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COMPUTERIZED DESIGN AND COST ESTIMATION FOR MULTIPLE-HEARTH SLUDGE INCINERATORS

U.S. ENVIRONMENTAL PROTECTION AGENCY

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COMPUTERIZED DESIGN AND COST ESTIMATION FOR MULTIPLE-HEARTH SLUDGE INCINERATORS

by

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ABSTRACT

A digital subroutine was developed for the preliminary design and cost estimation of an optimum multiple-hearth-furnace system for sewage sludge incineration. The subroutine provides the dimensions and ratings of incinerator components; the requirements for auxiliary fuel, power and labor; and all cost elements for the incineration system. The computer subroutine may also be used for the thermal analysis of an existing or planned incinerator without optimization and cost features.

The subroutine was primarily based on field data from nine operating municipal incineration plants, each having from one to four furnaces. The ranges of the furnace variables were 200 to 4500 lb dry solids per hour, 5 to 11 hearths, 6.0 to 22.25 ft diameter, and 85 to 2327 sq ft hearth area. Operating schedules and thermal cycling were considered, together with their influence on effective capacity, hearth replacement, and fuel consumption. Field data were correlated with the principal furnace parameters, and costs were normalized to 1969 dollars. Where possible, "non-dollar" expenditures, such as man-hours, pounds of fuel and kilowatt-hours, were established. Unit costs were then used to convert all non-dollar expenditures to dollars and hence to extract an annual total incinerator cost and a cost per ton of dry solids. A user's guide to input selection and numerical examples are included.

This report was submitted in fulfillment of Project Number 17070 EBP, Contract 14-12-547, under the sponsorship of the Environmental Protection Agency.

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I. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. A digital computer subroutine for multiple-hearth furnace sewage sludge incineration, suitable for inclusion in the WQO/EPA Executive Program for design and cost of the entire wastewater treatment systems, has been prepared. It realistically considers and models the furnace operating schedule, thermal cycling, hearth replacement schedule, standby capacity, etc., as well as the more usual technical and financial relationships.

2. In-depth data from field visits to furnaces of various sizes with preferably lengthy and well-documented operating histories have proven essential in providing needed information for modeling.

3. This model should remain useful for some time to come - it allows for updating of specific functional relationships, numerical coefficients and economic indicators as more and better data become available.

RECOMMENDATIONS

1. To assist in updating this model, additional and/or more reliable data should be generated, e.g., in the following areas: effect of thermal cycling on life of hearths and other components; extent to which dewatering chemicals in the sludge undergo chemical reaction in the furnace; analyses of stack and scrubber gases; and effect of automation on maintenance and required labor.

2. This model should be kept up-to-date by incorporation of additional and/or more reliable data. It should be used for preliminary design and its predictions compared with actual performance and costs.

3. Basic combustion research should be carried out to ascertain the controlling mechanisms in MHF sewage sludge incinerators for the purpose of (a) improving their efficiency, e.g., in terms of increasing the hearth loading (in lb per hr per sq ft), and (b) even more important, establishing reliable design and operating criteria for minimizing air pollutants in the exhaust gases. Knowledge in these areas would greatly improve both the technology and the usefulness of the mathematical model.

II. INTRODUCTION

The Water Quality Office of the EPA (formerly Federal Water Quality Administration) has developed an Executive Digital Computer Program (Ref. 1) as a tool for the process designer and water resource planner. This program contains the logic to compute the cost and performance of any group of wastewater treatment processes arranged in any configuration including recycle streams. Models for individual processes are each represented in the executive program by subroutines. Models for about 15 individual processes have so far been developed.

One of the most important treatment areas is the ultimate disposal of the wastewater concentrate, or sewage sludge, to the environment. Incineration of the sewage sludge is an important ultimate disposal process. The overall aim of this effort was to develop a subroutine for the multiple-hearth-furnace incineration of sewage sludge. This subroutine was to be suitable for integration into the Executive Program.

The specific objectives for the subroutine were taken to be:

1. Optimize design and operation for a multiple-hearth-furnace sewage sludge incineration system as part of an entire wastewater treatment plant, existing or planned.

2. For the optimum system, provide a breakdown in expenditures by "non-dollar" categories (man-hours, kilowatt-hours, etc.), and money (capital cost, total annual cost, cost per ton dry solids) in 1969 dollars.

3. Write the subroutine program in the Fortran computer language such that it is capable of being fitted into the Executive Program, occupying a place between sludge dewatering and ash disposal processes.

The approach taken toward meeting the stated objectives of the program consisted of combining the rational engineering analysis of the various physical phenomena occurring in the multiple-hearth furnace with design, operational, and economic data obtained from field visits to operating installations varying in size and capacity. Special attention was to be paid to the realistic modeling of operating and maintenance schedules of multiple-hearth furnaces (MHF's) where such data were available because of their effect on costs.

Chapter III, which follows, discusses existing literature on MHF Sludge Incineration Systems from the standpoints of operation and economics, and defines the system to be modeled. Chapter IV is devoted to the Thermal Analysis of MHF Incineration, based on material and energy balances combined with technical requirements. Chapter V describes Data Acquisition from nine field visits and other sources. Chapter VI contains the complete compilation of tables and figures generated in the process of Data Reduction and Correlation. Chapter VII is a Description of the Subroutine, with inputs, outputs, and the calculation scheme. Chapter VIII is the User's Guide to Input Selection, in which the factors affecting selection of each input are discussed, including also a standard set of inputs. Chapter IX, Use of Subroutine, explains the input format and presents numerical examples in the form of printouts of inputs and outputs. Chapters X, XI, and XII contain Acknowledgements, References, and Glossary. The Appendix contains the Fortran IV listing of the subroutine.

III. MHF SLUDGE INCINERATION SYSTEM

DESCRIPTION AND OPERATION

Rabbled-hearth furnaces have been in use for nearly a century, initially for roasting ores. The present air-cooled multiple-hearth furnace (MHF) is essentially the Herreshoff design of 1889. It has been used for sewage sludge incineration since the 1930's. The multiple-hearth furnace is a unique combustion device. Unlike other furnaces designed for the combustion of solid waste materials, this furnace employs no open burning grates. Furthermore, unlike most incinerators, the combustion zone is in the central part of the vertical furnace structure and not outside in another connecting chamber. The advantages of the MHF include simplicity, ease of control, flexibility of operation and durability.

A typical section through a multiple-hearth furnace is illustrated in Fig. 1 taken from Burd (Ref. 2). A typical incineration system comprising the furnace and ancillary equipment is diagrammed in Fig. 2. The furnace proper consists of a number of annular hearths stacked horizontally at fixed distances one above the other inside a refractory-lined, vertical, cylindrical steel shell. A centrally located cast iron shaft which runs the full height of the furnace supports cantilevered rabble arms (2 or 4) above each hearth. Each arm contains several rabble teeth which rake sludge spirally across the hearth below the arms as the latter rotate with the central shaft. The sewage sludge (dewatered to about 25 percent solids) is fed in at the periphery of the top hearth (IN-hearth) and raked by the rabble teeth towards the center to an opening through which it falls to the next hearth (OUT-hearth). On this hearth, the sludge is raked outward to the periphery where it drops to the next IN-hearth below. This in-out process is continued on down the furnace. Thus, the sludge and gas streams move counter-current to one another, the sludge passing down the furnace and finally turning into ash, while the combustion air flows over each hearth as it moves upward, finally exiting as flue gas at the top hearth.

Combustion air generally is of three kinds: (1) recycled cooling air which has traveled up through the hollow central shaft and is then, in part, ducted to the bottom hearth, as shown in Figs. 1 and 2; (2) ambient air from a blower, usually located at a central hearth in conjunction with auxiliary fuel burners (Fig. 2); and (3) ambient air admitted through adjustable ports and doors at various points into the furnace which is slightly below atmospheric pressure because of the induced draft (Fig. 2).

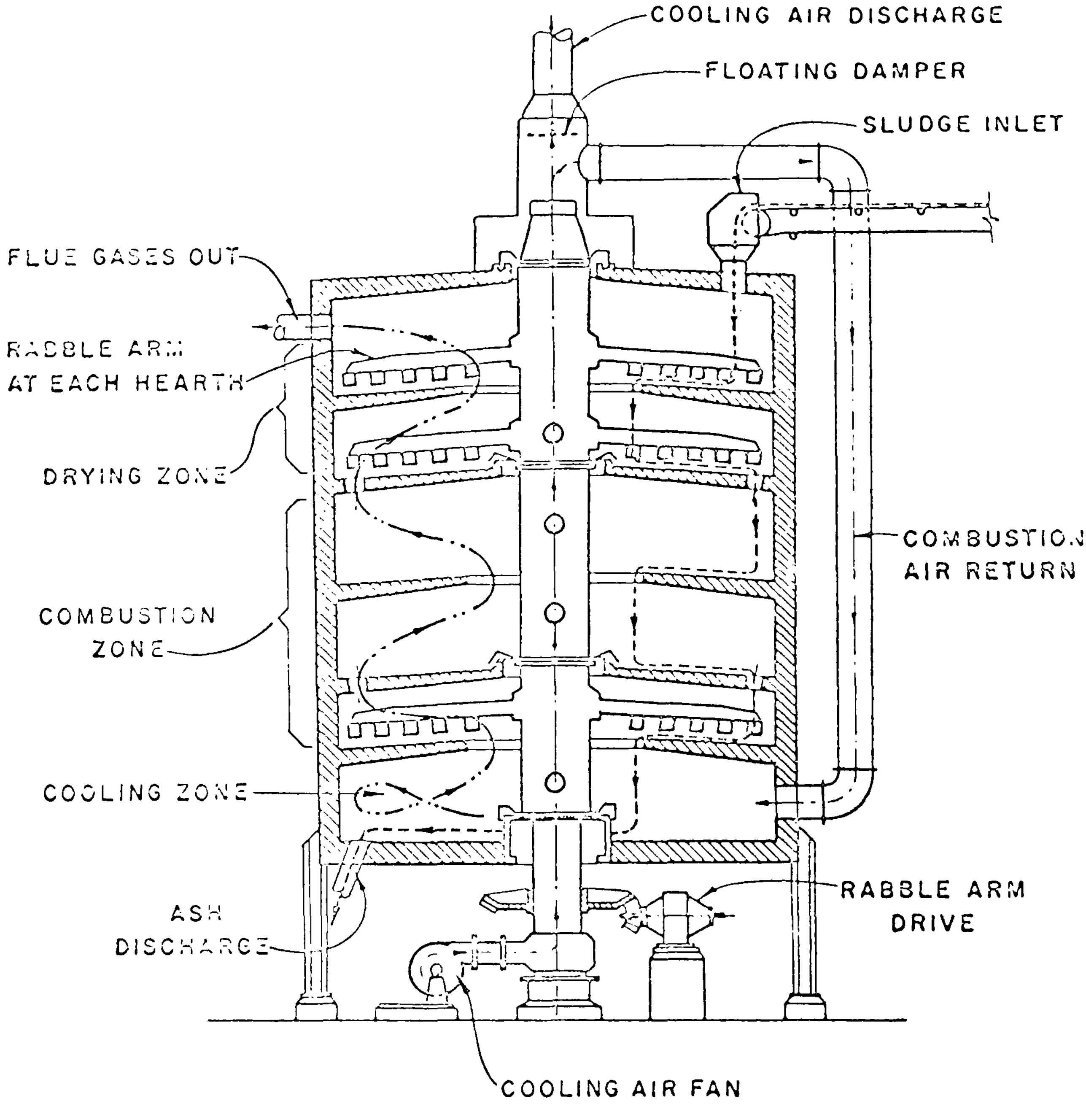
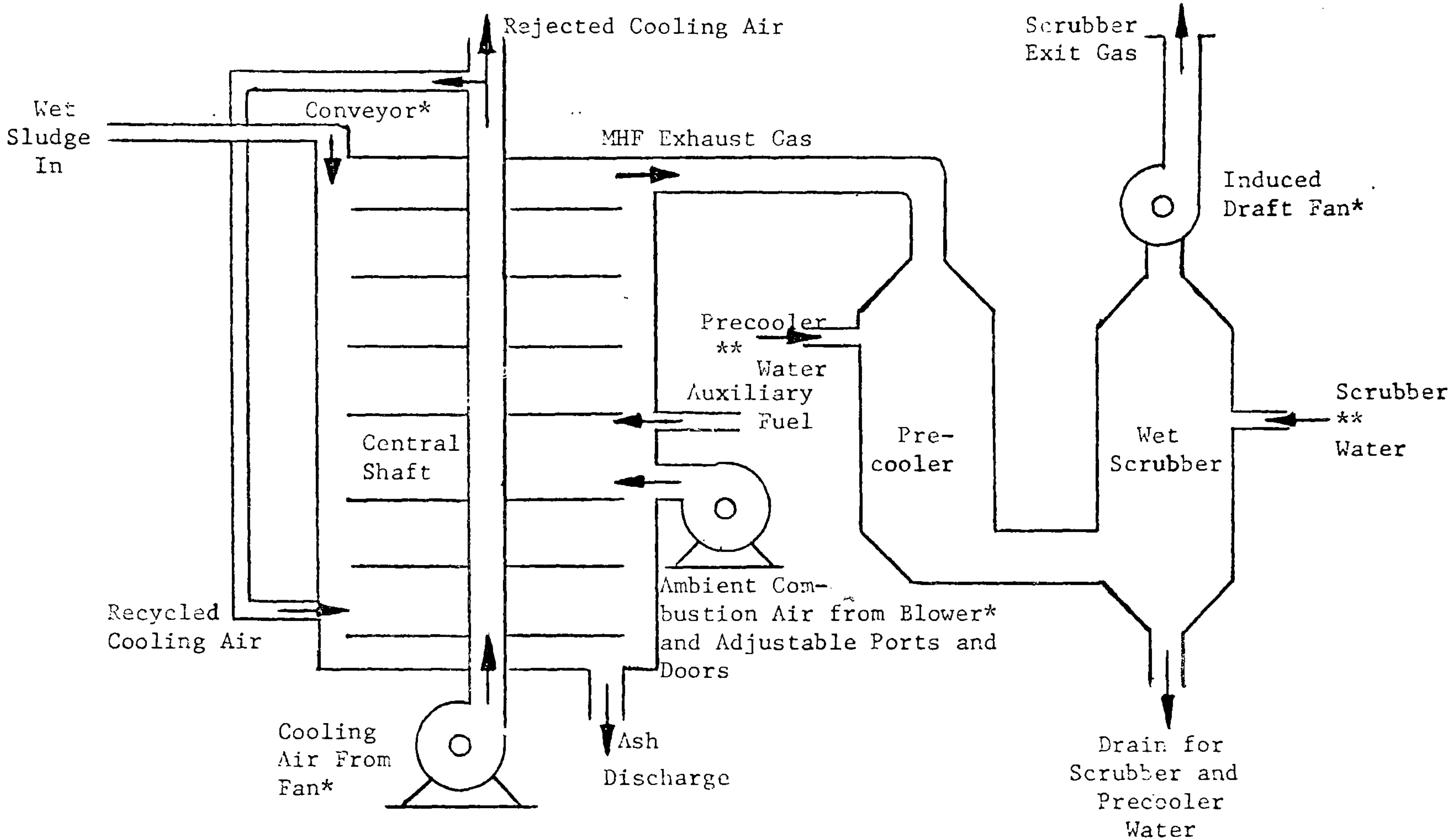


