in combustion calculations, the hydrogen in excess of that needed to consume the refuse oxygen, (H - 0/8), is "available" to burn with combustion air. All the carbon is deemed available for combustion.

Nitrogen is present in almost negligible amounts except in components that contain protein, which is 16 per cent nitrogen.

As sulfur is a necessary element in living matter, refuse of plant and animal origin will contain small amounts. Sulfur is added to rubber for vulcanization. The sulfur content of most refuse is low in comparison with that of coal and oil. It may be assumed that all the sulfur burns to sulfur dioxide (SO_2), although some is found in incinerator fly ash[2], and further investigation may reveal some trapping of sulfur in incinerator residue.

TABLE 1

PROXIMATE ANALYSES IN PER CENT BY WEIGHT, AS DISCARDED (A.D.) BY HOUSEHOLDERS

Refuse Component	Moisture	Volatile Matter	Fixed Carbon	Ash	Btu/lb A.D.	Btu/lb Dry Basis
1. Newspaper	5.97	81.12	11.48	1.43	7974	8480
2. Brown paper	5.83	83.92	9.24	1.01	7256	7706
3. Trade magazine	4.11	66.39	7.03	22.47	5254	5480
4. Corrug. paper boxes	5.20	77.47	12.27	5.06	7043	7429
5. Plastic coated paper	4.71	84.20	8.45	2.64	7341	7703
6. Waxed milk cartons	3.45	90.92	4.46	1.17	11327	11732
7. Paper food cartons	6.11	75.59	11.80	6.50	7258	7730
8. Junk mail	4.56	73.32	9.03	13.09	6088	6378
9. Veget. food wastes	78.29	17.10	3.55	1.06	1795	8270
10. Citrus rinds and seeds	78.70	16.55	4.01	0.74	1707	8015
11. Meat scraps, cooked	38.74	56.34	1.81	3.11	7623	12443
12. Fried fats	0.00	97.64	2.36	0.00	16466	16466
13. Leather shoe	7.46	57.12	14.26	21.16	7243	7826
14. Heel and sole composition	1.15	67.03	2.08	29.74	10899	11026
15. Vacuum cleaner catch	5.47	55.68	8.51	30.34	6386	6756
16. Evergreen shrub cuttings	69.00	25.18	5.01	0.81	2708	8735
17. Balsam spruce	74.35	20.70	4.13	0.82	2447	9541
18. Flower garden plants	53.94	35.64	8.08	2.34	3697	8027
19. Lawn grass	75.24	18.64	4.50	1.62	2058	8312
20. Ripe tree leaves	9.97	66.92	19.29	3.82	7984	8869

TABLE 2

ULTIMATE ANALYSIS, DRY BASIS IN PER CENT BY WEIGHT

Refuse Component	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Ash
1. Newspaper	49.14	6.10	43.03	0.05	0.16	1.52
2. Brown paper	44.90	6.08	47.84	0.00	0.11	1.07
3. Trade magazine	32.91	4.95	38.55	0.07	0.09	23.43
4. Corrug. paper boxes	43.73	5.70	44.93	0.09	0.21	5.34
5. Plastic coated paper	45.30	6.17	45.50	0.18	0.08	2.77
6. Waxed milk cartons	59.18	9.25	30.13	0.12	0.10	1.22
7. Paper food cartons	44.74	6.10	41.92	0.15	0.16	6.93
8. Junk mail	37.87	5.41	42.74	0.17	0.09	13.72
9. Veget. food wastes	49.06	6.62	37.55	1.68	0.20	4.89
10. Citrus rinds and seeds	47.96	5.68	41.67	1.11	0.12	3.46
11. Meat scraps, cooked	59.59	9.47	24.65	1.02	0.19	5.08
12. Fried fats	73.14	11.54	14.82	0.43	0.07	0.00
13. Leather shoe	42.01	5.32	22.83	5.98	1.00	22.86
14. Rubber composition heel and sole	53.22	7.09	7.76	0.50	1.34	30.09
15. Vacuum cleaner catch	35.69	4.73	20.08	6.26	1.15	32.09
16. Evergreen trimmings	48.51	6.54	40.44	1.71	0.19	2.61
17. Balsam spruce	53.30	6.66	35.17	1.49	0.20	3.18
18. Flower garden plants	46.65	6.61	40.18	1.21	0.26	5.09
19. Lawn grass, green	46.18	5.96	36.43	4.46	0.42	6.55
20. Ripe tree leaves	52.15	6.11	30.34	6.99	0.16	4.25

COMPOSITE MUNICIPAL REFUSE

By calculation, the reader may combine quantities of the components name, or add others, and determine the proximate and ultimate analyses, as well as the calorific values of the mixtures. The analyses must first be converted to the same basis as the weights, such as "moist" or "dry." The weight of each component times the decimal per cent of each element in it equals the weights of the elements. The weights of the elements, moisture, and ash are then totalled separately. The totals of the elements can then be related back to the grand weight total to establish the composite analysis.

The total calorific value is the sum of the calorific values of the components and is higher than the Btu calculated from burning

the same weights of carbon, net hydrogen, and sulfur.

Municipal refuse is a varying mixture of the 20 components previously named and a large number of minor components. The moisture content is influenced by the weather, especially rain, despite the use of covered containers and trucks. Refuse is also sprayed with water at some incinerators to suppress dust. Bacterial and enzyme action on moist refuse also alters the analysis in time.

By way of illustration, a composite was selected which was based on proportions of the 20 ingredients plus others that have been reported in published literature[2], [4] and obtained from private sources. The moisture content was adjusted to a total of 20 per cent by the addition of moisture, to bring the moisture content into the range normally experienced at incinerators.

Table 3 is the list of components and the percentage selected. Compared with older compositions, the selected group represents the current compositions more closely through an increase in paper and plastics and a reduction in ash and food waste. The reader will understand the seasonal and regional variability of such mixtures.

The proximate and ultimate analyses of the composite were calculated by use of the data in Tables 1, 2, 3 and previously published values. The resultant analyses and calorific values are given in Table 4.

The calorific value of the composite is the sum of the contributions from each component. As the metals are partly burned in municipal incinerators, probably 50 per cent oxidized, heat from that source should be added as was done in Table 4. Where metals are not incinerated, the heat from metals is to be omitted.

As the data in Table 4 may be converted to use for municipal refuse of other moisture and ash contents, it is of interest to know that the dry, ash-free combustible (60 per cent of the refuse listed in Table 4) has a higher heating value of 8766 Btu per lb without credit for the oxidation of metals, of 9070 Btu per lb with credit for oxidation of metals.

The calorific values are influenced greatly by the amount of fats, oils, and plastics present.

TABLE 3

COMPOSITION AND ANALYSIS OF A COMPOSITE MUNICIPAL REFUSE

Per Cent	
23.38	Corrug. paper boxes
9.40	Newspaper
6.80	Magazine paper
5.57	Brown paper
2.75	Mail
2.06	Paper food cartons
1.98	Tissue paper
0.76	Plastic coated paper
0.76	Wax cartons
2.29	Vegetable food wastes
1.53	Citrus rinds and seeds
2.29	Meat scraps, cooked
2.29	Fried fats
2.29	Wood
2.29	Ripe tree leaves
1.53	Flower garden plants
1.53	Lawn grass, green
1.53	Evergreens
0.76	Plastics
0.76	Rags
0.38	Leather goods
0.38	Rubber composition
0.76	Paints and oils
0.76	Vacuum cleaner catch
1.53	Dirt
6.85	Metals
7.73	Glass, ceramics, ash
9.05	Adjusted moisture
100.00	

TABLE 4

ANALYSES OF A COMPOSITE MUNICIPAL REFUSE

Proximate Analysis

Moisture	20.00 per cent
Volatile matter	52.70
Fixed carbon	7.30
Ash and metal	20.00
	100.00 per cent

Btu/lb: 5260 + 182[a] = 5442

Ultimate Analysis

Moisture	20.00 per cent
Carbon	29.83
Hydrogen	3.99
Oxygen	25.69
Nitrogen	0.37
Sulfur	0.12
Ash and metal	20.00
	100.00 per cent

[a] From 50 per cent oxidation of metals.

THEORETICAL AIR

As one purpose of the analysis is to determine the theoretical or stoichiometric amount of dry air required for complete combustion, Table 5 is included.

TABLE 5

THEORETICAL AIR REQUIRED

Carbon: 0.2983 x 11.53	= 3.439 lb
Net H: (0.0399 – 0.2569/8) x 34.34	= 0.268
Sulfur: 0.0012 x 4.29	= 0.005
50 per cent of metals: 0.0685 x 1.05	= 0.072
Total theoretical air per lb refuse	= 3.784 lb

or 50.5 cu ft at 70F.

The total air supplied to incinerator furnaces usually exceeds 2.25 times the theoretical, expressed as 125 per cent excess air, to prevent excessive temperatures.

When the air supply has been established, the volumes of carbon dioxide, oxygen, nitrogen and water vapor can be determined by conventional textbook methods. The refuse analysis provides much of the basic data needed.

The heat released per pound of theoretical air is useful in approximating the air requirement when only the calorific value of a refuse is given. In the foregoing case, the Btu released per pound of theoretical air was 1417 without metals, or 1438 with metals. These values are useful but are not precise for all types of solid waste. For example, the Btu released per pound of theoretical air is 1463 for corrugated cartons and 1424 for fried fats.

MORE REFUSE ANALYSES NEEDED

The sampling and analysis of refuse is a promising field of investigation. Analyses of refuse as it is burned at municipal refuse incinerators should be obtained, as well as calorific values for the analyzed samples. If the refuse from which the samples are taken is sorted, and the components are themselves sampled and analyzed, the data will have maximum value to others.

The analyses and calorific values of industrial wastes, plastics, and synthetic fabrics are needed as these materials will be present in future refuse in larger amounts than today. Data reported by C. A. Hescheles[5] indicate calorific values up to 19, 840 Btu per lb for waste from a rubber-chemical industry.

The variability of municipal refuse is a cause of much concern to incinerator operators. Engineers may base a plant design on an average refuse analysis, but performance falls off when the moisture content of the refuse rises. Moisture content is the most important refuse variable. By weight, the water vapor produced by the example refuse is 55.9 parts to 109.5 parts of carbon dioxide. If the free moisture is doubled, the total moisture increases to 75.9 parts. Air moisture adds to the total.

A study of refuse variability is a major undertaking by direct sampling and analysis. It may be feasible to use new methods of monitoring the flue gas for studying the subject as most changes in refuse analysis are reflected in the gaseous products of combustion.

SUMMARY

Chemical analyses and higher heating values of 20 refuse components have been presented and their usefulness to incinerator designers and operators has been described. A composite municipal refuse was described in which the dry combustible has a calorific value of 9070 Btu per lb, when credit is taken for 50 per cent oxidation of the metals present. Additional sampling and analysis is recommended.

REFERENCES

1 Incinerator Committee, Process Industries Div. (ASME), Proceedings of 1964 National Incinerator Conference, ASME. New York. 1964.

2 Kaiser, E. R. Refuse Composition and Flue-Gas Analyses from Municipal Incinerators. Proceedings of 1964 National Incinerator Conference, ASME, New York. 1964.

3 Etzel, J.E., and Bell, J.M. Methods of Sampling and Analyzing Refuse. APWA Reporter, pp 2-4, 18-21, November, 1962.

4 Municipal Refuse Disposal, Committee on Refuse Disposal, American Public Works Assn. 1961.

5 Hescheles, C.A. Thermal Recovery Systems from Burning Industrial Wastes. Paper No. 64-WA/PID-11, presented at ASME Winter Annual Meeting. 1964.

TERMINOLOGY USED IN INCINERATOR TECHNOLOGY

I FOREWARD

The definitions given below apply to conventional commercial, industrial, and municipal waste-incineration practices, and do not cover special applications of incineration; nor do they cover special features of certain types of incinerators, for example, catalytic devices.

II DEFINITIONS

1 Auxiliary-fuel Firing Equipment

Equipment to supply additional heat, by the combustion of an auxiliary fuel, for the purpose of attaining temperatures sufficiently high (a) to dry and ignite the waste material, (b) to maintain ignition thereof, and (c) to effect complete combustion of combustible solids, vapors, and gases.

2 Baffle

A refractory construction intended to change the direction of flow of the products of combustion.

3 Breeching

The connection between the incinerator and the stack.

4 Breeching By-pass

An arrangement of breeching and dampers to permit the intermittent use of two or more passages for products of combustion to the stack or chimney.

5 Bridge-wall

A partition wall between chambers over which pass the products of combustion.

6 Btu (British Thermal Unit)

The quantity of heat required to increase the temperature of one pound of water from 60° to 61°F.

7 Burners

Primary: A burner installed in the primary combustion chamber to dry and ignite the material to be burned.

Secondary: A burner installed in the secondary combustion chamber to maintain a minimum temperature of about 1400°F. It may also be considered as an after-burner.

After-burner: A burner located so that the combustion gases are made to pass through its flame in order to remove smoke and odors. It may be attached to, or be separated from the incinerator proper.

8 Burning Area

The horizontal projected area of grate, hearth, or combination thereof on which burning takes place.

9 Burning Rate

The amount of waste consumed, usually expressed as pounds per hour per square foot of burning area. Occasionally expressed as Btu per hour per square foot of burning area, which refers to the heat liberated by combustion of the waste.

10 Capacity

The amount of a specified type or types of waste consumed in pounds per hour. Also may be expressed as heat liberated, Btu per hour, based upon the heat of combustion of the waste.

11 Checker-work

Multiple openings above the bridge-wall, and/or below the drop arch, to promote turbulent mixing of the products of combustion.

12 Chute, charging

A pipe or duct through which wastes are conveyed from above to the primary

chamber, or to storage facilities preparatory to burning.

13 Combustion Air

Primary: Air introduced to the primary chamber through the fuel bed by natural, induced, or forced draft.

Secondary: Air introduced above or beyond the fuel bed by natural, induced, or forced draft. It is generally referred to as overfire air if supplied above the fuel bed through the side walls and/or the bridge-wall of the primary chamber.

Theoretical: Air, calculated from the chemical composition of waste, required to burn the waste completely without excess air. Also designated as Stoichiometric air.

Excess: Air supplied in excess of theoretical air, usually expressed as a percentage of the theoretical air.

14 Combustion Chamber

Primary: Chamber where ignition and burning of the waste occur.

Secondary: Chamber where combustible solids, vapors, and gases from the primary chamber are burned and settling of fly ash takes place.

15 Curtain Wall or Drop Arch

A refractory construction or baffle which serves to deflect gases in a downward direction.

16 Damper

A manual or automatic device used to regulate the rate of flow of gases through the incinerator.

Barometric: A pivoted, balanced plate, normally installed in the breeching, and actuated by the draft.

Guillotine: An adjustable plate normally installed vertically in the breeching, counterbalanced for easier operation, and operated manually or automatically.

Butterfly: An adjustable, pivoted, plate normally installed in the breeching.

Sliding: An adjustable plate normally installed horizontally or vertically in the breeching.

17 Draft

The pressure difference between the incinerator, or any component part, and the atmosphere, which causes the products of combustion to flow from the incinerator to the atmosphere.

Natural: The negative pressure created by the difference in density between the hot flue gases and the atmosphere.

Induced: The negative pressure created by the action of a fan, blower, or ejector, which is located between the incinerator and the stack.

Forced: The positive pressure created by the action of a fan or blower, which supplies the primary or secondary air.

18 Flue Gas Washer or Scrubber

Equipment for removing fly ash and other objectionable materials from the products of combustion by means of sprays, wet baffles, etc. Also reduces excessive temperatures of effluent.

19 Fly Ash

All solids including ash, charred paper, cinders, dust, soot, or other partially incinerated matter, carried in the products of combustion.

20 Fly Ash Collector

Equipment for removing fly ash from the products of combustion.

21 Grate

A surface with suitable openings, to support the fuel bed and permit passage

of air through the fuel. It is located in the primary combustion chamber and is designed to permit the removal of the unburned residue. It may be horizontal or inclined, stationary or movable, and operated manually or automatically.

22 Hearth

Cold drying: A surface upon which wet waste material is placed to dry prior to burning by the actual hot combustion gases passing only over the wet material.

Hot drying: A surface upon which wet material is placed to dry by the action of hot combustion gases that pass successively over the wet material and under the hearth.

23 Heat of Combustion

The amount of heat, usually expressed as Btu per pound of as-fired or dry waste, liberated by combustion at a reference temperature of 68°F. With reference to auxiliary gas it is expressed as Btu per standard cubic foot, and to auxiliary oil as Btu per pound or gallon.

24 Heat Release Rate

The amount of heat liberated in the primary combustion chamber, usually expressed as Btu per hour per cubic foot.

25 Heating Value

Same as heat of combustion. (23, above)

26 Incinerator

Equipment in which solid, semi-solid, liquid or gaseous combustible wastes are ignited and burned, the solid residues of which contain little or no combustible material. (See Classification of Incinerators.)

27 Incinerator, multiple chamber

An incinerator consisting of two or more refractory-lined chambers, interconnected by gas passage ports or ducts and designed in such manner as to provide for complete combustion of the material to be burned. Depending upon the arrangement of the chambers, multiple-chamber incinerators are designated as in-line or retort types.

28 Settling Chamber

Chamber designed to reduce the velocity of the gases in order to permit the settling out of fly ash. It may be either part of, adjacent to, or external to the incinerator.

29 Spark Arrester

A screen-like device located on top of the stack or chimney, to prevent incandescent material above a given size from being expelled to the atmosphere.

30 Stack or Chimney

A vertical passage whether of refractory, brick, tile, concrete, metal or other material or a combination of any of these materials for conducting products of combustion to the atmosphere.

REFERENCE

1 APCA publication, Vol. 15, No. 3, pp 125-126. March, 1965.

CLASSIFICATION OF WASTE TO BE INCINERATED
(Incinerator Institute of America)

Classification of Wastes Type	Description	Principal Components	Approximate Composition % by Weight	Moisture Content %	Incombustible Solids %	B.T.U. Value/lb. of Refuse as fired	B.T.U. of Aux. Fuel Per lb. of Waste to be included in Combustion Calculations	Recommended Min. B.T.U./hr. Burner Input per lb. Waste
*0	Trash	Highly combustible waste, paper, wood, cardboard cartons, including up to 10% treated papers, plastic or rubber scraps; commercial and industrial sources	Trash 100%	10%	5%	8500	0	0
*1	Rubbish	Combustible Waste, paper, cartons, rags, wood scraps, combustible floor sweepings; domestic commercial, and industrial sources	Rubbish 80% Garbage 20%	25%	10%	6500	0	0
*2	Refuse	Rubbish and garbage; residential sources	Rubbish 50% Garbage 50%	50%	7%	4300	0	1500
*3	Garbage	Animal and vegetable wastes, restaurants, hotels, markets; institutional, commercial, and club sources	Garbage 65% Rubbish 35%	70%	5%	2500	1500	3000
4	Animal solids and organic wastes	Carcasses, organs, solid organic wastes; hospital, laboratory, abattoirs, animal pounds, and similar sources	100% Animal and Human Tissue	85%	5%	1000	3000	8000 (5000 Primary) (3000 Secondary)
5	Gaseous, liquid or semi-liquid wastes	Industrial process wastes	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey
6	Semi-solid and solid wastes	Combustibles requiring hearth, retort, or grate burning equipment	Variable	Dependent on predominant components	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey	Variable according to wastes survey

*The above figures on moisture content, ash, and B.T.U. as fired have been determined by analysis of many samples. They are recommended for use in computing heat release, burning rate, velocity, and other details of incinerator designs. Any design based on these calculations can accommodate minor variations.

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CLASSIFICATION OF INCINERATORS

(Incinerator Institute of America)

Class I - Portable, packaged, completely assembled, direct fed incinerators having not over 5 cu. ft. storage capacity, or 25 lbs. per hour burning rate, suitable for Type 2 Waste.

Class IA - Portable, packaged or job assembled, direct fed incinerators 5 cu. ft. to 15 cu. ft. primary chamber volume; or a burning rate of 25 lbs. per hour up to, but not including, 100 lbs per hour of Type O, Type I, or Type 2 Waste; or a burning rate of 25 lbs per hour up to, but not including, 75 lbs. per hour of Type 3 Waste.

Class II - Flue-fed, single chamber incinerators with more than 2 sq. ft. burning area, suitable for Type 2 Waste. This type of incinerator is served by one vertical flue functioning both as a chute for charging waste and to carry the products of combustion to atmosphere. This type of incinerator installed in apartment houses or multiple dwellings not more than five stories high.

Class IIA - Chute-fed multiple chamber incinerators, with more than 2 sq. ft. burning area, suitable for Type 1 or Type 2 Waste. (Not recommeded for industrial wastes). This type of incinerator is served by a vertical chute for charging wastes from two or more floors above the incinerator and a separate flue for carrying the products of combustion to atmosphere.

Class III - Direct fed incinerators with a burning rate of 100 lbs. per hour and over, suitable for Type 0, Type 1 or Type 2 Waste.

Class IV - Direct fed incinerators with a burning rate of 75 lbs. per hour or over, suitable for Type 3 Waste.

Class V - Municipal incinerators suitable for Type 0, Type 1, Type 2, or Type 3 Wastes, or a combination of all four wastes, and are rated in tons per hour or tons per 24 hours.

Class VI - Crematory and pathological incinerators, suitable for Type 4 Waste.

Class VII - Incinerators designed for specific by-product wastes, Type 5 or Type 6.

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DESIGN PARAMETERS FOR I. I. A. INCINERATOR CLASSES IIA, III, IV, VI AND VII

R. Goder*

I INTRODUCTION

In a discussion of Design Parameters, it is advisable first to settle upon nomenclature and definitions. Accordingly, we show here a section through a typical Incinerator (Figure 1) with most widely used terms. These terms also correspond to those used in Incinerator Institute of America 1963 Standards which will be the principle reference work for this subject.

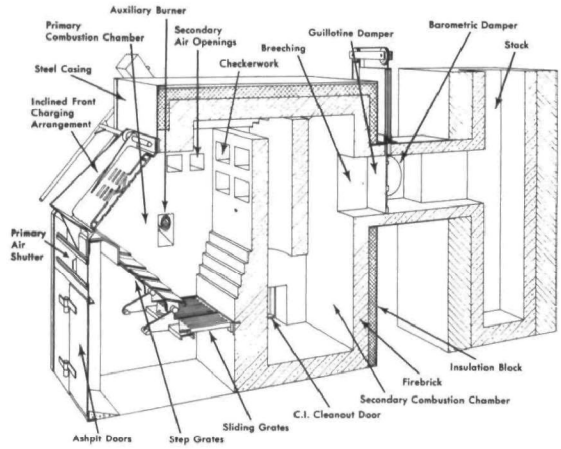


Figure 1. Incinerator Nomenclature

It is also important to note that there is no single set of Design Parameters. The design parameters of the Incinerator industry as per I. I. A. Incinerator Standards are used here together with those of the Los Angeles County Air Pollution Control District. We feel that there is basically no conflict here but such differences that exist will be shown and briefly discussed.

Only Class IIA, III, IV, VI and VII Incinerators as defined in I. I. A. Standards will be discussed. They are all multi-chamber incinerators.

*President, Joseph Goder Incinerators, Elk Grove Village, Illinois. (Prepared February, 1966).

II PRIMARY CHAMBER

This is the chamber into which refuse is charged and which contains the grate and hearth surfaces on which combustion is initiated. Its function, therefore, is to initiate combustion, provide for separation of ash from combustibles, provide some degree of refuse storage, and means for combustion air admission and regulation. An auxiliary burner is often added to provide heat for reluctant combustible waste.

A Volume

The volume is determined by the designer but according to I. I. A. must not be more than 60% of total Incinerator combustion volume. L. A. parameters do not have a specific value although by their grate area and arch height stipulations, a volume is rather closely determined and generally agrees with I. I. A.

B Grate Area:

The burning rate on the grate in an incinerator varies according to size of the incinerator or grate loading and according to type of waste. I. I. A. Standards contain a chart and formula. L. A. shows a curve according to the following equation:

$$A_G = \frac{R_C(\text{lb./hr.})}{L_G(\text{lb./hr./ft.}^2)} = \text{ft.}^2$$

Where A_G is the grate area, R_C the incinerator capacity and L_G the burning rate on the grate.

The differences, if any, between the two are minor since virtually the same curve is used.

C Arch Height

L. A. provides a formula as follows:

$$H_A = 4/3\ (A_G)^{4/11} = \text{ft.}$$

I. I. A. does not consider this equation applicable because of practical problems and insufficient field and laboratory data to show the validity of the equation. On a 50 pound per hour incinerator, one charge of an ordinary cardboard carton would upset the theoretical relation.

D Length-to-Width Ratio:

L. A. has a recommendation as follows:

1 Retort Model: up to 500 lbs per hr., 2:1 ratio

over 500 lbs per hr., 1.75:1 ratio

2 In-Line Model: 1.6:1 ratio for 750 lbs per hr. to about 1:1 ratio for 4000 lbs. per hr.

Although I. I. A. has no specification for this relationship, the L. A. ratio is considered desirable where space limitations permit.

III SECONDARY CHAMBER

The function of the secondary chamber is to complete combustion and to collect ash carried over from the primary chamber. Effective means of completing combustion are baffling and checkerwork to break stratification, air ports to supply combustion air, large volume to equalize temperature variations introduced in primary chamber and to settle fly ash.

I. I. A.: A baffle to form a "down-pass" and a velocity not exceeding 9 feet per second with gas volume at 1400°F. Also, limitations on length of gas travel.

L. A. Specifies a maximum gas velocity. Generally, a zone of low-gas velocity is required and a change in direction to effect "throw-out" of particles.

IV GEOMETRIC CONFIGURATION

This refers to the placement of the secondary combustion chamber in relation to the primary combustion chamber.

IN-LINE is that arrangement where secondary chamber is at the rear of primary chamber. See Figures 3 and 4.

RETORT is that configuration in which secondary chamber is at the side of primary chamber. See Figure 2.

SUPERIMPOSED is a more recent configuration designed to save floor space in which secondary chamber is superimposed on primary chamber.

V AUXILIARY FUEL BURNERS

Auxiliary fuel serves two basic purposes, namely, to supply heat to a waste that will not support combustion such as wet garbage, and to insure ignition of products of combustion, via an afterburner. I. I. A. prescribes minimum size burners that shall

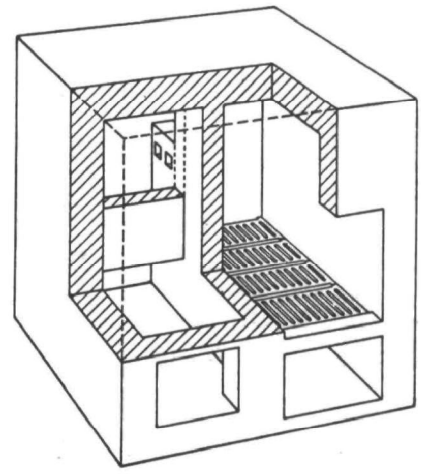


Figure 2. Retort Design Incinerator

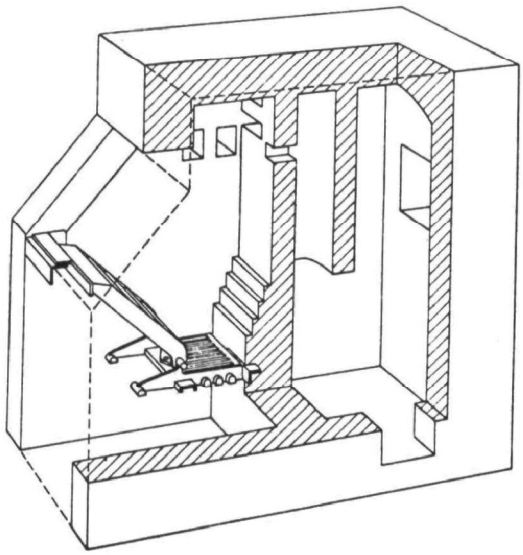


Figure 3. In-Line Design Incinerator

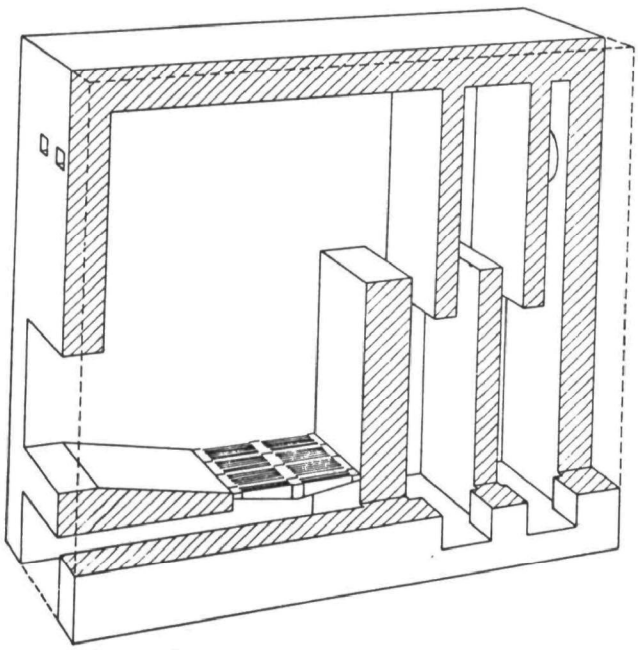


Figure 4. In-Line Design Incinerator

be used in (Table 1) but does not specify where it shall be admitted except in the case of Class VI Incinerators. Note, that burner input actually means burner size and actual input is expected to average less than burner capacity or input. I. I. A. also specifies that flame failure protection be provided. Local regulations may be more specific on flame failure protection.

Table 1. I. I. A. Recommended Auxiliary Fuel Burner Size(s)

Waste Type	Waste Description	Recommended Minimun Btu/hr. Burner Input/lb of Waste
1	Rubbish	0
2	Refuse	1500
3	Garbage	3000
4	Animal Solids and Organic Wastes	8000 (5000 Primary) (3000 Secondary)
5	Gaseous, Liquid or Semi-Liquid Wastes	Variable according to wastes survey
6	Semi-Solid and Solid Wastes	Variable according to wastes survey

VI DRAFT

Draft is the difference in air and flue gas pressures and is usually negative relative to the incinerator room atmosphere so air will flow into and through the incinerator to the chimney either by gravity or by means of a fan in the breeching. In this latter instance, it is called "induced draft."

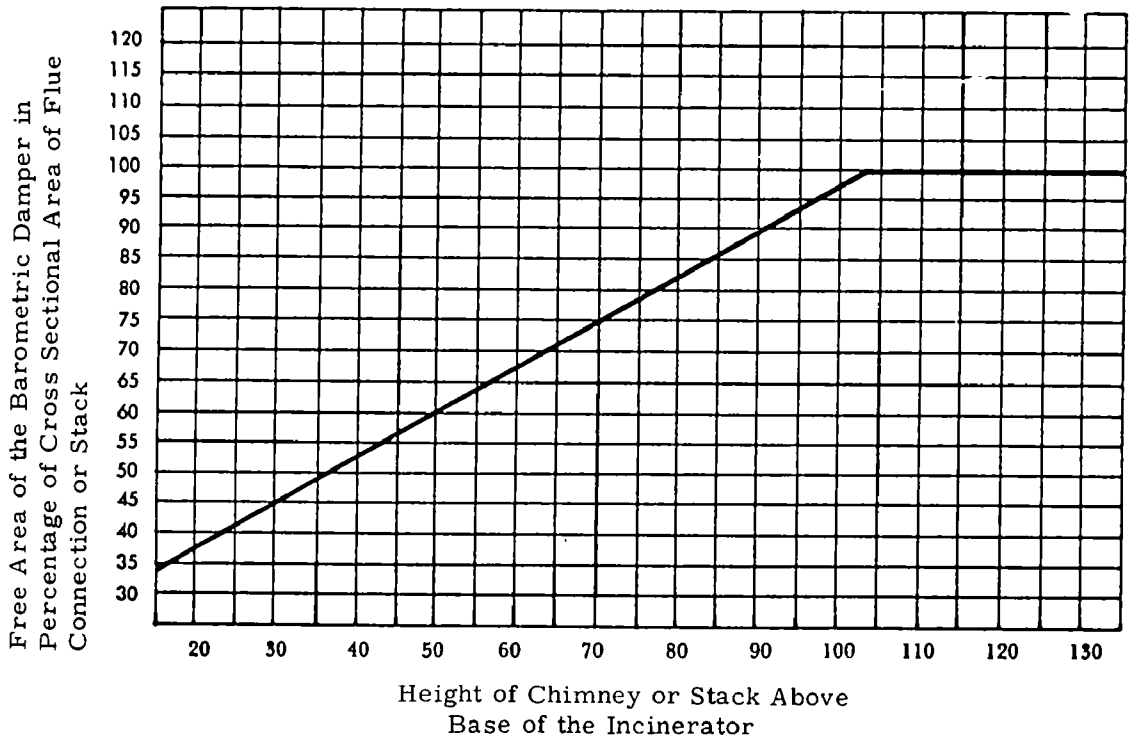
Draft is also required to draw air through the grates and fuel bed. This may be accomplished by gravity or by a blower. In the latter case, it is called "forced draft." Note, that forced draft does not imply a pressure in the primary chamber in relation to the incinerator room atmosphere.

Tables 2, 3, and 4 which show barometric damper sizes, chimney sizes, and air requirements in the incinerator room as specified by the I. I. A.

Table 2

USE TO DETERMINE MINIMUM FREE AREA

OF BAROMETRIC DAMPERS



VII BREECHING & STACK

It is very important to realize that the gases leaving an incinerator may be as high as 1800°F and they cannot be handled in the same manner as boiler flue gases which rarely exceed 600°F. This indicates the necessity for adequate breeching and chimney linings. Velocity of the incinerator flue gases is not really important although I. I. A. specifies a maximum velocity of 30 feet per second in the breeching.

VIII WASTE COMPOSITION

The I. I. A. specifications in design do consider different types of waste and a reference to Table 5 will show these changes in three different types of waste. These three types of waste vary generally by the average amount of unbound moisture or free water.

IX MATERIALS OF CONSTRUCTION

This is not a subject for a brief outline and the I. I. A. specifications should be the yardstick. These specifications also comply with the recommendations of the National Fire Protection Association.

X INSTRUMENTATION

There are no requirements for instrumentation in either I. I. A. or L. A. specifications. I personally feel that the incinerator should be equipped with a smoke indicator or a visual arrangement of windows or mirror so the operator can see the top of incinerator chimney. In incinerators approaching 1000 lbs per hour, a draft gauge, temperature indicator, and smoke density indicator should be used.

TABLE 3

NATURAL DRAFT STACKS OR CHIMNEYS

(Minimum Recommended)

Incinerator Capacity in lbs. per hour	Class III Incinerators						Class IV Incinerators			Class VI Incinerators		
	Type 1 Waste			Type 2 Waste			Type 3 Waste			Type 4 Waste		
	Air•• Supply	Stack		Air•• Supply	Stack		Air•• Supply	Stack		Air•• Supply	Stack	
		dia.	height•		dia.	height•		dia.	height•		dia.	height•
50										90	9"	25'
100	350	14"	30'	250	12"	25'	200	12"	30'	180	10"	25'
150	525	16"	30'	375	14"	30'	300	14"	30'	270	12"	25'
200	700	18"	35'	500	16"	30'	400	14"	35'	360	14"	25'
300	1050	20"	35'	750	18"	35'	600	16"	40'	540	16"	30'
400	1400	22"	40'	1000	20"	40'	800	18"	40'	720	18"	30'
500	1750	24"	40'	1250	22"	40'	1000	20"	45'	900	20"	30'
600	2100	26"	40'	1500	24"	40'	1200	22"	45'			
700	2450	28"	45'	1750	26"	45'	1400	24"	50'			
800	2800	30"	45'	2000	28"	45'	1600	26"	50'			
900	3150	32"	45'	2250	30"	45'	1800	28"	50'			
1000	3500	34"	45'	2500	32"	45'	2000	30"	50'			

NOTES:

••Air supply is given in C.F.M. @ 70° F. and is the minimum which must be available at all times in the incinerator room at atmospheric or a slight positive pressure. The incinerator room or rooms should never be under a negative or minus pressure. If the incinerator is charged from a room other than the incinerator room the quantity of air shown must be available in both rooms.

The quantity of air shown must be increased to satisfy the following:

(1) If stack or chimney is higher than minimum to satisfy the larger barometric damper involved.

(2) If any other equipment requiring air supply is located in the incinerator room or charging room.

•The stack heights are based upon the following:

(a) Installation made at or near sea level.

(b) Stack heights measured from base of the incinerator.

(c) Incinerator is side charged.

(d) Breeching or flue connection not exceeding 10' in length in a straight run or 3' including not more than 1-90° bend or 2-45° bends.

(e) Stack extends not less than 3' above any roof within 75' of the top of the stack.

The stack heights must be increased or may be decreased as follows:

(1) Increase height 5% per 1000' above sea level.

(2) Decrease height 25% if stack is directly on top of incinerator eliminating any breeching or flue connection.

(3) Increase height 15% if incinerator is top charged.

(4) Increase height 15% for each additional 10' of straight breeching and 15% for each additional 90° bend.

TABLE 4

INDUCED DRAFT FANS
(Minimum Recommended)

Incinerator Capacity in lbs. per hour	CLASS III INCINERATORS									
	Type 1 Waste					Type 2 Waste				
	Air•• Supply	lbs. per hour		Fan		Air•• Supply	lbs. per hour		Fan	
		flue gases	cooling air	C.F.M. @ 700° F.	"Cold" s.p.		flue gases	cooling air	C.F.M. @ 700° F.	"Cold" s.p.
100	850	1080	2160	1630	.7	600	768	1540	1130	.68
150	1275	1620	3240	2445	.7	900	1152	2310	1700	.7
200	1700	2160	4320	3260	.72	1200	1536	3080	2250	.7
300	2550	3240	6480	4890	.72	1800	2304	4610	3380	.72
400	3400	4320	8640	6520	.75	2400	3072	6150	4500	.75
500	4250	5400	10800	8150	.75	3000	3840	7680	5680	.75
600	5100	6480	12960	9780	.75	3600	4608	9220	6750	.75
700	5950	7560	15120	11410	.8	4200	5376	10750	7880	.8
800	6800	8640	17280	13040	.8	4800	6144	12290	9000	.8
900	7650	9720	19440	14670	.8	5400	6912	13830	10130	.8
1000	8500	10800	21600	16300	.8	6000	7680	15360	11250	.8

NOTES:

••Air supply is given in C.F.M. @ 70°F. and is the minimum which must be available at all times in the incinerator room for combustion and fan cooling air. See also notes regarding "air supply" Table V.

The total flue gases or total products of combustion are given in lbs. per hour.

The cooling air is given in lbs. per hour and is the air required to be bled into and mixed with the flue gases before entering the induced draft fan and unlined breeching section.

The fan capacity is given in C.F.M. @ 700° F. which is the anticipated temperature of the air-gas mixture entering the induced draft fan.

The static pressure of the fan is given as the "cold" (70° F.) static pressure and with the installation made at or near sea level. The static pressure at 700° F. is 45% of the "cold" static pressure. Increase the "cold" static pressure 3.5% for every 1000 feet above sea level.

Water sprays or a combination of water and air may be used to cool the flue gases before they enter the fan. The C.F.M. of the fan reduces but the static pressure of the fan increases to overcome the resistance created by the gas washer or scrubber used.

TABLE 4 (Contd)

INDUCED DRAFT FANS
(Minimum Recommended)

Incinerator Capacity in lbs. per hour	CLASS IV INCINERATORS — Type 3 Waste					CLASS VI INCINERATORS — Type 4 Waste				
	Air•• Supply	lbs. per hour		Fan		Air•• Supply	lbs. per hour		Fan	
		flue gases	cooling air	C.F.M. @ 700° F.	"Cold" s.p.		flue gases	cooling air	C.F.M. @ 700° F.	"Cold" s.p.
50						200	262	525	385	.68
100	485	625	1250	920	.7	400	523	1050	770	.68
150	728	938	1875	1380	.7	600	785	1570	1155	.68
200	970	1250	2500	1840	.72	800	1046	2100	1540	.68
300	1455	1875	3750	2760	.75	1200	1569	3050	2310	.7
400	1940	2500	5000	3680	.75	1600	2092	4200	3080	.7
500	2425	3125	6250	4600	.8	2000	2615	5250	3850	.7
600	2910	3750	7500	5520	.8					
700	3395	4375	8750	6440	.85					
800	3880	5000	9000	7360	.85					
900	4365	5625	10250	8280	.85					
1000	4850	6250	12500	9200	.85					

NOTES:

••Air supply is given in C.F.M. @ 70°F. and is the minimum which must be available at all times in the incinerator room for combustion and fan cooling air. See also notes regarding "air supply" Table V.

The total flue gases or total products of combustion are given in lbs. per hour.

The cooling air is given in lbs. per hour and is the air required to be bled into and mixed with the flue gases before entering the induced draft fan and unlined breeching section.

The fan capacity is given in C.F.M. @ 700° F. which is the anticipated temperature of the air-gas mixture entering the induced draft fan.

The static pressure of the fan is given as the "cold" (70° F.) static pressure and with the installation made at or near sea level. The static pressure at 700° F. is 45% of the "cold" static pressure. Increase the "cold" static pressure 3.5% for every 1000 feet above sea level.

Water sprays or a combination of water and air may be used to cool the flue gases before they enter the fan. The C.F.M. of the fan reduces but the static pressure of the fan increases to overcome the resistance created by the gas washer or scrubber used.

Table 5. I. I. A. Classification of Waste to be Incinerated

TYPE 1 WASTE

Rubbish, consisting of combustible waste such as paper, cartons, rags, wood scraps, sawdust, foliage, and floor sweepings from domestic, commercial, and industrial activities.

This type of waste contains up to 25% moisture, up to 10% incombustible solids, and has a heating value of 6500 B.T.U. per pound as fired.

TYPE 2 WASTE

Refuse, consisting of an approximately even mixture of rubbish and garbage by weight.

This type of waste is common to apartment and residential occupancy, consisting of up to 50% moisture, 7% incombustible solids, and has a heating value of 4300 B.T.U. per pound as fired.

TYPE 3 WASTE

Garbage, consisting of animal and vegetable wastes from restaurants, cafeterias, hotels, hospitals, markets, and like installations.

This type of waste contains up to 70% moisture, up to 5% incombustible solids, and has a heating value of 2500 B.T.U. per pound as fired.

TYPE 4 WASTE

Human and animal remains, consisting of carcasses, organs and solid organic wastes from hospitals, laboratories, abattoirs, animal pounds, and similar sources, consisting of up to 85% moisture, 5% incombustible solids, and having a heating value of 1000 B.T.U. per pound as fired.

TYPE 5 WASTE

By-product waste, gaseous, liquid or semi-liquid, such as tar, paints, solvents, sludge, fumes, etc., from industrial operations. B.T.U. values must be determined by the individual materials to be destroyed.

TYPE 6 WASTE

Solid by-product waste, such as rubber, plastics, woodwaste, etc., from industrial operations. B.T.U. values must be determined by the individual materials to be destroyed.

XI AIR POLLUTION CONTROL

Basically, the incinerator built to either I. I. A. or L. A. design parameters can be operated to function at emissions well below allowable limits. The I. I. A. Standards read, "The incinerators may be manually operated and controlled provided that the user has an operator in attendance a sufficient time during operation to guarantee functioning within the above limits, or in lieu of such an operator, mechanical draft regulation, fly ash collector, gas washer or scrubber, and temperature control shall be provided." Where large incinerators are used (1000 lbs. per hour or over) in a critical area, gas washers serve to reduce dependence on the operator. The concentration of the dust in the flue gas now may not be as important as the total pollutant emitted from the stack.

XII DESIGN VARIATIONS

Cognizance must be taken of studies on incinerator design, operation, and related performance made by the U.S. Public Health Service (see references) which show patterns for air admission, distribution and effects of varying temperatures on gaseous emissions and of unbound moisture on particulate emissions. This data is important to consideration of new parameters.

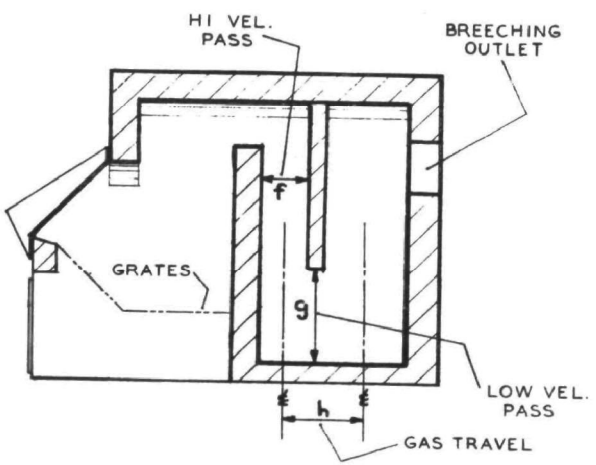
Also, important is to recognize the fact that certain design innovations, if satisfactorily tested, should be acceptable. In fact, we in the industry are very conscious of a great need for improvement and have written a Section 5, DESIGN, into the I. I. A. Standards to accommodate such improvements. By the same token, the I. I. A. Standards are regularly revised and a new issue to be dated April, 1966, will supersede the one used here (April, 1963) although for our purposes of explanation, the old Standards will suffice.

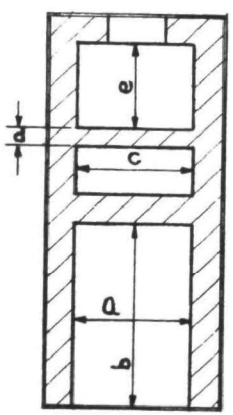
Class III, IV and VI Incinerators with capacities of 100 lbs to 500 lbs per hour must have 4-1/2 inch firebrick lining and a shell of 8 inch common brick casing or #12 ga. steel casing with 2 inch of hi-temp insulating block. Incinerators with capacities over 500 lbs. per hour must have 9 inch firebrick lining with 8 inch common brick casing or #12 ga. steel casing with 2-1/2 inch thick hi-temp insulating block.

INCINERATOR INSTITUTE OF AMERICA

QUICK CHECK CHART

CAPACITY LBS./HR.	TYPE 1 WASTE						TYPE 2 WASTE						TYPE 3 WASTE					
	BURNING RATE #/HR/FT.² GA.	GRATE AREA FT.²	TOTAL INCIN. VOL. FT.³	MIN. AREA IN HI-VEL. PASS FT.²	MIN. AREA IN LOW-VEL PASS FT.²	GAS TRAVEL FT.	BURNING RATE #/HR/FT.² GA.	GRATE AREA FT.²	TOTAL INCIN. VOL. FT.³	MIN. AREA IN HI-VEL. PASS FT.²	MIN. AREA IN LOW-VEL PASS FT.²	GAS TRAVEL FT.	BURNING RATE #/HR/FT.² GA.	GRATE AREA FT.²	TOTAL INCIN. VOL. FT.³	MIN. AREA IN HI VEL PASS FT.²	MIN. AREA IN LOW VEL. PASS FT.²	GAS TRAVEL FT.
100	26	3.85	26	40	1.57	1.25	20	5.00	18	2.86	1.11	1.05	16	6.25	14	.24	.93	.964
200	30	6.67	52	.80	3.13	1.76	23	8.70	36	5.71	2.22	1.48	18	11.11	28	.48	1.87	1.36
300	32	9.38	78	1.21	4.70	2.16	25	12.00	54	8.57	3.33	1.82	20	15.00	42	.72	2.80	1.67
400	34	11.77	104	1.61	6.27	2.50	26	15.38	72	11.43	4.44	2.10	21	19.05	56	.96	3.73	1.93
500	35	14.29	130	2.01	7.83	2.79	27	18.52	90	14.29	5.55	2.35	22	22.73	70	1.20	4.67	2.16
600	36	16.67	156	2.42	9.40	3.06	28	21.43	108	17.16	6.66	2.58	22	27.27	84	1.44	5.60	2.36
700	37	18.92	182	2.82	10.97	3.31	28	25.00	126	20.00	7.77	2.78	23	30.43	98	1.68	6.53	2.55
800	38	21.05	208	3.22	12.53	3.54	29	27.59	144	22.86	8.88	2.97	23	34.78	112	1.92	7.47	2.73
900	38	23.68	234	3.63	14.10	3.75	30	30.00	162	25.71	10.00	3.16	24	37.50	126	2.16	8.40	2.89
1000	39	25.64	260	4.03	15.67	3.95	30	33.33	180	28.57	11.11	3.33	24	41.67	140	2.40	9.33	3.05





PLAN

*GRATE AREA = a x b
MIN. AREA IN HI VEL. PASS = c x f
MIN. AREA IN LOW VEL. PASS = c x g
GAS TRAVEL h = 1/2 f + 1/2 e + d

*MEASURED IN HORIZONTAL PLANE.

BULLETIN D.I.-3
MARCH 1962

FOR

JOSEPH GODER INCINERATORS
4241 NORTH HONORE STREET
CHICAGO 13, ILL.

REFERENCES

1 Rose, A.H. Stenburg, R.L., Corn, M., Horsley, R.R., Allen, D.R., and Kolp, P.W. Air Pollution Effects of Incinerator Firing Practices and Combustion Air Distribution. JAPCA, 8, 297-306. February 1959.

2 Stenburg, R.L., Horsley, R.R., Herrick, R.A., and Rose, A.H. Effects of Fuel Moisture and Incinerator Design on Effluents from Incinerators. Proc. 52nd Annual Meeting APCA, Los Angeles, California. June 1959.

3 Stenburg, R.L., Hangebrauck, R.P., von Lehmden, D.J., and Rose, A.H. Effect of High Volatile Fuel on Incinerator Effluents. JAPCA, 11, 376-83. August 1961.

4 Stenburg, R.L., Hangebrauck, R.P., von Lehmden, D.J., and Rose, A.H. Field Evaluation of Combustion Air Effects on Atmospheric Emissions from Municipal Incinerators. JAPCA 12, 83-89. February 1962.

ADDENDUM: (Note: Enclosed is a Quick Check Chart for incinerator design used by Joseph Goder Incinerators)

The purpose of the following chart is to provide a convenient way of checking our own and our competitors' incinerators when drawings or specifications are available to see if the units meet the I.I.A. Standards. This chart will enable "on-the-spot" check at the architect's or engineer's office. Data not listed on this chart may be determined by interpolation. As a specific example, if capacity is 150 lbs per hour of Type 1 Waste, the burning rate would be determined by adding 26 and 30 in the burning rate column, dividing by two, and coming out with a factor of 28.

BURNING RATE: This is the amount of refuse that can be consumed on each square foot of grate area in each hour. It is figured by dividing the capacity in pounds per hour by the grate area in square feet.

GRATE AREA: As can be seen above, grate area is determined by dividing the capacity by the burning rate and is measured in a horizontal plane as can be seen in the sketch by dimensions (a) and (b). Grate area for Type 1 Waste can include some hearth but must not exceed 20% of total burning area. Hearth area for Type 2 Waste can consist of 50% of the total burning area. When burning Type 3 Waste, the grate area must not exceed 35% of the total burning area. Where step grates are used in lieu of hearth, they shall occupy at least 65% of the burning area surface.

TOTAL INCINERATOR VOLUME: Total interior incinerator volume is exclusive of the volume below the grates or hearth.

MIN. AREA IN HI-VELOCITY PASS: Minimun area in the hi-velocity pass as shown in the sketch is measured in a horizontal plane although this minimum area should be checked throughout the gas travel of the Incinerator as no cross-sectional are inside of the unit through which the gases pass should be less than this area. This minimum area is based on a velocity of 35 feet per second at 1400°F.

GAS TRAVEL: The gas travel is a measure of the distance the gases travel in a horizontal plane in the low-velocity pass and in the case of this sketch, it is the distance between the center line of the two chambers in the secondary combustion chamber of the incinerator. This distance is figured by taking the square root of the minimum area in the low-velocity pass.

Other physical factors must be considered when checking I.I.A. Standards such as wall construction, breeching size and construction, chimney size, and the amount of auxiliary fuel required. The most important construction feature we mention here:

OPERATION PRACTICES FOR I.I.A. INCINERATOR CLASSES IA, IIA, III, IV AND VII

R. Goder*

I INTRODUCTION

The ideal situation is one in which primary chamber is cold and secondary chamber is red-hot. The most practical situation is one in which a waste hopper can be kept filled. If exactly the right amount of air were admitted with no smoking at the doors or air ports, the draft is perfect. I. I. A. Standards require the manufacturer to furnish a name plate showing model, rating and waste type to be incinerated. Also, required is a written operating instruction. Work from this sheet.

II CHARGING

All of the following factors must be considered as related to each other:

A Loading vs Temperature

1 On cold start, feed non-smoky material slowly and increase frequency -- not size -- of charge until secondary chamber brickwork is a cherry red or about 1250°F.

2 Where smoke is a problem, load charging opening to keep it practically blocked with waste.

3 Do not continue charging beyond point at which incinerator brickwork turns light pink or about 1600°F. Oxides of nitrogen seem to form more readily at higher temperatures.

B Mixing Charges

It is often a great advantage to mix slow burning material with flash burning waste. This can be done to achieve more efficient incineration of wet garbage or it can be done to reduce smoke by mixing smoky materials, such as plastics and rubber, with paper waste.

III DRAFT

Control of draft is a relatively critical item in operation. There is no one proper value because the setting depends on the furnace design. An overfire draft setting of approximately 0. 05 inch water column seems to be the most reasonable value if this measurement is taken with incinerator operating at rated capacity and with charging opening closed.

I. I. A. specs require both a positive type damper such as guillotine damper and a barometric damper. The positive damper can be considered as the rough setting and the barometric as the fine setting. The positive damper also should be completely closed when cleaning the incinerator.

Excessive fly-ash is usually the result of too great a draft. Frequently, operators open the damper wide to permit higher burning rate.

IV AIR ADMISSION

Basically, underfire air which is air admitted under the grates causes a flyash problem because of the velocity of the air through the fuel bed. Start with air under the grates almost closed and increase only enough to bring incinerator to rated capacity. L. A. specs detail size of air ports which more or less proportions the air admission.

I. I. A. does not specify air ports and leaves this item to manufacturers' designs since there does not seem to be any well established proportional distribution.

V STOKING

This was somewhat explained under "charging" but it should be noted that ash must be sifted through grates by manipulating moveable grates or stirring fuel bed on stationary grates. The latter creates considerable nuisance.

*President, Joseph Goder Incinerators, Elk Grove Village, Illinois.

Ash removal is frequently neglected and a heavy accumulation of ash on the grates changes the design values radically.

Ash removal in the secondary chamber is even more neglected. It is significant that large quantities of ash do settle in the secondary chamber although only to a certain depth after which the "settling" effect of the chamber is lost.

VI COMBUSTION QUALITY CONTROL

In this group of classifications, at least on incinerators under 1000 pounds per hour, the operator's interest is generally poor. A draft gauge of the direct reading type with a mark on the face showing top limit should be provided as well as a series of observation ports to indicate temperature in the incinerator and to show probable smoke density.

An indicating pyrometer, motorized damper with draft indicator and smoke density indicator would be an effective group of control instruments on incinerators of 500 pounds per hour or over.

VII SECONDARY BURNER

Where the incinerator is equipped with a secondary burner, the procedure would be to switch on the burner at start of firing for about a one hour period and then for about 10 minutes at each charge.

Control by pyrometer is very difficult where firing is not heavy and continuous.

A secondary burner may also be controlled by smoke density indicator if time delay is incorporated in the circuit.

VIII AIR JETS

These are effective where the incinerator is fired heavily with smoky type wastes.

Class IA Incinerators are ordinarily supplied with a complete set of operating instructions by the manufacturer.

Class IIA Incinerators are operated very much in the same manner as outlined here for Class III, IV and VII Incinerators except that all waste should be charged through the intake doors at the several floors in the building and not in the primary chamber stoking or access door.

MUNICIPAL INCINERATORS-DESIGN PARAMETERS

Leonard C. Mandell, P. E. *

I Introduction

This outline is intended to provide an understanding of what municipal incinerator design considerations are, why certain parameters have been devised, and what new parameters appear to be needed. To gain this understanding, let us use the following approach by:

1. Simply stating what municipal incinerators are meant to accomplish.
2. Establishing pertinent design information and parameters to accomplish this intent.
3. Evaluating and appraising just how well the design, under actual operating conditions, meets its intended purpose.
4. Discussing needed improvements in design and/or additional capabilities in order to develop municipal incineration to the state where it becomes an effective, solid-waste disposal method.

II Municipal Refuse vs. The Incineration Process

A. The Refuse

Today's American urban society generates relatively large amounts of solid waste materials. It is estimated that approximately five lbs. of municipal refuse is produced per capita per day. This does not include the thousands of tons generated annually by the many industrial or redevelopment, demolition-type operations, which may actually increase the five lb. per capita rate by 50-100%. The American Public Works Association itemizes and describes these materials shown in Table I. Accordingly, municipal refuse may be defined as "any discarded solid-waste material arising in significant quantities, from the myriad of daily, conventional, human activities occurring within the confines of a municipality."

Table II lists the refuse contents of a typical municipal incinerator as received. The proximate analysis of a mixed refuse may be assumed as:

Volatiles	53%
Fixed Carbon	7
Moisture	20
Ash, metal and glass	20

The heat content for this refuse (1966) may be taken as 5500 Btu/lb. as received. Its stoichiometric-air value is 3.8 lbs. of dry air/lb. of refuse as received.

It is important to note that although many of the small household noncombustibles such as cans, bottles, and ashes are included in refuse charged into the incinerator--they are also discharged without disposal as part of the residue or ash.

B. The Municipal Incineration Process

The municipal incineration process was first attempted in England approximately 90 years ago.

The literal definition of "incinerate" means to burn to ashes. Burning implies fire and heat. Ashes refer to the solid residue after burning of the combustible material is complete. Fire is a manifestation of flame combustion with its generation of voluminous amounts of gases. Hence, incineration (as a perfect process) may be defined as "the conversion of combustible wastes (by flame combustion) to an inert residue and hot oxidized gases." Therefore, municipal incineration implies the application of the incineration process under controlled conditions to convert the municipal refuse to ashes and gases.

add 3

Table I

REFUSE MATERIALS BY TYPE, COMPOSITION, AND SOURCES*

Type	Composition	Sources
Garbage	Wastes from preparation, cooking and serving of food; market wastes; wastes from handling, storage, and sales of produce.	Households, restaurants, institutions, stores, markets.
Rubbish	Combustible: paper, cartons, boxes, barrels, wood, excelsior, tree branches, yard trimmings, wood furniture, bedding, dunnage.	
	Non-combustible: metals, tin cans, metal furniture, dirt, glass, crockery, minerals.	
Ashes	Residue from fires used for cooking and heating and from on-site incineration.	
Street Refuse	Sweepings, dirt, leaves, catch basin dirt, contents of litter receptacles.	Streets, sidewalks, alleys, vacant lots
Dead Animals	Cats, dogs, horses, cows.	
Abandoned Vehicles	Unwanted cars and trucks left on public property.	
Industrial Wastes	Food processing wastes, boiler house cinders, lumber scraps, metal scraps, rubber, plastic, shavings.	Factories, power plants.
Demolition Waste	Lumber, pipes, bricks, masonry, and other construction materials from razed buildings and other structures.	Demolition sites to be used for new building, renewal projects expressways
Construction Wastes	Scrap lumber, pipe, other construction materials.	New construction, remodeling.
Special Wastes	Hazardous solids and liquids: explosives, pathological waste, radioactive material.	Households, hotels, hospitals, institutions, stores, industry.
Sewage Treatment Residue	Solids from course screening and from grit chambers; septic tank sludge.	Sewage treatment plants; septic tanks.

*With permission of Public Administration Service and American Public Works Association.

Table II

COMPOSITION OF A TYPICAL MUNICIPAL REFUSE

		Wt %	HHV[a] Btu/lb MAF Basis[c]	Stoichiometric Air Needed[b] lbs/lb MAF Basis
Corrugated paper boxes		23.4		
Reading papers		19.0	7900	5.9
Brown paper, food-cartons, tissue paper		9.7		
Waxed papers and cartons		1.6		
Vegetable and fruit wastes	Garbage	3.8	7300	5.5
Cooked meat/fat scraps	Garbage	4.6	16,200	12.1
Wood		2.2	8400	6.3
Garden trimmings, leaves, grass		6.7	8600	6.5
Plastics		0.8	15,000-18,000	
Rags		0.8		
Leather goods		0.4		
Rubber composition		0.4	12,500	
Paints and oils		0.8		
Dirt	noncombustible = 16.8%	2.3		
Metals	noncombustible = 16.8%	6.8		
Glass, ash, ceramics	noncombustible = 16.8%	7.7		
Adjusted water		9.0		
		100.0		

(a) High Heating Value

(b) Based on .75 lbs. air/1000 Btu. If assumed as all cellulose, then a stoichiometric value of 5.1 lbs. air/lb cellulose results.

(c) Moisture-Ash Free Basis

It should be noted that approximately 50-100 times (by weight) more gases than ashes are created.

The nature of the man-made combustion-process tends towards inefficient burning with the liberation of smoke soot, fly-ash, complex hydrocarbons in vapor, gas and droplet forms, organic acids and other gaseous sulfur and nitrogen oxides--and a residue which is far from being completely mineral/ash. In fact, today's most advanced thermodynamic technology cannot simultaneously burn more than one of our best-prepared, homogeneous fuels in the same furnace with any degree of satisfactory performance and efficiency.

As you know, much of the municipal refuse is not suitable as incinerator-fuel due to its bulkiness and noncombustible nature (cans, metal-furniture, glass, dirt, ashes, etc.) Further, the make-up of many of the combustible items is extremely variable in size, weight, contamination, protein and organic composition, moisture, heat content, burning characteristics, etc. Hence, this should give us some idea of some of the difficulties to expect from the incineration of municipal refuse.

C. The Intent and the Compromise

It is obvious that an incinerator capable of converting all municipal refuse to an inert ash in an efficient, feasible manner compatible with the public health would be most desirable. The inherent nature of the incineration process vs. the characteristics of municipal refuse, in light of today's technology, indicates that an incinerator should imply the concept of a facility that contains the ability to accomplish this. This does not imply a (one) furnace system which we now have with all of its excessive costs, too much maintenance, and air pollution problems. It does mean an arrangement of several different types of furnaces and incinerators with such pre-treatment and after-treatment as size reduction, separation, particulate arrestance, pollutant gas removal, etc., required to attain the stated objective.

The current practice, which is just starting to change, is to have one furnace design to handle the small combustible and household non combustibles from the general population and the garbage/paper type commercial and industrial wastes. Investigation discloses that this amounts to only 20-25% of the municipal refuse generated.

Hence, by the evolution of events occurring during the past 90 years, the purpose of a municipal incinerator is mass reduction and conversion of small combustible household wastes and commercial/industrial paper/garbage wastes to an inert mineral residue and in the process accept at times small noncombustible refuse; items like cans and bottles in order to provide the small handling and cost savings of a separate pickup.

The compromise is that "this is being done in an efficient, costly manner with the dependence on an ancillary burial site together with the pollution of the immediate atmosphere by 5-10 times (by weight) of refuse burned, and over 50-100 times (by weight) as much pollutants as ashes created." It should be noted that a new trend is just now developing in the United States, and that is to have separate incinerators for specialized applications: e.g. the Dupont type pit incinerator for combustible demolition, skids, debris and industrial wastes; and the Detroit garage-type incinerator for brush, log and tree type wastes. These facilities are being added as separate entities usually on the general incinerator ground-site.

III Design Considerations/Parameters

A. Basic Requisites

Regardless of the incineration capability of the facility, the entire operation from refuse-receiving through ash-disposal must be effected in a safe, sanitary and feasible manner. This means in fact that the public health aspect of air pollution must be sufficiently controlled beyond doubt; also, the reduction/conversion process must be effective and its overall installation and operating cost reasonable. Further, adjacent property should not be damaged from soiling or corrosion nor should their owners suffer from real estate devaluation.

B. Parameters

In general, if you and I were charged with the responsibility of designing an incinerator, we would be concerned with at least the following aspects:

1. Land requirements/area
2. Zoning
3. Roads, access
4. Raw storage/odor control
5. Turning
6. Charging
7. Ignition chamber
8. Secondary/expansion chamber
9. Overfire/underfire air/draft
10. Ash removal
11. Flue gas cleaning
12. I. D. fans
13. Breeching
14. Chimney
15. Auxiliary fuel burners
16. Instrumentation
17. Materials of construction
18. Air Pollution
19. Water wastes
20. Economics

An engineering parameter may be defined as: "a consideration of an independent nature that can be used as a measure of related, dependent variables," i. e., burning rate as a parameter helps to determine the grate area and grate speed within a furnace; chimney draft as a parameter helps to determine the allowable flue-gas velocities, breeching cross-sections, and other flow-energy, absorbing occurrences: Heat release may be equivalent to combustion chamber volume; percentage carbon dioxide as a parameter is equivalent to combustion efficiency; grain loading is equivalent to the effectiveness of air pollution control. For the lecture at hand, the following parameters will be discussed: public health and economics, receiving and storage, charging, burning, draft, ash, and occupational health.

C. Public Health and Economics

Site Selection

Engineering and planning considerations together with public opinion and acceptance dictate the location of a proposed facility. The controlling factors are those of economics and the public health. Economics concern the installation and operating costs, the cost of hauling the refuse, the disposal of the ash, the adaptation of the site such as access roads, water and sewage problems, topography modifications, soil problems, aesthetic treatment, and the loss to neighboring taxpayers from air pollution damage and devaluation to their property. The adverse consequences to the public health of living within an environment that receives literally hundreds of tons of respirable air pollutants daily is not known. However, the inhalation of many metallic particulates is known to have serious respiratory etiology and these pollutants are emitted from municipal incinerators. The psychosomatic and psychological effects of mental unhappiness are also associated with such pollutants as objectionable and nuisance odors or the obscuring of the sunlight by light-scattering plumes. The synergistic action of low concentrations, especially on the aged, the allergenic and the ill, is not known.

No hard and fast rule has been set for land area requirements. However, a typical plant may use between 100-500 square feet or more per nominal ton of rating.

D. Refuse Generation

Custom has evolved the measure of "tons per day" to express the size of a municipal incinerator plant. This refers to the design burning rate in short tons per 24 hours. A 150 ton furnace has an hourly design burning rate of 12,500 lbs. of refuse per hour. The size of a plant should be based on a valid appraisal of the anticipated load that will result from the population and the expected commercial and industrial refuse forecast for 25 years in the future. Once this load rate is established, the incinerator may be sized. The designer together with responsible members of the community have the choice of setting up work schedules that usually vary from 8-10 hour shifts. Present day design is based on the value of 4.5 lbs./capita/day of refuse being received for municipal incineration. Hence, a city with a population of 200,000 would plan for a 450 ton/day plant. Reflection will indicate that three 150-ton/day furnaces will afford the important advantages of flexibility in operation, cost savings in maintenance and continued operation in the event of furnace failure or needed repairs. It should be noted that as of 1967, the size of municipal incinerators ranged between 50-1200 tons/day and furnace sizes ranged from 30-400 tons/day.

E. Receiving and Storage

1. Scale

Efficient incinerator operation requires the maintenance of accurate records which include the quantity and types of refuse to be burned. Upon arrival at the facility, all trucks should be weighed to obtain the net weight of the refuse. At that time, the type of refuse, its source, the truck identification, date and hour should be noted. A typical scale manufactured by Fairbanks Morse prints and indicates the net weight, date and hour. A typical scale has a dual range of up to 30,000 and 60,000 lbs., and should be located near the main building adjacent to the tipping floor area.

2. Tipping Floor

All refuse received at the plant is dumped into storage pits prior to being fed into the furnace. The approach area or apron where the packers and trucks tip their bodies for dumping is called the tipping floor. The floor should extend along the entire pit so that several trucks can unload at the same time. The floors should be made of dense, reinforced concrete with ample drainage. See Photo 1.

PHOTO 1

3. Storage Prior to Burning

The nature of combustible municipal refuse requires dense, reinforced concrete for rodent and ground water protection. Good drainage and provisions for extinguishing pit fires are also needed. Present design calls for 1-2 days of storage as related to the plant design capacity. Refuse as received varies between 300-700 lbs./cubic yard with an average of approximately 450 lbs./cubic yard (17 lbs./cubic foot for wrapped household garbage). Hence, the 450 ton plant would have a storage (360 lbs./cubic yard for combined refuse) pit volume between 1000-2000 cubic yards (27,000-54,000 cubic feet). Odor and decay will occur in the pit if the refuse is held too long (over 3 days)--especially in warm weather. Exhaust ventilation with activated carbon treatment will control these odors from an air pollution control standpoint. See Photo 2.

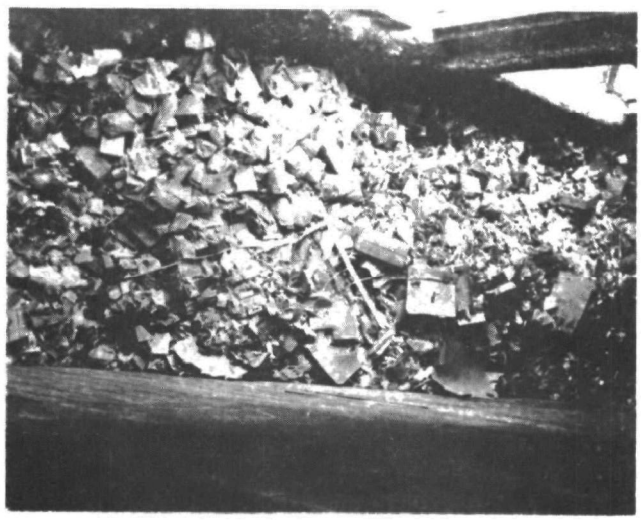


PHOTO 2

F. Charging

The introduction of the refuse into the furnace ignition area will influence the burn-out efficiency and the amount of suspended solids entrained with the moving flue gases.

Direct, periodic "drops" from overhead hoppers via electric or hydraulic or pneumatic charging gates have been common for the smaller size furnaces (100 tons/day). Continuous feed via an

inclined transfer-grate provides pre-drying, better combustion, and less air pollutants. The refuse is conveyed from the storage pits to the charging hoppers by overhead cranes which use clam buckets and/or grapplings.

Sizes vary from 1-4 yards/grab. Bridge cranes are best and standard usage is one for every 500 ton/day rating. Popular grapple sizes vary between 1 1/2 and 2 1/2 cubic yards. The maximum size is approximately 5 cubic yards.

G. The Burning

Burning of the refuse begins in the ignition zone of the primary combustion chamber. Today's drier material burns faster and with greater heat release. Hence, most of the entire combustion occurs in the primary chamber with final oxidation of the carbonaceous particulates and entrained-fly occurring in the secondary chamber.

1. The Furnace

The furnace normally refers to the enclosed refractory-lined chamber which includes the transfer grate, the hearth, the main grate, and the ash drop area. At present, there are three different types of furnace designs: (a) the cylindrical batch feed, (b) the unit cell batch type, and (c) the continuous feed/mechanical grate furnace. (Note: Batch feed furnaces are limited to the size of 250 ton/day. The larger modern incinerators are using the continuous mechanical grate that employs either some type of rocking, oscillating, or reciprocating mechanism or the travelling type grate that moves the burning, agitated refuse along at a controllable rate to the ash-drop location.)

Operating temperatures (which are proportional to the completeness of combustion and percent excess-air admitted) range from 1000 - 2000°F., with 1600 - 1700°F. as the preferred set-point. The maximum desirable is 2000°F. because of refractory deterioration and inability to withstand ash fusion effects related to the mineral components (clay from papers) of the refuse. See Photo 2A. (Note: Water-cooled metal walls lower the normal 150-300% excess air requirements down to 50-60%.)

PHOTO 3

A few comments on refractories are in order: Refractories are calcium aluminate type, fireclays in the forms of brick, plastic, and castables. Important properties are Pyrometric Cone Equivalent (PCE), spalling, thermal expansion, and porosity. Super duty clays have PCE of approximately 34, while silicone carbide has the best slag resistance. This is one of the real problems in refractory maintenance because of the cost of refractory replacement caused by the accumulation of slag. Slag adheres tenaciously, damages the refractory and obstructs flue-gas passages.

The furnace dimensions are sized according to two parameters: (a) the grate-loading or burning-rate and (b) the heat-release volume. Mixed refuse of garbage, rubbish, and non-combustibles burns at a rate of 75 lbs. per hour per square foot of grate for continuous feed, and 110 lbs. per hour per square foot for batch feed. Combustible rubbish alone has a design rating of 50 lbs. per hour per square foot for continuous feed, and 35.1lbs. per hour per square foot for batch feed. As a rule, in the newer furnaces, a burning rate of 300,000 Btu per hour per square foot of grate area for continuous feed, and 400,000 Btu per hour per square foot for batch feed, and 20,000 Btu per cubic foot heat release are followed. It should be noted that residence time is proportional to the furnace size and gas velocity through the furnace. It should be noted also that the trend is for combined ignition and primary chambers with 35-40 cubic feet of total volume per ton refuse burned.

2. The Secondary Combustion Chamber

The purpose of this chamber volume is to provide the additional time, temperature, and turbulence and oxygen to complete the combustion of the organic portion of the refuse. It should be noted that a small amount of solid deposition of inorganic material also occurs in the chamber because gas velocities are normally sized for under 2000 feet per minute at 1800°F.

Such items as air jets, bridge wall, and curtain wall may be part of this chamber. Their purpose is to alter the direction of the flue gases for better mixing and turbulence, also baffle impingement and settling of the large fly-ash. The leaving-end of the chamber usually leads to some type of suspended, solid-arrestance assembly.

H. Suspended Particulate Arresters

This is one area of municipal incinerator design that did not receive its share of importance until the early 1960's. The increase in the number of incinerators and the growing apprehension of chronic illness associated with air pollution have brought this about. The earlier designs, say until 1960, used little or nothing in the way of air pollution control equipment. The accepted device which in fact had little or no merit was the settling or subsidence chamber (velocities under 600 feet per minute could be maintained) which removed no more than 5 percent of the significant particulate pollutants. The next so-called improvement consisted of water-spray nozzles which removed about twice the pollutants, but unfortunately added a large quantity of water vapor to the flue gas. In the writer's opinion, this could at times be worse than if not used at all, because of the wetting of the fine solid aerosols. Their presence could be corrosive and injurious to health and property. In 1964, the wetted-baffle impinger displayed the first significant improvement. It removed approximately 50 percent of the significant suspended matter. Recently, the smaller diameter multiclone collectors (12-18") have shown promise with collection efficiencies approaching 80 percent. As far as the United States is concerned, this is the situation at present. The most popular fly-ash control methods in the United States now, are water sprays with wet bottom and baffles. Electrolectic precipitators used in Europe are now being evaluated and are expected to provide arrestance in excess of a 95% level.

I. Draft

1. Breeching

All connecting flue gas conduit between the exit of the incinerator proper and the inlet to the chimney can be called the breeching. This flue or duct is refractory-lined for protection of the metal shell. Duct velocities rarely exceed 3000 feet per minute. Good design is 2000 feet per minute. It is controlled by available draft -- either natural or induced.

2. Dampers

The inherent variability of the refuse and the thermodynamic characteristics of the burning process require some control of air movement into the furnace. The rate and path of flue-gas travel through and out of the incinerator is also important. Refractory-lined or water-cooled type dampers are used. As a rule, a draft over the fire of 0.06 "W.C. $\pm$ .02" will be adequate.

3. I.D. Fans

In systems where the overall pressure loss/energy requirements are greater than those attainable with conventional chimney draft, induced draft fans are used. They may be driven by electric motors or steam turbines. See Photo 3.

4. Chimneys

Besides creating the driving force to overcome draft and flue-gas flow requirements, chimneys provide an excellent mechanism for high altitude dispersion of incinerator emissions.

Chimneys are double-wall units with an interior refractory heat-resistant lining and exterior shell of wedge-shaped (radial) brickwork or carbon steel plate; when chimney heights exceed 200 feet and inside diameters

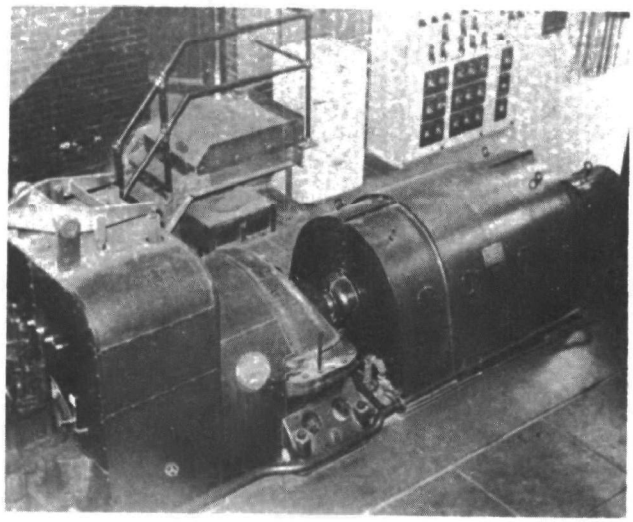


PHOTO 4

approach 8-9 feet, then reinforced concrete shells become feasible. They provide excellent structural strength but suffer from thermal and plastic stress cracking.

An important consideration in chimney work is the heavy bearing imposed on the soil from static and wind forces. Another important consideration is the cost of chimneys. They are expensive... about 7% of the total incinerator cost.

Every chimney requires certain accessories such as lightning protection, aircraft lighting, test openings, clean-out doors, ladders, catwalks, and caps. Test openings are important. They should be 6 inch diameter pipes which extend through both interior lining and exterior shell. At least two ports, set at 90^{o} of each other, are normally sufficient.

J. Ash Handling

From 5-25 percent of the refuse charged into the incinerator emerges as ash (not counting its wet weight). It consists of unburned material, ashes, cans, bottles, and other noncombustibles (average wet weight of 100 lbs. / ft^3). Ash must be removed from the grates and furnace-proper at a required rate. It is usually water-quenched to eliminate fires, smoke and odors, and most important, it requires burial at a suitable disposal site, since it may contain a significant amount of organic material.

The preferred quenching method employs the water trough with an endless drag-type chain conveyor that scrapes the ash up into an overhead hopper for unloading into a truck.

K. Occupational Health

Ventilation should be incorporated for odor and dust control in the storage pit and charging area and the operating floor for ambient space control of heat and smoke. Some of the pit exhaust can be used for combustion air. The balance can be filtered and adsorbed or oxidized for odor control. The exhaust air from the operating floor can be discharged to the atmosphere without any treatment.

Apart from the conventional considerations of natural ventilation, lighting, and sanitary facilities and those of accident prevention from ladders, catwalks, etc., due consideration should be given to the fire and explosive nature of certain dangerous materials: solvents, finely divided organic dusts and sealed aerosol containers which explode with sufficient pressure to cause serious personal injury and equipment damage.

L. Air Pollution Considerations

Evidence is accumulating from biostatistical and epidemiologic experiences, and from acute episodes and laboratory experiments to show that meaningful relationships exist be-

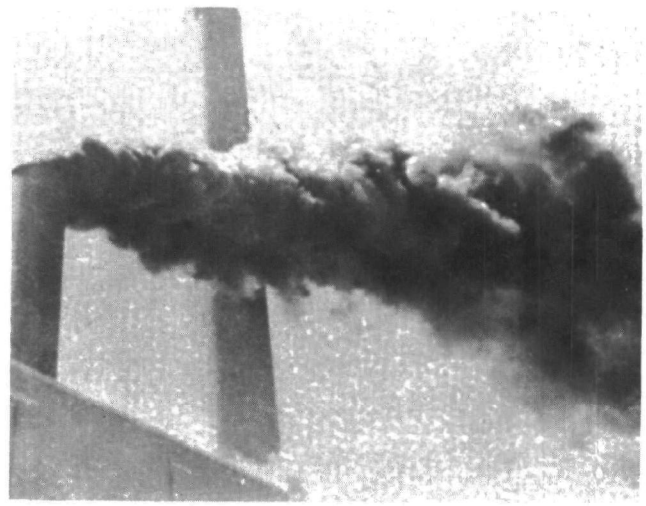


PHOTO 5

tween air pollution and respiratory illness, and that at the present time, adequate health standards do not exist. Hence, it appears prudent as a precautionary measure to use the best feasible control methods to reduce suscepitble pollutants. See Photo 4.