FIGURE 1

TYPICAL SECTION
MULTIPLE HEARTH
INCINERATOR

(from Burd: "Sludge Handling and Disposal," FWPCA Report WP-20-4)



* Electric Motor Drive
** Pump with Motor Drive

FIG. 2. MHF FLOW AND EQUIPMENT DIAGRAM

Isheim (Ref. 3) has given details of the materials and methods of present-day MHF construction. Of particular interest are the design features at the points of maximum temperature in the central hearths. To permit temperatures up to 2000 F, rabble arms and teeth are cast of a nickel-chrome alloy, and the vertical furnace wall is provided with a 13.5 in. thickness of insulation. This is made up of 4.5 in. firebrick next to the combustion zone, followed by 9 in. block type insulation next to the outer steel shell.

The effect of rabbling is continually to "plow up" the solids and break up lumps of material to expose more surface on each hearth to heat and oxygen. In this way, drying, combustion and heat exchange occur at high rates. Owen (Ref. 4) has suggested that the incinerator be divided into three zones (indicated in Fig. 1):

Zone 1 - Sludge Drying

Sludge containing approximately 75 percent water is fed to the top hearth, to be heated and dried by the exhaust gases. The gases are, in turn, cooled to temperatures ranging from 500 F to 1200 F (800 F typical) as they pick up moisture and leave the furnace. The actual exit temperature depends upon the moisture and calorific value of the sludge as well as the amount of additional fuel used. In general, the wetter the feed, the lower the gas outlet temperature, and the cleaner the exhaust gas (Harris, Ref. 5). Owen (Ref. 4) collected data on sludge in Zone 1, finding that its temperature generally did not exceed 160 F (wet bulb temperature) and its moisture content did not fall belo about 48 percent water. However, cake with this moisture content does ignite as it is contacted by upflowing oxidizing gases at 1400 F ("thermal jump").

Zone 2 - Sludge Combustion

After ignition, the volatile solid matter is burnt in a high-temperatur zone, usually in the 1400 to 1600 F range. This has been found adequat to destroy odors. The major portion of the fixed carbon is burnt in th lower hearths of the combustion zone after the volatiles have been incinerated. Excess air, typically 50 to 100 percent over theoretical, is required to maintain combustion temperatures in the 1400 to 1600 F range. The excess air also promotes complete combustion and a clean exhaust.

Zone 3 - Ash Cooling

On the lower hearths of the furnace, the descending hot ashes are cooled as the rising combustion air is heated. The ash discharge temperature will always exceed that of the entering combustion air, be it ambient or recycled cooling air.

Generally, the heat of combustion of sewage sludge lies near 10,000 Btu per pound of volatile solids. Whether or not additional fuel will be needed for incineration depends mainly on (1) the amount of water left in the sludge after vacuum or mechanical filtration, (2) any filtration aid used (quantity and compound, e.g., lime and ferric chloride, or some polyelectrolyte), and (3) whether the sludge is raw or has undergone anaerobic digestion (which converts some of the combustible solids to CO_2 and CH_4). Generally, sludge is autogenous when the solids content exceeds some 25 to 30 percent, with a volatile content (in the solids) about 70 percent. If added energy is required, auxiliary gas, oil, or grease burners located at central hearths (Zone 2) are used, with an independent ambient air supply from a blower.

Exhaust gases from the multiple hearth sludge incinerator are practically free from odors and need not be raised to 1400 F in an afterburner to destroy odors (Sawyer and Kahn, Ref. 6). The reason for this is that the odor-producing compounds are not distilled from the sludge on the top hearths (Harris, Ref. 5). Distillation of volatiles from sludge containing 75 percent moisture does not occur until 80-90 percent of the water has been driven off and by this time presumably the sludge is down far enough in the incinerator to encounter gases hot enough to burn the volatiles.

The size of MHF's used for sewage sludge incineration varies typically from small 6-hearth, 6 ft outer dia (O.D.) units with 85 sq ft total effective hearth area to 12-hearth, 22.25 ft O.D. units with over 3100 sq ft hearth area. Sebastian and Cardinal (Ref. 7) give a table of standard furnace sizes, with hearth areas, to cover the above-mentioned range. When sizing incinerators, a hearth loading, or burning rate, in the range of 7 to 12 lb wet sludge per hr per sq ft hearth area, is usual. The central shaft turns at a few rpm, and the rabbling is so arranged that a sludge depth of an inch or so exists at the design sludge flow, for good operation.

An important factor in MHF operation is the pollutants in the flue gas. It should be realized that, with the typical values cited previously, 100 lb of wet sludge may require some 300 lb of combustion air (without auxiliary fuel). The outflow from the incinerator is then the very desirable small amount of 10 lb ash combined with 390 lb of flue gas. In order to prevent a water pollution problem from turning into an air pollution problem, it is important to reduce unburned hydrocarbons, oxides of nitrogen and particulates to an absolute minimum in the exhaust gases. Incinerator emissions and their treatment are treated in the book edited by Corey (Ref. 8) and an article by Niessen and Sarofim (Ref. 9). The latter present data on the incinerator residence time required to cut down combustible particulates, as a function of temperature and oxygen concentration.

The provision of wet scrubbers, often preceded by pre-coolers, to remove particulates from exhaust gases is quite standard nowadays, see Fig. 2. Two factors must then be considered: disposal of scrubber water, and formation of steam plumes. If the hydraulic method of ash disposal is used, the ash is mixed with water from the scrubber, and after thorough agitation, the mixture is pumped as an ash slurry to a lagoon. Otherwise, Kalika (Ref. 10) describes designs for scrubber water recirculation, with particle collection by settling. He also gives the conditions for formation of steam plumes, primarily an esthetic problem, in terms of temperature and humidity ratio of the scrubbed gas.

ECONOMICS

The economics of MHF sewage sludge incineration have heretofore been studied mainly from an overall cost standpoint. Lacking adequate data, Smith (Ref. 11) estimated total annual cost, capital cost and combined operating and maintenance cost - all in terms of one variable, the dry solids incineration rate. The capital cost estimate was for a rotating-hearth furnace, and the other costs for an unspecified type of furnace. Burd (Ref. 2) quoted a manufacturer's brochure which gave MHF costs based on the size of the population served, and translated this into a total annual cost per ton of dry solids. MacLaren (Ref. 12) made an MHF estimate of a similar nature. Recently, two FWQA-sponsored cost studies have been completed on sewage sludge incineration by fluidized-bed furnaces (Refs. 13 and 14), but this type of furnace is physically quite different from the multiple-hearth.

Studies of MHF sludge incineration have been made for specific communities. Sebastian and Cardinal (Ref. 7) presented costs for city population equivalents ranging from 10,000 to 1 million (dry solids varying from 360 to 36,000 per annum). Quirk (Ref. 15) developed costs for a city of 100,000 (2530 tons of dry solids per annum) in some detail. Weller and Condon (Ref. 16) discussed MHF selection factors and their application to Kansas City, Missouri (average dry solids 30,400 tons per annum). Mick and Linsley (Ref. 17) compared actual performance and cost data for the year 1955 in four cities covering a range in population from 1/2 to 2 million (Buffalo, Cleveland, Detroit, and Minneapolis-St. Paul). The range in dry solids was from 7,242 to 84,290 tons per annum. Mick and Linsley pointed out the difficulties of securing good operation at all times and presented some of the practical considerations.

Burd (Ref. 2) has stated that a general literature review, presumably based on the references cited above, yielded a range in MHF incineration costs of $8 to $40 per ton of dry solids, exclusive of dewatering or ash disposal. Twenty dollars per dry ton was cited as an average. The trend seemed to be towards a lower cost per dry ton as plant capacity increased.

The Committee on Municipal Refuse Practices of the American Society of Civil Engineers (Ref. 18) listed the parameters which generally influence the cost of incineration. These included, in addition to technical and cost factors, the design and operational factors listed below:

1. Skill of operating labor, their productivity, and operating schedule
2. Management competence
3. Record keeping procedures
4. Extent of standby facilities built in

It is certainly an aim of this study to incorporate quantitatively the effects of operating schedule and standby facilities (1. and 4. above).

SYSTEM DEFINITION AND COST COMPONENTS

The system which forms the subject of this model comprises only the components of the MHF incinerator proper, as shown schematically in the MHF Flow Diagram of Fig. 2. This includes the hearths (consisting of castings and refractory); central shaft with rabble arms and teeth; fans and blowers for introducing cooling, combustion and auxiliary air; auxiliary fuel burner; precooler and scrubber for exit gases, with water pump and induced draft fan; the various electric motor drives; and associated instrumentation and controls.

Occupying a place between sludge dewatering and ash disposal processes, the MHF Incineration System includes (1) a conveyor for the incoming sludge, but none of the dewatering equipment upstream, (2) ash discharge duct, but none of the ash slurrying or disposal components downstream, and (3) scrubber gas exit duct (with induced draft fan), but no high stack for gas discharge. The expenditures of fuel, power, and labor are only those associated with the system components as here defined. The incinerator building, the engineering fee and the land occupied by the system are optional capital cost components which the user may elect to include.

The cost components which the model is to compute for the system above will consist of capital and total costs which may be summarized as follows:

<u>Total Capital Cost</u>

broken down into: Installed Capital Equipment
Building - optional
Engineering Fee - optional
Land - optional

Total Cost, per Year and per Ton Dry Solids

broken down into: Total Capital Charges
Replacement Parts (Hearths)
Materials and Supplies (Normal Maintenance)
Fuel
Power
Labor: Operating
Replacement Maintenance
Normal Maintenance

IV. THERMAL ANALYSIS

The previous Chapter has described the functioning of MHF sewage sludge incinerators. The desired conversion of wet sludge to ash plus exhaust gases is only feasible if sufficient heat can be generated to evaporate the water (typically 75 w/o in the sludge) and burn the resulting dried sludge. The known quantities are usually (1) the sludge composition and properties (including the heat value of the volatiles); (2) the desired temperatures of the exit streams (ash, gases, cooling air) for satisfactory operation; and (3) the desired minimum percent excess combustion air. The heat and mass balances for the steady-state thermodynamic system represented by the furnace (Fig. 2) can then be combined with the stoichiometry of the combustion of sludge volatiles and any other chemical reactions occurring (such as calcination of any calcium carbonate in the sludge) to solve for the unknowns.

The unknowns include (1) actual percent excess air for combustion of volatiles and the corresponding air flow required, (2) any additional heat required from an auxiliary fuel burner, (3) the resulting burner fuel and air flows, (4) the exhaust gas composition, and (5) the resulting scrubber water requirements, if any, to saturate the exhaust gases. The equations and procedures from which the unknowns are calculated are presented in this Chapter.

Description of each of the terms in all of the equations would unduly lengthen this Chapter and interrupt the continuity of the development. Consequently, the bulk of the nomenclature is included in the Glossary (Chapter XII) and only essential terms are explained in the text. It is strongly recommended that the reader reproduce the pages in the Glossary to avoid the need for constantly turning pages.

The Thermal Analysis option of the computer subroutine is described in Chapter VII and the Fortran listing appears in the Appendix.

SLUDGE COMBUSTION AND REACTIONS OF CHEMICAL ADDITIVES

It is assumed that the incoming sludge stream from the dewatering device immediately ahead of the incinerator has a known composition in terms of the reactive solids, i.e., sludge and chemical additives. With an ultimate sludge analysis in terms of elemental C, H, Ø, N, and S and a sludge heat value (higher calorific value) determined in a bomb calorimeter, the equilibrium combustion products composition at a specified volatile/air mixture ratio and initial temperature and pressure can be found by minimizing the free energy of the system. In the most general (high-temperature) case, hundreds of compounds may form because of dissociation effects.

In the present case, no adiabatic flame temperatures above 2000 F were considered, nor any rich mixture ratios. For stoichiometric and lean mixtures (excess air), then, the sludge air combustion products were taken to be CO_2, H_2O, SO_2, N_2, and O_2. The initial conditions are at sludge temperature (taken as datum) and 1 atmosphere pressure. All combustion and chemical reactions take place at one atmosphere. All calculations refer to one MHF. The Glossary (Chapter XII) defines all symbols used.

The theoretical (stoichiometric) oxygen flow (lb/hr) is then

$$\text{PØ2S} = \text{PVØL} \left[\frac{\text{FRVØ(1)}}{\text{ELMW(1)}} \cdot \text{SPMW(3)} + \frac{\text{FRVØ(2)}}{\text{ELMW(2)}} \cdot \frac{\text{SPMW(3)}}{2} + \frac{\text{FRVØ(5)}}{\text{ELMW(5)}} \cdot \text{SPMW(3)} - \text{FRVØ(3)} \right], \qquad (1)$$

where

$$\text{PVØL} = \text{(PSLU) (PERV) (PERS)}/10{,}000 \qquad (2)$$

With the specified minimum excess percentage (PXAIR), the total air flow (lb/hr) is

$$\text{PAIRT} = \frac{\text{PØ2S}}{0.233} \left(1 + \frac{\text{PXAIR}}{100}\right) \qquad (3)$$

where 0.233 is the weight fraction of oxygen in air

Knowing the fraction of cooling air recycled (FRAIR) and the total cooling air flow in standard cu ft per hr (SCFCL) then gives the ambient combustion air to be supplied by the combustion air blower as

$$\text{PAIRA} = \text{PAIRT} - \text{PAIRS} \qquad (4)$$

where

$$\text{PAIRS} = 28.84 \text{ (SCFCL (FRAIR)}/379 \qquad (5)$$

where 28.84 is the molecular weight of air, 379 is the volume in cu ft of 1 lb-mole of gas at 60 F and one atmosphere.

Allowance was made for three types of chemical additives in the dewatering process, namely, lime (calcium monoxide CaO or calcium hydroxide, $Ca(OH)_2$), ferric chloride (anhydrous $FeCl_3$ or $FeCl_3 \cdot 6H_2O$ crystal) and alum (aluminum sulfate, $Al_2(SO_4)_3 \cdot 14H_2O$). The reaction of these additives with the sludge produces calcium carbonate $CaCO_3$, ferric hydroxide $Fe(OH)_3$, and aluminum hydroxide $Al(OH)_3$. It was assumed that the concentrations of these compounds in the incoming sludge stream are known from the previous process step (sludge dewatering). In the incinerator, these compounds undergo endothermic reactions according to the following equations (heats of reaction from Refs. 19 and 20):

$$CaCO_3 + X(761\ \text{Btu/lb}\ CaCO_3) = X\ CaO(s) + XCO_2 + (1-X)\ CaCO_3 \quad (6)$$

$$Fe(OH)_3 + Y(225\ \text{Btu/lb}\ Fe(OH)_3) = 1.5Y\ H_2O + 0.5Y\ Fe_2O_3(s) + (1-Y)\ Fe(OH)_3 \quad (7)$$

$$Al(OH)_3 + Z(380.8\ \text{Btu/lb}\ Al(OH)_3) = 1.5Z\ H_2O + 0.5Z\ Al_2O_3(s) + (1-Z)\ Al(OH)_3 \quad (8)$$

where

X = FCAC is fraction $CaCO_3$ decomposed

Y = FFE is fraction $Fe(OH)_3$ decomposed

Z = FAL is fraction $Al(OH)_3$ decomposed

Considering the combustion of the sludge and the reactions of the chemicals, the flowrates of gaseous products (excluding contributions from auxiliary fuel combustion and initial sludge water) are:

$$WS(1),\ (\text{lb}\ CO_2/\text{hr}) = (PV\text{Ø}L \cdot FRV\text{Ø}(1) \cdot SPMW(1)/ELMW(1)) + (44.011\ FCAC \cdot PCAC \cdot PS\text{Ø}L/10{,}008) \quad (9)$$

$$WS(2),\ (\text{lb}\ H_2O/\text{hr}) = (PV\text{Ø}L.\ FRV\text{Ø}(2) \cdot SPMW(2)/ELMW(2)) + (27\ PFEHY.\ FFE.\ PS\text{Ø}L/10{,}687) + (27\ PALHY.\ FAL.\ PS\text{Ø}L/7800.3) \quad (10)$$

$$WS(3),\ (\text{lb}\ O_2/\text{hr}) = P\text{Ø}2S.\ PXAIR/100 \quad (11)$$

$$WS(4),\ (\text{lb}\ N_2/\text{hr}) = (PV\text{Ø}L.\ FRV\text{Ø}(4).\ SPMW(4)/ELMW(4)) + (0.767.\ PAIRT) \quad (12)$$

where 0.767 is the weight fraction of nitrogen in air

$$WS(5), \text{ (lb } SO_2\text{/hr)} = PV\emptyset L.\ FRV\emptyset(5).\ SPMW(5)/ELMW(5). \tag{13}$$

where

$$PS\emptyset L = PERS.\ PSLU/100 \tag{14}$$

$$PERW = 100\text{-}PERS \tag{15}$$

HEAT BALANCE

The total heat supplied (QIN) comes from three sources: heat from combustion of the volatiles (QVØLT), heat from the recycled shaft cooling air (QARIN), and heat from the incoming ambient air (QAMBA), assumed to be above sludge temperature, the datum. All gaseous (low pressure) specific heats were taken as functions of T from Ref. 21.

$$QIN = QV\emptyset LT + QARIN + QAMBA. \tag{16}$$

where

$$QV\emptyset LT = QV\emptyset L\ .\ PV\emptyset L. \tag{17}$$

$$QARIN = PAIRS \int_{TSLI}^{TAIRI} CPA.dT \tag{18}$$

$$QAMBA = PAIRA \int_{TSLI}^{TAMB} CPA.dT. \tag{19}$$

The total heat required (QREQ) to raise the combustion products to TEX and the ash to TASH is made up of eight components, as shown below (all in Btu/hr):

$$QREQ = HASH + HWSL + QC\emptyset\emptyset L + QCAL + QFE + QALHY + QTRAN + QSEN. \tag{20}$$

where

$$HASH = PASH.\ CPASH\ (TASH - TSLI) \tag{21}$$

$$PASH = PS\emptyset L\ (100\text{-}PERV)/100 \tag{22}$$

$$HWSL = HWSEN + HWVAP + HWGAS. \tag{23}$$

$$HWSEN = PWAT.\ CPWAT\ (212-TSLI) \qquad (24)$$

$$PWAT - PSLU\ (100-PERS)/100 \qquad (25)$$

$$HWVAP = 970\ PWAT \qquad (26)$$

$$HWGAS = PWAT. \int_{212}^{TEX} CPS.dT \qquad (27)$$

$$QC\emptyset\emptyset L \text{ (total cooling air)} = PAIRC \int_{TAMB}^{TAIRI} CPA.dT \qquad (28)$$

$$PAIRC = 28.84\ SCFCL/379 \qquad (29)$$

$$QCAL = 761\ PCAC.\ PS\emptyset L.\ FCAC/100 \qquad (30)$$

$$QFE = 225\ PFEHY.\ PS\emptyset L.\ FFE/100 \qquad (31)$$

$$QALHY = 380.8\ PALHY.\ PS\emptyset L.\ FAL/100 \qquad (32)$$

$$QTRAN = (HR + HC)\ (TSUR - TAMB)\ SAREA \qquad (33)$$

where

$$HR \text{ (Ref. 22)} = 0.1713 \left[\left(\frac{TSUR + 460}{100} \right)^4 - \left(\frac{TAMB + 460}{100} \right)^4 \right] \Big/ (TSUR-TAMB) \qquad (34)$$

$$SAREA = 3.142\ (HDIA)\ (0.5\ HDIA + 4\ NHEAR) \qquad (35)$$

$$HC \text{ (Ref. 22)} = 0.29\ (1 + 0.255\ VAMBF)\ (TSUR-TAMB)^{.25}\ (HDIA)^{.25} \qquad (36)$$

$$QSEN = \sum_{1}^{NUMSP} WS(I) \int_{TSLI}^{TEX} CP(I).dT + 1048\ WS(2) \qquad (37)$$

The excess of supplied over required heat is

$$QNET = QIN - QREQ \qquad (38)$$

If QNET is positive, TEX is above its assumed value and excess air must be added to reduce TEX to its desired value and QNET to approximately zero. This is carried out by iterating on PXAIR over equations (3) through (38). In this case, no auxiliary fuel is required.

If QNET is negative, auxiliary fuel must be burned at a temperature above TEX to provide the heat for the gases to reach TEX.

AUXILIARY BURNER SELECTION

The burner must supply additional fuel and air. The theoretical (stoichiometric) oxygen requirement (lb oxygen per lb fuel) for the burner is

$$BURN\emptyset = \frac{FRFU(1)}{ELMW(1)} SPMW(3) + \frac{FRFU(2)}{ELMW(2)} \frac{SPMW(3)}{2} + \frac{FRFU(5)}{ELMW(5)} SPMW(3) - FRFU(3) \quad (39)$$

The burner air (lb per lb fuel) needed for a specified burner percent excess air (EXAFU) is

$$BURAI = BURN\emptyset\ (1 + (EXAFU/100))/0.233 \quad (40)$$

The combustion products (lb per lb fuel) are then

$$BRN(1) = FRFU(1)\ SPMW(1)/ELMW(1) \quad (41)$$

$$BRN(2) = FRFU(2)\ SPMW(2)/ELMW(2) \quad (42)$$

$$BRN(3) = (BURN\emptyset)\ (EXAFU)/100 \quad (43)$$

$$BRN(4) = FRFU(4) + .767\ BURAI \quad (44)$$

$$BRN(5) = FRFU(5).\ SPMW(5)/ELMW(5) \quad (45)$$

The heat (Btu per lb fuel) to raise these products to TEX is

$$DHBUR = \sum_{1}^{NUMSP} BRN(I) \int_{TSLI}^{TEX} CP(I).dT + 1048\ BRN(2) \quad (46)$$

The percent available heat from the burner (or combustion efficiency of the fuel) is

$$FEFF = (QFU - DHBUR)/QFU \quad (47)$$

because the QFU is based on cooling the products back down to sludge temperature.

The gross heat requirement (Btu/hr) is then

$$QGR\emptyset S = QNET/FEFF \quad (48)$$

The total burner heat requirement (Btu/hr) is

$$QBUR = QGR\emptyset S\ (1 + (BUREX/100)) \tag{49}$$

where BUREX is a specified percent excess burner capacity.

The fuel flowrate (lb/hr) needed is

$$WGTF = QBUR/QFU \tag{50}$$

and the burner flowrate is

$$WBAIR\ (lb/hr) = (WGTF)\ (BURAI) \tag{51}$$

or

$$SCFAI\ (scfh) = 379\ WBAIR/28.84 \tag{52}$$

A quantity of some interest is the burner heat in BTU per scf of burner combustion air, given by

$$BTUV = QBUR/SCFAI \tag{53}$$

EXHAUST GAS COMPOSITION

The exhaust gases are increased by the amount of the burner combustion products making the total flow for the Ith species

$$T\emptyset T(I)\ (lb/hr) = WS(I) + WGTF.BRN(I) \tag{54}$$

or

$$V\emptyset L(I)\ (cu\ ft/hr) = 10.73\ T\emptyset T(I)\ (TEX + 460)/(SPMW(I))(PSCRE) \tag{55}$$

where

$$PSCRE = 14.696 - (4.2\ (ELE)/9000) \tag{56}$$

is a linear fit from 0 to 14,500 ft of the NACA Standard Atmosphere.

The total exhaust flow is

$$GT\emptyset T\ (lb/hr) = \sum_{I=1}^{NUMSP} T\emptyset T(I) \tag{57}$$

or

$$TV\emptyset L \text{ (acfh)} = \sum_{I=1}^{NUMSP} V\emptyset L(I) \quad (58)$$

The exhaust density (lb/cu ft) at TEX and entry to the scrubber is then

$$ROEX = GT\emptyset T/TV\emptyset L \quad (59)$$

SCRUBBER WATER FOR EXHAUST GAS SATURATION

The scrubber exit specific volume (cu ft per lb of dry gas) is

$$VSAT = 10.73\ (1+ [PSWAT\ /(PSCRE-PSWAT)\ ])(TSCRB + 460)/(DRYMO.PSCRE) \quad (60)$$

where

$$PSWAT = 1.78885 \exp\ [15.9014\ (TSCRB-121.48)/(TSCRB + 460)] \quad (61)$$

representing a curve fit of water vapor pressure data.

$$DRYMO = \sum_{I=1,3,4,5} SPMW(1).V\emptyset L(I)/VDRY \quad (62)$$

$$VDRY = TV\emptyset L - V\emptyset L(2) \quad (63)$$

The saturated exit gas flowrate from the scrubber (acfm) is

$$VSCEX = GDRY.VSAT/60 \quad (64)$$

where

$$GDRY = GT\emptyset T - T\emptyset T(2) \quad (65)$$

The scrubber water flowrate to saturate the exit gas is

$$WATSC \text{ (lb/hr)} = \frac{PSWAT.SPMW(2).GDRY}{DRYM\emptyset\ (PSCRE-PSWAT)} - T\emptyset T(2) \quad (66)$$

or

$$VWATS \text{ (gpm)} = WATSC/(8.345)\ (60) \quad (67)$$

If the water content of the gas entering the scrubber equals or exceeds the saturation level, no extra water is needed for saturation.