When it is realized (1) that 80-85% of all refuse charged into the incinerator is discharged as the conventional flue-gas of carbon dioxide, carbon monoxide, water vapor, sulfur oxides, and nitrogen oxides, and (2) that a myriad of other gases and fumes such as hydrogen chloride, hydrocarbons, tin, zinc, iron, chromium, vanadium, and many other metallic oxides as well as smoke accompany these discharges, (3) that a conventional size municipal incinerator (480 ton/day, servicing about 250,000 population) releases approximately 300,000 lbs. (4,000,000 standard cubic feet) of these flue-gases/hour, and (4) that normal atmospheric diffusion and turbulence will pollute at least 10-100 times this space, it indicates that a hard look, one free of apathy or prejudice, must be taken of the air pollution aspects.

IV. On Meeting the Needs

A. In General

Present municipal incinerator design does not adequately fulfill the needs of today's densely populated, waste-generating urban society. As stated previously, current equipment converts and reduces only approximately 20-25% of the total solid waste-generation rate, and it does this at an excessive cost. The urban incinera - tion operation is contributing significantly to the endemicity of chronic respiratory illness. It also acts as a retardant to the promotion of the well-being and public health of the community in which it is located.

B. Accomplishments

As expensive and as inefficient as it is, current municipal incinerator design does at least handle the current pressure of size-reduction and conversion of decomposable organic material in highly populated areas.

1. It reduces the bulk volume of raw municipal refuse by approximately 80-90%.

2. It reduces the weight of raw refuse by 75-90%.

3. It provides the greatest volumetric reduction of the available reduction methods.

4. Provides the most rapid conversion (within minutes) of combustible cellulose, animal, and hydrocarbon materials to reasonable mineral residue.

5. Provides sufficient mass-reduction within the ability of urban areas to dispose of the incinerator residue so that it has become the method of choice of most cities where air pollution has not become critical.

C. Deficiencies

1. A relatively inefficient combustion process with approximately 10-25% of original weight requiring subsequent land disposal, so that additional land area is needed.

2. Emits to the atmosphere 50-100 times as much polluted gases as refuse incinerated and 50-100 times as much flue gases as ashes, thereby constituting, in the writer's opinion, a significant air-pollution source.

3. The most expensive "so-called disposal method" costing $6000 to $8000 per ton of rating to build, and approximately $5.00 to $6.00 per ton for operation and maintenance as compared to sanitary land fill at $1.50 to $2.50 per ton for disposal.

4. Requires an undue amount of operational control, instrumentation, and maintenance.

V. Improvements Needed to Make Municipal Incineration a True Solid Waste Disposal Method

A. Relative to Combustion Process

1. Better fuel, more homogenous, perhaps requiring sorting or removal of bottles, cans, dirt, ashes; size reduction; continual turning and mixing, etc.

2. Better control of thermodynamic conditions within the furnace such as fuel/air contact, turbulence, and ambient temperature over the fire.

3. Better automatic control via instrumentation for primary and secondary air quantities, injection targets, and grate speeds.

4. More consistent and better burn-out to obtain efficiencies close to expected mineral content regardless of refuse composition in order to reduce loading, hauling,and burial requirements.

5. Better burn-out of airborne combustibles prior to leaving the secondary chamber.

B. Air Pollution

1. Much less particulate emissions into the atmosphere by the installation of reasonable maintenance-requiring equipment for removal of particulates down to the 0.1 micron size.

2. Continual quantitative monitoring of particulate concentration, size, and identification.

3. Meteorological interlock for operation and degree of control required.

4. The gaseous emission should be known, i.e., types and concentrations, and correlated into the community inventory to insure safety for public health respiration.

5. The particulate emission content should be known, especially for such toxic metals as lead, chromium, etc.

C. Relative to Special Wastes

Special incinerator furnaces and appurtenances and controls with adequate knowledge of pollutant effects for intractable wastes from industry and demolition operations.

D. Relative to Economics

1. The first cost of a municipal incinerator is too high. It should be reduced, perhaps by simplifying the physical plant of building and appurtenances.

2. Also, repairs and maintenance are too high, especially in regard to the refractory aspect and other high temperature materials of construction, etc.

Hence, considerably more research and design is needed to have municipal incineration fulfill the purpose and performance required as a preferred refuse disposal method even for the year of 1980, let alone the 21st century.

DESIGN PARAMETERS FOR MUNICIPAL INCINERATORS

Herbert C. Johnson*

I INTRODUCTION

There are no nationally recognized design standards for municipal incinerators. Much has been published but only a few authors have presented useable information on design. By digesting most available information it can be concluded that three basic designs are presented. These can be divided as single chamber, multiple chamber, and combination designs.

Design parameters applicable to each of these three designs will be covered after discussing air pollution requirements, methods of charging municipal incinerators, drying the refuse, and the effects of air distribution. Miscellaneous design parameters will be briefed, followed by a closure on considerations to minimize air pollution.

II PRINCIPLE OBJECTIVES OF MUNICIPAL INCINERATORS

Any attempt to evaluate existing design standards or to develop new standards should be based on a thorough understanding of all the objectives to be achieved. Basically municipal incinerators have just one justification to dispose of refuse at the lowest cost in a manner satisfactory to the community and to any surrounding communities. If other satisfactory disposal methods can be found that will show a lower total cost during the period of time being planned for, the alternative disposal method should be selected.

Community satisfaction normally infers that the appearance is not objectionable and air pollution standards are complied with. Since a municipal incinerator is expected to operate at least 20 to 25 years, consideration should be given to probable future regulations as well as existing air pollution emission allowances.

Future air Pollution requirements can be expected to include:

A Visible Plume

Present - #2 Ringelmann maximum allowable in most areas.

Future -

1 Dark smoke - #1 Ringelmann maximum

2 Equivalent opacity (light colored plume) equivalent to #2 Ringelmann maximum or less than #2 Ringelmann number.

B Fallout - No detectable fly ash fallout permitted now or in the future.

C Particulate

Present - 0.85 lb/1000 lb. gas at 12% CO_2 or 50% excess air in most areas, some have reduced to 0.6 or less.

Future - 0.5 lb/1000 lb. or less.

D Gases - Not controlled at present in most areas.

Future - Organic compounds restricted to on the order of 100 PPM total carbon.

Carbon Monoxide - No limits at present.

Future - Restricted to 50 to 200 PPM.

Oxides of Nitrogen - Not controlled at present. No controls likely in the foreseeable future.

III THE EFFECT OF DESIGN PARAMETERS ON EMISSIONS

At the risk of some emissions and simplifications known design parameters and their effects on the types of emissions outlined are as follows:

*Senior Air Pollution Engineer, Bay Area Air Pollution Control District, San Francisco, California, (prepared February, 1966).

A Dark Smoke - Primarily consists of small carbon particles caused by incomplete combustion; however, material causing light colored plumes may be masked by dark smoke.

General agreement that adequate time, temperature, turbulence, and oxygen should eliminate dark smoke.

B Fallout of Fly Ash

Large particles of fly ash usually are of two types: (1) charred material (2) ash particles containing essentially no combustible. Charred material should not escape if the three T's are adequate. Some ash particles, because of their low density, will become airborne. Gas washers or mechanical collectors of adequate efficiency will remove most ash that might be noticeable downwind, as well as any charred material not completely burned. Efficiency of settling chambers is very low.

Particulate is generally defined as solid material suspended in the flue gases. Quantity of particulate is in terms of weight per unit volume or weight of flue gases. Correction factors are normally applied to provide equal requirements regardless of excess air.

If complete combustion is achieved, the particulate emitted will consist of non-combustible material in the refuse. Part of it may be simply blown from the fuel bed, but a portion will be due to chemical reactions in the fuel bed. When formed by chemical reactions, the particle size will be small, from sub-micron to 1 - 10 micron in size.

Much of the weight of particulate is greater than 5 micron size, several types of collecting devices will remove a substantial percentage of large particles. Application of collection equipment to incinerators requires a knowledge of the problems. The hot gases must be cooled, corrosion and erosion taken into consideration. Adequate draft must be provided.

The quantity of particulate emission can be substantially reduced by the design of the incinerator, according to theory published by the Los Angeles County Air Pollution Control District and test data corroborating their theory.

C Opacity

A light colored plume is discharged from most municipal incinerators. Air pollution regulations of most large communities now limit opacity since such emissions contribute to reduced visibility. Los Angeles County APCD engineers concluded that this plume was caused by volatilization and/or other chemical reactions in the fuel bed. Their analysis showed appreciable quantities of metallic salts and oxides in microcrystalline form in the stack effluent, which must have condensed after volatilization in the fuel bed. Removal of these very small particles from the flue gases would be expensive; it has not been accomplished on a full-scale municipal incinerator in this country. However, substantial reduction of opacity has been accomplished by designs developed by engineers of the Los Angeles APCD.

D Gases

Organic compounds and carbon monoxide should be found only in very low concentrations in municipal incinerator effluent if the three T's and 0_2 are adequate.

IV WASTE CHARGING METHODS

A Continuous

B Batch

C Repetitive

A Continuous charging is normally by means of a chute feeding refuse onto a mechanical grate or the refuse may be pushed onto the grate by a hydraulic charger. The crane operator's instructions are to keep the chute filled with refuse to

provide more even temperatures and better control of excess air than other charging methods.

B Batch charging is defined as loading an incinerator with a large quantity of refuse at infrequent intervals, such as once per hour or half hour.

Each batch is allowed to burn down until just prior to the next charging, at which time all or part of the ash and remaining refuse is dumped into the ash pit. A variation is to dump into the ash pit less frequently, each new charge is dropped on top of the remaining burning refuse.

The results achieved depend heavily on the operators since the sequence of events can be selected as they see fit. Periods of overfiring can result in excessive maintenance and emission of air contaminants. Large quantities of cold air enter the charging door during the charging period.

C Repetitive charging is intended to provide relatively small charges at frequent intervals. If continuous operating mechanical grates are provided, each charge of refuse can be placed on a bare grate area rather than on top of previous charges. Controls can be provided to open and close the charging door quickly and to limit the charging rate; lack of such controls allow overcharging. Some types of inclined grates which do not operate continuously allow operators to adopt batch charging, destroying the advantages of repetitive charging.

V WASTE DRYING ZONE

Early incinerators needed some form of drying before the wet garbage could be burned. Drying was done in several ways, such as water tube grates to suspend the wet material above a fire on a stationary grate below. Preheated air was used in some installations. Flame and heat gases from dried refuse burning near the discharge end of mechanical grates were returned above the wet fresh charge for drying.

Today's refuse in this country averages only 5 - 10% garbage, 30 to 40% total moisture. Violent burning of dry material almost immediately after charging may indicate the need for a controlled ignition zone. The counterflow principle has been largely replaced with parallel flow, which can be utilized to provide flame and hot gases above the rear grate sections where garbage and other hard-to-burn material is aided in final burn-out.

VI PRIMARY COMBUSTION ZONE

Variations in design make definitions by zones difficult. Some present day municipal incinerators contain only one chamber in which all phases of combustion take place. Regardless of design volatiles are driven off rapidly in the first one-third to two-thirds of the grate in rectangular furnaces. Fixed carbon begins to burn almost immediately, completes burning on rear sections of the grate, or falls into the ash pit unburned.

VII INFLUENCE OF WASTE COMPOSITION ON INCINERATOR DESIGN

The effect of the low moisture content of today's refuse has been pointed out. Grates 30 to 40 feet long should allow practically all fixed carbon, in most types of refuse, to burn.

Exceptions may be large dense material such as timber or logs which may only partially burn during the time available on the grate.

The effects of non-combustible material are significant. Dust and dirt will increase particulate emission. The volatilization of metallic salts, etc., as previously described, cause a light colored plume and are believed to be responsible for slag formation which damages refractory.

Metals, such as tin cans, apparently cause no significant trouble. Bolts, screws, nails, etc. can damage some types of grates. Large pieces of metal can damage ash conveyors. High fuel bed temperatures can

melt glass, no difficulties have been reported on mechanical grates. Glass has been observed running through the stationary grate of a large single chamber incinerator.

Most plastics burn satisfactorily but fillers of clay, etc. undoubtedly increase particulate and may, along with chlorides, contribute to opacity.

Undoubtedly, there is a great deal known about the effects of various mixtures of materials which have not been reported and more will be learned if particulate emissions and effluent gases are analyzed.

VIII AIR SUPPLY

Probably the most important difference in design parameters is the location and quantity of air supplied in the first chamber because:

A Burning rates are effected by air supply.

B Combustion rates in various portions of the first chamber, as well as the need for additional chambers, are effected by air distribution and turbulence provided in the first chamber.

C The biggest factor effecting emissions is air distribution and turbulence.

D Arch height and volume of the first chamber are related rather directly to air distribution.

Keeping in mind that air distribution and turbulence are the key factors in incinerator design, the parameters developed to fit the different theories advanced can be explained as follows:

1 Single chamber theory

It has been proven that practically all of the combustibles can be burned in one large chamber if continuous or repetitive charging is provided at the proper rates. Parameters found in the literature[8] are:

a At least 50% of the total air is supplied as underfire air (through the grates).

b Overfire air is supplied under pressure through jets just above the fuel bed.

c Burning rates per square foot of grate of 60 or more $lb/ft^2/hr$ are achieved.

d A high arch provides a large combustion volume, allowing sufficient residence time to theoretically complete combustion. The parameter used is heat release ($Btu/ft^3/hr$). The heat release suggested should not exceed 20,000 $Btu/ft^3/hr$, arch heights are 12 to 18 feet.

e Mechanical grates 30 to 40 feet long are suggested to obtain effective burn out. Grate width is varied to provide desired capacity.

f Since particulate emission is very high with this type of combustion, settling chambers, mechanical collectors, or scrubbers are suggested.

A recent paper[9] recommends this type of incinerator with a completely water cooled interior, plus additional heat exchange surface to lower exit temperature sufficiently to allow installation of a high efficiency collecting device. Refractory maintenance is eliminated, excess air is greatly reduced, and large quantities of steam are generated.

2 Multiple chamber theory*

Both small and large incinerators designed to published standards[2, 3, 5] have demonstrated low emissions of particulate, and material causing opacity. The parameters of this design are:

*See Table I and Figure 1 for multiple-chamber retort incinerator and Figure 2 for multiple-chamber In-Line incinerator.

a Only 10 to 20% of the total air is supplied as underfire air.

b Sixty to seventy percent is supplied as overfire air (through ports), 10 to 20% as secondary air in the second chamber.

c Burning rates per ft^2 of grate is limited to 40 to 45 $lb/ft^2/hr$ for municipal size incinerators.

d Arch height is determined by a formula developed by the authors[5] based on test data, etc. However, a maximum average arch height of 8 feet has been recommended regardless of chamber size. Heat release is not specified, but if calculated would be 20,000 $Btu/ft^3/hr$ in the first chamber of municipal size incinerators to under 15,000 $Btu/ft^3/hr$ if all combustion volume is considered.

e A length/width ratio is developed for grates, which does not appear to be applicable to municipal incinerators. In private conversations the authors have recommended that length be limited to prevent excessive horizontal velocity in the first chamber. The width is selected to provide the grate area required.

f Two secondary chambers are included in this design. Sizing of these chambers is by velocities as shown in Table I.

g A gas washer was used to reduce particulate on the one municipal incinerator designed close to these standards. An induced draft fan produced the required draft.

3 Combination designs with rectangular furnaces

Many municipal incinerators have been designed in recent years that provide more than one combustion chamber but do not conform to the multiple chamber design standards previously cited.[2] While these units differ considerably, the parameters used generally are:

a High air flow through grates, usually 50 to 80% of total air.

b Secondary air usually thru ports, some jets may be included. Locations vary with designer.

c Burning rates of 50 to 70 lb/ft^2 of grate has become practically standard.

d Arch height varies with designer, usually 10 to 15 ft., which fixes first chamber volume.

e Length/width ratio of grates varies. The trend is to longer mechanical grates which operate continuously.

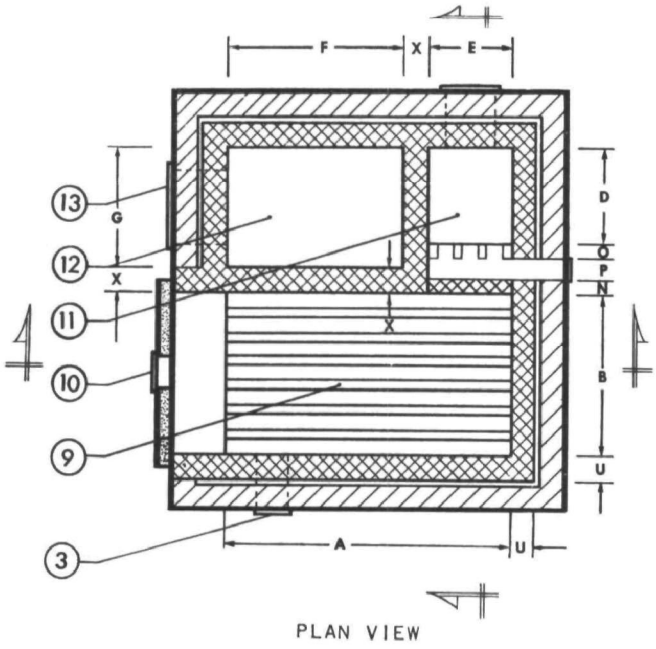
f Secondary chamber designs vary. A simple design consists of one chamber with a gas washer built into the exit end. More complex are those including two combustion chambers, a subsidence or settling chamber, often followed by spray chambers, gas washers or scrubbers.

g Tall stacks are required in some communities, others allow use of induced draft and short stacks.

IX MISCELLANEOUS DESIGN PARAMETERS

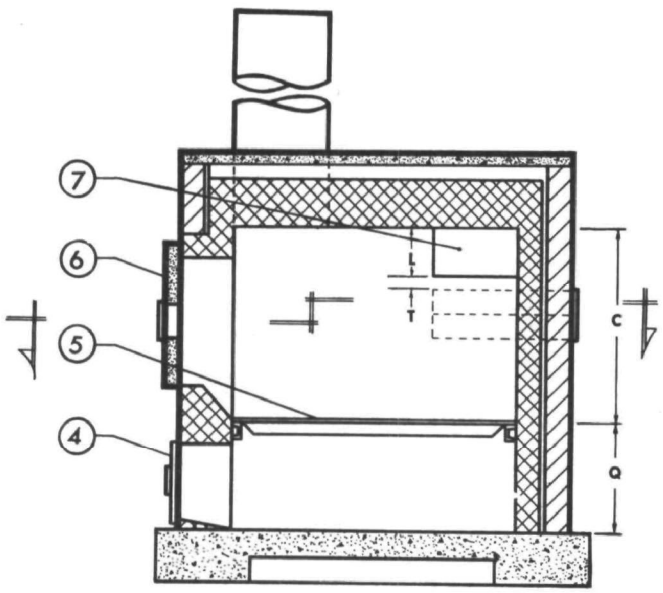
A Auxiliary Fuel Burners

These burners have seldom been included on municipal incinerators since continuous or repetitive charging of today's

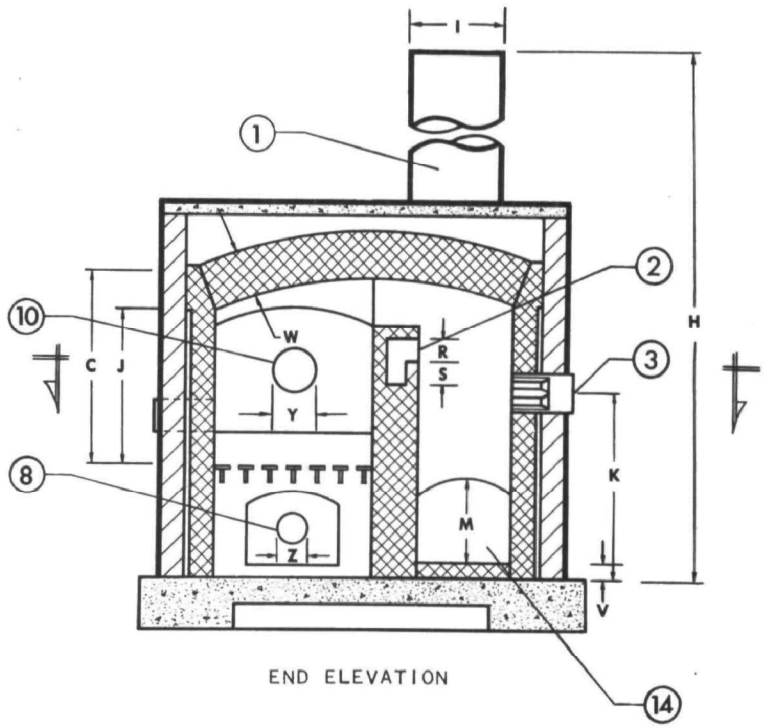


PLAN VIEW

1. STACK
2. SECONDARY AIR PORT
3. GAS BURNERS
4. ASH PIT CLEANOUT DOOR
5. GRATES
6. CHARGING DOOR
7. FLAME PORT
8. UNDERFIRE AIR PORT
9. IGNITION CHAMBER
10. OVERFIRE AIR PORT
11. MIXING CHAMBER
12. COMBUSTION CHAMBER
13. CLEANOUT DOOR
14. CURTAIN WALL PORT



SIDE ELEVATION

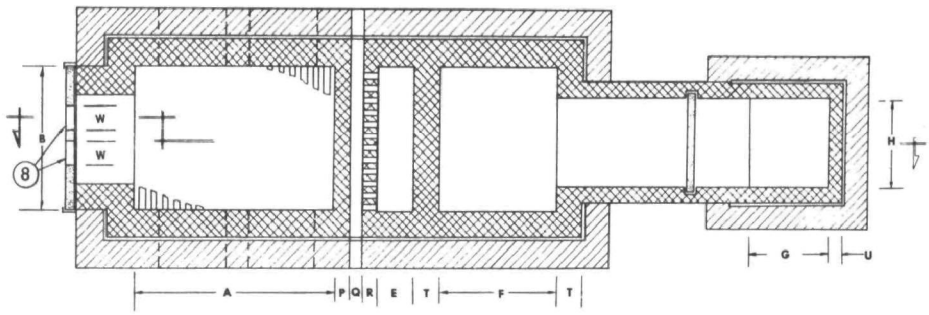


END ELEVATION

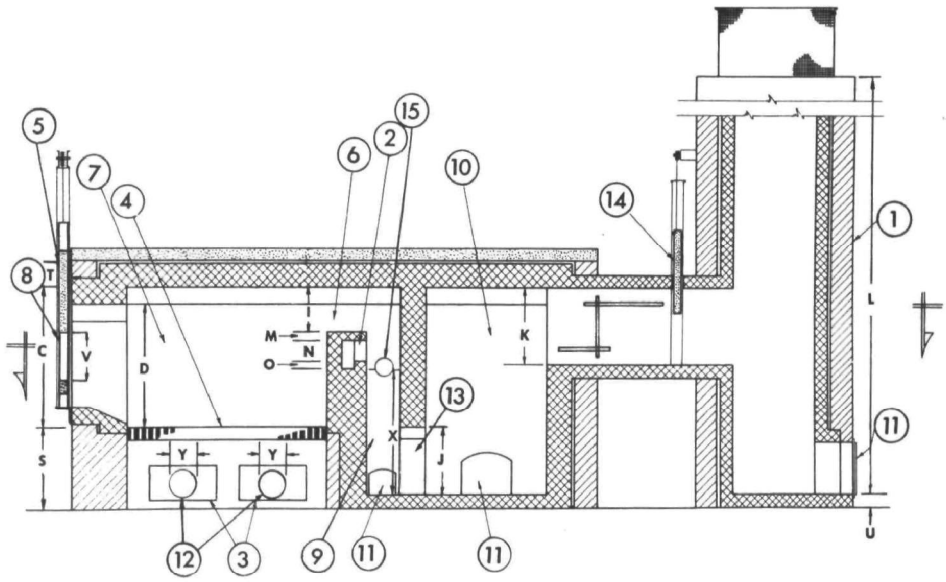
SIZE OF INCINERATOR POUNDS PER HOUR	LENGTH IN INCHES																									
	A	B	C	D	E	F	G	H*	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
50	31½	13½	22½	9	6¾	20¼	13½	18	8	18½	20	3¾	10	4½	2¼	2¼	9	2½	2½	2½	4½	2½	4½	4½	6	4
100	40½	18	28½	13½	9	27	18	19	12	23	28	5	15	2½	2½	4	14½	5	0	2½	4½	2½	4½	4½	8	5
150	45	22½	33½	15½	11½	29	22½	20	14	27	35½	5	16½	4½	2½	4½	18	5	2½	2½	4½	2½	4½	4½	9	6
250	54	27	37½	18	13½	36	27	22	18	30	40	7½	18	4½	4½	4½	20	5	2½	2½	4½	2½	4½	4½	12	6
500	76½	36	47½	27	18	49½	36	28	24	36½	48½	12½	23	9	4½	4½	26	5	5	2½	9	4½	9	9	16	8
750	85½	49½	54	36	22½	54	45	32	30	40	51½	15	28	9	4½	4½	25	5	10	2½	9	4½	9	9	18	8
1000	94½	54	59½	36	27	58½	45	35	34	45	54½	17½	30	9	4½	4½	27½	7½	12½	2½	9	4½	9	9	22	10

*Dimension "H" given in feet.

FIGURE 5. DESIGN STANDARDS FOR MULTIPLE-CHAMBER RETORT INCINERATORS



PLAN VIEW



SIDE ELEVATION

1. STACK	6. FLAME PORT	11. CLEANOUT DOORS
2. SECONDARY AIR PORTS	7. IGNITION CHAMBER	12. UNDERFIRE AIR PORTS
3. ASH PIT CLEANOUT DOORS	8. OVERFIRE AIR PORTS	13. CURTAIN WALL PORT
4. GRATES	9. MIXING CHAMBER	14. DAMPER
5. CHARGING DOOR	10. COMBUSTION CHAMBER	15. GAS BURNERS

SIZE OF INCINERATOR POUNDS PER HOUR	LENGTH IN INCHES																								
	A	B	C	D	E	F	G	H	I	J	K	L*	M	N	O	P	Q	R	S	T	U	V	W	X	Y
750	85½	49½	51½	45	15⅜	54	27	27	9½	24	18	32	4½	5	7½	9	2½	2½	30	9	4½	5	11	51	7
1000	94½	54	54	47½	18	63	31½	31½	11	29	22½	35	4½	5	10	9	2½	2½	30	9	4½	7	12	52	8
1500	99	76½	65	55	18	72	36	36	12½	32	27	38	4½	5	7½	9	4½	4½	30	9	4½	8	14	61½	9
2000	108	90	69½	57½	22½	79½	40½	40½	15	36	31½	40	4½	5	10	9	4½	4½	30	9	4½	9	15	63½	10

*Dimension "L" given in feet.

FIGURE 6. DESIGN STANDSRDS FOR MULTIPLE-CHAMBER IN-LINE INCINERATORS

TABLE I

MULTIPLE-CHAMBER INCINERATOR DESIGN FACTORS

ITEM AND SYMBOL	RECOMMENDED VALUE	ALLOWABLE DEVIATION
A. Primary Combustion Zone:		
1. Grate loading, L_G	10 Log R_c; lbs/hr-ft^2 where R_c equals the refuse combustion rate in lbs/hr (refer to Fig.3)	± 10%
2. Grate area, A_G	$R_c \div L_G$; ft^2	± 10%
3. Average arch height, H_A	$4/3(AG)^{4/11}$; ft(refer to Fig.4)	--
4. Length to width ratio (approx.):		
a. Retort	Up to 500 lbs/hr,2:1; over 500 lbs/hr,1.75:1	--
b. In-line	Diminishing from about 1.6:1 for 750 lbs/hr to about 1:1 for 4,000 lbs/hr capacity. Over-square acceptable in units of more than 11 ft ignition chamber length.	--
B. Secondary Combustion Zone:		
1. Gas Velocities:		
a. Flame port @ 1000°F, V_{FP}	55 ft/sec	± 20%
b. Mixing chamber @ 1000°F, V_{MC}	25 ft/sec	± 20%
c. Curtain wall port @ 950°F, V_{CWP}	About 0.7 of mixing chamber velocity	--
d. Combustion chamber @ 900°F, V_{CC}	5 to 6 ft/sec; always less than 10 ft/sec	--
2. Mixing chamber downpass length, L_{MC}, from top of ignition chamber arch to top of curtain wall port.	Average arch height, ft	± 20%
3. Length to width ratios of flow cross-sections:		
a. Retort, mixing chamber and combustion chamber	Range - 1.3:1 to 1.5:1	--
b. In-line	Fixed by gas velocities due to constant incinerator width	--
C. Combustion Air:		
1. Air requirement batch charging operation	Basis: 300% excess air. 50% air requirement admitted through adjustable ports; 50% air requirement met by open charge door and leakage	
2. Combustion air distribution:		
a. Overfire air ports	70% of total air required	--
b. Underfire air ports	10% of total air required	--
c. Mixing chamber air ports	20% of total air required	--
3. Port sizing, nominal inlet velocity pressure	0.1 inch water gage	--
4. Air inlet ports oversize factors:		
a. Primary air inlet	1.2	
b. Underfire air inlet	1.5 for over 500 lbs/hr to 2.5 for 50 lbs/hr	
c. Secondary air inlet	2.0 for over 500 lbs/hr to 5.0 for 50 lbs/hr	
D. Furnace Temperature:		
Average temperature, combustion products	1000°F	± 20°F
E. Auxiliary Burners:		
Normal duty requirements:		
1. Primary burner	1250-2500 Btu per lb of moisture in the refuse	
2. Secondary burner	2500-5000	
F. Draft Requirements:		
1. Theoretical stack draft, D_T	0.2-0.35 inch water gage	--
2. Available primary air induction draft, D_A. (Assume equivalent to inlet velocity pressure.)	0.1-0.2 inch water gage	
3. Natural draft stack velocity, V_S	Less than 30 ft/sec @ 900°F	--

REFERENCES

1 Rose, A.H. Stenburg, R.L., Corn, M., Horsley, R.R., Allen, D.R., and Kolp, P.W. Air Pollution Effects of Incinerator Firing Practices and Combustion Air Distribution. JAPCA, 8, 297-306. February 1959.

2 Stenburg, R.L., Horsley, R.R., Herrick, R.A., and Rose, A.H. Effects of Fuel Moisture and Incinerator Design on Effluents from Incinerators. Proc. 52nd Annual Meeting APCA, Los Angeles, California. June 1959.

3 Stenburg, R.L., Hangebrauck, R.P., von Lehmden, D.J., and Rose, A.H. Effect of High Volatile Fuel on Incinerator Effluents. JAPCA, 11, 376-83. August 1961.

4 Stenburg, R.L., Hangebrauck, R.P., von Lehmden, D.J., and Rose, A.H. Field Evaluation of Combustion Air Effects on Atmospheric Emissions from Municipal Incinerators. JAPCA 12, 83-89. February 1962.

ADDENDUM: (Note: Enclosed is a Quick Check Chart for incinerator design used by Joseph Goder Incinerators)

The purpose of the following chart is to provide a convenient way of checking our own and our competitors' incinerators when drawings or specifications are available to see if the units meet the I. I. A. Standards. This chart will enable "on-the-spot" check at the architect's or engineer's office. Data not listed on this chart may be determined by interpolation. As a specific example, if capacity is 150 lbs per hour of Type 1 Waste, the burning rate would be determined by adding 26 and 30 in the burning rate column, dividing by two, and coming out with a factor of 28.

BURNING RATE: This is the amount of refuse that can be consumed on each square foot of grate area in each hour. It is figured by dividing the capacity in pounds per hour by the grate area in square feet.

GRATE AREA: As can be seen above, grate area is determined by dividing the capacity by the burning rate and is measured in a horizontal plane as can be seen in the sketch by dimensions (a) and (b). Grate area for Type 1 Waste can include some hearth but must not exceed 20% of total burning area. Hearth area for Type 2 Waste can consist of 50% of the total burning area. When burning Type 3 Waste, the grate area must not exceed 35% of the total burning area. Where step grates are used in lieu of hearth, they shall occupy at least 65% of the burning area surface.

TOTAL INCINERATOR VOLUME: Total interior incinerator volume is exclusive of the volume below the grates or hearth.

MIN. AREA IN HI-VELOCITY PASS: Minimun area in the hi-velocity pass as shown in the sketch is measured in a horizontal plane although this minimum area should be checked throughout the gas travel of the Incinerator as no cross-sectional are inside of the unit through which the gases pass should be less than this area. This minimum area is based on a velocity of 35 feet per second at 1400°F.

GAS TRAVEL: The gas travel is a measure of the distance the gases travel in a horizontal plane in the low-velocity pass and in the case of this sketch, it is the distance between the center line of the two chambers in the secondary combustion chamber of the incinerator. This distance is figured by taking the square root of the minimum area in the low-velocity pass.

Other physical factors must be considered when checking I. I. A. Standards such as wall construction, breeching size and construction, chimney size, and the amount of auxiliary fuel required. The most important construction feature we mention here:

Adequate control of particulate and opacity will require a reassessment of municipal incinerator design. The Los Angeles design principles offer a possible solution; effectiveness in controlling emissions and costs remain uncertain. Opacity of the plume from all other designs in this country can be expected to be excessive since high fuel bed temperatures will volatilize metallic salts or oxides. If collection devices capable of removing particles in the sub-micron size range are to be considered, water cooled furnaces operating with minimum excess air may be the most economical solution. Other approaches are possible such as partial water cooling in areas where maintenance is high, using the steam generated to power induced draft fans; Venturi scrubbers operating at 30 to 50" H_2O pressure drop being used to control particulate and opacity.

When one considers the cost of such alternatives, increasing the grate area by some 50% as per Los Angeles theory appears to be well worth further investigation.

REFERENCES

1 Anon., I.I.A. Incinerator Standards, Incinerator Institute of America, 420 Lexington Avenue, New York 17, New York.

2 Williamson, J.E. et.al. Design Standards for Multiple Chamber Incinerators - Part I, Indus. Water and Wastes, pp. 61-65, May-June, 1961.

3 Williamson, J.E. et.al. Design Standards for Multiple Chamber Incinerators - Part II, Indus. Water and Wastes, pp. 97-101, July-August, 1961.

4 Greeley, S.A. et.al. Incinerator Design and the Fly-Ash Problem - Part II, The American City, pp. 112-114, June, 1955.

5 Rose, A.H. et.al Incinerator Design standards: Research Findings, LAAPCD, Publication No. 60.

6 Voelker, E.M. The Problems of Applying Incinerator Criteria, JAPCA, Vol. 14, No. 9, pp. 363-366, 377, Sept., 1964.

7 Anon., Proceedings of 1964 National Incinerator Conference, ASME, 345 E. 47th Street, New York 17, New York.

8 Meissner, H.G. Designing A Modern Incinerator, Power, April, 1958, pp. 80-83.

9 Flood, L.P. Air Pollution from Incinerators -- Causes & Cures, Civil Engineering, ASCE, December, 1965, 44 pp.

MUNICIPAL INCINERATION: GOOD OPERATING PRACTICES

Leonard C. Mandell, P. E.

I Introduction

The aim of present-day, municipal incineration is to convert and reduce small size (under 2 feet in length) combustible refuse, mainly cellulose material and garbage, into inert ashes and oxidized gases. Hence, good operating procedures should be established to attain and maintain the best performance with the plant's capability. Once established, a program of enforcement by inspection, coupled with education and supervision of the personnel should be followed.

II Desirable Operating Objectives

A. In this regard, the following objectives are desirable:

1. Operate (a) with a sensible minimum of labor, power and accessory costs, (b) with a minimum of political featherbedding and related incompetent personnel, (c) with a minimum of inefficient, shift schedules and gold-braiding of equipment and controls. Uneconomical waste-heat recovery and privileged, high-cost contractors are typical of additional wasteful expenditures.

2. Operate with a minimum of break-downs, repairs, and downtime, by hiring potentially capable people and training them in operating and maintenance procedures. A program of planned-maintenance with an adequate inventory of spare parts and well-equipped shops is necessary.

3. Operate with a minimum of air polluting emissions. This means that particulate control equipment should be incorporated to remove all solid and liquid aerosols above approximately 0.4 micron in diameter. This is an arrestance efficiency of approximately 98% by weight. Further, the combustion process itself should produce only completely oxidized gases of carbon, hydrogen sulfur, and nitrogen.

4. Operate with a minimum of unburnt organic matter in the residue. This should amount to approximately 2% – 3% by weight for combustible refuse and approximately 7% – 9% by weight for mixed refuse. This is controllable by feed and over and underfire air rates, effectiveness of turbulence, and further temperatures.

B. Conversely Operate with a Maximum of:

1. Operational continuity, performance, and reliability. This is best assured by securing well-trained, operating and maintenance personnel, the use of properly designed and maintained equipment and controls, and a planned program for their implementation and coordination.

2. Operate with maximum worker and process efficiencies. These requisites require continual effort by responsible individuals because of the inherent susceptibility to political interference and influence. Both should be kept to a minimum. It may be pointed out that too many times "the minimum" turns out to be the maximum. Hence, while influence may be tolerable, interference is unacceptable. A program of job education, good organization rapport, and better than adequate pay and fringe benefits (sick leave, Blue Cross, Blue Shield, and vacation pay) is important. Further, adequate maintenance of the operating equipment and instrumentation is essential.

3. Operate with a maximum of "mass refuse reduction." For combustible refuse this amounts to 95% – 97% by volume, and 95% by weight. For mixed refuse this amounts to approximately 90% by volume, approximately 85% by weight. (Note: Due to refuse variations, approximate values are expressed.)

C. Further-Operate with a Reasonable Degree of:

1. Safe, satisfactory working conditions for the employees. This implies adequate ventilation over the pits, the charging hoppers, and the operating floors. Good lighting; good housekeeping; cleanliness; safe walk-ways; handrails, especially around the charging wells or pits; washroom facilities; and a planned course of action for emergencies beyond the limits of applied first-aid should be established. The availability and use of safety belts and chains, the availability and use of safety goggles, gloves, non-slip hard-top shoes and also the availability of ready-to-use fire fighting equipment are all necessary safety requisites. Further, conspicuously mounted safety posters showing rules and good practices are also helpful. It should be noted that sincere, well-trained personnel are important. Their employment is mandatory for good operation. In addition, a sound, reasonable safety budget should not only be established, but maintained and expended year after year.

One effective way of attaining these operational goals is by a planned, thorough, yearly inspection of the Incinerator Facility from the personnel right down through the entire plant. Information obtained from this inspection should be recorded accurately, and evaluation for appropriate action should follow. The recorded information together with the actions taken should be placed on file for future reference.

II Operating Practices.

Successful incineration operation begins with the entrance of trucks and autos onto the property. An overall, organized plan starting with the weighing of the incoming-refuse, to the weighing of the outgoing-ash, and monitoring of gaseous effluents should be in effect for every hour of the day throughout the year. Effective controls should also be established for any liquid effluent prior to discharge. It should be noted that it is important to have rules and regulations for the collection crews and the citizenry to prevent the serious operational problems that may result from the entrance of explosive, oversize, and/or very wet, intractable wastes into the storage pit.

Finally, the importance of sincere, well-trained personnel cannot be over-emphasized. Hence, minimum placement or civil service examinations and status are highly desirable practices.

A. Duties of the Raw Refuse Handling Operator

All incoming refuse should be weighed, described, and its source recorded. Only small size combustible and mixed refuse should be allowed to enter the furnace. This control may be effected by four different operators, scale-master, dump floor pit attendant, crane operator, and charging floor attendant. Their duties are:

1. Scale-master: (a) to maintain a simple system of records of net weights, refuse description, time, date, and origin. (b) to check on licenses and collect tariffs that may be required. (c) to keep all undesirable materials from entering area.

2. Dump Floor Attendant: (a) to watch for and reject all liquids, large and dangerous items, and restricted or undesirable materials from entering the pits. (b) to watch for and sound alarm in the event of pit fires. (c) to direct all wet loads into a special section of the pit. (d) to be able to "double" as a crane operator. (e) to prevent congestion in the dumping area by proper traffic control and to discourage loitering by haulers.

3. Crane Operator: (a) should load proper type refuse into hoppers; dry, wet, or mixtures as required, and to help maintain desirable burning zone temperatures. (b) should manage the pit in such a manner that dry refuse is in the pit to bring units up to temperature for start-ups. (c) to watch for fires, clean them out, and drop burning, smoldering refuse into charging hoppers. It is his duty to keep the hoppers constantly full, especially where full hoppers serve as air seals.

4. Charging Floor Attendant: (a) to keep oversize and undesirable refuse from entering the furnace. (b) to watch for the entry of explosives. If one is sighted, he should stop the charging-stoker, call the foreman, and clear the area quickly. It is the foreman's responsibility to arrange for the safe removal of this danger. (c) to watch for fire in hopper and report immediately, so that corrective

action can be taken to operate the ventilating exhaust fans in order to remove smoke and other eye-tearing and smarting gases from work area. (e) to be able to "double" as the crane operator and as a fireman.

B. The Furnace/Operators Duties

1. Firemen: Their responsibility is to maintain good burn-out and efficient combustion in proportion to the load-demands of power-steam, if applicable, and/or pit accumulations. Their duties are: (a) to keep the furnaces clean and free of clogging. (b) check on and operate over-fire/under-fire air dampers. (c) check and maintain adequate draft (.04-.08") in ignition chamber. (d) to see that over-fire air starts above the 1100°F. flue gas temperature. This helps to burn fly-ash. (e) control drying-stokers speeds (30-50 ft/hour) of continuous feed design. (f) control burning stoker speeds (25-70 ft/hour) of continuous feed design. (g) to avoid running the burning stoker at greater speed than the drying-stoker as this results in poor burn-out and more smoke. A 60 ft/min. burning stoker speed is normal. (h) control the charging and fire dumping of batch charging type furnaces. (i) to keep ambient furnace temperatures below 1800°F. because grates and brickwork can be damaged above 1800°F. (j) admit secondary air as needed for cooling of gases to protect the furnace/incinerator and chimney structures.

2. Ash Conveyor Attendant/Truckman: (a) to keep the water in the ash-chute to overflow level at all times in order to maintain a draft-seal. (b) to keep the conveyors moving during firing, making sure that they do not become clogged. (c) in installations that do not have conveyor systems, the attendant keeps the dump chute cleared. (d) clean his equipment as often as once every 24 hours if required to prevent build-up of intractable material that can clog conveyor, and also prevent odors from developing. (e) lubricate bearings, sprockets, and chains as often as once per shift if required to prevent abrasion and wear to minimize break-downs.

III Maintenance and Repair Practice

A planned program of preventative maintenance with an adequate inventory of spare parts in conjunction with suitably equipped facilities constitutes good practice. A minimum of down-time due to breakdown and repairs can be attained by employing capable personnel who are properly trained in the operations and maintenance procedures related to the equipment by following these recommendations: (1) expend annually at least 5% of total capital plant cost for maintenance and repair. (2) expend at least 10-15% of operating cost: 50% for labor and 50% for materials. (3) conduct weekly inspections, cleaning and housekeeping, lubrication, clinker and slag removal, and minor preventative repairs. (4) plan thoroughly for all major repairs. (Note: Major modernization seems to be needed approximately every 15 years.) (5) maintain a good stock of firebricks, insulating bricks, grate components, motors, chain parts and other frequently replaced accessories and parts. (6) operate an up-to-date machine shop, electric shop, and welding shop staffed with master mechanics capable of performing the work. (7) maintain up-to-date personnel training programs. The foreman should report all defective parts and faulty mechanisms on his daily report to the superintendent. Proper repairs must be scheduled immediately. (8) maintain lubrication schedules as recommended by the manufacturer of the respective equipment, use lubricants approved by a recognized petroleum company. (9) maintain a high standard of plant cleanliness inside and outside as this is indicative of good overall plant operation. Clean up the outside grounds at least once a week. (10) provide periodic cleaning of all flues and chambers. (11) careful attention should be given to inspection and maintenance of air pollution control equipment. (12) the stack should be inspected at least every other year to locate loose and cracked bricks, corroded or loose bolt fastenings or outside bands and to determine the need for maintenance. (13) maintain a system of records, in the incinerator office, showing the cost, exactly what was done, when, why and by whom.

IV Air Pollution Control - Good Operating Practices

A. An Ideal Process and Its Variables

From a purely theoretical standpoint, perfect air pollution control applied to municipal incineration would emit an effluent with the following characteristics: (1) "a suspended particulate concentration equal to that in the air used for combustion." (2) a gas-mixture composition of nitrogen, oxygen, water vapor, and argon; also, carbon dioxide, methane, hydrogen, ozone, and the rare gases at the combustion-air concentrations.

With this plane of reference, it can be said that the average concentration of particulates, carbon dioxide, or any other gases except water vapor greater than the respective combustion-air concentration departs from the perfect condition. This degree of departure can be said to be a measure of the effluent's air pollution potential. Its classification as an air pollutant depends upon: (1) the quality of the combustion-air. (2) the local meteorology at the time of release into the atmosphere. (3) the local topography within the zone of significance of the atmospheric plume. (4) the population density and composition within this zone of significance. (5) the land use and activities within this zone of significance.

These seven parameters involve a dynamic, ecological relationship between the effluent, the immediate physical environment of land, water, and air. The acceptability of this relationship, from a Public Health and Welfare standpoint, is governed by the finite, self-cleansing ability of the environment to maintain concentrations below harmful thresholds.

From a practical standpoint, good practice calls for cessation of incinerator operation during critical periods of adverse meteorology. This implies that an alternate stand-by means of disposal be available during these critical periods. Controlling the quality of the combustion air, at present, presents no apparent advantage while the other items of topography, population, and land use is beyond the control of Incinerator Management.

B. Available Control Methods

1. In General. Good operating practice is in reality limited by the design of the incinerator facility. However, there are at least five opportunities for Air Pollution Control of which only one or more may be available in any plant. The degree of control will increase in proportion to the utilization of these opportunities: (a) pre-treatment of the refuse. (b) proper charging and feeding (c) good combustion efficiency. (d) effective air pollution control equipment. (e) adequate control instrumentation.

It should be noted that until six years or so ago, air pollution control equipment was not incorporated and designed into the conventional incinerator plant. Whatever control that was available consisted of attempts to burn the refuse without visible smoke. This was done by manual operation of grate speeds, mixing the refuse, feed rate, combustion air supply, and by incidental arrestance of ash and slag by wasteheat boiler-tubes, and other flue-gas type obstructions. Settling chambers, so-called, were provided for the relatively large size fly and char particles, greater than several hundred microns, which cause a soiling nuisance within 10-15 stack diameters of the emission point.

Typical effluents with little or no control, from 1945-1960 design incinerators, would contain the following pertinent pollutants: (a) suspended particulates, (smoke, soot, grit, dust, fume, fly-ash) in the plume of 3.5 - 5.0 lbs/1000 lbs. of gas (corrected to 50% excess air) with a mass median diameter of 30-50 microns and a count median just below 0.1 microns. By count, each pound of refuse when burned should give approximately 10^{16} particles of which 96% were greater than .01 and less than 0.1 micron in size. (b) component gases as sulfur oxides (SO_2), 0.2 - 1.3 ppm; nitrogen oxides (NO_2), 0.2-1.5; carbon monoxide, 30-1000 ppm; carbon dioxide, 1-4% by volume and oxidizable sulfur compounds 2-8 ppm.

2. Pre-treatment of the Refuse. Wherever feasible, all refuse should be opened, size-reduced, and sorted-free of bottles, cans, and other intractable type wastes. Light, water spraying of everyday refuse will also help

in preventing pre-ignition of the refuse in the charging hopper.

A recommended practice, not sufficiently in vogue, is to provide an effective sorting line and power disintegration of the refuse to obtain pieces in the 1 inch size instead of chunks of pieces in the 12 to 36 inch size. This tends to provide a more homogeneous refuse fuel that will burn easier and more efficiently, and be more adaptable to control influence--all of which will tend to reduce air pollution emissions.

3. Charging and Feeding Into the Furnace. (a) batch charging, at best, still creates excessive amounts of smoke and fly-ash due to the uncontrolled disturbance of the bed. Proper cycling and dumping of the grates with full-overhead hoppers constitutes good practice. Excessive entrance of refuse (overloading) also causes poor burn-out of the organic matter. (b) continuous feeding via a transfer of drying-grate with a full hopper (to act as a semi-gas seal) tends to maintain a relatively stable, overfire-draft. The transfer of feed-grate speed should be maintained slightly higher than the main stoker speed (this controls the depth of the fuel bed) to obtain good burn-out efficiency.

4. Combustion Efficiency. (a) the nature of flame combustion: the nature of the actual incineration process tends towards the probability of incomplete or inefficient oxidation with the generation of large amounts of smoke and pollutants. Good combustion requires continued watchfulness and related control responses to provide adequate air to fuel ratios in intimate dynamic timed-contact with the volatile and/or fixed carbon molecules. (Note: This presents an opportunity for "sincere, well-trained personnel" to show their worth.

Today's refuse contains a high percentage of volatile matter, and less than 20% fixed carbon, with the former burning above the fuel bed. Experience has shown that combustion occurs in three definite but overlapping and dependent phases: (1) evaporation of moisture (an endothermic phase) less than 212°F. (2) distillation of the volatile hydrocarbon (tar, oils, waxes, resins, etc.) that come off between 300-800° F. (an exothermic phase). (3) straightforward combustion of the remaining fixed carbon at 1100-1250° F. (an exothermic phase).

Stoichiometric combustion of conventional 1967 refuse creates furnace temperatures in excess of 3200° F. This is much too high for satisfactory refractory life and other materials of construction. Hence, provisions for cooling the gases and furnace-proper by excess air amounts up to 300% and/or water cooled walls (that bring excess air down to 50-70% level) must be available. (b) furnace operation: air pollution control starts in the furnace. Tests have shown that: (1) fly ash carry over is proportional to (Furnace Velocity)^2 (Furnace Size), (Heat Release), (2) flame temperatures are approximately 200-400° F. greater than wall temperatures, (3) the more effective the over-fire air, the smaller the fly ash carry over, (4) too much excess air cools gases before completion of combustion with smoke formation, (5) the more forced, under-fire air, the more fly ash.

Hence, the proper control of grate speeds, over-fire, and below grate air supplied together with induced secondary air must all be continually and carefully controlled by the operator.

The fuel bed depth should be controlled to provide a complete burn-out by the time the ash reaches the dump-line. This is proportional to stoker speeds, and over-fire and under-fire air rates and points of application. Efforts should be made to prevent large variations in temperature. This causes thermal shocks, spalling, expansion, and contraction breakage of the refractory materials.

Shift operating schedules disclosed by a recent survey showed that 36% of plants operate eight hours per day, 53% operate twenty-four hours per day, and 6% operate sixteen hours per day.

5. Air Pollution Control Equipment
Air pollution control equipment is just beginning to be designed as an integral part of the incinerator plant. As previously mentioned, until 1960 or so, subsidence or settling chambers and water sprays characterized the American design, their efficiencies

for suspended particulates were approximately 10 and 20% respectively.

A recent survey of shift operating schedules showed that the application of wet-baffles and multi-clones have increased the collection efficiency to 60-70%. It is the writer's opinion that the next 5-10 years will see the appearance of electrostatic precipitators with efficiencies in the 95% and higher range. It should be noted that high pressure-drop venturi scrubbers can give efficiencies in the 97% range and bag collectors to greater than 99% for particulates down to the 0.1 micron size.

6. Instrumentation. The existence of adequate instrumentation in the overage plant is lacking. The indication of draft and several gas temperatures in the furnace and flue-gas system are conventional. In addition the following would assist in air pollution control: (a) stoker speed indication. (b) CFM/jet for overfire air with total furnace indication. (c) CFM/jet under-fire air with total furnace indication. (d) a continual indication of unburnt material in residue coming off the grate. (e) an indication or record of smoke concentration entering the stack. (f) a measure of the particulate concentration entering the stack, (g) meteorological instrumentation: wind, speed, relative humidity, and wind direction. (h) a stack mirror to allow the operators to view the plume discharge. (i) good audio and visual communications, speakers, telephones, closed circuit TV to view the combustion chamber, ash drop area, stack, etc.

7. Comments Pertaining to Many of the Present Plants:
(a) on the negative side: there really isn't much that can be done: (1) because air pollution control equipment does not exist. (2) because of inadequate instrumentation. (3) because the quantity of refuse to be burned is much greater than the ability of the furnace to burn it efficiently. (4) because of under-trained, under-staffed, under-activated personnel. (b) the positive side: (1) schedule the burning rates in proportion to daily accumulation and storage capacity, in order to keep below or to a minimum the degree of exceeding the design rating of the plant. (2) maintain the furnace, ancillary equipment and auxiliaries in good condition. (3) maintain a high degree of worker morale. This encourages concern and proper attitude necessary for good operation. (4) have dust-arrestance equipment installed. (5) investigate better or more instrumentation for a running guide to the operators. (6) have at least a CO_2 and optical smoke records kept during all operations. (7) have a sufficient number of observation ports to ensure good visual inspections. (8) keep furnace and flue passages clean.

V. Conclusion

I would like to close with these few thoughts:

A. An incinerator should be operated for incineration purposes only, not as a heat source for steam generation unless proper provisions of auxiliary fuel and air pollution control are incorporated therein.

B. Operate the incinerator as a business with strict rules and regulations. It should be kept in mind that incineration is a part of the disposal concept and is accordingly susceptible to a high degree of apathetic thinking.

C. It is becoming generally accepted that clean air is as important to health as clean water. In this regard, sewage treatment together with the natural cleansing forces of time, sun, and aeration are provided for liquid wastes. Further, all water is treated again at the Potable Treatment plants. Hence, at least two efforts and most of the time three treatments are made to control water pollution and purity. In incineration, however, once the flue gases enter the atmosphere, there is no equivalent air treatment plant to clean the air before it is breathed. Hence, it appears advisable and even mandatory to incorporate both the equivalent of waste treatment and air treatment in the incinerator of the future.

GOOD OPERATION PRACTICES FOR MUNICIPAL INCINERATORS

Herbert C. Johnson*

Operating procedures for municipal incinerators vary considerably for different designs. The ideal design would minimize the influence of the operator on performance; his responsibility would be limited to keeping a hopper or chute filled with refuse, and removing ash. Most incinerators require considerable judgment to be exercised by the operator. Excessive air pollution, high maintenance and breakdowns often are the fault of the operators.

Good operation requires consideration of the following factors:

I CHARGING SCHEDULE

Rectangular furnaces with mechanical grates are usually designed for continuous or repetitive charging. The chute should be kept full of refuse at all times if a continuous charge system is provided.

Repetitive charging means that a charge is added frequently and at regular intervals through each charging door in sequence. The stokers are operated at frequent intervals to keep the refuse moving toward the discharge end. (Some stokers operate continuously, requiring periodic speed adjustment.) Refuse is usually charged into the incinerator at 2- to 5-minute intervals, depending on the size of crane bucket, number of charging doors, number of incinerators, and capacity of incinerators.

Batch charging is applicable only to certain types of incinerators such as round furnaces equipped with rotary grates. Manufacturer's recommendations should be followed unless tests prove other procedures reduce emissions, increase burning rate, or reduce maintenance. If the periodic burndown method is used, the procedure is (1) dump grates and clean fire (2) charge the prescribed amount of refuse, and (3) close charging door and allow refuse to burn nearly to completion. Repeat these three steps.

II PROPER FUEL BED DEPTH

The depth of refuse at the charging end of the furnace usually is, or should be, determined by design features of the charging system and crane bucket size (excluding batch charging). Depth should decrease toward the ash pit end so that only a relatively thin layer of ash covers the end of the grate. The operator can vary air flow thru the grates and grate speed, usually within a narrow range.

A Continuous feed systems are designed to provide a fixed depth of refuse at the charging end. The operator can vary air flow thru the grate and grate speed. Both should be adjusted to completely burn the refuse by the time it reaches the end of the grate. Emissions can usually be reduced by reducing both grate speed and underfire air, which also reduces burning rate.

B Repetitive charging systems are intended to be operated so that refuse is charged on the grate after the previous charge has moved beyond the charging area. Initial depth will depend on the size of the crane bucket, should not be more than 3 to 4 feet deep. Minimum depth and less underfire air should reduce emissions. Grate speed must be adjusted to provide, complete burnout on the grate.

C Batch Charge

Depth of fuel bed should follow manufacturer's instructions.

III NORMAL TEMPERATURES

First chamber gas temperature normally recommended is 1600°F. Flame temperatures in some regions may be much higher and may cause fictitious thermocouple readings.

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Secondary chamber gas temperatures should be only slightly lower in large incinerators and should be closer to actual gas temperatures than first chamber readings; 1400° to 1500°F should be satisfactory.

Stack temperature will be above 1000°F unless barometric dampers or water sprays are installed. Operators should be informed of design temperature range for stack.

IV EXCESS AIR - has two purposes: 1) to assure adequate oxygen for combustion, and 2) to control temperatures.

Today's refuse contains much more heat than necessary to maintain 1600°F if only the theoretical amount of air is supplied. Therefore, from 100 to 200% excess air must be supplied to cool the combustion products; temperature determines the amount of excess air supplied.

V COMBUSTION AIR DISTRIBUTION

A Underfire to overfire air ratio. Considerable controversy exists on this ratio, varying from 2 to 1 to 1 to 7. A 1 to 1 ratio is being used at present by many designers. Most operators tend to use too much underfire air, which increases air pollution. However, many incinerators will operate at their designed ratings only by supplying a high percentage of underfire air.

B Secondary combustion air is not provided for in most municipal incinerators. This is a feature of the Los Angeles design which should be further evaluated.

VI NORMAL STOKING PROCEDURE

The main purpose of mechanical grates is supposed to be to reduce the labor of hand stoking. Proper operation of mechanical grates (stokers), correct fuel bed depth, underfire air adjustment, and burning rate should eliminate most hand stoking.

VII NORMAL AIR PRESSURE IN COMBUSTION CHAMBERS

A negative pressure should always be maintained in all combustion chambers. A positive pressure will cause gas and flames to escape through overfire air ports, charging doors when opened, and any cracks that develop in the chamber lining. These conditions are dangerous to personnel, damage the chamber walls and arch, and may prevent the flow of adequate overfire air. Positive pressure is caused by 1) failure of draft system 2) supplying too much air under pressure to the furnace (underfire or overfire air) 3) too high a burning rate 4) failure to close charging doors promptly, and 5) leaving inspection or stoking doors open.

VIII INFLUENCE OF DILUTION AIR ON POLLUTION FORMATION

This was discussed under IV and V.

Obviously, no more air should be introduced than necessary for complete combustion and temperature control. Only sufficient underfire air should be used to burn out fixed carbon on the grate. Overfire air should be introduced where it is needed to burn volatiles, and properly cool the chamber with a minimum entraining effect on fly ash and particulate.

IX INFLUENCE OF PARTICULATE CONTROL EQUIPMENT ON INCINERATOR OPERATION

If no control equipment is installed, more careful operation of the incinerator is usually required to try to minimize particulate emission.

Some types of control equipment will limit gas flow and available draft, which means that operators may have to be careful not to overload the incinerator. Overloading may lead to smoke emission or positive pressure in the incinerator.

Operators must understand the operating procedures required to assure that the control equipment is removing particulate efficiently.

X INFLUENCE OF WASTE COMPOSITION VARIATIONS

Municipal incinerators receive a wide range of waste materials varying in calorific value, moisture content, and burning characteristics. The operators can exercise some control over conditions in the first chamber by selection of material from storage.

A If temperatures soar too high, select wet refuse.

B If temperatures drop, select dry refuse.

C If the grate speed must be reduced because of slow burning material, and temperature is falling, select wood scrap.

If most of the refuse is wet (with unbound moisture), overfire air will have to be reduced and underfire air may have to be increased. Addition of dry wood, if available, will help maintain temperature. Grate speed may have to be reduced.

If most of the refuse is quite dry, overfire air should be increased and underfire air reduced. It may be advisable to spray dry refuse with water prior to charging. The operator should remember that per unit of volume; wood, plastics, and rubber contain much more heat than loose paper, garbage, or rubbish.

Because of the variations in incinerator designs, the operating characteristics of each plant will have to be determined by operating personnel. Tests should be conducted under various conditions to be certain of the effects of operating variables.

After establishing the type of operation that results in the lowest emissions, the least maintenance, with satisfactory burning rates, this type of operation should be made mandatory.

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MULTIPLE-CHAMBER INCINERATOR DESIGN STANDARDS FOR LOS ANGELES COUNTY

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OCTOBER 1960

LOS ANGELES COUNTY AIR POLLUTION CONTROL DISTRICT

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I. INTRODUCTION

Disposal of combustible refuse and garbage is one of the most perplexing problems facing urban society today. The greater the population density the more disturbing the problem. This refuse is created by all elements of a community--industry, commerce, and the public.

In the past, disposal of combustible wastes was looked upon as a necessary evil to be accomplished as cheaply as possible. Industrial and commercial installations utilized a box-like, single-chamber type incinerator to burn up to several tons a day. Refuse from apartment houses was generally burned in a chute-fed, single-chamber incinerator. In some areas, especially Southern California, each homeowner disposed of his combustible refuse in a backyard type incinerator.

During the past fifteen years almost every large urban area in the world has experienced a drastic increase in the pollution of its atmosphere. As the discomforts of air pollution became more noticeable, public clamor for rigid regulation of air contaminating processes increased steadily. In Los Angeles County this led to the banning of open fires and single-chamber type incinerators in September of 1957. Since that date all incinerators constructed and put into operation in the County must meet stringent criteria of performance [1] as well as definite minimum design requirements.

Multiple-chamber incineration is a term fast becoming familiar in air pollution control work and rapidly assuming meaning to thousands of people who wouldn't have known what a "single-chamber incinerator" was five years ago. No discussion of multiple-chamber incinerators would be complete without showing to some degree how this awareness has come about.

Early in the evaluation of sources of air pollution in Los Angeles County, [2] incineration was determined to be a major contributor. Contaminants from open burning and single-chamber incineration [3] were found to range from solid matter of various particle sizes, through liquid organic compounds, to gaseous organic, sulfur, and nitrogen compounds. [4]

The need for a satisfactory means of refuse disposal at the source resulted in an investigation of incineration in all its aspects. The object was to develop an efficient combustion furnace that would provide maximum reduction in waste bulk with minimum emission of air contaminants

and be capable of stable operation over a wide range of fuel mixtures and operating conditions.

With the growing need for incinerators capable of complying with air pollution codes and restrictions, it has become necessary to provide design data that will help make satisfactory incinerators available. Recommendations and standards are offered here to assist air pollution control officials faced with incineration problems, architects and engineering designers who must provide adequate designs, and manufacturers or contractors who will, perhaps, design as well as build incinerators which must meet air pollution control regulations. It must be cautioned that only those qualified in combustion equipment design and refractory construction should try to apply the standards presented. Adequacy of design, proper methods of construction, and quality of materials are important to the satisfactory completion of an incinerator that will meet air pollution control requirements and have an average service life expectancy.

The design standards presented in this treatise are tools to create designs for multiple-chamber incinerators that may be expected to burn rubbish with a minimum discharge of air contaminants. Tabular presentations alone are not sufficient for the best application and understanding of the principles and philosophies of design involved. It is also essential to understand the many factors that created the need for a new approach to incineration and the development of the multiple-chamber incinerator. The design recommendations and supplementary discussions provide answers to many of the questions that confront designers and operators of multiple-chamber equipment.

II. CLASSIFICATION OF REFUSE

It is necessary in incineration designs not only to specify the general type of refuse but also to note specific properties such as composition and moisture content. For purposes of incineration combustion calculations, most refuse may be considered as reacting stoichimetrically as cellulose without serious error.

The multiple-chamber incinerator may serve nearly all incineration requirements involving refuse consisting primarily of dry rubbish (paper, rag and cardboard waste) with smaller amounts of wood, sawdust, shrubbery, green foliage and garbage. General refuse, for purposes of clarification and flexibility in application, is defined as refuse with component proportions of wide range within approximate limits as follows:

	Per cent by weight		
	Minimum		Maximum
Dry rubbish	50	-	100
Wood, scrap	0	-	40
Shrubbery	0	-	30
Garbage	0	-	30
Sawdust, shavings	0	-	10

III. PROCESS DESCRIPTION

The configuration of multiple-chamber incinerators may be traced back many years to the design of multiple-cell incinerators for both municipal and industrial waste disposal. "L"-shaped incinerators, vertically arranged incinerators, and incinerators with separate chambers have appeared as varieties of the basic designs when circumstances or designers have so dictated. Reduced to the simplest forms, each style has certain characteristics with regard to performance and construction that limit its application.

The configuration of multiple-chamber incinerators falls into two general types, as shown in Figures 1 and 2. These are the retort type, named for the return flow of gases through the "U" arrangement of a component chamber; and the in-line type, so-called because the three chambers follow one after the other in a line.

The combustion process proceeds in two stages--primary or solid fuel combustion in the "ignition chamber," followed by secondary or gaseous phase combustion. The secondary combustion zone is composed of two parts, a downdraft or "mixing chamber" and an up-pass expansion or "combustion chamber." Flow through the two-stage process is as follows:

a. The ignition chamber reaction includes the drying, ignition and combustion of the solid refuse. As the burning proceeds, the moisture and volatile components of the fuel are vaporized and partially oxidized in passing from the ignition chamber through the "flame port" connecting the ignition chamber with the mixing chamber.

b. From the flame port, the products of combustion and volatile components of the refuse flow through the mixing chamber where secondary air is induced. The combination of adequate temperature and additional air, augmented by mixing chamber or "secondary" burners as necessary, assist in initiating the second stage of the combustion process. Turbulent mixing, resulting from restricted flow areas and abrupt changes in flow direction, furthers the gaseous phase reaction. In passing through the "curtain wall port" from the mixing chamber to the final combustion chamber the gases undergo additional changes in direction accompanied by expansion and final oxidation of combustible

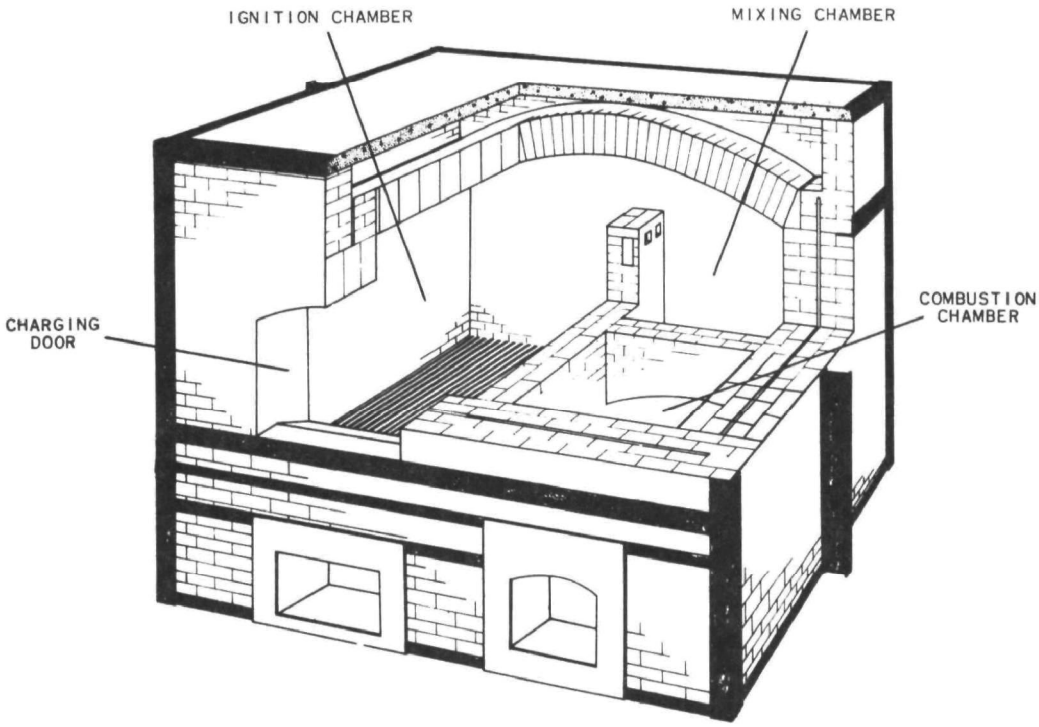


FIGURE 1. CUTAWAY OF A RETORT MULTIPLE-CHAMBER INCINERATOR

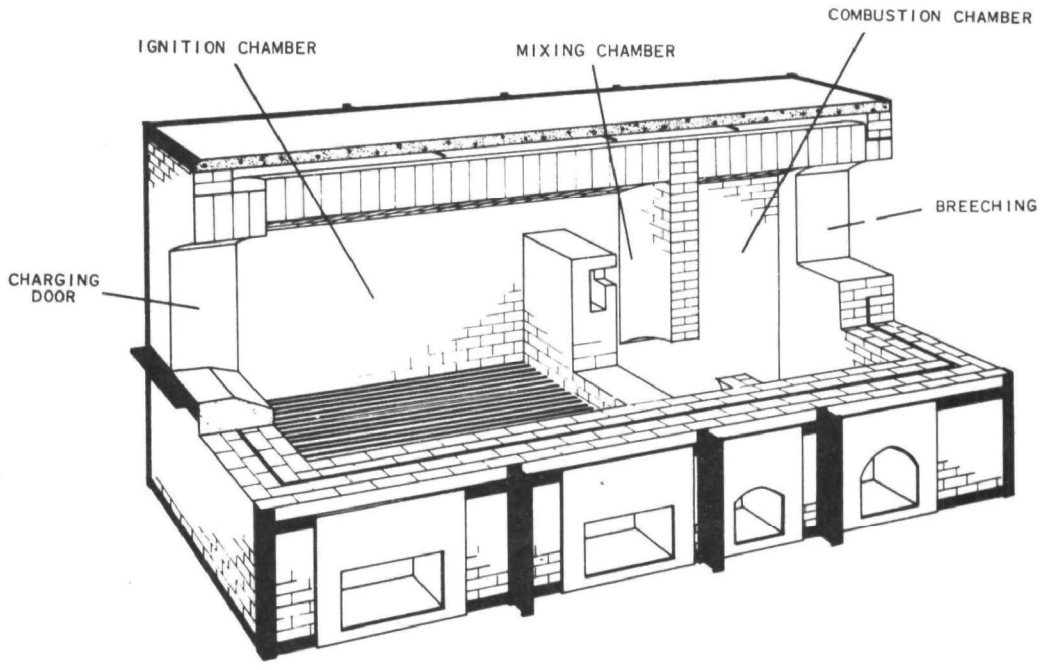


FIGURE 2. CUTAWAY OF AN IN-LINE MULTIPLE-CHAMBER INCINERATOR

components. Fly ash and other solid particulate matter are collected in the combustion chamber by wall impingement and simple settling.

c. The gases finally discharge through a stack or a combination of a gas cooler, e.g., a water spray chamber, and induced draft system. Either draft system must limit combustion air to the quantity required at the nominal capacity rating of the incinerator.

IV. PRINCIPLES OF COMBUSTION

Due to the heterogeneous nature of wastes found in refuse many factors are involved which cannot be predicted accurately except on an empirical basis. Theoretical treatment of the complex reactions taking place in combustion processes is as yet incomplete, but the empirical art of combustion engineering has developed to an advanced state. The principles of solid fuel combustion generally apply in incineration and basic precepts for combustion efficiency include the following:

a. Air and fuel must be in proper proportion.

b. Air and fuel, especially combustible gases, must be mixed adequately.

c. Temperatures must be sufficient for ignition of both the solid fuel and the gaseous components.

d. Furnace volumes must be large enough to provide the retention time needed for complete combustion.

e. Furnace proportions must be such that ignition temperatures are maintained and fly ash entrainment is minimized.

The problem of fuel quality fluctuation is one of the factors that makes satisfactory incinerator design difficult. In addition to the wide ranges of fuel composition, wetness and volatility, there is diversity in ash content, bulk density, heats of combustion, burning rates and component particle sizes. All of these affect, to some extent, the operating variables of flame propagation rate, flame length, combustion air requirements and the need for auxiliary heat.

The ignition mechanism should be basically one of fuel-bed surface combustion. This is attained by the predominant use of overfire combustion air and charging to attain concurrent travel of both air and refuse with minimum admission of underfire combustion air. The importance of limiting the admission of underfire air, and thereby maintaining relatively low fuel-bed temperatures, has been postulated from analyses of the solid particulate matter discharged when an overfired ignition mechanism was used. With a high air rate through the fuel bed, the stack effluent was found to contain appreciable quantities of metallic salts an

oxides in microcrystalline form. This led to the theory that, with high fuel-bed temperatures, vaporization of metals occurs accompanied by vapor phase reactions and followed by particle condensation in the cooling effluent gases as they leave the stack.

To accomplish fuel-bed surface combustion through the use of overfire air, the charging door should be located at the end of the ignition chamber farthest from the flame port, and fuel should move through the ignition chamber from the front to the rear. In this way, the volatiles from the fresh charge pass through the flames of the stabilized and heated portion of the burning fuel bed. In addition, the rate of ignition of unburned refuse is controlled, preventing the flash volatilization, flame quenching and smoke creation that attend top and side charging methods. The use of top or side charging is no longer considered acceptable because of the suspension of dust, disturbance of the stabilized fuel bed and additional stoking required.

With good control of the burning rate through proper charging, air port adjustment, and use of an ignition or "primary" burner, the need for stoking will be reduced to that necessary for fuel-bed movement prior to charging. Control of the combustion reaction and reduction in the amount of mechanically entrained fly ash are most important in the efficient design of a multiple-chamber incinerator.

V. IGNITION CHAMBER

Fundamental relationships for parameter evaluation were derived by Rose and Crabaugh[5] and by the ASME Subcommittee on Incineration Design Standards. These fundamentals are:

a. Relationship of combustion air distribution to the degree and rate of combustion attained and to the discharge of air contaminants.

b. Relationship of furnace proportions, i.e., chambers and ports to the degree and rate of combustion attained and to the discharge of air contaminants.

c. The effects of temperature and furnace design on the percentage of acid, volatile organic, and solid contaminants discharged and the percentage of combustibles in the solid contaminants discharged.

d. Relationship of combustion gas velocities to the effects on turbulence and flame travel and to the degree of combustion attained.

e. Relationship of the material burned to the formation of acid and volatile organic compounds.

Ignition chamber parameters were regarded as basic, since solid contaminant discharges only could be functions of the mechanical and chemical processes taking place in the primary stage. Incinerators were tested[6] burning general refuse, as defined, with a gross heating value of 7,500 Btu/lb or less. Formulas governing ignition chamber design were tentatively postulated from data obtained from tests of units of varying proportions operating at maximum combustion rates.

Subsequent to the publication of the tentative formulas, additional testing and evaluation of units consuming materials with a gross heating value of 9,000 Btu/lb revealed that the optimum formulas for the average grate loading as well as the arch height should be increased approximately 20 per cent. The gross heating value of general refuse normally falls between 7,500 and 9,000 Btu/lb.

Optimum values of the arch height and grate area may be determined by using the gross heating value of the refuse to be burned and interpolating between the upper and lower curves given in Figures 3 and 4. An allowable deviation of these values of plus or minus 10 per cent is considered to be reasonable. Rather than establish formulas for both the upper and lower curves of Figures 3 and 4, a formula for the average values of the two curves has been given. This curve corresponds to a gross heating value of 8,250 Btu/lb.

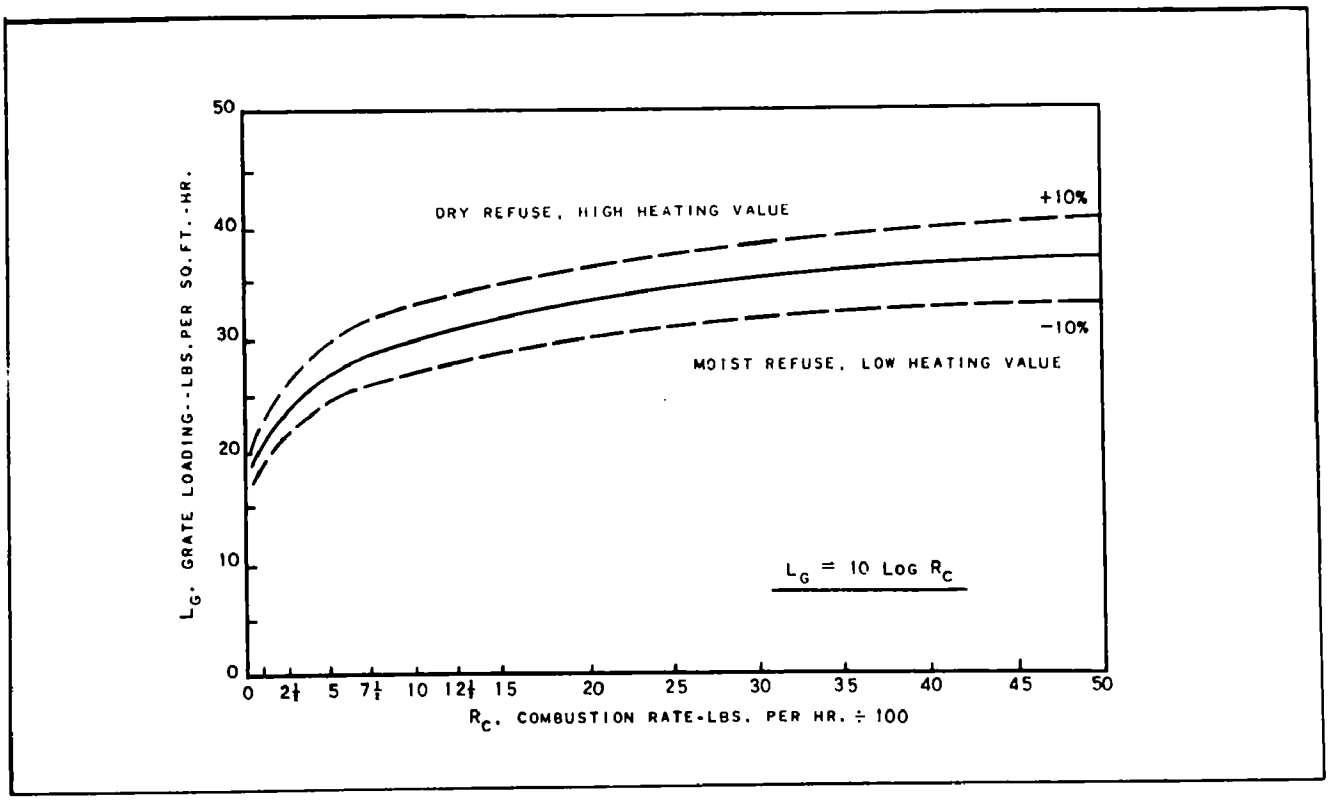


FIGURE 3. RELATIONSHIP OF GRATE LOADING TO COMBUSTION RATE FOR MULTIPLE-CHAMBER INCINERATORS

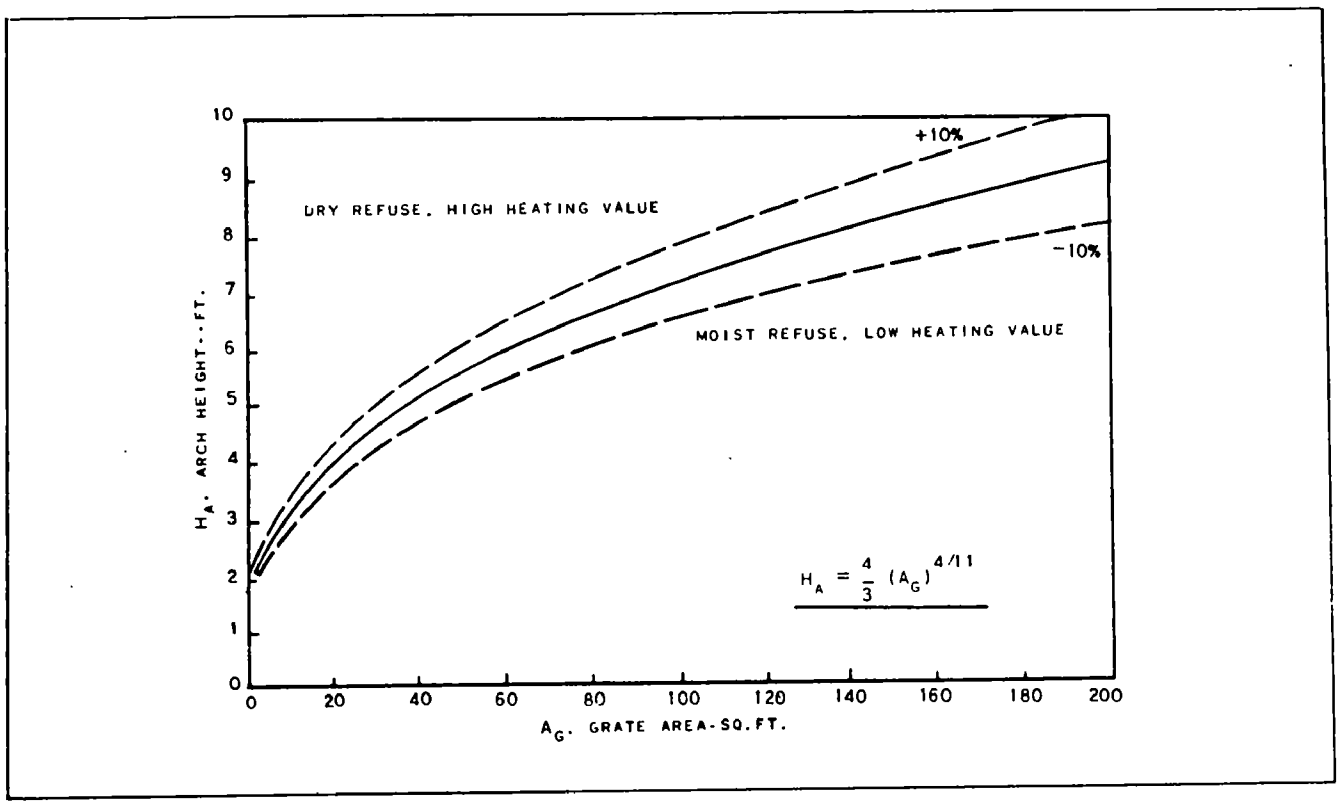


FIGURE 4. RELATIONSHIP OF ARCH HEIGHT TO GRATE AREA FOR MULTIPLE-CHAMBER INCINERATORS

VI. MIXING AND COMBUSTION CHAMBERS

In the process of confirming the parameter relationships in the ignition chamber, the factors controlling the design of the gas phase combustion zone were also developed. Application of the fundamental evaluation precepts combined with trials of various proportions in both chamber and port dimensions and secondary air admission established parameters for the mixing and combustion chamber portions of the multiple-chamber incinerator. The primary effect of proper design has been attainment of a higher degree of completion of combustion of volatile and solid combustible effluent components. By designing the combustion chamber as a settling chamber it has been possible to achieve some reduction in fly ash emissions as well.