The Thermal Analysis Subroutine uses the results of the Sections titled "Heat Balance" and "Exhaust Gas Composition" to print out a heat balance (which contrasts the required vs supplied heat quantities) and a mass balance (which considers all streams: sludge, ash, air, exhaust gas and auxiliary fuel) for the MHF system.

V. DATA ACQUISITION

DATA REQUIREMENTS

The Thermal Analysis described in Chapter IV consists of thermodynamic relationships among the various streams (characterized by flowrate, composition, and temperature) which flow in and out of the MHF incinerator. Practical considerations dictate the values or ranges of values which certain streams must assume to ensure satisfactory operation. These technical considerations, discussed in Chapter III, include:

1. Hearth and exhaust gas temperature level high enough to prevent odors;

2. Hearth, exhaust, and ash temperatures low enough to prevent failure of furnace parts due to overheating;

3. Heatup and cooldown transients slow enough to prevent failure of refractory due to thermal stresses;

4. Combustion efficiency and percent excess air high enough to keep pollutants in exhaust gas below maximum allowable concentrations.

Requirements for effective operation include:

1. Efficient operating schedule, well integrated with operation of entire wastewater treatment plant;

2. Good use of operating manpower, considering operator skill and integration with the rest of the treatment plant;

3. Effective maintenance schedule to maximize the processing capacity of the MHF.

A field study of a number of operating MHF sludge incinerators was considered the best means to acquire data on the design and operational factors listed above, and on their relationship to costs. Hopefully, the field study was to provide information on how the simultaneous requirements set forth above were met in practice. At the same time, the data were to be used to model various relationships which could be used to optimize MHF incineration systems for many applications in a rational manner.

FIELD DATA

It was thought essential to study municipal incineration plants which varied as to number of MHF's; size and capacity of a unit MHF; sludge type and composition; plant operating mode; and manufacture. The scope of the project permitted a survey in depth at seven locations. A selection procedure narrowed the dozens of cities in the U.S. with MHF sludge incinerators down to these seven cities, comprising nine incineration plants:

Cleveland, Ohio (2 incineration sizes)
Minneapolis-St. Paul, Minnesota (installed 1938, 1951)
Kansas City, Missouri
Battle Creek, Michigan (2 incineration sizes)
Saginaw, Michigan (installed 1963)
Hatfield, Pennsylvania
Bridgeport, Pennsylvania

In addition to the in-depth data on the nine basic incineration plants, capital cost and other limited data were obtained on another four plants located at:

South Tahoe, California
Minneapolis-St. Paul (installed 1965)
Saginaw (installed 1969)
East Rochester, New York

In order to get the most out of the field visits, a carefully thought-out set of "Instructions to Field Personnel" was developed to cover all aspects (design, performance, operation, cost). Through coordination with the FWQA, and state and local authorities (as applicable), as much advance information as possible was gathered before the actual visits. The visits took place in the latter half of 1969 and were conducted by engineering personnel with a design and/or operation background in MHF sludge incineration.

For each of the seven cities visited, a comprehensive Field Report was written by the field engineer. The information in these reports was obtained from actual inspections and conversations with plant personnel, and from records on file. Each Field Report was subjected to three reviews before being finalized. The seven Field Reports are on file with the WQO-EPA Project Officer whose name appears in the Acknowledgements (Chapter X) of this report and are available for inspection by qualified requestors.

The task of reducing and correlating data from the Field Reports was not straightforward because data were reported differently and sometimes were not available. A second contact was made in about half the cases studied to obtain clarifications or additional information of a detailed nature. To verify installed capital costs, the consulting engineers associated with all the incinerators were contacted for their records.

Data, which could be worked up in numerical form and presented in useful correlations, appear in the next Chapter (VI) on Data Reduction and Correlation. The present chapter contains field information useful in itself, discussed below.

Summary of MHF Installations

Overall data on the 13 plants mentioned above are presented in Table 1.

Effectively, the incineration plants studied in depth (Nos. 1 through 9) provide variations in

Number of furnaces	From 1 to 4
Single-furnace design capacity	From 200 to 4500 lb dry solids per hr
Number of hearths	From 5 to 9 per furnace
Outer diameter	From 6 to 22.25 ft.
Effective hearth area	From 85 to 2327 sq ft per furnace
Total solids in sludge	From 20 to 53 weight percent

Summary of Annual Average MHF Steady-State Operation

The annual utilization of MHF incinerators, by capacity and time, for all plants studied, is shown in Table 2. The nominal operating schedule, which varied from round-the-clock down to 16 hr per week, is seen to have a large effect on the annual "load factor". This is the product of two quantities X and Y. The quantity X is the total annual operating hours divided by the number of round-the-clock hours per year. The quantity Y is the actual dry solids flow rate in the operating incinerator divided by the design dry solids flowrate.

In one plant, (MHF No. 1), less than the total number of MHF's ran at one time, while in another plant (MHF No. 6) the annual amount incinerated exceeded the nominal value, due to operation at over-capacity and over-time. In yet another plant (MHF No. 3), only 2 of the 3 total units operate simultaneously, so that there is always a standby unit. The operating schedule is an important factor in the Subroutine, see Chapters VI and VII.

TABLE 1

SUMMARY OF MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATORS

MHF No.	MHF Incinerator Location	B=Bid C=Contract First Operating Year	No. of MHF's	MHF Unit Data			Opg. Data Period Years 19--	Dry Solids Rate/MHF		Avg. Total Solids, Wt. %	Avg. Hearth Loadg, Dry Lb/Hr Ft²	Mfr. B=BSP N=Nerco
				Outer Dia, Ft-In	No. of Hearths	Hearth Area, Ft²		Avg. Lb/Hr	Max. Lb/Hr			
1	Cleveland	1966	4	22-3	9	2327	66-69	4167*	7910	25*	1.79*	B
2	Minn.-St.Paul	1938, 1951	3,1	22-3	8	2084	38-68	3600	5080	35-27	1.73	N
3	Kansas City	1966	3	22-3	8	2084	67-69	4500*	4800	29	2.16*	N
4	Cleveland	1940	4	18-9	8	1425	58-66	2083*	5370	25*	1.47*	N
5	Battle Creek	1966	1	18-9	6	1068	68-69	2050*	3650	26	1.92*	B
6	Battle Creek	1962	1	18-9	5	890	62-67	1625*	1690	26	1.83*	N
7	Saginaw	1963	1	16-9	6	845	66-69	1880	2820	53**	2.22	N
8	Hatfield	1967	1	10-9	5	230	67-69	400	480	20	1.74	N
9	Bridgeport	1964	1	6-0	6	85	69	200*	336*	25*	2.35*	N
10	South Tahoe	1967C	1	14-3	6	575	Not	900*	-	15*	1.57*	B
11	Minn.-St. Paul	1965C	3	22-3	11	2808	Part	6250*	6775*	25*	2.23*	B
12	Saginaw	1969B	1	22-3	6	1560	of Main	5170*	--	45***	3.32*	N
13	East Rochester	1963C	1	10-9	5	230	Study	480*	600*	25*	2.09*	B

* Design

** High Oil/Grease Content

TABLE 2

SUMMARY OF STEADY-STATE OPERATION PER MHF (ANNUAL AVERAGES)

MHF No.	Location	Eff. Hearth Area per MHF, Sq Ft.	Total No. of MHF's	Nominal Steady-State Operating Schedule Fraction of Full Time	Year or Period	Actual Steady-State Operation Fraction of Full Time, (X)	Actual/Design Dry Solids Flow Ratio (Y)	Actual Tons/Yr / Full-Time Design Tons/Yr = Load Factor, (X).(Y)
1	Cleveland	2327	4	1.0	1966	.260	.723	.188
				(24 Hr x	1967	.223	.690	.154
				7 Day/Wk)	1968	--	--	.230
2	Minn.-St. Paul	2084	4		1966	.885	.590	.520
					1967	.889	.670	.595
					1968	.855	.813	.691
4	Cleveland	1425	4		62-65	.718	.621	.446
7	Saginaw	845	1		1966	.851	1.06	.900
					1967	.846	.99	.837
					1968	.920	1.01	.926
					1969	.930	.996	.926
3	Kansas City	2084	3	0.714	67-69	.476	.775	.369
5	Battle Creek	1068	1	(24 Hr x	1968	.654	1.03	.675
				5 Day/Wk)	1969	.666	.937	.624
6	Battle Creek	390	1		1964	.597	.846	.505
					1965	.759	1.075	.816
					1967	.796	1.012	.806
9	Bridgeport	85	1	0.357 (12 x 5)	1969	.2975	.848	.252
8	Hatfield	230	1	0.095 (8 x 2)	67-69	.033	--	--
						.080		

MHF Air, Ash and Gas Temperatures

Table 3 collects available data, which vary widely due to different MHF "technical" operation, e.g., ash discharge temperatures vary over hundreds of degrees. Much of this spread is probably due to differences in the temperature of the incoming combustion air, which may vary hundreds of degrees, depending on whether it is mainly ambient or recycled cooling air.

MHF Hearth Temperatures

Table 4 shows that hearth temperature profiles were only available for about half the furnaces visited. Except for the Hatfield plant, all MHF's in the table are quite comparable, having 5 and 6 hearths and a small variation in hearth area (845 to 1068 sq ft). They appear to be well-operated, with a 1600-1700 F maximum at hearth 3, a bottom hearth at 450-500 F, and a top hearth at 800-920 F. For MHF Nos. 5, 6, and 7, the top hearth temperature is measured above the hearth, and so is close to the exit gas temperature (Table 3). For MHF No. 8, the 160 F on the top hearth is the sludge temperature, probably the wet bulb temperature mentioned in Chapter III.

MHF Air Sources

Table 5 indicates the variety of adjustable openings to admit ambient air to MHF's. All the units are operated manually, and in many cases the degree of openings of doors, ports and registers is left to a subjective judgment, based on experience. Every MHF, of course, has a cooling air fan and a combination air blower. It is interesting to note that in Minneapolis (MHF No. 2) cooling air is recycled to hearths 4 and 6, as well as to the bottom hearth 8.

Maintenance Log for Minneapolis-St. Paul from Annual Reports 1951-65

Table 6 is a detailed compilation of every maintenance action listed in the annual reports by "General Maintenance" and by individual incinerator. This record is unique among the plants studied, and gives an idea of what maintenance may be necessary in a well-run MHF subject to round-the-clock operation. In Chapter VI, these data are used as a basic for extraction of a 25 yr lifetime hearth replacement for incorporation into the Subroutine.

TABLE 3

MHF AIR, ASH AND GAS TEMPERATURES

MHF No.	Location	Percent Excess Air	Cooling Air Exit Temp, °F	Ash Temp, °F	Combustion Gas Exit Temp, °F	Scrubber Exit Temp, °F	Furnace Draft, in Water
1	Cleveland	(Est.) 50	200		800–1000		-0.1
2	Minn.-St. Paul	(Est.) 50		100	800	No Scrubber*	-0.2
3	Kansas City	(Est.) 50-60	300	$>$ 850	685	165	-0.25 to -0.3
5	Battle Creek	(Est.) 80		180	800	180	-.02
7	Saginaw	20	380	350–400	1000–1360	170	-0.9
8	Hatfield	50		750	750		-2
9	Bridgeport	(Est.) 50	250–350 Vented**	150	350 800 ?		-0.2

* Dust-precipitating flue used instead

** Cooling air not recycled

TABLE 4

MHF HEARTH TEMPERATURES

MHF No.	5			6			7			8		
Location	Battle Creek			Battle Creek			Saginaw			Hatfield		
MHF Size	18.75 Ft.OD x 6 Hth			18.75 Ft.OD x 5 Hth			16.75 Ft.OD x 6 Hth			10.75 Ft.OD x 5 Hth		
Hth.Area,Sq Ft.	1068			890			845			230		
Shaft RPM	1.0			1.0			2.0			< 1		
Hearth Number	Rabble Arms	Rabble Teeth	Temp. °F	Rabble Arms	Rabble Teeth	Temp. °F	Rabble Arms	Rabble Teeth	Temp. °F	Rabble Arms	Rabble Teeth	Temp. °F
1 (top)	4	15	800*	4	16	800*	4	12	920	4	20	160
2	4	16	1200*	2	15	1200	4	14	1700	4	20	525
3	4	17	16/1700*	2	16	16/1700*	4	12	1720	2	10	1325*
4	2	19	16/1700	2	15	1200*	2	13	1240*	2	10	900
5	2	17	1200*	4	16	500*	2	11	--	2	10	750*
6	2	19	500				2	14	450*			

*Location of Auxiliary Fuel Burners

NOTE: Average height of each hearth = 3-1/2 ft, approximately

TABLE 5 : MHF AIR SOURCES

MHF No.	Location	Air Sources
1	Cleveland	Comb. air blower, Cooling air Opened doors (full open 3000 SCFM ea) Burner air
2	Minneapolis- St. Paul	Comb. air blower (700 CFM) Cooling air (Fed to HTH 4, 6, & 8) Opened doors (2'6" x 16-1/2")
3	Kansas City	Cooling air @ 300 F fed at HTH 8 (2500 CFM @ 2-1/2" H_2O) Peep doors 4-1/2" x 7" (400 SCFM @ .25" H_2O) Comb. air blower used only with burners on
4	Battle Creek	Comb. air blower (3000 SCFM) Opened furn. doors (865 SCFM-13"x17") Air ports (14 SCFM @ .02" W) Cooling air to HTH 5 Burner air
5	Saginaw	Comb. air blower Opened doors (1850 SCFM @ 0.09" W) Ports (235 ft^3/min @ 0.09" W)
6	Hatfield	Cooling air to hearth 5 Burner air
7	Bridgeport	Ports Burner registers Slightly open doors (3-6 lb air/lb dry sludge)

TABLE 6

MAINTENANCE LOG FOR MINNEAPOLIS-ST. PAUL
FROM ANNUAL REPORTS 1951 - 1965

NOTES: (1) When no items are recorded for the 4 individual incinerators (B, C, D, E), refer to general maintenance (A) for that year, especially for arm and tooth maintenance.
(2) ppter = precipitator

A. General Maintenance

1951	(Minor maintenance) 2 rabble arms replaced with rebuilt arms 20 new rabble teeth Brick repaired in all incinerators 2 panels in the dust ppter flue were rebricked 1 channel support reinforced Sludge feeders rebuilt New-plates welded around no 3 hearth of all incinerators.
1952	2 rabble arms replaced with rebuilt arms 2 rabble teeth replaced with used teeth Inner lining of chimney repaired Top 8 ft. of acid-resistant brick in chimney were replaced
1953	5 rabble arms replaced - only 1 with new arm 24 rabble teeth Steel plates and brick in dust ppter replaced
1954	6 rabble arms replaced in incinerators No. 1, 2, 3 81 rabble teeth replaced in incinerators No. 1, 2, 3 Few liner bricks replaced in fly ash ppter.
1955	Ash pump overhauled 10 rabble arms replaced 80 rabble teeth replaced
1956	Fly ash ppter flue replaced Extensive duct work changes made 16 rabble arms replaced - 4 scrapped 58 rabble teeth replaced
1957	12 rabble arms replaced - 1 scrapped 55 rabble teeth replaced
1958	Nominal repair 2 rabble arms repaired

TABLE 6 (Continued)

A. General Maintenance (Continued)

1959	3 rabble arms replaced (none scrapped) 18 rabble teeth replaced Brick work in boilers repaired Oil preheater insulated Paddle alarm devices installed on the incinerator conveyor belts
1960	Nominal brick work 11 rabble arms replaced 44 rabble teeth replaced Remote controls for central shaft drive installed on incinerators No. 2, 3, and 4
1961	Light maintenance 7 rabble arms replaced (none scrapped) 9 rabble teeth replaced
1962	New belt installed on south incinerator belt conveyor North incinerator belt drive overhauled 4 rabble arms replaced 3 rabble teeth replaced
1963	Ash sluicing pump P-57 overhauled 5 rabble arms replaced A few rabble teeth replaced
1964	Repairs of dust ppter & water cooled damper guides Damper guides reanchored Ducts rebuilt and lined with castable refractory and then insulated on exterior 11 rabble arms replaced A number of rabble teeth replaced Sump Pumps - new triple ball floats and switches installed
1965	Ash pump P-56, P-57 had sheave changes to increase pump speed Ash pump P-56 had complete overhaul General inspection and repair of incinerators Some teeth replaced

B. Incinerator #1 (first full operating year: 1939)

1951	Minor maintenance
1952	Minor maintenance
1953	Minor maintenance

B. Incinerator #1 (Continued)

1954	Hearths 2 and 4 completely rebuilt from steel shell Hearth 3 rebuilt from brick wall Insulation and wall brick between 2-4 replaced
1955	Hot gas ducts insulated on top half-saddles and pipe columns installed 2 low (rabble) arms replaced 9 teeth replaced
1956	Hearth 1 rebuilt Hearth 3 ring of brick added Hearth 6 several bricks replaced Hearths 4 and 6 lute caps rebuilt Several arms and teeth replaced
1957	OK
1958	Nominal
1959	Bottom bearing replaced for first time
1960	Exterior shell plates welded on at hearths 2 and 3 Central shaft Reeves drive overhauled Plates welded on cooling tower
1961	Bricks replaced 4 rabble arms replaced 7 rabble teeth replaced
1962	Down for repairs at close of year
1963	5 rabble arms were replaced A few rabble teeth were replaced Some brick work on 2 hearths replaced
1964	Broken rabble arms on hearth 3 and on hearth 5 replaced Burner box (southeast) was rebuilt Bypass damper replaced with rebuilt damper
1965	Repacked shaft at cooling air inlet 5 rabble teeth installed Oil burner installed on hearth 4

C. Incinerator #2 (first full operating year: 1939)

1951	Minor maintenance
1952	Minor maintenance
1953	Minor maintenance

TABLE 6 (Continued)

C. Incinerator #2 (Continued)

1954 Hearths 2, 3, and 4 were rebuilt and insul. and brick wall replaced

1955 Hot gas ducts insulated on top half-saddles & pipe columns installed
Hearths 2, 3, and 4 were rebuilt-cont. from 1954
Repair to wall brick and burner boxes
8 rabble arms replaced
51 rabble teeth replaced

1956 Hearth 6 - several wall brick were replaced
Hearth 1 - being rebuilt

1957 Hearth 1 rebuilding completed

1958 Nominal

1959 Nominal

1960 Bottom bearing replaced (first time)
Exterior shell plates welded at hearths 2 and 3
Remote control of central shaft drive installed

1961 1 burner box repaired

1962 OK

1963 OK

1964 5 rabble arms replaced (2 on hearth 2, 1 on hearth 4, 1 on hearth 5, and 1 on hearth 7)
A number of rabble teeth replaced
2 burner boxes on hearth 4 and 1 on hearth 6 repaired
Hearth 6 brick work bad; hearth was virtually rebuilt
Bypass damper and seat installed
Reeves drive on central shaft overhauled
Small oil burner installed on hearth 2
Smoke indicator installed

1965 Cooling fan and motor drive belts replaced
General inspection

D. Incinerator #3 (first full operating year: 1939)

1951 Minor

1952 Replaced bottom bearing on bottom of central shaft

1953 Hearth No. 2 relaid
Wall brick from underside of hearth 1 to top of hearth 3 replaced

D. Incinerator #3 (Continued)

1954	Hearth No. 4 rebuilt from steel shell Hearth No. 3 rebuilt from brick wall
1955	2 burner boxes replaced 4 teeth replaced
1956	1 burner box replaced Some arms replaced
1957	Some brick replaced Lute cap on hearth 2 rebuilt
1958	Nominal
1959	Nominal
1960	Exterior shell plate weld on at hearths 2 and 3 Central shaft Reeves drive overhauled; gear reducer overhauled and rebuilt
1961	3 rabble arms replaced 2 rabble teeth replaced Arm hub on central shaft on hearth 4 built up by welding 1 burner box repaired
1962	2 rabble arms replaced 3 rabble teeth replaced
1963	OK
1964	4 rabble arms replaced (1 low arm on hearth 4, 1 broken arm on hearth 5, 2 arms on hearth 2) Some rabble teeth replaced on hearths 1 and 4 Burner box partly replaced (southeast box on hearth 4)
1965	Cooling fan - new belts and sheaves installed Reeves drive - new shaft support bearings and belts installed Oil burner installed on hearth 4 - water-cooled damper replaced

E. Incinerator #4 (first full operating year: 1952)

1951	Incinerator installation is completed
1952	OK
1953	OK
1954	OK
1955	Hearth 3 rebuilt and 2 rings of brick added to increase drying area Bell on cooling air realigned and repacked Burner boxes rebuilt to conform to other incinerators 16 teeth replaced

TABLE 6 (Concluded)

E. Incinerator #4 (Continued)

1956	5 rabble teeth replaced
1957	Lute cap of hearth 6 replaced
1958	Nominal
1959	Nominal
1960	Nominal
1961	Nominal
1962	Bottom button bearing replaced 2 rabble arms on hearth 1 replaced (none scrapped)
1963	1 burner box repaired A few rabble teeth replaced
1964	2 new rabble arms installed on hearth 4 5 new teeth installed on hearth 4 and teeth on hearth 1 Burner box on hearth 4 was rebuilt
1965	General inspection Lute ring on hearth 4 replaced Insulation replaced on central shaft 2 burner boxes on hearth 4 repaired Cooling air fan-new motor bearings and outboard bearing installed Water cooled damper repaired Rabble teeth replaced on hearth 2 Oil burner installed on hearth 4

Comparison with Air Pollution Codes

Among all the cities visited, only one, Cleveland, has an air pollution standard of any kind. As of 15 October 1969, the maximum allowable emission of particulates in the flue gas of existing incinerators was 0.2 lb per 1000 lb stack gas, or 200 parts per million by weight. A flue gas analysis taken in 1966 on MHF No. 1 gave a value of 0.064 to 0.069 per 1000 lb (within the specification) at the stack breeching, reduced from 0.772 at the furnace outlet by scrubber action.

VI. DATA REDUCTION AND CORRELATION

The preceding chapter on Data Acquisition contains tabulations of raw data, such as experimental temperatures at various points in the MHF's. Such information is useful as a guide to operating a MHF sewage sludge incinerator from the viewpoints of MHF life and air pollution. Other raw data, on the various operational and cost components must be correlated in terms of meaningful variables to model the effects of size and passage of time. For cost items, it is necessary to establish a framework of economic indicators which allow all data taken in the past to be expressed in 1969 dollars. For equipment and material, and also the "non-dollar" expenditures (man-hours, kilowatts, land, etc.) the effect of plant size or capacity must be included.

The review of prior studies of MHF sewage sludge incineration economics in Chapter III gave little indication on how numbers quoted were derived from basic data. Therefore, it was decided to base correlations on variables which resulted in good fits, and for which a realistic rationale could be established. The Sections in this Chapter (except the first, which deals with Economic Indicators) pertain to the operational and cost items considered important in the subroutine.

ECONOMIC INDICATORS AND LABOR RATES

The conversion of all costs to 1969 dollars required adjustments to raw data obtained during the previous three decades on capital equipment and other materials, and on the cost of all the types of labor involved. Much effort was devoted to arriving at realistic conversion methods which are summarized in Tables 7 and 8, standardized to 1969. The principal considerations are detailed in the following paragraphs, by column.

Installed Capital Equipment (Col. 1, Table 7) - The cost of installed MHF incinerator systems was considered to be the sum of the fabricated equipment costs (castings, blowers, motors, controls, etc.) and the charges for construction. Castings include the center shaft, rabble arms, teeth and other structural components. A cost ratio of 60% equipment/40% construction was taken as typical, based on industry experience. The Average Marshall and Stevens Equipment Cost Index (Ref. 23) and the Engineering News Record Construction Cost Index (Ref. 24) were combined in the 60/40 ratio to produce the MHF Capital Cost Index (Col. 1 of Table 7).

TABLE 7

SUMMARY OF ECONOMIC INDICATORS
FOR CAPITAL EQUIPMENT AND MATERIALS

(Standardized to 1969)

Year	MHF Installed Capital Cost	Normal Maintenance Parts & Supplies	MHF Castings Cost	Refractory Cost
	(1)	(2)	(3)	(4)
1938	25.6			30.5
9	25.2			30.1
1940	25.7			30.6
1	27.5			32.1
2	29.7			34.1
3	30.3			34.3
4	31.0			34.4
1945	31.5			34.7
6	36.8			42.1
7	44.7	41.8	50.1	51.2
8	48.8	45.5	54.2	55.5
9	49.0	46.8	56.8	55.5
1950	51.4	49.1	59.6	57.4
1	55.0	54.6	65.7	61.4
2	55.9	56.3	66.5	61.5
3	57.3	59.0	69.2	62.1
4	58.6	59.9	71.1	63.2
1955	60.9	62.3	73.2	64.9
6	65.8	66.4	79.1	71.0
7	70.2	69.8	84.2	77.0
8	72.2	71.2	85.9	79.4
9	74.5	73.5	87.4	81.4
1960	76.0	75.0	87.4	82.7
1	76.6	76.3	86.8	82.3
2	77.7	78.1	87.5	82.6
3	78.7	79.7	87.6	82.7
4	80.4	81.7	88.0	84.0
1965	82.1	83.7	88.9	85.2
6	85.3	86.8	91.1	87.5
7	89.0	89.9	93.3	91.8
8	93.8	94.5	96.2	95.5
1969	100.0	100.0	100.0	100.0

TABLE 8

SUMMARY OF ECONOMIC INDICATORS FOR LABOR
(Standardized to 1969)

Year	Labor Categories					
	Operating		Maintenance and Castings		Refractory	
	Index (1)	$ Per Hr (2)	Index (3)	$ Per Hr (4)	Index (5)	$ Per Hr (6)
1958	62.1	2.41	71.2	2.90	60.5	2.97
9	65.2	2.53	73.5	2.99	63.7	3.13
1960	68.3	2.65	75.0	3.06	66.6	3.27
1	70.6	2.74	76.3	3.11	68.6	3.37
2	73.5	2.85	78.1	3.18	71.1	3.49
3	76.0	2.95	79.1	3.25	72.9	3.58
4	78.4	3.04	81.7	3.33	75.2	3.69
1965	81.7	3.17	83.7	3.41	78.4	3.85
6	85.0	3.30	86.8	3.54	81.9	4.02
7	88.7	3.44	89.9	3.66	85.9	4.22
8	93.6	3.63	94.5	3.85	91.4	4.49
1969	100.0	3.88	100.0	4.07	100.0	4.91

Normal Maintenance Parts and Supplies (Col. 2, Table 7) - The Plant Maintenance Cost Index (Ref. 25) was used for updating normal maintenance materials. This index actually is a mix of labor and materials, but was here adopted for materials alone.