Basic Parameters

Incinerator design factors which have been selected as basic include the ratios of combustion air distribution, supplementary draft and temperature criteria, and ignition chamber length-to-width ratios as well as the ignition chamber parameters and the secondary combustion stage velocity and proportion factors. Some of these factors are functions of the desired hourly combustion rate and are expressed in empirical formulas, while others are assigned values which are independent of incinerator size.

The values determined for the several parameters are mean empirical values, accurate in the same degree as the experimental accurach of the evaluation tests. The significance of exact figures is reduced further by the fluctuation of fuel composition and conditions. For purposes of design, permissible variations from the optimum mean are plus or minus 10 per cent, and velocities may deviate as much as 20 per cent without serious consequences.

Table I, Multiple-Chamber Incinerator Design Factors, lists the basic parameters, evaluation factors and equations, and gives the optimum values established for each.

TABLE I

MULTIPLE-CHAMBER INCINERATOR DESIGN FACTORS

ITEM AND SYMBOL	RECOMMENDED VALUE	ALLOWABLE DEVIATION
A. Primary Combustion Zone:		
1. Grate loading, L_G	10 Log R_c; lbs/hr-ft^2 where R_c equals the refuse combustion rate in lbs/hr (refer to Fig.3)	± 10%
2. Grate area, A_G	$R_c \div L_G$: ft^2	± 10%
3. Average arch height, H_A	4/3(AG)4/11; ft(refer to Fig.4)	--
4. Length to width ratio (approx.):		
a. Retort	Up to 500 lbs/hr,2:1; over 500 lbs/hr,1.75:1	--
b. In-line	Diminishing from about 1.6:1 for 750 lbs/hr to about 1:1 for 4,000 lbs/hr capacity. Over-square acceptable in units of more than 11 ft ignition chamber length.	--
B. Secondary Combustion Zone:		
1. Gas Velocities:		
a. Flame port @ 1000°F, V_{FP}	55 ft/sec	± 20%
b. Mixing chamber @ 1000°F, V_{MC}	25 ft/sec	± 20%
c. Curtain wall port @ 950°F, V_{CWP}	About 0.7 of mixing chamber velocity	--
d. Combustion chamber @ 900°F, V_{CC}	5 to 6 ft/sec; always less than 10 ft/sec	--
2. Mixing chamber downpass length, L_{MC}, from top of ignition chamber arch to top of curtain wall port.	Average arch height, ft	± 20%
3. Length to width ratios of flow cross-sections:		
a. Retort, mixing chamber and combustion chamber	Range - 1.3:1 to 1.5:1	--
b. In-line	Fixed by gas velocities due to constant incinerator width	--
C. Combustion Air:		
1. Air requirement batch charging operation	Basis: 300% excess air. 50% air requirement admitted through adjustable ports; 50% air requirement met by open charge door and leakage	
2. Combustion air distribution:		
a. Overfire air ports	70% of total air required	--
b. Underfire air ports	10% of total air required	--
c. Mixing chamber air ports	20% of total air required	--
3. Port sizing, nominal inlet velocity pressure	0.1 inch water gage	--
4. Air inlet ports oversize factors:		
a. Primary air inlet	1.2	
b. Underfire air inlet	1.5 for over 500 lbs/hr to 2.5 for 50 lbs/hr	
c. Secondary air inlet	2.0 for over 500 lbs/hr to 5.0 for 50 lbs/hr	
D. Furnace Temperature:		
Average temperature, combustion products	1000°F	± 20°F
E. Auxiliary Burners:		
Normal duty requirements:		
1. Primary burner	1250-2500 Btu per lb of moisture in the refuse	
2. Secondary burner	2500-5000	
F. Draft Requirements:		
1. Theoretical stack draft, D_T	0.2-0.35 inch water gage	--
2. Available primary air induction draft, D_A. (Assume equivalent to inlet velocity pressure.)	0.1-0.2 inch water gage	
3. Natural draft stack velocity, V_S	Less than 30 ft/sec @ 900°F	--

VII. DESIGN TYPES AND LIMITATIONS

During the evaluation and development phases of the multiple-chamber incinerator, different incinerator configurations were tested with variations in the sizes and shapes of the several chambers and ports. When tests indicated optimum performance on a contaminant discharge basis, and visual inspection revealed satisfactory flame travel, flame coverage and fly ash control, the characteristics of the incinerator were noted and the design limitations and parameters were established. The results of these tests, while providing data for development of design factors, also showed the optimum operating limits for the two basic styles of multiple-chamber incinerators.

Retort Type

Essential features which distinguish the retort type of design are:

a. The arrangement of the chambers causes the combustion gases to flow through 90^{o} turns in both lateral and vertical directions.

b. The return flow of the gases permits the use of a common wall between the primary and secondary combustion stages.

c. Mixing chambers, flame ports and curtain wall ports have length-to-width ratios in the range from 1:1 to 1.5:1.

d. Bridge wall thickness under the flame port is a function of dimensional requirements in the mixing and combustion chambers. This results in construction that is somewhat unwieldy in the size range above 500 pounds per hour.

In-Line Type

Distinguishing features of the in-line design are:

a. Flow of the combustion gases is straight through the incinerator with 90^{o} turns in only the vertical direction.

b. The in-line arrangement of the component chambers gives a rectangular plan to the incinerator. This style is readily adaptable to installations which require separated spacing of the chambers for operating, maintenance or other reasons.

c. All ports and chambers extend across the full width of the incinerator and are as wide as the ignition chamber. Length-to-width ratios of the flame port, mixing chamber and curtain wall port flow cross-sections range from 3:1 to 5:1.

Comparison of Types

A retort incinerator in its optimum size range offers the advantage of compactness and structural economy that are permitted by its cubic shape and a reduction in exterior wall length. It has been demonstrated that the retort incinerator performs more efficiently than its in-line counterpart in the capacity range from 50 pounds per hour to about 750 pounds per hour. The in-line incinerator is well suited to high capacity operation but is not too satisfactory for service in small sizes. The smaller in-line incinerators are somewhat less efficient with regard to secondary stage combustion than retort type. The capacity range in which the in-line incinerator is found to function best is from 1000 pounds per hour to whatever limit is imposed by practicability.

The incinerator type capacity recommendations overlap at the 750-1000 pounds per hour capacity level and there are no outstanding factors which favor either in this size range. The choice of in-line or retort is dictated by personal preference, space limitations and, perhaps, the nature of the refuse and charging conditions.

The basic factors which tend to cause a difference in performance in the two incinerator types are: (1) proportioning of the flame port and mixing chamber to maintain adequate gas velocities within dimensional limitations imposed by the particular type involved, (2) maintenance of proper flame distribution over the flame port and across the mixing chamber, and (3) flame travel through the mixing chamber into the combustion chamber.

The additional turbulence and mixing promoted by the turns in the retort incinerators cause the nearly square cross-sections of the ports and chambers in small size units to function adequately. In the retort size

range above 1000 pounds per hour the reduced effective turbulence in the mixing chamber caused by the increased size of the flow cross-section results in inadequate flame penetration, distribution and secondary air mixing.

As the capacity increases, the in-line model exhibits structural and performance advantages. Certain weaknesses of the small in-line type are eliminated as the size of the unit increases. For instance, with an in-line incinerator of less than 750 pounds per hour capacity, the shortness of grate length tends to inhibit flame propagation across the width of the ignition chamber. This, coupled with thin flame distribution over the bridge wall, may result in the passage of smoke from smoldering grate sections straight through the incinerator and out of the stack without adequate mixing and secondary combustion. In-line models in sizes of 750 pounds per hour or larger have grates long enough to maintain burning across their width resulting in satisfactory flame distribution in the flame port and mixing chamber. Since smaller in-line incinerators have relatively short grates, a problem of construction is added. As the bridge wall usually is not provided with any structural support or backing, and secondary air lanes are built into it, the wall is very susceptible to mechanical abuse. Careless stoking and grate cleaning in short chambered in-line incinerators can ruin the bridge wall in a short time.

No upper limit has been given the use of the in-line incinerator as little is known of operating efficiencies in capacities of over 4 tons per hour. Incinerators in the capacity range under 2000 pounds per hour may be standardized for construction purposes to a great degree. Incinerators of larger capacity, however, are not readily standardized as problems of construction, material usage, mechanized operation with stoking grates, induced draft systems, and other factors make each such installation essentially one of custom design. Even so, the design factors advocated herein are as applicable to the design of larger incinerators as to the design of smaller units.

VIII. DESIGN STANDARDS FOR NORMAL REFUSE INCINERATORS

Dimension standards presented in Figures 5 and 6 for retort and in-line incinerators are based upon recommended factors and parameters. The development of the standards was in accord with the following design notes:

a. Refuse: Normal refuse as defined.

b. Construction:

(1) Retort or in-line style constructed of standard pre-fired refractory firebrick with unspecified exterior shell construction.

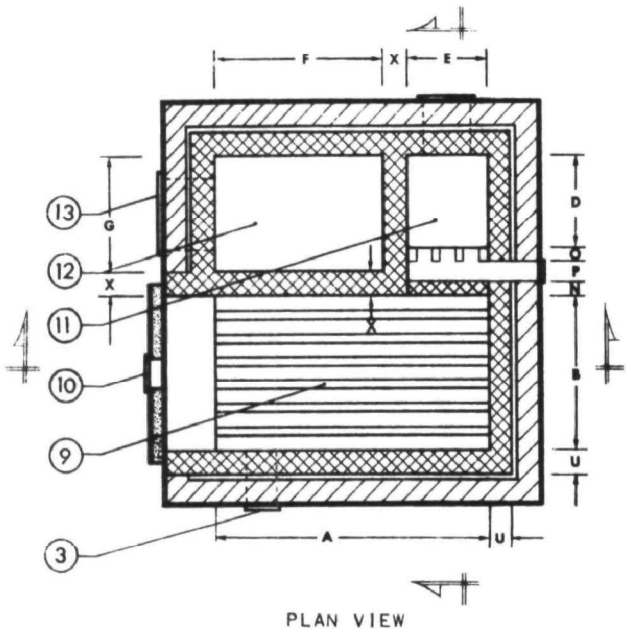
(2) Arch height and other vertical dimensions are averages based on construction with 60^{o} sprung arches.

(3) Sizes listed for ports shown as circular are nominal diameters of round air inlet spinners which have 35 to 50 per cent net open flow areas. Allowances must be made to provide equivalent areas in other port styles.

The dimensions itemized will vary in some cases from optimum values due to the elimination of partial or "cut" firebrick in wall construction. All dimensions are nominal, since brick construction tolerances vary.

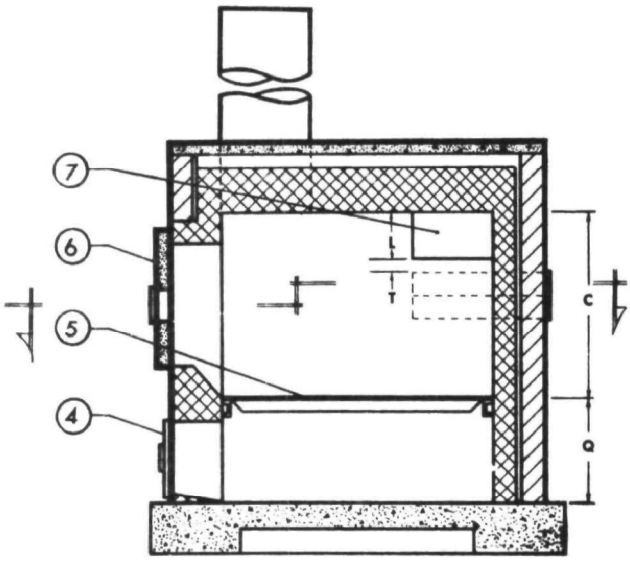
Dimension allowances must be made when construction differs from that used as the basis for the standards, i.e., flat or suspended arches instead of sprung arches; square or rectangular stack cross-sections instead of round. Average arch heights and recommended flow areas must be maintained.

External construction must be adequate structurally for the support of the refractory materials, with proper allowances for expansion and insulation. Foundation and stack construction details should be in accord with good structural practices and in conformance with local building ordinances.

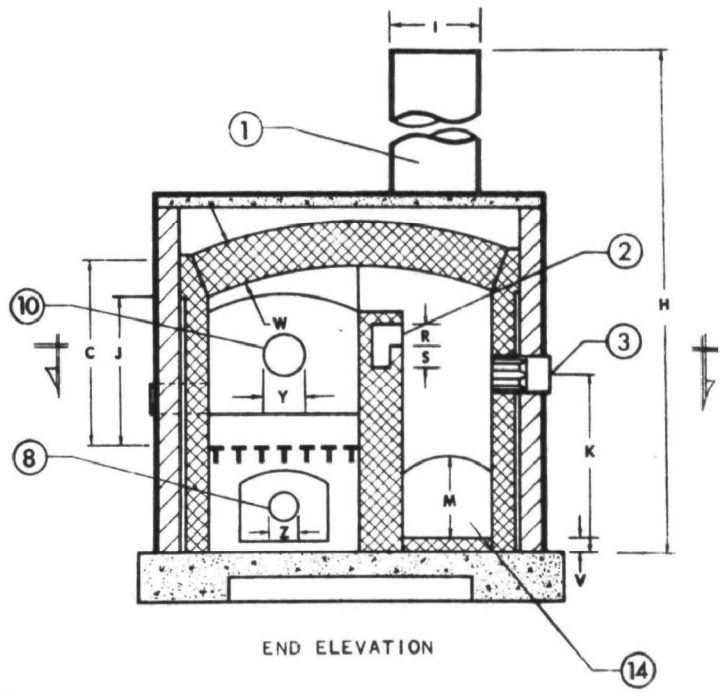


PLAN VIEW

1. STACK
2. SECONDARY AIR PORT
3. GAS BURNERS
4. ASH PIT CLEANOUT DOOR
5. GRATES
6. CHARGING DOOR
7. FLAME PORT
8. UNDERFIRE AIR PORT
9. IGNITION CHAMBER
10. OVERFIRE AIR PORT
11. MIXING CHAMBER
12. COMBUSTION CHAMBER
13. CLEANOUT DOOR
14. CURTAIN WALL PORT



SIDE ELEVATION

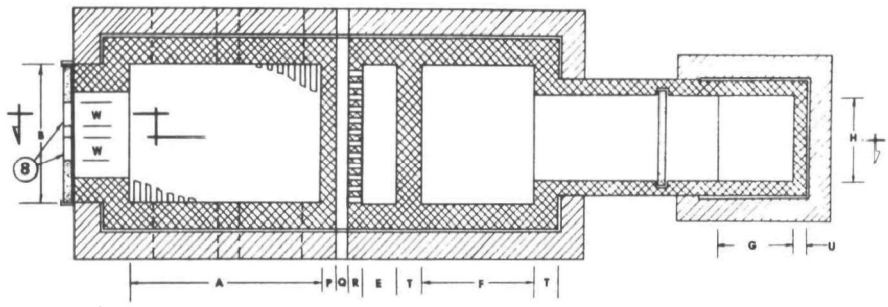


END ELEVATION

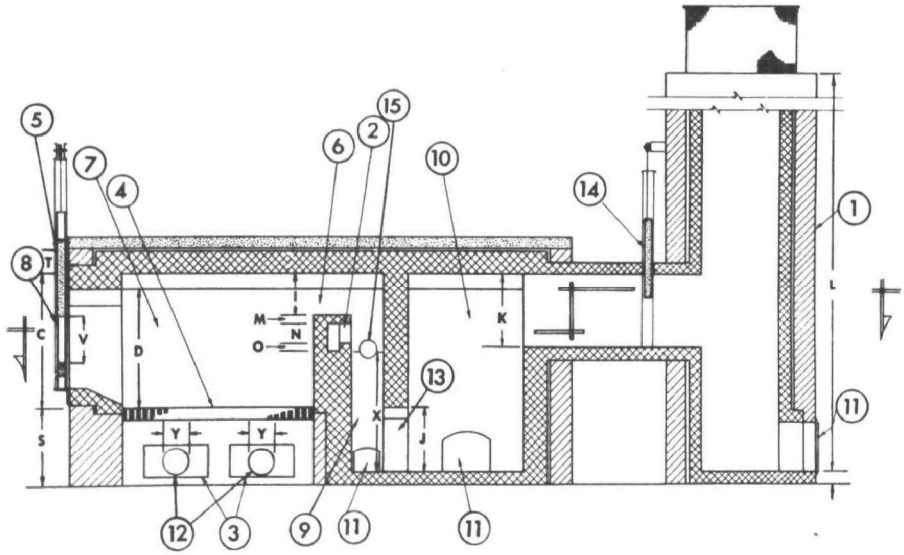
SIZE OF INCINERATOR POUNDS PER HOUR	LENGTH IN INCHES																									
	A	B	C	D	E	F	G	H*	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
50	31½	13½	22½	9	6½	20½	13½	18	8	18½	20	3½	10	4½	2½	2½	9	2½	2½	2½	4½	2½	4½	4½	6	4
100	40½	18	28½	13½	9	27	18	19	12	23	28	5	15	2½	2½	4	14½	5	0	2½	4½	2½	4½	4½	8	5
150	45	22½	33½	15½	11½	29	22½	20	14	27	35½	5	16½	4½	2½	4½	18	5	2½	2½	4½	2½	4½	4½	9	6
250	54	27	37½	18	13½	36	27	22	18	30	40	7½	18	4½	4½	4½	20	5	2½	2½	4½	2½	4½	4½	12	6
500	76½	36	47½	27	18	49½	36	28	24	36½	48½	12½	23	9	4½	4½	26	5	5	2½	9	4½	9	9	16	8
750	85½	49½	54	36	22½	54	45	32	30	40	51½	15	28	9	4½	4½	25	5	10	2½	9	4½	9	9	18	8
1000	94½	54	59½	36	27	58½	45	35	34	45	54½	17½	30	9	4½	4½	27½	7½	12½	2½	9	4½	9	9	22	10

*Dimension "H" given in feet.

FIGURE 5. DESIGN STANDARDS FOR MULTIPLE-CHAMBER RETORT INCINERATORS



PLAN VIEW



SIDE ELEVATION

1. STACK	6. FLAME PORT	11. CLEANOUT DOORS
2. SECONDARY AIR PORTS	7. IGNITION CHAMBER	12. UNDERFIRE AIR PORTS
3. ASH PIT CLEANOUT DOORS	8. OVERFIRE AIR PORTS	13. CURTAIN WALL PORT
4. GRATES	9. MIXING CHAMBER	14. DAMPER
5. CHARGING DOOR	10. COMBUSTION CHAMBER	15. GAS BURNERS

SIZE OF INCINERATOR POUNDS PER HOUR	LENGTH IN INCHES																							
	A	B	C	D	E	F	G	H	I	J	K	L*	M	N	O	P	Q	R	S	T	U	V	W	X	Y
750	85½	49½	51½	45	15½	54	27	27	9½	24	18	32	4½	5	7½	9	2½	2½	30	9	4½	5	11	51	7
1000	94½	54	54	47½	18	63	31½	31½	11	29	22½	35	4½	5	10	9	2½	2½	30	9	4½	7	12	52	8
1500	99	76½	65	55	18	72	36	36	12½	32	27	38	4½	5	7½	9	4½	4½	30	9	4½	8	14	61½	9
2000	108	90	69½	57½	22½	79½	40½	40½	15	36	31½	40	4½	5	10	9	4½	4½	30	9	4½	9	15	63½	10

*Dimension "L" given in feet.

FIGURE 6. DESIGN STANDSRDS FOR MULTIPLE-CHAMBER IN-LINE INCINERATORS

IX. DESIGN CALCULATIONS

To use the factors itemized in Table I, calculations must be made that will yield incinerator data in usable form. The calculations fall into three general categories: (1) combustion calculations based upon the refuse composition, assumed air requirements and estimated heat loss, (2) flow calculations based upon the properties of the products of combustion and assumed gas temperatures, and (3) dimensional calculations based upon simple mensuration and empirical sizing equations.

Simplifying assumptions that are made in connection with the incineration process should be reasonable estimates of conditions known to exist. Their value lies in the resultant ease of application of the calculated data in preparing incinerator designs and comparing them with the established parameters and with similar satisfactory units. The simplifying assumptions upon which calculations are based may be summarized as follows:

a. The burning rate and average refuse composition are taken as constant. An exception may be required when extremes in material quality and composition are encountered. The most difficult burning condition is assumed in such cases.

b. The average temperature of the combustion products is determined through normal heat loss calculations except that losses due to radiation, refractory heat storage and residue heat content are assumed to average 20-30 per cent of the gross heating value of the refuse during the first hour of operation. Furnace data generally available indicate that the losses approximate 10 to 15 per cent of the gross heat after four to five hours of continuous operation.

c. The overall average gas temperature should be about 1000°F when calculations are based on 300 per cent excess combustion air and the heat loss assumptions previously given. The calculated temperature is not flame temperature and does not indicate the probable maximum temperatures attained in the flame port or mixing chamber. Should the temperature be lower, the need for auxiliary primary burners is indicated and should be sized as indicated in Table I.

The temperatures used in checking gas flow velocities are approximations of the actual temperature gradient in the incinerator as the products of combustion cool as they pass from the flame port to the stack outlet.

d. Indraft velocities in the combustion air ports (overfire, underfire and secondary) are assumed to be equal, with a velocity pressure of 0.1 inch water column (equivalent to 1,265 ft. per min.). Control in design of the draft system so that available firebox draft is about 0.1 inch water column and oversizing of adjustable air ports insures maintenance of proper air induction.

e. Air ports must be sized for admission of theoretical air plus 100 per cent excess air. The remaining air enters the incinerator through the open charging door during batch operation and through expansion joints, cracks around doors, etc.

The combustion calculations needed to determine weights and velocities of the products of combustion and average temperatures may be derived from standard calculation procedures when the preceding assumptions are followed, using average gross heating values and theoretical air quantities. The sizing of inlet air areas in the proportions designated is accomplished readily once the volumes of air and inlet velocities are established. The minimum areas required should be oversized in practice by the factor indicated in Table I in order to provide operational latitude.

Determination of velocities requires only volume and temperature data for the products of combustion and the cross-sectional flow areas of the respective ports and chambers. Calculations for draft characteristics follow standard stack design procedures common to all combustion engineering. The stack velocity given for natural draft systems is in line with good practice and minimizes flow losses in the stack.

The remainder of the essential calculations needed to design an incinerator are based on substitution in the parameter equations and measurement of the incinerator dimensions. Recommended grate loading, grate area and average arch height may be calculated by equation or estimated from Figures 3 and 4. Proper length-to-width ratios may be determined and compared with proposed values.

Supplementary computations are usually required in determining necessary auxiliary gas burner sizes and auxiliary fuel supply line piping. Where moisture content of the refuse is less than 10 per cent by weight, burners usually are not required. Moisture content from 10 to 20 per cent normally will indicate the necessity of installation of mixing chamber burners, and moisture percentages of over 20 per cent usually will mean that ignition chamber burners must be included.

The criteria presented for incinerator design are applicable to the planning of most combustible refuse burners. The allowable deviations given in Table I should be interpreted with discretion to avoid consistently high or low deviation from the optimum values. Application of these factors to design evaluation must be tempered by judgment and by an appreciation of the practical limitations of construction and economy.

The following example shows the mathematical calculations necessary to design an incinerator.

Problem:

Design a multiple-chamber incinerator to burn 100 lbs/hr of paper with 15 per cent moisture.

Given:

Specific heat of products of combustion--0.26 Btu/lb/^{o}F

Gross heating value of one pound dry paper--7590 Btu
0.56 lb of water formed from the combustion of 1 pound of dry paper
21.7 pounds of products of combustion formed from the combustion of 1 pound of paper with 300 per cent excess air
68.05 scf of air theoretically necessary to burn 1 pound of dry paper
1265 fpm is equivalent to velocity pressure of 0.1 inch
283.33 scf of products of combustion formed from the combustion of 1 pound of paper with 300 per cent excess air
0.0092 inch of theoretical draft per foot of stack at 900^{o}F

Solution:

1. Composition of refuse

Dry combustibles	(100 lbs/hr)(0.85)	=	85 lbs/hr
Moisture	(100 lbs/hr)(0.15)	=	15 lbs/hr

2. Gross heat of combustion

(85 lbs/hr)(7590 Btu/lb) = 645,200 Btu/hr

3. Heat losses

Radiation, etc.(0.20)(645,200 Btu/hr)	= 129,040 Btu/hr
Evaporation of contained moisture (15 lbs/hr)(1060 Btu/lb)	= 15,900 Btu/hr
Evaporation of water from combustion (0.56 lb/lb)(85 lbs/hr)(1060 Btu/lb)	= 50,400 Btu/hr
Total	195,340 Btu/hr

4. Net heat

645,200 Btu/hr - 195,340 Btu/hr = 449,860 Btu/hr

5. Weight of products of combustion with 300 per cent excess air

Paper	(85 lbs/hr)(21.7 lbs/lb)	=	1,844 lbs/hr
Water	15 lbs/hr		15 lbs/hr
			1,859 lbs/hr

6. Average gas temperature

$$T = \frac{449,860 \text{ Btu/hr}}{(0.26 \text{ Btu/lb/}^{o}\text{F})(1859 \text{ lbs/hr})} = 930^{o}\text{F}$$

$$T = 930^{o}\text{F} + 60^{o}\text{F} = 990^{o}\text{F}$$

7. Combustion air requirement

Basis: 300 per cent excess air. 50 per cent of the air is admitted through open charging door and leakage around doors, ports, expansion joints, etc.

Combustion air
(85 lbs/hr)(68.05 cf/lb)(2) = 11,580 cfh
192.8 cfm
3.2 cfs

8. Air port opening requirements @ 0.1" wc

Total $\frac{(192.8 \text{ cfm})(144 \text{ in}^2/\text{ft}^2)}{1265 \text{ ft/min}}$ = 22.0 in^2

Overfire air port (0.7)(22.0 in^2) = 14.5 in^2

Underfire air port (0.1)(22.0 in^2) = 2.2 in^2

Secondary air port (0.2)(22.0 in^2) = 4.4 in^2

9. Volume of products of combustion

Basis: 60°F and 300 per cent excess air

Paper (85 lbs/hr)(283.33 cf/lb) = 24,080 cfh

Water (15 lbs/hr) $(\frac{379}{18})$ = 316 cfh

24,396 cfh
6.8 cfs

10. Volume of products of combustion through flame port

Total volume minus secondary air

6.8 cfs - (3.2 cfs)(0.20) = 6.16 cfs

11. Flame port area:

$\frac{(6.16 \text{ cfs})(1560^\circ\text{F})}{(60 \text{ fps})(520^\circ\text{R})}$ = 0.31 ft^2

12. Mixing chamber area:

$\frac{(6.8 \text{ cfs})(1460^\circ\text{R})}{(25 \text{ fps})(520^\circ\text{R})}$ = 0.76 ft^2

13. Curtain wall port area:

$$\frac{(6.8 \text{ cfs})(1410^{\circ}\text{R})}{(20 \text{ fps})(520^{\circ}\text{R})} = 0.92 \text{ ft}^2$$

14. Combustion chamber area:

$$\frac{(6.8 \text{ cfs})(1360^{\circ}\text{R})}{(6 \text{ fps})(520^{\circ}\text{R})} = 2.96 \text{ ft}^2$$

15. Stack area:

$$\frac{(6.8 \text{ cfs})(1360^{\circ}\text{R})}{(25 \text{ fps})(520^{\circ}\text{R})} = 0.71 \text{ ft}^2$$

16. Grate area:

From Figure 3 grate loading for average refuse is 18 $\text{lbs/ft}^2\text{/hr}$

$$\frac{(100 \text{ lbs/hr})}{18 \text{ lbs/ft}^2\text{/hr}} = 5.56 \text{ ft}^2$$

17. Arch height:

From Figure 4: 2'3"

18. Stack height:

$$\frac{0.17 \text{ inches wc}}{0.0092 \text{ inches wc}} = 18'6"$$

X. STANDARDS FOR CONSTRUCTION

Mechanical design and construction of multiple-chamber incinerators are regulated in several ways. Ordinances and statutes which set forth basic building requirements have been established by most, if not all, municipalities. Air pollution control authorities have also set some material and construction limitations which must be met; and manufacturers' associations have established recommended minimum standards to be followed. The building codes governing incinerator construction adopted in the past have been based primarily upon concepts of structural safety and fire prevention by restricting the rate of heat transfer through the walls. Little or no attention was given to the abrasion, erosion, spalling, and slagging that are encountered in a high temperature incinerator; yet these conditions lead to equipment failure which are comparable to structural or insulation failures. During the process of developing multiple-chamber units it has been found that high quality materials are necessary if a reasonable and satisfactory service life is to be expected.

The structural features and materials used in the construction of multiple-chamber incinerators can be discussed only in general terms. There are as many methods of erecting the walls of a multiple-chamber incinerator as there are materials from which to build them. The exterior of the incinerator may be either of brick or steel plate construction, and the refractory lining may be of firebrick, castable refractory or plastic firebrick or combinations thereof.

In accordance with standard practices, the exterior walls are protected further from extreme temperature conditions by providing a suitable peripheral air space in brick construction, or by using air cooling lanes or insulation in units fabricated from steel.

Changes in the methods of construction of multiple-chamber incinerators are typified in the portable prefabricated units available today. Installation of such incinerators is reduced simply to placement of the unit on its foundation and attachment of an auxiliary fuel supply where needed. Transportation considerations of weight and size limit the capacities of these units to 500 pounds per hour or less. Plastic and castable refractory linings in steel exteriors are used widely for this type of fabrication. All large incinerators of any type construction and those for which brick is desired as an exterior wall are erected on the site.

Refractory

The most important element of multiple-chamber incinerator construction, other than the design, is the proper installation and use of refractories. It is imperative that manufacturers use suitable materials of construction and be experienced in high temperature furnace fabrication and refractory installation, as faulty construction may well offset the benefits of good design. In choosing one of many available materials, service conditions alone should dictate the type of lining for any furnace. Minimum specifications of materials in normal refuse service should include high heat duty firebrick or 120 pounds per cubic foot castable refractory. These materials, when properly installed, have proved capable of resisting the abrasion, spalling, slagging and erosion resulting from high temperature incineration.

As incinerator capacity and severity of duty increase, superior refractory materials such as super duty firebrick and plastic firebrick should be employed. A recent improvement in standard construction has been the lining of all stacks with a 2000°F refractory lining of 2-inch minimum thickness.

Grates and Hearths

The grates commonly used in multiple-chamber incinerators are cast iron with "tee" or channel cross-section. As the size of the incinerator increases, the length of the ignition chamber also increases. In the larger hand-charged incinerators, is is difficult to keep the rear section of the grates completely covered because of the greater length of the ignition chamber. The substitution of a hearth at the rear of the ignition chamber in these units has been accepted as good practice, as a hearth in this region prevents open areas from being formed in the normally thin refuse pile. This prevents excessive underfire air from entering in front of the bridge wall and reduction of flame carryover into the mixing chamber. As surface combustion is the primary combustion principle, the use of a hearth has little effect upon the combustion rate.

Installation of a sloping grate, which slants down from the front to the rear of the ignition chamber, facilitates charging. Such a grate also increases the distance from the arch to the grates at the rear of the chamber and reduces the possibility of fly ash entrainment which frequently occurs when the fuel bed surface approaches the level of the flame port.

Air Inlets

Positive control for all combustion air inlets should be provided by means of fully adjustable dampers. The retort incinerator designs shown in Figure 5 incorporate round spinner type controls with rotating shutters for both underfire and overfire air openings and rectangular ports with sliding or hinged dampers for the secondary air openings. The in-line incinerator designs shown in Figure 6 have rectangular ports for both overfire and secondary air openings and spinner style ports for the underfire air openings. Air ports may be of any convenient shape although the port arrangement indicated in the in-line designs with rectangular overfire ports is preferred since the combustion air is distributed more evenly across the fuel bed.

Stack Construction

Stacks for incinerators with a capacity of 500 pounds per hour or less are usually constructed of a steel shell lined with refractory and mounted over the combustion chamber. A refractory lined, reinforced red brick stack is used as an alternate method of construction when appearance is deemed important. Stacks for incinerators larger than 500 pounds per hour are normally constructed in the same manner as those for smaller incinerators but often are free-standing for structural stability, as indicated in Figure 6. Stack linings should be of increased thickness in proportion to the incinerator size.

Induced Draft

The replacement of a stack by an induced draft system introduces complications. It is necessary to cool the effluent gases to reduce their temperature to that for which the draft fan is rated. Evaporative cooling with water is standard practice. The contact of the flue gas with water forms a solution of weak acid. The action of the acid eventually corrodes the evaporative cooler and accessory equipment, making replacement necessary. To overcome these problems, stainless steel or acid resistant brick may be installed. The excess spray water also creates a problem, requiring a sewer outlet for its disposal or a recirculation system for its re-use. Recirculation of acidic water not only results in more rapid corrosion of the spray chamber and fan, but also subjects the pump, piping and spray nozzles to corrosion.

XI. OPERATION

The most important single aspect of operation of a multiple-chamber incinerator is the charging of refuse into the ignition chamber. A multiple-chamber incinerator must be charged properly at all times in order to reduce the formation of fly ash and to maintain adequate flame coverage of the burning rubbish pile and the flame port.

A recommended charging cycle starts with the placing of the initial charge of refuse in the incinerator. The ignition chamber should be filled to a depth approximately two-thirds to three-fourths of the distance between the grates and the arch prior to light-off. After approximately half of the refuse has been burned, the remaining refuse should be carefully stoked and pushed as far as possible to the rear of the ignition chamber. New refuse should be charged over the front section of the grates which were emptied by the moving of the burning refuse. To prevent smothering the fire, no new material should be charged on top of the burning refuse at the rear of the chamber. Using this charging method, "live" flames will cover the rear half of the chamber, fill the flame port and provide nearly complete flame coverage in the mixing chamber. The fire will propagate over the surface of the newly charged material, spreading evenly and minimizing the possibility of smoke emission. Since the refuse pile need not be disturbed unduly, little or no fly ash will be emitted.

It is characteristic of the multiple-chamber incinerator that emission control is built-in, if it is operated with reasonable care. The discharge of combustion contaminants is almost entirely a function of ignition chamber design and the actions of the operator. Control of smoke is attained by proper admission of combustion air and by utilization of secondary burners in cases of incineration of refuse with a low heating value or a high moisture content. The use of secondary burners is required at times as the efficiency of the mixing chamber depends upon both luminous flame and adequate temperatures for vapor phase combustion. The need for supplementary burners may be determined readily by observing the nature of the flame travel and coverage at both the flame port and the curtain wall port.

The overfire and underfire air ports are usually half open at light-off and are opened gradually to a full open position as the incinerator reaches its rated burning capacity. If black smoke is emitted, it is advisable to admit more secondary air and reduce the capacity of other air ports. On the other hand, white smoke is usually the result of too

cold a furnace and may be eliminated by reducing or closing all air ports. Following the final charge of refuse, the air ports are closed gradually so that during the burndown period the only air introduced into the furnace is provided through leaks around door and port openings.

When ignition and mixing chamber burners are necessary, the mixing chamber or secondary burner is lighted prior to placing the incinerator in operation. The burner should remain in operation for the first 15 to 20 minutes of operation, and should be used thereafter as needed. Under normal conditions, the ignition chamber or primary burner is used only when wet refuse is charged. At other times, its use also may be required when burning refuse containing high percentages of inorganic compounds such as clay fillers used in quality paper.

XII. CONCLUSIONS

The most important item to be considered in the selection of an incinerator is its capacity. A complete survey of the quantity and type of refuse produced should be conducted and accurate weights obtained. Consideration should be given to possible future expansion of existing facilities. On the basis of this information, the size of the incinerator is determined by the scheduled number of hours of operation.

It is also important that the site for the incinerator be selected with reasonable care. Its position will be dictated primarily by the location of existing equipment and spatial provisions necessary for convenient operation and adequate storage. Also to be considered are the proximity of surrounding buildings, the need for incinerator mobility and the aesthetic requirements to be met in some situations.

The purchase of an incinerator always should be by contract that explicitly specifies structural and refractory requirements. The contractor should be required to guarantee that the operation of the incinerator will comply with the statutes of all agencies and that mechanical performance, including refractory and material service life, will be satisfactory for a reasonable period.

Combustion engineering and furnace design authorities agree that multiple-chamber incineration combines the best means of disposing of combustible refuse at the source with a minimum emission of air contaminants. Furnace manufacturers have found that construction of multiple-chamber incinerators of designs that comply with air pollution control regulations is only slightly more difficult or expensive than equivalent construction of industrial incinerators of earlier design.

The multiple-chamber incinerator has been accepted by industry and the public in Los Angeles County as a practical device to dispose of combustible wastes economically and within the limits of air pollution control regulations.

XIII. REFERENCES

1. State of California Health and Safety Code, Section 24242. A person shall not discharge into the atmosphere from any single source of emission whatsoever any air contaminant for a period or periods aggregating more than three minutes in any one hour which is: (a) As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or (b) Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subsection (a) of this section.

   Los Angeles County Air Pollution Control District Rules and Regulations, Rule 53. Specific Contaminants. A person shall not discharge into the atmosphere from any single source of emission whatsoever any one or more of the following contaminants, in any state or combination thereof, exceeding in concentration at the point of discharge: (a) Sulphur Compounds calculated as sulphur dioxide (SO_2): 0.2 per cent, by volume. (b) Combustion Contaminants: 0.3 grain per cubic foot of gas calculated to 12 per cent of carbon dioxide (CO_2) at standard conditions. In measuring the combustion contaminants from incinerators used to dispose of combustible refuse by burning, the carbon dioxide (CO_2) produced by combustion of any liquid or gaseous fuels shall be excluded from the calculation to 12 per cent of carbon dioxide (CO_2).

2. Chass, R. L., Lunche, R. G., Shaffer, N. R., and Tow, P. S., "Total Air Pollution Emissions in Los Angeles County." Presented at the 52nd Annual Meeting of the Air Pollution Control Association, Los Angeles, California, June 1959.

3. Chass, R. L., and Rose, A. H., "Discharge from Municipal Incinerators." Journal of the Air Pollution Control Association (Air Repair), Vol. 3, No. 2, November 1953.

4. MacKnight, R. J., Williamson, J. E., Sableski, J. J., and Dealy, J.O., "Controlling the Flue Fed Incinerator." Journal of the Air Pollution Control Association, Vol. 10, No. 2, April 1960.

5. Rose, A. H., and Crabaugh, H. R., "Incinerator Design Standards." A.S.M.E., First International Congress on Air Pollution Controls, March 1955.

6. Kanter, C. V., Lunche, R. G., and Fudurich, A. P., "Techniques of Testing for Air Contaminants from Combustion Sources." Journal of the Air Pollution Control Association, Vol. 6, No. 4, February 1957.

THE PROBLEMS OF APPLYING INCINERATOR CRITERIA

Edward M. Voelker

I AIR POLLUTION CONTROL AUTHORITIES

Today many communities, counties and states have created Air Pollution Control Authorities and the authorities have in turn adopted criteria for the design of incinerators. Each day more and more authorities are being established and again many are adopting criteria of their own. Much of the "criteria" or "rules" are incomplete making it almost mandatory to obtain prior approval before making a recommendation to an architect, engineer, or owner and certainly before bidding the job.

Needless to say this in many cases is impossible because of time and cost limitations, and in other cases where time does permit, the prior approval is not recognized by the air pollution authority at the time of formal submission since he, in the meantime, has had some new thoughts on the subject.

In attempting to compare the criteria being issued by these governing bodies, it becomes immediately apparent that the air pollution control officials are not aware of the situations being created by their various independent actions. Unfortunately it is impossible to make a direct comparison of all regulations in effect at the present time nor for that matter can any one individual become familiar with all such regulations. In many cases a direct comparison is impossible because of the lack of some basic design factor in the published version of the criteria, or the regulations are changed and quite often not in written or published form.

The need for test procedures, and incinerator criteria acceptable to all Air Pollution Control Authorities is of vital importance to the incinerator industry. To achieve this goal the Incinerator Institute of America has established liaison between its organization and the TA-3 Committee of APCA and also with the Incinerator Committees of the American Society of Mechanical Engineers and the American Gas Association.

The Incinerator Institute of America has also established an associate membership for companies and individuals who are not in the incinerator business but whom the Institute believes can contribute to the modern requirements of air pollution control. We sincerely invite such organizations as oil and gas burner manufacturers, firebrick, instrument, gas washer and scrubber manufacturers to join and become active on our technical and standards committees.

II INCINERATOR CRITERIA

The incinerator criteria being adopted today by states, counties and communities fall into two distinct categories:

A The very rigid criteria usually in the form of charts and diagrams and covering only incinerators for Type 1 and Type 2 Waste.

B The flexible criteria which sets forth minima and maxima governing designs of incinerators for burning all types of waste.

From the viewpoint of the Air Pollution Control Authority or Department, the rigid criteria is the more acceptable because by its very nature it is the easier and simpler to apply. The examiner, when reviewing an application, has no problems - either the application and accompanying drawing conforms to the charts and diagrams in the criteria and he approves the application, or they do not and he rejects it. However, such rigid criteria leave nothing to the imagination of the incinerator designer and certainly leave no room for meritorious improvements.

Eventually the responsibility for the design must be decided by the Courts. In areas where the Air Pollution Authority advises the incinerator designer exactly how he must design the incinerator and exactly how he must construct it, is the Air Pollution Authority or the designer and builder responsible if the installation cannot be operated at capacity and within the emission limits?

III RIGID CRITERIA

Since there is such a wide variation among the rigid criteria adopted in various areas, one can only assume that certain features of such criteria are based on the whim of one individual involved and not the combined thinking of experienced designers. In the East we have rigid criteria based on the assumption that complete combustion of a homogeneous mass of refuse can be obtained in one single chamber and in the far West we have criteria based on many tests performed proving that multiple chambers are necessary for complete combustion. What has happened to the three "Ts" - temperature, time, and turbulence - which have always been considered a must in good incinerator design? Many articles have been written on this subject over the years confirming these points, yet have never been disputed.

At the Air Pollution Control Association Annual Meeting in New York in June 1961, H. G. Meissner presented a paper from which is quoted the first paragraph:

> "The three Ts of combustion, namely "time," "temperature," and "turbulence" are so closely related that they must be considered together in determining the performance of the incinerator. Without time enough for the combustible matter to burn, the desired temperature will not be obtained, and without adequate turbulence neither the time or temperature requirements will be achieved."

At about the same time the New York City criteria was issued with no request or provisions for turbulence as a means of encouraging complete combustion, with complete combustion to take place in the primary chamber, and secondary chambers provided for fly ash settlement only.

Reasonably high velocities and turns for the products of combustion, or forced air in the form of jets are the two systems most generally accepted as the means of creating turbulence and mixing to promote complete combustion. The former method is certainly the more reasonable in cost and for most refuse burning, as effective as the latter.

Under the criteria issued by Allegheny County, Pa., the incinerator designer cannot provide in the incinerator any zone where the products of combustion exceed five feet per second. When designing an incinerator to be built in Columbus, Ohio, the designer must provide an area in the incinerator where the velocity of the products of combustion must reach fifty-five feet per second.

The Allegheny County criteria does not cover the important basic design points of quantities of theoretical and excess air nor operating temperatures. Columbus, Ohio, on the other hand, calls for 300% excess air and design temperatures considerably below those acceptable to most air pollution control authorities and incinerator designers.

This brings us to an even more important weakness of a rigid criteria in which precise dimensions and configuration of design are outlined; namely the difficulty of differentiating between designs for materials other than Type 1 or Type 2 Waste. Most rigid criteria which are now in effect are based upon the burning of normal rubbish which may contain small quantities of garbage or other reluctantly combustible materials. Such criteria, however, so restrict the incinerator designer that he has difficulty in providing equipment which he feels can handle such other wastes as might be collected.

The presence of a refractory hearth area will, of course, provided for the retention of wet materials until the moisture can be driven off and the organic materials burned. But in the rigid criteria the interior dimensions of the incinerator are determined by need for large volumes and great quantites of excess air for burning Type 1 Waste and a change is required in the criteria if proper operation is to be achieved. It is not sufficient to say that multiple units should be provided each with its special design in order to take care of its particular material since this involves the owner in collection and selection of waste which is at best impractical. From experiences we know that all of these materials are collected together and it has long been the goal of the incinerator designer to provide equipment which is as versatile as possible. The modern hospital will produce large

quantities of bulky dry waste which must, of course, be disposed of in the incinerator. The same hospital will, however, also produce wet garbage from the kitchen area as well as anatomical and pathological wastes from the laboratories and operating rooms and possibly such materials as cage wastes from their animal laboratories.

The incinerator design which is capable of handling such heterogeneous materials may vary considerably from that which has been predetermined by the local Air Pollution Authority as proper for incinerator design. This same problem often arises in the field of industry where the wastes may include Types 4, 5, and 6 in appreciable quantities. Again the incinerator design for general rubbish may have to be varied considerably to provide facilities for special materials but most "rigid criteria" have no provisions for flexibility of design.

IV FLEXIBLE CRITERIA

From the viewpoint of the incinerator designer or builder, the flexible criteria are by far the more acceptable. The incinerator must, of course, be designed within the maximum and minimum set forth, so the inexperienced cannot go too far afield, but the experienced designer can apply his knowledge and experience to both design and construction. Most important of all, however, is that he, the designer and constructor, is held responsible for his design. This the architect, engineer, and owner want and this the responsible designer is willing to accept.

In metropolitan areas around the country, it is becoming increasingly important that criteria in one form or another be established in order that the engineer and/or architect can properly plan the waste disposal equipment and its space requirements. A modern hospital or laboratory facility is designed in such a way that no waste space is provided and each and every factor in its operation must be carefully planned. The incinerator designer is constantly being asked to make recommendations upon which space allocations can be established and which in turn will determine what stack facilities, utility services, etc., must be provided. They cannot wait until a general contractor has been established and he in turn has determined all of his subcontractors, including the incinerator contractor, in order to determine what will be acceptable in the way of incincerator facilities for their various waste materials.

Neither can the incinerator designer provide the necessary data to allow a formal application to be presented to the local Air Pollution Authorities. This then leaves the absolute necessity of establishing acceptable limits of design based not only on Type 1 Waste materials but on the anticipated character of wastes whatever they may be. It further necessitates an approach by Air Pollution Authorities which will allow the incinerator designer prior knowledge as to the acceptability of a special design. A flexible criteria augmented by a practical means of confirming operation within acceptable limits would, therefore, leave the incinerator designer free to make proper recommendations, based upon his experiences, to archietects or engineers with the assurance that these recommendations would be acceptable to the local authorities.

If after such an installation were made, criticism is then leveled at the owner for the operation of his equipment, there is no question of responsibility since it lies entirely with the incinerator designer and he must make whatever changes are necessary to comply with the local ordinances.

As outlined above, the use of flexible criteria does indeed place the responsibility for the design upon the incinerator engineer. It further points up the need for an economical, visual, and practical test of the operation of such equipment in order to prove compliance with the local ordinances as they apply to stack emissions.

V INCINERATOR STANDARDS OF I. I. A.

It is the sincere belief of the members of the Incinerator Institute of America that the Incinerator Standards of April 1963, its fifth published version, outlines the basis for good incinerator design. The Standards are in sufficient detail, yet flexible enough to

allow the designer leeway in providing for any type of waste, and not restrictive to meritorious improvements.

The requests for copies is definite proof of its popularity and, since more and more communities are adopting it, in whole or in part, as their incinerator criteria, it is further proof of its reasonable approach to good incinerator design.

It is interesting to note that one of the Incinerator Institute members, Joseph Goder Incinerator Company, has constructed and tested three incinerators one designed on the basis of the I. I. A. Standards, another based on the Los Angeles criteria and the third based on the New York City criteria. The results of the tests, conducted by a recognized testing laboratory, are available through I. I. A. and show that the incinerator designed according to the I. I. A. Standards is as efficient as the other two. If the efficiency of operation is compared to construction costs, the I. I. A. design was approximately 20% more efficient than the Los Angeles design and approximately 100% more efficient than the New York City design.

In comparing the criteria published by the various Air Pollution Control Authorities with the Incinerator Institute Standards, there appears to be no disagreement with the following portions of the I. I. A. Standards:

A Definitions

B Waste Analysis

C Classification of Incinerators

D Specifications of Incinerators by Classes

E Cast iron and hearth area requirements for the burning of solid refuse. (Although there appears to be some minor disagreements on the use of hearth areas and the proportion of one to the other and the proportion of length versus width, it must be remembered that the areas stipulated in the Institute Standards are minimum and can be increased at the discretion of the incinerator designer.)

F Auxiliary burner capacity

The points of disagreement might be listed as follows:

1 Furnace volume: The point of disagreement on this subject appears to center more on whether complete combustion takes place entirely in the primary chamber or continues after turbulence has been provided.

2 "Time," "temperature," and "turbulence": These we do not believe are actual subjects of disagreements but rather oversights in many of the criteria being issued. Apparently Allegheny County recognizes this and now permits a higher velocity than five feet per second in the first gas port. Columbus, Ohio, on the other hand, have apparently concluded the 55 feet per second for velocity is excessive and they now permit a 20% reduction on all sizes of incinerator and as much as 85% reduction on units with a capacity of 100 lbs per hour or less.

3 Amounts of excess air to be used in calculations: This again appears to be an oversight not to have included the requirement in the criteria rather than a disagreement. The Institute Standards require 100% excess air, New York City speaks of 200% but actually uses 100%, whereas Columbus, Ohio, requires 300% with a resultant lower furnace temperature.

4 Velocity reduction required to settle out fly-ash.

To give you a visual comparison of incinerators based on published criteria and standards, there is shown below five designs. Each incinerator shown has a rated capacity of 1000 lbs hour of Type 1 Waste.

All of the figures are drawn to scale with 1/4 inch equal to one foot, and "A" indicating location of secondary air inlet and "B" the auxiliary gas burner.

When using the I. I. A. Standards, the exact locations of secondary air inlets and auxiliary burner are determined by the incinerator designer.

Furnaces in Figs. 1, 2, and 3 have an internal width of five feet and furnaces shown in Figs. 4 and 5, an internal width of four feet six inches.

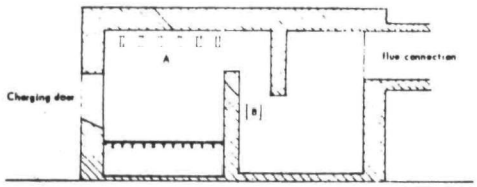


Fig. 1.

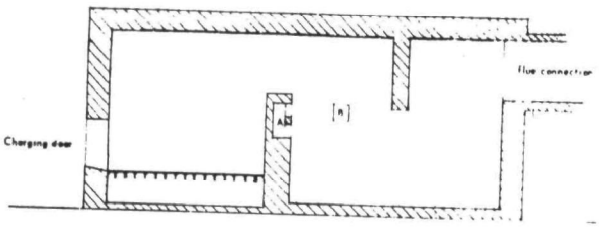


Fig. 2.

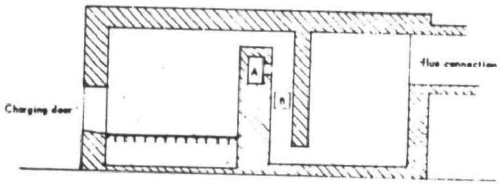


Fig. 3.

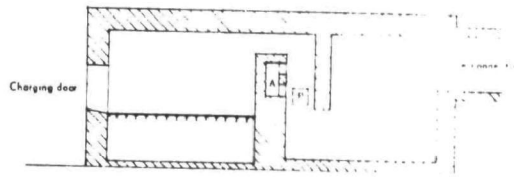


Fig. 4.

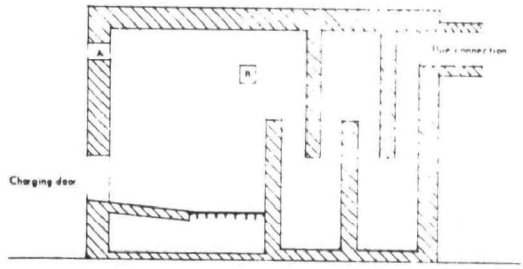


Fig. 5.

REFERENCE

1 A. P. C. A. Publication, Vol. 14, No. 9, Sept. 1964. pp 363-365.

DISCUSSION OF "THE PROBLEMS OF APPLYING INCINERATOR CRITERIA"

H.G. Meissner* and H.C. Johnson**

The author discourses at considerable length on the relative merits of "flexible" vs. "rigid" criteria, without defining either term. He acknowledges that there must be maximum and minimum values, so that the "inexperienced cannot go too far afield, but the experienced designer can apply his knowledge and experience to both design and construction." Unfortunately there seems to be more inexperienced than experienced incinerator designers, at least in this territory.

Criteria are in many ways similar to building codes and specifications, in that they set up standards that will be acceptable, so that designers will know beforehand what to expect and how to plan. When the criteria are too flexible, the examiners personal opinion may decide approval or disapproval. The IIA Standards are in some respects inadequate for this reason, as H.C. Johnson notes in his discussion. We have found in checking various incinerator manufacturer catalogs, as much as 100% variation in sizing for the same capacity. In one test, the incinerator could not burn more than 25% of its rated capacity, yet we have been asked why we consider the refuse burning rate such an important factor.

Basing approval entirely on test results may be satisfactory where the number of incinerators is limited, but would place an impossible burden on both parties, where hundreds of applications are filed yearly, many of which would have to be tested to prove compliance. At present we know of no "economical, visual, and practical test of the operation of such equipment in order to prove compliance with the local ordinances, as they apply to stack emissions," which the author suggests is desirable.

The New York City Criteria state that "in order to preclude prohibition of meritorious improvements not in compliance with these Criteria, the Commissioner may consider alternate designs. Experimental or temporary permits may then be issued, with final approval when and if the incinerators are found to operate satisfactorily."

The so-called tests run on three designs of incinerators by the Joseph Goder Incinerator Company, were of such short duration, and under such unfavorable operating conditions of draft, etc., that the results would be considered unsatisfactory for all three designs.

The author's comparison of efficiency of operation with construction costs, to show that one design is 100% more efficient than another, is novel but totally unacceptable to a control agency, as this would favor a poor design just because it was cheap.

This paper would be of more value if the author had been more specific in what he wants. Repeated reference to the IIA Standards, which are in themselves not too specific, leaves the reader wondering just what Criteria the author would favor.*

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This paper questions the role of air pollution control agencies in setting incinerator design standards. It infers that the design standards set up by the Incinerator Institute of America should be adopted in preference to any other standards. I believe that most air pollution authorities would be willing to accept the standards of some organization such as IIA, the APCA, or the ASME, if they could be assured that adoption of such standards would result in satisfactory incineration in their area.

The question to be answered then is what standards will provide incinerators which in actual day-to-day operation, will discharge the least amount of objectionable materials into the atmosphere, and provide the lowest total cost of incineration?

Diagrams of four basic designs are presented tests on three of these are mentioned. The apparent similarity between the Los Angeles and IIA diagrams in this paper is misleading. The IIA Standards as presently written allow wide variations in design not shown or mentioned in the paper. No test data or stack observations have been presented to show the effect of these many possible design variables on emissions. Intelligent analysis of these design standards cannot be made until an extensive test program has been carried out on all of the possible incinerator designs under these standards. Before such a testing program is carried out, agreement should be reached on test methods, types of material to be burned, and operating procedures during the tests. The test results will not be representative of actual emissions from incinerators unless the materials burned represent the usual type of refuse to be burned, and incinerators are operated in the normal manner to be expected by the majority of operators. Most operators and owners display little interest in their incinerator, therefore, it must be designed to be as foolproof as possible. An incinerator must be capable of burning a wide variety of refuse charged in varying amounts and varying cycles without violating air pollution requirements.

Under these adverse operating conditions, we have found the Los Angeles design discharges less visible plume, particulate, and combustibles than other designs observed or tested in this area. Los Angeles engineers have supplied design data for several special designs which have not yet been published; this includes pathological, insulation burners, and wood waste burners.

The Los Angeles multiple chamber incinerator admittedly is an expensive design, but the statement that the IIA design is 20% cheaper than the Los Angeles design needs clarification. This difference represents the difference in burning rate per square feet of grate between IIA and Los Angeles publications. Burning rate tests have been conducted by this District on Los Angeles and IIA designs. Very little difference in burning rate per square feet of grate per hour were noted. In fact, under normal operating conditions, burning rates were considerably below either the Los Angeles or IIA ratings. Therefore, if incinerators are given a nominal rating that can be normally achieved, the first cost should be compared on the basis of square feet of grate area. When put on this basis, the cost of the Los Angeles and IIA design are not far apart according to the representatives of the Bay Area Incinerator Industry.

We have had no experience with the New York Allegheny County designs, and have received no test data on these units. However, our experience with the Los Angeles design indicates that while some improvement in fly ash emission may have been achieved with these designs, all other emissions could be expected to be considerably higher. The emission of fly ash is prohibited in this District if it falls on the property of others and causes an annoyance. The few complaints received have been completely solved only by the installation of some type of water spray chambers. No baffle chambers have been tried, but settling chambers have not proved effective in preventing the emission of paper ash containing essentially no combustibles.

The question of flexible vs. rigid criteria should also be considered. This District depends entirely on emission standards, compliance being determined by tests and plume observations. The West Coast Incinerator Industry has standardized on the Los Angeles designs, which have been quite satisfactory in this area. However, several special designs have been installed to fit into existing space, which could lead to new designs to reduce cost or achieve other desired characteristics. **

**Senior Air Pollution Engineer, Bay Area APCD, San Francisco, California.

REFERENCE

1 APCA publication, Vol. 14, No. 9, pp. 366-377. September, 1964.

COMBUSTION AND HEAT CALCULATIONS FOR INCINERATORS

Elmer R. Kaiser*

I ABSTRACT

The design of industrial and municipal incinerators is based on combustion and heat considerations. The procedures are given for calculating the quantities of air, flue gas, water and heat, as well as the gas temperatures. To assist the reader, a municipal incinerator is used as an example. The relation between refuse analysis and flue gas analysis is explained. Sections on dry and wet dust collection are included.

II INTRODUCTION

Incineration is a combustion process which today is becoming more technical and scientific. More understanding of the process through quantitative measurement and analysis will surely aid in developing the incinerator art as it has similar arts, such as steam generation and gas manufacture.

Coupled with experience factors and valid assumptions, combustion and heat calculations are invaluable in designing an incinerator and in evaluating its performance. The sizing of furnaces, gas passages, dust collectors, fans and stacks are based on expectations deduced with the help of combustion and thermal data.

The purpose of this paper is to provide some of the methods and formulas for establishing the relationships between the quantities of air, refuse, residue, water and fly ash, as well as the heat and material balances. When the flow sheet and temperatures have thus been established for a given incinerator, the engineer can size the equipment. The latter subject includes many experience factors beyond the scope of this paper.

The methods and procedures that will be helpfull shall be presented for a hypothetical incinerator and refuse. Data which will be assumed are close to those for actual incinerators and refuse, but are intended for illustration only. In actual designs the reader is advised to use data that apply to the designs.

The calculations are presented in a basic form for clarity and for the precision necessary for heat and material balances. Short cuts are possible and desirable, especially for any specific type of incinerator. Nomograms graphs, tables and special factors are available elsewhere or may be prepared by the reader. However, one frequently returns to the fundamental relationships and should retain facility with them. The weight method of combustion calculation is used in this paper rather than the mole method. Both methods are explained in the 37th edition of "Steam".(1)

III EXAMPLE INCINERATOR

A hypothetical municipal incinerator furnace is assumed which has continuous charging, 24-hr a day, and continuous residue discharge.

A Rated Capacity

Usually expressed as tons per 24-hr, the rated capacity of this incinerator is 240 tons. The hourly charging rate is 10 tons or 20,000 lb of refuse.

B Grate Loading - Firing Rates

Assume the grate had a projected plan area of 333 sq ft. The firing rate = 20,000/333 = 60 lb per sq ft-hr.

C Furnace Volumes - Combustion Chamber Volume

Assume the primary furnace has a volume above the grates of 31.2 cu ft per ton of rated capacity, the furnace volume is 31.2 (240) = 7500 cu ft.

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A combustion chamber usually follows the furnace and has the purpose of completing combustion of the gases and suspended particles, as well as trapping some of the fly ash. Volumes range up to 2.4 times the furnace volume.[2] In some cases the primary furnace discharges its gases into a spray chamber where water quenches combustion and traps particulates matter.[3] For the present purpose, one may assume complete combustion of the gases but allow 4 per cent unburned carbon in the total residue.

D Heat Release Rates

The higher heating value of the refuse is assumed at 4230 Btu/lb as fired. The nominal heat release per cu ft of furnace volume is 20,000(4230)/7500 = 11,280 Btu/cu ft-hr. Because of unburned carbon in the residue, the actual heat release rate is 10,890 Btu/cu ft-hr.

E Gas Cleaning

Because of the carry-over of fly ash from the furnace and combustion chamber, and alternative possibilities for cleaning the gases, calculations will be presented for the furnace and combustion chamber in combination with:

1 A spray chamber followed by a dry-type dust separator, ID fan and stack.

2 A gas scrubber, ID fan and stack.

Hence, the hypothetical incinerator consists essentially of a furnace with continuous charging, a combustion chamber, a spray chamber for partially cooling the gases and trapping some fly ash, one of several methods of collecting dust, an induced-draft fan and stack.

Steady-state operation is assumed at rated capacity.

IV BASIC ASSUMPTIONS

A Refuse

The charging rate is assumed at 20,000 lb an hr of refuse consisting of:

	Per cent
Moisture	30.00
Carbon	22.95
Hydrogen	3.25
Oxygen	18.80
Nitrogen	negl.
Sulfur	negl.
Non-combustibles*	25.00
	100.00

The net hydrogen (H) available for combustion is 3.25 - (18.80/8) = 0.90 per cent. The bound water in the above refuse, which is released during combustion, is 18.80(9/8) = 21.15 per cent of the residue.

In essence, the dry combustible matter consists in this case of 4 parts of cellulose, starch and sugar ($C_6H_{10}O_5$) and 1 part of a mixture of proteins, fats, oils, waxes, rubber, plastics, etc. The main constituent is cellulose, which like starch and sugar has the following makeup:

	Per cent	
Carbon	44.4	Approximate higher heating value (HHV): 7500 Btu/lb[4]
Net hydrogen, (H)	0.0	
Moisture (bound water)	55.6	
	100.0	

The mixture of proteins, fats, oils, etc. has, for practical purposes, the following composition:

	Per cent	
Carbon	77.4	Approximate higher heating value (HHV): 17,000 Btu/lb
Net hydrogen, (H)	10.0	
Moisture (bound water)	12.6	
	100.0	

*Non-combustibles include ash, glass, ceramics, mineral dirt and metals. The latter are partially oxidized, release heat, and increase in weight. The design calculations for the burning of the metals may be neglected in this case.

Nitrogen is about 0.3 per cent and sulfur is below 0.2 per cent of municipal refuse. They are not included in these calculations. By arithmetic, the HHV of the combined refuse is:

$$\frac{4(7,500) + (17,000)}{5} (0.45) = 4230 \text{ Btu/lb.}$$

B Air

To prevent furnace temperatures high enough to cause slag to run down the furnace walls, enough air is supplied to control the temperature of the furnace exit gases at 1600 - 1800°F. As a first approximation, the air to the grate and furnace is 2.3 times the stoichiometric air requirement, or 130 per cent excess air. The air is supplied at 80°F and 30 in. Hg barometer. The air contains 0.0132 lb water vapor per lb dry air. The air, refuse, and water for sprays are all assumed to be at 80°F. At any specific location a different set of conditions may be assumed.

C Residue and Fly Ash

The total solid residue is assumed to contain 4 per cent carbon. All of the unburned carbon is assumed to remain in the grate residue, although in actual practice some is lost in the stack gases. The residue from the grate is cooled from 1200°F to 150°F by spraying with water or dropped into water before removal from the ash pit. The water vapor produced joins the furnace gases. The carry-over of solids with the furnace exit gases is assumed at 40 lb/ton of refuse, or 400 lb per hr.

D Other Assumptions

The heat loss through the furnace and combustion chamber walls is assumed at 1,800,000 Btu/hr (Btuh). The heat losses through the walls of other equipment ahead of the ID fan will be assumed and stated in the calculations. The heat losses through the walls can be predicted reasonably well from thermal conductivities of the refractory and insulation.

Alternate methods of tempering the furnace exit gases in preparation for dust collection will be considered in turn. Only two of many types of dust separators are considered. The ultimate objective is to clean the gases to legal limits, which vary with communities from about 1.0 to 0.4 lb per 1000 lb of flue gas, corrected to 50 per cent excess air.

Among the many questions to be answered by calculation are:

1 How much air does the furnace require?

2 What is the flue-gas analysis?

3 What is the actual cfm flowing from the furnace to the spray chamber? From the spray chamber?

4 How much water is required for the spray chamber? For a gas scrubber?

5 What is the saturation temperature of the flue gas, an index to white fog plume from the stack?

6 How can the fog plume from a scrubber be prevented?

7 What is the dust loading of the stack gases, corrected to 50 per cent excess air?

V COMBUSTION CALCULATIONS

A Refuse

For combustion purposes the refuse may be restated in the following form:

Carbon: (0.2295)(20,000)	=	4,590	
Less C in residue: (0.04)(0.24)(20,000)(0.96)	=	208	4,382
Available hydrogen: (0.009) (20,000)	=		180
Moisture, initial: (0.30) (20,000)	=	6,000	
bound water (0.2115) (20,000)	=	4,230	10,230
Residue, all forms			
Ash, metal, glass: (0.25) (20,000)	=	5,000	
Carbon	=	208	5,208
	Hourly total		20,000 lb

B Combustion

We are now ready to analyze the combustion process in more detail. The first question to answer is: How much theoretical or stoichiometric air is required to burn the carbon and available hydrogen gasified?

The stoichiometric proportions are:

1 lb carbon requires 11.53 lb air to produce 3.665 lb of carbon dioxide and 8.865 lb nitrogen. 1 lb hydrogen requires 34.34 lb air to produce 8.936 lb of water vapor and 26.404 lb nitrogen.

The dry air theoretically required for combustion of the refuse actually burned is

For the carbon: 4382 (11.53)	=	50,524 lb
For the available hydrogen: 180 (34.34)	=	6,181
Theoretical dry air, hourly	=	56,705 lb
Excess air = 1.30 × 56,705	=	73,717
Total dry air per hr	=	130,422 lb

The calculations are carried beyond the usual 3 or 4 significant figures to reduce adjustment later in the heat and material balances.

Dry air consists of 23.15 per cent oxygen and 76.85 per cent nitrogen by weight, and 20.9 per cent oxygen and 79.1 per cent nitrogen by volume. Some engineers use 21.0 and 79.0 per cent, respectively, for the volumes. As outdoor air contains moisture, it is standard practice in combustion calculations for boilers to add 0.0132 lb of moisture per lb of dry air. This value corresponds to 60 per cent relative humidity at 80°F dry bulb temperature.

The water vapor produced in quenching the grate residue is added to the furnace gas. The dry grate residue is 5208 - 400 = 4808 lb. Sp. ht. = 0.25. The heat liberated by residue = 4808(0.25) (1200 - 150) = 1,262,000 Btu. Approximate heat gained by each lb of quench water evaporated:

$$1150 - 48 = 1102 \text{ Btu/lb}$$

$$\text{Lb water evaporated} = 1{,}262{,}000/1102 = 1145 \text{ lb/hr to quench grate residue.}$$

At this point it is advisable to summarize the weights in the form of a material balance. The tabulation provides an overall view of the process, and assists in tracking down errors in calculations as input must equal output. Table 1 is based on the calculations for the example incinerator.

C Flue-Gas Composition

Assuming complete combustion, if the flue gases that leave the combustion chamber were sampled and analyzed by Orsat apparatus, the following analysis would be obtained:

TABLE I

MATERIAL BALANCE FOR FURNACE AND COMBUSTION CHAMBER

Input		Lb/hr
Refuse		20,000
Dry air		130,422
Air moisture		1,722
Quench water		1,145
	Total, hourly	153,289 lb
Output		
Dry flue gas		133,375
CO_2: 4382 (3.665)	16,073	
O_2: 130,422 (1.30/2.30)(0.2315)	17,073	
N_2: 130,422 (0.7685)	100,229	
Water vapor		14,706
from refuse	10,230	
from air (130,422)(0.0132)	1,722	
from combustion of (H), (180)(8.936)	1,609	
from ash pit	1,145	
Grate residue		4,808
Carry-over solids		400
	Total, hourly	153,289 lb

Gas	Wgt, lb	Cu ft/lb*	Cu ft*	Orsat, dry vol. per cent
CO_2	16,073	8.548	137,390	8.15
O_2	17,073	11.819	201,786	11.96
CO	0	13.506	0	0.0
N_2	100,229	13.443	1,347,378	79.89
	133,375		1,686,554	100.00

If we did not know the percentage excess air, we could calculate it from the analysis of the flue gases by substituting gas volume percentages in the following equation:

$$\text{Excess air, per cent} = 100 \times \frac{O_2 - CO/2}{0.264N_2 - (O_2 - CO/2)}$$

$$= \frac{1196}{0.264(79.89) - 11.96}$$

$$= \frac{1196}{21.09 - 11.96} = \frac{1196}{9.13} = 131\%,$$

a good check on 130 per cent originally assumed.

From the Orsat data one can also determine the lb air/lb C + (H) and the lb C + (H) per lb air.

$$\frac{\text{Lb C + (H)}}{\text{Lb air}} = \frac{0.528\,N_2 + 4\,CO_2 - 2O_2 + 5\,CO}{18.3N_2}$$

$$= \frac{0.528\,(79.89) + 4(8.15) - 2(11.96) + 5(0.0)}{18.3\,(79.89)}$$

$$= 0.0348.$$

The reciprocal,

$$\frac{\text{Lb air}}{\text{Lb C + (H)}} = \frac{1}{\text{Lb C + (H)/lb air}} = \frac{1}{0.0348} = 28.7,$$

which checks $\frac{130,422}{4382 + 180} = 28.6$

from the weights of carbon burned and the net hydrogen.

When cellulose, starch, sugar or carbon are burned completely, alone or in any combination, the Orsat readings of CO_2 and O_2 total 20.9 per cent. When some available hydrogen is present, the total of CO_2 and O_2 is reduced, while nitrogen increases above 79.1 per cent. If the C:(H) ratio of the fuel burned is not known, it may be calculated from the Orsat analysis, thus:

$$\text{C:(H) ratio} = \frac{CO_2}{8.80 - 0.421\,(CO_2 + O_2)}$$

$$= \frac{8.15}{8.80 - 0.421\,(8.15 + 11.96)}$$

$$= 24.4.$$

*At 60°F, 30 in. Hg abs. press. The water vapor is not measured by Orsat, but would be determined by condensing the moisture from a measured volume of flue gas. Incidently, the Orsat apparatus measures only to 0.1 per cent. A series of readings without error must be averaged to obtain significant values beyond 0.1 per cent.

The actual ratio was $\frac{4382}{180}$ = 24.4 ck. If all the carbon had been burned, the ratio would have been $\frac{4590}{180}$ = 25.5.

VI HEAT CALCULATIONS

A Furnace and Combustion Chamber

The heat input is the heating value of the refuse, to which should be added the heat of vaporization of the air moisture as all other water is initially in the liquid state. The base temperature is 80°F.

Refuse:	20,000 (4230)	84,600,000
Air moisture:	1,722 (1048.6)	1,805,690
	Total heat input	86,405,690 Btuh.

The known heat losses from the furnace include:

1) Sensible heat in carry-over solids at an estimated 1630°F;* sp. ht. of ash assumed at 0.25.

400(0.25) (1630-80) = 155,000 Btuh.

2) Sensible heat in quenched grate residue,

4808(0.25) (150-80) = 84,140

3) Sensible heat lost through furnace and combustion chamber enclosure

= 1,800,000

4) Latent chemical heat of the carbon in the residue:

208 (14,093) = $\frac{2,931,340}{4,970,480}$ Btuh

The heat of vaporization at 80°F for moisture in the flue gas is 14,706 (1048.6) = 15,420,710 Btuh. The heat remaining for superheating gases and vapor above 80°F is

86,405,690 - 4,970,480 - 15,420,710 = 66,014,500 Btuh.

*Resultant of successive approximations of exit gas termperature from bustion chamber. The correct temperature assumed must finally equal the temperature obtained from Figure 1.

As the resultant gas temperature is to be read off Figure 1, we must first establish the moisture content of the gases in per cent of the flue gas, thus:

$\frac{14,706}{133,375 + 14,706}$ = 9.85% moisture by weight of total flue gas.

The enthalpy of the flue gas above 80°F, with all moisture in vapor form is

$\frac{66,014,500}{133,375 + 14,706}$ = 446 Btu/lb.

Figure 1 indicates a gas temperature of 1630°F at the combustion-chamber exit; hence the assumed temperature is correct. The wall and arch temperatures in the furnace would probably be slightly hotter in the zone closest to the hottest flames. Slag deposition and running on the walls is experienced above 1800°F. The assumed conditions and exit gas temperature are in the range of good practice. The temperature can be increased by decreasing the amount of excess air entering the furnace.

The heat balance for the furnace and combustion chamber, Table 2, can be completed with the aid of steam tables. It is not necessary to achieve a perfect balance; minor differences may be carried as "unaccounted for."

VII SPRAY CHAMBER

When the furnace gases are to be cleaned by a cyclonic, electrostatic or other dry dust collector, the gases must be cooled or tempered. A waste heat boiler would accomplish the result, or water sprays with or without additional ambient air could be used. The objective in this example is to cool the furnace gases to 600°F by adding air and water in a chamber following immediately after the combustion chamber. Water sprays alone could do the job but the addition of air is a practical

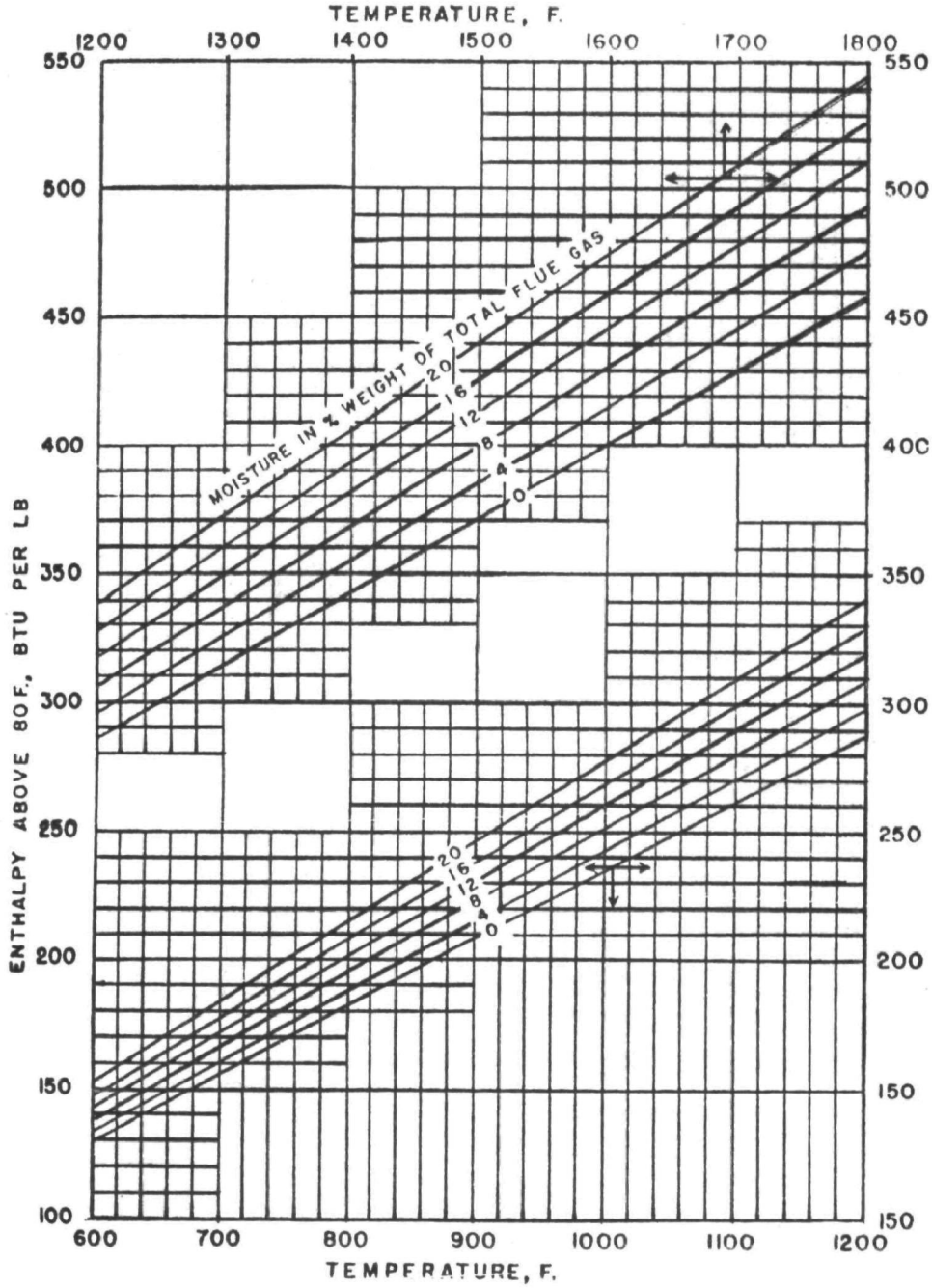

FIG. 1. ENTHALPY OF FLUE GAS ABOVE 80 F.

aid in the protection of refractories and in temperature control.

The additional air bled into the example spray chamber, including leakage, assumed at 50,000 lb/hr, consists of 49,350 dry air and 650 lb air moisture. Heat lost through the walls is 1,200,000 Btuh. The amount of spray water needed is that quantity which will absorb the excess of heat above 600°F after the other losses have been deducted. Each lb of spray water evaporated will absorb 1334.8 - 48.0 or 1286.8 Btu. To sluice ash out of the spray chamber 10 gpm of water is added. The ash trapped is assumed a 175 lb per hr. As the available heat for the sprays can be calculated by difference, we prepare the heat balance for the spray chamber, Table 3.