MHF Castings Cost (Col. 3, Table 7) - The Process Machinery sub-component of the Equipment component of the Plant Cost Index (Ref. 26) was used for castings. Of the seven sub-components, it is the one which appeared most representative of castings.

Refractory Cost (Col. 4, Table 7) - The Clay Products component of the Marshall and Stevens Equipment Cost Index (Ref. 23) was adopted for the furnace brick.

Operating Labor (Cols. 1 and 2, Table 8) - In this (and every other labor category) there are regional differences, but their consideration was felt to be an unwarranted refinement in view of the other simplifications made. The National Average Hourly Gross Earnings per Nonsupervisory Worker in Electric, Gas, and Sanitary Services (Ref. 27) were selected. The 1969 rate was $3.88 per hour.

Normal Maintenance Labor (Cols. 3 and 4, Table 8) - As for Normal Maintenance Parts and Supplies, the variation of the associated labor was also represented by the Plant Maintenance Cost Index (Ref. 25). Ref. 28, which dealt with a wage survey in the Industrial Chemicals industry, was used to obtain absolute hourly rates. From the maintenance standpoint, it was felt that the duties, and therefore wages, would be comparable. The Nationwide Average of all Maintenance Skills (varying from janitor to instrumentation repair) for November 1965 was given in Ref. 28 as $3.41 per hour which corresponded to a 1969 rate of $4.07 according to Ref. 25.

Casting Replacement Labor (Cols. 3 and 4, Table 8) - This was taken to be identical in all respects to the Normal Maintenance Labor above, in view of similar skills being involved.

Refractory Replacement Labor (Cols. 5 and 6, Table 8) - This work involves bricklaying and is more highly paid than Normal Maintenance. The National Average Straight Time for Masonry, Stonework and Plastering (Ref. 29) was adopted, with its 1969 rate of $4.91.

INCINERATOR CAPACITY

The usual indicator of capacity in wastewater treatment is a flowrate. In incineration, typically, the rate at which dry solids are processed is a variable indicative of capacity. In terms of economics, however, a "hardware" variable is preferable, so that cost may be linked to a physically measurable size or mass. The obvious variable here is the total effective hearth area (FHA), sq ft, which is a function of the outer diameter and number of hearths in the furnace. Strictly speaking, FHA is the gross hearth area less the area lost to center shaft, drop holes and lute caps. The ratio which connects dry solids flowrate in lb per hr (DSF) and effective hearth area is the hearth loading (HLD) expressed in lb dry solids per hour per sq ft.

Table 1 lists the hearth loadings in the last column, derived from hearth area and average (or design) dry solids flowrates. Fig. 3 is a plot of the points, with the least-square fit

$$FHA = 0.501\ (DSF), \text{ or } HLD = 1.996 \qquad (68)$$

A comparison of this value with the values in the next-to-last column of Table 1 shows that most of the installations surveyed were designed within 10% of the fitted value, with the more recent MHF's showing the higher hearth loadings. It should be noted that the range of sludge total solids content, considering all installations studied, was from 15 to 53 percent by weight, or conversely, 47 to 85 percent water by weight. It is suggested that Eq. (68) represents current practice over the stated range of moisture content. While it may seem surprising that HLD tends to be constant independent of sludge moisture content, this may indicate that a much larger fraction of the total hearth area is used for combustion of dried sludge than for drying of the wet sludge.

The field survey and perusal of manufacturers' brochures indicated that for sewage sludge incineration current preferred practice for unit MHF's was a range in number of hearths (NHEAR) from a minimum of 6 (although 5-hearth furnaces are in use) to a maximum of 12; and in internal diameter from 4.5 ft to 20 ft. The "heavy-duty" wall thickness of 13.5 in. (rather than 9 or even 6 in.) was considered preferable, giving an outer diameter (HDIA) range from 6.75 to 22.25 ft. Actually, the largest sewage sludge incineration MHF in use today is a 22.25 ft dia - 12 hearth installation which has been operated in Toronto, Canada, since 1968. With these ranges, a set of 59 standard unit MHF sizes resulted, arranged in ascending order by effective hearth area (FHA) in Table 9. The range in FHA from 85 to 3120 sq ft was considered to provide enough flexibility in selection of optimum furnaces from the subroutine.

These results formed the basis for three decisions:

1. Effective hearth area (FHA) was taken as the physical variable indicative of furnace capacity.

2. A value of HLD = 2 was taken as a minimum in MHF design.

3. The unit MHF sizes will be restricted to 59 standard values (FHA range from 85 to 3120) as shown in Table 9.

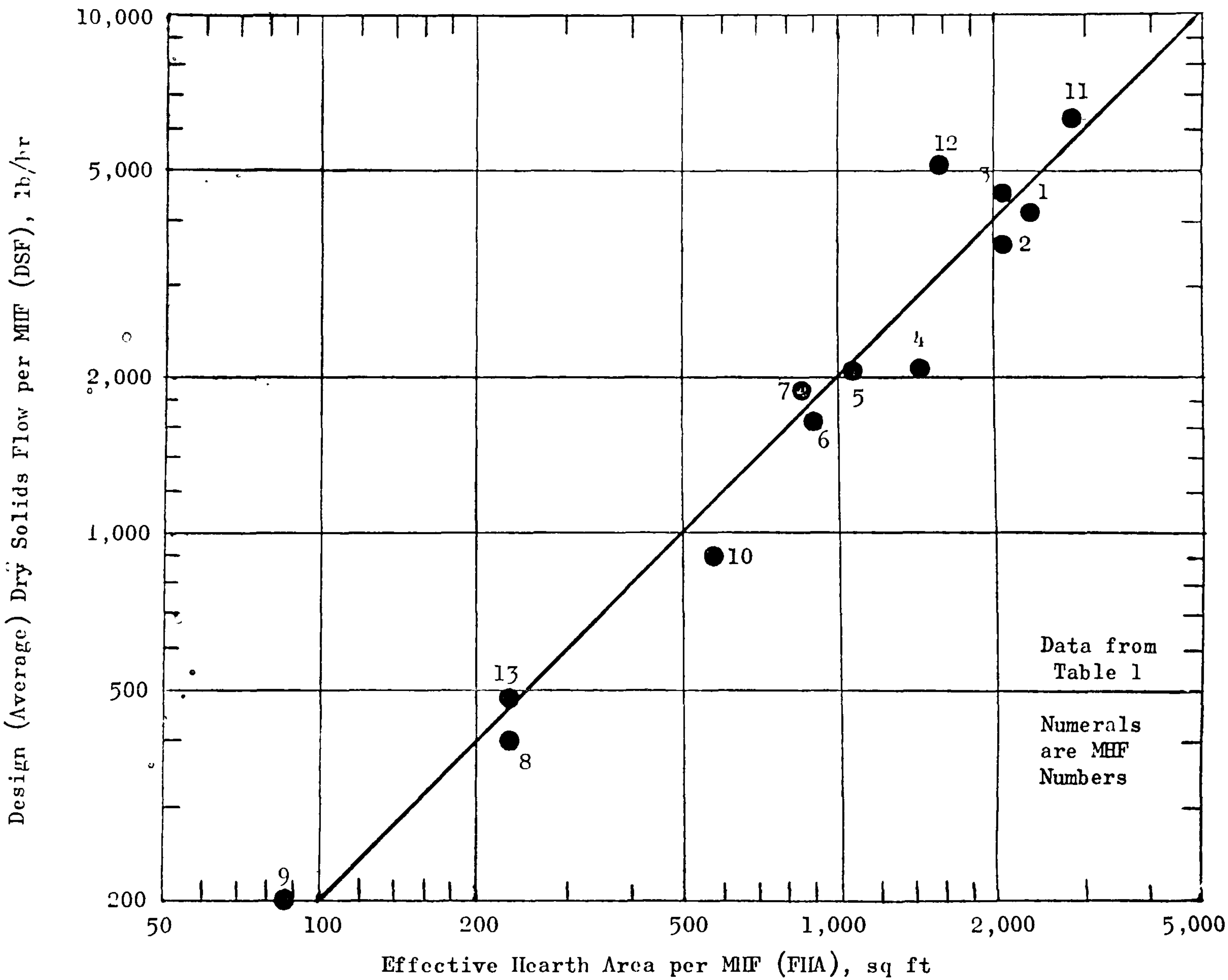


FIG. 3. MHF DESIGN CAPACITY VS. MHF SIZE

TABLE 9

STANDARD SIZES OF MULTIPLE-HEARTH FURNACE UNITS

No. of Hearths (NHEAR):	6 to 12
Wall Thickness, Inch:	13.5
Outer Diameter, Ft. (HDIA):	6.75 to 22.25
Effective Hearth Area, Sq. Ft. (FHA):	85 to 3120

FHA Sq. Ft.	HDIA Ft.	NHEAR No. Hearths	FHA Sq. Ft.	HDIA Ft.	NHEAR No. Hearths
85	6.75	6	988	16.75	7
98	6.75	7	1041	14.25	11
112	6.75	8	1068	18.75	6
125	7.75	6	1117	16.75	8
126	6.75	9	1128	14.25	12
140	6.75	10	1249	18.75	7
145	7.75	7	1260	16.75	9
166	7.75	8	1268	20.25	6
187	7.75	9	1400	16.75	10
193	9.25	6	1410	18.75	8
208	7.75	10	1483	20.25	7
225	9.25	7	1540	16.75	11
256	9.25	8	1580	22.25	6
276	10.75	6	1591	18.75	9
288	9.25	9	1660	20.25	8
319	9.25	10	1675	16.75	12
323	10.75	7	1752	18.75	10
351	9.25	11	1849	22.25	7
364	10.75	8	1875	20.25	9
383	9.25	12	1933	18.75	11
411	10.75	9	2060	20.25	10
452	10.75	10	2084	22.25	8
510	10.75	11	2090	18.75	12
560	10.75	12	2275	20.25	11
575	14.25	6	2350	22.25	9
672	14.25	7	2464	20.25	12
760	14.25	8	2600	22.25	10
845	16.75	6	2860	22.25	11
857	14.25	9	3120	22.25	12
944	14.25	10			

INSTALLED MHF CAPITAL COST

In practically all cases, the largest item contributing to total MHF cost (per annum or per ton of dry solids processed) is the capital charges. The conventional method of financing public works by municipal and other bonds, typically with a 25-year payoff period, and the custom of soliciting bids for each individual job from qualified vendors are the principal factors in determining the capital charges. It is well known that few price lists for equipment are issued by wastewater processing equipment manufacturers, even for items of "shelf" availability. It is difficult to establish the exact value for a piece of equipment such as a furnace because contracting is usually by competitive bidding. In the present case, all the MHF units examined were built by two vendors: BSP Corporation of San Francisco, and Nichols Engineering and Research Company (NERCO) of New York. The conversion of original costs (some dating as far back as 1938) to 1969 levels was made according to Column 1 of Table 7.

Table 10 gives the breakdown of installed capital costs, which include the metal and refractory parts of the furnace proper, assembled with the various air blowers, fuel injectors, drive motors, scrubbers, controls, instrumentation and other accessories necessary to the operation of the furnace. The installed cost does not include consulting engineering fees, sludge dewatering, ash handling and disposal, building or land. Surprisingly, the field visits with few exceptions did not produce good capital cost data - many capital cost figures were approximate or not known. It was then decided to contact the consulting engineers on the various installations; in all cases cooperation was excellent and files going back decades yielding desired information and in some cases also corrections of field data. One bonus was that the 9 basic units examined could be expanded to 13, for capital cost only, because the installed costs of other recently constructed MHF sludge incinerators were made available to this program. Hearth area was chosen to be the variable indicative of capacity because it related directly to hardware and so to its first cost.

In three of the units only combined costs of incineration, dewatering, disposal, etc., were available, so estimates were made for the incineration cost alone. Table 10 indicates the data sources and the nature of any adjustments made. The contract dates are the basis for dollar cost conversion.

Fig. 4 is a log-log plot of the 13 points (cost vs hearth area). A least-square fit of the points to a power function resulted in an exponent of 0.60, which happens to be the "classical" value for chemical process equipment. No doubt, this close an agreement is fortuitous but it does point up the chemical process aspect of incineration. Some inflationary trend was noted with the cost adjustment

TABLE 10

MHF INSTALLED CAPITAL COST

MHF No.	Location	(B=Bid) Contract Year	No. of MHF's	Unit MHF Hearth Area, Ft^2	Source for Costs; Remarks (CE=Consulting Engrs.)	Orig. Cost per Unit MHF (1000$)	1969 Cost per Unit MHF (1000$)
1	Cleveland	1963	4	2327	Havens & Emerson (CE)	376	478
2A	Minn.-St. Paul	1938	3	2084	Toltz,King,Duvall,Anderson(CE)	127	496
2B	Minn.-St. Paul	1950	1	2084	1951 M-St.P. Sanitary District Report (19th Annual), p.86	163	314
3	Kansas City	1964	3	2084	Black & Veatch (CE)	247	338
4	Cleveland	1938	4	1425	Havens & Emerson (CE); bulky combustion air preheater included.	99	386
5	Battle Creek	1966	1	1068	McNamee, Porter & Seeley (CE); Elaborate controls included.	380	446
6	Battle Creek	1960	1	890	Malcolm Pirnie & Co.(CE); Estd cost of building subtracted.	241	317
7	Saginaw	1963	1	845	Hubbell, Roth & Clark (CE)	197	250
8	Hatfield	1967	1	230	Tracy Engineers, Inc. (CE)	225	253
9	Bridgeport	1964	1	85	George B. Mebus, Inc.(CE);costs of MHF components available.	74	92
10	South Tahoe	1967	1	575	South Tahoe Public Util. Dist; Estd.dewatering etc. costs subtracted.	233	262
11	Minn.-St. Paul	1965	3	2808	Toltz,King,Duvall,Anderson(CE); Estd dewater.costs subtracted.	816	993
12	Saginaw	1969B	1	1560	Metcalf and Eddy (CE)	630	630
13	East Rochester	1963	1	230	Lozier Engineers (CE)	80	102

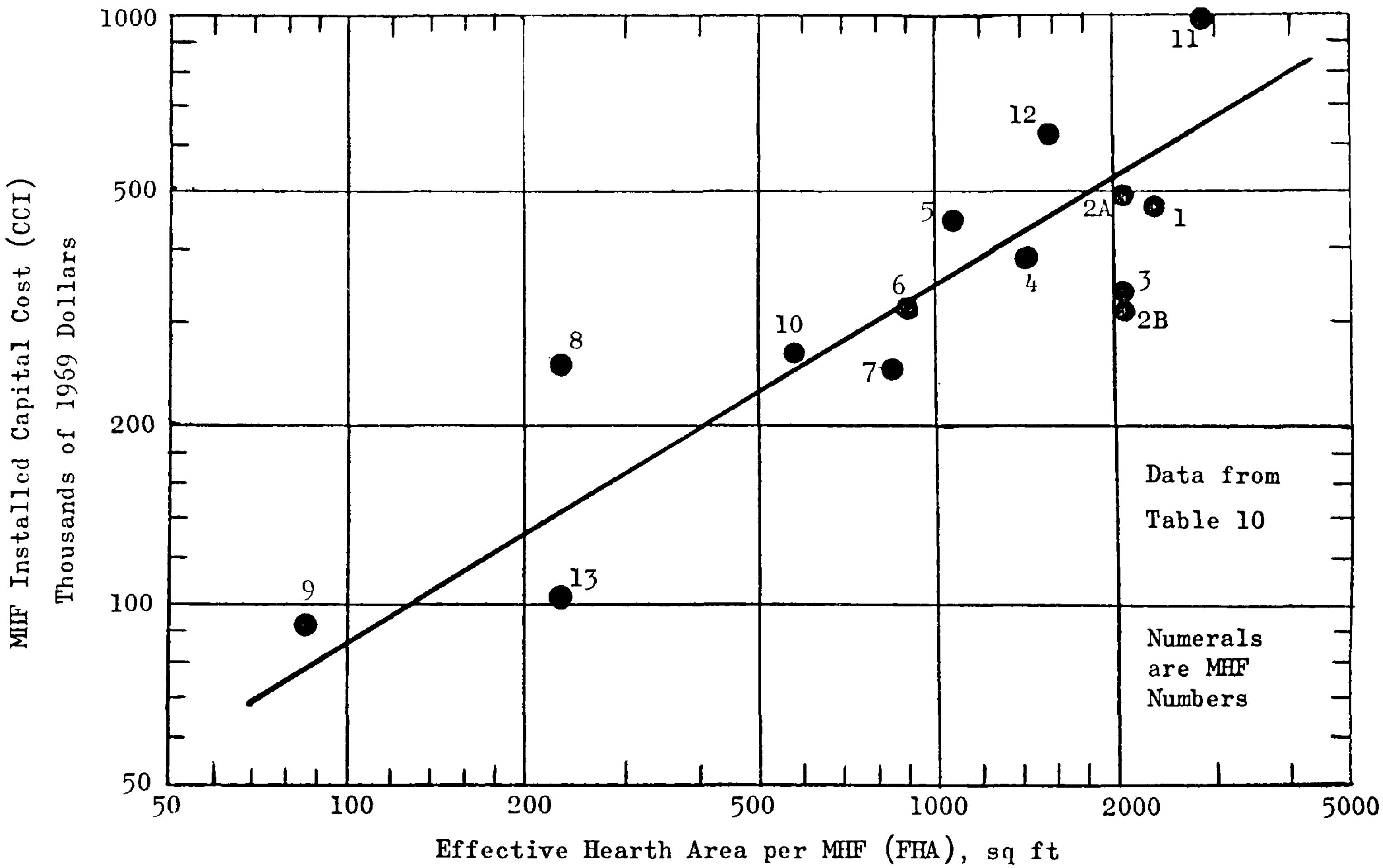


FIG. 4. MHF INSTALLED CAPITAL COST

chosen in that MHF's for which contracts had been signed in or after 1966 tended to fall above the least-squares line, while MHF's ordered before 1951 tended to fall below the line. The equation of the least square line is the power function

$$CCI = 5464\ (FHA)^{0.60} \tag{69}$$

COOLING AIR FANS AND COMBUSTION AIR BLOWERS

It is, of course, quite possible to determine the required capacities of cooling air fans and combustion air blowers given the dimensions of the flow channels, the cooling rate required to maintain adequate apparatus operating life, the sludge feed rate and combustion air (including excess air) requirements. Consideration of heat transfer correlations, friction factors, thermodynamics, and stoichiometry could then be used to predict the blower and fan requirements. However, manufacturers of MHF's have presumably already solved this problem empirically or otherwise with every furnace delivered. A realistic procedure, then, consists of utilizing information on fans and blowers collected during the field visits. Table 11 and Figs. 5 and 6 show all the available data points on air/flowrate, fan and blower horsepower, and wet sludge rate, contributed by half the plants visited. Straight-line fits through the origins of Figs. 5 (horsepower vs wet sludge rate) and 6 (air flowrate vs horsepower) give the following results:

Combustion Air

Blower rated hp = 0.15 per daily ton of wet sludge
Air Flow at 16 osi = 150 scfm per rated hp
i.e., air flow = 22.5 scfm per daily ton of wet sludge

Cooling Air

Fan rated hp = 0.08 per daily ton of wet sludge
Air flow at 8 in. water = 450 scfm per rated hp
i.e., air flow = 36 scfm per daily ton of wet sludge

The correlation of cooling air with wet sludge rate is convenient here because of the need for an *a priori* value for cooling air flow as an input to the Thermal Analysis (Chapter IV). The crude procedures used are considered adequate for this preliminary-design purpose since the contribution of the cooling air stream to the MHF energy balance is small. For accurate sizing of combustion air blowers and cooling air fans, however, more details must be taken into account, especially for high daily sludge tonnages. The data in Table 11 are obviously insufficient for elaboration into equipment design parameters.

TABLE 11

COOLING AIR FANS AND COMBUSTION AIR BLOWERS

MHF No.	Location	Hearth Area/MHF sq ft	Avg. Wet Sludge Ton/Day(a)	Cooling Air		Combustion Air	
				Fan HP	Flow SCFM(b)	Blower HP	Flow SCFM(c)
1	Cleveland	2327	200	15	6000	30	--
2	Minn.-St. Paul	2084	144	7.5	--	25	--
3	Kansas City	2084	186	15	7190(d)	15	3300
4	Cleveland	1425	--	--	--	--	--
5	Battle Creek	1068	94.6	7.5	3490	7.5	1180
6	Battle Creek	890	75	7.5	3490	30	3000
7	Saginaw	845	42.5	5	--	7.5	990
8	Hatfield	230	24	3	--	3	--
9	Bridgeport	85	9.6	0.5	--	2	--

(a) Product of design dry solids flowrate and total solids w/o.

(b) At static head of 8 in. water.

(c) At pressure of 16 OSI (OSI = oz per sq in)

(d) Adjusted from 13 in. water

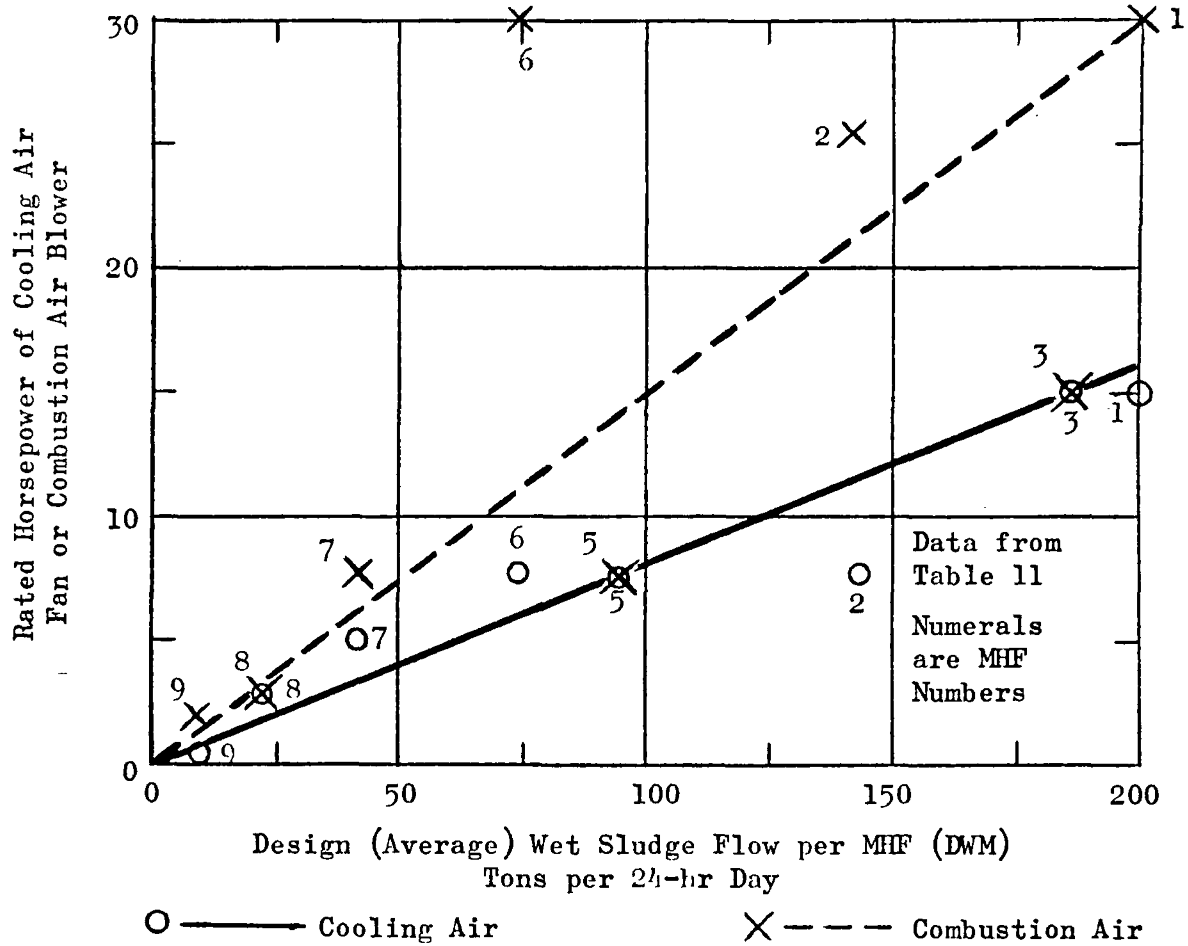
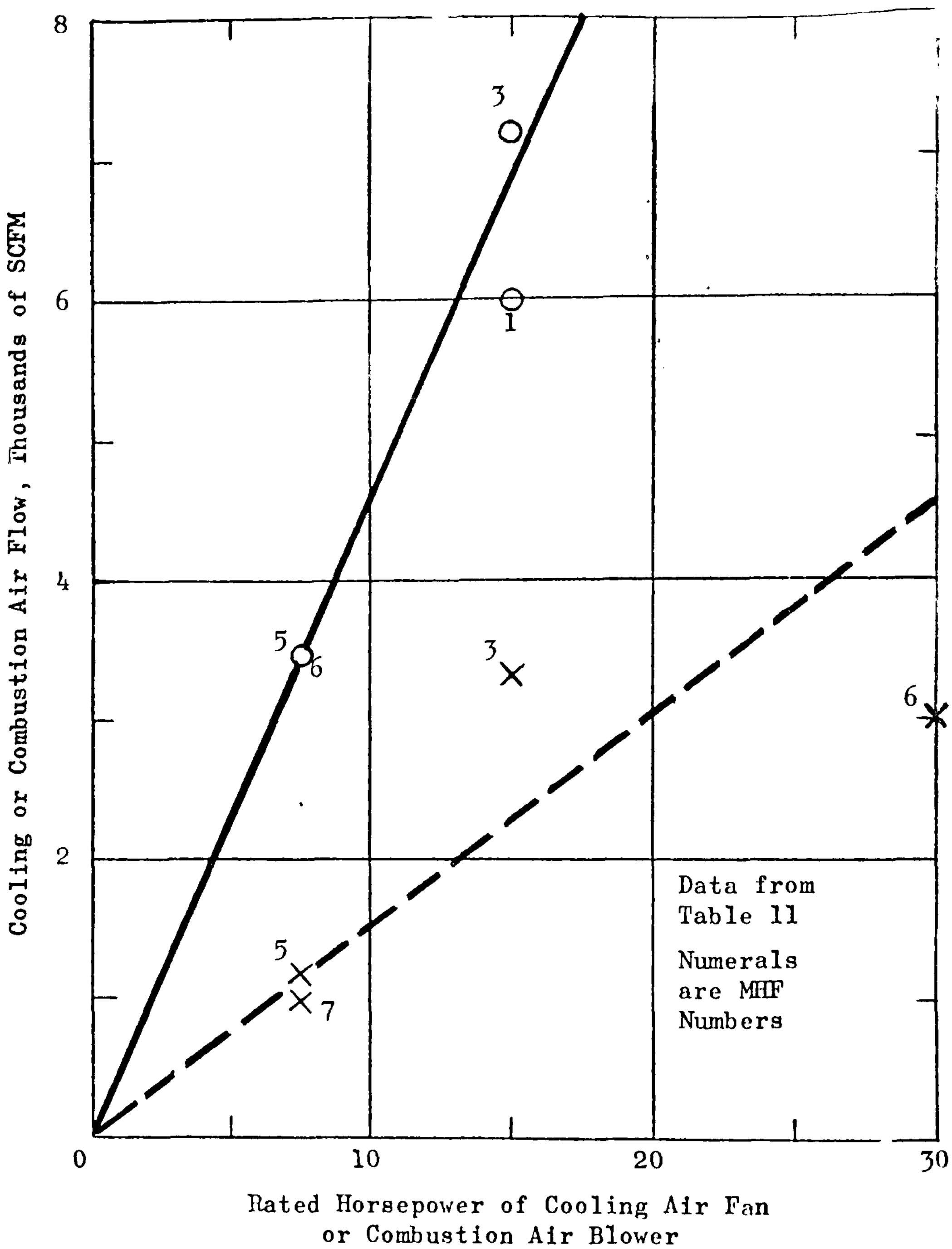