Table 2. HOURLY HEAT BALANCE FOR FURNACE AND COMBUSTION CHAMBER HEATS ABOVE 80°F

Input	Btuh	Per cent
Heating value of refuse 20,000 (4230)	84,600,000	97.9
Latent heat of air moisture 1722 (1048.6)	1,805,690	2.1
Total	86,405,690	100.0
Output		
Sensible heat of dry gas at 1630°F 133,375 (408) - from Fig. 1	54,417,000	63.0
Sensible and latent heat in water vapor 14,706 (1874-48) - from steam tables	26,882,568	31.1
Sensible heat in dust carry-over 400 (0.25) (1630-80)	155,000	0.2
Sensible heat in grate residue 4808 (0.25) (150-80)	84,140	0.1
Sensible heat loss through walls	1,800,000	2.1
Chemical heat of carbon in residue (14,093) (208)	2,931,340	3.4
Unaccounted for	135,642	0.1
Total	86,405,690	100.0

Table 3. HOURLY HEAT BALANCE FOR SPRAY CHAMBER HEATS ABOVE 80°F

Input at 1630°F	Btuh
Sensible heat of dry gas from furnace	54,417,000
Sensible and latent heat in water vapor from furnace	26,882,568
Sensible heat in carry-over	155,000
Unaccounted for heat from furnace	135,642
Latent heat of moisture in bleed air = (1048.6) (650)	681,590
Total	82,271,800
Output at 600°F	
Sensible heat in dry gas: (49,350 + 133,375) (128) - Fig. 1	23,388,800
Sensible heat in carry-over* 225 (0.25) (600-80)	29,250
Sensible and latent heat in bleed air moisture 650 (1334.8 - 48.0)	836,420
Sensible heat in sluice water at 150°F: 10 (8.33) 60 (150-80)	349,860
In sluice ash, 175 (0.25) (150-80)	3,063
Sensible heat loss through walls	1,200,000
Sensible and latent heat in vapor from furnace and spray water, by difference: 43,880 (1334.8-48.0)	56,464,407
Total	82,271,800

The amount of evaporated spray water is 43,800 - 650 - 14,706 = 28,524 lb/hr, or 57.0 gpm. The sluice water is an additional 10 gpm.

*Total carry-over less carry-over trapped = 400 - 175 = 225 lb.

*At 60°F, 30 in. Hg. abs. pressure.

All of the data are now available for Table 4, the material balance of the spray chamber, which should now be prepared. The material balance for the furnace and combustion chamber provides much of the data needed.

TABLE 4

HOURLY MATERIAL BALANCE FOR SPRAY CHAMBER

Input		Lb/hr
Dry gases from combustion chamber		133,375
Carbon dioxide	16,073	
Oxygen	17,073	
Nitrogen	100,229	
Dry bleed air		49,350
Water vapor:		15,356
In gas from combustion chamber	14,706	
In bleed air	650	
Water supply:		33,522
To sprays (evaporated)	28,524	
To sluice	4,998	
Fly ash		400
Total		232,003
Output		
Dry gases:		182,725
Carbon dioxide	16,073	
Oxygen 17,073 + 0.2315(49,350)	28,498	
Nitrogen 100,229 + 0.7685(49,350)	138,154	
Water vapor: 28,524 + 15,356		43,880
Sluice water: 10 gpm		4,998
Trapped fly ash		175
Fly ash in gases		225
Total		232,003

Humidity ratio: $\frac{43,880}{182,775} = 0.240$. Saturation temperature, 154F.

Stream fog occurs when the mixture is cooled below the saturation temperature.(5)

The Orsat analysis of the gas leaving the spray chamber would show the composition below if no CO_2 is absorbed by the water or ash. Conflicting data exist on the latter point.

Gas	Wgt	Cu ft/lb*	Cu ft	Dry vol. per cent
CO_2	16,073	8.548	137,390	5.89
O_2	28,498	11.819	336,818	14.44
N_2	138,154	13.443	1,857,204	79.67
			2,331,412	100.00

Note that the *C:(H)* ratio is 24.4 as before:

$$C:(H)\text{ ratio} = \frac{5.89}{8.80 - 0.421\,(5.89 + 14.44)} = 24.4.$$

If CO_2 is absorbed in the spray chamber, the sum of CO_2 and O_2 will decrease and the C:(H) ratio will not match that of the original combustible burned.

$$\text{The final per cent excess air} = \frac{100\,(O_2)}{0.264N_2 - O_2} =$$

$$\frac{1444}{0.264(79.67) - 14.44} = \frac{1444}{21.03 - 14.44} = 216 \text{ per cent,}$$

which compares with the per cent excess air by weight:

$$\frac{\text{Total air} - \text{Theoretical air}}{\text{Theoretical air}} = \frac{130{,}422 + 49{,}350 - 56{,}705}{56{,}705} =$$

2.17 or 217 per cent ck.

VIII COMBINED PROCESS

The result obtained by the furnace, combustion chamber, and spray chamber may be compared with the total input by a Process Materials Balance and Process Heat Balance. For this purpose the process is ended at the discharge from the spray chamber. However, process balances can also be prepared to include later stages if desired.

TABLE 5

PROCESS MATERIAL BALANCE—FURNACE, COMBUSTION, AND SPRAY CHAMBERS

Input		Lb/hr
Refuse, as fired		20,000
Dry Air		179,772
Air moisture at 0.0132 lb/lb air		2,372
Quench and sluice water, 69.3 gpm		34,667
	Total input, lb	236,811
Output		
Dry flue gas:		182,725
CO_2	16,073	
O_2	28,498	
N_2	138,154	
Water vapor		43,880
Residue: Grate		4,808
Fly Ash		225
Spray-chamber slurry		5,173
Water	4,998	
Solids	175	
	Total output, lb	236,811

If additional water is required for wetting and transporting residue, this extra water does not affect the combustion and heat calculations.

IX DUST LOADING OF STACK GASES — DRY COLLECTOR

The spray chamber tempers the gases to 600°F but discharges 225 lb of fly ash per hr mixed with 226,605 lb of flue gas. Incinerator fly ash is not easy to catch mechanically, because it readily degrades to fine powder. Nevertheless, methods are available which have a wide range of efficiency. By way of illustration, we may assume a dry dust separator of 60 per cent collection efficiency. Hence, 90 lb of dust per hr is emitted out the stack.

TABLE 6

PROCESS HEAT BALANCE—FURNACE, COMBUSTION, AND SPRAY CHAMBERS

Input	Btu/hr	Per cent
Heating value (HHV) of refuse, 4230 Btu/lb	84,600,000	97.2
Latent heat of air moisture, 2372 (1048.6)	2,487,280	2.8
Total, hourly	87,087,280	100.0
Output		
Sensible heat in dry gas at 600F	23,388,800	26.8
Sensible and latent heat in water vapor at 600F	57,300,967	65.9
Sensible heat in sluice water and solids at 150F	352,923	0.4
Sensible heat in grate residue at 150F	84,140	0.1
Sensible heat in fly ash at 600F	29,250	
Sensible heat lost through walls	3,000,000	3.4
Chemical heat in unburned carbon	2,931,000	3.4
Unaccounted for heat	200	
Total, hourly	87,087,280	100.0

Roughly two-thirds of the heat in the refuse is lost to water vapor, one-fourth to dry gas and the remaining twelfth to all other losses.

What is the magnitude of this emission in relation to the oft-accepted standard limit of 0.85 lb per 1000 lb flue gas, corrected to 50 percent excess air?[6]

The actual emission is 90/226.605 = 0.397 lb per 1000 lb flue gas. By sampling the stack gases one would establish the dust loading as well as the 216 per cent excess air (by Orsat) and the moisture content of the flue gas. The amount of spray water evaporated would not normally be determined, nor would the moisture content of the refuse be known. The CO_2 content of the flue gas is 5.89 per cent, dry volume.

It is common practice to assume that 50 per cent excess air corresponds to 12 per cent CO_2 volume in the dry flue gas. If this assumption is accepted, the corrected dust loading is $0.396 \times 12/5.89 = 0.809$ lb/1000 lb of corrected flue gas.

The validity of this assumption and resultant calculation can be compared with the actual flue gas corrected to 50 per cent excess air in the example case. The total air supplied was 179,772 lb at 217 per cent excess air. At 50 per cent excess air, the total air would have been 179,772 (1.50/3.17) = 85,065 lb/hr. The flue gas would be 226,605 - (179,772 - 85,065) = 131,898 lb/hr at 50 per cent excess air. The corrected dust loading on the weight basis would be 0.397 × 226,605/131,898 = 0.683 lb per 1000 lb flue gas.

If the evaporated spray water is also determined and deducted as dilution of the stack gases, the corrected weight of flue gas at 50 per cent excess air would be 131,898-28,524 = 103,374 lb per hr. The corrected dust loading on this basis would be 0.397 × 226,605/103,374 = 0.870 lb per 1000 lb of corrected flue gas.

The three corrected dust loadings vary from 0.683 to 0.870 lb per 1000 lb of corrected flue gas, or from well below the above the old ASME standard, depending on interpretation of the method of correction. The high moisture content of incinerator refuse and the effect of sprays cause the difference in results. Standardization of the method of correcting the dust loading is needed.

X FLUE-GAS SCRUBBER

The use of flue-gas washers or scrubbers with incinerators presents interesting thermal problems which are amenable to calculation. When this method of gas cleaning is used, the equipment beyond the combustion chamber is a duct for quenching of gases, a scrubber with demister, ID fan and stack. The gases leaving the combustion chamber enter the quench section where the gases are cooled and saturated with spray water. The gases and excess water then enter the scrubber proper.

The thermal exchange in the scrubber system has an important bearing on the composition of the gas-vapor mixture received by the ID fan and stack. For the calculations the quench duct and scrubber may be considered together. The scrubber water and 1630°F flue gas are intimately mixed and come to equilibrium at a temperature which is that of water-saturated gas, not the boiling point of water. A small excess of water is supplied to the scrubber to carry away the trapped fly ash via an overflow pipe.

The loss in enthalpy of the flue gas equals the enthalpy gained by the scrubber water. Collection efficiency is obtained by an expenditure of fan power. The higher efficiencies are obtained under conditions of high pressure drop for initimate contact of gas and water, which increases the load on the ID fan.

Assume a case in which water is supplied to the quench duct and scrubber at 80°F. The water loss to the drain is assumed at 10 gpm to carry away the solids. The initial enthalpy (above 80°F) of the flue gas is obtained from Table 2. Assume a heat loss from the scrubber system to the surroundings of 1.1 million Btu/hr in this case.

Determine the quantity of scrubber water required and the temperature of the scrubber exhaust. First prepare heat and material balances to the extent possible. Then solve by successive approximations of temperature with use of Reference 5, assuming the dry flue gas is the same as air. The humidity ratio of the scrubber exhaust must match that for air at the exhaust temperature.

The fan capacity is based on the cfm. The water required by the scrubber equals the water vapor in the scrubber exhaust plus the sluice water less the water vapor in the gas from the combustion chamber: 70,582 + 4998 - 14,706 = 60,874 lb/hr or 122 gpm. The material balance of the quench section and scrubber is presented in Table 8.

A vapor plume is produced when the scrubber exhaust enters cold air, which may be undesirable under some conditions and negligible in others. The amount of water evaporated in the scrubber can be reduced by the extraction of heat from the flue gases ahead of the scrubber, as by a boiler or heat exchanger. Reheating the scrubber exhaust is also helpful. The vapor plume should be discharged at a sufficient height to insure that it is dispersed by natural evaporation without becoming a nuisance or hazard to visibility.

TABLE 7

SCRUBBER HEAT BALANCE, HOURLY BASIS

Input (1630F from Table II)	Btuh	Per Cent
Dry gas	54,417,000	66.6
Water vapor	26,882,568	33.0
Carry-over solids	155,000	0.2
Unaccounted for heat	135,782	0.2
	81,590,350	100.0
Output 175 F		
Dry gas (42.087-19.221)(133,375)	3,049,753	3.7
Water vapor 70,582(1136.17 - 48.05)	76,801,686	94.3
Heat in drain water, 4998 (175 - 48.0)	621,546	0.7
Heat in trapped solids, 360(0.25)(175-80)	8,550	-
Heat in escape solids 40(0.25)(175-80)	950	-
Heat loss to air from apparatus	1,100,000	1.3
Unaccounted for heat	7,865	-
	81,590,350	100.0

The volume of gas-vapor mixture at standard barometer, (30 in. Hg) and 175F is as follows:

CO_2:	16,073 (8.548) (460 + 175)/(520)(60)	=	2,760
O_2:	17,073 (11.819) (635)/(520)(60)	=	4,110
N_2:	100,229 (13.443) (635)/(520)(60)	=	27,400
H_2O:	70,582 (13.475)/(0.5292) 60	=	29,950
	203,957 lb/hr Total		64,220 cfm

XI GAS AND VAPOR VOLUMES AND FLOW RATES

The data in the previous tables enable one to calculate volumes and flow rates for the purpose of sizing equipment.

A Furnace and Combustion Chamber

Air at 80°F, 60 per cent humidity.

Volume of 1 lb dry air = 13.601 ×

29.92/30.0 = 13.56 cu ft

Volume of water vapor = 0.60 × 0.486 ×

29.92/30.0 = 0.29

Ambient air volume per lb dry air at 30 in. Hg

= 13.85 cu ft

130,422 (13.85)/60 = 30,106 cfm air and air moisture to furnace and combustion chamber.

Density of air to fan inlet = 1.0132/13.85 = 0.0731 lb/cu ft

Table 8. SCRUBBER MATERIAL BALANCE, HOURLY BASIS

Input	lb/hr
Dry gas	133,375
Water vapor	14,706
Carry-over solids	400
Water	60,874
Total, hourly	209,355
Output	
Dry gas	133,375
Water vapor 14,706 + 55,876	70,582
Solids in exit gas at 90 per cent collection efficiency	40
Scrubber water to drain	4,998
solids to drain	360
Total, hourly	209,355

The humidity ratio of scrubber exhaust = 70,582/133,375 = 0.5292 lb/lb dry gas, which is the humidity ratio of saturated air at 175°F.

B Combustion-Chamber Outlet and Spray-Chamber Inlet: 148,081 lb/hr

		Cfm
Water vapor at 1630F: Sp. vol. = 84.64 cu ft/lb 14,706 (84.64)/60		20,745
Dry gas volumes		
CO_2: 16,073 (8.548)(460 + 1630)/(460 + 60)(60)	=	9,200
O_2: 17,073(11.819)(2090)/(520)(60)	=	13,530
N_2: 100,229(13.443)(2090)/(520)(60)	=	90,050
Total *cfm* at 1630F		133,525 *cfm*
Sp. vol. of furnace gas = 60 (133.525)/148,081	=	54.1 cu ft/lb

C Spray-Chamber Outlet and Dry Dust-Separator Inlet

		Cfm
Water vapor at 600F, Sp. vol. = 42.86 cu ft/lb 43,880 (42.86)/60	=	31,345
Dry furnace gas		
CO_2: 16,073 (8.548)(460 + 600)/(460 + 60)(60)	=	4,670
O_2: 28,498 (11.819)(1060)/(520)(60)	=	11,450
N_2: 138,154 (13.443)(1060)/(520)(60)	=	63,100
Total *cfm* at 600F		109,565 *cfm*
Sp. vol. of exit gas = 60 (109,565)/226,605	=	29.0 cu ft/lb

D Scrubber Exhaust

When the scrubber receives untempered gas from the combustion chamber, the scrubber exhausts at 175°F. The exhaust cfm at 30 in. Hg abs. pressure is 64, 220 cfm and the density is 203, 957/(64, 220) (60) = 0.0530 lb per cu ft.

XII SUMMARY

A A hypothetical municipal incinerator operating at 240 tons a day capacity was used as an example to present the methods for calculating the following items:

1 Refuse composition for combustion calculation.

2 Air required for combustion and temperature control.

3 Gas analyses, excess air, fuel-air ratios.

4 Heat and material balances.

5 Tempering of combustion gases by spray water and air.

6 Dry dust collectors and gas scrubbers.

7 Dust loading of stack gases, corrected to 50 per cent excess air and to 12 per cent CO_2.

8 Flow rates and densities of gas-vapor mixtures.

B When burning a refuse of 4230 Btu/lb heating value, 130 per cent excess air is required for a gas temperature of 1630°F leaving the combustion chamber. The flue gas consists of CO_2 8.15 per cent, O_2 11.96 per cent and N_2 79.89 per cent by volume, dry basis. The weight of air required is 6.5 times the weight of refuse.

C To cool the furnace gases from 1630 to 600°F, requires about 2.50 lb air and 1.43 lb spray water evaporation per lb refuse, or equivalent proportions of these coolants. Sluice water to remove trapped ash is additional.

D A gas scrubber that received gases directly from the combustion chamber at 1630°F would evaporate 2.79 lb water per lb refuse. The scrubber would exhaust at 175°F and the gases would contain 3.53 lb water per lb refuse.

E Because of high content of water vapor in incinerator stack gases, several different corrected dust loadings can be calculated from the same test data. Calculations for the example incinerator show that the corrected dust loading per 1000 lb stack gas is considerably lower at 50 per cent excess air than at 12 per cent CO_2.

ACKNOWLEDGMENT

The research in this paper was supported by grant EF-00530-01 from U.S. Public Health Service, Division of Environmental Engineering and Food Protection.

REFERENCES

1 Steam, Its Generation and Use. The Babcock and Wilcox Co., New York, N.Y., Appendix 37th ed. 1955.

2 Municipal Incinerator Design. Prepared by Amer. Soc. Civil Engineers, published by U.S. Public Health Service. 1958.

3 Damiano, D.J. Incinerator Refractory Studies. The American City. April 1962.

4 International Critical Tables. Vol. 5, 1926. p. 167.

5 ASHRAE Guide and Data Book. Published annually by American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York, N. Y.

6 Example Sections for a Smoke Regulation Ordinance. Information Bulletin published by ASME. May 1949.

BIBLIOGRAPHY ON INCINERATION OF REFUSE

The following bibliography on incineration of refuse was compiled in two parts. For convenience both parts have been integrated alphabetically according to the author's last name. The following references were consulted in preparing Part I of the bibliography:

1 Library of Congress Bibliography on Air Pollution.

2 San Francisco Bay Area Air Pollution Control District, Uniterm Cards (through June, 1960).

3 Engineering Index, 1945 - 1955.

4 Chemical Abstracts, 1945 - 1956.

5 APCA Abstracts, January 1957 - October 1960.

References consulted for Part II of the bibliography include the following:

1 Engineering Index (Jan. 1961 - Aug. 1965).

2 Science and Technology Index (Jan. 1961 - July 1965).

3 APCA Abstracts (Jan. 1961 - Aug. 1965).

4 Public Health Engineering Abstracts (Jan. 1962 - July 1965).

5 Chemical Abstracts (1961 - July 1965).

6 Library of Congress - Air Pollution Index.

7 "Disposal - Incineration". Section of Unpublished Annotated Bibliography. Supplement F, Refuse Collection and Disposal 1962 - 1963, U.S. Public Health Service.

8 Bay Area Air Pollution Control District Uniterm File (1961 - 1964).

*Compiled by Air Pollution Training Section, Training Program, U.S. Public Health Service, Division of Air Pollution. Part I was prepared in 1961 by the Engineering Research and Development Section, Laboratory of Engineering and Physical Sciences (Cincinnati). Part II was prepared in 1965 by the Engineering Control Section, Technical Assistance Branch (Cincinnati).

1 Afflerbaugh, C.B. It's O.K. in Los Angeles. Am. City, Vol. 70, No. 12, Dec. 1955. pp 72-4.

2 Air Pollution Control Association Incinerator Committee. Proposed Standards Commercial and Industrial Incinerators Class III and IV. APCA Report to Members of Incinerator Committee T-2, Dec. 13, 1955.

3 Air Pollution Control Association News. Auto Burning Problems Eased. APCA News, Vol. 7, No. 1. January 1959.

4 Air Pollution Control Association News. New York Times Cites Possible Gas Incinerator Boom. APCA News, Vol. 5, No. 3, April 1957.

5 Air Pollution Control Association Technical Coordinating Committee. Tentative Incinerator Codes, Part I & II. J. Air Pollution Control Assoc., Vol. 6, No. 1, May 1956. pp 44-7.

6 Albinus, G. Refuse Incineration, Fundamental Considerations of Refuse Disposal by Combustion. Combustion, Vol. 34, No. 4, Oct. 1962. p 54.

7 American Gas Association. Domestic Gas-Fired Incinerators. Am. Gas Assoc. Subcommittee on Domestic Gas-Fired Incinerators.

8 American Gas Association. Uniform Standards and Regulations. Am. Gas Assoc., Incineration Committee, Industrial and Commercial Gas Section, 1959.

9 American Society of Civil Engineers, Committee on Refuse Collection and Disposal. Incineration. Report of Proc. Am. Soc. Civil Engrs. Committee on Refuse Collection and Disposal, Vol. 80, Separate No. 497, Sept. 1954.

10 American Society of Civil Engineers, Committee of Sanitary Engineering Division of Refuse Collection and Disposal. Refuse Collection and Disposal. Proc. Am. Soc. Civil Engrs. Vol. 75, No. 6, June 1949. pp 809-20.

11 American Society of Civil Engineers. Municipal Incineration of Refuse: Foreword and Introduction. Progress Report of the Committee on Municipal Practices. Journal of The Sanitary Engineering Division Proceedings of The American Society of Civil Engineers, Vol. 90, No. SA3, June 1964. p 13.

12 American Society of Civil Engineers, Solid Wastes Engineering Research Committee on Sanitary Engineering Research. Municipal Incinerator Design -- A Survey of Engineering Practices. U.S. Department of Health, Education, & Welfare, Public Health Service, 21 pgs.

13 American Society of Mechanical Engineers, Emission Study Subcommittee. Recommended Emission Limitations from Specific Sources. Section II: Combustion for Waste Disposal or Salvage, Nov. 29, 1962.

14 American Standards Association. Approval Requirements for Domestic Gas-Fired Incinerators. American Standard Z21.6 --1949, 20 pgs. See also, American Gas Assoc., Inc., November 28, 1955.

15 American Standards Association. Approval Requirements for Domestic Gas-Fired Incinerators. American Standards Assoc. (Addenda to Am. Standards Z21.6--1949) Am. Standard Z21.6b, 1954. 5 pgs.

16 Andreas, E. Harbor and Bulky Refuse in Amsterdam. International Research Group on Refuse Disposal No. 18, Aug. 1963. p 24.

17 Andrews, W.H. Atmospheric Pollution from House Refuse Incineration. Smokeless Air, No. 63, 1947. pp 38-42.

18 Andritzky, M. Munich Refuse Power Station. Combustion, Vol. 34, No. 4, (Abstract), Oct. 1962. p 54.

19 Anon. Algiers Incinerator Has a Modern Stoker System. Refuse Removal Journal, Vol. 5, No. 9, Sept. 1962. p 42.

20 Anon. Automated Waste Disposal. Safety and Maintenance, Vol. 28, Sept. 1964. p 55.

21 Anon. Baltimore Uses New Lift Trucks at Incinerator. Refuse Removal Journal, Vol. 6, No. 1, Jan. 1963. p 30.

22 Anon. Barrel-Grate Incinerator Rounds Out Third Test Year. Power, Vol. 108, May 1964. p 74.

23 Anon. Berne, Switzerland Makes Thermal Power from Waste. Refuse Removal Journal, Vol. 6, No. 1, Jan. 1963. p 30.

24 Anon. Boston Seeks Federal Aid to Construct Two Incinerators. Refuse Removal Journal, Vol. 7, No. 8, Aug. 1964. p 22.

25 Anon. Chicago Incinerator Turns Rubbish Into Saleable Products. Refuse Removal Journal, Vol. 7, No. 2, Feb. 1964. p 18.

26 Anon. Chicago Proposes Bond Issue for Incinerators. Refuse Removal Journal, Vol. 5, No. 4, April 1962. p 22.

27 Anon. Cities Report on 'Demolition' Refuse Problem. Public Works Engrs. Newsletter, Vol. 25, No. 11, Nov. 1958. pp 1, 2, 8, 9.

28 Anon. Complete Sludge Disposal for the Small Town. Public Works, Vol. 93, No. 2, Feb. 1962. p 110.

29 Anon. Continued Improvement for the Hempstead Incinerator. Public Works, Vol. 92, Sept. 1964. p 133.

30 Anon. Costs Less To Burn It. Textile Industries, Vol. 128, Jan. 1964. p 131.

31 Anon. Cyclones Clean Incinerator Stack Discharge. Public Works, Vol. 93, No. 5, May 1962. p 170.

32 Anon. Darien, Connecticut Enlarges Its Incinerator. Refuse Removal Journal, Vol. 5, No. 3, March 1962. p 28.

33 Anon. Europe's Latest Plant. Public Cleansing, Vol. 52, No. 2, Feb. 1962. p 80.

34 Anon. Fisherman Fight Boston Plan to Incinerate Refuse on Ships at Sea. Refuse Removal Journal, Vol 7. No. 11, Nov. 1964. p 16.

35 Anon. Fulham's New Refuse Destructor on Site of Two Previous Plants. Surveyor (Great Britain), Vol. 123, No. 3737, Jan. 18, 1964. p 24.

36 Anon. Gas, The Garbage Man. Gas Age, Vol. 131, Sept. 1964. p 31.

37 Anon. General Section of Incinerator for Cotton Gin Trash Disposal. U.S. Department of Agriculture, Agricultural Research Administration, Cotton Ginning Investigation, March 30, 1951.

38 Anon. Handling and Disposing of Grease by Incineration. Wastes Eng., Vol. 25, No. 9, Sept. 1954. pp 414-15.

39 Anon. Houston, Texas, Builds Dual Incinerator. Am. City, Vol. 63, No. 1, Jan. 1948. p 98.

40 Anon. In Hampstead, Long Island the Incinerator Has to be Big -- And It Has to be Tidy. Am. City, Vol. 68, No. 7, July 1953. pp 89-91.

41 Anon. Incinerator Burns Away Litter Problem at Suburban Shop-Rite Supermarket. Modern Sanitation and Building Maintenance, Vol. 14, No. 8, Aug. 1962. p 40.

42 Anon. Incinerator Capacity Doubled Without Building Enlargement. Eng. News-Record, Vol. 155, No. 9, Sept. 1, 1955. pp 51-2.

43 Anon. Incinerator Designed for Suburb. Am. City, Vol. 70, No. 11, Nov. 1955. pp 106-8.

44 Anon. Incinerator Fire Jet System. Safety and Maintenance, Vol. 121, Feb. 1961. p 33.

45 Anon. Incinerator Fly-Ash Meter Under Development. The American City, Vol. 80, No. 4, April 1965. p 21.

46 Anon. Incineration Gobbles Up Plant Wastes. Chem. Eng., Oct. 5, 1959. pp 50-2.

47 Anon. Incinerator Hoist. Public Works, Vol. 93, No. 1, Jan. 1962. p 130.

48 Anon. Incinerators for Hong Kong. Public Cleaning, Vol. 53, No. 5, May 1963. p 230.

49 Anon. Incinerator Meets Strict Tests. Eng. News-Record, Vol. 155, No. 12, Sept. 22, 1955. pp 24-5.

50 Anon. Incineration of Municipal Garbage. Engineering, Vol. 193, No. 5017, June 15, 1962. p 778.

51 Anon. An Incineration for New Oreleans. Public Works, Vol. 93, No. 10, Oct. 1962. p 150.

52 Anon. Incinerator Plants Closed Circuit TV Cuts Labor Costs. Air Engineering, Vol. 7, No. 7, July 1965. p 20.

53 Anon. Incinerator-Residue Study Under Way. The American City, Vol. 80, No. 3, March 1965. p 20.

54 Anon. Incineration for Retail Stores. Modern Sanitation and Building Maintenance, Vol. 15, No. 7, July 1963. p 22.

55 Anon. Incineration Solves Waste Disposal Problem. Chem. Eng., Vol. 55, No. 3, March 1948. pp 110-11.

56 Anon. Incinerator That Invites Inspection. Am. City, Vol. 68, No. 9, Sept. 1953, pp 102-3.

57 Anon. Incinerator Uses Cone-Shaped Grate. Refuse Removal Journal, Vol. 7, No. 11, Nov. 1964. p 30.

58 Anon. 433% Larger - Bablyon, New York Rebuilds Its Ten Year Old 90 Tone Incinerator to 390 Ton Capacity. Am. City, Vol. 71, Feb. 1956. pp 106-8.

59 Anon. Liberty Builds Incinerator. Public Works, Vol. 81, No. 6, June 1950. pp 46-7.

60 Anon. Long Island Incinerator to Convert Salt Water. Refuse Removal Journal, Vol. 7, No. 3, March 1964. p 12.

61 Anon. Long-Lasting Protection (Incinerator Maintenance). The American City, Vol. 78, No. 8, Aug. 1963. p 27.

62 Anon. Massachusetts' Most Attractive Incinerator. Am. City, Vol. 67, Sept. 1952. pp 126-27.

63 Anon. Miami, Florida, Plans World's Largest Incinerator. Am. City, Vol. 63, No. 7, July 1948. p 75.

64 Anon. Modern 200-Ton Incinerator for Framingham. Public Works, Vol. 86, Sept. 1955, p 119.

65 Anon. Modification of Incinerator Precipitator Baffle Saves $15,000 Per Unit. Public Works, Vol. 92, July 1961. p 174.

66 Anon. The Munich Refuse Incineration Power Plant. The APWA Reporter, Vol. 30, No. 9, Sept. 1963. p 16.

67 Anon. New Gas Fired Incinerator Helps Fight Air Pollution. Gas Age, Vol. 129, Dec. 1962. p 28.

68 Anon. A New Grate for Refuse Burning. Public Cleansing, Vol. 53, No. 6, June 1963. p 270.

69 Anon. A New Incinerator. Smokeless Air, Vol. 33, No. 123, Autumn 1962. p 62.

70 Anon. New Incinerator Design Standards Set in World's Largest Plant. Am. City, Vol. 65, No. 4, April 1950. pp 108-10.

71 Anon. New Incinerator for Frankfurt. Public Cleansing, Vol. 52, No. 10, Oct. 1962. p 436.

72 Anon. New Incinerator at Ministry of Agriculture Laboratories. Gas World. Vol. 136, No. 3548, Aug. 1952. (Indus. Gas) p 26.

73 Anon. New Incinerator Promises Less Smog. Eng. News-Record, Vol. 157, Oct. 11, 1956. pp 47-8.

74 Anon. A New Sludge-Disposal Method. The American City, Vol. 77, No. 6, June 1962. p 175.

75 Anon. New Smokeless Incinerator. Smokeless Air, Vol. 32, No. 121, Spring 1962. p 216.

76 Anon. New Way to Incinerate Cyanide Wastes. Air Engineering, Vol. 4, No.2, Feb. 1962. p 367.

77 Anon. New York Develops New Gas Incinerator. Gas, Vol. 38, No. 11, Nov. 1962. p 94.

78 Anon. Norfolk's Incineration Standards. Am. City, Vol. 63, No. 5, May 1948. pp 75-7.

79 Anon. Observations About Municipal Incinerators. Am. City, Vol. 72, Nov. 1957. pp 31, 189.

80 Anon. Omaha Plans Paunch Manure Incinerator. Engineering News-Record, Vol. 173, Nov. 1964. p 59.

81 Anon. 100-Tons-A-Day Plant for Bradford. Public Cleansing, Vol. 52, No. 9, Sept. 1962. p 390.

82 Anon. Planning for Incineration: Abstract of Papers. Civil Engineer, Vol. 34, Sept. 1964. p 35.

83 Anon. Pneumatic Conveyor Speeds Fly Ash Removal. Public Works, Vol. 96, April 1965. p 115.

84 Anon. Fan-Fed Incinerator. The American City, Vol. 79, No. 12, Dec. 1964. p 69.

85 Anon. Refuse Collection and Disposal Articles, No. 1 - Refuse Clinic Includes Landfill Operations; No. 2 - Philadelphia Insists on Closed Garbage Trucks; No. 3 - Incinerator Research Underway; No. 4 - Most Cities Bury Refuse - Few Feed Pigs. Am. City, Vol. 72, July 1957, p 27.

86 Anon. Refuse Collection and Disposal - 49 Per Cent Overload O.K. on Test Run. Am. City, Vol. 68, Nov. 1953. p 23.

87 Anon. Refuse Disposal by Incineration. Public Works, Vol. 93, Aug. 1962. p 138.

88 Anon. Refuse Disposal Plant, Engineering, Vol. 178, No. 4616, July 16, 1954. pp 85-6.

89 Anon. Refuse Disposal Plant at Port Glasgow. Engineering, Vol. 177, No. 4596, Feb. 26, 1954. p 281.

90 Anon. Refuse Disposal Plant at Shefffield. Engineering, Vol. 176, No. 4581, Nov. 13, 1953. pp 633-34.

91 Anon. A Revolutionary Method of Refuse Incineration. Public Cleansing, Vol. 53, No. 11, Nov. 1963. p 532.

92 Anon. Rubbish. Engineering, Vol. 193, No. 5018, June 1962. p 832.

93 Anon. St. Louis Park Creates A Pattern for Incinerators. Am. City, Vol. 70, Oct. 1955. pp 110-12.

94 Anon. Sanitary Landfill or Incineration. Am. City, Vol. 66, No. 3, March 1951.

95 Anon. Should Apartment-House Incinerators be Permitted? Am. City, Vol. 67, April 1952, p 15.

96 Anon. Sludge Burns Under Water in New Incinerator. Eng. News-Record, Vol. 161, No. 22, Nov. 27, 1958. pp 44-6.

97 Anon. Smog Experts Condemn Los Angeles Refuse Burning. Am. City, Vol. 70, Feb. 1955. pp 141-43.

98 Anon. Smokeless Brush Burning Plants Reduce Air Pollution in Detroit. Refuse Removal Journal, Vol. 8, No. 3, March 1965. p 8.

99 Anon. Smolekess Burner for Burning Rubber Scrap and Other General Plant Refuse. Rubber World, Vol. 146, No. 1, April 1962. p 92.

100 Anon. Spray System Suppresses Incinerator Odors. Am. City, Vol. 71, Jan. 1956. p 13.

101 Anon. Squeezing Heat from Garbage with Modern Municipal Incinerators. Power, Vol. 108, March 1964. p 68.

102 Anon. Stockholm Uses Burners to Aid Disposal. Refuse Removal Journal, Vol. 6, No. 4, April 1963. p 16.

103 Anon. Trash Burner Desalts Water Too. Engineering News-Record, Vol, 171, No. 19, Nov. 7, 1963. p 23.

104 Anon. TV To Monitor Incinerator Operation. The American City, Vol. 8, No. 1, Jan. 1965. p 34.

105 Anon. Use Industrial Waste for Factory Power. Refuse Removal Journal, Vol. 6, No. 10, Oct. 1963. p 26.

106 Anon. Volund Incinerators Installed by Fords. Public Cleansing, Vol. 52, No. 10, Oct. 1962. p 446.

107 Anon. Von Roll Blaze a Trail Round the World. Public Cleansing, Vol. 53, No. 2, Feb. 1963. p 59.

108 Anon. Waste Elimination: Incinerating Plastics Waste Solves Manufacturer's Refuse Problem. Plastics World, Vol. 22, Dec. 1964. p 52.

109 Ausseterre, M. The New Incineration Plant for Household Refuse at Saint-Ouen. La Technique Sanitaria et Municipale, Vol. 50, Aug.-Sept. 1955. pp 159-170.

110 Ballman, H. C. How Do We Handle Complaints about Incinerators. Air Pollution and Smoke Prevention Assoc. Amer., 1951. pp -84.

111 Ballman, H. C. Incinerators and Air Pollution. Am. City, Vol. 69, Oct. 1954. pp 89-90.

112 Barkley, J. F. and Morgan, R. E. Burning Wood Waste for Commercial Heat and Power. U.S. Bureau of Mines Information Circular No. 7580, September 1950.

113 Banister, Manly. Mobil Leaf Burner. Popular Mechanics, Vol. 120, No. 3, Sept. 1963. p 184.

114 Bender, D. O. We Incinerate Our Refuse Now. Am. City, Vol. 73, No. 4, April 1958, pp 167-68.

115 Benline, Arthur J., and Wolff, Richard A. Smoke-Outs From Flue Fed Incinerators. New York City Department of Air Pollution Control. Nov. 1961.

116 Benn, Charles L. On-Site Domestic Incinerators. The APWA Reporter. Vol. 30, No. 1, Jan. 1963. p 16.

117 Beorse, B., Kurtz, P., Mizushima, J. A Study of Air Pollution Control Aspects of Refuse Incineration. University of California Report No. 55-27, Period ending June 30, 1955. pp i-v, 1-63.

118 Bjorkman, A. Tepees Burn Stockholm's Rubbish. Public Cleansing, Vol. 52, No. 12, Dec. 1962. p 546.

119 Blum, J. K. Achieving Good Combustion in Incinerators. Air Pollution and Smoke Prevention Assoc. Amer. 1951. pp 47-8.

120 Boubel, R. W., Northcraft, M., Von Vliet, A., and Popovich, M. Wood Waste Disposal and Utilization. Oregon State College, Eng. Experiment Station, Corvallis, Oregon, Bulletin No. 39, August 1958.

121 Bowerman, F.R. Summary of the Conference on Incineration, Rubbish Disposal and Air Pollution. Air Pollution Foundation Report, Vol. 1, No. 3, Jan. 1955. p 50.

122 Bowerman, F.R. and Gotaas, H.B. Can Waste Heat from Refuse Incinerators be Employed Economically. Civil Eng. Vol. 22, No. 5, May 1952. pp 48-50.

123 Bradley, H.D. New Ideas Embodied in Toronto's Latest Garbage Incinerators. Municipal Utilities Magazine, Vol. 94, No. 10, October 1956. pp 25-9.

124 Bradley, H.D. Toronto's Newest Incinerator. Am. City, Vol. 72, Feb. 1957. pp 107-9.

125 Brooks, W.E. How to Make Incinerator Pay. Power, Vol. 94, No. 8, Aug. 1950. pp 94-6.

126 Brown, W.D. and Fyle, L.E. Incinerator Styles are Changing. Am. City, Vol. 72, No. 7, July 1957. pp 103-5.

127 Bush, A.F., Bowler, E., Kurtz, P., and Mizushima, J. Fundamental Considerations of Incinerator Design. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. pp 1-30a.

128 Cadmus, T.W. How Can We Get Incineration? Public Works, Vol. 84, No. 10, October 1958. pp 82-3.

129 Calaceto, Ralph R. Sludge Incinerator Fly Ash Controlled by Cyclonic Scrubber. Public Works, Vol. 92, No. 2, Feb. 1963. p 113.

130 Carrol, A.F.G. Saskatoon Has Gas-Fired Incinerator Program. The APWA Reporter, Vol. 30, No. 8, Aug. 1963. p 5.

131 Casey, I.J. How to Make an Old Incinerator Work Like New. Am. City, Vol. 67, Dec. 1952. pp 106-7.

132 Cates, H.J. Garbage and Refuse Incineration Yields Revenue for Atlanta. Public Works, Vol. 80, No. 3, March 1949. pp 22-3.

133 Cayton, S. Incineration and Waste Disposal. A paper presented to, and reprinted from the proceedings of, The Harigate, 1962, Conference of The National Society for Clean Air - Great Britain.

134 Cerniglia, V.J., and Campbell, H.C., Jr. We Borrowed from Steel Industry to Reduce Problems of Incinerator Maintenance. The American City, Vol. 79, No. 5, May 1954. p 89.

135 Chass, R.L. and Feldman, E.S. Incineration of Wood Waste in the Los Angeles Area. Forest Products Research Soc. J., Vol. 1, No. 1, Sept. 1951. pp 135-43.

136 Chass, R.L. and Rose, A.H., Jr. Discharge from Municipal Incinerators. Air Repair, Vol. 3, No. 2, Nov. 1953. pp 119-22.

137 Chesarek, R.F. How to Select Incinerator Bucket. The American City, Vol. 79, No. 8, Aug. 1964. p 80.

138 Chirico, J.J. Reconditioning Steel Drums Via Incinerator. Air Repair, Vol. 1, Feb. 1952. pp 43-44.

139 City of Philadelphia - Air Pollution Control Section. Domestic Incinerator Report. Feb. 1963.

140 Clarke, S.M. Capacity Criteria for Refuse Incineration. J. Sanitary Engineering Division, Proceedings of Am. Soc. Civil Engrs., Sept. 1958. pp 1783-1 to 1783-7.

141 Clarke, S.M. Testing New Winnipeg Refuse Incinerator. Water & Sewage, Vol. 86, No. 8, Aug. 1948. pp 17-31, 46-9.

142 Clarke, Samuel M. Incinerating Plant Costs. Public Works, Vol. 93, No. 9, Sept. 1962. p 122.

143 Clift, M.A. Incinerating Wastes from Large Pharmaceutical Establishment. Sewage Works Eng., Vol. 19, No. 1, January 1948, pp 21-2, 24.

144 Corey, R.C. Some Fundamental Considerations in the Design and Use of Incinerators in Controlling Atmospheric Contamination. Air Pollution, McGraw Hill Book Co., 1952. pp 394-407.

145 Corey, R.C., Ingram, T., and Greenburg, L. Bad Design Causes Air Pollution: Lack of Basic Design Information Prevents Improvement of Combustion Units. Chem. Eng. News, Vol. 32, April 5, 1954. p 1352.

146 Corey, R.C., Orning, A.A., Schwartz, C.H., and Pfeiffer, J.J. A Progress Report on the Experimental Studies of Incineration by the U.S. Bureau of Mines. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. New York University.

147 Corey, R.C., Spano, L.A., Schwartz, C.H., and Perry, H. Experimental Study of Effects of Tangential Overfire Air on the Incineration of Combustible Wastes. Air Repair, Vol. 3, No. 2, Nov. 1953, pp 109-16.

148 Cosulich, W.F. Air Pollution Control for Incinerators. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. pp 121-24. New York University.

149 Cotton, Robert A. For Longer Incinerator Life. The American City, Vol. 78, No. 11, Nov. 1963. p 92.

150 Cotton, Robert A. Refractories Make the Difference in Incineration Construction. Plant Engineering, Vol. 17, Nov. 1963. p 118.

151 Dahlmeyer, Fred. Inexpensive Method Solves Fly Ask Problems. Public Works, Vol. 93, No. 8, Aug. 1962. p 105.

152 Damiano, David J. Incinerator Refractory Studies. The American City, Vol. 77, No. 4, April 1962. p 84.

153 Daugherty, R.L. Incinerator Testing and Test Results. J. Air Pollution Control Assoc., Vol. 7, Aug. 1957. p 118.

154 Deming, Leroy F. Navy Contemplates Steam Generating Incinerator. Public Works, Vol. 96, No. 7, July 1965. p 92.

155 Dennis, R., Billings, C.E., Samples, W.R., and Silverman, L. Gas Cleaning Studies of U.S. Bureau of Mines Incinerators. TID-7513 (Pt. 1) 4th A.E.C. Conference, Nov. 1955 and June 1956. pp 219-45.

156 Droege, H., Johnson, H.C., Clayton, L. and McEwen, T. Performance Characteristics and Emission Concentrations from Various Type Incinerators. Information Bulletin #1-63, Bay Area Air Pollution Control District - San Francisco, 1963.

157 Easterlin, John D. Complete Combustion with Minimum Excess Air. The American City, Vol. 80, No. 2, Feb. 1965. p 99.

158 Eliassen, R. Incinerator Mechanization Wins Increasing Favor. Civil Eng., Vol. 19, No. 4, April 1949. pp 17-21.

159 Elliott, W.S. Waste Incineration. Presented at Am. Soc. Mech. Engrs. Annual Meeting. Dec. 4, 1958. New York.

160 Ellsworth, R.D., Ballinger, E.P., and Engdahl, R.B. Final Report on Preliminary Survey on Development of an Incinerator for Removal of Combustibles from Scrapped Auto Bodies. Battelle Memorial Institute to Institute of Scrap Iron & Steel, Columbus, Ohio, Aug. 30, 1957. 27 pgs.

161 Ellsworth, R.D., Ballinger, E.P., and Engdahl, R.B. Preliminary Investigation of a Design for an Automobile-body-burning Incinerator. Air Pollution Control Association 51st Annual Meeting, Philadelphia, Pennsylvania, May 1958, Paper No. 58-30, 13 pgs.

162 Ellsworth, R.D., and Engdahl, R.B. The Control of Effluents from Municipal Incinerators. J. Air Pollution Control Assoc., Vol. 7, No. 1, May 1957. pp 43-6.

163 Erhard, H. Refuse Disposal - A Communal or A Thermo-Economical Problem? Combustion, Vol. 34, No. 4, (Abstract), Oct. 1962. p 54.

164 Ettinger, I., Braverman, M.M., and Jacobs, M.B. The Determination of Oxidizable Sulfur Compounds in Incinerator Flue Gases by Automatic Bromometric Titration. Presented at Am. Chem. Soc. Meeting-in-Miniature, March 1958.

165 Ettinger, I., Braverman, M.M., and Jacobs, M.B. The Use of the Von Brand Filtering Recorder in the Evaluation of Incinerator and Smoke Abatement Devices. J. Air Pollution Control Assoc., Vol. 8, No. 2, Aug. 1958. pp 120-23.

166 Estey, Horace S. An Incinerator Without Frills. The American City, Vol. 77, No. 12, Dec. 1962. p 95.

167 Evans, M. Halfway Measures Make Good Incineration Impossible. Power, Vol. 97, No. 5, May 1953.

168 Fairlie, P.D. Mechanical Refuse Disposal. Surveyor (G. Britain) Vol. 108, No. 2994, June 1949.

169 Fannon, W.P. Modern Design Features New Incinerator. Public Works, Vol. 12, Dec. 154. pp 87-8.

170 Fannon, W.P. Municipal Incineration in Baltimore. Air Repair, Vol. 3, No. 2, Nov. 1953, pp 123-25.

171 Fannon, W.P. New Idea in Incinerator Stoking. Am. City, Vol. 68, No. 5, May 1953, pp 114-15.

172 Feldman, E.S., and Rosnick, L.M. Wood Waste Disposal and Air Pollution Control in the L.A. Area. Forest Products Research Society, 1949. Preprint.

173 Feldstein, M. Analysis of Hydrocarbons from Incinerator Effluents with a Comgas Indicator. Am. Ind. Hyg. Assoc. J., Vol. 22, 1961. p 286.

174 Feldstein, M. Concentration and Photoreactivity of Organic Compounds in San Francisco Bay Atmosphere. Bay Area Air Pollution Control District, 1964. p 50.

175 Feldstein, M. Studies on the Analysis of Hydrocarbons from Incinerator Effluents with a Flame Ionization Detector. Air Pollution Control Assoc., 54th Annual Meeting, June 1961. Paper No. 61-27.

176 Feldstein, Milton. Studies on the Analysis of Hydrocarbons from Incinerator Effluents with a Flame Ionization Detector. Journal of the Air Pollution Control Association, Vol. 12, No. 3, March 1962. p 139,

177 Fisher, Morris A., and Langer, Gerhard. New Instrumentation in Municipal Incinerators. Refuse Removal Journal, Vol. 5, No. 1, Jan. 1962. p 10.

178 Flood, L.P. Air Pollution Resulting from Incineration - Its Reduction and Control. Presented at Process Industries Session of Am. Soc. Mech. Engrs. Annual Meeting, New York, Nov. 30 - Dec. 5, 1958.

179 Flood, L.P. Solving the Problem of Flue Fed Incinerators. Presented at Air Pollution Control Association Meeting, St. Louis, Missouri, June 2-6, 1957.

180 Foster, W.S. Elements of Refuse Collection and Disposal. Am. City, Vol. 66, No. 6, pp 104-5.

181 Foster, W.S. Incinerator Design. Am. City, Vol. 62, No. 2, Feb. 1954. pp 126-29.

182 Foster, W.S. Some Principles in the Design and Operation of Municipal Incinerators. Air Repair, Vol. 3, No. 2, Nov. 1953. pp 126-29.

183 Foster, W.S. What's Needed in Incinerator Design. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. New York University.

184 Fox, Earle B., Jr. Cooperation Spells Economical Incineration. The APWA Reporter, Vol. 30, No. 7, 1963. p 4.

185 Fox, Earle B., Jr. 49 Municipalities Join in County-Wide Incinerator Plan. Public Works, Vol. 94, No. 2, Feb. 1963, p 100.

186 Friedman, E. Open-Air Incinerator Design. Am. City, Vol. 70, No. 4, April 1955. pp 136, 159, 161.

187 Froula, H., Bush, A., Byloff, R. Study of Particulate Matter in Municipal Incinerator Stack Discharges. University of California, Department of Engineering, Nov. 1951. 4 pgs.

188 Gabbert, W.L. Equipment for the Collection of Fly Ash, Dust, Soot, and Smoke from the Flue-Fed Incinerator. Air Repair, Vol. 4, No. 3, Nov. 1954. pp 119-23.

189 Garrett, Jack T. Multipurpose Incineration. Manufacturing Chemist's Assoc., Inc., Air and Water Pollution Abatement Conference, Washington, D.C., April 1957. pp 83-8.

190 Gaylord, W.W. Shavings Make Steam. Power, Vol. 86, No. 6, June 1941. pp 67-9.

191 George, R.E. Effects of Design Factors on Stack Emissions from Multiple-chamber Incinerators. Air Pollution Control Assoc. Proceedings West Coast Section 1st Tech. Meeting, Los Angeles, California, March 25-6, 1957. pp 92—101.

192 Gerhardt, P., Jr. Chicago Completes First of Four Incinerators. Am. City, Vol. 72, Jan. 1957. pp 96-8.

193 Gerhart, Paul, Jr. Incinerator to Utilize Waste Heat for Steam Generation. Public Works, Vol. 94, No. 5, May 1963. p100.

194 Gewecke, Gordon. Built to Fit the Site. The American City, Vol. 78, No. 6, June 1963. p 120.

195 Glauberman, H., and Loysen, P. The Use of Commercial Incinerators for the Volume Reduction of Radio Activity Contaminated Combustible Wastes. Health Physics, Vol. 10, April 1964.

196 Goder, R. Incinerator Manufacturers Contribution to Incinerator Research. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957, New York University.

197 Goder, R. Incinerators in Today's Economy. Air Pollution Control Assoc., Sept. 22-23, 1955. 12th East Central Meeting, Indianapolis, Indiana, pp 14-17.

198 Gordon, C.W. Deodorization of Stack Gases when Drying or Incinerating Sewage Sludge. Presented at a conference on Sewage Sludge as a Soil Conditioner in Toronto, Canada, Sept. 1956.

199 Graydon, S.W. Atlanta's Enlarged Incinerator. Am. City, Vol. 67, July 1952. pp 94-5.

200 Greeley, S.A. Background of Design Criteria for Municipal Incinerators, The Designer's View. J. Air Pollution Control Assoc., Vol. 6, No. 3, Nov. 1956. pp 133-138.

201 Greeley, S.A. Criteria for Municipal Incinerators... The Designer's View. Mech. Eng., Vol. 78, No. 11, Nov. 1956. pp 1024-1027.

202 Greeley, S.A., and Clarke, S.M. Incinerator Practice - 1910 and Today. Eng. News-Record, Vol. 141, No. 16, Oct. 14, 1948. pp 87-91.

203 Greeley, S.A., Clarke, S.M., and Gould, R.H. Incinerator Design and Fly-Ash Problem. Am. City, Vol. 70, No. 5, 6, 7; May 1955, pp 102-3, June, pp 112-14, and July, pp 126-27, 169, and 171.

204 Greenburg, L. Apartment House Incinerators -- A Necessary Evil? New York City Department of Air Pollution Control.

205 Gruber, Charles W.; and Schumann, Charles E. The Use of Adhesive-Coated Paper for Estimating Incinerator Particulate Emissions. Journal of the Air Pollution Control Association, Vol. 12, No. 8, Aug. 1962, p 376.

206 Gurnham, C.F. Waste Solvent Incinerator: Successful at Upjohn Co., Kalamazoo, Michigan. Ind. Wastes, Vol. 2, March-April 1957, pp 29-31.

207 Habeeb, Virginia T. The Case of the Disappearing Household Trash. The American Home, Vol. 66, No. 4, May 1963. p 52.

208 Hachborn, E.G. City of Kitchener Installs Modern Refuse Incinerator. Municipal Utilities, Vol. 90, No. 8, Aug. 1952. pp 21-3, 49-50.

209 Hafeli, R.J. Refuse Analysis. International Research Group on Refuse Disposal, Information Bulletin #15, Aug. 1962. p. 16.

210 Hair, Albert M., Jr. The Incinerator's Anniversary. The American City, Vol. 77, No. 11, Nov. 1962. p 23.

211 Hamming, Walter J. Results of Incinerator Ban. Los Angeles Air Pollution Control District, October 28, 1958, 5 pgs. Presented before the California State Interim Committee on Public Health, State Building, Los Angeles, California.

212 Hammon, James H. Ocean Incinerator Proposed for Boston. The Boston Sunday Globe, Oct. 6, 1963.

213 Hangrauck, R.P., von Lehmden, D.J., and Meeker, J.E. Emissions of Polynuclear Hydrocarbons and Other Pollutants from Heat-Generation and Incineration Processes. Journal of the Air Pollution Control Association, Vol. 14, No. 7, July 1964.

214 Hawkins, George A. The Residue Tells the Story. The American City, Vol. 78, No. 9, Sept. 1963. p 104.

215 Hayden, J.L. Incinerator Model Convinces Public. Public Works, Vol. 95, July 1964. p 94.

216 Hein, G., Yocom, J., Tighe, J., and Teitelbaum, C. Summary Report-Study of Effluents from Back Yard Incinerators to Air Pollution Foundation. Battelle Memorial Institute, Columbus, Ohio, Oct. 20, 1955. pp 1-30.

217 Hein, Glen M. (Battelle Mem. Inst.) Odor Control by Catalytic and High Temperature Oxidation. Ann. N.Y. Acad. Sci., Vol. 116, No. 2, 1964. p 656.

218 Hemeon, Wesley, C.L. Gas Cleaning Efficiency Requirements for Different Pollutants. Journal of the Air Pollution Control Association, Vol. 12, No. 3, March 1962. p 105.

219 Hesney, Frank L. Regional Approach to Incineration. The APWA Reporter, Vol. 30, No. 1, Jan. 1963. p 10.

220 Hettenbach, C.F. An Extra-Feature Incinerator. Am. City, Vol. 72, No. 7, July 1957. pp 119-21.

221 Hofft, M.A. Design of Furnaces and Fuel Feeders for Burning Refuse. Wood Industries, Vol. 53, No. 5, Jan.-Apr. 1931. pp 1-13.

222 Holbrook, F.C. Experimental Stoker-Fired Incinerator Furnace. Combustion, Vol. 21, No. 9, March 1950. pp 45-6.

223 Holbrook, F. C. Stocker-Fired Incinerator Furnace -- Experiment. Combustion Eng., Vol. 5, No. 8, March 1951. pp 110-11.

224 Hommon, H. B. Garbage Incinerator with Associated Drying Hearth. United States Patent 2, 516, 213, July 25, 1950.

225 Hopper, T. W. Incinerator Modernization Provides Control of Smoke, Odor and Fly Ash. Public Works, Vol. 85, No. 11, Nov. 1954. pp 92-5.

226 Houry, E., and Koin, H. W. Principles of Design of Smokeless Odorless Incinerators for Maximum Performance. Research Bulletin No. 93 Cleveland: American Gas Association Laboratories, Dec. 1962. 41 pp, $2.50.

227 Houdry, E. J. World's Biggest Cleaning Job. J. Franklin Inst., Vol. 258, No. 3, Sept. 1954. pp 175-85.

228 Houston, P. C. Don't Regard Material Burning a Nightmare! Scrap Age--Waste Age, June 1957. p 3.

229 Houston, P. C. Scrapyards Cut Down Smoke with Incinerator Controls. Iron Age, Vol. 179, May 9, 1957. pp 114, 116.

230 Hurst, W. D. New 300-Ton-Per-Day Refuse Destructor for Winnipeg. Water and Sewage, Vol. 86, No. 1, Jan. 1948. pp 18-21, 42, 44, 46, and 48.

231 Incinerator Institute of America. I. I. A. Incinerator Standards. Incinerator Institute of America, New York, April 1958.

232 Incinerator Institute of America, Technical Committee I. I. A. Incinerator Standards, New York: Incinerator Institute of America, April 1963. 24 pp.

233 Ingram, W. T. Incinerator Design Standards. Presented at Air Pollution Control Association 51st Annual Meeting, Philadelphia, Pa., May 25-29, 1958. Paper No. 58-11.

234 Ingram, W. T., et al. Proceedings, Symposium on Developments in Incinerator Research. New York University, College of Engineering, May 23, 1957.

235 Ingram, William T. Sampling and Monitoring Incinerator Gases. 1963 American Public Works Association Yearbook, p 214.

236 Jacobs, M. B., Braverman, M. M., Hochheiser, S., and Ettinger, I. Sampling and Analysis of Incinerator Flue Gases. Presented at Air Pollution Control Association 51st Annual Meeting, Philadelphia, Pa., May 25-29, 1958.

237 James, G. Gas Incineration is Good Story. Gas Age, Vol. 117, No. 3, Feb. 9, 1956. pp 34, 62.

238 Janssens, A., and Standaert, R. Refuse Incinerator. Technisch-Wetenschappelijk Tydschrift, Vol. 21, No. 2, Feb. 1952. pp 32-42.

239 Jarrett, W. M. Costs of Municipal Refuse Incineration. Public Works, Vol. 84, No. 7, July 1953. pp 71-2.

240 Johnson, H. C. Disposal of Waste Materials Incidental to the Clearance and Development of Land for Sub-division or Building Purposes. Information Bulletin #5-62, Bay Area Air Pollution Control District, San Francisco, 1962.

241 Johnson, Herbert C. How Regulation 2 Effects Metal Salvage Operations In the Bay Area. Bay Area Air Pollution Control District Bulletin 7-61. April 10, 1961.

242 Kaiser, E. R. Unsolved Problems with Flue-Fed Incinerators. Presented at Air Pollution Control Association 53rd Annual Meeting, June 1960. Paper No. 60-68.

243 Kaiser, E. R., Halitsky, J., Jacobs, M. B., and McCabe, L. C. Modifications to Reduce Emissions from a

Flue Fed Incinerator. J. Air Pollution Control Assoc., Vol. 10, No. 3, June 1960. pp 183-97.

244 Kaiser, E. R., Halitsky, J., Jacobs, M. B. and McCabe, L. C. Performance of a Flue Fed Incinerator. J. Air Pollution Control Assoc., Vol. 9, No. 2, Aug. 1959. pp 85-91.

245 Kaiser, E. R., and Tolciss, J. Smokless Burning of Automobile Bodies. Air Pollution Control Assoc., 54th Annual Meeting, June 1961. Paper No. 61-36.

246 Kaiser, Elmer R. Unsolved Problems with Flue-Fed Incinerators. Journal of the APCA, Vol. 11, No. 5, May 1961. p 254.

247 Kaiser, E. R., and Tolciss, J. Burning Proven Best to Clean Auto Steel. Refuse Removal Journal, Vol. 7, No. 11, Nov. 1964. p 18.

248 Kaiser, E. R. Combustion and Heat Calculations for Incinerators. American Society of Mechanical Engineers, National Incinerator Conference, New York, May 18-20, 1964.

249 Kaiser, E. R., and Tolciss, J. Control of Air Pollution from the Burning of Insulated Copper Wire. Journal of the Air Pollution Control Association, Vol. 13, No. 1, Jan. 1963. p 15.

250 Kaiser, E. R. Refuse Composition and Flue-Gas Analysis from Municipal Incinerators. American Society of Mechanical Engineers, National Incinerator Conference, New York, May 18-20, 1964.

251 Kaiser, E. R., and Tolciss J. Smokeless Burning of Automobile Bodies. Journal of the Air Pollution Control Association. Vol. 12, No. 2, Feb. 1962. p 64.

252 Kampschulte, J. Refuse Incineration in Hamburg and Its Extension with Von-Roll Furnace. Combustion, Vol. 34, No. 4, (Abstract), Oct. 1962. p 54.

253 Kanter, C. V., Lunche, R. G., and Fudurich, A. P. Techniques of Testing for Air Contaminants from Combustion Sources. J. Air Pollution Control Assoc., Vol. 6, No. 4, Feb. 1957. p 191.

254 Kern, A. Viewpoints for the Design of Modern Refuse Combustion Plants. Combustion, Vol. 34, No. 4, (Abstract), Oct. 1962. p 54.

255 Keshen, A. S. A Dual Combustion Chamber Incinerator Solves an Air Pollution Problem Resulting from Burning Solid Rubber Wastes. Industrial Wastes, Vol. 4, No. 1, Jan. 1959. pp 14-15.

256 King, M. M. New Incinerator for Santa Monica. Western City, Vol. 28, No. 8, Aug. 1952. pp 45-7.

257 King, M. M. Santa Monica Builds a Double-Grate Incinerator. Am. City, Vol. 67, Nov. 1952. pp 116-18.

258 Kirk, W. B. Can Residential Incinerators be Good Neighbors? Presented at Meeting of Ohio Valley Conference on Air Pollution Control, Oct. 22, 1957. Cincinnati, Ohio.

259 Kirk, W. B. Incinerator Developments Through Research. Am. Gas Assoc. Research and Utilization Conference, May 7-9, 1957, Cleveland, Ohio.

260 Klegerman, M. H. Arlington's 300-Ton Incinerator. Sewage & Ind. Wastes Eng., Vol. 21, No. 4, April 1950. pp 199-201.

261 Knight, R. R. Mechanics of Municipal Refuse Destructors and Incinerators. Water & Sewage, Nov. 1946, pp 16-19, 52-54.

262 Kuchuck, F. D. An Incinerator Can Be Attractive. The American City, Vol. 78, No. 3, March 1963. p 96.

263 Laboon, J. F. Incineration of Liquid Sludge Proves Economical. Sewage

Works Eng., & Munic. Sanit., Vol. 20, No. 2, Feb. 1949. pp 66-70.

264 Lamson, B.F. Information for Bidders on Garbage and Refuse Incinerators. Water & Sewage, Vol. 86-No.2, Feb. 1948. pp 23-4, 36.

265 Lamson, B.F. Refuse Disposal by Incineration. Water & Sewage, Vol. 86, No. 1, Jan. 1948. pp 25-7.

266 Langer, G., and Radner, S. Emission and Performance Study of a Pilot Plant Rotary Type Incinerator. Air Pollution Control Asso. News, Vol. 5, Oct. 1957. pp 4-5, 8.

267 Larson, G.P. A Smog Source Not Yet Controlled. Los Angeles County Air Pollution Control District Publication No. 35, 4 pgs.

268 Larson, L.C. Mechanically Stoked Incinerator for Alhambra's Wastes. Public Works, Vol. 81, No. 1, Jan. 1950. pp 23-5.

269 Larson, L.C. Rubbish Incinerator in Residential City Satisfies Rigid Requirements. Eng. News-Record, Vol. 141, No. 24, Dec. 9, 1948. pp 104-7.

270 Leake, J.W. Louisville Incinerator Operates on Production Line Basis. Am. City, Nov. 1957. pp 104-7.

271 Leet, C.A. Fly Ash Collection When Incinerating Sewage Sludge. Presented at a conference on Sewage Sludge as a Soil Conditioner in Toronto, Canada, Sept. 1956.

272 Lenchan, Joseph H. Air Pollution Control in Municipal Incineration. Journal of the Air Pollution Control Association, Vol. 12, No. 9, Sept. 1962. p 414.

273 Lester, G.T., Sr. Furnace for Burning Comminuted Fuel Including Tangential Air Feed. United States Patent 2,518,800, Aug. 15, 1950.

274 Lewis, J.V. Garbage Reduction-Land Fill Replaced by Incineration. Wastes Eng., Vol. 25, No. 2, February 1954. pp 66-8, 91-2.

275 Lewis, J.V., and Nussbaumer, N.L. Rochester, N.Y., Documents Design Construction and Operating Costs of Its Two New Incinerators. Am. City, Vol. 71, Sept. 1956, pp 105-8.

276 Liebman, H. Modern Incinerator Design Developed by New York City. Public Works, Vol. 83, No. 8, Aug. 1952. pp 62-4, 94, 96.

277 Liebman, H. New York City Adopts Incineration for Refuse Disposal. Public Works, Vol. 80, No. 9, Sept. 1949. pp 41-4.

278 Linsky, B., and Maxwell, W.S. Can Small Incinerators be Made to Behave? Am. City, Vol. 68, Nov. 1953. p 131.

279 deLorenzi, O. Some Recent Developments in Burning Wet Wood. Mech. Eng., Vol. 72, No. 3, March 1950. pp 255-7.

280 deLorenzi, O. Turbulent Suspension Burning of Wet Wood, Bark and Other Fuels. Am. Soc. Mech. Engrs. Meeting November 30 - December 5, 1952. Paper No. 52-A-104, 17 pgs.

281 Los Angeles County Air Pollution Control District. Approved Standing Operating Procedures for Wood Burning Incinerators.

282 Los Angeles County Air Pollution Control District. Disposal of Waste Materials Arising from Land Clearance Activities April 5, 1956. 24 pgs.

283 Los Angeles County Air Pollution Control District. Incinerator Design Factors.

284 Los Angeles County Air Pollution Control District. Test Procedures and Methods in Air Pollution Control, 1952.

285 Lyall, J.D. Use and Care of Wigwam Refuse Incinerators. Plant Eng., Vol. 3, No. 3, March 1949. pp 42-3.

286 McCabe, Louis C. Air Pollution. Proceedings of U.S. Technical Conference on Air Pollution, 1950 (Pub. 1952).

287 McCabe, Louis C. Multiple-Chamber Wood-Burning Incinerators. Ind. & Eng. Chem., Vol. 44, April 1952. pp 111A, 112A, and 114A.

288 McCabe, Louis C. Pollution Levels are Set for L.A. County. Ind. & Eng. Chem., Vol. 47, No. 6, June 1955. pp 101A, 102A, & 104A.

289 McCabe, Louis C., Kaiser, E.R., and Halitsky, J.A. Flue-Fed Incinerator Research at New York University. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. New York University.

290 McDevitt, F.J. Generating Electric Power from Waste Incinerator Gases. Public Works, Vol. 86, Jan. 1955, pp 85-6.

291 McDevitt, F.J. St. Louis Turns to Incineration. Am. City, Vol. 71, No. 7, July 1956. pp 124-26.

292 McElwain, John S. Gas Incinerators: 12 Reasons Why You Can Sell Them. American Gas Association Monthly, Vol. 45, No. 9, Sept. 1963. p 28.

293 McEwen, M., Schauer, P.J., and Aponyi, T. Development of the Flow Sheet for Incinerating Contaminated Combustible Wastes. U.S. Atomic Energy Commission Mound Laboratory, Miamisburg, Ohio, May 15, 1951. Ed. MLM-567, 51 pgs.

294 McPherson, Howard L. Lab Research Improves Disposer Performance. American Gas Association Monthly, Vol. 45, No. 3, March 1963. p 15.

295 McQuay, J.C. Your Best Answer for Waste Disposal. Mill and Factory, Vol. 52, No. 2, Feb. 1953. pp 93-95.

296 Machis, A., and Geyer, J.C. Burning Radioactive Wastes in Institutional Incinerators. Am. Ind. Hyg. Assoc. Quart., Vol. 13, 1952. pp 199-205.

297 McKnight, R.J., Williamson, J.E., Sableski, J.J., and Dealy, J.O. Controlling the Flue Fed Incinerator. Air Pollution Control Assoc. 52nd Annual Meeting, June 1959. Paper No. 59-4.

298 MacKnight, Robt. A., Williamson, J.E., and Netzley, Arthur B. An Engineering Evaluation and Planning Division Report on The City of Los Angeles Lacy Street Incinerator. Los Angeles Air Pollution Control District Publication.

299 Major, W.S. Refuse Burning in Spreader Stoker Fired Furnances. Ind. Power, Vol. 62, No. 5, May 1952.

300 Marble, G.E. Apartment House Incinerators. Gas Age, Vol. 116, No. 7, Oct. 6, 1955. pp 54-6.

301 Marble, G.E. Design for Successful Commercial Incineration. Gas Age, Vol. 115, No. 2, Jan. 27, 1955. pp 19-22.

302 Marble, G.E. Gas Burners for Flue Fed Apartment House Incinerators. Am. Gas Assoc., Industrial & Commercial Gas Section, July 1955.

303 Marks, J.C. Incineration of Industrial Solid Waste. Southern Power and Industry, Vol. 74, No. 4, April 1956. pp 48-50.

304 Martin, W.S. Patent for Multiple Unit Hearth for Drying and Incineration of Sewage Study. U.S. Patent 2,655, 883, Oct. 20, 1953.

305 Maxwell, W.S. The Incinerator Menance. Air Pollution Control Assoc. News, Vol. 1, Oct. 1953. pp 7-10.

306 Megonnell, W.H., Ludwig, J., and Silverman, L. Dust Exposures During Ash Removal from Incinerators. Arch. Ind. Health, Vol. 15, No. 3, March 1957. pp 215-222.

307 Meissner, H. G. Designing a Modern Incinerator. Power, Vol. 102, No. 4, April 1958. pp 80-3.

308 Meissner, Harold G. Incinerator Furnace Temperature-How To Calculate and Control It. Journal of the Air Pollution Control Association, Vol. 11, No. 10, Oct. 1962. p 479.

309 Meissner, H. G. The Engineering of a Modern Incinerator. Combustion, Oct. 1957, pp 38-43.

310 Meissner, H. G. Heat from Incineration, Available Quantities and Utilization. The Am. Soc. Mech. Engrs. Incineration Comm., Region II, New York, Annual Meeting, Nov. 13, 1958.

311 Meissner, H. G. Incinerator Furnace Temperature, How to Calculate and Control It. Air Pollution Control Assoc., 54th Annual Meeting, June 1961. Paper No. 61-23.

312 Meissner, H. G. A Simplified Method of Incinerator Design. Am. City, Vol. 72, No. 9, Sept. 1957. pp 135-38.

313 Metzler, D. F. Analyzing the Small Incinerator. Arch. Engr., April 1947. pp 130-35.

314 Michaels, Abraham. Design Critieria for Municipal Incinerators - The Customer's View. Am. Soc. Mech. Engrs. Paper 56-SA-60. See also, J. Air Pollution Control Assoc., Vol. 6, Nov. 1956. p 138.

315 Michaels, Abraham. Incinerator Automation. Am. City, Vol. 70, Oct. 1955. pp 130-31.

316 Mills, Ross E. Process Waste Burner Destroys Liquid Organic Chemical Wastes Safely. Water & Sewage Works, Vol. 3, No. 7, July 1964. p 337.

317 Milton, Harold E. Incinerator Cuts Air Pollution with New Engineering Devices. Refuse Removal Journal, Vol. 8, No. 6, June 1965. p 10.

318 Mirus, E. C., Dr. National Aniline's Incineration Plant. Air & Water Pollution Abatement Conference, Mfg. Chemist's Assoc., Inc., Washington, D. C. April 1957. pp 76-82.

319 Mitchell, J. N., and Gillette, S. G. Control of Emissions from the Processing of Noncombustible Municipal Refuse. Air Repair, Vol. 5, No. 1, May 1955. pp 13-16, 22.

320 Mitchell, Robert J. Incinerator Program. Civil Engineering, Vol. 33, No. 6, June 1963. p 64.

321 Mitchell, Robert J. Pennsylvania County Selects Incinerators Over Landfill Operation. Refuse Removal Journal, Vol. 6, No. 8, Aug. 1963. p 10.

322 Morse Boulger Destructor Co. The Burning of Combustible Materials from Car Bodies. Morse Boulger Destructor Co., Bulletin No. 141.

323 Morse, J. F., and Eddy, H. P., Jr. Charleston's Hand-Operating Incinerator. Am. City, Vol. 43, No. 10, Oct. 1948. pp 96-7.

324 Muller, H. J. Refuse Incineration by the Volund System. Combustion, Vol. 34, No. 4, (Abstract), Oct. 1952. p 54.

325 Munson, James S. Incinerator Helps Heat Shopping Center. Air Engineering, Vol. 5, No. 2, Feb. 1963. p 18.

326 Murray, G. J., Jr. An Organized Attack on the Smoke and Fumes Problem. Smoke & Fumes Committee, Report to Board of Directors of Los Angeles Chamber of Commerce, Nov. 1946. 9 pgs.

327 Myers, D. M. Economic Combustion of Waste Fuels. Dept. of Interior, 51 pgs.

328 New York Department of Air Pollution. Criteria Used in the Examination of Applications for Permits to Install Flue Fed Incinerators in the City of New York, March 1962.

329 New York University. Proceedings of Symposium on Developments in Incinerator Research. New York University, College of Engineering, May 23, 1957.

330 Nickelsporn, Harold B. Factors in Incinerator Design. Public Works, Vol. 93, No. 3, March 1962. p 123.

331 Norotny, J. J. Incinerator Burns Liquid Waste Safely. Plant Engineering, Vol. 18, No. 12, Dec. 1964. p 116.

332 Nussbaumer, N. L. Seven-in-One Incinerator Depot Replaces Unslightly, Unsanitary Open Dump. Eng. News-Record, Vol. 142, No. 7, February 17, 1949. pp 54-7.

333 Nussbaumer, N. L., and Martin, A. G. Operation of Monohearth Garbage and Refuse Incinerator. Water & Sewage Works, Vol. 95, No. 6, June 1948. pp 223-26.

334 Oates, E. T. Developments in Refuse Disposal. The Sanitarian, Vol. 71, No. 2, Nov. 1962. p 61.

335 Orning, A. A., Pfeiffer, J. J., Harrold, W. C., and Schultz, J. Experimental Study of Incineration. Air Pollution Control Assoc. 51st Annual Meeting, Philadelphia, Pa., May 25-29, 1958. Paper No. 58-12.

336 Owen, M. B. Sludge Incinerator. J. Sanitary Eng. Div., Proceedings of Am. Soc. Civil Engrs., Vol. 83, Feb. 1957. pp 1172-1 to 1172-27.

337 Palm, R. Refuse Analysis. International Research Group on Refuse Disposal, Information Bulletin #17, May 1963. p 27.

338 Palmer, Clyde L. Smokeless Brush Disposal. Public Works, Vol. 96, No. 5, May 1965. p 90.

339 Patterson, H. R. Modernization of Refuse Disposal Plants Adds Needed Capacity. Public Works, Vol. 87, Sept. 1956. pp 122-23.

340 Paulus, J. D., and Harrington, W. M., Jr. Some Operating Experiences at a Municipal Refuse Incinerator. Am. Society of Mechanical Engineers Meeting, Nov. 27 - Dec. 2, 1960. Paper No. 60-WA-235.

341 Pendray, G. E. The Public and Air Pollution Control. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. New York University.

342 Penfield, Walker. The Air Pollution Abatement Program of the Manufacturing Chemists' Association. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957. New York University.

343 Perkins, C. E. Refuse Collection and Disposal Cost and Methods. Public Works, Vol. 82, No. 9, Sept. 1951. pp 54-5.

344 Phelps, J. Grady. Removing Cinders From Municipal Incinerators. 1963 American Public Works Association Yearbook, p 208.

345 Phillips, Cushing. Los Angeles Refuse Collection and Disposal System. Proceedings West Coast Section 1st Technical Meeting, Los Angeles. Air Pollution Control Assoc., Pittsburgh, Pa., March 25-26, 1957. pp 36-44.

346 Pierce, E. M. Municipal Incineration of Combustible Waste. Dravo Corp., Jan. 23, 1957.

347 Popovich, M. How to Burn Wood Waste Without Smoke. Air Engineering, Vol. 4, No. 10, Oct. 1962. p 16.

348 Popovich, M., et al. Wood Waste Incineration. Robert A. Taft Sanitary Engineering Center, Technical Report A61-3, Cincinnati, Ohio, 1961.

349 Popovich, M., Northcroft, M., Boubel, R. W., and Thornburg, G. E. Wood Waste Incineration. U.S. Public Health Service, SEC Tech. Report A61-3. 1961.

350 Popovich, M., Northcraft, M.E., Thornburgh, G.E., and Boubel, R.W. Wood Waste Incineration. Oregon State College, Engr. Experiment Station, Corvallis, Oregon.

351 Poscoe, G., and Lapar, R.E. Cleaning Refuse from Storage Pit Corners. Public Works, Vol. 95, Jan. 1964. p 131.

352 Quillen, Bill D. Low Cost Refuse Burner Eliminates Dump. Public Works, Vol. 96, No. 3, March 1965. p 96.

353 Quick, T.P. Economic Aspects of Incineration vs. Incineration Drying. Water Pollution Control Federation Journal, Vol. 36, Nov. 1964. p 1355.

354 Quon, Jimmie E. Thermal Decomposition of Human Waste. Proceedings of the American Society of Civil Engineers, Journal of the Sanitary Division, Vol. 89, No. SA1, Jan. 1963. p 1.

355 Raisch, William. There's No Ugliness Here. The American City, Vol. 77, No. 10, Oct. 1962. p 155.

356 Rapson, I.J. Incineration - Logical Load. Gas Age, Vol. 104, No. 1, July 7, 1949. pp 19-20, 62, 64.

357 Reed, R.J., and Truitt, S.M. Selecting Incinerator Smoke and Odor Burners. Air Repair, Vol. 4, Nov. 1954. p 109.

358 Rehm, F.R. Incinerator Testing and Test Results. J. Air Pollution Control Assoc. Vol. 6, No. 4, Feb. 1957. p 199-204.

359 Reilly, B.B. Incinerator and Sewage Plant Work Together. Public Works, Vol. 92, July 1961. p 109.

360 Reizenstein, Milton. Development of Incinerator for Cleaning Bitumastic Material from Steel Drums. Air Repair, Vol. 4, No.2, Aug. 1954. pp 2, 44.

361 Requardt, C.J., and Harrington, W.M., Jr. Use of Incinerator Ash as Cover for Landfills. Refuse Removal Journal, Vol. 5, No. 11, Nov. 1962. p 25.

362 Richards, Glenn C. Burn Brush Without Smoke. The American City, Vol. 78, No. 9, Sept. 1963. p 34.

363 Ritter, R.H., and Regnier, R.C. Old Plant Guides Design of New Baltimore Incinerator. Civil Eng., Vol. 25, No. 2, Feb. 1955. pp 40-3.

364 Rocheleau, Robert F. Incineration of Organic Wastes (Sludges & Chemicals). Air and Water Pollution Abatement Conference, Mfg. Chemist's Assoc., Inc., Washington, D.C. April 1957. pp 89-98.

365 Rodger, W.A., and Hampson, D.C. Operating Characteristics and Economics of a 100 ft. 3/day Incinerator for Radioactive Wastes. J. Air Pollution Control Assoc., Vol. 6, No. 1, May 1956. pp 41-3.

366 Rogus, C.A. New York City Makes Teammates of Sanitary Fills and Incinerators. Am. City, Vol. 70, No. 3, March 1955. pp 114-15.

367 Rogus, C.A. New York City Turns to Incineration. Civil Eng., Vol. 22, No. 12, Dec. 1952. pp 54-9, 102.

368 Rogus, Casimir A. Municipal Solid-Waste Disposal, Part III. The American City, Vol. 77, No. 4, April 1962. p 104.

369 Rogus, Casimir A. Municipal Solid-Waste Disposal, Part IV. The American City, Vol. 77, No. 5, May 1962. p 106.

370 Rogus, Casimir A. Refuse Collection and Disposal in Western Europe, Part IV. Public Works, Vol.93, No. 7, July 1962. p 71.

371 Rose, A.H., et al. Air Pollution Effects of Incinerator Firing Practices and Combustion Air Distribution. J. Air Pollution Control Assoc., Vol. 8, Feb. 1959. pp 297-309.

372 Rose, A.H., and Crabaugh, H.R. Incinerator Design Standards: Research Findings. Los Angeles County Air

Pollution Control District, Publication No. 60, March 1-2, 1955. 13 pgs.

373 Ruff, R. J. Catalytic Fume Elimination, Design Considerations for Application. Am. Ind. Hyg. Assoc. Quart., Vol. 14, No. 3, Sept. 1953. pp 183-87.

374 Saburn, A. Walter. Twice as Big-Better Than Ever. The American City, Vol. 78, No. 2, Feb. 1963. p 91.

375 Sanders, N. H. Memphis Slavage Operations Prove Profitable. Electric World, Vol. 161, April 6, 1964. p 103.

376 Sanders, N. H. They Even Sell the Ashes: Salvage Shop of the City of Memphis (Tenn.), Light, Gas, and Water Division. Public Works, Vol. 94, Aug. 1963. p 98.

377 Schaefer, F. Incineration and Its Problems. Proceedings of East Central Section Meeting, Columbus, Ohio, Air Pollution Control Assoc., Sept. 17, 1956. pp 39-44.

378 Schneider, Carl. A Modern Incinerator for $2,280 a Ton. The American City, Vol. 77, No. 9, Sept. 1962. p 104.

379 Schoefer, E. A. Metals for High Temperature in Incinerators. Presented at Annual Am. Soc. Mech. Engrs. Meeting, New York City, Nov. 30, 1958.

380 Schwarz, W. Freschmuellverwertungsanlagen. Gesundheits Ingenieur, Vol. 70, No. 1-2, Jan. 1949. pp 36-8.

381 Scott, H. J. Beverly Hills Incinerator Meets all City and Smog Control Requirements. Western City, Vol. 24, No. 12, Dec. 1948, pp 21-3. See also, Am. City, Vol. 64, No. 2, Feb. 1948. pp 123, 139.

382 Scudder, G. H. Town of Huntington Looks Ahead-With Incinerators. Am. City, Vol. 71, No. 4, April 1956. pp 106-8.

383 Segeler, George C. The Gas Industry and Its Contribution to Air Pollution Control. 54th Annual Meeting of the Air Pollution Control Association, June 14, 1961.

384 Sheaffer, John R., von Boehm, Berndt, and Hackett, James E. Refuse Disposal Needs and Practices in Northeastern Illinois. Technical Report No. 3, Northeastern Illinois Metropolitan Area Planning Commission, Chicago 3, Illinois. June 1963.

385 Shequine, E. R. Steam Generation from Incineration. Public Works, Vol. 95, No. 8, Aug. 1964. p 92.

386 Skipworth, D. W., Hein, G. W., and Nelson, H. W. Design of Domestic Gas-Fired Incinerators for Elimination of Smoke, Odors, and Fly Ash. Research Bulletin 78 (Domestic Gas Incinerator Research) Am. Gas Assoc. Laboratories.

387 Sleeger, W. H. Three Florida Incinerators. Am. City, Vol. 72, June 1957. pp 138-40.

388 Smauder, E. E. The Importance of Incineration as it Applied to Air Pollution Control. Air Pollution and Smoke Prevention Assoc., Am., 1950, 43rd Annual Convention, Montreal, Canada, pp 54-8.

389 Smauder, E. E. Problems of Municipal Incineration. Air Pollution Control Assoc. 1st Technical Meeting, West Coast Section, Los Angeles, California, March 25-26, 1957. pp 69-81.

390 Smauder, E. E. Wet Collectors for Incinerators. Air Pollution Control Assoc., 48th Annual Meeting, Detroit, Michigan, May 23-26, 1955. pp 28-1 to 28-4.

391 Smelli, J. H. The Utilization of Waste Materials for Heat Production. The Sanitarian, Vol. 70, No. 9, June 1962. p 387.

392 Smith, H. T. The Application of Electrostatic Precipitators to Scrap Yard Burning. Air Pollution Control Assoc., East Central Section Meeting, Columbus, Ohio, Sept. 17, 1956. pp 1-2.

393 Stanford Research Institute. Investigation of Incinerator Effluent. Tech. Report,

Alhambra Municipal Incinerator. Stanford Research Institute, California. Jan. 1951.

394 Steinbacher, B. C. A Discussion of Rubbish Burning Multiple Chamber Incinerators. Air Pollution Control Assoc., First Technical Meeting of West Coast Section, March 25-26, 1957.

395 Stenburg, R. L., et al. Field Evaluation of Combustion Air Effects on Atmospheric Emissions from Municipal Incinerators. Air Pollution Control Assoc., 54th Annual Meeting, June 1961, Paper No. 61-2.

396 Stenburg, R. L. Research on Air Pollution Aspects of Incineration. Proceedings on Symposium on Developments in Incinerator Research, May 23, 1957, New York University.

397 Stenburg, R. L., et al. Effects of Fuel Moisture and Incinerator Design on Effluents from Incinerators. J. Air Pollution Control Assoc., April 1960. pp 114-20.

398 Stenburg, R. L., et al. Effects of High Volatile Fuel on Incinerator Effluents. Air Pollution Control Assoc., 53rd Annual Meeting, June 1960. Paper No. 60-67.

399 Stenburg, Robert L. Advice on Incineration Disposal of Solid Waste. Refuse Removal Journal, Vol. 5, No. 12, Dec. 1962. p 27.

400 Stenburg, Robert L., Hangebrauck, Robert P., and von Lehmden, Darryl J. Effects of High Volatile Fuel on Incinerator Effluents, Journal of the Air Pollution Control Association, Vol. 11, Aug. 1961. p 376.

401 Stenburg, Robert L, Hangebrauck, Robert P., von Lehmden, Darryl J., and Andrew H. Rose, Jr. Field Evaluation of Combustion Air Effects on Atmospheric Emissions from Municipal Incinerators. Journal of the Air Pollution Control Association, Vol. 12, No. 2, Feb. 1962. p 83.

402 Stenburg, Robert L. Incineration of Community Wastes. 1962 American Public Works Association Yearbook, p. 212.

403 Stenburg, Robert L. Modern Methods of Incineration. Air Engineering, March 1964.

404 Stenburg, Robert L. Status of the Flue-Fed Incinerator as a Source of Air Pollution. American Industrial Hygiene Association Journal, Vol. 24, No. 5, Sept. - Oct. 1963. p 505.

405 Stephenson, Junius W. Get the Best Incinerator for Your Engineering Dollar. 1964 American Public Works Association Yearbook, p. 198.

406 Sterling, Morton. Air Pollution Control and the Gas Industry. Air Pollution Control Association Journal, Vol. 2, No. 8, Aug. 1961. p 354.

407 Sterling, M., and Bower, R. Testing of Domestic Incinerators. Air Pollution Control Assoc., 51st Annual Meeting, Philadelphia, Pa. May 25-29, 1958. Paper No. 58-29, 19 pgs.

408 Stern, Arthur C., Editor. Combustion in Furnaces, Incinerators, and Open Fires. (Volume II, Chapter 19), Air Pollution, Volumes I and II, New York: Academic Press, 1962. 656 pgs and 586 pgs.

409 Stilson, A. E. Incinerators - Design, Construction, Cost and Location. Public Health News, Vol. 24-26, 1940-1942, New Jersey Dept. of Health.

410 Stilson, A. E. Twelve Factors to Consider in Planning for Incineration. Public Works, Vol. 83, Aug. 1953. pp 91-3, 134.

411 Stone, R., and Bowerman, F. R. Incineration and Alternative Refuse Disposal Processes. Am. Soc. Civil Engrs. -- Proceedings, Vol. 80, Separate No. 471, Aug. 1954. 30 pgs.

412 Stone, R., and Gotaas, H. B. Incineration as Municipal Waste Disposal Process. Wastes Eng., Vol. 23, No. 2, Feb. 1952. pp 66-8, 91.

413 Stone, R., and Ludwig, H. F. You're Burning Dollars in Your Incinerator. Eng. News-Record, Vol. 148, No. 12, March 1952. pp 55-7.

414 Strom, G. H. Atmospheric Dispersal Phase of Incinerator Air Pollution. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957, New York University. pp 145-64.

415 Sved, J. R., and Hanauer, S. L. Historical Review of Flue-Fed Incinerator Design. Air Pollution Control Assoc., 54th Annual Meeting, June 1961. Paper No. 61-17.

416 Sved, J. R., and Hanauer, S. L. Historical Review of Flue-Fed Incinerator Design. Paper 61-17 presented at 54th Annual Meeting of the Air Pollution Control Association, June 1961.

417 Swietlik, W. M. Water Sprays Give Milwaukee a Fly-Ash Free Incinerator. Am. City, Vol. 69, Sept. 1954. pp 90-2.

418 Sylvester, M. E. Harbor Refuse Disposal in Large Port. Public Works, Vol. 83, No. 10, Oct. 1952. pp 80-1, 118-20.

419 Tanner, R. New Experiences with Combustion of Solid Urban Wastes in Some Modern Incinerator Plants. Termotecnica (Milan) Vol. 12, May 1958. pp 225-31.

420 Tanner, R. New Refuse Incinerator of L. von Roll A-G. Schweiz Bauzeitung, Vol. 69, No. 14, April 7, 1951, pp 179-83.

421 Tanner, R. The New Refuse Incinerator of L. Von Roll, A.-G. Journal of the Air Pollution Control Association, Vol. 12, No. 6, June 1962. p 285.

422 Taricco, L., and Reid, R. H. Industrial Incinerators. Gas, Vol. 27, No. 2, Feb. 1951. pp 44, 46.

423 Taylor, H. W. Design and Operation of Modern Incinerators. Sewage Works Eng., Vol. 19, No. 1, Jan. 1948. pp 17-18.

424 Taylor, H. W. In and Out of Incinerator. Eng. News-Record, Vol. 140, No. 2, Jan. 8, 1948. pp 100-3.

425 Technical Advisory Board to the Department of Air Pollution, City of Chicago. Code of Recommended Practices for Refuse Burning Equipment for Domestic and Non-Domestic Use - Sections 2 and 3 of Supplement to Chicago Air Pollution Control Ordinance, Chapter 17 of The Municipal Code.

426 Thorburn, R. C., and Chandler, R. J. An Incinerator for Uranium Contaminated Wastes. Industrial Water and Wastes, Vol. 6, No. 2, March-April 1961. p 46.

427 Tidmore, W. E. Operation of Incinerators to Dispose of Municipal Waste. Proceedings of Smoke Prevention Assoc. Am., 42nd Annual Meeting, Birmingham, Alabama, May 23-27, 1949. pp 17-25.

428 Turner, C. A. Problem of Metropolitan District System of Refuse Disposal Incinerators. Boston Soc. Civil Engrs. J., Vol. 42, No. 1, Jan. 1955. pp 60-9.

429 Turner, E. T. Wood Refuse Burning in Central Steam Plant, Hollinger Mine. Can. Mining Met. Bull., Vol. 44, No. 474, Oct. 1951. pp 652-57.

430 Uicker, G. B. Survey of Gas-Fired Domestic Incinerators. J. Air Pollution Control Assoc., Vol. 5, No. 4, Feb. 1956. pp 199-202, 243.

431 Ulrich, H. H. Incinerator is Good Investment. Am. City, Vol. 71, No. 1, Jan. 1956. pp 88-90.

432 United States Bureau of Mines. Experimental Study of Incineration. Report for Quarter Ending June 30, 1956. Air Pollution Control Project 1881-782-A.

433 United States Department of Agriculture. Square Gin Trash Incinerator With Stack Built Over Pit in the Ground. Bureau of Entomology and Plant Quarantine, San Antonio 6, Texas, Sept. 10, 1947.

434 United States Department of Health, Education & Welfare. Engineering Design of Refuse Incinerators - A Manual Prepared for the National Park Service, U.S. Department of Health, Education, & Welfare Publication, June 1958. 34 pgs.

435 United States Department of the Interior, National Park Service. Incinerator and Refuse Receptacles. U.S. Government Printing Office, Superintendent of Documents, Washington, D.C.

436 United States Public Health Service. Engineering Design of Refuse Incinerators - A Manual Prepared for the National Park Service. U.S. Department of Health, Education, & Welfare Publication, June 1958. 34 pgs.

437 United States Public Health Service. Incinerator Bibliography for 1954-1955. Refuse Collection & Disposal, An Annotated Bibliography 1954-1955, pp 18-26.

438 United States Public Health Service. Refuse Collection and Disposal, an Annotated Bibliography. Public Health Bibliography Series No. 4. Supplement 3: 1960-1961. Supplement F: 1962-1963.

439 University of California. Bibliography on Incineration of Refuse. Technical Bulletin No. 3, Series No. 37, Inst. of Eng. Research (Berkeley) Aug. 1950.

440 University of California. Municipal Incineration, A Field Study of Performation of Three Municipal Incinerators. Technical Bulletin No. 6, Series No. 37, Inst. of Eng. Research (Berkeley) Nov. 1951. pp 65.

441 University of California. Municipal Incineration, A Study of the Factors Involved in Municipal Refuse Disposal by Incineration. Technical Bulletin No. 5, Series No. 37, Inst. of Eng. Research (Berkeley), October 1951, pp 100.

442 Updegraff, W.R., and Bowerman, F.R. Refuse Collection and Disposal in 194 Western Cities. Western City, Vol. 34, Pt. I, May 1958, pp 32-40, 42; Pt. II, June 1958, pp 32-34, 36-38; and Pt. III, July 1958, pp 28-34.

443 Vandaveer, F.E. Domestic Gas-Fired Incinerators. J. Air Pollution Control Assoc., Vol. 5, No. 4, Feb. 1956. pp 197-98, 242.

444 Vandaveer, F.E. Domestic Gas-Fired Incinerators, Present & Future. Am. Gas Assoc., Research and Utilization Conference, Cleveland, Ohio. 1956. p 27.

445 Vandaveer, F.E. The Domestic Gas-Fired Incinerator's Role in Air Pollution Control. J. Air Pollution Control Assoc., Vol. 6, No. 2, Aug. 1956, pp 90-7.

446 Vandaveer, F.E. Gas Incinerator Characteristics: Acceptance, Servicing and Load. Am. Gas Assoc., Monthly, Vol. 36, No. 10, Oct. 1954. pp 33-4.

447 Vandaveer, F.E. Tomorrow's Incinerators Today. Am. Gas Assoc., Monthly, Oct. 1956. pp 18-34.

448 Velzy, C.R., and Landman, W.J. Incinerator with Power and Other Unusual Features. American Society of Mechanical Engineers Paper 64, WA/PID-Z for Meeting, Nov.29-Dec 4. 1964.

449 Velzy, C.R., and Velzy, C.O. Unique Indicator Develops Power and Provides Salt Water Conversion. Public Works, Vol. 95, No. 4, April 1964. p 90.

450 Venezia, Ronald A. Municipal Incinerator in Florida 1962. Florida State Board of Health, Bureau of Sanitary Engineering. Jacksonville, Fla.

451 Voelker, Edward M. Incinerator Standards. Journal of the Air Pollution Control Association, Vol. 12, No. 10, Oct. 1962. p 487.

452 Voelker, Edward M. The Problems of Applying Incinerator Criteria. Journal of the Air Pollution Control Association, Vol. 14, No. 9, Sept. 1964. p 363.

453 Wagner, N. W. Stamford Supercharges Its Incinerator. Am. City, Vol. 70, No. 8, Aug. 1955. pp 94.

454 Warrington, K. R. Three Years' Experience with Modern Wood-Waste-Burning System. Power, Vol. 85, No. 1, Jan. 1941. pp 97-9 and 140.

455 Watson, J. W. New Incinerator Designed to Reduce Fly Ash Emission. Public Works, Vol. 89, No. 4, April 1958. pp 97-8.

456 Webber, L. E. Basic Facts on Wood Burning. Power, Vol. 85, No. 3, March 1941. pp 60-2.

457 Weiche, A. V. The Refuse Incinerator Pilot Plant in Dusseldorf. Combustion, Vol. 34, No. 4, (Abstract) Oct. 1962. p 55.

458 Weigle, C. C., and School, G. J. A Boiler Plate, Brick Lined Incinerator with Individual Smoke Stack.

459 Wellstead, L. R. Will It Pay To Incinerate Your Wastes? Industry & Power, Vol. 68, No. 6, June 1955. pp 59-61.

460 Westergaard, V. Traveling Grates Find a New Field of Usefulness. Combustion, Vol. 26, No. 12, June 1955. pp 40-5.

461 White, R. G. Reconditioning Steel Drums. J. Air Pollution Control Association, Vol. 5, No. 3, April 1957. pp 7, 8.

462 Whitehouse, B. H. Smokeless Combustion of Wood Waste. Power Plant Eng., Vol. 48, No. 12, Dec. 1944. pp 96-7.

463 Williamson, J. E., MacKnight, R. J., and Chass, R. L. Design Standards for Multiple Chamber Incinerators, Part I, Industrial Water and Wastes, Vol. 6, No. 3, May - June 1961. p 61.

464 Williamson, J. E., MacKnight, R. J., and Chass, R. L. Design Standards for Multiple Chamber Incinerators, Part II, Industrial Water and Wastes, Vol. 6, No. 4, July - August, 1961. p 97.

465 Williamson, J. E., and Twiss, H. M. Multiple-Chamber Incinerator Design Standards for Los Angeles County. Proceedings of Symposium on Developments in Incinerator Research, May 23, 1957, New York University. See also, Technical Publication, Los Angeles County Air Pollution Control District.

466 Winkler, T. E. Detroit Suburban Communities Join to Plan Refuse Disposal. Public Works, Vol. 96, No. 2, Feb. 1965. p 88.

467 Wohlers, H. C. Emissions from Waste Incineration. Investigation of Air Pollution in the Vicinity of Portland, Oregon. Research Institute, Oct. 4, 1956. pp 23-

468 Xanten, W. A. Nuisance-Free Operations for New Incinerator in Washington, D. C. Civil Eng., Vol. 26, No. 4, April 1956. pp 50-3.

469 Yocom, J. E., Hein, G. M., and Nelson, H. W. A Study of the Effluents from Backyard Incinerators. J. Air Pollution Control Assoc., Vol. 6, No. 2, Aug. 1956. pp 84-9.

470 Zankl, W. The Cell-Grate Refuse Disposal Plant, Combustion, Vol. 34, No. 4, (Abstract) Oct. 1962. p 54.

471 Zurmuhlen, F. H. New York Builds Incinerator 800-Ton Daily Capacity. Civil Eng., Vol. 20, No. 4, April 1950. pp 17-21.

Section 4

BURNING OF GAS AEROSOL WASTE

Catalytic, Furnace and Flare Combustion - Basic Concepts and Selected Applications

Catalytic Incineration

Catalytic Incineration - Design Parameters and Operation Practices (by Clark)
Catalytic Incineration - Design Parameters and Operation Practices (by Romeo, et al.)

Thermo Oxidation

Thermo Oxidation of Gaseous and Aerosol Waste
Controlled Endo-Exothermic Oxidation of Industrial Wastes

Flare Combustion

Flare Combustion
Flare Burning of Waste Gases

CATALYTIC, FURNACE AND FLARE COMBUSTION-BASIC CONCEPTS AND SELECTED APPLICATIONS

Darryl J. von Lehmden*

I INTRODUCTION

Many organic compounds released from manufacturing operations can be converted to innocuous carbon dioxide and water by rapid oxidation -- combustion. Three rapid oxidation methods are used to destroy combustible contaminates: 1) furnaces, 2) flares and 3) catalytic combustion. The furnace and flare methods are characterized by the presence of a flame during combustion. Whereas, catalytic combustion utilizes a metallic catalyst to promote rapid oxidation. Catalytic combustion is a flameless-type combustion.

II BASIC CONCEPTS

A Flare Combustion

All process plants which handle hydrocarbons, hydrogen, ammonia, hydrogen cyanide, or other toxic or dangerous gases are subject to emergency conditions which occasionally require immediate release of large volumes of such gases for protection of plant and personnel. In many petrochemical processes, hydrocarbons present with inert gases, such as nitrogen and carbon dioxide, must be continuously released in variable volume and concentration. Where these gases are released at energy concentrations constantly within or above the flammable range, their disposal can be handled most economically and safely by application of flares. However, smokeless burning of hugh quantities of gases by flares presents some serious design problems. First, the flare must be sufficiently elevated above ground level for heat and flame protection of adjacent buildings and personnel. Flame must be sustained at varying rates, exceeding by many times to operating range of industrial burners. These physical demands prevent the employment of combustion chambers.

Flare combustion is often characterized by a luminous (yellow) flame. The luminous flame results when oxygen in the air surrounding the flame comes in contact with the hydrocarbons by diffusion only. The luminous color results from incandescent carbon which result from the cracking of the hydrocarbon molecules.

Blue-flame flare combustion can be accomplished by adding water vapor, under proper temperature conditions, as the gas is burned. A water-gas reaction is set up, generating carbon monoxide and hydrogen which assists in the production of blue flame burning by removing the unburned carbon. Combustion of carbon monoxide and hydrogen results in carbon dioxide and water.[1]

$$C + H_2O = CO + H_2 \quad \text{(water-gas reaction)}$$

$$CO + \tfrac{1}{2}O_2 = CO_2$$

$$H_2 + \tfrac{1}{2}O_2 = H_2O$$

One design of a steam injected flare is illustrated in Figure 1.[2]

B Furnace Combustion

Whereas flares are effective in destroying waste gases which are released continuously or periodically at concentrations above the lower limit of flammability, gases vented from industrial processes are generally exhausted at concentrations far below the lower flammable limit. At these concentrations of gases, combustion in an enclosed chamber is necessary.

Furnace combustion is commonly called "direct flame incineration" since a separately fired burner is normally employed to sustain rapid oxidation. The flame, per se, has no influence on the

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reaction except as it provides the time - temperature - turbulence factors.

Since "the three T's" allow considerable latitude in design, numerous combinations of the "three T's" will result in complete combustion. Generally, however, furnace construction costs requires a practical limit on holding time.

When there is 1 percent or less (by volume) combustible matter in a gas stream of otherwise inert material, experience shows[3] clearly that design temperature in the order of 1800°F to 2000°F with a residence time of 3 to 5 seconds in the presence of not less than 25% excess air will be required to secure complete oxidation of some combustibles, particularly odors with low threshold limits.

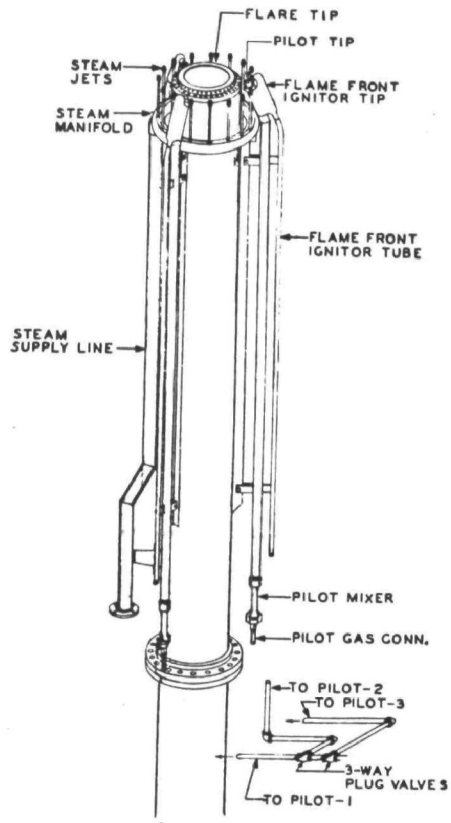

Figure 1. STEAM INJECTION TYPE FLARE

A diagram of a waste gas and odor incinerator is shown in Figure 2.

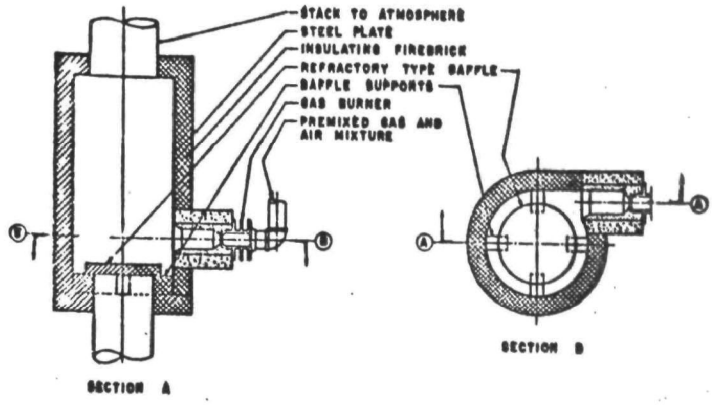

Figure 2. DIAGRAM OF A WASTE GAS AND ODOR INCINERATOR

C Catalytic Combustion

Catalytic combustion is the lowest temperature method of rapidly oxidizing combustible gases and vapors. Many substances exhibit catalytic properties, but metals in the platinum family are recognized for their ability to produce the lowest catalytic ignition temperatures and are therefore conventionally used.

Since catalytic oxidation is a surface reaction, relatively small amount of platinum are used in a way which exposes the maximum surface area to the gas stream. This is accomplished by coating a high surface area substance with the catalyst and arranging the catalyst coated substances in catalyst beds.

Sufficient surface area must be supplied to permit the oxidation reaction to be completed within the bed, since "the three T's" still apply if "exposed catalyst surface" is substituted for "time." Turbulence is achieved in the passage of the contaminated gases through the bed. Catalyst temperature results from the oxidation reaction itself, plus burner or electric preheating where necessary. With platinum alloy catalysts, oxidation of hydrogen will be initiated at ambient temperature, naptha at 450°F, and methane at 750°F.[1]

The temperatures required to catalytically oxidize many organic compounds are given in Table 1.

Catalytic combustion is generally applicable where the following conditions apply: 1) where the gas stream to be handled contains vaporized or gaseous combustible materials, and 2) where there is no large amount of dust, fly ash, or other solid inorganic material in the gas stream.

Catalytic systems are designed to prevent condensate formation in exhaust equipment. The exhaust fan in a catalytic system is located on the hot side of the system so that all vapors passing through it are above the condensation temperature.

A typical catalytic combustion system employing a preheat burner is shown in Figure 3.[1]

Heat evolved by the catalytic oxidation can also be used to preheat the gas stream. Figure 4[4] shows a heat exchanger and preheat burner arrangement to heat the gas stream to the catalytic ignition temperature.

III SELECTED APPLICATION OF COMBUSTION TO AIR POLLUTION CONTROL

A Flare Combustion

Table 1. INDUSTRIAL APPLICATIONS OF CATALYTIC COMBUSTION

Industrial process	Contaminating agents in waste gases	Approximate temperature required for catalytic oxidation
Asphalt Oxidizing	Aldehydes, Anthracenes, Oil Vapors, Hydrocarbons	600° - 700°F
Carbon Black Mfg.	H_2, CO, CH_4, Carbon	*1200° - 1800°F
Catalytic Cracking Units	CO, Hydrocarbons	650° - 800°F
Core Ovens	Wax, Oil Vapors	600° - 700°F
Formaldehyde Mfg.	H_2, CH_4, CO, HCHO	650°F
HNO_3 Mfg.	NO, NO_2	** 500° - 1200°F
Metal Lithography Ovens	Solvents, Resins	500° - 750°F
Octyl-phenol Mfg.	C_6 H_5OH	600° - 800°F
Phthalic Anhydride Mfg.	Maleic Acid, Phthalic Acid, Naphthaquinones, Carbon Monoxide, Formaldehyde	600° - 650°F
Polyethylene Mfg.	Hydrocarbons	500 - 1200°F
Printing Presses	Solvents	600°F
Varnish Cooking	Hydrocarbon Vapors	600° - 700°F
Wire Coating and Enameling Ovens	Solvents, Varnish	600° - 700°F

* Temperatures in excess of 1200°F required to oxidize carbon,
** Reducing atmosphere required.

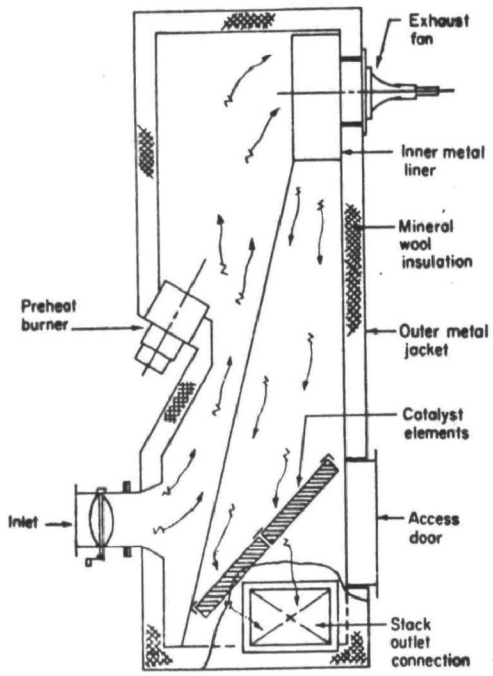

Figure 3. CATALYTIC COMBUSTION SYSTEM INCLUDING PREHEAT BURNER AND EXHAUST FAN

1 Dimethylamine odor control during the manufacture of soaps and detergents[5]

New and improved products for the consumer requires new processes and new chemical raw materials. The manufacture of new products by a soap and detergent company required the use of dimethylamine as a raw material.

Dimethylamine $[NH(CH_3)_2]$ is a gaseous material at 40°F and atmospheric pressure. The material is a first cousin of ammonia (NH_3) and at concentrations in excess of 100 ppm the odor of this amine is nearly identical to that of ammonia. As the amine concentration becomes diluted it takes on an odor resembling fish which has been in the sun too long. As the concentration falls below 100 ppm the fish odor becomes predominant over the ammonia odor.

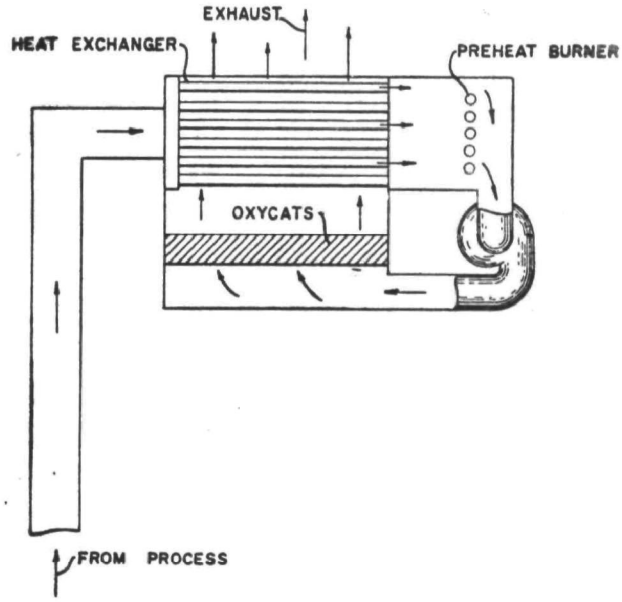

Figure 4. CATALYTIC COMBUSTION SYSTEM INCLUDING HEAT EXCHANGER, PREHEAT BURNER AND HEAT FAN

In order to protect residence 2500 feet from the plant from this fishy odor a method was needed to destroy the dimethylamine emissions. The solution to this odor problem was obtained through the use of a 100-foot flare stack. The amine-laden waste gases are vented to a holding tank for storage. A continuous flow of the amine-laden gases enters the base of the flare stack; passes through a flame arrestor and are incinerated at the top of the flare stack. The stack is equipped with four natural gas pilot lights to assure ignition of all combustibles released from the stack. The result has been a smokeless flare which reduces the odor problem several orders of magnitude.

B Furnace Combustion

1 Methyl mercaptan, hydrogen sulfide and methyl sulfides odor control from the Kraft Pulping Process[6]

Odors resulting from the Kraft (sulfate) pulping process have been reduced by rapid oxidation of the non-condensable gases emitted from the black liquor.

Gaseous emissions from the black liquor contain the odorous compounds, methyl mercaptan, hydrogen sulfide and methyl sulfide. The oxidation of these compounds results in sulfur compounds which are less volatile and therefore less odorous than the original contaminants.

Several west coasts pulp and paper mills have installed equipment to incinerate these odorous sulfur gases. One mill utilizes an integral part of the Kraft process, the lime kiln, to incinerate the odors. Another method of reducing the odors has been the oxidation of the black liquor itself.

Emissions of gaseous sulfur compounds may be as high as 100 pounds per ton of pulp from an uncontrolled Kraft process.

2 Vapor control from paint and varnish cookers[7]

In the burning of combustible vapors from paint and varnish cookers, adequate consideration must be given to prevent fire or explosion in the kettle as a result of flashback through the vapor. Safeguards can be achieved by diluting the vapor concentration to less than 25 percent of the lower explosive limit and by maintaining gas velocities in the ducts well in excess of 20 feet per second, the rate at which flame could propagate along the duct.

A fume (vapor) combustion system for incinerating vapors from paint and varnish cookers is shown in Figure 5.

A correctly proportioned and well insulated furnace requires a fuel input between 600 and 1200 BTU per hour per gallon of processed batch. In some processes, enough vapors are produced to appreciably supplement the regular fuel.

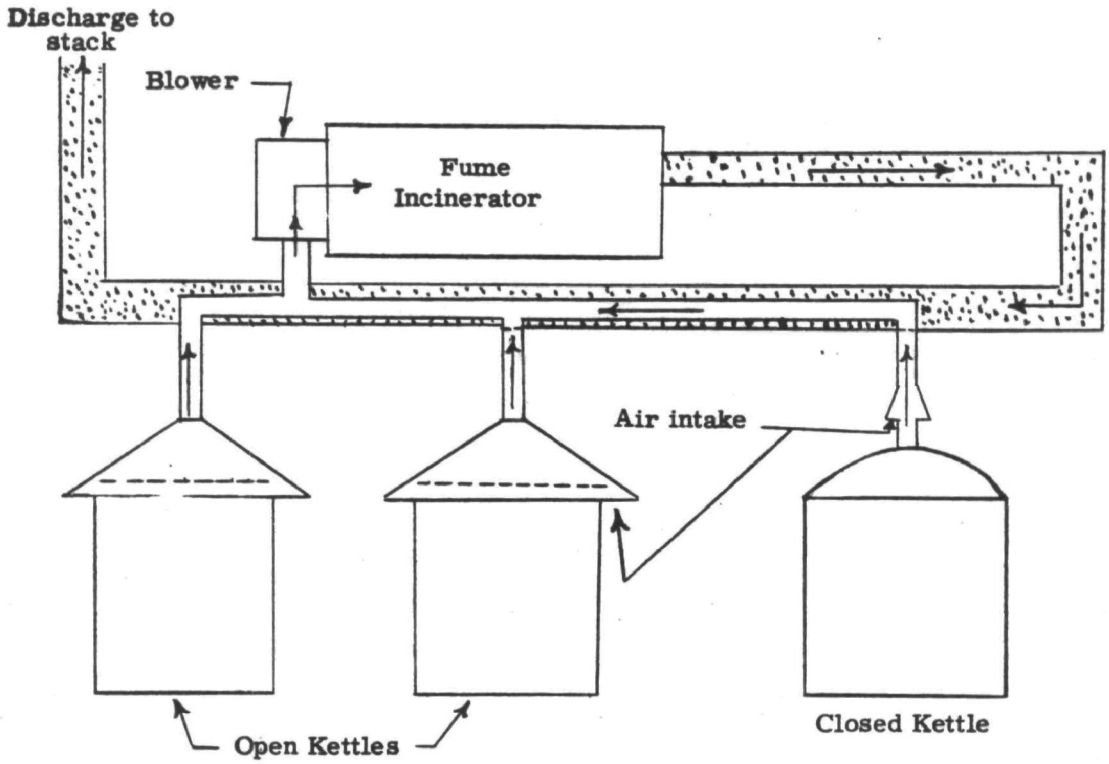

Figure 5. LAYOUT OF FUME COMBUSTION SYSTEM FOR PAINT AND VARNISH COOKING

3 Odor control from coffee roasters[8]

The combustibles in coffee roasting effluent gases may be present in concentration ranging from 0.17 to 0.27 grains per cubic feet, depending upon the type of roaster and the rate of exhaust flow.

The roaster exhaust gases include the following compounds: formic acid, high fatty acids, furfural, methylamine, pyrole, acetic acid, acetone, ammonia pyridine and hydroquinone.

Furnace combustion is presently being employed to incinerate the combustible gases from coffee roasters and to reduce the odor per se.

C Catalytic Combustion

1 Catalytic oxidation of lithographic oven vapors[4]

Catalytic combustion is used in many industrial processes to destroy odors and contaminant gases. Among the processes in which catalytic oxidation is used includes varnish cooking, carbon black manufacture and metal lithographic ovens.

Figure 6 shows a catalytic oxidation system used on a metal lithographic oven. Here a portion of the process effluent, after having been catalyzed and cleaned, is channeled back to a lithographying oven. The returned exhaust, split among several zones in the oven, provides all or a part of the oven heat requirements. Excess exhaust over that needed to heat the oven is vented directly to the atmosphere.

2 Catalytic reduction (deoxidation) of nitrogen oxides in waste gases from nitric acid manufacture[10]

Catalytic combustion is also used to reduce contaminants to lower oxidation-state compounds. Waste gases (tailgas) from the manufacture of nitric acid contain NO, NO_2 and nitric acid vapors. Concentrations of nitrogen oxides in these waste gases range from less than 0.1 percent to almost 50 percent by volume. By mixing a hydrocarbon (e.g., methane) or reactive fuel (e.g., carbon monoxide with the waste gases and passing the gases through a catalyst, the following reaction takes place if the reaction goes to completion.

$$(n_1)\ NO_x + (n_2)\ HC = (n_3)\ H_2O + (n_4)\ CO_2 + (n_5)\ N_2$$

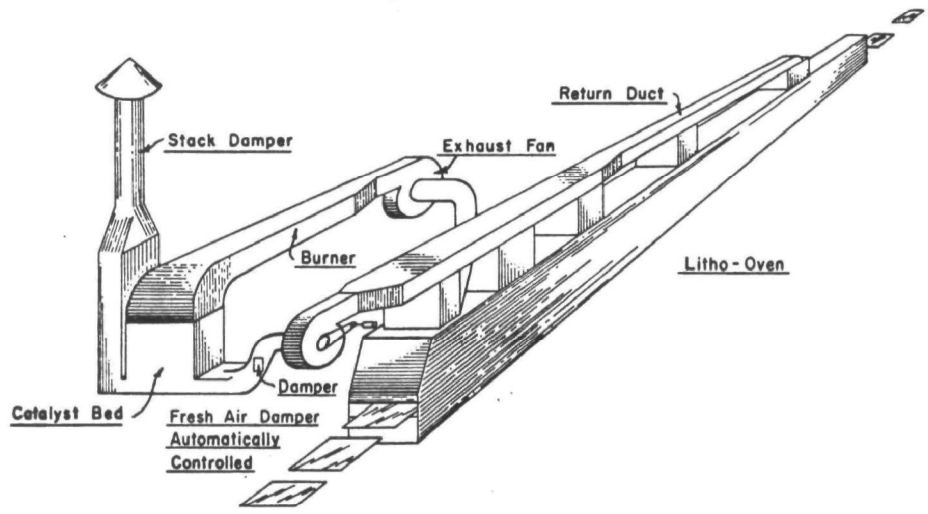

Figure 6. CATALYTIC OXIDATION OF SOLVENT FROM METAL LITHOGRAPHIC OVENS

This reaction can be made to proceed at comparatively low temperature (500 - 1200°F)* The amount of free oxygen contained in the waste gas stream presumably influences the ease with which the reaction can be completed. Obviously, when the waste gas stream is is entirely devoid of free oxygen, then oxidation of the hydrocarbons can occur only through simultaneous reduction of the nitrogen oxides to a lower oxidation state or free nitrogen.

A schematic of a catalytic reduction system for nitric acid waste gases is shown in Figure 7.

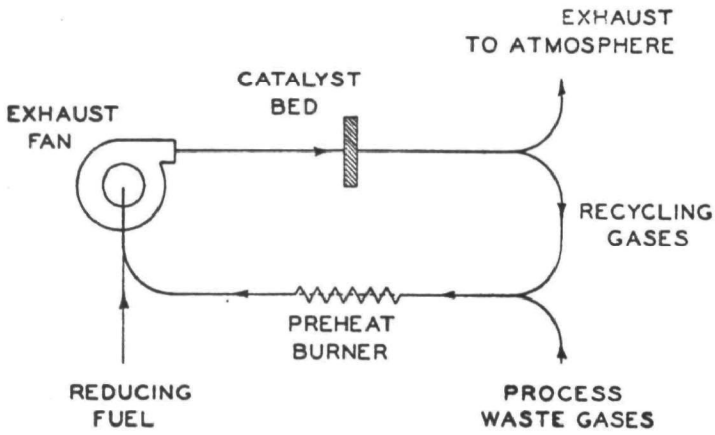

Figure 7. SCHEMATIC OF CATALYTICAL REDUCTION SYSTEM FOR NO_x

REFERENCES

1 Stern, A. C. Air Pollution. Academic Press, New York City, Vol. II, Chapter 32.

2 Coward, H. F. et al. U. S. Bureau of Mines - Bulletin 503. Vol. 4, 1952.

3 Reed, R. D. Controlled Endo-Exothermic Oxidation of Industrial Waste. Presented at Waste Disposal Conference, Oklahoma State University. Nov. 16, 1965.

4 Oxy-Catalyst, Inc. Basic Engineering Principles of the Oxycat. Berwyn, Pennsylvania.

5 Byrd, J. F. et al. Solving a Major Odor Problem in a Chemical Process. JAPCA, Vol. 14, pp 509-516. December, 1964.

6 Hendrickson, E. R. et al. Black Liquor Oxidation as a Method for Reducing Air Pollution from Sulfate Pulping. JAPCA, Vol. 14, pp 487-490. December, 1964.

7 Stenburg, R. L. Control of Atmospheric Emissions From Paint and Varnish Manufacturing Operation. U. S. Public Health Service. R. A. Taft Sanitary Engineering Center. Technical Report A58-4.

8 Anon. Discussion of Coffee Roasting Process. LAAPCD.

9 MacKnight, R. J. et al. Controlling the Flue-Fed Incinerator. JAPCA, Vol. 10. April, 1960.

10 Donahue, J. L. System Designs for the Catalytic Decomposition of Nitrogen Oxides. JAPCA, Vol. 8, pp 209-212, 222. November, 1958.

*Table 1.

CATALYTIC INCINERATION-DESIGN PARAMETERS AND OPERATION PRACTICES

L. W. Clark*

In order to become familiar with the rudimentals of catalytic incineration design I feel the best procedure would be to follow through a simple design example. Accordingly, the following would be representative of a typical catalytic incineration problem.

> One gal/hr of napthalene is being emitted from an oven operation in a gas volume of 100,000 SCFH at 200°F. It is desired to remove at least 90% of the napthalene and, if possible, provide heat exchange to heat the oven intake air to 200°F. Natural gas and 440 volt electricity are available as utilities.

The first step is to determine the catalyst entry temperature of the heated gas from the burner. The temperature to which the gas is heated is a function of the ease of oxidation of the contaminators along with the desired efficiency. Alcohols, ketones and aromatics are relatively easy and require an entry temperature of roughly 600°F, whereas tars and asphaltic vapors need a 900°F temperature. A difficult odor removal problem may also require the higher oxidation temperatures. For our problem we will choose a 600°F entry temperature.

Next we will determine the heat duty of the burner by first determining the heat required to raise 100,000 SCFH of 200°F gas to 600°F by the following calculation:

$$100{,}000 \text{ SCFH} \times \frac{1}{53} \frac{\text{BTU}}{\text{SCF} - {}^{\circ}\text{F}} \times (600 - 200){}^{\circ}\text{F} =$$

$$755{,}000 \frac{\text{BTU}}{\text{hr.}}$$

This heat duty might be considered a preliminary estimate. There is a fallacy in the calculation for we neglected to include the heating of the combustion air. Theoretically this is a calculus integration over the temperature range.

$$Q = Q \text{ inlet gas} + \int_{70}^{600} C_p$$

(quantity of combustion gas)

However, for burner sizing an integration factor of 1/.7 is commonly used giving an operating heat duty of:

$$Q = 1/.7 \times 755{,}000 = 1.08 \times 10^6 \text{ BTU/hr.}$$

Our problem calls for 1.08×10^6 BTU/hr.; and natural gas has a heat capacity of 1000 BTU/SCF. This means 1080 SCFH of gas which combined with a 10 to 1 ratio of combustion air gives 11,880 SCFH of combustion products to be heated under operating conditions. Consequently, the effect of combustion air is significant.

The maximum heat duty of the burner occurs during start-up when cold air is heated to the catalyst entry temperature before the contaminated gases are introduced.

$$Q = 100{,}000 \times 1/53 \times (600 - 70) \times 1/.7 \times 1.25 =$$

$$1.78 \times 10^6 \frac{\text{BTU}}{\text{hr.}}$$

The burner itself may be of the atmospheric type when the system is under suction. This type of burner has an effective turn-down ratio of 3 to 1 which fits our requirements. The natural gas should be available with at least 4-6 inches water gage pressure. The fan for moving the contaminated gas is preferably installed between the burner and the catalyst. This allows for an atmospheric burner and for complete mixing of the gases before reaching the catalyst. Pressure

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burners are not uncommon in catalytic work, but they need combustion air at 4 - 6 inches water gage pressure requiring a blower. However, the pressure burner does have a 10:1 turn-down ratio, and it is necessary for fuel oil burning.

Most catalysts for air pollution work are a platinum, palladium alloy with only occasional traces of rhodium and ruthenium. Generally, palladium seems to be the most effective and is used in heavier concentrations for the difficult oxidations of methane and nitrogen oxides.

The choice of catalyst support is a more arbitrary decision than the type of catalyst and perhaps the best procedure would be to list the various types and their characteristics.

1 Alumina or ceramic honeycomb

advantages:

a effective use of surface area in pitted nature of substance and in design;

b low pressure drop - a 12 inch depth has roughly a 0.5 inches water gage drop.

disadvantages:

a cannot be reactivated or washed;

b breakable due to brittleness.

2 Wire ribbon - a chromium-nickel alloy best suited for corrosion, heat resistance and ease of electrolytic coating.

advantages:

a low pressure drop;

b ability to reactivate and wash;

c very rugged with the ribbon inclined to hold in the absence of a retaining screen.

disadvantages:

a perhaps not as effective use of surface area;

b heat destruction of the metal at continuous 1400°F temperatures. However, the catalyst also vaporizes at this temperature.

3 Ceramic spheres

advantages:

a reasonable use of surface area.

disadvantages:

a high pressure drop - roughly three times that of the honeycomb and ribbon;

b must be effectively retained by a screen.

4 Wire screen - Sufficient for easy oxidations where surface contact can be inefficient. Very low pressure drop is involved, but screens are not good for any degree of difficulty in oxidation.

Returning to our example, the next step is to determine the number of catalyst elements. Our ribbon design is available in an 18 X 24 inch unit. The D-2 unit is 2 1/2 inches thick and designed for 600 SCFM. For our 100,000 SCFM three elements are required. It is possible to have a thicker unit, but the system pays for it in pressure drop. For instance a D-3 element has 1.2 inches water gage pressure drop for 3 3/4 inches thickness but is capable of 960 SCFM or two elements for our example. The reason for this consideration is the smaller housing.

The enthalpy of napthalene is 120,000 BTU/gal. Our loading then produces a 120,000 BTU/hr. heat content of organics. The outlet temperature of the gas leaving the catalyst can then be calculated:

$$120{,}000 \frac{\text{BTU}}{\text{hr.}} \times \frac{1}{100{,}000 \text{ SCFH}} \times 53 = 63.5^{\circ}\text{F}$$

From the catalyst we now have 100,000 SCFH of air at 663°F. This air is to be passed through a heat exchanger, but preferably not to cool beneath 400°F due to condensation considerations in downstream equipment. Typically, a tubular heat exchanger of 2 1/2 inch tubes would be considered. An overall

heat transfer coefficient is roughly 3.5 BTU/hr. - ft^2 - ^oF. Assuming the same 100,000 SCFH of air is to be heated from 70^oF to 200^oF, the following determines the surface area of the heat exchanger:

$$Q = U A \text{ delta } T_{LM}$$

where:

$$Q = 100{,}000 \text{ SCFH} \times (663 - 400)^oF \times 1/53 \text{ BTU/SCF} - {}^oF$$

$$Q = 4.96 \times 10^5 \text{ BTU/hr.}$$

$$\text{delta } T_{LM} = \frac{(400 - 70) - (663 - 200)}{\text{Ln } 330/463} = 388^oF$$

$$A = \frac{4.96 \times 10^5}{388 \times 3.5} = 366 \text{ ft}^2$$

There are two standard instruments provided with the catalytic incinerator. A burner controller is placed before the catalyst to insure a constant temperature to the catalyst. A high-low limit is placed before and after the catalyst, and by flipping a switch the temperature rise across the catalyst can be read. The lower limit is set for roughly 550^oF and is used primarily for start-up. The system will heat-up on air until 550^oF when a damper isolating the process opens. This prevents unburned organics from passing through the system eliminating the possibility of deposits on the catalyst. The high limit set for 1200^oF cuts out the burner and closes the damper to the process in order to protect the materials of construction.

Usually a heat resistant steel is suitable for the housing of the unit. Our product uses Armco steel - steel with an aluminum alloy plating - as an inner liner with a 4 inch thick rock wool insulation and a 20 gage steel jacket. This type of steel can be used due to the lower operating temperatures relative to a thermal system. Occasionally stainless steel is used for heat and corrosion resistance. No differentiation is made between the preheat and combustion zone.

The life of the catalyst is normally three to five years depending on the service and upkeep. The catalyst life is not so much a function of the gases being oxidized as the presence of the various contaminents, such as the following:

1 A dirty environment causing the catalyst to be coated.

2 Catalyst poisons which may be as simple as galvanized ductwork. Typical poisons are Pb, Zn, Hg, Cu, Fe, Sb, Bi, phosphates and silicones.

3 Suppressants which slowly destroy the catalyst activity. Common suppressants are the halogens of F, Cl, Br, and I and the sulfur compounds of H_2S, SO_2 and the sulfates. A suppressant may be periodically washed off the catalyst by a mild acid solution, but there is an unpredictable degree of reactivation.

4 High temperature excursions vaporizing the catalysts.

5 Low temperature start-up causing organic particulates to reach the catalysts, which in turn cause carbonization on the catalyst.

CATALYTIC INCINERATION-DESIGN PARAMETERS AND OPERATION PRACTICES

P. L. Romeo and A. Warsh*

The removal of objectionable gases and vapors from industrial process off-gases is usually accomplished by one of the following methods.

1 Absorption in a liquid

2 Adsorption on a solid

3 Chemical conversion to an innocuous compound

  a non-catalytic

  b catalytic

4 Incineration

  a non-catalytic

  b catalytic

An economic or technical evaluation describing the comparative advantages and disadvantages of each method is beyond the scope of this discussion.

Briefly, however, it is safe to say that under ideal conditions and where the objectionable component has a substantial salvage or re-use value, methods (1) and (2) are generally preferred. Where the value of the objectionable component is low, and purity of the recovered product is beyond tolerable limits, methods (1) and (2) are difficult to justify.

Therefore, one is left to choose between chemical conversion or incineration. From a chemical and economical standpoint, the choice between chemical conversion and incineration is often relatively clear cut. However, should incineration be indicated, the choice between catalytic and non-catalytic treatment is not easily determined and many factors must be considered.

Examples of chemical conversion are the non-catalytic oxidation of various hydrocarbons to carbon dioxide in permanant solutions; and the catalytic reduction of nitrogen dioxide to nitrogen and water using ammonia as the reducing agent.

At this point in the discussion, it may be worthwhile to define the basic differences between catalytic and non-catalytic incineration.

In order for non-catalytic incineration to be considered, the concentration of both oxygen and the combustible impurity must be within the limits of flammability, which is defined as the maximum and minimum percentages of a fuel in an air-fuel mixture which will burn. Concentrations of combustibles outside these limits are not flammable by the usual interpretation.

The energy contained in a mixture of air and fuel, while at the lower flammable limit, is - almost without regard to the type of fuel - equivalent to approximately 52 BTU per SCF. At room temperature, therefore, the combustible in the air must provide at least 52 BTU per SCF in order that a flame may be initiated by a high temperature source, and be self sustaining. If these conditions are not satisfied, the gas temperature must be raised above the auto-ignition point of the component to be removed in order to permit the oxidation reaction to occur; or auxiliary fuel and/or oxygen (air) must be added to provide for burning on a self propagating basis.

Because of safety considerations, high concentrations of undesirable combustibles are generally diluted to 25% or less of the lower explosive (flammability) limit and heat is provided by independently burning a second source of fuel.

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Catalytic incineration, on the other hand, can be accomplished in any concentration range and is usually limited only by the prescribed operating temperature limits of the catalyst and related equipment. A point worth mentioning is the catalytic incineration is flameless.

In general, where large amounts of the undesired combustible impurities are present, and sufficient heat and oxygen is already available, non-catalytic treatment is often more economical. However, in the case of streams with widely varying amounts of impurities or where preheat is required, catalytic treatment offers many advantages.

Table 1 compares auto-ignition temperatures for various substances with experimentally determined catalytic ignition temperatures. From the table, it can be seen that significantly less heat must be required to raise the gas temperature to that required for combustion via the catalytic method as opposed to the non-catalytic method.

It has been found that for a simple catalytic incinerator, with the same capital investment as that required for direct flame incineration, operating fuel costs can, at times, be as low as 30% of the flame incinerator. As an example, let us consider the case of carbon monoxide. Assuming the carbon monoxide concentration is outside the limits of flammability and the stream is available at ambient temperature, almost four times as much auxiliary fuel would be required for flame incineration as that required for catalytic incineration.

Having ascertained the applicability of catalytic incineration, it must then be decided which catalyst will best meet the needs for the particular application under consideration.

Contrary to the often expressed axion that precious metals have a definite order of reactivity for all reactions, it has been established that each combustible must be evaluated individually to ascertain which metal catalyst exhibits maximum activity at the lowest ignition temperature.

TABLE 1

Compound	Flammability Range Mol%	Auto Ignition °F	Catalytic Ign. °F
Acetylene	2.5 - 80	365	280
Benzene	1.4 - 7.1	1076	500
n-Butane	1.6 - 8.5	806	570
Carbon Monoxide	12.5 - 74.2	1204	300
Hydrogen	4.1 - 74.2	1076	32
Methane	5.3 - 13.9	999	800
Naphtha	1.1 - 6.	950	570
Propane	2.4 - 9.5	870	660
Xylene	1.0 - 6.0	924	570

The probable cause of this phenomenon can best be understood if we examine the five steps in any solid-catalyzed vapor phase reaction.

The five basic steps in catalysis are:

1 Diffusion of the reactants through the stagnant fluid around the surface of the pellet, and diffusion through the pores of the pellet to the catalytic surface.

2 Adsorption of reactants on the catalytic surface.

3 Reaction of the adsorbed reactants to form products.

4 Desorption of the products from the catalytic surface.

5 Diffusion of the products through the pores and surface film to the bulk vapor phase outside the pellets.

Given the identical support, (e.g., Al_2O_3 pellets), the rate of steps (1) and (5) would be approximately equal, regardless of the catalytically dispersed metal which is present, for each specific hydrocarbon.

The criteria which govern the order of reactivity for various catalytic metals must, therefore, fall into steps (2), (3) or (4).

For example, it is a well-known fact that the diffusion and adsorption of hydrogen into palladium is rapid and substantial. (Commercial units utilize this principle for the generation and purification of hydrogen; e.g., the Palladium-Alloy Diffusion Purifiers). No other metal approaches palladium in this property.

One would assume, therefore, that step (2) would be considerably more rapid when using a palladium catalyst in the presence of H_2, than for other metals.

This is proven by examining the following reactions:

1) $H_2 + 1/2\ O_2 \rightarrow H_2O$

2) $C_2H_2 + H_2 \rightarrow C_2H_4$

Palladium is, by far, the preferred catalyst for these reactions under a wide variety of commercially attainable conditions.

Further examples showing order of reactivity of hydrocarbon combustions over different catalysts is given in U.S. Patents 3,056,646 and 3,098,712.

Not only is the order of reactivity governed by the hydrocarbon being reacted, but it is also governed by such factors as the available excess oxygen, and the availability of more than the required inlet temperature.

Table 2 is a summary of results obtained, using methane as a fuel.

TABLE 2

Order of Reactivity	Neutral Atmosphere	Oxidizing Atmosphere
1	Rhodium	Palladium
2	Palladium	Rhodium
3	Iridium	Ruthenium
4	Ruthenium	Iridium
5	Platinum	Platinum

(Economic, as well as technical factors, will affect the choice of catalyst in individual cases, and thus palladium may often be chosen to operate in a neutral atmosphere, where rhodium shows a slight technical advantage.) Conclusion:

Each gas purification problem requires specific evaluation concerning the proper choice of catalyst for maximum performance.

Operating experience has shown that, while one metal may prove superior for the oxidation of one compound or class compounds, the exact reverse may be true for a separate compound.

WHAT SHAPE CATALYST?

The geometric configuration or individual catalysts often profoundly influences the extent and direction of a reaction.

Catalysts are currently supplied in the following forms:

1 Pellets

2 Spheres

3 Wire Gauze

4 Raschig Rings

5 Low Pressure Drop, Unitary Ceramic

6 Berl Saddles

7 Extrudate

8 Metallic Ribbon

The variety of shapes, coupled with the variety of catalytic metals, offers a multitude of catalysts available for each application. As a result, a good general rule to follow is to consult with a catalyst manufacturer on the most suitable catalyst and optimum bed configuration.

Catalyst life, in general, is in excess of two years. In some instances, catalyst charges have operated satisfactorily for over seven (7) years without requiring regeneration or replacement.

Catalysts are susceptible to various poisons. Among these are base metals, halogens, and concentrated acids. Poisons of this type have a cumulative effect and when present in high concentrations, can shorten catalyst life appreciably. Recent data also indicates that the presence of sulfur dioxide has a marked deleterious effect on catalyst life.

Some types, e.g., pelleted, spherical, and wire ribbon catalysts, can also act as filters and become plugged and inoperative when processing dust-laden gas streams. Therefore, in these instances, pre-filtration equipment may also be required.

Table 3 gives an indication of the wide variety of applications for which catalytic incineration can be and is used. Table 4 lists the sources of hydrocarbon air pollutants from a typical refinery operation alone.

Catalytic incineration is flexible in that a relatively wide variety of systems and purification schemes can be employed. Figures 1 through 5 schematically depict some typical systems.

Figure 1 depicts the simplest type of catalytic incineration system. In this case, the contaminated stream is delivered to the catalyst element at some constant predetermined temperature, purified over the catalyst, and vented through a stack. In such cases, sufficient pressure is already available in the primary system to overcome the inherent pressure drop through the catalytic unit.

In Figure 1 through Figure 5 it is assumed that sufficient oxygen is already present in the contaminated stream so that an auxiliary source of combustion air is not required.

TABLE 3

TYPICAL INDUSTRIAL USES OF CATALYTIC SYSTEMS

Asphalt Blowing	Metal Decorating
Burnoff Ovens	Nitric Acid Manufacturing
Chemical Processing	Paint Baking
Deep Fat Frying	Paint and Varnish Kettle Cooking
Fat Rendering	Paper Printing and Impregnating
Fish and Vegetable Oil Processing	Pharmaceutical Manufacturing
Fool Processing	Phthalic and Maleic Anhydride
Foundry Core Baking	Sewage Disposal
High Purity Gas Purification	Textile Finishing
	Wire Enamelling

TABLE 4

TYPICAL REFINERY SOURCES OF HYDROCARBON AIR POLLUTANTS WHICH CAN BE TREATED BY CATALYTIC INCINERATION

Air Blowing	Loading Facilities
Barometric Condensers	Process Heating
Blind Changing	Pumps
Blow Down Systems	Storage Tanks
Boilers	Sampling
Catalyst Regenerators	Turnarounds
Compressor Engines	Vacuum Jets
Cooling Towers	Valves
High Pressure Equipment Handling	Waste Water Separators
Decoking	Incinerators

It should be pointed out, however, that in many cases either sufficient oxygen for complete combustion is not available, or the gas velocity is not adequate to provide for good premixing. In these instances, make up combustion air must be supplied, which in many cases necessitates the addition of a secondary air mover to the system.

Figure 2 depicts a system into which a secondary air mover has been incorporated because the primary system pressure was insufficient to overcome the pressure drop across the incinerator.

Please note that the preheat burner is located ahead of (up stream) the blower.

Although locating the blower at this point requires more expensive materials of construction, two important operating advantages are gained, namely;

1) Condensation of vapors on the fan blades is minimized thus requiring less frequent maintenance.

2) Adequate mixing of hot and cold gases is obtained in the blower prior to entry into the catalyst bed, thereby insuring uniform reaction.

Figure 3 depicts a somewhat more elaborate system which incorporates two additional features.

A recycle damper (F) has been added to provide for the mixing of the hot purified effluent gas with the cold inlet gas, thereby minimizing fuel requirements. Naturally, only a portion of the hot purified gas is mixed with the inlet gas. This feature is often used where the concentration of the undesirable or combustible impurity in the inlet stream exceeds 25% of the lower explosive limit. The addition of the effluent gas dilutes the combustible concentration to a tolerable level.

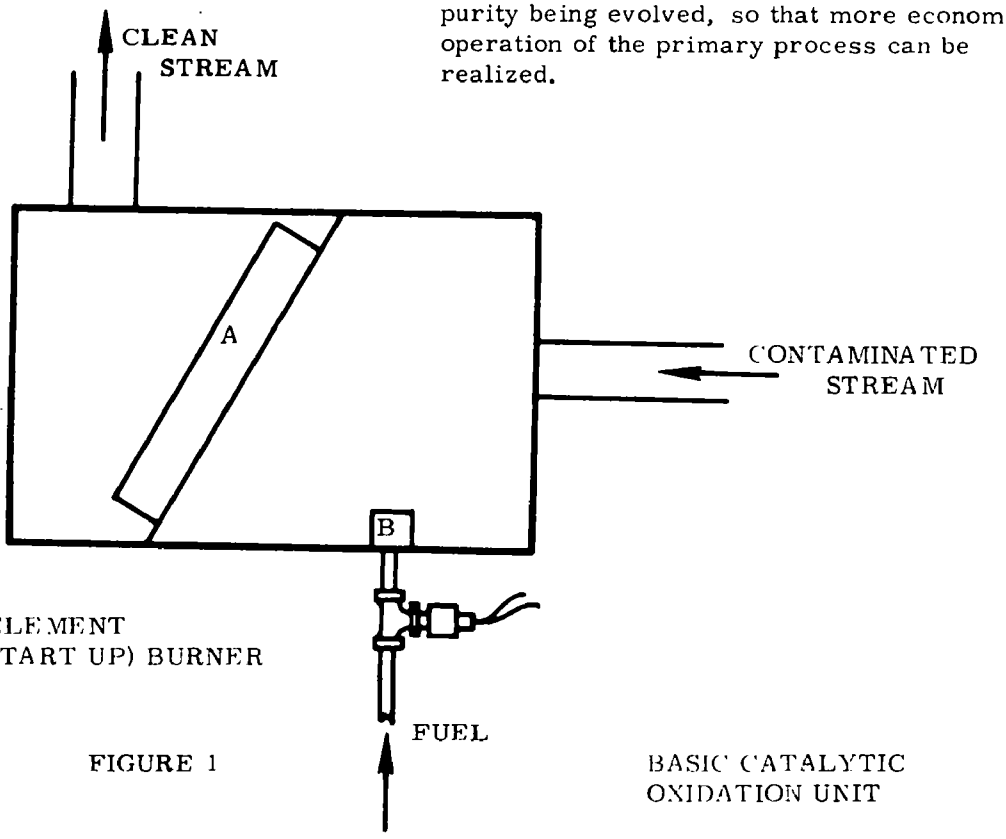
A second feature incorporated into the system is the counter-current heat exchanger (G). A portion of the heat produced during the catalytic incineration of the undesirable combustible is transferred to the cold inlet gas stream thereby further minimizing fuel requirements.

These features may be used separately or together depending on individual process requirements.

Figure 4 depicts the ideal situation where sufficient combustibles are liberated from the primary process (A) to supply, after catalytic incineration in the pollution abatement equipment (E) a substantial portion of the energy requirements for the process.

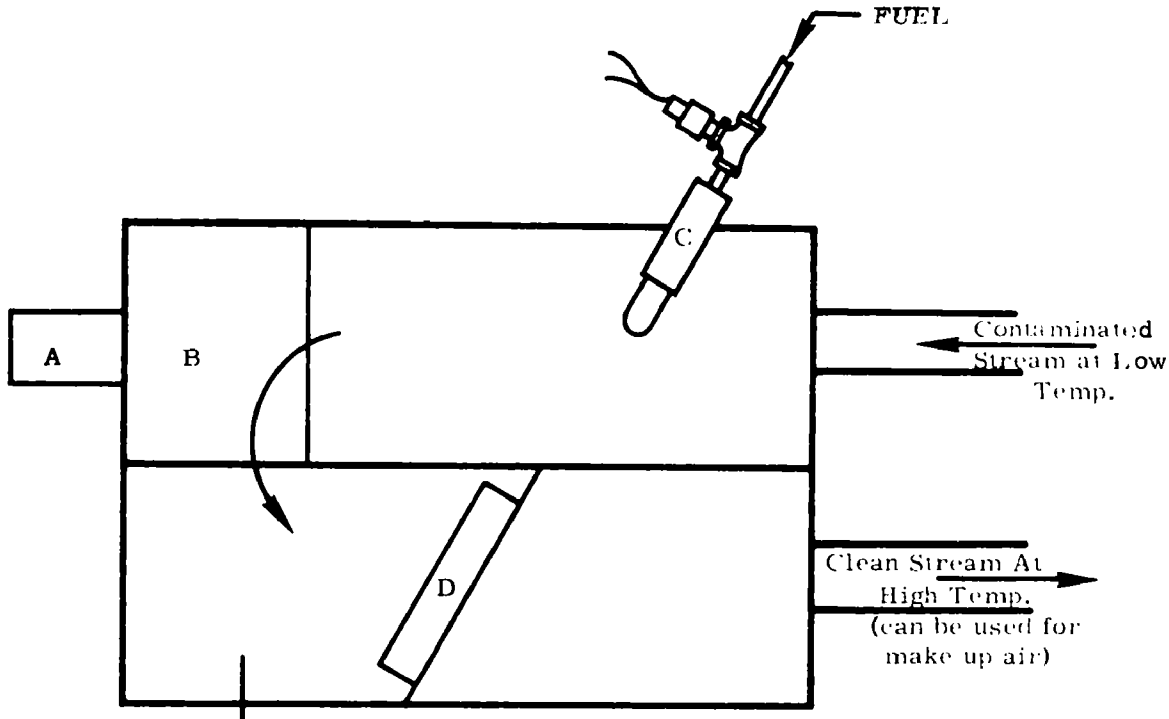
Examples of applications where the decontaminated stream is returned to process would be paint baking or wire enamelling ovens.

Figures 5A and 5B illustrate even more elaborate systems which, in addition to incorporating many of the previously mentioned features, also supply a signal to the primary process proportioned to the amount of impurity being evolved, so that more economic operation of the primary process can be realized.



A. CATALYTIC ELEMENT
B. AUXILIARY (START UP) BURNER

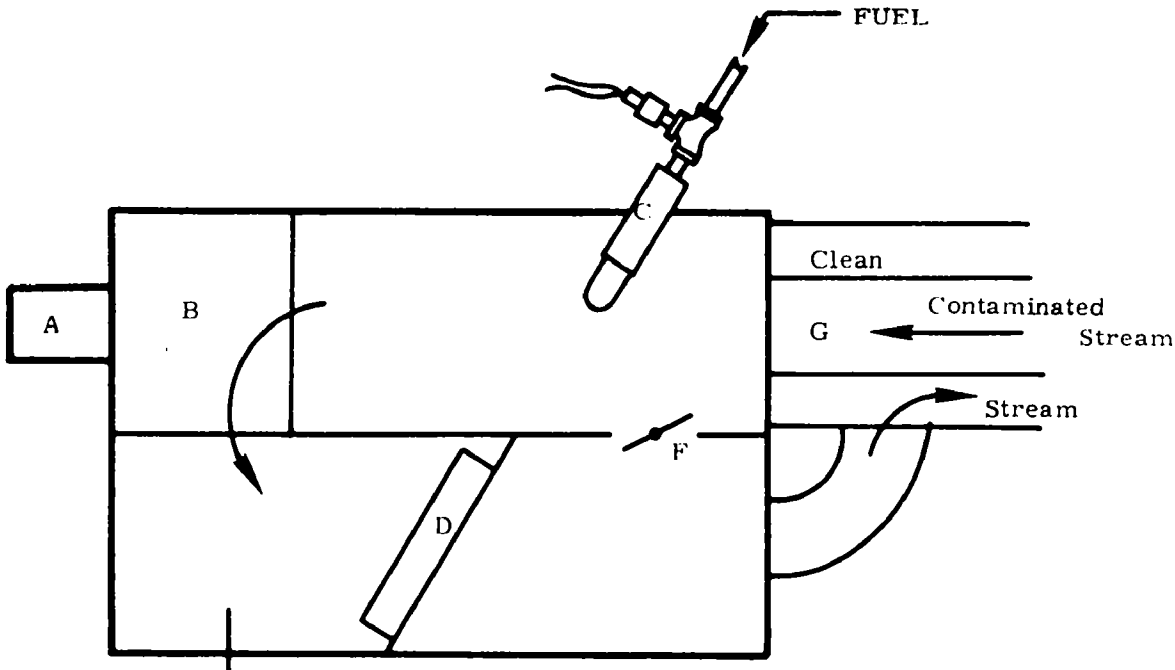
FIGURE 1 BASIC CATALYTIC OXIDATION UNIT



A. Blower Motor
B. Blower (Mixer)
C. Fuel Burner
D. Catalytic Burner
E. Temperature Controller

FIGURE 2

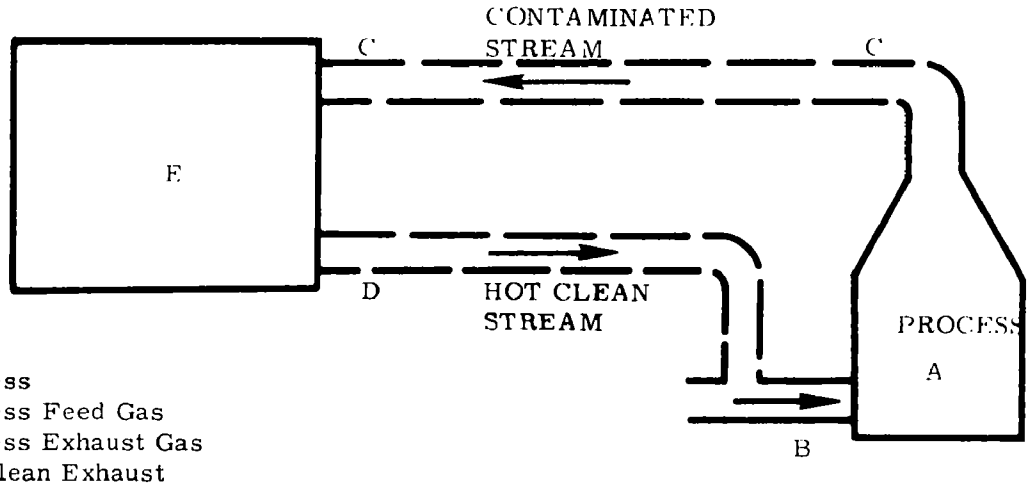
Catalytic Oxidation
Low Temperature
Feed



A. Blower Motor
B. Blower (Mixer)
C. Fuel Burner
D. Catalytic Element
E. Temperature Controller
F. Recycle Damper
G. Heat Exchanger

FIGURE 3

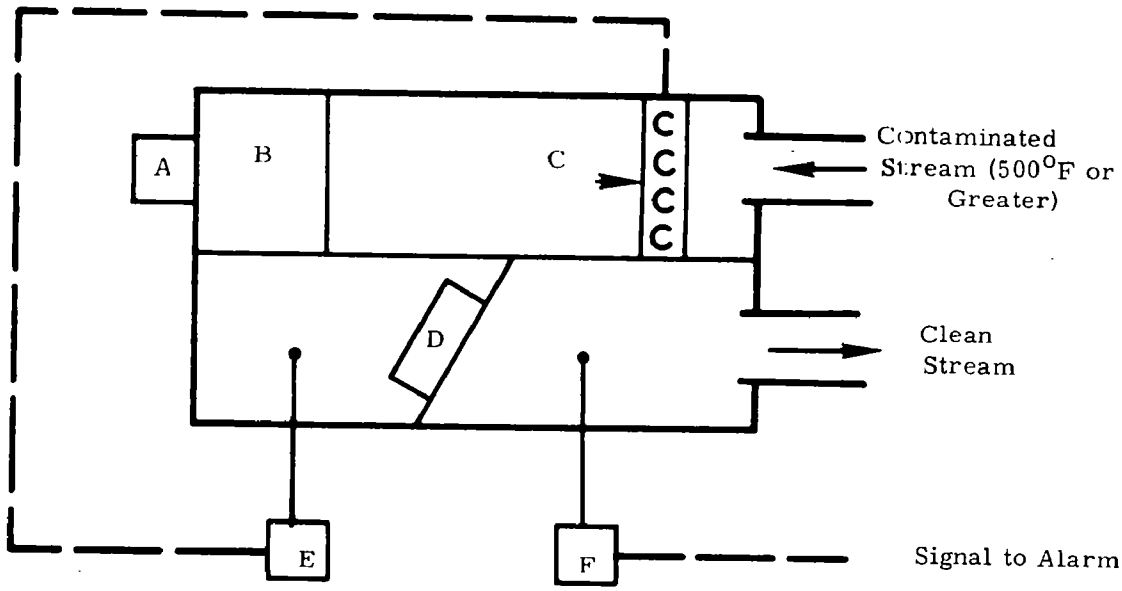
Catalytic Oxidation
Low Temp. Feed With
Recycle and Heat
Exchanger



A Process
B Process Feed Gas
C Process Exhaust Gas
D Hot Clean Exhaust
E Pollution Abatement Equipment

Catalytic Oxidation
Recycle to Process

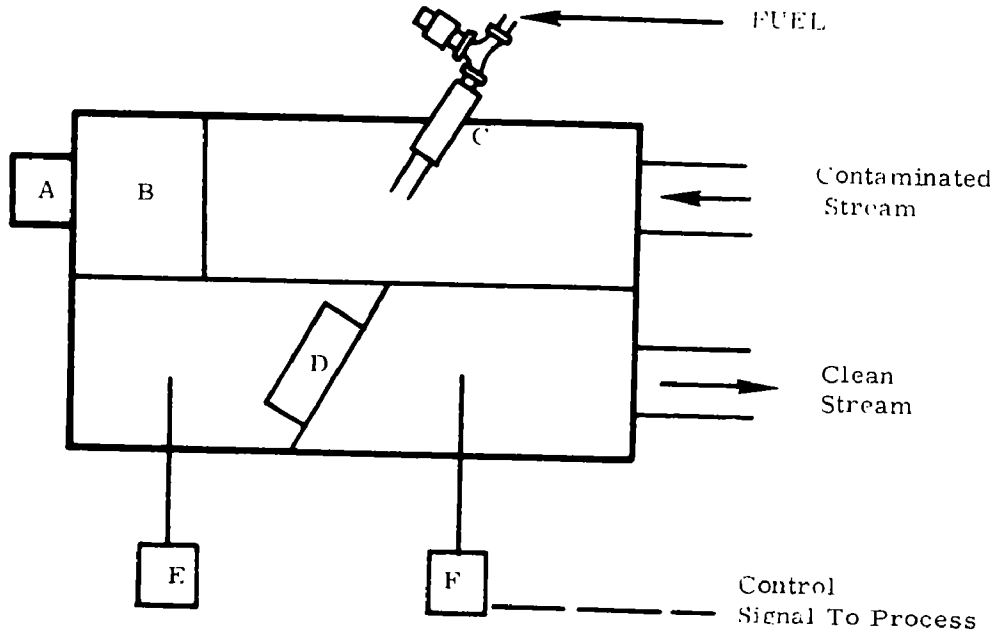
FIGURE 4



A. Blower Motor
B. High Temperature Blower
C. Auxiliary Electric Heater
D. Catalyst Bed
E. Temperature Controller (Inlet Gas)
F. Temperature Controller (Outlet Gas)

Schematic Diagram
Engelhard Deoxair Purification System

FIGURE 5A



A. Blower Motor
B. Blower
C. Fuel Burner
D. Catalyst Bed
E. Temperature Controller (Feed Heater)
F. Temperature Controller (Process Controller)

Catalytic Oxidation
With Combustion
Analyzer Control
Signal For Process

FIGURE 5B

THERMO OXIDATION OF GASEOUS AND AEROSOL WASTE

Jim Fraser*

I INTRODUCTION

Thermo oxidation of gaseous and aerosol waste is not a new concept having been used for many years in limited manufacturing processes. The deodorizing type air heater, for example, was developed for use with drying systems where vent gases had an objectionable odor. However, this application was always part of the process system and was usually too large and costly to be thought of as a deodorizer by itself.

In recent years a larger emphasis has been placed on a more effective and practical means of eliminating odorous air pollutants through incineration methods. There is a wide range of these odorous air pollutants and they include most organic materials plus inorganic combustibles such as ammonia, hydrogen sulfide, hydrazine and cyanide gases.

A few substituted hydrocarbons cannot be effectively and economically oxidized to materials suitable for discharge by methods now available. These include certain halogen compounds, metallic inorganics and organic phosphates.

Odorous combustible gases are released from a great many industrial processes. A list of a few typical applications is given below:

Chemical Processing
Resin manufacturing
Coil and strip coating
Fungicide and pharmaceutical
Carbon furnaces
Tar and asphalt blowing and coating
Bonding and burn-off
Rendering

With very few exceptions these fume streams contain pollutant gases mixed with air in non-flammable concentrations, that is, concentration below the lower flammable limit. For this reason they cannot simply be ignited or flared. They may also contain certain catalyst poisons or solid particles which rule out low temperature or catalytic oxidation. Therefore, it is necessary to heat them to temperatures in the 1000 to 1500 degree F. range in temperature for direct thermal incineration.

II DESIGN PARAMETERS

The 1000 to 1500°F thermal incineration range lends itself to a very practical and economical all metal type incinerator such as that designed and manufactured by the UOP Air Correction Division which we will be considering in the following design parameters.

The design parameters must provide thorough mixing of the combustibles with air. Enough heat input to raise the temperature and gas stream to the required level for oxidation, even temperature and flow distribution and sufficient dwell time at temperature to accomplish the degree of oxidation required. These conditions are met by supplying the necessary temperature through a burner firing into a holding chamber where oxidation occurs. Actual design conditions for temperatures and dwell times will differ according to the reaction kinetics for the particular pollutant present and combustion efficiency required for odor cleaning. The required dwell time is set by the size of the holding chamber. The cross-sectional area is normally fixed to give the desired linear velocity and the length varied to obtain the required dwell time. Because of economics, systems are usually designed so that dwell time does not exceed one second.

The reaction chamber temperature then becomes the controlling variable and is adjusted to obtain the desired combustion efficiency. The mixing and distribution are supplied by design features of the incinerator.

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We might also mention the fact that in many applications, it is possible to add heat recovery equipment to the odor correction system to reduce operating fuel costs. This is a function of B.T.U. demand and fuel savings versus the pay-out time for the recovery equipment.

III PREHEAT BURNER

There are many reliable burner manufacturers which can be considered for supplying equipment. An important consideration is to get a high turndown burner which will adjust to requirements of the entire system. This burner may be picked to burn various types of fuel, the most common being natural gas or oil. However, one point that should be stressed here is that when oil fuel is picked, it should be one with a low sulfur content that burns without producing a lot of ash or sulfur pollutants.

The burner size is a function of the desired incineration temperature. The volume of the fume stream handled and the thermal inefficiency of the system. Additional capacity is sometimes added if it is anticipated that more stringent combustion efficiencies will be required in the future.

The outlet temperature will generally be regarded by air pollution control officials as the primary measure of performance, with all other phases of the operation normal to a casual inspection, maintenance of a specified outlet temperature will generally be accepted as providing acceptable conversion level.

IV HEAT EXCHANGER

Of critical importance in the design of heat exchangers is the handling of expansion and contraction. Nearly all designs involve the use of tubes or tubelike members. These are supported between the tube sheets and enclosed within a housing. The metal comprising the housing will ordinarily operate at a different temperature than the tubes themselves. This requires that the sheets are free to move relative to the housing. Careful integration of the combustion chamber and heat exchanger design is necessary to take into account all the expansion factors.

Pressure drop and heat transfer rate are the other critical variables in heat exchanger design. The pressure drop on both sides must be carefully calculated in order to provide accurate information for fan selection. The overall heat transfer coefficient must be known to avoid oversizing the heat exchanger (for high combustible loads an oversized heat exchanger might mean an uncontrollable unit) and to insure that adequate temperature levels may be sustained by the burner.

V MATERIALS OF CONSTRUCTION

The odorous air pollutants encountered today from industrial processes of which some have been listed, can normally be incinerated in the range of 1000 to 1500°F within the design parameter discussed above. This makes it possible to use easily available metallic materials for incinerator and heat exchanger construction and refractory material is not normally required. This has a 2-fold advantage. First, the ease and economics of fabrication which allows for ease in handling and transportation of the equipment. Second, the light weight materials make it possible to install this equipment where weight limitations are imposed such as roof tops, etc. However, it is very important that good engineering design be followed to accommodate for thermal expansion and gas distribution in the all metal construction.

The heat exchanger also forms a vital part of the thermal incineration system regarding materials of construction. It reduces the exit temperature to a level where ordinary steel may be used for the ductwork and stack. The heat exchanger may be constructed of stainless steel; or if the tube walls and tube sheets are properly handled, of carbon steel. Even where the hot gas temperature exceeds the usual temperature limits for carbon steel, aluminized steels are available for tubewall design temperature up to 1200°F.

VI INSTRUMENTATION REQUIREMENTS

Instrumentation burner control, safety control and wiring used in the thermal incinerator are of the same type as conventionally used in ovens and dryers and set up by the insurance underwriters covering the operation on which the equipment will be installed.

Process gases are maintained at the desired temperature by controlling the preheat burner. As the temperature, volume and combustible concentration of the fume stream varies, the burner input is automatically adjusted proportionately. An independent high and/or hi-low temperature indicating alarm controller is also incorporated in the instrumentation to protect against extreme temperature conditions. The incinerator will automatically shut down and divert through a bypass to the exhaust stack.

The auxiliary equipment used for heat recovery is again controlled using approved control circuits and equipment. The recovery train is custom designed and the controls will vary depending on the particular application for which the recovery will be applied.

VII OPERATING CONDITIONS

In most air correction problems, the fume stream will carry sufficient oxygen to be used as a source of secondary air allowing the burner to operate at stochiometric proportions or less primary air. However, in some cases it is necessary to add excess primary air in amounts up to 5 percent if the fume stream has a large percentage of inerts and consequently, minimum oxygen. Since the fume stream has to be heated to the reaction for air pollution control, it provides an economic source of secondary combustion air. Any primary air added must be heated to the reaction temperature and adds to the operating cost. Excess primary air has little influence on the combustion efficiency and wastes fuel.

VIII RATE OF REACTION

The kinetic theory of gases in relation to the rate of reaction of variables such as time, temperature and degree of reaction is not a clear cut proposition. If sufficient background data and fume analysis is not available, pilot tests or source tests have to be conducted on the fume stream to determine this reaction rate.

The design of equipment for the primary purpose of odor elimination is not simply a matter of reducing total pollutant concentration to some arbitrary level. Different gases and vapors have different odor thresholds. To complicate the problem still further, a mixture of materials will usually have a different odor threshold than any of the individual components. Because most industrial exhaust gases contain mixtures of pollutants and because these mixtures vary greatly from one process to another, it is frequently necessary to run pilot or laboratory tests to determine the degree of cleanup necessary to accomplish odor freedom. Much of this vital data has been correlated by our source testing department, from which practical and economical system design is obtained. It has been found in many cases a typical reaction rate can be utilized for common air pollutants.

Various air pollution control authorities have set up design standards of their own. For example, the Engineering Department of the Los Angeles Air Pollution Control District requires that all thermal incinerators be designed for a fume stream velocity of 40 f.p.s. and at least 0.6 sec. residence time, having the ability to operate in the temperature range of 1500°F.

IX SUMMARY

In conclusion, odor elimination can be accomplished effectively by thermo oxidation in nearly all cases where combustible gases and aerosol waste are involved.

The importance of the basic design parameters should not be underestimated and to review, these are: through mixing of the combustibles with air, even temperature and flow distribution, high enough temperature, and sufficient dwell time. By proper selection of these parameters through reliable fume stream analysis, pollutant destruction closely approaching 100 percent can be achieved.

CONTROLLED ENDO-EXOTHERMIC OXIDATION OF INDUSTRIAL WASTES

Robert D. Reed*

Uncontrolled venting of waste gases and liquids to the atmosphere and to the waterways of the world which once was an accepted way of life in industry is no longer to be tolerated and is rapidly becoming illegal.

Cost for means to avoid air and stream pollution is, at times, considered awe-inspiring according to the nature of the materials for disposal. In fact, necessity for avoidance of pollution in any respect may well be the determining factor in choice of plant location according to local ordinances or pollution regulations.

Fuel demand for satisfactory disposal is entirely governed by the nature of the gases or liquids for disposal. If no means for heat recovery are to be provided the fuel cost represents a complete loss except for the fact that the cost is an operating expense and represents means for some tax relief.

Capital expense of erection of means for disposal is significant in any case. The total capital expenditure is also governed by the nature of the products for disposal as well as local regulations for control of pollution. Separate studies of disposal problems should be made in each case with the study to take into careful consideration minimum acceptable standards for the service as required.

The separate and careful studies are suggested because there is ample history of under-designed facilities causing great financial loss as well as embarrassment where lack of knowledge of the problem in all details as well as reluctance to make a suitable capital expenditure may be considered as causes.

Where endo-exothermic oxidation is the means to the end of disposal of waste matter, the end-products required are those of complete oxidation. Any matter which contains elements which are subject to oxidation in exposure to adequate temperature level for a great enough length of time is subject to such disposal means whether it be in the liquid or the gaseous phase.

Requirement for such disposal means must be based on the design temperature level, great enough residence at the design temperature level, a suitable condition of controlled turbulence and the presence of adequate quantities of oxygen. It is, perhaps, a bit disconcerting to consider that carbon tetrachloride (CCl_4) held at 1800°F (982.22°C) for a period of 5 seconds and in the presence of oxygen is converted to $CO_2 + 2\ Cl_2$ in a series of reactions which terminate in an exothermic state.

Thus the factors time, temperature and turbulence which are classic for the burning of fuels become factors in disposal by oxidation. However, there are equally important supplementary factors which also must be considered.

Experience shows clearly that the auto-ignition temperatures of disposal products are of small concern. Experience shows equally clearly that the deciding factor for design temperature level for speed of oxidation with any fuel can best be stated as one of molecular proximity. In this sense the proximity of molecules of fuel to molecules of oxygen governs.

In the case of a stoichiometric mixture of air and methane (CH_4) where both methane and air are dry, there will be approximately 18.92% oxygen, 9.46% CH_4 and 71.62% nitrogen. Under normal conditions this mixture will burn in approximately 10 milliseconds at 1500°F environmental temperature. This speed of burning is established by the molecular proximity of oxygen to methane typical of this mixture or the readiness of combination as based on typical molecular dispersion in a homogeneous mixture such as this.

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If, however, the methane should be diluted with nitrogen so that there is only 2% methane in the methane-nitrogen fuel and if this fuel should be mixed homogeneously with air in stoichiometric mixture the burning time would be very greatly increased because of reduction in proximity of oxygen to CH_4 in the mixture and the burning time would now be approximately 0.32 seconds AFTER the time required to elevate the temperature of the fuel-air mixture to auto-ignition temperature to produce an observed burning time very close to 1 second at environmental temperature of 1500°F.

If the dilution of the fuel with inert matter is carried further, burning times at 1500°F begin to be tremendous and the cost of a structure for disposal to provide the required time at 1500°F goes far beyond economic limits. Fortunately the equations of arrhenius in point of the effect of temperature on reaction velocities provide a very suitable solution for this problem but at the expense of greater fuel demand.

Where there is 1% or less of burnable toxic or noxious matter in a stream of otherwise inert material experience shows clearly that design temperature in the order of from 1800°F to 2000°F with a time factor of from 3 to 5 seconds will be required to secure complete oxidation in the presence of not less than 25% excess air.

At this point, it becomes expedient to more comprehensively define the term "complete combustion" or oxidation of fuel. In the typical practice of burning fuels for production of useful heat, combustion is considered complete when the Orsat or the electrical flue gas analyzer shows absence of combustibles in the gases following burning. However, these devices are seldom capable of accuracy better than 0.05%. With accuracy at 0.05% there could be as much as 500 ppm of the toxic or noxious material in the flue gases following the burning period. Complete combustion, as we define it, does not exist in this case.

It is true that thermal rise and exit velocity effects will produce dilution of the stack gases so that as the gases reach grade downwind of the stack, the concentration of toxic materials may be reduced to tolerable limits for most toxic or noxious materials with dilution obtained through selection of proper stack height. There are standard calculation methods for determination of stack height to obtain the required dilution. However, the formulation contains both empirical and judgment factors which may introduce error to a greater or lesser degree.

Average target concentration at grade and downwind of the stack is in the order of 0.10 ppm or perhaps less. For most toxic or noxious substances this concentration is satisfactory; however, there are many substances where this small concentration is far too great and severe odor or health nuisance is created. A further hazard is the tendency for products not present in the disposal stream to be synthesized in the course of passage through the furnace. These products can be alcohols, aldehydes, organic-sulphur compounds and others.

It is interesting to note that according to the Manual of Disposal of Refinery Wastes, Volume II, Waste Gases and Particulate Matter as published by the American Petroleum Institute the following substances will cause odor nuisance in concentrations as shown.

Iso-butyl alcohol	.003 ppm
Iso-amyl alcohol	.0026 ppm
Methyl mercaptan	.041 ppm
Ethyl mercaptan	.0028 ppm
nPropyl mercaptan	.0016 ppm
nButyl mercaptan	.001 ppm
Iso-amyl mercaptan	.00043 ppm
pThiocresol	.0027 ppm
Methyl sulphide	.0037 ppm
Ethyl sulphide	.000056 ppm
Propyl sulphide	.011 ppm
nButyl sulphide	.015 ppm

It is considered in order to question the absolute accuracy in measurement of such tiny concentrations; however, if the accuracy is only 50% odor nuisance will still exist. In the "blowing" of hot asphalt to improve the characteristics of the asphalt through partial oxidation, the gases contain odorants and while there is no definition of odor perception levels for these compounds in the literature there is mounting evidence that concentrations in the order of 0.01 ppm are capable of creation of odor nuisance.

Various researches[1] which have not been reported into the literature have shown that in the burning of compounds containing sulphur from 10 weight per cent to 25 weight per cent of the sulphur will appear in the stack gases as SO_3 when the burning has been carried out in a refractory lined furnace. The remainder of the sulphur is as SO_2. The influence of SO_3 on the dew point characteristics of combustion gases is such that dew point occurs immediately after departure from the stack to produce a light gray-blue "smoke" of sub-micron size particles of SO_3. The particles are small enough to be air-colloid. Such "smoke" diffuses very poorly and, from an airplane, has been observed[1] in travel over more than 75 miles from the point of origin of the "smoke" to disappear into the haze in the distance. This phenomenon was observed in a very dry climate and at mean ground altitude of 4000 feet with ground wind velocity at approximately 20 MPH.

In disposal of liquid streams the residence time factor must provide for the time interval required for conversion of the liquid to the gaseous state. This can be quite appreciable. Also in disposal of liquid streams and when mineral salts are present it has been repeatedly shown that the mineral exists from the furnace in the form of its oxide and as sub-micron size particles which also are air-colloid to appear at the stack as "smoke."

In one particular instance where there was approximately 5 weight per cent of sodium acetate in the liquid stream for disposal and at 1800°F there was very little accumulation of mineral residue within the furnace after a period of approximately 6 months. In this case the waste stream was approximately 5 gpm continuously for the period of operation. Also in this case there was no report of hazard or damage due to the gas carried particles of sodium oxide. Operation has continued safely and without incident for a number of years. Operation of the furnace at excess air in the order of 175% completely suppresses any tendency for the mineral oxides to appear as "smoke."

The fuel cost factor for disposal is subject to considerable relief if suitable heat recovery systems follow the disposal system; however, the business of heat recovery must not be allowed to interfere with complete burning. Heat recovery can be as steam generation; heating of process materials or air-preheat, but the recovery means must suit the disposal problem and must be chosen according to the nature of the problem.

REFERENCE

1 Private communications, John Zink Company.

FLARE COMBUSTION

Leonard C. Mandell, P.E.*

I INTRODUCTION

"Flare Combustion" is a highly-specialized type of unsteady state, exposed-flame-burning - - - - into the free atmosphere. It has been developed mainly by and for the Petroleum Industry. Flares provide a means of safe disposal whenever it is impractical to recover large and/or rapid releases of combustible or toxic gases/vapors. These releases may occur under emergency conditions resulting from power or compressor failures, fires or other equipment breakdowns; or under day-to-day routine conditions of equipment purging, maintenance and repair, pressure-relieving and other unwanted accumulations - - - - such disposal being compatible with the public health and welfare. Flaring has become more of a safety or emergency measure. Combustible releases with heat contents as high as 4,000,000,000 Btu/Hr. have been successfully flared.

Flares must burn without smoke, without excessive noise, or radiant heat. They should have a wide capacity to handle varying gas-rates and Btu contents. Positive pilot ignition and good flame stability during adverse weather conditions are also necessary.

Typical gases that can be successfully flared range from the simple hydrocarbon alkanes through the olefins, acetylenes, aromatics, napthenes, as well as such inorganic gases as anhydrous ammonia, carbon monoxide, hydrogen, and hydrogen sulfide - - - - in fact, almost any combustible gas - - if feasibility so indicates.

Air Pollution can result from flare combustion. As we realize, pollution implies an adverse ecological situation. Air being man's universal and most vital environment makes the control of air pollution a major responsibility of The Public Health Profession.

A survey would indicate that air pollution means different things to people. However, all of these meanings can be placed in one of three categories, namely:

A Adverse effects upon our health

B Nuisance irritation to our basic senses

C Economic loss

These affects may occur singularly or in various combinations with each other. Experience has shown that the slightest unwanted change in the air causes great consternation among people. We have become accustomed to expect certain things from the air: that is, odorless, tasteless, and invisible - that it should be neutral in regard to its physical and bio-chemical effects. Further, air is expected to fulfill certain requirements that relate to our well-being and enjoyment, namely:

> When respired, air will effect the metabolic needs for our activities without adverse physiological consequences of either an acute or chronic nature.
>
> That air not be offensive to our basic senses of hearing, seeing, feeling, tasting or smelling.
>
> That air not cause damage to our property, be it buildings, furniture, automobiles, livestock, vegetation, or other physical or animal assets - all of which would result in economic loss.

Accordingly, anything that modifies the nature of air as we have learned to know and enjoy it, may be called an Air Pollutant.

Flares may rightly be classed as significant, potential sources of local pollution because they can emit gases that are not only toxic but that can cause property damage, personal injury, nuisance and psychosomatic illness.

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Toxicity may evolve from the nature of the raw vent gases - - as the highly dangerous carbonyl chlorides and phthalic anhydrides, chlorine, hydrogen cyanide -- or from products of incomplete incombustion as phenols, aldehydes, organic acids, or from products of complete combustion as sulfur oxides and hydrochloric acid vapors.

Property damage may vary from being rather apparent as soiling from soot/smoke or heat-damage from radiant flames; or more subtle as from corrosive damage of sulfur trioxide, mist-size aerosols.

Personal injury may occur from falling and burning liquid aerosols that somehow should not have arrived at the burner-tip for flaring.

The nuisance aspect is excellently brought out by the odor problem from say hydrogen sulfide or the organic mercaptans. It should be noted that noise is also becoming a problem -- especially with high, specific steam ratios.

The psychosomatic aspect can be involved with ones knowledge of just the presence of the flare, (in his effective environment) whether it is creating an invisible-plume or a smokey, sunlight obscuring plume.

Hence, it behooves the "operators" to minimize these effects -- any of which can cause not only poor community relations but even costly litigation. It has been the author's experience that, as a rule, industry is desirous of being a good neighbor and will do the right thing if shown the need and if properly handled.

II BASIC THERMODYNAMICS

It should be noted that very few if any textbooks on combustion or thermodynamics contain any information on flares -- not withstanding the fact that successful flare-burning is a highly-specialized thermodynamic, combustion process. Perhaps, the reasons are that the universal need for flares is relatively very small and what information has been learned is treated as proprietary - and so kept confidential for business reasons.

III COMBUSTION - In General:

Any combustion gas can be completely oxidized if exposed to an adequately high temperature level for a long period of time in an atmosphere of sufficient oxygen and turbulence.

For purposes of this lecture let us look at combustion as a continuous, highly-complex, high-temperature, gas-phase oxidation process with very specific characteristics, namely:

A It involves a very rapid chemical reaction between the elements and compounds of hydrogen, carbon and sulfur and the oxygen in the air.

B That this reaction in order to be rapid enough requires fuel/air mixture temperatures much higher than the conventional ambient of $70^{o}F$, and within definite ranges of concentrations for various combustible compounds.

C That concurrent heat energy will for the most part be liberated and/or occasionally be required by the reaction to maintain its continuity. The common oxidation reactions of carbon, hydrogen and sulfur are exothermic liberating 14,500 BTU'S and 4000 BTU'S per lb. solid of carbon and sulfur, and 61,000 BTU'S/lb. of gaseous hydrogen respectively.

The water-gas reactions of:

1 $C + H_2O \rightarrow CO + H_2$

2 $C + 2H_2O \rightarrow CO_2 + 2H_2$

These reactions are quite rapid at temperatures greater than $1650^{o}F$.

require heat inputs of approximately 5900-6000 BTU/lb. carbon.

D That the combustion process requires close control of adequacy and intimacy of contact between the gas fuel and the oxygen molecules in order to obtain complete combustion; otherwise undesirable pollutants such as soot, smoke, aldehydes and carbon monoxide, etc. will be formed.

E That the reaction occurs with presence of a luminous flame. Certain Basic Concepts must be understood:

L. E. L. or Lower Explosive Limit or lower inflammable limit: This is the leanest mixture (minimum concentration) of the gas-in-air which will support combustion (where flame propagation occurs on contact with an ignition source).

U. E. L. or Upper Explosive Limit: This is the richest (Maximum proportion) of the gas in air which will propagate a flame.

Autogenous Ignition Temperature or Auto Ignition Temperature: The minimum temperature at which combustion can be initiated:

It is not a property of the fuel but of the fuel/air system. It occurs when the rate of heat gain from the reaction is greater than the rate of heat loss so that self-sustained combustion occurs.

Flame Propagation - The speed at which a flame will spread through a combustible gas-air mixture from its ignition source, it is usually lower at L. E. L. and the U. E. L., and higher at the middle of range.

Flame: A mass of intensely, heated gas in a state of combustion whose luminosity is due to the presence of unconsumed, incandescent, fractional-sized, particles - mainly carbon. (Small particles of suspended carbon/soot formed by cracking of hydrocarbons). Visibility ceases at complete combustion or where the glow of the ash ceases.

Infra Red Radiation: Is, for the most part an invisible, electromagnetic phenomena. Relatively large amounts of heat are radiated at elevated temperatures by such gases as carbon dioxide, water vapor, sulfur trioxide, and hydrogen chloride. The I. R. spectrum begins at 0. 1 micron wave length and extends up to 100 microns. For reference, I. R. solar radiation (10, 240°F) lies within the 0. 1 to 3 micron range. (We know that a large proportion is emitted in the visible band of 0. 4 to 0. 8 micron. A 2300°F black body emits most of its energy between 0. 7 and 40 microns. For the discussion at hand, (temps between 1500 and 2500°F) radiant emission may be assumed between 0. 5 micron and 50 microns with maximum intensity occurring at the 2 micron wave-length.

Timing is important in that the attainment of satisfactory combustion requires sufficient, high-ambient, reaction temperatures, and an adequate oxygen-fuel mixing. Both phenomena are related to time/probability functions.

IV BASIC COMBUSTION CONCEPTS AS APPLIED TO FLARES:

A Gaseous fuels alone are flared because they:

Burn rapidly with very low percentage of excess air resulting in high flame temperatures.

Leave little or no ash residue.

Are adaptable to automatic control.

B The natural tendency of most combustible gases when flared is smoke:

An important parameter is the H/C ratio. Experience has shown that with hydrocarbon gases such as: Acetylene (C_2H_2) with a H/C ratio = 0. 083, real black soot will result from simple burning.

Propane (C_3H_8) with a H/C ratio = 0. 22 creates black smoke.

Ethane (C_2H_6) with a H/C = 0.25 - a bright yellow flame with light trailing smoke will result. A H/C of 0.28 gives very little if any smoke, and methane (CH_4) with a H/C of 0.33 gives a bright yellow flame with no smoke.

If the H/C is less than 0.28, then steam-injection close to the point of ignition into the flame makes the flare smokeless. It should be noted that steam injection can be applied to the point of clearing up the smoke and reducing luminosity before reaching the point of extinguishing the flame. Hydrogen is the cleanest, most rapid and highest-heat evolving fuel component. It helps to: heat the carbon and also provides for better carbon/oxygen contact which results in cleaner burning; also, the reaction of carbon monoxide to carbon dioxide goes much easier in the presence of water vapor.

C In flare burning of sulfur-bearing compounds: approximately 90% or more appears as sulfur dioxide and 10-30% of the (SO_2) mutually appears as sulfur trioxide. Blue grey smoke becomes visible as the sulfur trioxide falls below its dew point temperature.

D In flare burning of chlorine-bearing compounds, most will appear as hydrogen chloride vapor. However, appreciable quantities of chlorine will remain.

E A relation exists between the auto-ignition temperature of the gas, its calorific value and its ease of successful flare burning.

At 800°F AIT: A minimum H.V. of 200 BTU/cu. ft. is required.

At 1150°F AIT: A minimum H.V. of 350 BTU/ cu. ft. is required.

At 1300°F AIT: A minimum H.V. of 500 BTU/cu.ft. is required.

F Since the heat content of many gases vary much below 100 BTU/cu.ft. and since complete burning is required regardless of the weather; pilots are used to initiate ignition of the flare gas mixtures, -- and to help maintain flame temperatures to attain rapid burning.

G Yellow-flame combustion results from the cracking of the hydrocarbon gases that evolve incandescent carbon due to inadequate mixing of fuel and air. - Some flames can extend to several hundred feet in length.

H Blue-flame combustion occurs when water (steam) is injected properly to alter the unburnt carbon.

I Actual Flare Burning Experience (John Zink Company)

(Dilution/Temperature Effects for acetylene in air)

C_2H_2 @1800°F temperature will burn completely in 0.011 sec -- 50% Dilution

C_2H_2 @ 1800°F temperature will burn completely in .016 sec. -- 75% Dilution

C_2H_2 @ 1800°F temperature will burn completely in .034 sec --90% Dilution

C_2H_2 @ 1800°F temperature will burn completely in .079 sec --95% Dilution

C_2H_2 @ 1800°F temperature will burn completely in 1.09 sec --99% Dilution

C_2H_2 @ 1800°F temperature will burn completely in 4.08 sec --99.5% Dilution

Note: The 4.08 sec. time @ 1800°F falls to less than 1 sec. @ 2000°F temperature.

J Flared gases must be kept at temperatures equal to or greater than auto ignition temperature until combustion is complete.

K Carbon monoxide burns rapidly with high heat and flame temperature, whereas carbon burns relatively slow.

L A smokeless flare results when an adequate amount of air is mixed sufficiently with fuel so that it burns completely before side reactions cause smoke.

What is Required? Premixing of air + fuel

Inspiration of excess air into the combustion zone

Turbulence (mixing) and time

Introduction of steam: to react with the fuel to form oxygenated compounds that burn readily at relatively lower temperatures; retards polymerization; and inspirates excess-air into the flare.

Note: 1) Steam also reduces the length of an untreated or smokey flare by approximately 1/3 of its length.

2) With just enough steam to eliminate trailing smoke, the flame is usually orange. More and more steam eliminates the smoke and decreases the luminosity of the flame to yellow to nearly white. This flame appears blue at night.

M The luminosity of a flare can be greatly reduced by using say 150% of steam required for smokeless operation. Since a major portion of flame originates from contained incandescent carbon.

N Water sprays, although effective in low-profile, ground-flares, have not been effective to date in elevated flares. The water although finely atomized, passes out and away from the flame without vaporizing or intimately mixing with burning gases -- especially where any kind of wind occurs. The plugging of spray nozzles is also a problem - the "Rain" from spray that may fall near base of stack is very corrosive.

Note: Recent water shortages dictate the use of steam since specific water wastes of 1-2 lbs. water/lb. of gas is customary.

Approximately 2-3 times as much water as steam is needed for ground-level flaring.

O The following table summarizes some pertinent gas characteristics for flaring.

GAS PROPERTIES RE-FLARING

Element/ Compound	Mol. Wt.	H/C	AIT	" % by Vol. in Air" LEL	UEL	Btu/cu. ft. Net	Flame Temp-°F	Flame Speed
H_2	2		1000-1100°F	4.1	74	275	4100°F	1-16'/Sec.
C_2H_2	26	.083	600- 800°F	2.5	80	1435	4200	2-5
NH_3	17		1200	16	27	365		
H_2S	34		550- 700	4.3	46	596		
CO	28		1200	12.5	74	321	4200	1-4
C_3H_8	44	.222	1000-1100	2.1	11.4	2360		
CH_4	16	.33		5.3	14.0	914	3800	.8-2.2
HCN			1000					
C			750°					
S			470°					
C_2H_4	28	.17		3	29	1512		
C_4H_6	54	.13		2	11.5	2840		

V TYPES OF FLARES:

Flares are arbitrarily classed by the elevation at which the burning occurs; i. e. -- The elevated-flare, the ground-flare and the-Pit. Each has its pros and cons. As should be expected, the least expensive flare will normally be used to do the required job-compatible with the safety/welfare of the Company and the Public.

A The Pit: The venturi type is, as a rule, the least expensive. It can handle large quantities such as 14,000 cfm or 20,000,000 cu. ft. / day. It consists of one or more banks of burners set horizontally in a concrete/refractory wall. The other three-sides are earth-banks approximately 4 ft. high. The typical ground-area may be approximately 30 ft × 40 ft. The pit excavation may be 6 ft. deep, all burners discharge horizontally. The burners may vary from the simple orifice to the better venturi - aspirating units with pressure-valve regulation. Piping and appurtenances include proper pitch, knock-out drums, liquid seals, and constant-burning, stable pilots. As a rule, burning pits are the least satisfactory but also are least expensive. However, if location and air pollution are not significant, the pit method becomes attractive.

Note: Rothschild Oil built a 2,000,000 Scfd (standard cubic feet per day unit) in 1953 for $5,000.00.

B Ground Flares: In general, ground flares require approximately 2½ times as much steam to be smokeless as elevated flares. They also require much more ground space. At least a 500 feet radius should be allowed all around the flare. In addition to the burner and combustion auxiliaries, ground flares also require a ground-shield for draft control and at times a radiant shield for heat and fire protection. Hence, large open areas are needed for fire-safety (plenty of real-estate) and air pollution attenuation. Ground flares do however offer the advantages of less public visibility and easier burner maintenance. The cost of present-day, ground flares as a rule are more expensive than elevated flares. However, they may also cost less depending upon location requirements. Ground flares are normally designed for relatively small volumes, with a maximum smokeless operation up to approximately 100,000 standard cubic feet per hour of butane or equivalent. There is heat sterilization of areas out to a radius of approximately 100 ft. At least 3 types are known to the author; the Esso multi-jet smokeless and Non-Luminous Flare, the conventional center nozzle with spray water for inspiration of combustion-air; and the dry-type for clean burning gases.

Typical water spray flare-design requirements are;

The spray must intimately mix with the burning gases

These gases require an outer shell to retain heat and flame.

Combustion air of at least 150% must be allowed to enter the base through the surrounding shells. The higher the molecular weight of the gas, the greater the spray rate: Example:

200,000 Scfhr. M. wt. = 28	30-40 psig. @35 gpm. is required.
200,000 Scfhr. M. wt. = 37	120 psig.@ 80 gpm. is required.

Back in 1959, Esso Research developed the Multi-Jet Flare. It operates in a smokeless and non-luminous manner with very little noise. The flare requires little of the conventional auxiliaries. It consisted of a series of rows of horizontal pipes containing 1 inch diameter jets that served as burners. These burners were located at the base of the stack approximately 2 ft. above ground level. The jets require flame-holders (rods) to provide time and turbulence for adequate air-mixing

for smokeless combustion. A 32 ft. high stack was required to shield the flame. A 3 ft. diameter flare handled up to 140,000 standard cubic feet per day and a 6 ft. diameter stack up to 600,000 Scf/day. It operated with a 25 ft. high flame. A cost comparison with other flares types at that time was made: - Based on 12,000,000 Scf/day of a 40 Mol. wt. gas, the multi-jet cost $148,000. This was twice the cost of an elevated flare without steam, or one half the cost of an elevated flare with steam. This was also about the same cost as a ground-flare with water.

C Elevated Flares:

This type of flare provides the advantages of desirable location in associated equipment-areas with greater fire and heat safety: also considerable diffusion/dilution of stack concentrations occur before the plume-gases reach ground level.

Major disadvantages are:

1 Noise problems result if too much steam is used

2 Air vibrations severe enough to rattle windows 1/2 mile or more away.

There are 3 general types:

The non-smokeless flare which is recommended for relatively clean, open-air, burning gases such as hydrogen, hydrogen sulfide, carbon monoxide, methane, and ammonia.

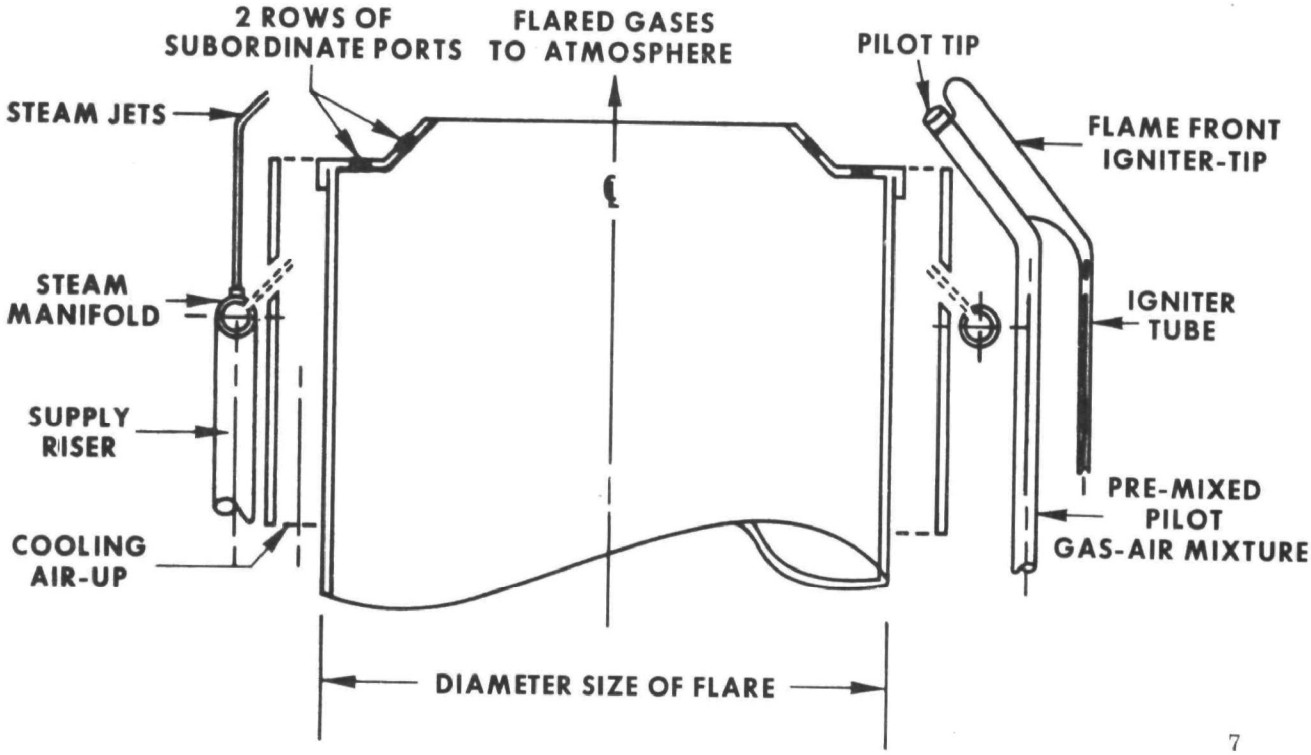
The smokeless flare which incorporates steam injection to obtain clean burning of low H/C ratio gases such as acetylene, propylene, and butadiene.

The endothermic type which incorporates auxiliary means of adding heat energy to the vent gases of low heat contents in the 50-100 BTU/cu. ft.). This flare may or may not operate smokelessly.

Elevated flares require special burner tips, special pilots and ignitors, wind screens, refractory lining, and instrumentation--for acceptable performances.

Let us take a moment and review what happens at the flare-tip.

HAPPENINGS AT THE FLARE TIP:



Gas is ignited just as it reaches the top of the stack. Before adequate oxygen/fuel mixing can occur throughout the entire gas profile certain things occur:

Part of the gas burns immediately resulting in an oxygen deficiency which induces carbon-formation.

The unburned-gases crack to form smaller olefins and paraffins; and at the same time some molecules polymerize to longer chain hydrocarbons. More carbon is created from combustion of these newly formed compounds in a reducing atmosphere.

The long, luminous-flame in ordinary flaring is made up of incandescent, carbon particles which form smoke upon cooling. Steam-mixing suppresses carbon formation by:

a) Separating the hydrocarbon molecules, thereby minimizing polymerization.

b) Simultaneously forming oxygenated compounds which burn at a reduced rate/temperature not conducive to cracking/polymerization.

Note: The absence of incandescent carbon also gives the appearance of a shorter flame.

That the idea of injecting water/steam into flares originated at Esso Refinery in Everett, Massachusetts.

VI TYPICAL DESIGN CONSIDERATIONS AND PARAMETERS

A Ignition and stable-burning must be insured.

B Capacity must handle the maximum expected quantity if toxic, or a statistical compromise of the maximum expected release. This may indicate normal operation of 1-5% of these capacities.

C Pilots must be stable in high winds (80 mph) and heavy rains.

D Pilots must be ignitable in high winds (80 mph) and heavy rains.

E The height of the flare is determined by fire and heat safety. Dilution may also be important from an air pollution standpoint.

F Steam requirements are related to the H/C ratio (wt.). For H/C ratios greater than 0.33 - no steam is needed. Lower ratios can demand up to 2 lbs. steam/lb. of vent-gas to obtain smokeless operation. As a rule, 0.6 lb/lb. appears to be the average required. Steam requirements are proportional to the degree of unsaturation and the molecular weight of the gas being flared. Flares are designed to be smokeless for up to 15% of capacity only.

G Sizes may vary from $1\frac{1}{2}$ inch pipe to 120 inch diameter.

H The burning rate can vary from 0.5% - 100% of design.

I Systems up to 1,000,000 lb/hr. of 43 mol. wt. @ 700°F have been flared. (Zink)

J Typical data for hydrogen sulfide flares would appear as follows:

DATA	SIZE OF FLAME	
lbs/hr:	600 lbs/hr.	10,000 lbs/hr
cfm	112 cfm	1900 cfm
cfday	164,000 of day	2,750,000 cf day
flare size	2 inch diameter	12 inch diameter
cost installed	$2300	$5800
type	non smoking	non smoking
steam	no'	no'
flame dimensions	10 ft. ht. × 1 ft. diam.	40 ft. long × 3 ft. diam.
Ht. above ground to negate heat effects from flame	50 inch*	85 inch*

* May be much higher for air pollution control.

K It should be noted that radiant, flame effects can be serious. Radiation and solar heating should not exceed 1000 BTU/Hr./Sq. Ft. at ground level with 700 BTU/Hr./Sq. Ft. from the flame and 300 from the sun. (Zink)

L The ignitors operates only to start the pilot. The pilot burns continuously. A 2-3 inch diameter flare requires one pilot. A 4-6 inch diameter flare requires two pilots and flares greater than 6 inch diameter requires three pilots.

M Auxiliary heat is needed for gases with lower heating values of from 50-100 BTU/cu. ft.

N Flare heights range from 25-375 ft. with flame radiation being the determining factor.

O Hydrogen, carbon monoxide, and ammonia burn smokelessly without assistance.

P Tendency for smoking begins at H/C of 0.25 and becomes heavy @H/C of 0.20.

Q In general, flare operation of gases less than 150 BTU/cu. ft. heat content becomes quite critical in point of maintenance of ignition in all-weather conditions. Here endothermic design is needed. Only very few are in use. Usually they are limited by economics to sizes less than 5,000,000 BTU/hr equivalent of auxiliary fuel.

R Steam may also be required for preheating in very cold areas -- besides being needed for smoke control.

VII AUXILIARIES REQUIRED FOR SUCCESSFUL FLARE OPERATIONS:

A Flare Tips of Inconel or other stainless alloys with steam jets, air cooling, stabilizing parts, etc.

B Ignitors are used to light the pilot at start-up or at Pilot flame failure.

C Pilot Burners to light flare and keep it lit

D Mist Trap: to remove fine, liquid aerosols from reaching the stack.

E Flame arrestor: to prevent flame-travel back into piping.

F Liquid seal: To reduce pulsations from surges: to prevent air from entering vent-gas lines: to prevent reverse-flame, flash-back.

G Flow Sensors for steam control

H Pilot flame detectors

I Auto reignition system for pilots

J Shrouds are not of real value in smoke control, however, they can be used in preventing downwash.

Note: The pilots initiate combustion of the flared gases. They also help to heat and maintain flame temps. The ignition system consists of premixed 15 psig. fuel gas/air mixture that is pre-ignited in a special in-line, pipe-chamber by a spark plug. The flame-front, under flow-pressure, travels through a 1 inch igniter pipe to the tip of the pilot burner. Once the pilot is ignited, the fuel and air valves are closed. Time for ignition of all 3 pilots averages 1-2 minutes. Pilots must burn at a rate of at least 30,000 BTU/hr. each.

VIII MATERIALS OF CONSTRUCTION:

Reflection will indicate that many flare-gases are corrosive at normal atmosphere temperatures. Chemical activity, as a rule, increases with increasing temperatures. Hence, the selection of suitable materials for the handling/conveying of these gases -- especially at the flare-tip becomes significant to the feasibleness of this particular method of combustible, gas disposal.

It should be remembered that metals or alloys provide the function of corrosion-resistance by either formation of a surface film or resistance to chemical activity with the environmental materials. Accordingly, other corrosive factors as gas velocity, thermal shock and catalytic influences must be considered in addition to temperature effects. Another practical consideration is the deleterious carbide precipitation that results from the welding process. It removes some of the corrosion resistant and strength constituents from the alloy.

The stainless-steel, iron alloys (approximately 74% steel) are at present, the most feasible metals for flare construction. The stainless steels compose a class of nickel and chrominum alloys that owe their corrosion resistance to the high metal content and the strength to the chromium. Tenacious, protective film develops ----- especially in oxidizing atmosphere. Typical stainless compositions are:

TYPICAL STAINLESS STEEL ALLOYS

ALLOY	% Cr	% Ni	% C	% Mo	% Si	% Mu	Co
304	18-20	8-10	.08 max.		.75 max.	2.0 max.	
316	16-18	10-14	.10	2-3	.75 max.	2.0 max.	
347	17-19	9-12	.10		.75 max.	2.0 max.	1.0% max.
430	14-18	----	.12		.75 max.	0.50	
Hastelloy's	X	X		X			
Inconel (6% Fe)	10	84					

Leading suppliers of special stainless steels are International Nickel Company; Haynes Stellite, Division of Union Carbide; Carpenter Steels, etc.

Experience has shown that:

Type 304 s. steel is satisfactory for 1600°F -sulfur exposure

Type 309 s. steel is satisfactory for 2000°F -sulfur exposure

Inconel - a high heat resistant alloy for hydrogen sulfide, but not satisfactory for hydrogen chloride, sulfur dioxide or sulfuric acid vapors.

Hastelloy - (special s. steel) manufactured by Haynes Stellite is good for SO_3, H_2SO_4 and Hcl.

Hastelloy B for chlorine resistance, H_2SO_4

Hastelloy A for Hcl, H_2S, SO_3, H_2SO_4

Type 430 is suitable for general use up to 1600°F

In the final analysis of material selection, the cost of replacement must be carefully weighed against the longer life and higher initial cost of the most resistant materials.

REFERENCES

1 American Petroleum Institute, N. Y. Manual on Disposal of Refinery Wastes, Volume II Waste Gases and Particulate Matter, 1957.

2 Reed, Robert D. John Fink Co., Tulsa, Oklahoma, Private Communications, 1966.

3 Smith, Richard H. J. Arthur Moore Co., N. Y. C., Private Communications. 1966.

4 The Various Petroleum Companies, (such as Shell, Esso, Gulf) Research and Engineering Departments.

5 Petroleum Processing Journals.

FLARE BURNING OF WASTE GASES

Robert D. Reed*

Flare design for safe and satisfactory disposal of waste gases is far more important in point of avoidance of air pollution than would normally be considered.

Abatement of air pollution would require that all the components of the waste gases not only be subject to complete oxidation by burning but that the flare must be capable of complete oxidation of such gases as are directed to the flare.

Compounds which completely oxidize to CO_2 and H_2O are many. Some are as follows:

Paraffins	Acetylenes
Iso-Paraffins	Olefin-Acetylenes
Olefins	Aromatics
Diolefins	Cyclo-Paraffins
Alcohols	Glycols
Glycerols	Ketones
Carbon Monoxide	Hydrogen

Many of these compounds when only partly oxidized form highly toxic compounds such as phenol, formaldehyde, acidic anhydrides and others. Thus the flare must be capable of accepting and completely oxidizing any gas which is delivered to it.

Flared gases which contain sulphur or chlorine in one form or another such as the following are serious in point of air pollution:

Hydrogen Sulphide	Mercaptans
Organic Sulphides	Carbonyl Sulphide
Carbonyl Chloride	Organic Chloride
Sewage Disposal Gases	

It is to be seen, then, that the flare design must provide not only for as nearly as possible completion of combustion but the height and thermal rise following burning must be such as to diffuse the toxic SO_2-SO_3, Cl_2 and HCl resulting from complete burning to non-toxic concentrations as the combustion gases return to grade.

Note that according to proprietary research which has been repeatedly verified and in flare burning of sulphur-bearing compounds approximately 10% of the sulphur weight will appear in the combustion gases as SO_3 and not necessarily as SO_2.

Again in cases of proprietary research most of the chlorine will appear as HCl but in all cases an appreciable portion of the chlorine will appear as Cl_2. Neither will be corrosive in the absence of hydration or wetting but wetting is possible in most cases due to dew-point of hydrogen-burning which accompanies production of products of oxidation, as well as rain.

Thus corrosion hazard adds to the problems of complete burning; of diffusion of products following burning and consideration of the flare location in view of prevailing winds.

Resistance to anticipated corrosion or corrosive conditions must be based on the flare metallurgy. There is rather a wide choice of metals for these conditions but there is yet another consideration in flare design which is the ability of the metals as chosen to resist heat attack.

Flare structure metals must be wisely chosen for the conditions which are to exist at the point of burning of the flared gases.

The Series 300 steels (304, 309 and 310) resist heat attack well in the temperature range of from 1600°F to 2000°F but all are subject to Sigma-Phase embrittlement in continued exposure to heat.

The 300 steels resist attack of elemental sulphur to varying degrees at elevated temperature levels.

*Vice President, Engineering, John Zink Company, Tulsa, Oklahoma.

Note the emphasis on elemental sulphur as distinguished from oxides of sulphur which have little more effect on steels than oxides of carbon. When the metal is exposed to H_2S, Mercaptans, Organic Sulphides, Carbonyl Sulphide and others, dissociated sulphur as such does attack the metal at high temperature levels.

The rate or magnitude of the attack seems to be governed by the percentage of nickel present in the alloy, thus of the 300 steels the 304 and 309 are superior to 310 at any temperature condition but the 304 is suitable for temperature limited to 1600°F, whereas 309 is suitable for 2000°F.

Series 300 steels are the metals of choice if resistance to sulphur attack governs but the metallurgy for chlorine attack is quite different. For such conditions of corrosion the metals of choice are Hastelloy B, Monel, Inconel, Incolloy, Titanium and others.

Because of the nature of the service which will not permit selection of favorable weather conditions for flaring of gases the flare must be designed for satisfactory operation in all weather conditions such as wind, rain, cold, atmospheric inversion and others.

Complete burning of flared gases can be said to exist if the flare is equipped with a flame-retaining tip or discharge nozzle of completely proven design for any discharge rate; a number of extremely stable pilots according to the flare size and minimum calorific value of the flared gas in the 200-500 btu/cu. ft. range according to the nature of the combustibles present.

A single-stable pilot is satisfactory only for flares up to 2" in size; two pilots are demanded for flares in the 3" and 4" size and three or more pilots are demanded in flare sizes from 6" and up.

When the auto-ignition temperature of the combustible matter in the flared gases is 800°F or less the gas calorific value (Lower Heating Value) may be as low as 200 btu/cu. ft. If the auto-ignition temperature of the combustible matter is 1150°F the minimum calorific value is 350 btu/cu. ft. (LHV) and if the auto-ignition temperature is 1300°F or more the minimum calorific value is 500 btu/cu. ft.

Pilots must provide a minimum of 300,000 btu/hr each as based on the LHV of the pilot fuel; must be capable of completely stable burning in an inert atmosphere; must be capable of projecting flame to and over the flare tip in any condition of wind, rain or temperature; must be capable of reliable and instantaneous ignition from a point at grade and remote from the flare base in any weather condition or wind velocity and must be proven capable of ignition of 1% of the design gas flow to the flare.

It is to be seen, therefore, that pilot design is a most critical element in complete burning of flared gases and that pilots designed for other services are far from suitable for application to the flare as has been repeatedly proven in flare operation.

Gases burn with speed and completeness according to the temperature level of the flame. Heat from the pilots not only initiates ignition of the flared gases but more importantly, perhaps, the heat from the pilot elevates and maintains flame temperature at levels suitable for complete burning regardless of weather conditions. Gases of less than 200 btu/cu. ft. can be forced to burn through addition of enough pilots, or heat.

Hydrocarbons and hydrocarbon-derived organics burn with speed and excellence according to the weight-ratio of hydrogen to carbon present in the flared gases.

The flare will at times and according to gases as flared, produce smoke to a greater or lesser degree. The smoke may be black or grey-blue and light according to hydrocarbons or sulphur compounds as burned respectively.

When black smoke is produced there is incomplete burning of hydrocarbons. The black smoke is carbon from the hydrocarbons.

Light blue-grey smoke is produced as sulphur compounds are burned and is present as the SO_3 produced in complete burning reaches dew-point temperature.

Hydrocarbons as flared burn with excellence and completeness according to the weight-ratio of hydrogen to carbon present (H/C ratio by weight). Methane (H/C = 0.33) produces a bright yellow flame with no smoke. Propane (H/C = 0.22) makes quite heavy smoke. Ethane (H/C = 0.25) also makes a bright yellow flame but with light trailing smoke. Thus it can be presumed that gases having H/C ratios of 0.28 can be burned without smoke.

Flares can be designed for smokeless operation where the H/C ratio by weight is less than 0.28 through forced entry of water vapor to the flame. The water vapor may be either as steam or from water sprayed into the flame.

The carbon combines with water vapor through the water-gas shift reactions ($C + H_2O = CO + H_2$ or $C + 2\ H_2O = CO_2 + 2\ H_2$) to enrich the H/C ratio through production of rapid burning gases. These reactions are quite rapid at 1650°F or more.

Black smoke from flare burning of gases, being carbon in particle size range from 0.01 to 0.13 microns (Perry), is much more a nuisance than toxic. However, oxides of sulphur, Cl_2 and HCl are toxic and there are severe limitations on ground-level concentrations of them.

Thermal-rise from the flare is based on 1800°F for diffusion of products of flare burning in the Sutton-Lowery equations for establishment of flare height. These equations as well as much air-pollution data are to be found in "Air Pollution Handbook" (McGraw-Hill).

At the present time there is but one source of definitive information on flare design because of the great complexity of flare design functions and because of patent status. The only group which has the facilities for research and knowledge of theoretical combustion functions is the John Zink Company, Tulsa, Oklahoma.

Section 5

STATE OF THE ART AND RESEARCH

Current Research on SO_x Control
Formation and Control of Oxides of Nitrogen
in Combustion Processes

CURRENT RESEARCH ON SOx CONTROL

Daniel Bienstock*

I THE PROBLEM OF SULFUR OXIDES

A Concern

The sulfur oxides irritate the respiratory system of man, cause extensive damage to plants even at very low concentrations, and are corrosive to building materials. It is probably the number one air pollution problem.

B Magnitude

Approximately 21 million tons of SO_2 are emitted each year as the result of the combustion of coal and fuel oil. If only 50% of this amount could be recovered as sulfur it could add about 5 million tons of elemental sulfur to the economy, worth about $123 million per year. Some recovery processes involve further oxidation and recovery of the sulfur as sulfuric acid. This would provide 15 million tons of sulfuric acid worth approximately $300 million.

C Sources of Sulfur Dioxide Emission

SO_2 pollution can result from the burning of coal; the combustion of petroleum products; the refining of petroleum; the smelting of ores containing sulfur; the manufacture of sulfuric acid; the burning of refuse; and the burning or smoldering of coal refuse banks.

II LIQUID FUELS

A Desulfurization of Fuel Oil

The combustion of petroleum products accounts for 21% of the SO_2 emitted in the country. Of this about 77% of the total emission of SO_2 from petroleum products results from the combustion of residual fuel oil.

Hydrogen treating at high pressures in presence of a catalyst is the most practical way of accomplishing any significant degree of sulfur reduction for most refinery stocks. There are several commercial processes available: The H-Oil, Gulf HDS, and the Texfining of Texaco.

Bechtel recently completed a computer study of the economics of residual fuel desulfurization. The cost of lowering the sulfur content in a California residual fuel from 1.6 to 1% S is 21¢ per barrel and to 0.5% S is 55¢ per barrel. The cost of lowering a Kuwait residuum from 4.3% S to 1% S is 52¢ per barrel and to 0.5%S is 65¢ per barrel.

III SOLID FUELS

A Coal

In 1963 some 458,000,000 tons of bituminous and 18,300,000 tons of anthracite were mined in the U.S. Of this tonnage 14,000,000 tons of SO_2 was emitted to the atmosphere.

The use of coals that are low in sulfur content would be of considerable aid in decreasing the SO_2 content of flue gas. However as the supply of such fuel is limited, treatment of coal before combustion to lower the sulfur content must be considered.

B Magnetic Separation

Only a small part of the pyrite needs to be converted into a ferromagnetic phase to serve as a "handle" to pull the entire particle out of the pulverized coal. The U.S. Bureau of Mines is conducting tests in this area.

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*Project Coordinator, Bureau of Mines, Pittsburgh Coal Research Center, Pittsburgh, Pa. (February, 1966).

C Corona

General Electric has treated coal with hydrogen in a corona discharge to split off the sulfur. No significant success reported.

D Extraction

The spencer Chemical Company under contract by Office of Coal Research has produced an ash and sulfur-free coal. The cost, however, of converting the coal is far too expensive for consideration as a boiler fuel.

E Bacterial Action

Use of bacteria to attack the pyrite has been studied. This requires fine grinding of coal and a water slurry. Method does not appear promising for processing large quantities of coal for power boilers.

F Gasification

Gasification and removal of the sulfur as H_2S has been considered but the conclusion reached that this route is uneconomic.

IV LIQUID SCRUBBING PROCESSES

A Battersea

Since 1935 a gas-washing plant at the coal-fired Battersea Power Station has used the water of the Thames River to which a small quantity of chalk has been added. More recently the same process was installed at Bankside Power Station for scrubbing the flue gas resulting from burning a high-sulfur fuel oil.

B Howden-I. C. T. Process, Use of Lime in a Cyclic Non-Regenerative Process

Employs a lime or chalk slurry (5-10%) circulated through wooden grid-packed towers. The plant of the Fulham Power Station, London, worked for several years, was shutdown during World War II and not reopened.

C Ammoniacal Solutions

By employing an ammonia solution instead of lime the sulfur is recovered in a more useful form principally as ammonium sulfate, sulfur dioxide, or elemental sulfur.

In these wet processes the scrubbed gas is cooled, loses its buoyancy, and descends in the neighborhood of the stack. Unless complete removal of SO_2 is effected, a greater local awareness of the presence of SO_2 occurs than before the gas cleaning. Three hot SO_2- removal processes have been developed to the experimental stage from which operating data and cost information are obtainable. These are the Reinluft, the Catalytic Oxidation, and the Alkalized Alumina Processes.

D The Reinluft Process

The absorbent is a fixed slowly moving bed of an activated char. The SO_2 in the gas is oxidized to SO_3 and adsorbed with H_2O on the char to form H_2SO_4.

E The Catalytic Oxidation Process

The flue gas passes through a fixed bed of V_2O_5 where the SO_2 is oxidized to SO_3. The product is 70% H_2SO_4.

F The Alkalized-Alumina Process

The flue gas is fed at 625°F where the SO_2 and SO_3 are absorbed by alkalized alumina spheres, 1/16-inch diameter, in free fall. Elemental sulfur is the end product.

A cost estimate was recently made in treating the effluent of an 800 MW power plant by these 3 processes.

CAPITAL REQUIREMENTS AND NET OPERATING COSTS

Process	Capital Requirement dollars	Net operating cost $/yr.	Net operating cost $/ton of coal
Reinluft	15,800,000	3,191,900	1.44
Alkalized alumina	8,510,000	2,205,800	1.00
Catalytic oxidation	17,460,000	1,670,200	0.75

FORMATION AND CONTROL OF OXIDES OF NITROGEN IN COMBUSTION PROCESSES

J. D. Sensenbaugh*

During the early investigation of the Los Angeles smog problem, the reactions responsible for the smog formation were not understood. In 1952, Haagen-Smit[1] suggested that a complex series of photochemically-initiated reactions between hydrocarbons and oxides of nitrogen might be responsible for the observed phenomena. Since then, numerous investigators have firmly established this mechanism for the production of photochemical smog. The hydrocarbons required for these reactions enter the atmosphere primarily from vehicle exhausts, while the oxides of nitrogen are produced by combustion processes of all kinds.

I CHEMISTRY OF NITROGEN OXIDES

A number of oxides of nitrogen are known. The most common are nitrous oxide, N_2O; nitric oxide, NO; nitrogen trioxide, N_2O_3; nitrogen dioxide, NO_2; nitrogen tetroxide, N_2O_4; and nitrogen pentoxide, N_2O_5.

Nitrous oxide is reasonably stable at room temperature, but decomposes readily on being heated. There is no evidence that N_2O participates in the smog-forming reactions.

Nitric oxide is the most stable oxide of nitrogen. It is formed by the reaction of nitrogen and oxygen at high temperatures. At room temperature, nitric oxide oxidizes in air to nitrogen dioxide:

$$2NO + O_2 \longrightarrow 2NO_2$$

Nitrogen trioxide is a blue liquid below -21°C (-6°F). When heated to room temperature and above, N_2O_3 dissociates, giving a mixture of NO and NO_2.

$$N_2O_3 \rightleftharpoons NO + NO_2$$

As mentioned above, nitrogen dioxide, NO_2, is formed in air by the oxidation of NO. It exists in equilibrium with its dimer, nitrogen tetroxide, N_2O_4:

$$2NO_2 \rightleftharpoons N_2O_4$$

This equilibrium is shifted to the right on cooling and to the left on heating. At normal ambient temperatures, NO_2 predominates.

Nitrogen pentoxide is the anhydride of nitric acid. At room temperature, it exists as a white solid. There is no indication that N_2O_5 occurs in polluted atmospheres to any extent, if at all.

In summary, the evidence indicates that, of the oxides of nitrogen discussed, only NO and its oxidation product, NO_2, are of significance as air pollutants.

II FORMATION OF NO IN COMBUSTION

In ordinary combustion calculations, it is customary to assume that the nitrogen in the combustion air supplied to the furnace is inert and does not participate in the combustion reactions. From the standpoint of chemical reactivity, nitrogen is, indeed, a relatively inert element. However, a mixture of nitrogen and oxygen, when subjected to a high temperature (in the range of 2800 - 4000°F) such as provided by a flame, will react to produce a significant quantity of NO, according to the reaction:

$$N_2 + O_2 \longrightarrow 2NO \qquad \Delta H = +43.2 \text{ kcal.}$$

The relatively high positive heat formation shown indicates that a high temperature is necessary to furnish the heat absorbed in this reaction.

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Thermodynamic considerations indicate that, the higher the temperature, the greater the amount of NO produced, provided that chemical equilibrium is attained. However, in a practical situation, equilibrium conditions are not reached. In addition to the thermodynamics of the reaction, one must take into consideration the factor of kinetics, i.e., the rate of chemical reactions. As a matter of fact, the formation of NO by the reaction of N_2 and O_2 is a reversible reaction:

$$N_2 + O_2 \underset{k_r}{\overset{k_f}{\rightleftharpoons}} 2NO,$$

with the reaction rate donstant for the forward (formation) reaction indicated by k_f and for the reverse (decomposition) reaction indicated by k_r. These reaction rate constants for both the forward and reverse reactions, i.e., both k_f and k_r, increase rapidly with temperature. However, the decomposition rate constant, k_r, is always greater than the formation rate constant, k_f. For example, at 4400°F, $k_r = 150\ k_f$, while at 2800°F, $k_r = 8000\ k_f$. Thus, as the temperature decreases in passing through a boiler, the decomposition rate predominates, leading to lower net NO concentrations.

Theoretical curves, based on typical boiler operating conditions and including both thermodynamic and kinetic considerations, are shown in Figure 1. It is seen that below 2800°F, the net production of NO is very small. From a practical standpoint, this means that, as the temperature falls below 2800°F in passing through a boiler system, the NO formed at higher temperatures is effectively "frozen" into the gas mixture, since the system is quenched too rapidly for the reverse reaction to become effective, and equilibrium concentrations are never approached.

The above discussion has been concerned with the formation of NO. Spectroscopic studies by Haagen-Smit et al.[2] have indicated that almost all of the oxides of nitrogen found in boiler flue gas is present as NO, with only a minor proportion present as NO_2. It has been previously stated that NO is oxidized in air to NO_2. However, the rate of this oxidation reaction is strongly dependent on the NO concentration. The rate is rather slow at concentrations found in the atmosphere. For example, at 1 ppm NO, it takes about 100 hours for half the NO to be oxidized to NO_2, and at 0.1 ppm NO, about 1000 hours are required for 50% conversion to NO_2. These figures hold in the absence of ozone, hydrocarbons, sunlight, or other factors that increase the rate of NO oxidation. In any case, the principal nitrogen oxide emitted to the atmosphere in boiler flue gas is NO, and subsequent oxidation in the atmosphere is dependent on a number of factors included in the whole complex of reactions involved in photochemical smog formation.

Insofar as emissions to the atmosphere from combustion processes are concerned, the question of the particular nitrogen oxide emitted is immaterial. This is because the usual method of measuring such emissions, the phenoldisulfonic acid method,[3] does not differentiate between NO and NO_2, but measures the total of these two oxides. Accordingly, it has become customary to refer to the total oxides of nitrogen measured by this method as NO_x, a practice that will be followed in the balance of this paper.

III FACTORS AFFECTING NO_x FORMATION

The concentration of NO_x in boiler flue gas depends on a host of factors involved in boiler design and operation. Generalizations can be made regarding the effect of these variables, but extensive studies[4, 5] of NO_x emissions have shown that the exact level of emission from a particular unit cannot be predicted. In this connection, the authors of one extensive report[5] make the following statement:

> "The degree and direction of the effect of operating variables upon NO_x production must be determined individually for each particular unit to be considered. It was found that actual rates of NO_x emission from sister units may be different for operating conditions which are the same for each unit within the limits of ability to determine."

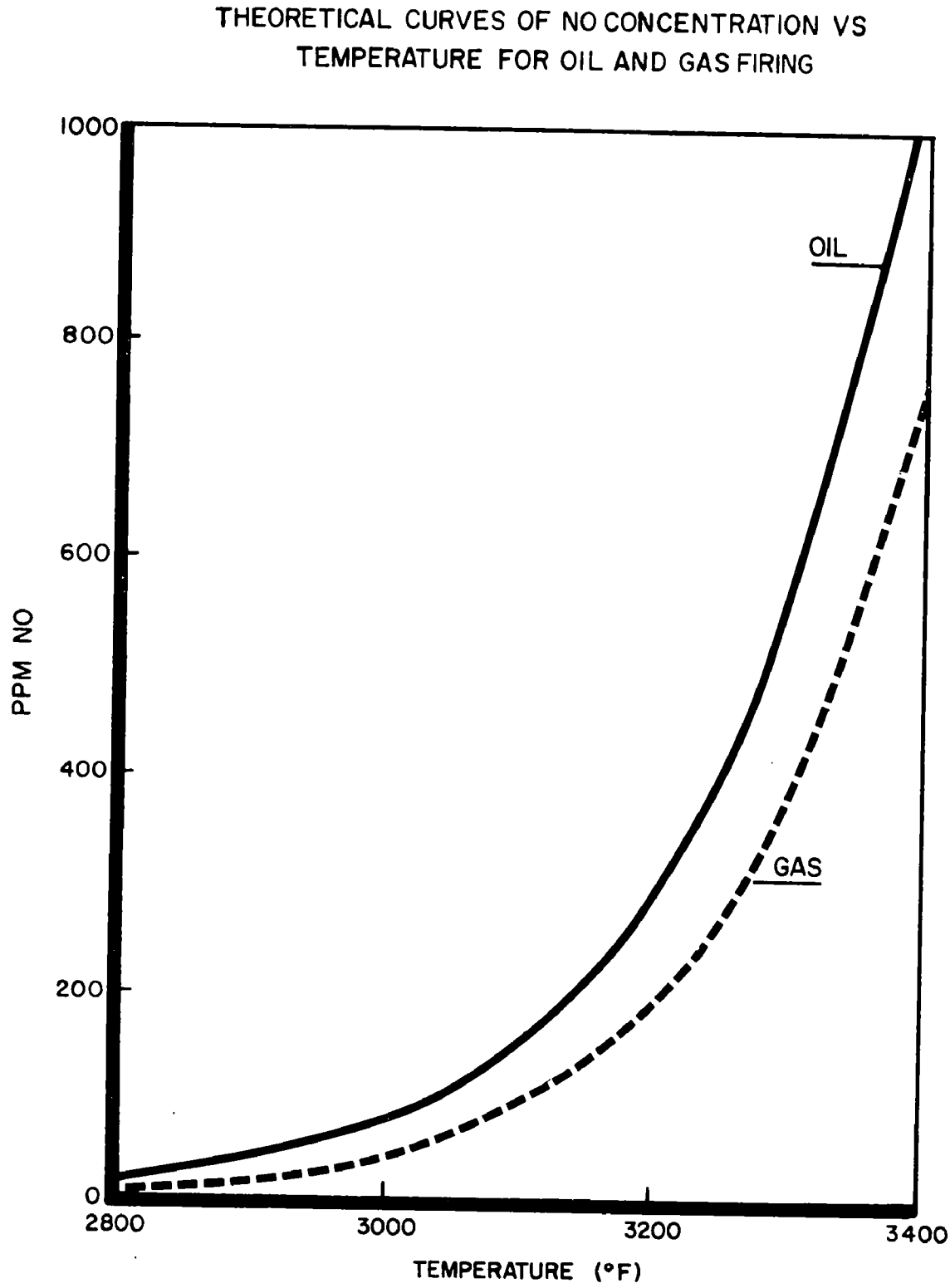
THEORETICAL CURVES OF NO CONCENTRATION VS
TEMPERATURE FOR OIL AND GAS FIRING
1000
800
600
400
200
0
PPM NO
OIL
GAS
2800
3000
3200
3400
TEMPERATURE (°F)

Figure 1

IV EFFECT OF FUEL AND TYPE OF FIRING

Two of the major factors affecting NO_x production are the fuel used and the method of firing. These will be discussed together.

Most of the work on oxides of nitrogen production has been done with oil and gas fuels. The general ranges for these fuels with horizontal and tangential firing are as follows:

Fuel	Firing	ppm NO_x
Oil	Horizontal	500 - 700
Oil	Tangential	200 - 400
Gas	Horizontal	300 - 500
Gas	Tangential	100 - 200

Data from a number of plants are shown in Table 1 and Figure 2. The average NO_x concentration found in these tests for horizontally-fired, oil-burning units is 560 ppm, compared with an average of 293 ppm for tangential firing of oil. In other words, the average concentration obtained with tangential firing is 52% of that found with horizontal firing. With gas fuel, the average concentration found for horizontal firing is 339 ppm, while that for tangential firing is 160 ppm. In this case, the average concentration for tangential firing is 47% of that for horizontal firing.

Little work has been done on NO_x emissions from coal-fired units. Results of tests on four units with different types of firing have been published.[6, 7, 8] Data obtained at full load are shown in Table 2. It should be noted

Table 1. COMPARISON OF TYPE OF FIRING AND FUEL
NORMAL FULL LOAD OPERATION

Plant	Fuel	Firing	Ave. ppm NO_x
El Segundo (11)	Oil	Horizontal	685
A	Oil	Horizontal	567
B	Oil	Horizontal	505
C	Oil	Horizontal	482
E	Oil	Tangential	362
F	Oil	Tangential	309
G	Oil	Tangential	209
El Segundo (11)	Gas	Horizontal	520
A	Gas	Horizontal	290
B	Gas	Horizontal	319
D	Gas	Horizontal	226
E	Gas	Tangential	164
F	Gas	Tangential	157

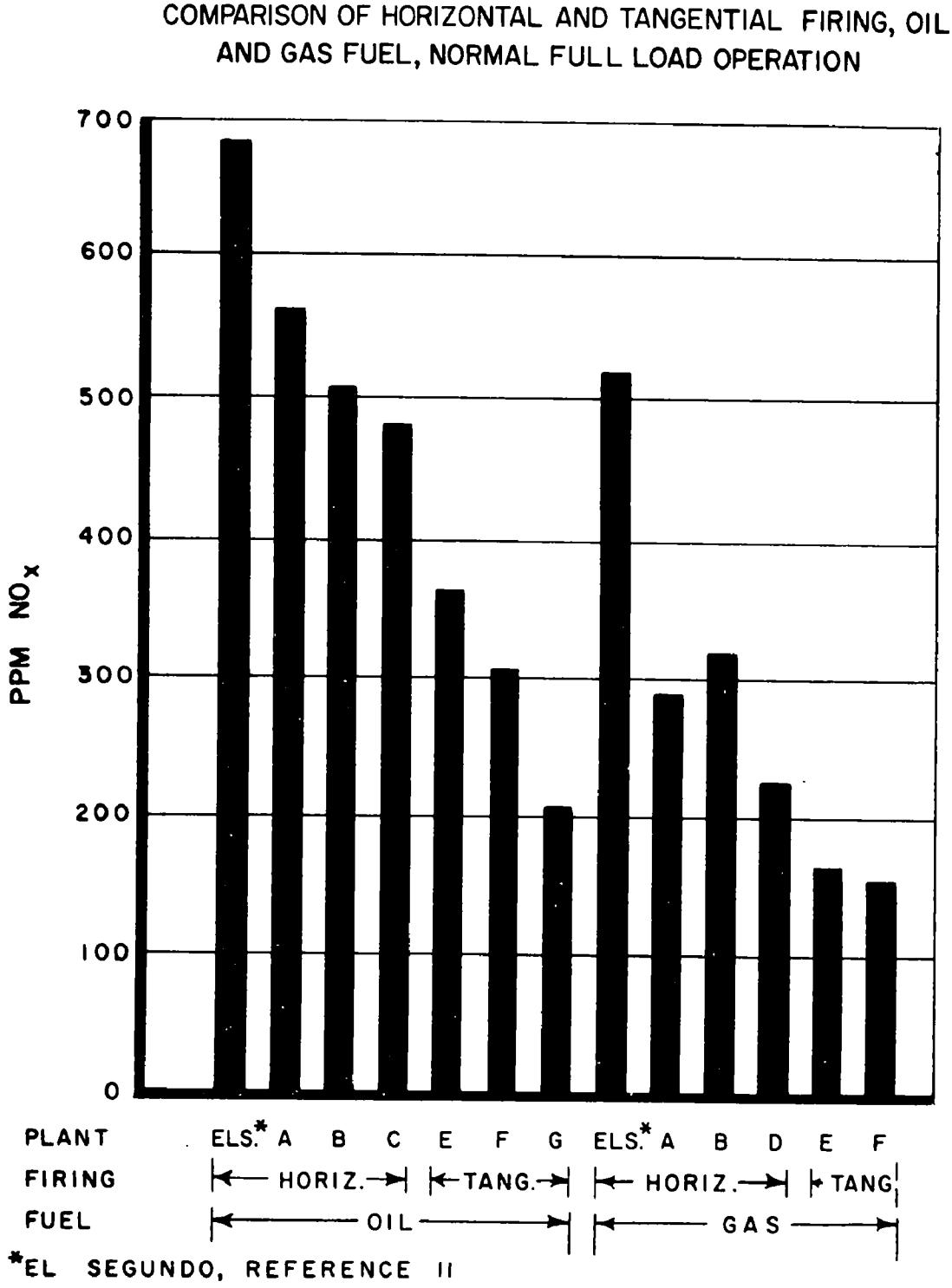
COMPARISON OF HORIZONTAL AND TANGENTIAL FIRING, OIL AND GAS FUEL, NORMAL FULL LOAD OPERATION
PPM NOx
700
600
500
400
300
200
100
0
PLANT
ELS.* A B C E F G ELS.* A B D E F
FIRING
HORIZ. TANG. HORIZ. TANG.
FUEL
OIL
GAS
*EL SEGUNDO, REFERENCE 11

Figure 2

Table 2. NO_x from Coal-Fired Units, Full Load Operation, Samples Taken Before Dust Collector (Data Taken from Reference 8)

Unit	Type of Boiler	Average ppm NO_x Corrected to Constant CO_2
A	Downward-fired, dry bottom	267
B	Front-fired, dry bottom	595
C	Tangentially-fired, dry bottom	500
D	Horizontal opposed, wet bottom	520

that only one unit of each type was included in these studies, so the results are not necessarily representative of the emissions to be expected from a particular type of firing.

V EFFECT OF EXCESS AIR

Since NO is formed by the high temperature reaction of nitrogen and oxygen, one would expect that the amount of excess air available would affect NO production. Data obtained at several plants for oil and gas fuels are shown in Figures 3 and 4. It will be seen that, at the O_2 levels present in conventional operation, a decrease in excess air produced a decrease in NO_x. The effect is particularly pronounced for horizontal firing.

In recent years, there has been a trend toward operation of oil-fired units at low excess air levels of 2 - 5% (0.4 - 1% O_2) instead of the conventional 10 - 20% (2 - 4% O_2). This has been done to avoid problems associated with the formation of SO_3. However, low excess air operation is also beneficial from the standpoint of reducing NO_x. Figure 5 shows test data from three plants. These units are similar in size and are all tangentially fired. In this case, the results from three units fall nicely on the same curve.

VI EFFECT OF GAS RECIRCULATION

Many units employ the recirculation of a portion of the flue gas into the furnace as a means of steam temperature control. Introduction into the furnace of gas containing less oxygen than the combustion air would be expected to affect the formation of NO. Also, depending on the point of introduction, the recirculated gas may act to lower the flame temperature.

Test results from two different plants are shown in Figures 6 and 7. In both cases, the NO_x concentration decreases with increasing gas recirculation, although in the case of the tangentially-fired unit shown in Figure 6 the reduction was relatively small. In going from zero to 15% gas recirculation, the NO_x concentration was reduced about 15% from its initially rather low value.

There is so much variation from one unit to another in the quantity of gas recirculation needed for steam temperature control and in the point at which the recirculated gas is introduced that the effect of gas recirculation is difficult to predict.

VII EFFECT OF UNIT SIZE

It would be useful to be able to predict the NO_x emission from a given unit on the basis of data on other units using the same type of fuel and firing method. An attempt was made to correlate NO_x data from a laboratory package boiler burning oil with data obtained in the field on horizontally-fired oil-burning with data obtained in the field on horizontally-fired oil-burning units. Although some similarities in trends were found, no useful correlation curves could be developed. This was attributed to the fact that the single burner in the package boiler "sees" only cool surface,

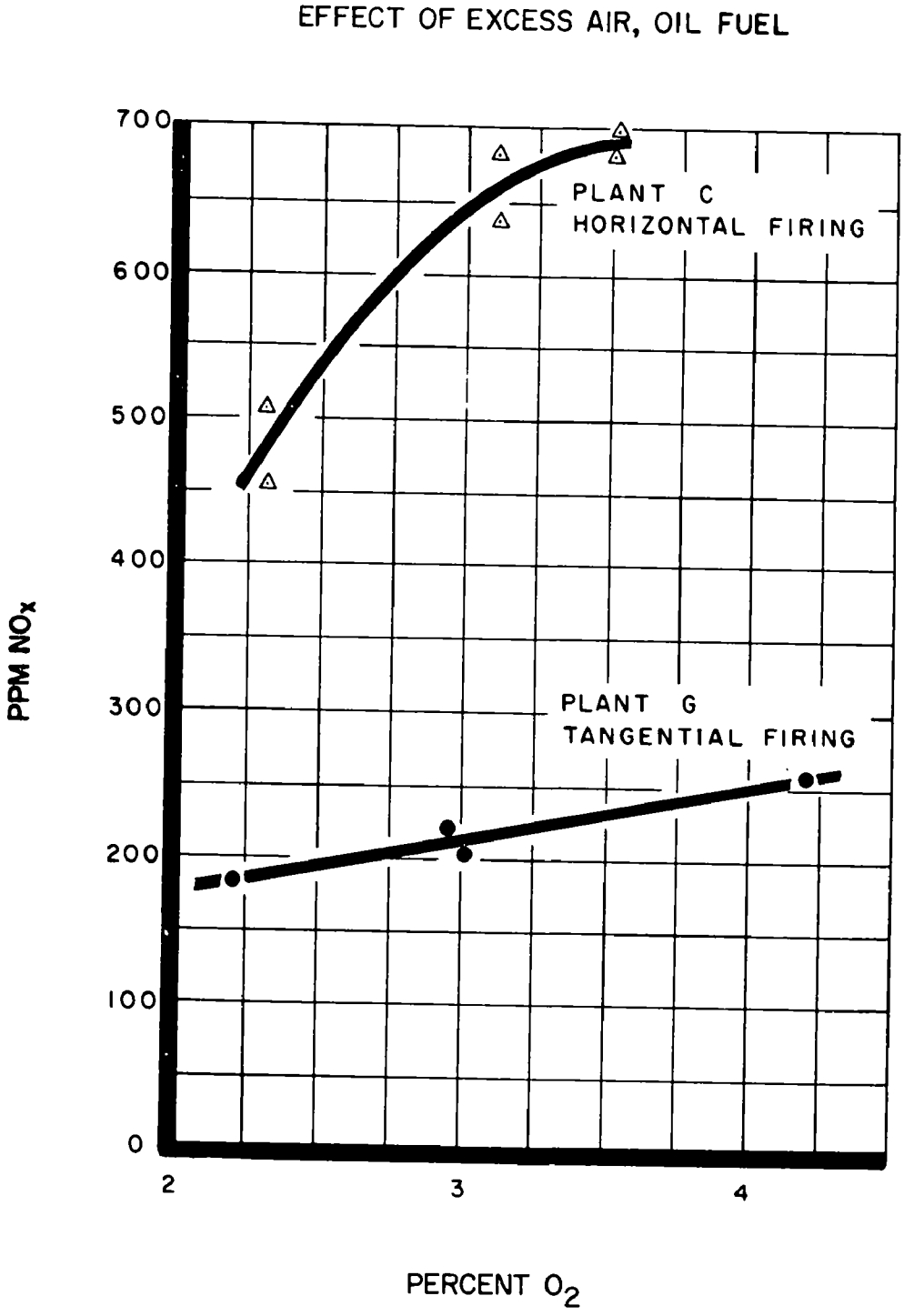
EFFECT OF EXCESS AIR, OIL FUEL
700
600
500
400
300
200
100
0
PPM NOx
PLANT C
HORIZONTAL FIRING
PLANT G
TANGENTIAL FIRING
2
3
4
PERCENT O2

Figure 3

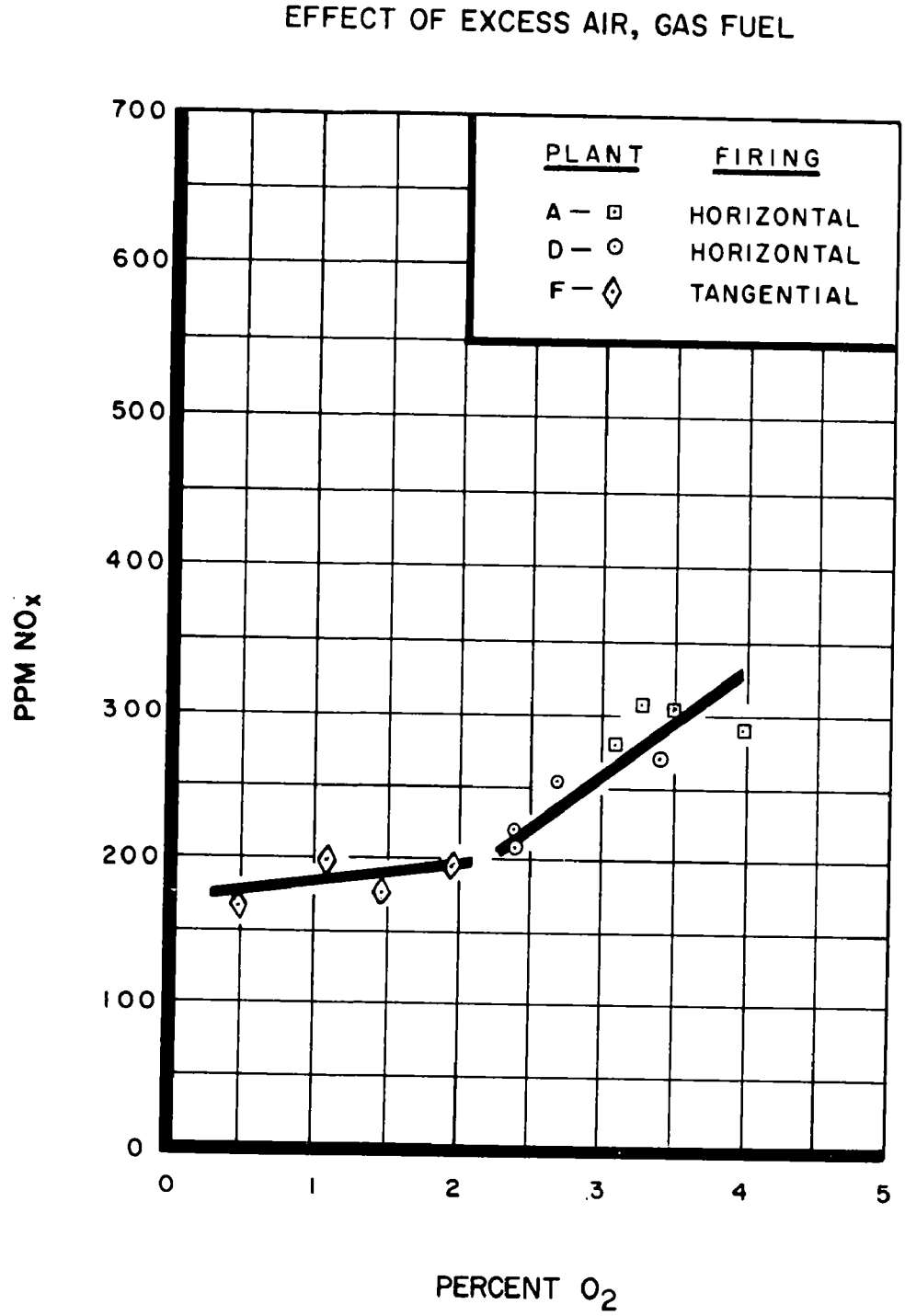
EFFECT OF EXCESS AIR, GAS FUEL
PLANT
FIRING
A — HORIZONTAL
D — HORIZONTAL
F — TANGENTIAL
PPM NOx
700
600
500
400
300
200
100
0
0
1
2
3
4
5
PERCENT O2

Figure 4

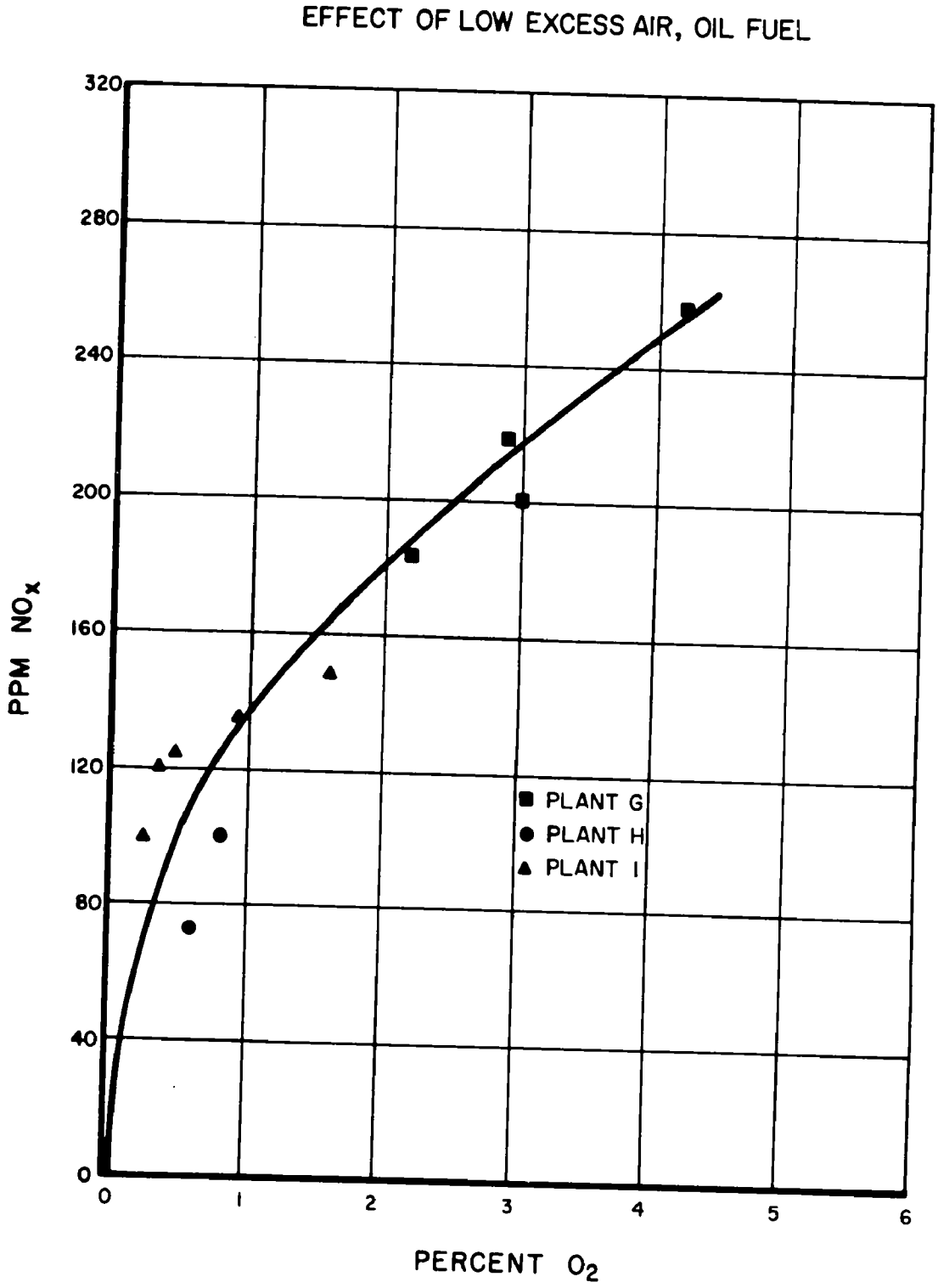
EFFECT OF LOW EXCESS AIR, OIL FUEL
PPM NO_x
320
280
240
200
160
120
80
40
0
0
1
2
3
4
5
6
PERCENT O_2
PLANT G
PLANT H
PLANT I

Figure 5

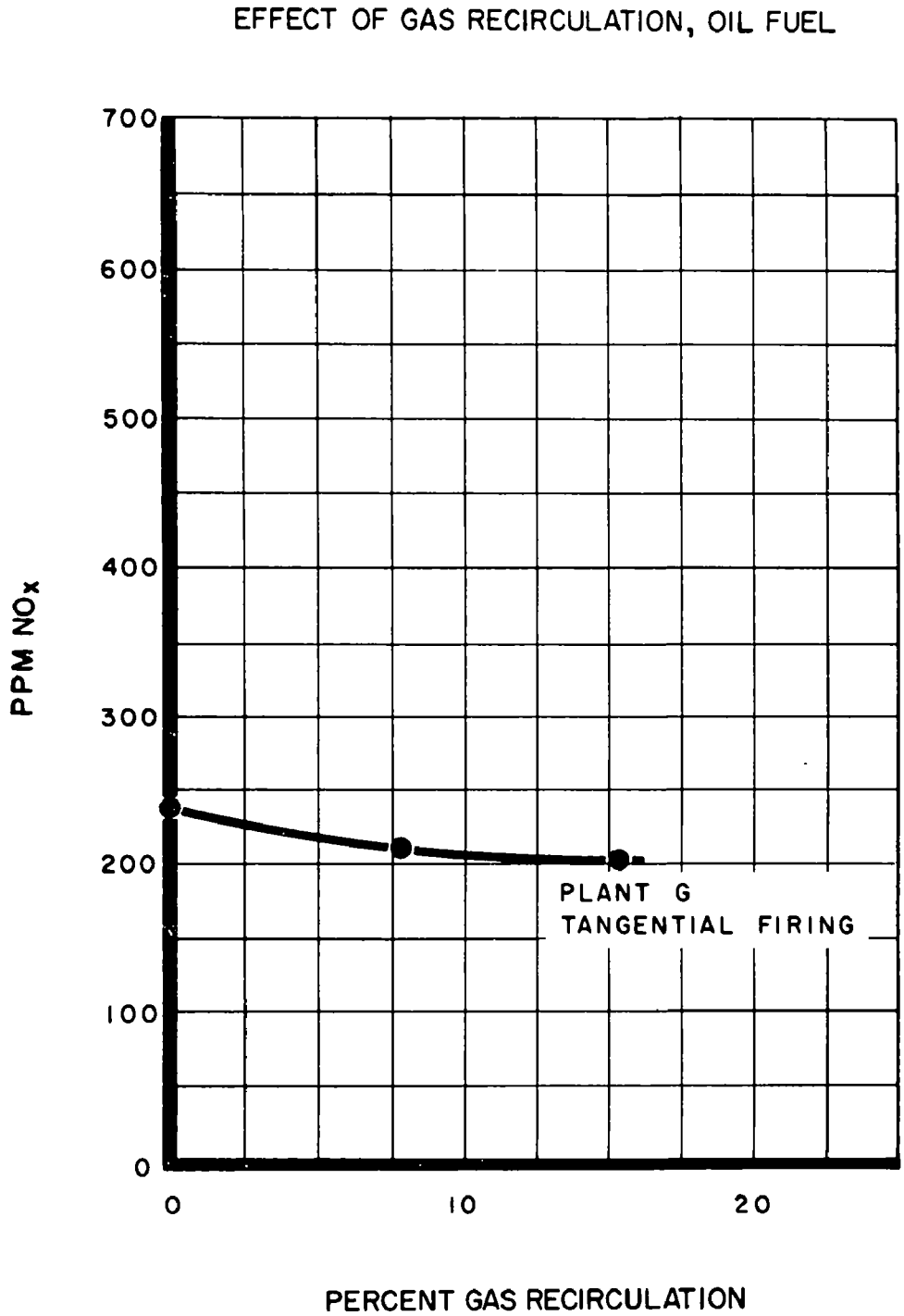
EFFECT OF GAS RECIRCULATION, OIL FUEL
700
600
500
400
300
200
100
0
PPM NOx
0
10
20
PLANT G
TANGENTIAL FIRING
PERCENT GAS RECIRCULATION

Figure 6

EFFECT OF GAS RECIRCULATION, OIL FUEL, HORIZONTAL FIRING (REFERENCE 5)

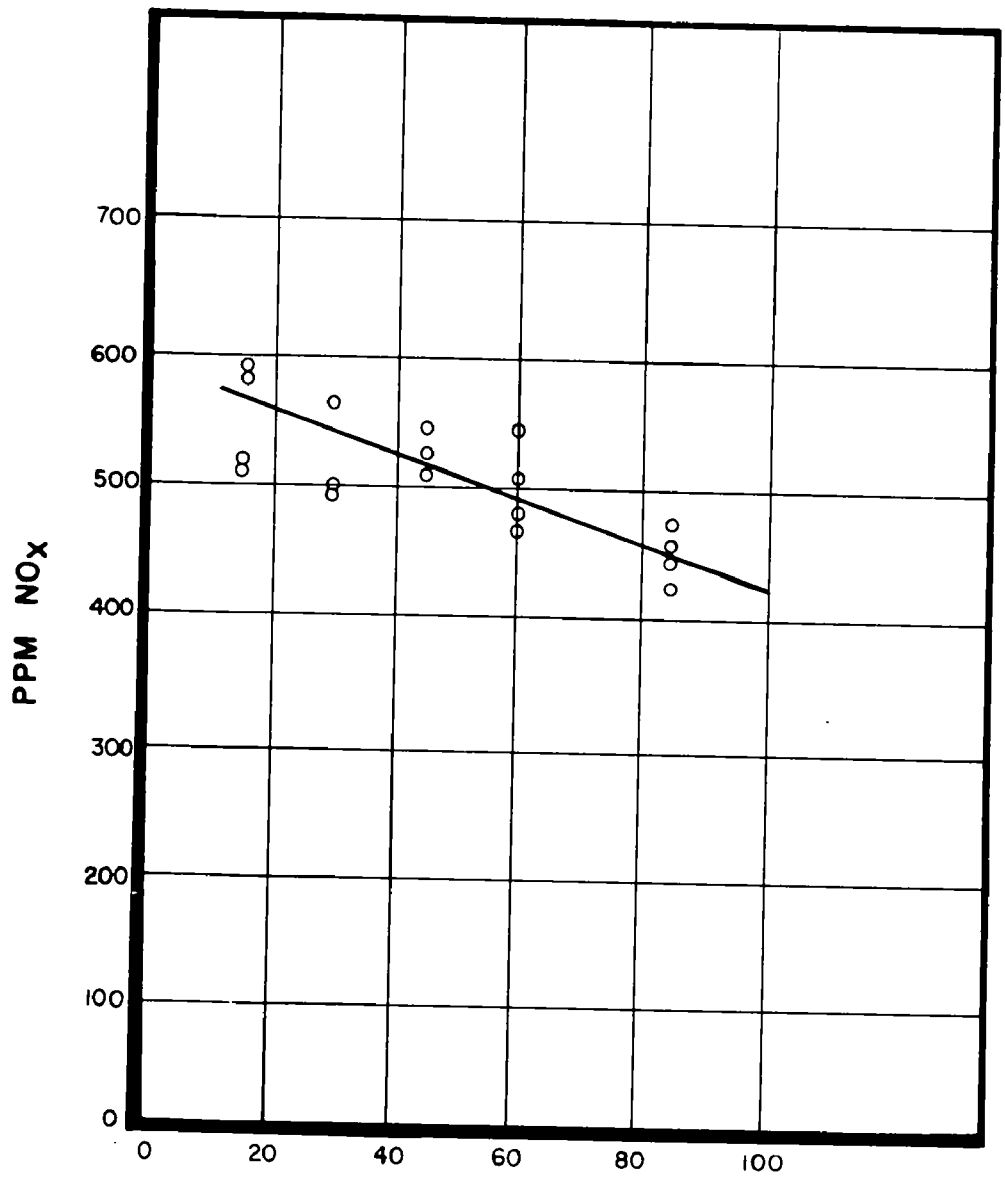

Figure 7

while interaction occurs between the flames in a multiple burner installation.

Similar results were reported[5] in tests on large units where the number and spacing of burners in use were varied. It was found that, when the burners in operation were closely grouped or when more burners were in use, more NO_x was produced than when the same amount of fuel was burned using fewer burners with wider spacing. Again, the results were attributed to the relative amount of cold waterwall each burner sees; when more cooling surface is available to absorb radiant heat from each individual flame, less NO_x is formed.

A correlation has been published between NO_x emission and gross heat input to a unit.[9, 10] This correlation takes the form of log-log plots covering some six or seven decades. The authors of one of these reports[9] give the following precaution regarding the use of the plots:

> "The graph should not be used to estimate NO_x emissions from any given unit, because individual units are subject to so many operating variables as well as individual combustion parameters that actual emissions of NO_x from any single unit at a given time may vary widely from the average for the group."

This precaution is very important. For example, the curves would predict a concentration of 700 ppm NO_x for burning oil at full load in a particular tangentially-fired boiler. The average measured value under these conditions was 209 ppm. Part of this discrepancy may be due to the fact that tangentially-fired utility boilers were not included in the test data on which the correlation is based, so that, at the high heat input end, the curve is weighted in favor of the higher emission rates typically shown by horizontally-fired boilers. In any case, the correlation must be used with full recognition of the fact that it will give only a rough idea of the emission from a particular unit.

VIII POSSIBLE CONTROL METHODS

The preceding discussion of factors affecting NO_x formation suggests that NO_x emissions could be reduced in the following ways:

a Change of fuel

b Minimize NO_x formation by

1 Lower excess air

2 Lower flame temperature

If it is not possible to obtain sufficient reduction by means of the approaches indicated above, NO_x might be removed from flue gas after formation by means of the following:

c Absorption

d Adsorption

e Catalytic decomposition

A Change of Fuel

There is no doubt that the substitution of gas for oil would result in lower NO_x emission. However, this is not always a practical course to follow. In many areas, considerations of fuel supplies and economics make another course more desirable.

B Minimize NO_x Formation

The present trend toward low excess air firing of oil is well established and is expected to continue. As indicated previously, the excess air levels in question are effective in reducing NO_x emissions.

The strong temperature dependence of the NO formation reaction indicates that any measure resulting in lower flame temperature would lead to lower NO_x concentrations. One approach is to use the tangential firing concept, which uses the furnace itself as the burner and inherently produces lower maximum flame temperatures.

If horizontal firing is preferred, NO_x formation can be greatly reduced by the use of two-stage combustion, as described by Barnhart and Diehl.[11] In this system, 90 - 95% of the theoretical air is introduced through the burners with the remaining 15 - 20% required for combustion entering through auxiliary air ports above the burners. Their results at El Segundo using 95% of theoretical air through the burners are shown in Figure 8. It may be seen that a 44% reduction in NO_x concentration was obtained with two-stage combustion compared with normal operation.

Figure 8 also shows the results of tests in which two-stage operation was simulated at two plants. These tests were conducted by operating at reduced load with the top row of burners off and the dampers closed in order to get a reference value. This was followed by the introduction of auxiliary air through the idle top burners. Again, approximately 95% of theoretical air was introduced through the burners. At plant B, with horizontal firing, a 45% reduction in NO_x was found with two-stage combustion compared with normal operation. At plant G, with tangential firing, the reduction in NO_x with two-stage combustion was only 22%; however, as usual with tangential firing, the NO_x level for normal operation was much lower.

C Absorption and Adsorption

If NO_x has to be removed from flue gas after formation, absorption or adsorption processes might be considered. Peters[12] and Peters and Holman[13] have studied the absorption of NO_2 in water and aqueous NaOH solutions using a variety of absorption tower packings. They found that extremely large quantities of water would be required to absorb NO_2 appreciably from gases containing less than 2000 ppm NO_2. Also, at temperatures below 100°F, there was no significant difference in NO_2 absorption by water and by 20% NaOH. Since NO is only slightly soluble in water, it would be expected to be absorbed only slightly by water or basic solutions.

Littman, et al.[14] have studied the adsorption of NO_x on activated charcoal. It was found that NO_2 was adsorbed, but NO was not. Foster and Daniels[15] studied a process in which gas containing NO was dried and passed over silica gel. The silica gel acted as a catalyst for the oxidation of the NO to NO_2, and the latter was adsorbed on the silica gel. At room temperature and with a gas stream containing 1.0 - 1.5% NO, adsorption efficiencies as high as 99% were obtained. However, when the NO_2 content was reduced to 2000 ppm (still 3-10 times the NO_x concentration commonly found in boiler flue gas), the efficiency of NO_2 removal dropped to about 50%.

Even if an efficient adsorption process were developed, the adsorbent would have to be recovered for recycling. This would involve desorbing the NO_2 by heating, with subsequent collection of the NO_2, perhaps by absorption.

Both absorption and adsorption methods have inherent disadvantages. To achieve effective collection, both methods must be carried out at relatively low temperatures. Final disposal of the collected material must also be provided. The studies cited indicate that large amounts of absorption or adsorption media would be required, leading to large equipment size and high costs.

D Catalytic Decomposition

Another approach to the removal of NO_x from flue gas might be catalytic decomposition to nitrogen and oxygen. In general, this appears to be more suited to small volume applications such as automotive exhaust, since the cost would probably be excessive for treating boiler flue gas. Catalytic systems have been described[16] for promoting the reaction between NO_x and hydrocarbons to yield carbon dioxide, water, and nitrogen. Such systems have been applied to nitric acid plant tail gas containing of the order of 5000 ppm NO_x. However, as usual in such situations, the problems are much more severe when dealing with much more dilute boiler flue gas.

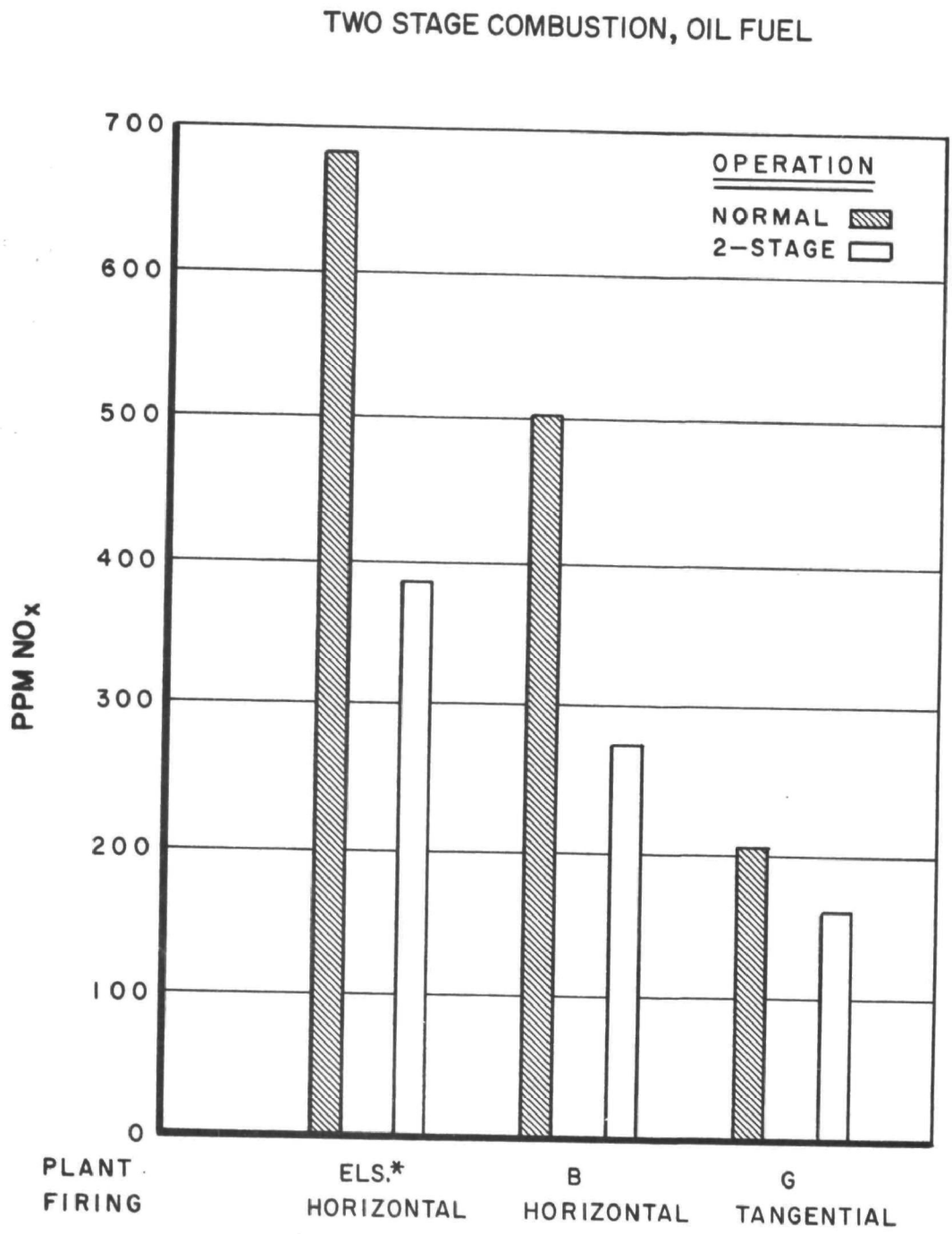
TWO STAGE COMBUSTION, OIL FUEL
OPERATION
NORMAL
2-STAGE
PPM NOx
700
600
500
400
300
200
100
0
PLANT FIRING
ELS.*
HORIZONTAL
B
HORIZONTAL
G
TANGENTIAL
*EL SEGUNDO, REFERENCE 11

Figure 8

The reduction of NO_x by carbon monoxide or carbon monoxide and hydrogen in the presence of various copper-containing catalysts has been described.[17, 18, 19] Such systems appear to be technically feasible for application to motor vehicle exhaust gas, but the necessary hardware has not be developed. However, in view of the recent action by the California State Board of Health in setting a 350 ppm standard for NO_x in auto exhaust,[20] the required exhaust treatment devices will be developed in time. As a matter of interest, almost six years elapsed between the adoption of exhaust standards for carbon monoxide and hydrocarbons and the installation of approved devices on automobiles.

IX SUMMARY

Of the various oxides of nitrogen, only NO and NO_2 participate in the reactions involved in the formation of photochemical smog. The NO originates in high temperature combustion processes, while NO_2 is formed by the oxidation of NO.

The concentration of NO_x in boiler flue gas depends on so many interrelated factors that the concentration to be expected from a particular unit cannot be predicted without measurement. However, certain generalizations can be made. The production of NO_x will vary with the fuel and type of firing. Oil produces greater NO_x concentrations than gas, and horizontal firing gives higher concentrations than tangential firing. In general, a reduction in excess air produces lower NO_x levels. This is particularly noticeable at the low excess air levels now in use with oil firing.

Possibilities for reducing the quantity of NO_x formed include 1) change of fuel, 2) low excess air operation, and 3) reducing flame temperatures. A change in fuel used is not always economically attractive, so other ways should be considered. Low excess air operation with oil firing is practical and effective; it is expected that this approach will be increasingly employed in the future. Lower flame temperatures with resulting lower NO_x formation may be realized by use of tangential firing or by two-stage combustion with horizontal firing.

Removal of NO_x from boiler flue gas by absorption, adsorption, or catalytic decomposition methods does not appear to be practical. However, the use of catalytic decomposition does appear feasible for automotive exhaust, and it will probably be used in this application.

REFERENCES

1 Haagen-Smit, A. J. Ind. Eng. Chem. 44:1342. 1952.

2 Haagen-Smit, A. J., Taylor, V. D., and Brunelle, M. F. Int. J. Air Poll. 2:159. 1959.

3 ASTM Standard No. D-1608.

4 Sensenbaugh, J. D., and Jonakin, J. ASME Paper No. 60-WA-334.

5 Report No. 3 of Joint Project on Emissions of Oxides of Nitrogen from Stationary Sources in Los Angeles County. 1961.

6 Cuffe, S. T., Gerstle, R. W., Orning, A. A. and Schwartz, C. H. J. Air Poll. Control Assn., 14:353. 1964.

7 Gerstle, R. W., Cuffe, S. T., Orning, A. A. and Schwartz, C. H. Ibid. 15:59. 1965.

8 Orning, A. A., Scwartz, C. H., and Smith, J. F. ASME Paper No. 64-WA/FU-2.

9 Report No. 4 of Joint Project on Emissions of Oxides of Nitrogen from Stationary Sources in Los Angeles County. 1961.

10 Woolrich, P. F. Amer. Indus. Hyg. Assn. Journal. 22:481. 1961.

11 Barnhart, D. H., and Diehl, E. K. J. Air Poll. Control Assn. 10:397. 1960.

12 Peters, M. S. Chem. Eng. 62:197. 1955.

13 Peters, M. S., and Holman, J. C. Ind. Eng. Chem. 47:2536. 1955.

14 Littman, F. E., Ford, H. W., and Endow, N. Ibid. 48:1492. 1956.

15 Foster, E. G., and Daniels, F. Ibid. 48: 986. 1951.

16 Donahue, J. L. J. Air Poll. Control Assn. 8:209. 1958.

17 Sourirajan, S. and Blumenthal, J. L. Int. J. Air and Water Poll. 5:24. 1961.

18 Baker, R. A., Doerr, R. C. J. Air Poll. Control Assn. 14: 409. 1964.

19 Baker, R. A., and Doerr, R. C. Ind. Eng. Chem. Proc. Des. and Devel. 4:188. 1965.

20 Clean Air Quarterly. 9:4, 1. 1965.

Section 6

PERMIT SYSTEM

Permit System - Combustion Evaluation

PERMIT SYSTEMS - COMBUSTION EVALUATION

Herbert C. Johnson*

I INTRODUCTION

Installation permits must be obtained for fuel burning equipment in most cities and many counties of most states. Permits usually are issued by building departments, fire departments, health departments, or air pollution control agencies. Central permit bureaus are being established, or some other coordinating system developed in some cities to expedite issuance of permits.

Well administered permit systems have contributed to health and safety, to more efficient use of fuels, and to reduced maintenance costs.

A Information Required to Obtain a Permit

1 Location of installation, address, firm name.

2 Plot plan showing equipment location on property, type and height of adjacent buildings.

3 Plan of room or location of equipment should be to scale showing clearances, air supply, fuel supply, breeching, and stack. For incinerators, show storage for refuse and space for charging and ash cleaning. Show fire doors, fire protection, fire walls, etc.

4 Supply manufacturer's drawings and specifications, including materials of construction, type and size of burners, combustion volume, size of air ports, and draft required.

5 Capacity requirements

a Btu's required for heat or processing average, maximum, minimum, etc.

b Incinerators, lb/day to be burned, type of refuse.

6 Piping and wiring diagrams, and flame safety devices may be required to assure meeting codes.

7 Process flow sheet - not usually required for small equipment, may be necessary where industrial processes are involved.

8 Proposed stack height. For large equipment burning sulfur containing fuels or discharging other air contaminants, calculations showing adequacy of dispersion by stack may be required.

9 Air pollution control devices. Additional control equipment may be required to remove fly ash or other forms of air pollution. Manufacturer's guarantees should be included.

B Obtaining an Operating Permit

Assuming that installation has been obtained and equipment installed.

1 Notify inspection agency of completion, request inspection.

2 Correct any discrepancies in installation found by inspector.

3 Demonstrate operation for inspector. Make adjustments as required by inspector.

4 Perform stack tests or other tests required to determine compliance.

5 Modify equipment or install additional control equipment as necessary to comply with regulations.

*Senior Air Pollution Engineer, Bay Area Air Pollution Control District, San Francisco, California.

PA. C. ce. 22. 7. 66

C Retaining on Operating Permit

The intent of a permit system implies continued surveillance and testing if necessary. To continue meeting all requirements.

1 Inspection and preventive maintenance to assure proper operation.

2 Type of fuel or refuse must conform to permit application.

3 Operators should be properly instructed and supervised.

4 Load on equipment should not be allowed to exceed designed capacity.

A permit system will be successful only if adequate information is included in the application, the reviewing engineer is qualified in the field of fuel burning equipment and combustion, and the installing contractor completes the installation according to plans and specifications. Adjustment and testing is necessary before the installation is turned over to the operators. Proper training and supervision of the operating personnel, plus maintenance and inspection, are requisites to successful continued operation.

Incinerators require careful operation, periodic cleaning, and maintenance. Continued firm supervision is usually necessary to prevent development of improper operating procedures.

Section 7

POLLUTANT CALCULATIONS AND CORRECTIONS

Expression of Pollutant Concentration and Emission

I EXPRESSION OF PARTICULATE POLLUTANT CONCENTRATION AND EMISSION

A Particulate Pollutant Concentration

1 General expressions

a Pounds per thousand pounds (#/1000#)

A particulate pollutant concentration may be expressed as pounds of pollutant per one thousand pounds of gas-mixture according to the following definition:

$$\#/1000\# = \frac{(10)^3 \text{ (pounds of particulate pollutant)}}{\text{(pounds of gas-mixture)}} \qquad (1)$$

b Weight per cubic foot

A particulate poliutant concentration may be expressed as a weight of pollutant per cubic foot of gas-mixture according to the following definition (the weight units commonly used are pounds or grains):

$$\text{(Weight/ft}^3\text{ at a specified T and P)} = \frac{\text{(Weight of particulate pollutant)}}{\text{(Cubic feet of a gas-mixture at a specified T and P)}} \qquad (2)$$

2 Expressions for effluents from coal combustion

The weight of dry effluent gas per unit weight of coal is given by:[6]

$$\frac{\left[11\ CO_2 + 8\ O_2 + 7\ (CO + N_2)\right]}{3\ (CO_2 + CO)} \qquad (3)$$

where proportion by volume (not %) is substituted for the appropriate chemical symbols.

With no excess air and complete combustion, coal, when burned, theoretically yields 18.5% CO_2, 0.0% O_2, and 81.5% N_2. When 50% excess air is used and there is complete combustion, experiment shows an effluent of 12.25% CO_2, 6.75% O_2, and 81% N_2. The latter data when substituted in equation (3) provides 20.6, the constant appearing in the following equations.

Equations (4) through (7) that follow, are related to effluents from coal furnaces only:

$$\text{(Weight/ft}^3\text{ at a specified T and P and 12\% } CO_2\text{)} = \frac{\text{(Weight of particulate pollutant)}}{\left\{\text{Cubic feet of a gas-mixture at a specified T and P}\right\}} \frac{(12)}{\left\{\begin{matrix}\%\text{ of } CO_2 \text{ by} \\ \text{volume on a} \\ \text{wet basis*}\end{matrix}\right\}} \qquad (4)$$

$$\text{(Weight/ft}^3\text{ at a specified T and P and 50\% excess air)} = \frac{\text{(Weight of particulate pollutant)}}{\left\{\text{Cubic feet of a gas-mixture at a specified T and P}\right\}} \frac{\left\{\begin{matrix}\text{Weight of dry effluent} \\ \text{gas per unit weight of} \\ \text{coal. See equation} \\ \text{(3) above.}\end{matrix}\right\}}{(20.6)} \qquad (5)$$

$$B_{s(wet)} = B_{s(dry)} \left[1 - B_w\right]$$

$$\left(\begin{array}{l}\#/1000\# \text{ referred} \\ \text{to } 12\%\ CO_2\end{array}\right) = \frac{(10)^3 \text{ (pounds of particulate pollutant) (12)}}{\text{(pounds of gas-mixture)} \left\{\begin{array}{l}\%\text{ of } CO_2 \text{ by volume} \\ \text{on a wet basis*}\end{array}\right.} \quad (6)$$

$$\left(\begin{array}{l}\#/1000\# \text{ re-} \\ \text{ferred to 50\%} \\ \text{excess air}\end{array}\right) = \frac{(10)^3 \text{(pounds of particulate pollutant)} \left\{\begin{array}{l}\text{Weight of dry effluent} \\ \text{gas per unit weight} \\ \text{of coal. See equation} \\ \text{(3) above.}\end{array}\right.}{\text{(pounds of gas-mixture)} \quad (20.6)} \quad (7)$$

B Particulate Pollutant Emission

1 Mass rate

A mass rate of emission of a particulate pollutant is expressed according to the following definition. Units are commonly grams per second (gm/sec).

$$\text{Mass Rate} = \frac{\text{(Mass of particulate pollutant emitted)}}{\text{(Time)}} \quad (8)$$

2 Weight rate

A weight rate of emission of a particulate pollutant is expressed according to the following definition. Units are commonly pounds per hour (#/hr).

$$\text{Weight Rate} = \frac{\text{(Weight of particulate emitted)}}{\text{(Time)}} \quad (9)$$

II EXPRESSION OF GASEOUS POLLUTANT CONCENTRATION AND EMISSION

A Gaseous Pollutant Concentration

1 Parts by volume

a Parts per million (ppm)

A gaseous pollutant concentration is expressed as parts per million by volume according to equation (10) that follows:

$$\text{ppm} = \frac{(10)^6 \text{ (volume of gaseous pollutant at a given T and P)}}{\text{(Volume of a gas-mixture at the same T and P to which the gaseous pollutant is referred in the numerator)}} \quad (10)$$

b Parts per hundred million (pphm)

A gaseous pollutant concentration is expressed as parts per hundred million according to the following definition:

$$\text{pphm} = \frac{(10)^8 \text{ (volume of gaseous pollutant at a given T and P)}}{\text{(Volume of a gas-mixture at the same T and P to which the gaseous pollutant is referred in the numerator)}} \quad (11)$$

c Parts per billion (ppb)

A gaseous pollutant concentration is expressed as parts per billion according to the following definition:

$$\text{ppb} = \frac{(10)^9 \text{(volume of gaseous pollutant at a given T and P)}}{\text{(Volume of a gas-mixture at the same T and P to which the gaseous pollutant is referred in the numerator)}} \quad (12)$$

2 Percent by volume (%)

A gaseous pollutant concentration is expressed as percent by volume according to the following definition. Such an expression is equivalent to parts per hundred by volume.

*Same as page #1 asterisk

$$(\%) = \frac{(10)^2 \text{(volume of gaseous pollutant at a given T and P)}}{\text{(Volume of a gas-mixture at the same T and P to which the gaseous pollutant is referred in the numerator)}} \quad (13)$$

3 Pounds per thousand pounds (#/1000#)

A gaseous pollutant concentration may be expressed as pounds of pollutant per one thousand pounds of gas-mixture according to the following definition:

$$(\#/1000\#) = \frac{(10)^3 \text{(pounds of gaseous pollutant)}}{\text{(pounds of a gas-mixture)}} \quad (14)$$

4 Grains per cubic foot (gr/ft^3)

A gaseous pollutant concentration may be expressed as grains of pollutant per cubic foot of gas-mixture according to the following definition:

$$(gr/ft^3) = \frac{\text{(Grains of gaseous pollutant)}}{\text{(Cubic feet of a gas-mixture at a specified T and P)}} \quad (15)$$

5 Micrograms per cubic meter ($\mu g/M^3$)

A gaseous pollutant concentration may be expressed as micrograms of pollutant per cubic meter of gas-mixture according to the following definition:

$$(\mu g/M^3) = \frac{\text{(Micrograms of gaseous pollutant)}}{\text{(Cubic meters of a gas-mixture at a specified T and P)}} \quad (16)$$

B Gaseous Pollutant Emission

1 Mass rate

A mass rate of emission of a gaseous pollutant is expressed according to the following definition. Units are commonly grams per second (gm/sec)

$$\text{Mass Rate} = \frac{\text{(Mass of gaseous pollutant emitted)}}{\text{(Time)}} \quad (17)$$

2 Weight rate

A weight rate of emission of a gaseous pollutant is expressed according to the following definition. Units are commonly pounds per hour (#/hr).

$$\text{Weight Rate} = \frac{\text{(Weight of gaseous pollutant emitted)}}{\text{(Time)}} \quad (18)$$

3 Volume rate

Volume rate of emission of a gaseous pollutant is expressed according to the following definition.

$$\text{Volume Rate} = \frac{\text{(Volume of gaseous pollutant at a specified T and P)}}{\text{(Time)}} \quad (19)$$

REFERENCES

1 Mark, L.S. Mechanical Engineers' Handbook, McGraw-Hill Book Co., Inc. New York. 1951.

2 Smithsonian Meteorological Tables, Sixth Edition, Washington, D.C. 1951.

3 Tables of Thermal Properties of Gases, Circular 564. National Bureau of Standards. 1955.

4 Vennard, J.K. Elementary Fluid Mechanics, John Wiley and Sons, Inc. New York. 1947.

5 Perry, J.H. Chemical Engineers' Handbook, McGraw-Hill Book Co., Inc. New York. 1960.

6 Jacobs, M.B. The Chemical Analysis of Air Pollutants, Interscience Publishers. New York. 1960.

Section 8

AIR POLLUTANT EMISSIONS FROM COMBUSTION

Air Pollutant Emissions from Selected Heat
General and Incineration Sources

AIR POLLUTANT EMISSIONS FROM SELECTED HEAT GENERATION AND INCINERATION SOURCES

Darryl J. von Lehmden*

I INTRODUCTION

Emission rates for various types of air pollutants from heat generation and incineration sources have been published in the literature.

The results from one such study[1] are summarized in the Tables 1 through 7. Although the results are unique to the combustion sources tested, they do permit relative comparisons of emission rates from the burning of various fuels (i.e., coal vs. fuel oil vs. natural gas). The results also permit relative comparisons of air pollutant emission rates based on the combustion source size (i.e., commercial vs. municipal incinerators; domestic home heating vs. industrial process heating).

The emissions measured in the study and shown in the Tables include: polynuclear hydrocarbons, carbon monoxide, carbon dioxide, formaldehyde, gross hydrocarbons, sulfur oxides, nitrogen oxides and total particulates.

II SUMMARY OF RESULTS

The results from the heat generation sources tested are summarized in Tables 1, 2 and 3. The results from the incineration and open-burning sources tested are summarized in Tables 4, 5, 6 and 7.

REFERENCE

1 Hangebrauck, P. R., von Lehmden, D. J., and Mecker, J. E. Hydrocarbon and Other Pollutants from Heat Generation and Incinerator Processes. JAPCA, Vol. 14, No. 7, pp 267-278. July 1964.

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Table 1. DESIGN AND OPERATIONAL SUMMARY - HEAT GENERATION SOURCES

Source No.	Design Data: Fuel Used	Firing Method	Type of Unit	Utilisation	Rated Capacity per hr: 10^3 Lb Steam	Rated Capacity per hr: Million Btu[a]	Dust Collector	Fuel Data as-received basis: Volatile, %	Ash, %	S, %	Operating Conditions During Test: Fuel Rate, Lbs	Gross Btu Input Per Hr, Million Btu	Steam Rate Per Hr, 10^3 Lb	Steam Pressure Psig	Smoke, Opacity, %
1	Coal	Pulverized (dry bottom furnaces)	Water-tube boiler	Electric generation	1060		Mechanical electrical	31	20.2	2.3	132,000	1560	1120	2000	30–40
2				Process heating	200		Multiple cyclone	36	4.3	0.9	9,420	130	106	307	60
3		Chain grate stoker	Water-tube boiler	Electric generation	125		None	44	7.0	3.8	12,400	147	111	450	20–40
4		Spreader stoker (with reinjector)		Process heating	70.5		Multiple cyclone	37	4.7	0.8	4,290	59.2	49	160	0–20
5		Underfeed stokers	Fire-tube boiler	Process heating		7.2	None	36	4.7	0.7	317	4.4		110	20–40
6				School heating		3.8		19	5	0.8	214	3.0		37	0–20
7			Cast-iron sectional boiler	Home heating		0.26		38	3.9	1.0	4.8	0.066		9	0–20
8		Hand-stoked	Hot-air furnace	Home heating		0.20		38	2.7	0.5	8	0.115			40–80
9	Oil	Steam-atomized	Water-tube boiler	Process heating	22	23	None	No. 2 Fuel Oil (28.5° API)		3.2	1,110	21	17.9	250	5
10					30	30		No. 6 Fuel Oil (13.5° API)		0.7	769	14.4	10.3	125	5
11		Low-pressure air-atomized	Scotch-marine boiler	Hospital heating		4.2		No. 1 Fuel Oil (43.5° API)			35	0.70		95	0
12		Centrifugal-atomized	Cast-iron sectional boiler	Home heating		0.25		No. 2 Fuel Oil (31.5° API)			8.8	0.17			0
13			Hot-air furnace			0.14		No. 2 Fuel Oil (31.5° API)			4.4	0.085			0
14		Vaporized	Hot-air furnace	Home heating		0.09		No. 1 Fuel Oil (43° API)		0.05	1.2	0.025			0
15	Gas	Premix burners	Fire-tube boiler	Process heating		7.2	None	Natural gas (94.2% methane 3.6% ethane)			402	9.3		108	0
16			Scotch-marine boiler	Hospital heating		4.2					42	0.98		96	0–20
17			Double-shell boiler	Home heating		0.18					7.9	0.18			0
18			Hot air furnace			0.21					7.4	0.17			0
19			Wall space heater			0.025					0.52	0.012			0

[a] Gross heat input.

Table 2. POLLUTANT EMISSION SUMMARY - HEAT GENERATION SOURCES

Source No.	Fuel Used	Firing Method	Flue Gas Conditions in Stack: Flow, scfm	Temp. °F	H_2O, %	Dry Basis: CO_2, %	Dry Basis: O_2, %	Total Particulates: 1000 Lb[b]	Total Particulates: Lb Per Million Btu	Total Particulates: Ton of fuel[c]	% Benzene-Soluble Organics	Carbon Monoxide: Lb Per Million Btu	Carbon Monoxide: Ton of fuel[c]	Hydrocarbons (as Methane): Lb Per Million Btu	Hydrocarbons (as Methane): Ton of fuel[c]	Oxides of Nitrogen (as NO_2): Lb Per Million Btu	Oxides of Nitrogen (as NO_2): Ton of fuel[c]	Oxides of Sulfur (as SO_2): Ppm by Vol.	Oxides of Sulfur (as SO_2): Lb Per Million Btu	Oxides of Sulfur (as SO_2): Ton of fuel[c]	Formaldehyde: Lb Per Million Btu	Formaldehyde: Ton of fuel[c]
1	Coal	Pulverized	415,000	260	5.4	12.3	6.9	0.50	0.59	14.0	0.7	0.004	0.1	0.007	0.16	0.47	11	1490	3.72	88	1.3×10^{-4}	30×10^{-4}
2			32,300	235	6.2	12.3	6.1	1.90	2.23	61.6	0.3	0.10	2.5	0.004	0.11			405	1.00	28	0.9×10^{-4}	28×10^{-4}
3		Chain grate stoker	45,000	430	6.7	12.1	7.7	0.99	1.31	31.0	0.3	0.51	12	0.005	0.11			2030	6.14	146	1.4×10^{-4}	33×10^{-4}
4		Spreader stoker	18,100	405	6.9	10.6	8.5	0.66	0.82	22.6	1.4	<0.1	<3	0.006	0.16						2.2×10^{-4}	60×10^{-4}
5		Underfeed stokers	3,340	380	2.1	3.0	17.2	0.68	0.62	17.0	1.1	0.16	4.5	0.116	3.2						21×10^{-4}	590×10^{-4}
6			3,290	235	2.1	2.5	18.1	0.24	0.25	7.0	3.6	0.14	3.9	0.036	1.0	0.30	8.3	205	2.3	62	3.8×10^{-4}	100×10^{-4}
7			43	345	2.2	2.6	17.1	0.52	0.44	12	1.2	1.1	31	0.12	3.3	0.36	9.8	178	1.2	32		
8		Hand-stoked	78	220	2.1	2.8	17.7	1.80	1.29	37	17	3.5	99	0.73	21	0.11	3.2	80	0.54	15		
												<0.1	<4	0.013	0.51			1250	3.0	116	0.63×10^{-4}	24×10^{-4}
9	Oil	Steam-atomized	5,200	530	8.5	9.0	8.2	0.32	0.306	11.7	1.0											
10			10,000	340	5.4				0.267	10.0	2.7	0.055	2.2	0.004	0.17	0.31	12	188	1.3	48	2.4×10^{-4}	89×10^{-4}
11		Low-pressure air-atomized	195	230	7.4	8.8	9.0	0.049	0.051	2.0	60							125	0.35	14	1.6×10^{-4}	62×10^{-4}
12		Centrifugal-atomized	145	170	3.0	2.9	16.9	0.041	0.046	1.8	39	0.038	1.5			0.44	17	14	0.12	4.8		
13			115	175	2.6	1.8	18.3	0.070	0.080	3.1	9.4	0.075	2.9	0.021	0.82			35	0.48	18	6.4×10^{-4}	250×10^{-4}
14		Vaporized	49	185	1.9	1.2	19.3	0.067	0.071	2.8	11	0.25	9.8	0.030	1.2	0.03	1.3	4	0.08	3	5.8×10^{-4}	230×10^{-4}
15	Gas	Premix burners	3,640	380	8.4	3.6	14.3	0.026	0.021	1.0	11	0.013	0.6	0.003	0.14	0.14	6.4				0.89×10^{-4}	41×10^{-4}
16			325	210	11.4	5.9	10.0	0.030	0.032	1.5	8.0	3.00	140	0.082	3.8	0.16	7.3				2.2×10^{-4}	100×10^{-4}
17			92	170	4.8	2.4	16.9	0.010	0.006	0.3	33	0.02	0.9			0.35	16	0	0	0	2.4×10^{-4}	110×10^{-4}
18			82	140	4.1	2.2	17.3	0.011	0.007	0.3	23	0.026	1.2	0.022	1.0	0.09	4.1	0	0	0	1.1×10^{-4}	53×10^{-4}
19			11	295	4.4	2.0	17.5	0.027	0.026	1.2	19	0.030	1.4	0.016	0.74	0.06	2.8				26×10^{-4}	1200×10^{-4}

[a] Blanks in the table indicate that no test was made.
[b] Pounds of particulate per 1000 pounds of dry flue gas adjusted to 50% excess air.
[c] API gravities of the fuel oils are given in Table 1; the density of natural gas = 0.0443 lb per cu ft (60°F, 1 atm).

Table 3. POLYNUCLEAR HYDROCARBON EMISSION SUMMARY - HEAT GENERATION SOURCES

Source No.	Fuel Used	Firing Method	Group 1: Benzo(a)pyrene[a] µgm per 1000 M^3[b]	Group 1: Benzo(a)pyrene[a] µgm per Lb Fuel	Group 1: Pyrene	Group 1: Benzo(e)-pyrene	Group 1: Perylene	Group 1: Benzo(g,h,i)-perylene	Group 1: Anthanthrene	Group 1: Cornene	Group 2: Anthracene	Group 2: Phenanthrene	Group 2: Fluoranthene	Group 2: Benz-(a)-anthracene
			Micrograms Per Million Btu Heat Input											
1	Coal	Pulverized	42	0.22	19	150							180	19
2			75	0.43	32	240	92				370		550	
3		Chain grate stoker	71	0.44	37	390	130						680	
4		Spreader stoker	49	0.35	26	590	350			26			360	
5		Underfeed stokers	7,900	140	10,000	16,000	7,900	1,600	4,500	290	330	850	10,000	38,000	3900
6			61	1.6	120	1,700	230						1,000	3,200	
7			3,400	52	3,800	7,700	5,400		580		1,200		29,000	47,000	560
8		Hand-stoked	340,000	6000	400,000	600,000	100,000	60,000	300,000	90,000	30,000	400,000	1,000,000	1,000,000	
9	Oil	Steam-atomized	<38	<0.3	<20	49								56	
10			40	0.89	47	300							1,800	270	27
11		Low-pressure air-atomized	1,900	18	900	6,100			300		2,100	3,900	3,500	1,900	
12		Centrifugal-atomized	<26	<0.9	<40	1,800							8,900	5,000	
13			<27	<1	<60	15								76	
14		Vaporized	<34	<2	<100	1,200								15,000	
15	Gas	Premix burners	<20	<0.4	<20	160				14				100	
16			350	1.6	200	18,000	490		1,800	200	5,300			2,900	
17			<23	<0.5	<20	170								320	
18			<30	<0.6	<20	120	18						77	110	

[a] "Less than" values for benzo(a)pyrene were calculated for those samples having concentrations below the limit of quantitative determination (approximately 0.6 microgram per sample). Similar calculations were not included for the other polynuclear hydrocarbons (indicated by blanks in the table).
[b] Micrograms per 1000 cubic meters of flue gas at standard conditions (70°F, 1 atmosphere).

Table 4. DESIGN AND OPERATIONAL SUMMARY, INCINERATION AND OPEN-BURNING SOURCES

Source No.	Type of Unit	Design: Rated Capacity, Tons/Day	Design: Grate Area, Ft²	Design: Dust Collector	Fuel: Type	Fuel: Moisture Content, %	Operating Conditions During Test: Charging Rate Tons/Day	Underfire Air, %	Excess Air, %	Gas Temp., °F	Smoke, % Opacity
	Municipal Incinerators										
20	Multiple chamber, traveling grate (continuous feed)	250	288	Settling chamber	Residential refuse (14 to 20% noncombustible)	35	260	80	185[c]	1910[b]	20
21	Multiple chamber, batch charged, reciprocating stoker grates	50	85.5	Water spray scrubber	Residential and commercial refuse (14 to 20% noncombustible)	25	49	50-60	108[c]	1470[c]	
	Commercial incinerators										
22	Single chamber	5.3	13	None	Cardboard, packing crates	20	4.7	0	465[c]	1300[b]	0-20
23	Multiple chamber with auxiliary gas burner in primary chamber	3	19.7	None	60% paper 40% wet garbage	50	2.3			1850[b]	0-50
24	Open Burning				Municipal refuse	20					20-100
25					Automobile tires						20-100
26					Glass clippings, leaves, tree branches						20-100
27					Automobile bodies						20-100

[a] In breeching.
[b] In furnace.
[c] In stack.

Table 5. POLLUTANT EMISSION SUMMARY - INCINERATION SOURCES[a]

Source No.	Type of Unit	Sampling Point	Flue-Gas Conditions: Flow scfm	Temp. °F	H_2O %	CO_2 Dry Basis %	O_2 Dry Basis %	Total Particulates: Lbs Per 1000 Lb[b]	Lbs Per Ton of Refuse	% Benzene Soluble Organics	Carbon Monoxide	Hydrocarbons (as methane)	Oxides of Nitrogen (as NO_2)	Formaldehyde
	Municipal											Lbs Per Ton of Refuse		
20	250-Ton/Day Multiple chamber	Breeching (before settling chamber)	52,000	1270	8.8	6.2	13.7	2.1	18[c]	0.32	0.67	<1[d]	2.5	0.0014
21	50-Ton/Day Multiple chamber	Breeching (before scrubber)	5,400	1470	9.1	8.7	11.0	1.0	8.1	0.15	4	<0.08	2.4	0
		Stack (after scrubber)	12,700	420	12.4	3.7	16.7	0.34	2.6	0.96	<2		2.8	0
	Commercial													
22	5.3-Ton/Day Single chamber	Stack	1,075	1090	9.5	3.5	17.2	0.66	4.1	1.3	4.3	0.45	1.6	0.016
23	3-Ton/Day Multiple chamber	Stack	580	670	9.3	3.3	16.4	0.96	6.6	4.4	25	3.6		

[a] Blanks in the table indicate that no test was made. [b] Pounds particulate per 1000 pounds dry flue gas adjusted to 50% excess air. [c] Particulate loading in breeching adjusted to indicate emission from stack. [d] Measured by hexane-sensitized nondispersive infrared analyzer; reported as methane.

Table 6. POLYNUCLEAR HYDROCARBON EMISSION SUMMARY - INCINERATOR SOURCES[a]

Source No.	Type of Unit	Sampling Point	Benzo(a)pyrene µgm per 1000 M3[b]	Group 1: Benzo(a)pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo-(g,h,i)-perylene	Anthan-threne	Coronene	Group 2: Anthra-cene	Phenan-threne	Fluoran-thene	Benz(a)-anthra-cene
				Micrograms Per Lb of Refuse Charged										
	Municipal													
20	250-Ton/Day Multiple chamber	Breeching (before settling chamber)	19	0.075	8.0	0.34				0.24			9.8	0.37
21	50-Ton/Day Multiple chamber	Breeching (before scrubber)	2,700	6.1	52	12		34		15		18	4.6	
		Stack (after scrubber)	17	0.089	2.1	0.58		0.63		0.63			3.3	0.15
	Commercial													
22	5.3-Ton/Day Single chamber	Stack	11,000	53	320	45	3.1	90	6.6	21	47	140	220	4.6
23	3-Ton/Day Multiple chamber	Stack	52,000	260	4200	260	60	870	79	210	86	59	3900	200

[a] A blank in the table for a particular compound indicates it was not detected in the sample.
[b] Micrograms per 1000 cubic meters of flue gas at standard conditions (70°F, 1 atmosphere).

Table 7. POLYNUCLEAR HYDROCARBON CONTENT OF PARTICULATE MATTER EMITTED - INCINERATION AND OPEN-BURNING SOURCES[a]

Source No.	Type of Unit	Sampling Point	Group 1: Benzo(a)-pyrene	Pyrene	Benzo(e)-pyrene	Perylene	Benzo(ghi)-perylene	Anthan-threne	Coronene	Group 2: Anthra-cene	Phenan-threne	Fluoran-thene	Benz(a)-anthracene
			Micrograms Per Gram of Particulate										
	Municipal incinerators												
20	250-Ton/Day Multiple chamber	Breeching (before settling chamber)	0.016	1.9	0.08				0.06			2.2	0.09
21	50-Ton/Day Multiple chamber	Breeching (before scrubber)	3.3	28	6.5		19		8.2		9.8	2.5	
		Stack (after scrubber)	0.15	3.6	0.97		1.1		1.1			5.5	0.26
	Commercial incinerators												
22	5.3-Ton/Day Single chamber	Stack	58	350	49	3.3	98	7.1	23	51	150	240	5.0
23	3-Ton/Day Multiple chamber	Stack	180	2600	180	36	540	45	130	53	62	2400	210
	Open Burning												
24	Municipal refuse	In smoke plumé	11	29	4.5					4.7		13	
25	Automobile tires		1100	1300	450	72	660	53	81	110	450	470	560
26	Grass clippings, leaves, branches		35	120	21		5.4			4.7		110	25
27	Automobile bodies		270	670	120	33	150	12	15	220	160	450	40

[a] A blank in the table for a particular compound indicates it was not detected in the sample.

Section 9

SPECIAL TOPICS

Test Methods for Determining Emission
Characteristics of Incinerators

TEST METHODS FOR DETERMINING EMISSION CHARACTERISTICS OF INCINERATORS

Fred R. Rehm

I BACKGROUND INFORMATION

Many people close to the field of incineration have long appreciated the pressing need for standardized techniques and test methods for determining the air pollution emission characteristics of incinerators. Those who would be greatly concerned and affected by such test standards include incinerator designers, manufacturers and consultants, along with the people working in the field of governmental air pollution control. It is generally conceded that it is one of the functions and responsibilities of this latter group to assess and to evaluate these and other air pollution emissions. It has been stated that not until standardized test methods are adopted and accepted will standardized emission limitations for incinerators be possible and truly meaningful. The incinerator manufacturers have regularly striven for standardized air pollution regulations to aid them in achieving standardized production models of incinerators and lower costs.

When one considers the problem of incinerator air pollution emission charactistics, early attention must be given to defining the type discharges which are of greatest concern. It is this Sub-Committee's conviction that we are principally interested at this time in the following three categories of incinerator effluents - visual emissions (smoke), particulates, and odor. It is in these three areas that the greatest present need exists with respect to air pollution performance evaluation standards or limitations and standardized test methods. With the heterogeneous nature of refuse being incinerated and hence the wide range of gaseous effluents possible - and the increased attention being directed to the health aspects of air pollution, we may some day direct additional attention to these gaseous discharges. However at this stage of the science of air pollution control, we must of necessity direct our principal attention to the nuisance-type discharges that have plagued the development and improvement of this class of combustion equipment. It is toward the standardization of testing of these three classes of incinerator effluents that this report is pointed.

II VISUAL EMISSION TESTING

Almost everyone who has worked with combustion processes and is familiar with the basic requirements of air pollution control ordinances, must of necessity be familiar with the Ringelmann Chart, as published by the U.S. Bureau of Mines, and its use in assessing the visual or smoke emissions from incinerators. From a strictly scientific standpoint, the Ringelmann Chart leaves much to be desired in our efforts to quantitatively assess visual effluents. Nevertheless, its use is practically basic in the field of air pollution control and in the smoke control programs which were the forerunners of the present day expanded air pollution control efforts. Until some better, more practical tool evolves, the Ringelmann Chart will undoubtedly continue to serve as the most frequently used method for assessing visual smoke emissions from incinerators and all other combustion processes. Numerous discussions on the use of the Ringlemann Chart appear in the literature and it is not out intention here to belabor the use of this test method on visual incinerator effluents. In recent years, a refinement has been introduced to the test methods used in the visual field which permits the grading of colored effluents other than shades of black and white as intended by the Ringelmann Chart. Even this improvement or refinement device, which is frequently referred to as the "opacity" of a visual emission, is usually compared with an "equivalent Ringelmann density" as its standard. Opacity assessment is related to the ability "to see through" a column of smoke. Visual black smoke emissions have not generally been a serious problem in refuse incinerator operation. Off-color visual

discharges which could be more readily graded on an opacity basis are the more usual type visual effluents emanating from refuse incinerator operation. Widespread application and enforcement of an opacity limitation by air pollution control agencies on incinerator discharges, undoubtedly, would have a significant effect on future incinerator designs. In recent years, some interest has been shown by a few incinerator investigators in the use of paper tape filters and photoelectric devices to measure smoke or visual effluents. The moving paper tape sampler is said to have a number of advantages in measuring smoke emissions. One obvious advantage of both the moving tape filters and photoelectric devices is the continuous smoke performance record such systems provide. Photoelectric smoke measuring devices have been used quite successfully in combustion processes where oil and coal are burned. This class of smoke measuring device has seen little usage in the incinerator field - the main exception being in new municipal incinerator plants where this type smoke measuring device is often incorporated. The high cost and the lack of portability of this type equipment mitigates against its use as a field measuring tool.

III SURVEY CONDUCTED

In May 1961, the Air Pollution Control Association TA-3 Incinerator Committee took cognizance of the need for a review and study of the test methods which had been, and were being, used by investigators working in the incinerator air pollution field. It was hoped that such a review and study might ultimately lead to a recommended standardized test procedure for certain categories of pollutants. The actual study and review of incinerator test methods was delegated to the Performance Evaluation Sub-Committee of the parent Incinerator Committee. It was agreed that this group would most profitably concentrate its efforts in the particulate and odor emission categories. Accordingly, the Performance Evaluation Sub-Committee queried representatives of various groups or organizations for the names of people or groups who had previously, or were known or suspected to be presently, engaged in the measurement of incinerator particulate and odor emissions. Interest was expressed in all classes and sizes of incinerators ranging from domestic to municipal. Some of the groups contacted were:

Air Pollution Control Departments

American Gas Association

Commercial and Industrial Incinerator Manufacturers

Domestic Incinerator Manufacturers

Incinerator Institute of America

Municipal Incinerator Consultants

Municipal Incinerator Contractors

Research Organizations

U.S. Public Health Service

The result of this survey produced the names of 43 different individuals or groups who were said to have displayed a proficiency in the field of incinerator particulate or odor measurement. Subsequently, a carefully prepared questionnaire was sent to each of the 43 parties querying them on the details of the test methods they used in their incinerator studies and requesting that they comment on the advantages and disadvantages of the test methods they favored. Of the 43 persons and organizations queried, replies were received from 32. Of the 32 replies, only 16 groups indicated that they have had extensive experience and familiarity with incinerator particulate or odor measurement. The results of the second phase of this survey were most revealing in that it was apparent that only a very small number of groups or individuals had first-hand knowledge, familiarity and experience in the incinerator particulate or odor test field. This finding seems very incongruous and disturbing since refuse incineration has been frequently described as being one of the larger contributing sources to a community's air pollution problem.

IV ODOR TESTING

The results of the survey of the Performance Evaluation Sub-Committee have been tabulated and are now under study by this group. A copy of the tabulation is appended to this report. One of the findings this survey disclosed was

that only a limited amount of work has been conducted on odor testing of incinerator effluents with the exception of the domestic incinerator size ranges. In the domestic incinerator field, odor measurement and testing has principally been performed by using the American Gas Association, Inc., and American Standards Association, Inc., open burning newspaper technique.[1] (1) In this method, three observers smell the gases produced by the burning of two sheets of newspaper in an open container. Then, at 15-minute intervals, they enter the incinerator test room from the outside and compare the odor from the gases aspirated from an AGA test stack with that of the two burning sheets of newspaper. It is obvious that this test method suffers from the inconsistencies, differences and subjectivity of the human olfactory mechanism. Modifications of the AGA incinerator odor panel technique have also been described in the literature. All such systems rely on the human nose as the test instrument. The newest and a most promising odor measuring techniqud developed for domestic gas incinerators was recently reported by Battelle Memorial Institute.[2] (2) In this test method, it has been demonstrated that the carbon monoxide (CO) concentration in incinerator emissions may be used as a valid, objective indicator of the odor intensity of domestic gas-fired incinerator effluents when burning an A.S.A. domestic waste charge, including both the olfactory (smell) and trigeminal (pain or irritation) components.

In the commercial, industrial and municipal incinerator field, the few investigators reporting a quantitative concept of odor measurement strongly favored the ASTM Standard Method for Measurement of Odor in Atmospheres (Dilution Method) D 1391-57. In this method, a sample of the gas, whose odor is to be measured, is diluted with odorfree air until a dilution is reached in which an observer can barely perceive the odor. The ratio of the total volume of this diluted sample to the volume of original sample in the diluted sample, is a measure of the concentration of odor in the original sample. This technique assumes that the odor concentration is to be measured without regard to the material or materials that cause the odor, or the concentration of these causants. It also does not take into account the character of an odor. A number of investigators have reported a relationship may exist between the concentration of carbonyls (aldehydes and ketones) in incinerator effluents and odor levels. From the above findings, it would appear that an incinerator odor test method based on the ASTM Standard D 1391-57 may be generally acceptable in other than the domestic gas incinerator field where the Battelle CO method appears to have much merit.

V PARTICULATE TESTING

The greatest amount of incinerator emission test work that has been performed has been done in the particulate emission field. Of the 16 groups supplying detailed information on incinerator particulate or odor testing, 15 reported having conducted tests on particulate emissions, while only 11 reported conducting odor measurements. Of this group reporting on odor measurements, the experience of seven of the 11 respondents was limited to the domestic incinerator field. An analysis of the particulate test methods used by all reporting investigators showed they could be grouped into three general type categories. One test technique can be described as the so-called American Gas Association, Inc. or American Standards Association, Inc. testing scheme which has been used almost exclusively in the performance testing of domestic incinerators not exceeding 4-bushel capacity. This test method is detailed in the American Standard Association, Inc., publication "Approval Requirements for Domestic Gas-Fired Incinerators." The second general test category which has been used involves the low sampling volume technique (less than two cfm); this is a modification of the procedures outlined in the Western Precipitation Corporation Bulletin WP-50, "Methods for Determination of Velocity, Volume, Dust and Mist Content of Gases." The third general type test technique which has been used is the large sample volume method (greater than two cfm); this is a modification of the procedures outlined in the ASME Power Test Codes PTC 27-1957, "Determining Dust Concentration in a Gas Stream" and PTC 21-1941, "Dust Separating Apparatus."

Ideally, it would be preferable to utilize a test method which gave instantaneous readings of dustloadings of effluent gas streams. Unfortunately however, such a method or technique has not been developed as yet. An instantaneous dustloading test device would greatly reduce the effort and vagaries in assessing the effect of the many variables in the incineration of refuse. The variables which have been suspected or reported as affecting the air pollution performance of an incinerator are almost as numerous and varied as is the character of the refuse charged to an incinerator. Through such a test device, it would be possible to rapidly assess the effect of design parameters, air supply and distribution, refuse characteristics and operating procedures. As it is, all of the three test methods presently in use must rely on reporting average dustloading test results. All three of the previously mentioned particulate test methods incorporate the following basic requirements. They vary, however, in the manner in which these basic requirements are achieved.

A Securing a truly representative sample of the gas and suspensoid from the main gas stream.

B Filtering of the particulates from the sampled gas stream.

C Accurately measuring the sampled gas volume.

D Making such other measurements as are necessary to assess the total emission characteristics. These include temperature, pressure, gas velocity, gas composition, molecular weight and density.

Analyzing each of these four basic requirements in terms of the three general particulate test methods reported as being used, it was discovered that the main divergence of method and technique occurs in the securing of a truly representative gas and particulate sample. The problem of securing a representative gas and suspensoid sample would be eliminated if it were practical to use the total gas flow as the sample stream. This is not a practical approach due to instrument size and portability requirements. Failing to secure a truly representative effluent sample by any of the three methods reported as being used will yield meaingless results no matter how refined and accurate are the mechanics and techniques of determining the other three basic test requirements.

The very nature of the AGA, Inc., and ASA, Inc., test facility and test method leaves it wanting for consideration as a standardized test method for all size ranges of incinerators. This test technique was designed to evaluate the air pollution performance of highly defined and confined conditions of design, construction, refuse materials and conditions of operation. This test method provides for a standardized test stack arrangement, a fixed gas sampling rate, fixed position sampling in the small test stack, standardized refuse charge compositions and specific operating cycles. For the express purpose for which it was developed, this test method appears to be well conceived. This type test method, however, does not lend itself well to widespread usage in the commercial, industrial and municipal incinerator field due to the physical size of these classes of incinerators, the great number of "on-the-spot" constructed incinerator installations, the lack of standardization of designs caused by the widely varying needs and requirements for these classes of incinerators, the wide range of composition of refuse normally handled by incinerators of these classes and the wide range of operating procedures practiced in field installations. A standardized test facility and test method of this same general type could well serve the needs of an incinerator manufacturer to evaluate the effect on air pollution performance of developmental changes and modifications on some of the smaller commercial-sized incinerators. It is our understanding that the American Gas Association has under consideration the development of a standardized test facility, test methods and approval requirements for small commercial-sized refuse incinerators. In setting up such a standardized test facility and test methods, special consideration should be given to representative effluent sampling for particulates when dealing with these larger sized incinerators where stratification problems are likely to occur in a field installation due to widely varying design, refuse and operating conditions.

The use of adhesive coated paper for the estimation of particulate incinerator emissions has been reported within the past year. At least one community has established an ordinance emission limitation based upon the utilization of the adhesive coated paper estimating procedure.

1 Representative sampling

The remainder of this report will be limited to a discussion and analysis of the modified dustloading test methods outlined in the ASME Test Codes and the WP-50 Bulletin which were reported as being used by various incinerator investigators. It is apparent that the WP-50 Bulletin test method describes the use of field test equipment which has a maximum sampling rate of approximately two cfm. Whereas the ASME Test Codes do not favor or promote the use of any particular type test apparatus, they were obviously written or directed toward power plant testing. Due to the widely varying particle size and chemical composition of incinerator particulates, special emphasis must be placed on the problem of securing representative gas and suspensoid samples in incinerator testing. As long as most air pollution dustloading limitations are directed at the "nuisance producing potential" of the effluents rather than on health effects - or other aspects, it must be possible to assess such potential in any test method that is proposed as a standard. This requires the sampling of the large sized incinerator char particles which are a most frequent cause of incinerator particulate complaint, as well as the smaller sized particulates. It has been suggested that sampling nozzles should be a minimum of 3/4 inch inside diameter in order to capture and sample most incinerator char and flake material. The larger the size of the sampling nozzle used, the less the likelihood of biasing against the larger sized particulates. Work conducted by Armour Research Foundation[3] at the Chicago Calumet Incinerator has substantiated and corroborated this biasing effect in the use of small sized nozzles for sampling incinerator particulates. With conventional design incinerator breeching and stack velocities now being used, a minimum sampling nozzle diameter limitation of 3/4 inch would also preclude the use of the low volume sampling train and equipment described in the WP-50 Bulletin, if isokinetic sampling is to be achieved. Limiting factors affecting the size of the sampling nozzle to be used will be the availability of an adequate suction or aspirating device to "isokinetically" sample at the nozzle opening, the pressure drop across the sampling train and the size and portability of the sampling apparatus. Incinerator breeching and stack velocities can range from 15 feet per second to 90 feet per second.

The matter of "isokinetic" sampling is a particularly acute problem in incinerator test work, principally due to the method and type charging procedures used and the variable nature of the refuse being burned. Both of these factors have a significant effect on the temperature and velocity characteristics of an incinerator system. Even with the new continuous feed municipal incinerators, the variable nature of the refuse causes rapid gas temperature and velocity changes in the system. Another recent innovation affecting municipal incinerator system velocities has been the use of variable speed induced draft fans. Such fans have been used to compensate for rapidly changing refuse characteristics and to help maintain steady state draft conditions. This type draft-producing system further complicates the problem of isokinetic sampling. It has been a generally accepted fact that invalid dustloading test results are obtained when true isokinetic sampling is not realized. Non-isokinetic sampling results in the securing of non-representative gas and dust samples. Due to the rapid and frequent velocity changes in an incinerator system, some investigators have

found it a practical necessity to use the null "static balanced tube" method of testing to secure representative samples. In this type sampling, the velocity of the gases entering the sample nozzle is continually adjusted to equal the velocity in the duct or stack at the sampling location. In the alternative sampling method, velocity head and temperature changes at the sampling point are translated to changes in the gas sampling rate. Considerable time is lost and needless error is introduced in the period it takes to mathematically and actually translate these system changes to the physical sampling system. Significant sampling errors are likewise introduced in incinerator testing when one uses a fixed gas sampling rate based on a velocity determination that was made a matter of 15 minutes to 60 minutes before the dustloading test period. Such procedure ignores the dynamic nature of the incineration process.

Sampling location is an important consideration in any particulate testing. It is even more important in incinerator testing where sizeable percentages of the particulates are above 44 microns in particle size. Both the ASME Test codes and the WP-50 Bulletin recommend sampling in vertical flow ducts. In incinerator installations, this usually means the stack. Sampling at such a location reduces the possibility for error introduced by dust and gas stratification. There is practically no substitute for experience in selecting a suitable sampling location. Some incinerators provide relative freedom from stratification in three to five stack diameters above the top of the breeching saddle where other incinerators have required five to 10 stack diameters to produce the same results. Horizontal ducts and breechings of incinerators are particularly prone to dust stratification problems. Accessibility and room for freedom of movement at a sampling location are important considerations in the placement of test openings.

Even with wise and proper selection of the sampling location, it has been found important that ample and adequate traversing of the stack or duct be performed. Both the ASME Test Codes and the WP-50 Bulletin agree that adequate traversing of the stack in dustloading and velocity tests is necessary. The Sub-Committee, wholeheartedly, concurs with this recommendation. The suggested minimum number of sample points outlined in the ASME Test Codes for various cross-sectional areas appears to be satisfactory. The need for additional sampling points in traverse of a stack or duct for any particular test is a determination that is best made on the basis of each individual situation.

Due to the relatively high temperatures in an incinerator system, it is almost mandatory that water-jacketed stainless steel probes be used for dustloading test work. Water jacketing of the probe serves a number of purposes. It preserves the sampling probe and thus reduces the errors caused by the corrosiveness of the sampled gases. It cools and reduces the combustion losses of the sampled particulates as many of these particles are aglow when sampled. It permits the use of lower temperature range filtration media. In-stack filtration of the sampled particulates is not recommended for incinerator test work due to the combustion losses suffered as a result of the high stack temperatures. Even water-cooling of the filtration media holder often fails to arrest combustion losses of the sampled particulates when in-stack filtration is used.

2 Filtration media

The principal area of difference between the ASME Test Codes and the WP-50 Bulletin with respect to filtration media results from the basic difference between a high and low volume sampling rate test method. Both recommended that high particulate filtration efficiencies be achieved. Both techniques agree that

pressure drop across the filtration media is an important limitation in sizing the sampling train. Both methods suggest a high catch to weight ratio for the filtering media. A problem peculiar to incinerator sampling is the relatively low concentration of particulates encountered and the high percentage of water vapor present in incinerator emissions. The combination of these two conditions, along with others, makes the selection of the filtration system and filtration media a difficult one. The necessarily high gas volume sampling rate, the relatively low dust concentration, the high moisture content of the gases, the need for high separation efficiency at relatively low pressure drop, the weight stability of the filtration media, the ruggedness requirement for field usage, the high gas temperatures and a test system portability requirement are a number of considerations that go into the selection of the filtration device and filtration media. It is most difficult to find a filtration device and media providing optimum characteristics in lieu of all these considerations. It is often necessary to compromise on one or more of these considerations in selecting the system and media. If undue emphasis is placed on the high sample catch to filter weight ratio requirement for the filtration media, the length of a dust test run would be unreasonably extended in view of the relatively low dust concentrations. A medium which is light in weight and needing most of the other criteria suffers from lack of ruggedness for use under trying field conditions. The high water vapor content of incinerator gases also present serious problems for the lighter weight filtration media. Heat jacketing of the filtration media holder has been suggested as a means to minimize filter condensation problems. Temperature limitations of various filter media has been adequately treated in the ASME Test Codes. It has been suggested that a dual filtration system, consisting of a small diameter cyclone followed by a fabric filter, is a satisfactory compromise arrangement. The cyclone tends to precipitate the larger sized particulates from the sampled gas stream as well as serving as an entrainment separator for any condensed or entrained moisture. This permits use of the filter media without undue presure buildup due to condensation. This arrangement is particularly suitable for evaluating wet scrubber dust collector systems which have found widespread application in the municipal incinerator field. This type arrangement requires considerable filtration media weighing technique to minimize errors caused by the hygroscopic tendencies of a fabric filter.

3 Measuring sampled gas volume

The principal differences between the ASME Test Codes and the WP-50 Bulletin techniques with regard to measuring the sampled gas volume also revolves about the discrepancy in sampling rates for each method. Emphasis seems to be placed in the ASME Test Codes in the use of orifice-type gas metering devices. The WP-50 Bulletin, in contrast, seems to encourage the use of dry gas meters. Either method is satisfactory if proper precautions are taken to insure the accuracy of the equipment used. At the high gas sampling rates associated with the larger sized sampling nozzles needed to secure a representative sample in incinerator testing, the required size of a dry gas meter would be cumbersome, and may be unmanageable in a field test. The WP-50 Bulletin treats the matter of measuring the high moisture content of incinerator gases in a more thorough manner than does the ASME Test Codes. The measurement of the water vapor content of incinerator gases is especially important when any special type dust collection system has been provided. The need for water vapor measurement applies especially to incinerators that use wet scrubber or mechanical centrifugal dust collector systems. Water spray systems are often used in mechanical collector installations to cool

the incinerator effluent gases to within the temperature limitations of the dust collector and the induced draft fan.

4 Supplementary measurements

Neither of the test methods that have been discussed adequately treat the problem of making supplementary measurements needed to complete a dust-loading determination in light of the presently used methods of expressing the results of such tests in terms of excess air or carbon dioxide adjustment or correction. Most dustloading limitations that are being enforced by air pollution control agencies these days include provision for some such correction. Some investigators have suggested that any correction or adjustment of test results be limited to an excess air basis reported in terms of the oxygen content of the effluent gases. It is not the Sub-Committee's intention to argue for or against the merits of the presently used practices of adjusting and reporting test results at this time. It has been our experience that a well-designed, engineered, constructed and operated incinerator is capable of performance within the requirements of most of these stringent limitations embodying either a 12% CO_2 or 50% excess air correction, if effective provisions are incorporated in the unit to reduce particulate loadings. Any test method for measuring particulates in incinerators must take cognizance of the rapidly changing gas analyses and excess air conditions encountered in the incineration process, particularly with presently used incinerator designs and operating practices. These wide variations in gas analyses and excess air conditions exist in the newer continuous feed incinerator plants, as well as in the batch charge type units. Because of these rapidly varying analyses, it is necessary to use continuous gas analyzing equipment to measure these dynamic conditions. It has been reported that either, or both, continuous carbon dioxide analysis or continuous oxygen analysis equipment is desirable to accurately assess and measure these variations. The continuous gas sampling equipment should be backed up by regular Orsat gas analyses. The Orsat analyses check the proper functioning of the continuous gas analyzers as well as providing data for gas molecular weight and density calculations. Some investigators have collected integrated gas samples over either a salt or acidified sodium sulfate solution for the full period of a test run and then have conducted Orsat analyses of these composite samples. The detailed information gained by the continuous gas analyzers may well be worth the extra cost and inconvenience of using this additional equipment. By taking frequent readings of the continuous gas analyzers, the need for a continuous recorder is minimized. Recording equipment is not readily portable and is often not sufficiently rugged to withstand the rough treatment and conditions encountered in field testing. Recording equipment also adds appreciably to the cost of making a test determination.

It was the feeling of many of the investigators that it would be impractical and meaningless to try to standardize on refuse charges and charge cycles for commercial, industrial and municipal incinerators as part of an overall standardized test method for determining emission characteristics. We are all cognizant that incinerator refuse material is completely heterogeneous and that it varies from charge to charge, day to day and from city to city. Recommended operating practices and procedures will also vary widely from one design unit to another making a standardized charge cycle a synthetic practice that has little significance. Any standardization in the test method from a refuse and refuse charge standpoint might well be limited to testing the emissions under rated capacity and in accordance with the recommended conditions and procedures of the incinerator manufacturer. Some investigators have suggested that performance tests be principally conducted during the period of stable operation of the incinerator. These conditions and

operating procedures could then be detailed in the test report.

In summary it is the Performance Evaluation Sub-Committee's opinion that the ASME Test Codes PTC 21-1941, "Dust Separating Apparatus" and PTC 27-1957, "Determining Dust Concentration in a Gas Stream," with modifications and additions as discussed, could form the basis of an acceptable standardized test method for determining incinerator particulate emission characteristics.

a "Approval Requirements for Domestic Gas-Fired Incinerators" Z 21.6-1957 American Standards Association, Inc.

b "Development of an Odor-Measurement Technique for Domestic Gas Incinerators" - Battelle Memorial Institute Project DAG-4-M.

c "Sampling Studies on Emissions from Municipal Incinerators" - Armour Research Foundation Project C832.

Summary of Survey on Incinerator Particulate and Odor Testing by Performance Evaluation Sub-Committee of APCA Incinerator Committee TA-3

In the following summary, an abbreviated form of heading is used to avoid needless repetition. Following is a complete explanation of these abbreviations:

Code - The test code or standard followed by this organization, group, or individual.

Probe - The sampling probe and its isokinetic features.

Filter - Filter media employed.

Gas - Sampled gas measurement (particulate testing).

Vacuum - Vacuum production (particulate testing).

Velocity - Velocity determination (particulate testing).

Incinerator - Size and type tested.

Charges, Charging - The standardized charges and charging used.

Method - Odor method used and comments.

American Standards Association, Inc. Approval Requirements for Domestic Gas-Fired Incinerators.

Code: ASA, Inc., Approval Requirements for Domestic Gas-Fired Incinerators.

Probe: ASA. Pyrex glass - 1 in. I.D. × 48 in. long. Fixed sample rate - 35 ft^3/hr. Fixed duct - 8 in. × 10 in. Fixed position - no traverse. Probe flushed. One sample flow rate adjustment for temperature at start of test.

Filter: ASA. Unimpregnated glass wool filter paper. MSA type 1106B. Cat. no. CT-25310. Two weighed without drying initially. One used. After run, store at room temperature alongside blank. Weigh. Record gain in weight with blank correction.

Gas: ASA. Calibrated thin plate square edged orifice with slope gauge. 35 ft^3/hr (120°F). Temperature correction three times in 15-min test run.

Vacuum: ASA. Tank type vacuum cleaner blower and motor. Equiv. to Lamb Electric #4450.

Velocity: No determination.

Advantages: 1) Developed after much study and developmental work. 2) Relatively simple and inexpensive equipment.

Disadvantages: 1) Requires trained and skilled personnel.

Incinerator: Domestic.

Charges: ASA. 1) Mixed refuse (weights in ounces): Food refuse - white potatoes 7, cabbage 3, unpeeled oranges 2, white bread 2, rice 2.4, beef suet 1, water 2.6; Dry combustible - corrugated cardboard 6.6, newspaper 3.3, waxed paper 12 in. wide 3.3. 2) Shredded newspaper 1 lb/bushel.

Charging: ASA. 1) Mixed refuse on specified cycle. 2) Shredded paper on specified cycle.

Excess Air Adj.: ASA. CO_2 and O_2 read by Orsat three times in 15 min test. Average used in calculations to a 50% excess air basis.

Method: ASA. Using three persons, they shall smell the gases produced by burning two sheets of newspaper. They shall enter the incinerator room from the outside or from a room where fresh air is present. They shall note the presence of odor in the room and the odor of flue gas aspirated from the test stack. Such odor shall not be more objectionable than that caused by the two sheets of newspaper.

The Adams Manufacturing Co., 1530 St. Clair, Cleveland 14, Ohio, Mr. Harry Friedberg (private communication).

Code: ASA, Inc., smoke filter method.

Probe: Small probe. Fixed volume sample - 2250 ± 100 $in.^3$ gas/$in.^2$ of filter area.

Filter: Equivalent in thickness, porosity and whiteness to Whatman #4 paper. Smoke recorder unit should be equivalent to: Bacharach Industrial Instrument Co., Research Applicance Co., Von Brand Co.

Gas: Sampling rate preset prior to test. Calibrated pressure drop mechanism across filter tape.

Vacuum: By sampler pump or plunger.

Velocity: No determination.

Advantages: Equipment is relatively simple and sufficiently reliable.

Incinerator: Domestic.

Charges: ASA.

Charging: ASA.

Excess Air Adj.: None.

Method: Recommends Battelle odor method of measurement of CO concentration. His experience presently limited to ASA. New Battelle method sufficiently accurate for control purposes, as is ASA method.

Consolidated Natural Gas System, 1201 East 55th Street, Cleveland 3, Ohio, Dr. F. E. Vandaveer, Director of Research.

Code: ASA.

Probe: ASA.

Filter: ASA.

Gas: ASA.

Vacuum: ASA.

Velocity: No determination.

Advantages: Satisfactory.

Incinerator: Domestic, comm.

Charges: ASA.

Charging: ASA.

Excess Air Adj.: ASA.

Method: ASA with reference to Battelle Project DAG-4-M.

Locke Stove Company, N. L. Martin (private communication).

Method: ASA

The Majestic Co., Inc., Huntington, Ind., Mr. Don Winegardner, Vice-President (private communication).

Code: ASA.

Probe: ASA.

Filter: ASA.

Gas: ASA.

Vacuum: ASA.

Velocity: No determination.

Advantages: Satisfactory.

Incinerator: Domestic.

Charges: ASA.

Charging: ASA.

Excess Air Adj.: ASA.

Method: ASA.

Martin Stamping and Stove Co., Huntsville, Ala., Frederick H. Martin, Executive Vice-President (private communication).

Code: ASA.

Probe: ASA.

Filter: ASA.

Gas: ASA.

Vacuum: ASA.

Velocity: No determination.

Advantages: Satisfactory. If unit passes AGA tests, it will not become an air pollution nuisance.

Incinerator: Domestic:

Charges: ASA.

Charging: ASA.

Excess Air Adj.: ASA.

Method: ASA. However, feels that a repeatable measurement for odor is hard to attain and not necessary. With a clear stack and a minimum temperature of 800°F on most incinerators (with reservations), there will be no foreseen odor nuisance.

Whirlpool Corp., St. Joseph, Mich., W. R. Crawford, Research Engineer (private communication.

Code: Modified ASA.

Probe: Tear drop probe - Diagonal in ASA duct. Ten 1/4 in. or 1/8 in. holes - Center point of equal area sections. Continuous isokinetic sampling rate using fixed pitot tube location (0.9 × center velocity).

Filter: Two layers of MSA glass fiber filter web, Cat.No. CT-75428. Millipore filter type holder. Developed special moisture diffusion system to remove moisture from sample gas line.

Gas: Calibrated flow meter and manometer. Flow rate 0.15 to 0.60 cfm.

Vacuum: Gast Mfg. Corp. Model 0211 vacuum pump, 1.7 cfm capacity.

Velocity: Pitot tube continuously measures velocity head. Nomographs convert to gas velocity and volume.

Advantages: 1) Found results reproducible and correlated with field observations. 2) Measures the particulate discharge of five microns or under which can be classed as "permanently" airborne and permits calculation of the total amount discharged. 3) Measures and permits calculation of

total particulate matter over five microns in size which will fall out on adjacent properties. 4) Removes moisture from particulate measurement system with a diffusion tube which permits rapid weighing and use of efficient filter papers conveniently at room temperatures. 5) Procedure is based on scientific methods giving numerical results with no opinions or judgments involved in evaluations.

Disadvantages: 1) High cost of equipment. 2) Lacks portability in present form.

Incinerator: Domestic.

Charges: ASA.

Charging: ASA.

Excess Air Adj.: Calculations based on isokinetic sampling. Measured total particulate. No excess air adjustments indicated.

Method: A method was developed to dynamically and continuously analyze for odor in a gas using the human nose as a detector. This method employs the continuous dilution of the odorous gas with fresh air until the smell threshold of the nose is reached. This threshold is constant for a given material. The ratios of the flow of fresh air to the flow of odorous gases at threshold may then be quantitatively compared by expressing them as odor numbers. Uses the threshold level of the human nostril as an odor measurement reference level with provision for simple observer training and check out of sensitivity of observer. Permits plotting a profile of odor output discharged vs. time as well as an expression for total odor generated.

Division of Smoke Regulation, Columbus, Ohio (1951 to 1958), Herbert C. Johnson, Director (private communication).

Code: ASME (1941) Test Code for Dust-Separating Apparatus. Western Precipitation equipment with modifications.

Probe: Stainless steel probe with different size nozzle heads. Special pitot tube arrangement attached to sampling probe to provide for isokinetic sampling rate adjustment. Traversed as per ASME and WP-50 Bulletin requirements.

Filter: Fiberglass bags in holder - outside of stack or duct.

Gas: Calibrated orifice.

Vacuum: Not stated.

Velocity: Standard pitot tube.

Advantages: 1) Equipment was relatively inexpensive, rugged and easy to set up. 2) Sampling time could be extended several hours, if desired, providing dustloadings were not unusually heavy, or the moisture content exceptionally high. (A heater system was finally developed which practically eliminated moisture problems). 3) Technicians who were willing could learn to conduct tests in a relatively short time. Calculation of results was reasonably simple.

Disadvantages: 1) Lack of correction for moisture content of products of combustion. This can be overcome by additional test equipment and proper calculations. 2) Percentage of samples lost from the fiberglass bags not known; believed collection efficiency was 98.0% plus for incinerator particulates. 3) Collection of the samples at temperatures only slightly above ambient in the presence of moisture conceivably could result in the formation of particulate not present in the stack.

Incinerator: Domestic, comm., mun.

Charges: Variable - field installations.

Charging: Variable - field installations.

Excess Air Adj.: Periodic Orsat analyses.

Department of Air Pollution Control, Milwaukee County, Fred R. Rehm, Deputy Director, JAPCA - Feb. 1957.

Code: Modified ASME Test Code for Dust-separation Apparatus (1941) and Test Code for Determining the Dust Concentration in a Gas Stream (1957).

Probe: Stainless steel water jacketed probes of different inlet diameter - minimum diameter recommended 3/4 in. Static balanced tube method of isokinetic sampling. Sampling in vertical ducts preferred. Traverse as per ASME Test Codes. Balanced tube feature permits isokinetic sampling regardless of widely varying flow rates as

experienced in incinerator testing. Large diameter sampling nozzles - 3/4 in. to 2 in. I.D. permit sampling rates from three to 20 cfm.

Filter: 1 1/2 in. diameter stainless cyclone followed by a fabric filter. Filter requirements as per ASME Test Codes. While the ASME suggested catch to filter weight ratio of five to one is desirable, it would not be practical for incinerator sampling due to the low dust concentration and therefore extended period of sampling required.

Gas: Sampled gas volumes measured by calibrated pressure drop mechanism on cyclone. Also measured by calibrated orifice ...per ASME Test Codes. Correction made for moisture content.

Vacuum: Clements - Cadillac G-10 blower and exhaust fan. Per ASME Test Codes.

Velocity: Combined reverse inconel, pitot tube. Per ASME Test Code traverse requirements. Volumetric determination not required as part of dustloading tests.

Advantages: 1) Reasonably reproducible results are obtainable with care. 2) Best method encountered to secure reliable quantitative results after considerable experience with: a) WP-50 equipment. b) Impingers, etc. 3) Test results reasonably correlate with nuisance problems. 4) System variations in velocity do not pose serious sampling problems.

Disadvantages: 1) Difficult and hazardous. 2) Tests are time consuming. 3) Average results rather than instantaneous results obtained. 4) Requires skilled personnel. 5) Requires quite expensive field and lab equipment.

Incinerator: Domestic, comm., mun., flue fed., spec.

Charges: All field tests made with material on hand which is defined in the test report. Some laboratory or controlled tests run using ASA and other standardized charges of our own. This work limited to domestic and commerical incinerators.

Charging: All field tests made with material on hand which is defined in the test report. Some laboratory or controlled tests run using ASA and other standardized charges of our own. This work limited to domestic and commercial incinerators.

Excess Air Adj.: Continuous carbon dioxide analysis with readings taken on a two to three min cycle. Thermco CO_2 electrical conductivity analyzer used. Orsat analyses run regularly to check continuous analyzer and to get information on gas composition, molecular weight and density.

Method: No quantitative odor tests reported but odor observations made on all tests. Analyses for noxious gases have included aldehyde and ketone concentration of incinerator effluents.

Air Pollution Control District, County of Los Angeles, California, Carl V. Kanter, JAPCA - Feb. 1957.

Code: Modification or extension of principles and procedures outlined in WP-50 Bulletin.

Probe: Sampling probes of glass or stainless steel. Nozzle sizes varied to be in the isokinetic sample volume rate. Sampling rate of 1/2 to one cfm makes nozzle size range from 1/8 in. to 1/2 in. diameter. One reference point in traverse used in sampling. Several points necessary if flow varies widely. Pitot tube used and checked every five minutes at a fixed point to adjust sampling rate.

Filter: Three Greenburg-Smith impingers are used with a paper thimble usually. For special purposes an alundum thimble or a miniature glass cyclone can be used.

Gas: A dry gas meter is used. Correction is made for moisture content. Meter is of the Sprague 1A type.

Vacuum: A sampling pump is used.

Velocity: Standard or combined reverse pitot tube used. Necessary to dustloading test to make sample rate changes on five minute interval.

Advantages: No comments included.

Disadvantages: No comments included.

Incinerator: Domestic, comm.mun.,flue fed. spec.

Charges: For use in field tests. No standardization of charges for field tests reported.

Charging: For use in field tests. No standardization of charge size or cycle for field tests reported.

Excess Air Adj.: A sample of gas is collected in a five liter bottle by acidified sodium sulfate displacement. An Orsat analysis is run on the integrated gas sample. This analysis used in excess air calculations.

Department of Air Pollution Control, City of New York, M.M. Braverman, Director of Laboratory (private communication)

Code: Modification or extension of procedures outlined in WP-50 Bulletin, ASME Test Codes.

Probe: Stainless steel probe. Fixed sample location. Sampling rate periodically adjusted to isokinetic. Pitot tube used at fixed point to indicate velocity variations. Low rate sampling indicated - less than one cfm.

Filter: Paper thimbles, cloth filters and Greenburg-Smith impingers.

Gas: A dry gas meter.

Vacuum: An air ejector or sampling pump.

Velocity: Standard pitot tube.

Advantages: Suggests that method involving filter paper sampling would be simpler, more automatic and less time consuming than WP-50 technique. Suggests incorporating principles described in use of Von Brand-Filtering Recorder as possible improved standard.

Disadvantages: 1) Present methods are long, tedious and cumbersome. 2) Suggests that more investigative work is necessary before standardized test procedures are set up.

Incinerator: Domestic, comm., mun., flue fed.

Charges: No information supplied or indicated on standardized charges.

Charging: No information supplied or indicated.

Excess Air Adj.: Periodic Orsat analysis.

Method: Threshold Dilution Method outlined by ASTM Method D-1391.

Bay Area Air Pollution Control District, John Yocom, Director of Technical Services, BAAPCD Booklet Test Methods.

Code: Modifications or extension of procedures outlined in WP-50 Bulletin.

Probe: Short probes of glass, brass and stainless steel - 3/16 in. to 1/2 in. I.D. One point sampling in ducts less than 4 ft^2 in velocities are reasonably uniform. Sampling velocity adjusted by aid of one point pitot tube reference or by pretest pitot tube traverse.

Filter: Media incorporated in holder inside stack or duct. Alundum and glass fibre filter paper mentioned.

Gas: A Sprague 1A type dry gas meter.

Vacuum: A sampling pump of 1.3 cfm capacity or a Penberthy XL-96 ejector.

Velocity: A combined, reverse or Stauscheibe pitot tube.

Advantages: Eliminates problems caused by condensation in the sampling train.

Disadvantages: Loss of particulates by combustion or volatilization in filter holder when used in stack.

Incinerator: Domestic, comm.

Charges: For use in field tests. No standardization of charges for field tests reported.

Charging: For use in field test. No standardization of charge size or cycle for field tests reported.

Excess Air Adj.: Periodic Orsat analyses are made and corrections made to a 6% O_2 basis.

Method: Suggests no detectable odor as a standard using the nose as the instrument. Also suggests tests show that below 50 ppm carbonyls as formaldehyde have little detectable odor.

New York University College of Engineering, Research Division, Elmer R. Kaiser, Senior Research Scientists, JAPCA - Aug. 1959 (private communication)

Code: Modifications or extension of procedures outlined in WP-50 Bulletin and per ASME Test Codes.

Probe: Western Precipitation stainless steel sampling probe with 1/2 in. sharp-edged nozzle. Sampling done at fixed locations. Isokinetic sampling adjustment made by use of Prandtl pitot tube. Sample rate less than two cfm. Water-cooled probes with 3/4 in. diameter nozzles were used on special incinerator studies.

Filter: Paper thimbles and Greenburg-Smith wet and dry impingers.

Gas: A Sprague 1A type dry gas meter. A flowrator or rotameter was used to gauge sampling velocity.

Vacuum: A central vacuum system.

Velocity: A Prandtl pitot tube of high temperature alloy steel.

Advantages: 1) While probes were used at fixed locations they could be used for traversing. 2) The water-cooled probes were necessary to prevent combustion of carbonaceous particles in the probe. 3) Impingers made good condensate-dust catches.

Disadvantages: 1) The uncooled probe with paper thimble was useful only in cool gas with a dew point below ambient temperature. 2) Recommend an orifice meter above two cfm. 3) Recommends null-type probe rather than pitot tube and special chart to secure isokinetic sampling.

Incinerator: Flue fed, spec.

Charges: For use in field tests. No standardization of charges for field tests reported.

Charging: For use in field tests. No standardization of charge size or cycle for field tests reported.

Excess Air Adj.: Gas samples collected over salt solution during test and analyzed for CO_2 and O_2 occasionally by Orsat analysis.

Method: The ASTM Method D1391-1957 "Measurement of Odor in Atmosphere (Dilution Method)" was used. Gas sampled continuously into a one liter bottle containing mercury. By mercury displacement a composite sample was obtained. The determination of threshold concentration was made by one observer early next morning. The ASTM odor method using syringes is simple and inexpensive. A plastic bag with aluminum foil liner could be used instead of mercury for sample procurement.

U.S. Public Health Service, R.A. Taft Sanitary Engineering Center, Andrew H. Rose, Jr., Chief, Engineering Research and Development JAPCA - Feb. 1959.

Code: Modification or extension of procedures outlined in ASME Test Codes.

Probe: Isokinetic sampling was conducted at a fixed point in the laboratory studies. Traversing was done on field municipal incinerator studies. Isokinetic adjustment was made by using pitot tube. A 1 in. I.D. sampling probe was used on the laboratory tests.

Filter: MSA type 1106-BH glass-fiber filter without organic binder.

Gas: Dry type bellows meter. A calibrated orifice meter was used to control the instantaneous sampling rate. Adjusted for moisture content.

Vacuum: A vacuum pump.

Velocity: A standard pitot tube.

Advantages: No comments on sampling included in paper.

Disadvantages: No comments on sampling included in paper.

Incinerator: Comm., mun.

Charges: In laboratory tests, standardized charges were used. A sack containing a five lb charge of fuel had a moisture content ranging from 23% to 27% consisted of 1 1/2 lb newspaper, 1 1/2 lb of cardboard, one lb wood and one lb wet vegetables.

Charging: 10 and 15 lb fuel charges were used as were charging rates of 140 lb/hr and 180 lb/hr. Stoking interval was 10 min and 20 min.

Excess Air Adj.: O_2, CO_2 and CO continuously recorded in laboratory tests. Orsat analyses used in field tests of municipal incinerators. CO measured by MSA squeeze bulb method at municipal incinerator.

Method: Odor observations were made and reported as sufficiently low to be undetectable in the immediate vicinity of the stack.

Battelle Memorial Institute, Richard B. Engdahl, Chief, Fuels and Air Pollution Research. Report Project DG-3M. Report Project DAG-4-M.

Code: American Standards Association, Inc. Method with slight modification. Modified ASME Test Codes followed in field tests of Municipal incinerators.

Probe: 1 in. I.D. Pyrex glass sampling probe in ASA test stack.

Filter: MSA type 1106B glass-fiber filter. ASA method used plus a Greenburg-Smith impinger was used in series with the filter.

Gas: ASA.

Vacuum: ASA.

Velocity: No determination.

Advantages: ASA modified for sampling over entire period of burning rather than for a 15 min period as specified.

Disadvantages: ASA.

Incinerator: Domestic, mun.

Charges: ASA. Mixed refuse and shredded paper charge.

Charging: ASA. Mixed refuse and shredded paper charge size and cycle used.

Excess Air Adj.: A gas sample collected over salt brine during test. Orsat analysis of the average gas sample.

Method: ASA odor method with 50 ml glass syringe, and two people used to make observations and comparing results with burning two sheets of newspaper in an open container. A recent study indicated that the CO concentration of domestic gas-fired incinerators was a valid, objective indicator of odor intensity when using ASA domestic waste charges.

Wisconsin Chemical & Testing Company, Fred R. Rehm, Consultant (private communication).

Code: Modified ASME Test Code for Determining the Dust Concentration in a Gas Stream PTC 27-1957 and Test Code for Dust-Separating Apparatus.

Probe: Balanced static tube method of isokinetic sampling used. Stainless steel, water-jacketed, probes and nozzles used - 3/4 in. to two in. I.D. Large sized sample rates three to 20 cfm considered essential to secure representative sample.

Filter: 1 1/2 in. diameter, stainless cyclone followed by fabric filter. Filter requirements as per ASME Test Codes, except for five to one catch to bag weight ratio which is impractical.

Gas: Calibrated orifices and calibrated pressure drop mechanism as per ASME Test Codes.

Vacuum: Clements - Cadillac G-10 blowers and exhausters.

Velocity: Combined reverse, inconel, pitot tube and standard pitot for clean gases, as per ASME Test Codes.

Advantages: See No. 8, above.

Disadvantages: See No. 8, above.

Incinerator: Domestic, comm., mun., flue fed., spec.

Charges: Standardized charges used on some lab tests consisting of: (25% H_2O max) 54.2% paper, 36.9% wood boxes, 8.9% rubber foot pads. No standardization on field tests.

Charging: Charging on five minute cycles. No standardization on field tests.

Excess Air Adj.: Continuous CO_2. Analysis checked regularly by Orsat analysis.

Method: Odor observations made on all tests. Analysis of incinerator gases for carbonyl content made and degree of correlation to odor levels attempted.

Bureau of Air Pollution Control, City of Detroit, Morton Sterling, Director, Robert S. Bower, Sr., Assistant Mechanical Engineer (private communication), JAPCA - Aug. 1961.

Code: Modified ASME PTC 21-1941 Modified ASA.

Probe: ASA.

Filter: ASA.

Gas: ASA.

Vacuum: High volume pump.

Velocity: Velometer.

Advantages: 1) ASME PTC-21 acceptable method for particulate testing. 2) ASA-Z 21.6 1957 probably satisfactory for lab testing. 3) Smoke emissions need not be measured at all if restrictive and accurate particulate and odor tests are conducted.

Disadvantages: 1) Tests are time consuming and costly.

Incinerator: Domestic.

Charges: There is a need for a standard test charge, but the components should be of a more rigorous and representative nature than the present innocuous ASA food charge. Items like coffee grounds, carpet sweepings, plastic wrappers, damp cotton should be included. ASA and three other standardized charges used.

Charging: ASA.

Excess Air Adj.: Integrated gas samples taken at a constant rate by liquid displacement during the particulate sampling period. Orast analyses run on the integrated gas sample for excess air adjustment.

Method: A special odor panel technique using five members compare odors in a special room with that from two burning sheets of newspaper in an open container. The odor is assessed at one minute intervals. A 15 to one air to gas dilution ratio was used. While the technique used was imperfect in some respects, it proved fairly satisfactory. Odor tests were found the most difficult for incinerators to pass. Feels that adequate odor measurement technique alone may be sufficient measure of performance evaluation of domestic incinerators.

Performance Evaluation Sub-Committee:

Fred R. Rehm, Chairman
Leo P. Flood
Elmer R. Kaiser
Andrew H. Rose, Jr.
John R. Sved

REFERENCE

1 Rehm, F. R. Test Methods for Determining Emission Characteristics of Incinerators. J. A. P. C. A. Vol. 15, No. 3, pp 127-35. March 1965.

Section 10

REFERENCE MATERIALS

Conversion Factors and Tables

CONVERSION FACTORS

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CONVERSION FACTORS - TEMPERATURE

Given Units	Desired Units: ^{o}F	^{o}C	^{o}R	^{o}K
Degrees Fahrenheit		. 5555 x (^{o}F - 32)	^{o}F + 460	. 5555 x (^{o}F-32) + 273
Degrees Centigrade	1. 8^{o}C + 32		1. 8^{o}C + 492	^{o}C + 273
Degrees Rankin	^{o}R - 460	. 5555 x (^{o}R - 492)		. 5555 x (^{o}R-492) + 273
Degrees Kelvin	1. 8(^{o}K-273) + 32	^{o}K - 273	1. 8(^{o}K-273) + 492	

CONVERSION FACTORS – PRESSURE

Given units \ Desired units	$\frac{gm_m}{cm\text{-}sec^2}$	$\frac{dynes}{cm^2}$	$\frac{\#_m}{ft\text{-}sec^2}$	$\frac{poundals}{ft^2}$	$\frac{gm_f}{cm^2}$	$\frac{\#_f}{ft^2}$	$\frac{\#_f}{in^2}$	"Atmospheres"
$\frac{gm_m}{cm\text{-}sec^2}$	1	1	6.7197×10^{-2}	6.7197×10^{-2}	1.0197×10^{-3}	2.0885×10^{-3}	1.4504×10^{-5}	9.8692×10^{-7}
$\frac{dynes}{cm^2}$	1	1	6.7197×10^{-2}	6.7197×10^{-2}	1.0197×10^{-3}	2.0885×10^{-3}	1.4504×10^{-5}	9.8692×10^{-7}
$\frac{\#_m}{ft\text{-}sec^2}$	14.882	14.882	1	1	1.5175×10^{-2}	3.1081×10^{-2}	2.1584×10^{-4}	1.4687×10^{-5}
$\frac{poundals}{ft^2}$	14.882	14.882	1	1	1.5175×10^{-2}	3.1081×10^{-2}	2.1584×10^{-4}	1.4687×10^{-5}
$\frac{gm_f}{cm^2}$	980.665	980.665	65.898	65.898	1	2.0482	1.4223×10^{-2}	9.6784×10^{-4}
$\frac{\#_f}{ft^2}$	478.80	478.80	32.174	32.174	4.8824×10^{-1}	1	6.9444×10^{-3}	4.7254×10^{-4}
$\frac{\#_f}{in^2}$	6.8948×10^{4}	6.8948×10^{4}	4.6331×10^{3}	4.6331×10^{3}	70.307	144.00	1	6.8046×10^{-2}
"Atmospheres"	1.0133×10^{6}	1.0133×10^{6}	6.8087×10^{4}	6.8087×10^{4}	1.0332×10^{3}	2.1162×10^{3}	14.696	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS - AREA

Given Units	Desired Units: Square Inch	Square Feet	Square Yard	Square Mile	Acre	Square Centimeter	Square Decimeter	Square Meter	Square Kilometer
Square Inch	1	6.9444×10^{-3}	77.1605×10^{-5}	2.49×10^{-10}	15.94×10^{-6}	6.452	6.452×10^{-2}	6.452×10^{-4}	6.452×10^{-10}
Square Foot	144	1	0.1111	3.587×10^{-8}	2.296×10^{-5}	929.0341	929.0341×10^{-2}	929.0341×10^{-4}	929.0341×10^{-10}
Square Yard	1296	9	1	3.228×10^{-7}	2.066×10^{-4}	83.61×10^{2}	83.61	83.61×10^{-2}	83.61×10^{-8}
Square Mile	40.144×10^{8}	2.788×10^{7}	3.098×10^{6}	1	640	2.589998×10^{10}	2.589998×10^{8}	2.589998×10^{6}	2.589998
Acre	62.73×10^{7}	4.3560×10^{4}	4840	15.625×10^{-4}	1	4046.873×10^{4}	4046.873×10^{2}	4046.873	4046.873×10^{-6}
Square Centimeter	15.5×10^{-2}	10.764×10^{-4}	1.1960×10^{-4}	3.8610×10^{-11}	2.471×10^{-8}	1	1×10^{-2}	1×10^{-4}	1×10^{-10}
Square Decimeter	15.5	10.764×10^{-2}	1.1960×10^{-2}	3.8610 x 10-9	2.471 x 10-6	1×10^{2}	1	1×10^{-2}	1×10^{-8}
Square Meter	15.5×10^{2}	10.764	1.1960	3.8610×10^{-7}	2.471×10^{-4}	1×10^{4}	1×10^{2}	1	1×10^{-6}
Square Kilometer	15.5×10^{8}	10.764×10^{6}	1.1960×10^{6}	3.8610×10^{-1}	2.471×10^{2}	1×10^{10}	1×10^{8}	1×10^{6}	1

To convert a value from a given unit a desired unit, multiply the given value by the factor opposite the given units and beneath the desired unit.

CONVERSION FACTORS – VOLUME

Given Units \ Desired Units	Cubic Yard	Cubic Foot	Cubic Inch	Cubic Meter	Cubic Decimeter	Cubic Centimeter	Liter
Cubic Yard	1	27	4.6656×10^{4}	0.764559	764.559	7.64559×10^{5}	764.54
Cubic Foot	3.7037×10^{-2}	1	1728	2.8317×10^{-2}	28.317	2.8317×10^{4}	28.316
Cubic Inch	2.143347×10^{-5}	5.78704×10^{-4}	1	1.63872×10^{-5}	1.63872×10^{-2}	16.3872	1.63868×10^{-2}
Cubic Meter	1.30794	35.314445	6.1023×10^{4}	1	1000	1×10^{6}	999.973
Cubic Decimeter	1.3079×10^{-3}	3.5314×10^{-2}	61.023	0.001	1	1000	.99997
Cubic Centimeter	1.3079×10^{-6}	3.5314×10^{-5}	6.1023×10^{-2}	1×10^{-6}	1×10^{-3}	1	9.99973×10^{-4}
Liter	1.3080×10^{-3}	3.5316×10^{-2}	61.025	1.000027×10^{-3}	1.000027	1000.027	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS – FLOW

Given Units \ Desired Units	$\frac{M^3}{sec}$	$\frac{M^3}{min}$	$\frac{M^3}{hour}$	$\frac{ft^3}{sec}$	$\frac{ft^3}{min}$	$\frac{ft^3}{hour}$	$\frac{L}{sec}$	$\frac{L}{min}$	$\frac{cm^3}{sec}$	$\frac{cm^3}{min}$
$\frac{M^3}{sec}$	1	60	3600	35.3144	21.1887×10^{2}	12.7132×10^{4}	999.973	59.998×10^{3}	1×10^{6}	6×10^{7}
$\frac{M^3}{min}$	0.0167	1	60	0.5886	35.3144	21.189×10^{2}	16.667	999.973	16.667×10^{3}	1×10^{6}
$\frac{M^3}{hour}$	2.778×10^{-5}	16.667×10^{-3}	1	98.90×10^{-4}	0.5886	35.3144	27.777×10^{-2}	16.667	2.777×10^{2}	1.666×10^{4}
$\frac{ft^3}{sec}$	28.317×10^{-3}	1.699	101.94	1	60	3600	28.316	16.9896×10^{2}	2.8317×10^{4}	1.699×10^{6}
$\frac{ft^3}{min}$	4.7195×10^{-4}	28.317×10^{-3}	1.699	16.667×10^{-3}	1	60	47.193×10^{-2}	28.316	4.7195×10^{2}	2.8317
$\frac{ft^3}{hour}$	7.8658×10^{-6}	4.7195×10^{-4}	28.317×10^{-3}	2.778×10^{-4}	16.667×10^{-3}	1	7.866×10^{-3}	0.4719	78.658	4.7195×10^{2}
$\frac{L}{sec}$	1.000027×10^{-3}	6.00016×10^{-2}	3.6	35.316×10^{-3}	2.11896	127.138	1	60	1000.027	16.667
$\frac{L}{min}$	1.6667×10^{-5}	1.000027×10^{-3}	6.00016×10^{-2}	5.886×10^{-4}	35.316×10^{-3}	2.11896	1.6667×10^{-2}	1	16.667	1000.027
$\frac{cm^3}{sec}$	1×10^{-6}	6×10^{-5}	3.6×10^{-3}	3.5314×10^{-5}	2.1189×10^{-3}	1.271×10^{-3}	9.99973×10^{-4}	5.9998×10^{-2}	1	60
$\frac{cm^3}{min}$	1.6667×10^{-8}	1×10^{-6}	6×10^{-5}	5.886×10^{-7}	0.3531×10^{-4}	2.11887×10^{-3}	5.9998×10^{-2}	9.99973×10^{-4}	16.667×10^{-3}	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired unit.

CONVERSION FACTORS-WEIGHT

Given Units	Desired Units: Microgram	Milligram	gram	Kilogram	grain	Ounce (avdp)	Pound (avdp)	Ton (U.S. short)	Tonne (metric)
Microgram	1	1×10^{-3}	1×10^{-6}	1×10^{-9}	15.4124×10^{-6}	3.5274×10^{-8}	2.2046×10^{-9}	1.1023×10^{-12}	1×10^{-12}
Milligram	1×10^{3}	1	1×10^{-3}	1×10^{-6}	15.4324×10^{-3}	3.5274×10^{-5}	2.2046×10^{-6}	1.1023×10^{-9}	1×10^{-9}
gram	1×10^{6}	1×10^{3}	1	1×10^{-3}	15.4324	3.5274×10^{-2}	2.2046×10^{-3}	1.1023×10^{-6}	1×10^{-6}
Kilogram	1×10^{9}	1×10^{6}	1×10^{3}	1	15.4324×10^{3}	35.274	2.2046	1.1023×10^{-3}	1×10^{-3}
grain	64.799×10^{3}	64.799	64.799×10^{-3}	64.799×10^{-6}	1	22.857×10^{-4}	1.4286×10^{-4}	7.143×10^{-8}	64.799×10^{-9}
Ounce (avdp)	28.349×10^{6}	28.349×10^{3}	28.349	28.349×10^{-3}	437.5	1	62.5×10^{-3}	3.125×10^{-5}	28.349×10^{-6}
Pound (avdp)	453.59×10^{6}	453.59×10^{3}	453.59	453.59×10^{-3}	7000	16	1	5×10^{-4}	453.59×10^{-6}
Ton (U.S. short)	905.185×10^{9}	907.185×10^{6}	907.185×10^{3}	907.185	14×10^{6}	3.2×10^{4}	2000	1	0.907185
Tonne (metric)	1×10^{12}	1×10^{9}	1×10^{6}	1×10^{3}	1.543×10^{7}	3.5274×10^{4}	2204.62	1.10231	1

CONVERSION FACTORS - CONCENTRATION

Given Units	Desired Units: $\frac{\mu g}{M^3}$	$\frac{mg}{M^3}$	$\frac{\mu g}{L}$	$\frac{oz}{ft.^3}$	$\frac{lbs.}{ft.^3}$	$\frac{grams}{ft.^3}$	$\frac{lbs.}{1000\ ft.^3}$	$\frac{grains}{ft.^3}$
$\frac{\mu g}{M^3}$	1	1000	1.000027	9.989×10^{-7}	6.243×10^{-8}	2.8317×10^{-5}	6.243×10^{-5}	4.37×10^{-4}
$\frac{mg}{M^3}$	1×10^{-3}	1	1.000027×10^{-3}	9.989×10^{-10}	6.243×10^{-11}	2.8317×10^{-8}	6.243×10^{-8}	4.37×10^{-7}
$\frac{\mu g}{L}$	.999973	9.99973×10^{2}	1	9.988×10^{-7}	6.242×10^{-8}	2.8316×10^{-5}	6.242×10^{-5}	4.37×10^{-4}
$\frac{oz}{ft.^3}$	1.00115×10^{6}	1.00115×10^{9}	1.00118×10^{6}	1	62.5×10^{-3}	28.349	62.5	4.375×10^{2}
$\frac{lbs.}{ft.^3}$	1.602×10^{7}	1.602×10^{10}	1.602×10^{7}	16	1	453.59	1×10^{3}	7×10^{3}
$\frac{grams}{ft.^3}$	3.531×10^{4}	3.531×10^{7}	3.531×10^{4}	3.5274×10^{-2}	2.20462×10^{-3}	1	2.2046	15.43
$\frac{lbs.}{1000\ ft.^3}$	1.602×10^{4}	1.602×10^{7}	1.602×10^{4}	1.6×10^{-2}	1×10^{-3}	453.59×10^{-3}	1	7
$\frac{grains}{ft.^3}$	2.288×10^{3}	2.288×10^{6}	2.288×10^{3}	2.2857×10^{-3}	1.4286×10^{-4}	6.4799×10^{-2}	14.286	1

CONVERSION FACTORS – LENGTH

Given Units \ Desired Units	Inch	Foot	Yard	Mile	Micron	Millimeter	Centimeter	Meter	Kilometer
Inch	1	83.33×10^{-3}	27.778×10^{-3}	1.578×10^{-5}	2.54×10^{4}	25.4	2.54	2.54×10^{-2}	2.54×10^{-5}
Foot	12	1	3333	1.894×10^{-4}	30.48×10^{4}	304.8	30.48	30.48×10^{-2}	30.48×10^{-5}
Yard	36	3	1	5.682×10^{-4}	91.44×10^{4}	914.4	91.44	91.44×10^{-2}	91.44×10^{-5}
Mile	6.3360×10^{4}	5280	1760	1	1.6094×10^{9}	1.6094×10^{6}	1.6094×10^{5}	1.6094×10^{3}	1.6094
Micron	3.937×10^{-5}	32.808×10^{-7}	10.94×10^{-7}	62.137×10^{-11}	1	1×10^{-3}	1×10^{-4}	1×10^{-6}	1×10^{-9}
Millimeter	3.937×10^{-2}	32.808×10^{-4}	10.94×10^{-4}	62.137×10^{-8}	1×10^{3}	1	0.1	1×10^{-3}	1×10^{-6}
Centimeter	3.937×10^{-1}	32.808×10^{-3}	10.94×10^{-3}	62.137×10^{-7}	1×10^{4}	10	1	1×10^{-2}	1×10^{-5}
Meter	39.37	32.808×10^{-1}	10.94×10^{-1}	62.137×10^{-5}	1×10^{6}	1×10^{3}	1×10^{2}	1	1×10^{-3}
Kilometer	3.937×10^{4}	32.808×10^{2}	10.94×10^{2}	62.137×10^{-2}	1×10^{9}	1×10^{6}	1×10^{5}	1×10^{3}	1

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS – EMISSION RATES

Given units \ Desired units	gms/sec	gms/min	kg/hr	kg/day	lbs/min	lbs/hr	lbs/day	tons/hr	tons/day	tons/yr
gms/sec	1.0	60.0	3.6	8.640 × 10	1.3228 × 10^{-1}	7.9367	1.9048 × 10^{2}	3.9683 × 10^{-3}	9.5240 × 10^{-2}	3.4763 × 10
gms/min	1.6667 × 10^{-2}	1.0	6.0 × 10^{-2}	1.4400	2.2046 × 10^{-3}	1.3228 × 10^{-1}	3.1747	6.6139 × 10^{-5}	1.5873 × 10^{-3}	5.7938 × 10^{-1}
kg/hr	2.7778 × 10^{-1}	16.667	1.0	2.4000 × 10	3.6744 × 10^{-2}	2.2046	5.2911 × 10	1.1023 × 10^{-3}	2.6456 × 10^{-2}	9.6563
kg/day	1.1574 × 10^{-2}	6.9444 × 10^{-1}	4.1667 × 10^{-2}	1.0	1.5310 × 10^{-3}	9.1860 × 10^{-2}	2.2046	4.5930 × 10^{-5}	1.1023 × 10^{-3}	4.0235 × 10^{-1}
lbs/min	7.5598	4.5359 × 10^{2}	2.7215 × 10	6.5317 × 10^{2}	1.0	60.0	1.44 × 10^{3}	3.000 × 10^{-2}	7.2000 × 10^{-1}	2.6280 × 10^{2}
lbs/hr	1.2600 × 10^{-1}	7.5598	4.5359 × 10^{-1}	1.0886 × 10	1.6667 × 10^{-2}	1.0	24.0	5.0000 × 10^{-4}	1.2000 × 10^{-2}	4.3800
lbs/day	5.2499 × 10^{-3}	3.1499 × 10^{-1}	1.8900 × 10^{-2}	4.5359 × 10^{-1}	6.9444 × 10^{-4}	4.1667 × 10^{-2}	1.0	2.0833 × 10^{-5}	5.0000 × 10^{-4}	1.8250 × 10^{-1}
tons/hr	2.5199 × 10^{2}	1.5120 × 10^{4}	9.0718 × 10^{2}	2.1772 × 10^{4}	3.3333 × 10	2.0 × 10^{3}	4.8000 × 10^{4}	1.0	24.0	8.7600 × 10^{3}
tons/day	1.0500 × 10	6.2999 × 10^{2}	3.7799 × 10	9.0718 × 10^{2}	1.3889	8.3333 × 10	2.0 × 10^{3}	4.1667 × 10^{-2}	1.0	365.0
tons/yr	2.8766 × 10^{-2}	1.7260	1.0356 × 10^{-1}	2.4854	3.8052 × 10^{-3}	2.2831 × 10^{-1}	5.4795	1.1416 × 10^{-4}	2.7397 × 10^{-3}	1.0

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

CONVERSION FACTORS – VELOCITY

Given units \ Desired units	m/sec	ft/sec	ft/min	km/hr	mi/hr	knots	mi/day
m/sec	1.0	3.2808	1.9685×10^{2}	3.6	2.2369	1.9425	5.3687×10
ft/sec	3.0480×10^{-1}	1.0	60	1.0973	6.8182×10^{-1}	5.9209×10^{-1}	1.6364×10
ft/min	5.0080×10^{-3}	1.6667×10^{-2}	1.0	1.8288×10^{-2}	1.1364×10^{-2}	9.8681×10^{-3}	2.7273×10^{-1}
km/hr	2.7778×10^{-1}	9.1134×10^{-1}	5.4681×10	1.0	6.2137×10^{-1}	5.3959×10^{-1}	1.4913×10
mi/hr	4.4707×10^{-1}	1.4667	88.0	1.6093	1.0	8.6839×10^{-1}	24
knots	5.1479×10^{-1}	1.6890	1.0134×10^{2}	1.8533	1.1516	1.0	2.7637×10
mi/day	1.8627×10^{-2}	6.1111×10^{-2}	3.6667	6.7056×10^{-2}	4.1667×10^{-2}	3.6183×10^{-2}	1.0

To convert a value from a given unit to a desired unit, multiply the given value by the factor opposite the given units and beneath the desired units.

LOGARITHMS TO BASE 10

N	0	1	2	3	4	5	6	7	8	9	Proportional Parts 1	2	3	4	5	6	7	8	9
10	0000	0043	0086	0128	0170	0212	0253	0294	0334	0374	4	8	12	17	21	25	29	33	37
11	0414	0453	0492	0531	0569	0607	0645	0682	0719	0755	4	8	11	15	19	23	26	30	34
12	0792	0828	0864	0899	0934	0969	1004	1038	1072	1106	3	7	10	14	17	21	24	28	31
13	1139	1173	1206	1239	1271	1303	1335	1367	1399	1430	3	6	10	13	16	19	23	26	29
14	1461	1492	1523	1553	1584	1614	1644	1673	1703	1732	3	6	9	12	15	18	21	24	27
15	1761	1790	1818	1847	1875	1903	1931	1959	1987	2014	3	6	8	11	14	17	20	22	25
16	2041	2068	2095	2122	2148	2175	2201	2227	2253	2279	3	5	8	11	13	16	18	21	24
17	2304	2330	2355	2380	2405	2430	2455	2480	2504	2529	2	5	7	10	12	15	17	20	22
18	2553	2577	2601	2625	2648	2672	2695	2718	2742	2765	2	5	7	9	12	14	16	19	21
19	2788	2810	2833	2856	2878	2900	2923	2945	2967	2989	2	4	7	9	11	13	16	18	20
20	3010	3032	3054	3075	3096	3118	3139	3160	3181	3201	2	4	6	8	11	13	15	17	19
21	3222	3243	3263	3284	3304	3324	3345	3365	3385	3404	2	4	6	8	10	12	14	16	18
22	3424	3444	3464	3483	3502	3522	3541	3560	3579	3598	2	4	6	8	10	12	14	15	17
23	3617	3636	3655	3674	3692	3711	3729	3747	3766	3784	2	4	6	7	9	11	13	15	17
24	3802	3820	3838	3856	3874	3892	3909	3927	3945	3962	2	4	5	7	9	11	12	14	16
25	3979	3997	4014	4031	4048	4065	4082	4099	4116	4133	2	3	5	7	9	10	12	14	15
26	4150	4166	4183	4200	4216	4232	4249	4265	4281	4298	2	3	5	7	8	10	11	13	15
27	4314	4330	4346	4362	4378	4393	4409	4425	4440	4456	2	3	5	6	8	9	11	13	14
28	4472	4487	4502	4518	4533	4548	4564	4579	4594	4609	2	3	5	6	8	9	11	12	14
29	4624	4639	4654	4669	4683	4698	4713	4728	4742	4757	1	3	4	6	7	9	10	12	13
30	4771	4786	4800	4814	4829	4843	4857	4871	4886	4900	1	3	4	6	7	9	10	11	13
31	4914	4928	4942	4955	4969	4983	4997	5011	5024	5038	1	3	4	6	7	8	10	11	12
32	5051	5065	5079	5092	5105	5119	5132	5145	5159	5172	1	3	4	5	7	8	9	11	12
33	5185	5198	5211	5224	5237	5250	5263	5276	5289	5302	1	3	4	5	6	8	9	10	12
34	5315	5328	5340	5353	5366	5378	5391	5403	5416	5428	1	3	4	5	6	8	9	10	11
35	5441	5453	5465	5478	5490	5502	5514	5527	5539	5551	1	2	4	5	6	7	9	10	11
36	5563	5575	5587	5599	5611	5623	5635	5647	5658	5670	1	2	4	5	6	7	8	10	11
37	5682	5694	5705	5717	5729	5740	5752	5763	5775	5786	1	2	3	5	6	7	8	9	10
38	5798	5809	5821	5832	5843	5855	5866	5877	5888	5899	1	2	3	5	6	7	8	9	10
39	5911	5922	5933	5944	5955	5966	5977	5988	5999	6010	1	2	3	4	5	7	8	9	10
40	6021	6031	6042	6053	6064	6075	6085	6096	6107	6117	1	2	3	4	5	6	8	9	10
41	6128	6138	6149	6160	6170	6180	6191	6201	6212	6222	1	2	3	4	5	6	7	8	9
42	6232	6243	6253	6263	6274	6284	6294	6304	6314	6325	1	2	3	4	5	6	7	8	9
43	6335	6345	6355	6365	6375	6385	6395	6405	6415	6425	1	2	3	4	5	6	7	8	9
44	6435	6444	6454	6464	6474	6484	6493	6503	6513	6522	1	2	3	4	5	6	7	8	9
45	6532	6542	6551	6561	6571	6580	6590	6599	6609	6618	1	2	3	4	5	6	7	8	9
46	6628	6637	6646	6656	6665	6675	6684	6693	6702	6712	1	2	3	4	5	6	7	7	8
47	6721	6730	6739	6749	6758	6767	6776	6785	6794	6803	1	2	3	4	5	5	6	7	8
48	6812	6821	6830	6839	6848	6857	6866	6875	6884	6893	1	2	3	4	4	5	6	7	8
49	6902	6911	6920	6928	6937	6946	6955	6964	6972	6981	1	2	3	4	4	5	6	7	8
50	6990	6998	7007	7016	7024	7033	7042	7050	7059	7067	1	2	3	3	4	5	6	7	8
51	7076	7084	7093	7101	7110	7118	7126	7135	7143	7152	1	2	3	3	4	5	6	7	8
52	7160	7168	7177	7185	7193	7202	7210	7218	7226	7235	1	2	2	3	4	5	6	7	7
53	7243	7251	7259	7267	7275	7284	7292	7300	7308	7316	1	2	2	3	4	5	6	6	7
54	7324	7332	7340	7348	7356	7364	7372	7380	7388	7396	1	2	2	3	4	5	6	6	7
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

The proportional parts are stated in full for every tenth at the right-hand side. The logarithm of any number of four significant figures can be read directly by adding the proportional part corresponding to the fourth figure to the tabular number corresponding to the first three figures. There may be an error of 1 in the last place.

LOGARITHMS TO BASE 10

(continued)

N	0	1	2	3	4	5	6	7	8	9	Proportional Parts 1	2	3	4	5	6	7	8	9
55	7404	7412	7419	7427	7435	7443	7451	7459	7466	7474	1	2	2	3	4	5	5	6	7
56	7482	7490	7497	7505	7513	7520	7528	7536	7543	7551	1	2	2	3	4	5	5	6	7
57	7559	7566	7574	7582	7589	7597	7604	7612	7619	7627	1	2	2	3	4	5	5	6	7
58	7634	7642	7649	7657	7664	7672	7679	7686	7694	7701	1	1	2	3	4	4	5	6	7
59	7709	7716	7723	7731	7738	7745	7752	7760	7767	7774	1	1	2	3	4	4	5	6	7
60	7782	7789	7796	7803	7810	7818	7825	7832	7839	7846	1	1	2	3	4	4	5	6	6
61	7853	7860	7868	7875	7882	7889	7896	7903	7910	7917	1	1	2	3	4	4	5	6	6
62	7924	7931	7938	7945	7952	7959	7966	7973	7980	7987	1	1	2	3	3	4	5	6	6
63	7993	8000	8007	8014	8021	8028	8035	8041	8048	8055	1	1	2	3	3	4	5	5	6
64	8062	8069	8075	8082	8089	8096	8102	8109	8116	8122	1	1	2	3	3	4	5	5	6
65	8129	8136	8142	8149	8156	8162	8169	8176	8182	8189	1	1	2	3	3	4	5	5	6
66	8195	8202	8209	8215	8222	8228	8235	8241	8248	8254	1	1	2	3	3	4	5	5	6
67	8261	8267	8274	8280	8287	8293	8299	8306	8312	8319	1	1	2	3	3	4	5	5	6
68	8325	8331	8338	8344	8351	8357	8363	8370	8376	8382	1	1	2	3	3	4	4	5	6
69	8388	8395	8401	8407	8414	8420	8426	8432	8439	8445	1	1	2	2	3	4	4	5	6
70	8451	8457	8463	8470	8476	8482	8488	8494	8500	8506	1	1	2	2	3	4	4	5	6
71	8513	8519	8525	8531	8537	8543	8549	8555	8561	8567	1	1	2	2	3	4	4	5	5
72	8573	8579	8585	8591	8597	8603	8609	8615	8621	8627	1	1	2	2	3	4	4	5	5
73	8633	8639	8645	8651	8657	8663	8669	8675	8681	8686	1	1	2	2	3	4	4	5	5
74	8692	8698	8704	8710	8716	8722	8727	8733	8739	8745	1	1	2	2	3	4	4	5	5
75	8751	8756	8762	8768	8774	8779	8785	8791	8797	8802	1	1	2	2	3	3	4	5	5
76	8808	8814	8820	8825	8831	8837	8842	8848	8854	8859	1	1	2	2	3	3	4	5	5
77	8865	8871	8876	8882	8887	8893	8899	8904	8910	8915	1	1	2	2	3	3	4	4	5
78	8921	8927	8932	8938	8943	8949	8954	8960	8965	8971	1	1	2	2	3	3	4	4	5
79	8976	8982	8987	8993	8998	9004	9009	9015	9020	9025	1	1	2	2	3	3	4	4	5
80	9031	9036	9042	9047	9053	9058	9063	9069	9074	9079	1	1	2	2	3	3	4	4	5
81	9085	9090	9096	9101	9106	9112	9117	9122	9128	9133	1	1	2	2	3	3	4	4	5
82	9138	9143	9149	9154	9159	9165	9170	9175	9180	9186	1	1	2	2	3	3	4	4	5
83	9191	9196	9201	9206	9212	9217	9222	9227	9232	9238	1	1	2	2	3	3	4	4	5
84	9243	9248	9253	9258	9263	9269	9274	9279	9284	9289	1	1	2	2	3	3	4	4	5
85	9294	9299	9304	9309	9315	9320	9325	9330	9335	9340	1	1	2	2	3	3	4	4	5
86	9345	9350	9355	9360	9365	9370	9375	9380	9385	9390	1	1	2	2	3	3	4	4	5
87	9395	9400	9405	9410	9415	9420	9425	9430	9435	9440	0	1	1	2	2	3	3	4	4
88	9445	9450	9455	9460	9465	9469	9474	9479	9484	9489	0	1	1	2	2	3	3	4	4
89	9494	9499	9504	9509	9513	9518	9523	9528	9533	9538	0	1	1	2	2	3	3	4	4
90	9542	9547	9552	9557	9562	9566	9571	9576	9581	9586	0	1	1	2	2	3	3	4	4
91	9590	9595	9600	9605	9609	9614	9619	9624	9628	9633	0	1	1	2	2	3	3	4	4
92	9638	9643	9647	9652	9657	9661	9666	9671	9675	9680	0	1	1	2	2	3	3	4	4
93	9685	9689	9694	9699	9703	9708	9713	9717	9722	9727	0	1	1	2	2	3	3	4	4
94	9731	9736	9741	9745	9750	9754	9759	9763	9768	9773	0	1	1	2	2	3	3	4	4
95	9777	9782	9786	9791	9795	9800	9805	9809	9814	9818	0	1	1	2	2	3	3	4	4
96	9823	9827	9832	9836	9841	9845	9850	9854	9859	9863	0	1	1	2	2	3	3	4	4
97	9868	9872	9877	9881	9886	9890	9894	9899	9903	9908	0	1	1	2	2	3	3	4	4
98	9912	9917	9921	9926	9930	9934	9939	9943	9948	9952	0	1	1	2	2	3	3	4	4
99	9956	9961	9965	9969	9974	9978	9983	9987	9991	9996	0	1	1	2	2	3	3	3	4
N	0	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9

The proportional parts are stated in full for every tenth at the right-hand side. The logarithm of any number of four significant figures can be read directly by adding the proportional part corresponding to the fourth figure to the tabular number corresponding to the first three figures. There may be an error of 1 in the last place.

INTERNATIONAL ATOMIC WEIGHTS

BASED ON CARBON - 12

	Symbol	Atomic Number	Atomic Weight		Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	[227] *	Mercury	Hg	80	200.59
Aluminum	Al	13	26.9815	Molybdenum	Mo	42	95.94
Americium	Am	95	[243] *	Neodymium	Nd	60	144.24
Antimony	Sb	51	121.75	Neon	Ne	10	20.183
Argon	Ar	18	39.948	Neptunium	Np	93	[237] *
Arsenic	As	33	74.9216	Nickel	Ni	28	58.71
Astatine	At	85	[210] *	Niobium	Nb	41	92.906
Barium	Ba	56	137.34	Nitrogen	N	7	14.0067
Berkelium	Bk	97	[249] *	Nobelium	No	102	[254] *
Beryllium	Be	4	9.0122	Osmium	Os	76	190.2
Bismuth	Bi	83	208.980	Oxygen	O	8	15.9994 [a]
Boron	B	5	10.811 [a]	Palladium	Pd	46	106.4
Bromine	Br	35	79.909 [b]	Phosphorus	P	15	30.9738
Cadmium	Cd	48	112.40	Platinum	Pt	78	195.09
Calcium	Ca	20	40.08	Plutonium	Pu	94	[242] *
Californium	Cf	98	[251] *	Polonium	Po	84	[210] *
Carbon	C	6	12.01115 [a]	Potassium	K	19	39.102
Cerium	Ce	58	140.12	Praseodymium	Pr	59	140.907
Cesium	Cs	55	132.905	Promethium	Pm	61	[147] *
Chlorine	Cl	17	35.453 [b]	Protactinium	Pa	91	[231] *
Chromium	Cr	24	51.996 [b]	Radium	Ra	88	[226] *
Cobalt	Co	27	58.9332	Radon	Rn	86	[222] *
Copper	Cu	29	63.54	Rhenium	Re	75	186.2
Curium	Cm	96	[247] *	Rhodium	Rh	45	102.905
Dysprosium	Dy	66	162.50	Rubidium	Rb	37	85.47
Einsteinium	Es	99	[254] *	Ruthenium	Ru	44	101.07
Erbium	Er	68	167.26	Samarium	Sm	62	150.35
Europium	Eu	63	151.96	Scandium	Sc	21	44.956
Fermium	Fm	100	[253] *	Selenium	Se	34	78.96
Fluorine	F	9	18.9984	Silicon	Si	14	28.086 [a]
Francium	Fr	87	[223] *	Silver	Ag	47	107.870 [b]
Gadolinium	Gd	64	157.25	Sodium	Na	11	22.9898
Gallium	Ga	31	69.72	Strontium	Sr	38	87.62
Germanium	Ge	32	72.59	Sulfur	S	16	32.064 [a]
Gold	Au	79	196.967	Tantalum	Ta	73	180.948
Hafnium	Hf	72	178.49	Technetium	Tc	43	[99] *
Helium	He	2	4.0026	Tellurium	Te	52	127.60
Holmium	Ho	67	164.930	Terbium	Tb	65	158.924
Hydrogen	H	1	1.00797 [a]	Thallium	Tl	81	204.37
Indium	In	49	114.82	Thorium	Th	90	232.038
Iodine	I	53	126.9044	Thulium	Tm	69	168.934
Iridium	Ir	77	192.2	Tin	Sn	50	118.69
Iron	Fe	26	55.847 [b]	Titanium	Ti	22	47.90
Krypton	Kr	36	83.80	Tungsten	W	74	183.85
Lanthanum	La	57	138.91	Uranium	U	92	238.03
Lead	Pb	82	207.19	Vanadium	V	23	50.942
Lithium	Li	3	6.939	Xenon	Xe	54	131.30
Lutetium	Lu	71	174.97	Ytterbium	Yb	70	173.04
Magnesium	Mg	12	24.312	Yttrium	Y	39	88.905
Manganese	Mn	25	54.9380	Zinc	Zn	30	65.37
Mendelevium	Md	101	[256] *	Zirconium	Zr	40	91.22

* Value in brackets denotes the mass number of the isotope of longest known half life (or a better known one for Bk, Cf, Po, Pm, and Tc).

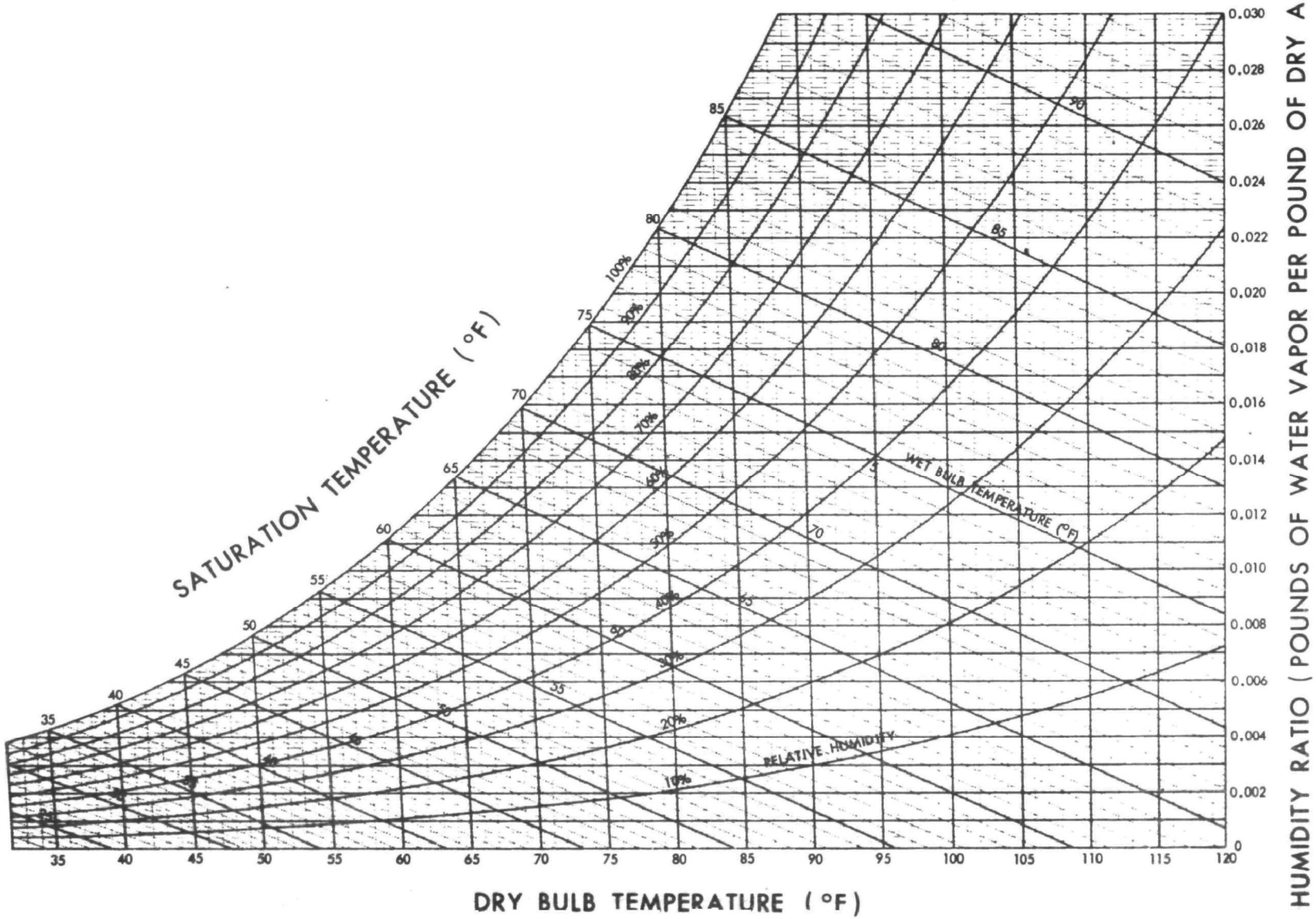
[a] Atomic weight varies because of natural variation in isotopic composition: B, ±0.003; C, ±0.00005; H, ±0.00001; O, ±0.0001; Si, ±0.001; S, ±0.003.

[b] Atomic weight is believed to have following experimental uncertainty: Br, ±0.002; Cl, ±0.001; Cr, ±0.001; Fe, ±0.003; Ag, ±0.003. For other elements, the last digit given for the atomic weight is believed reliable to ±0.5. Lawrencium, Lw, has been proposed as the name for element No. 103, nuclidic mass about 257.

VAPOR PRESSURES OF WATER AT SATURATION
(inches of Mercury)

Temp. Deg. F.	0	1	2	3	4	5	6	7	8	9
—20	.0126	.0119	.0112	.0106	.0100	.0095	.0089	.0084	.0080	.0075
—10	.0222	.0209	.0199	.0187	.0176	.0168	.0158	.0150	.0142	.0134
—	.0376	.0359	.0339	.0324	.0306	.0289	.0275	.0259	.0247	.0233
0	.0376	.0398	.0417	.0463	.0441	.0489	.0517	.0541	.0571	.0598
10	.0631	.0660	.0696	.0728	.0768	.0810	.0846	.0892	.0932	.0982
20	.1025	.1080	.1127	.1186	.1248	.1302	.1370	.1429	.1502	.1567
30	.1647	.1716	.1803	.1878	.1955	.2035	.2118	.2203	.2292	.2383
40	.2478	.2576	.2677	.2782	.2891	.3004	.3120	.3240	.3364	.3493
50	.3626	.3764	.3906	.4052	.4203	.4359	.4520	.4586	.4858	.5035
60	.5218	.5407	.5601	.5802	.6009	.6222	.6442	.6669	.6903	.7144
70	.7392	.7648	.7912	.8183	.8462	.8750	.9046	.9352	.9666	.9989
80	1.032	1.066	1.102	1.138	1.175	1.213	1.253	1.293	1.335	1.378
90	1.422	1.467	1.513	1.561	1.610	1.660	1.712	1.765	1.819	1.875
100	1.932	1.992	2.052	2.114	2.178	2.243	2.310	2.379	2.449	2.521
110	2.596	2.672	2.749	2.829	2.911	2.995	3.081	3.169	3.259	3.351
120	3.446	3.543	3.642	3.744	3.848	3.954	4.063	4.174	4.289	4.406
130	4.525	4.647	4.772	4.900	5.031	5.165	5.302	5.442	5.585	5.732
140	5.881	6.034	6.190	6.350	6.513	6.680	6.850	7.024	7.202	7.384
150	7.569	7.759	7.952	8.150	8.351	8.557	8.767	8.981	9.200	9.424
160	9.652	9.885	10.12	10.36	10.61	10.86	11.12	11.38	11.65	11.92
170	12.20	12.48	12.77	13.07	13.37	13.67	13.98	14.30	14.62	14.96
180	15.29	15.63	15.98	16.34	16.70	17.07	17.44	17.82	18.21	18.61
190	10.01	19.42	19.84	20.27	20.70	21.14	21.50	22.05	22.52	22.99
200	23.47	23.96	24.46	24.97	25.48	26.00	26.53	27.07	27.62	28.18
210	28.75	29.33	29.92	30.52	31.13	31.75	32.38	33.02	33.67	34.33
220	35.00	35.68	36.37	37.07	37.78	38.50	39.24	39.99	40.75	41.52
230	42.31	43.11	43.92	44.74	45.57	46.41	47.27	48.14	49.03	49.93
240	50.84	51.76	52.70	53.65	54.62	55.60	56.60	57.61	58.63	59.67
250	60.72	61.79	62.88	63.98	65.10	66.23	67.38	68.54	69.72	70.92
260	72.13	74.36	74.61	75.88	77.17	78.46	79.78	81.11	82.46	83.83
270	85.22	86.63	88.06	89.51	90.97	92.45	93.96	95.49	97.03	98.61
280	100.2	101.8	103.4	105.0	106.7	108.4	110.1	111.8	113.6	115.4
290	117.2	119.0	120.8	122.7	124.6	126.5	128.4	130.4	132.4	134.4
300	136.4	138.5	140.6	142.7	144.8	147.0	149.2	151.4	153.6	155.9
310	158.2	160.5	162.8	165.2	167.6	170.0	172.5	175.0	177.5	180.0
320	182.6	185.2	187.8	190.4	193.1	195.8	198.5	201.3	204.1	206.9
330	209.8	212.7	215.6	218.6	221.6	224.6	227.7	230.8	233.9	237.1
340	240.3	243.5	246.8	250.1	253.4	256.7	260.1	263.6	267.1	270.6
350	274.1	277.7	281.3	284.9	288.6	292.3	296.1	299.9	303.8	307.7
360	311.6	315.5	319.5	323.5	327.6	331.7	335.9	340.1	344.4	348.7
370	353.0	357.4	361.8	366.2	370.7	375.2	379.8	384.4	389.1	393.8
380	398.6	403.4	408.2	413.1	418.1	423.1	428.1	433.1	438.2	443.4
390	448.6	453.9	459.2	464.6	470.0	475.5	481.0	486.6	492.2	497.9
400	503.6	509.3	515.1	521.0	526.9	532.9	538.9	545.0	551.1	557.3

NORMAL TEMPERATURE PSYCHROMETRIC CHART
(ENGLISH UNITS)



EMPERATURE PSYCHROMETRIC CHART
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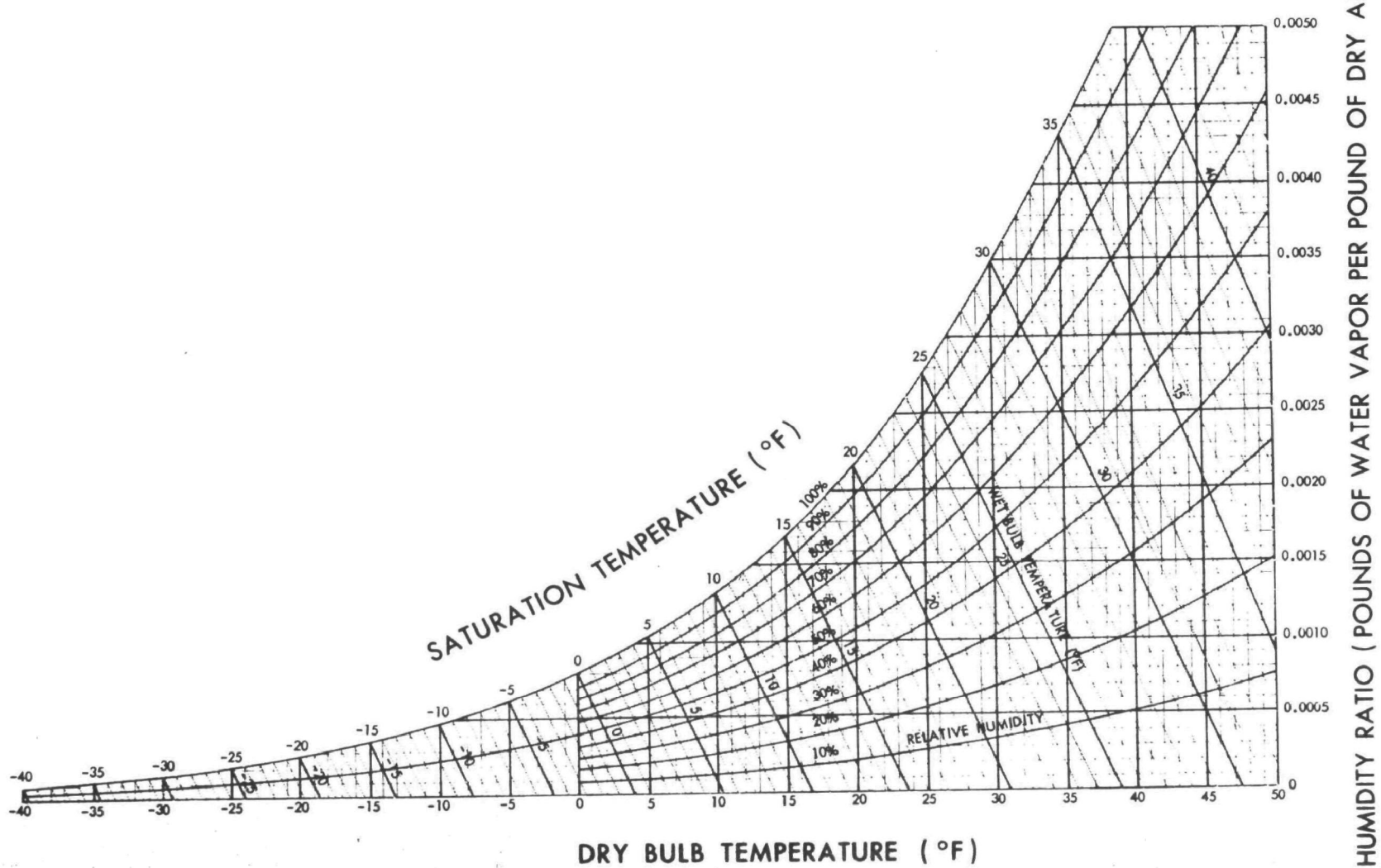

HIGH TEMPERATURE PSYCHROMETRIC CHART
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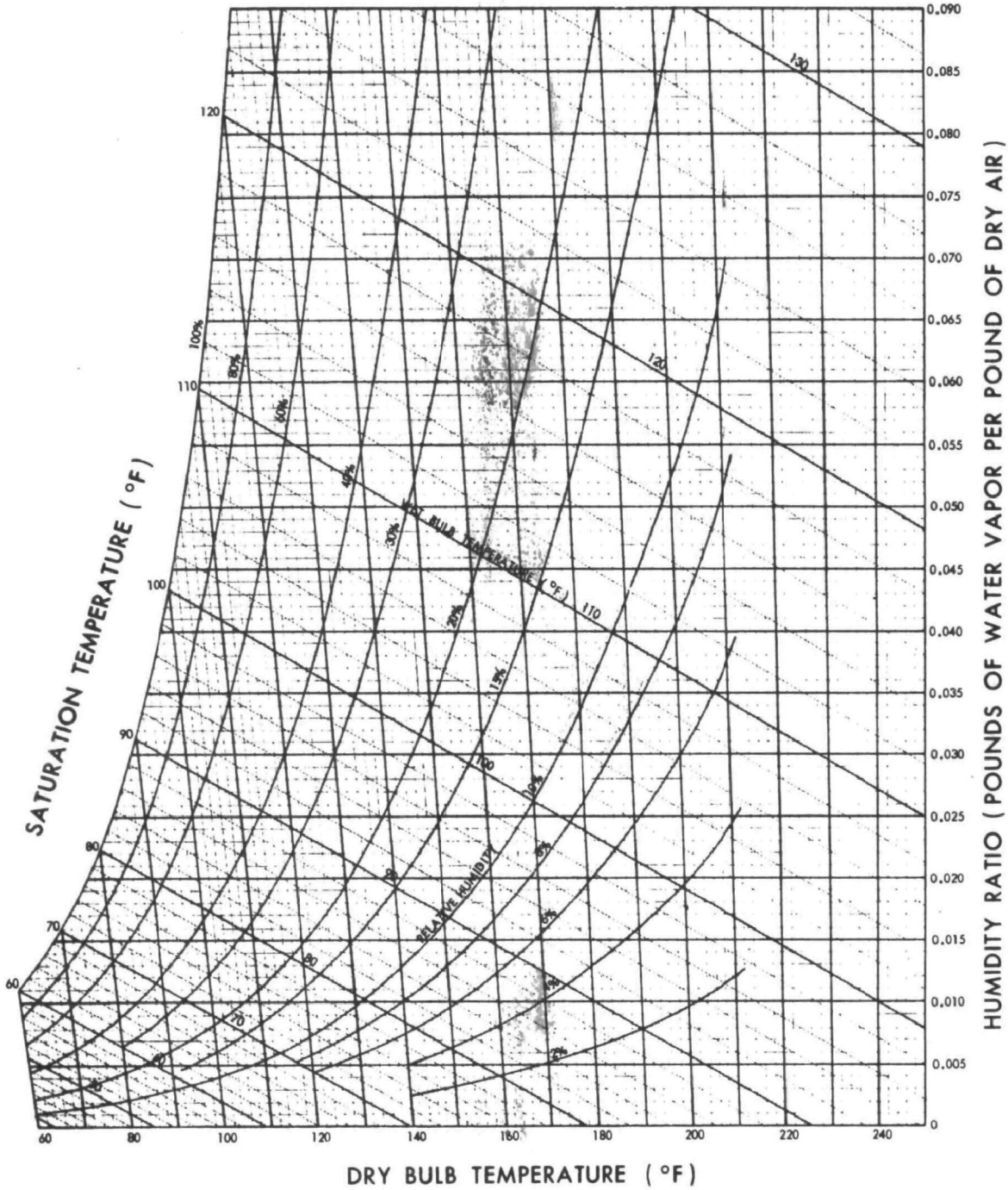


SPECIFIC WEIGHT OF DRY AIR IN lbs/ft^3 FOR °F AND ABSOLUTE PRESSURE OF 29.92 in.Hg

Temperature (°F)	Specific weight (lbs/ft^3)	Temperature (°F)	Specific weight (lbs/ft^3)
0	0.08633	180	0.06203
10	0.08449	200	0.06015
20	0.08273	220	0.05838
30	0.08104	240	0.05671
40	0.07942	260	0.05514
50	0.07785	280	0.05365
60	0.07636	300	0.05223
70	0.07492	350	0.04901
80	0.07353	400	0.04615
90	0.07219	450	0.04362
100	0.07090	500	0.04135
110	0.06966	550	0.03930
120	0.06845	600	0.03744
130	0.06729	700	0.03422
140	0.06617	800	0.03150
150	0.06509	900	0.02911
160	0.06403	1000	0.02718

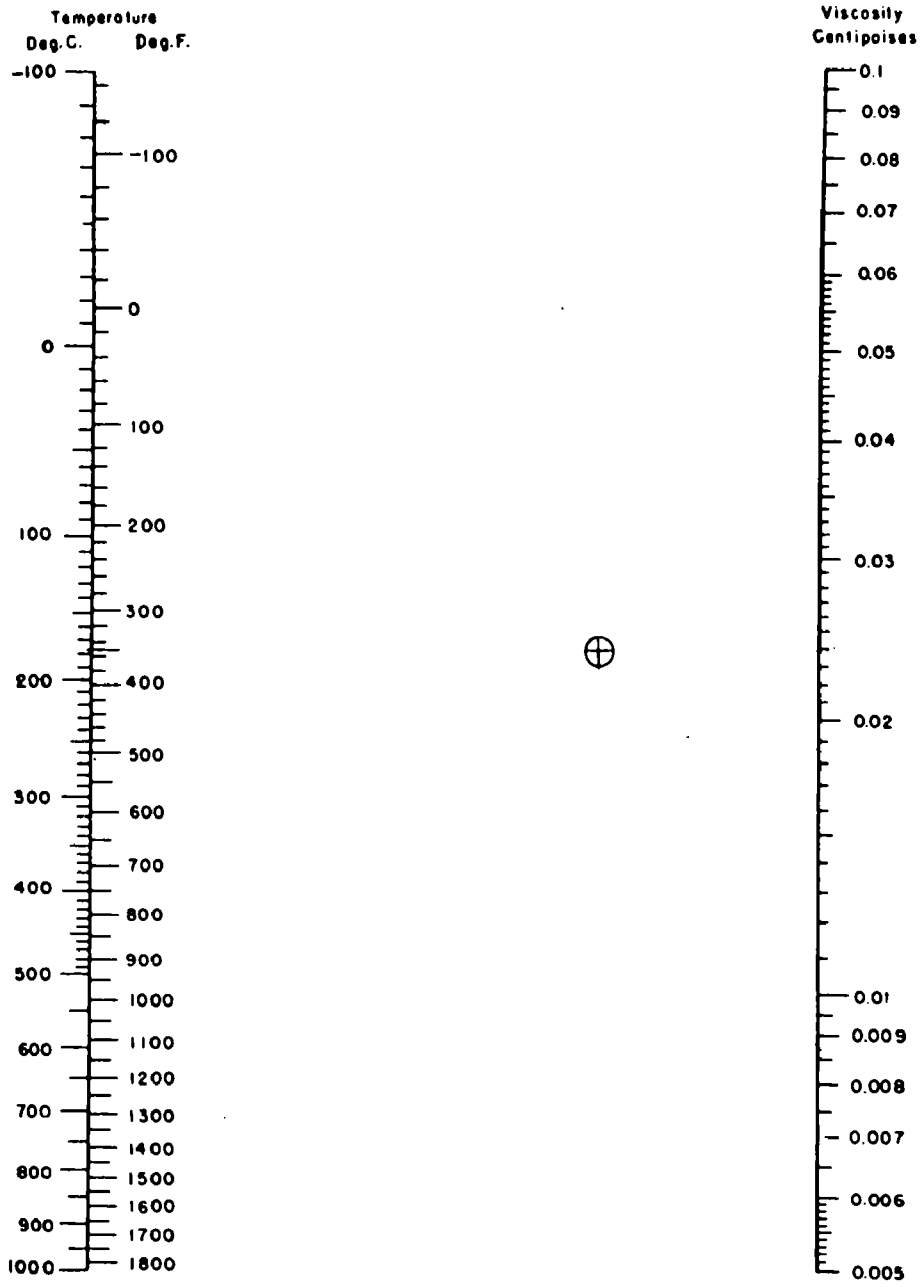
KINEMATIC VISCOSITY (ft^2/sec) OF DRY AIR AT AN ABSOLUTE PRESSURE OF 29.92 in. Hg AND VARIOUS TEMPERATURES °F

Temperature (°F)	Kinematic viscosity (ft^2/sec)
0	$1.26\ (10)^{-4}$
20	$1.36\ (10)^{-4}$
40	$1.46\ (10)^{-4}$
60	$1.58\ (10)^{-4}$
80	$1.69\ (10)^{-4}$
100	$1.80\ (10)^{-4}$
120	$1.89\ (10)^{-4}$
150	$2.07\ (10)^{-4}$
200	$2.4\ \ (10)^{-4}$

SPECIFIC HEAT RATIO OF GASES AT ONE ATMOSPHERE

Compound	Formula	Temperature, °C.	Ratio of specific heats, $(\gamma) = C_p/C_v$
Acetaldehyde	C_2H_4O	30	1.14
Acetic acid	$C_2H_4O_2$	136	1.15
Acetylene	C_2H_2	15	1.26
		−71	1.31
Air		925	1.36
		17	1.403
		−78	1.408
		−118	1.415
Ammonia	NH_3	15	1.310
Argon	A	15	1.668
		−180	1.76 (?)
		0–100	1.67
Benzene	C_6H_6	90	1.10
Bromine	Br_2	20–350	1.32
Carbon dioxide	CO_2	15	1.304
		−75	1.37
disulfide	CS_2	100	1.21
monoxide	CO	15	1.404
		−180	1.41
Chlorine	Cl_2	15	1.355
Chloroform	$CHCl_3$	100	1.15
Cyanogen	$(CN)_2$	15	1.256
Cyclohexane	C_6H_{12}	80	1.08
Dichlorodifluormethane	CCl_2F_2	25	1.139
Ethane	C_2H_6	100	1.19
		15	1.22
		−82	1.28
Ethyl alcohol	C_2H_6O	90	1.13
ether	$C_4H_{10}O$	35	1.08
		80	1.086
Ethylene	C_2H_4	100	1.18
		15	1.255
		−91	1.35
Helium	He	−180	1.660
Hexane (n-)	C_6H_{14}	80	1.08
Hydrogen	H_2	15	1.410
		−76	1.453
		−181	1.597
bromide	HBr	20	1.42
chloride	HCl	15	1.41
		100	1.40
cyanide	HCN	65	1.31
		140	1.28
		210	1.24
Hydrogen (*Cont.*):			
iodide	HI	20–100	1.40
sulfide	H_2S	15	1.32
		−45	1.30
		−57	1.29
Iodine	I_2	185	1.30
Isobutane	C_4H_{10}	15	1.11
Krypton	Kr	19	1.68
Mercury	Hg	360	1.67
Methane	CH_4	600	1.113
		300	1.16
		15	1.31
		−80	1.34
		−115	1.41
Methyl acetate	$C_3H_6O_2$	15	1.14
alcohol	CH_4O	77	1.203
ether	C_2H_6O	6–30	1.11
Methylal	$C_3H_8O_2$	13	1.06
		40	1.09
Neon	Ne	19	1.64
Nitric oxide	NO	15	1.400
		−45	1.39
		−80	1.38
Nitrogen	N_2	15	1.404
		−181	1.47
Nitrous oxide	N_2O	100	1.28
		15	1.303
		−30	1.31
		−70	1.34
Oxygen	O_2	15	1.401
		−76	1.415
		−181	1.45
Pentane (n-)	C_5H_{12}	86	1.086
Phosphorus	P	300	1.17
Potassium	K	850	1.77
Sodium	Na	750–920	1.68
Sulfur dioxide	SO_2	15	1.29
Xenon	Xe	19	1.66

VISCOSITY OF AIR (CENTIPOISES) AT ONE ATMOSPHERE FOR VARIOUS TEMPERATURES °C AND °F



(1) centipoise	$(10)^{-2}\ \frac{gm}{cm\text{-}sec}$ $(10)^{-2}$ poise	$2.09(10)^{-5}\ \frac{\#_f\ -\ sec}{ft^2}$	$2.09(10)^{-5}\ \frac{slug}{ft\ -\ sec}$	$6.72(10)^{-4}\ \frac{\#_m}{ft\ -\ sec}$