FIG. 5. COOLING AND COMBUSTION AIR:
HORSEPOWER VS. WET SLUDGE RATE



O ——— Cooling Air   X– – – Combustion Air

FIG. 6. COOLING AND COMBUSTION AIR:
AIR FLOW VS HORSEPOWER

EXHAUST GAS SCRUBBERS AND PRECOOLERS

Data on these items were collected in Table 12 in an attempt at a correlation similar to that made for cooling air fans and combustion air blowers. The data gives an idea of the relative magnitude of the gas and water flows, but are not complete enough for a correlation.

BUILDING COST

Installed capital cost for an MHF never includes the building, if any, in which the furnace is housed. In many cases, furnaces are installed in existing buildings, or the latter may be enlarged. When entirely new buildings accompany the furnace, the costs may vary widely. In the 1965 Minneapolis-St. Paul contract (MHF No. 11, Table 10), one new building housed four incinerators with dewatering equipment, controls, instrumentation, lockers, lunch room and service facilities. An estimate of the cost of that portion of the building applicable to incinerators alone gave a ratio of building cost to incinerator installed cost of 0.513. For the Battle Creek 1960 contract (MHF No. 5) the same ratio was estimated as 0.667. No other examples of simultaneous furnace and building construction came to light. Obviously, the cost of a new building is significant compared to the MHF installed capital cost.

ENGINEERING FEE

Under the current system of contracting for treatment plant equipment, a fairly consistent fee structure has evolved for consulting engineers, as a percentage of the net construction cost, here taken as the installed cost of the MHF plus building, if any. Table 13 lists percentages recommended in the states of Kansas, Missouri, and Ohio (Ref. 30) and by the American Society of Civil Engineers (Ref. 31). For the present purpose, the Missouri fee structure was selected as being in the middle of the range of fee structures examined. A plot of the values in Table 13 for absolute engineering fee vs installed cost appears on Fig. 7. The least-square power law fit for these points, in the cost range from \$10,000 to \$5 million is

$$EFC = 0.5\ (CCI + BGC)^{0.846} \qquad (70)$$

LAND COST

One of the advantages of an MHF (which is built "up" rather than "out") is the small land area occupied. As shown in Table 14, the four available data points were used to establish a ratio of land area to

TABLE 12

EXHAUST GAS SCRUBBERS AND PRECOOLERS

MHF No.	Location	Hearth Area Per MHF, Sq. Ft.	Avg. Wet Sludge Ton/Day Per MHF*	Precooler		Cyclone Scrubber	
				Gas CFM @ °F	Water GPM @ PSIG	Gas CFM @ °F	Water GPM @ PSIG
1	Cleveland	2327	200	Yes	140	23,600 @ 175	50 (10 HP Booster Pump
2	Minn.-St. Paul	2084	144	(No Scrubber - Dry Flue Precipitation)			
3	Kansas City	2084	186	90,000 @ 1400	200 @ 60	49,000 @ 180	100 @ 60
4	Cleveland	1425	--	--	--	--	--
5	Battle Creek	1068	94.6	24,200 @ 1350	30 @ 75	13,100 @ 187	85 @ 75
6	Battle Creek						
7	Saginaw	845	42.5	--	--	Yes	(10 HP Pump)
8	Hatfield	230	24	Yes		Yes	
9	Bridgeport	85	9.6	Yes		Yes	

*Product of design dry solids flowrate and total solids w/o.

TABLE 13

ENGINEERING FEE STRUCTURE

Correlating Equation: $Y = 0.5X^{0.846}$

Installed Cost (MHF Plus Building)	Fee, Percent of Installed Cost					Selected Absolute Engineering Fee (Missouri Minimum)
	Kansas Engin. Soc. 1962 Ref. (30)	ASCE Median 1967 Ref. (31) Complexity:		Missouri Soc. Prof. Engrs. Pre-1968 Ref. (30)	Ohio Soc. Prof. Engrs. Pre-1968 Ref. (30)	
		Average	Above Avg.			
Dollars	Med.-High			Minimum	Minimum	Dollars
(X)				*		(Y)
10,000	12.5	--	--	13.0	--	1,300
25,000	11.1	--	--	12.0	--	3,000
50,000	10.0	9.4	12.7	11.0	--	5,500
100,000	9.0	8.25	10.75	10.0	12.0	10,000
200,000	8.0	7.3	9.25	8.25	9.75	16,500
300,000	6.75	6.85	8.6	7.25	9.0	21,750
400,000	5.9	6.5	8.1	7.0	8.63	28,000
500,000	5.2	6.25	7.75	6.75	8.4	33,750
750,000	4.0	5.85	7.25	6.25	7.6	46,875
1 Million	3.5	5.6	6.8	5.75	7.2	57,500
5 Million	--	4.75	5.8	4.67	5.84	233,500

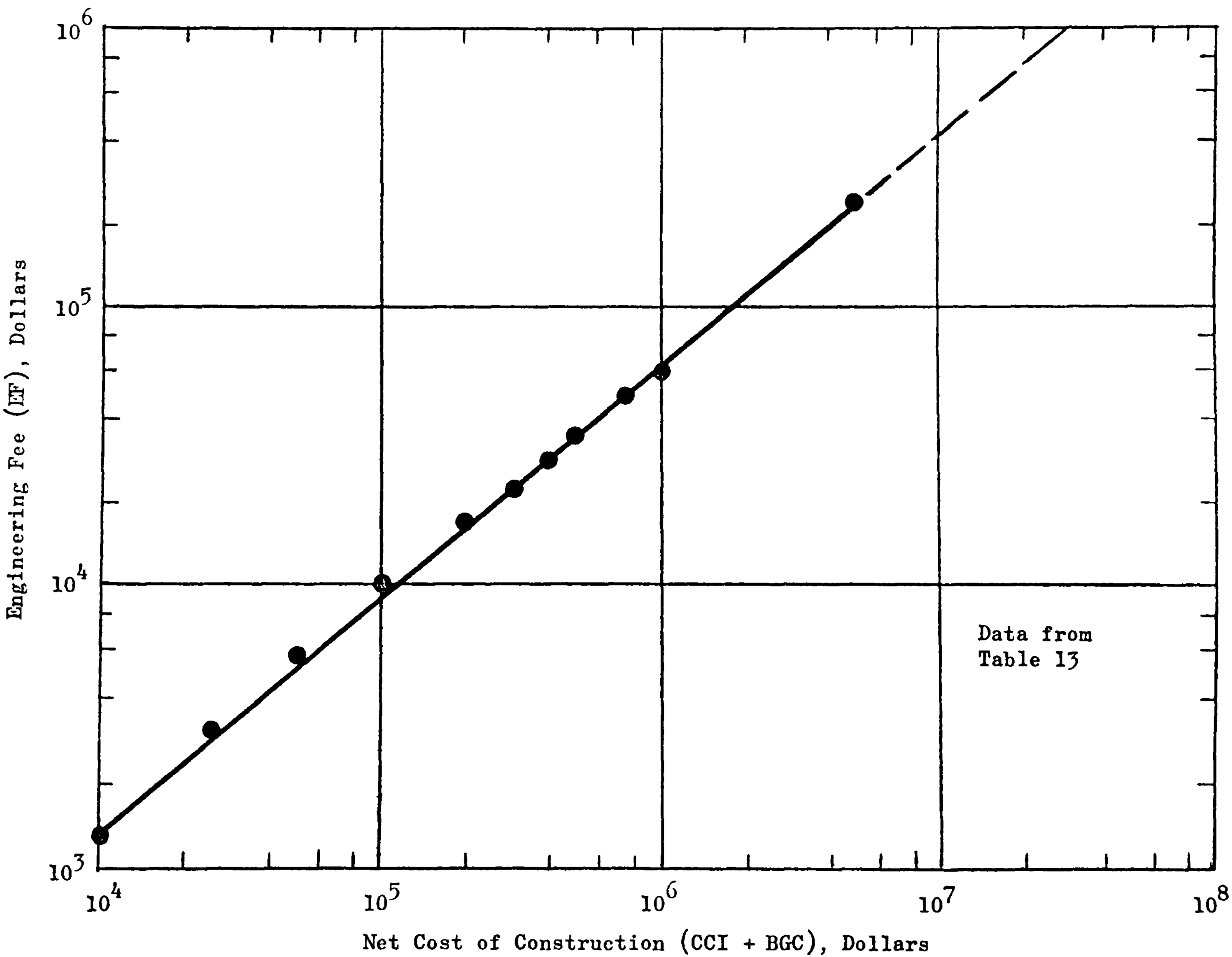


FIG. 7. ENGINEERING FEE STRUCTURE

TABLE 14

MHF LAND AREA

MHF No.	Location	N, No. of Incinerators	D_o, Outer Diameter, Ft.	$.785 \, N \, D_o^2$ Superficial Area, Sq Ft	Land Area, Sq Ft
1	Cleveland	4	22.25	1555	9000
2	Minn-St. Paul	4	22.25	1555	6400
5	Battle Creek	1	18.75	276	1300
6	Battle Creek	1	18.75	276	1190
				(X)	(Y)

Least Square X-Y Fit of Straight Line Through Origin: $Y = 4.938 X$

superficial circular area based on MHF outer diameter. This ratio was found to be KLA = 4.938. In all cases, the land area is a small fraction of an acre, and thus a minor cost item.

HEARTH REPLACEMENT MATERIAL, LABOR, AND FREQUENCY

During the life of a MHF it may become necessary to replace one or more hearths because of their deterioration due to exposure to high temperature and to heating/cooling cycles. Based on hardware experience, estimates were made for material and labor required to replace the two components which make up a hearth: castings (e.g., rabble arms and structural supports) and refractory (brick lining of horizontal and vertical hearth surfaces).

Table 15 shows that all replacement expenditures per hearth increase with diameter. Castings are more expensive than refractories from the material standpoint, while the amount and unit cost of refractory replacement labor exceed those for castings (see columns 4 and 6 of Table 8). Correlating polynomials for all four hearth replacement expenditure items were fitted to the data in Table 15. The equations are valid for Outer Diameter (HDIA) values from 6 to 23 feet and apply to replacement of <u>one hearth</u>:

On-Site Castings Material
$$CAST = 1081 - 220\ HDIA + 89.5\ (HDIA)^{1.5} \quad (71)$$

On-Site Refractory Material
$$REFR = 458 - 120\ HDIA + 14.6\ (HDIA)^{2} \quad (72)$$

Casting Man-Hours
$$CLH = 7.47 - 0.105\ HDIA + 0.0299\ (HDIA)^{2} \quad (73)$$

Refractory Man-Hours
$$RLH = 69.1 - 0.105\ HDIA + 0.530\ (HDIA)^{2.25} \quad (74)$$

Frequency of hearth replacement should preferably be based on the lifetime history of a MHF. As indicated by Table 6, part of a lifetime replacement history was available for the three Minneapolis-St. Paul units commissioned in 1940, during the period 1951-1965. Table 16 compiles the number of hearth castings and refractories replaced during the 15-year period. For the castings, it was assumed that each rabble arm replaced was equivalent to 1/4 casting and each tooth to 1/40 casting. The result is that the equivalent of 44 hearth castings and 10 hearth refractories were replaced during years 11 through 25. With the assumption that the replacement frequency for the first 10 years was only half of that during years 11 through 25, the following tabulation results:

TABLE 15

HEARTH REPLACEMENT MATERIAL AND LABOR

Outer Diameter, Ft (13.5 in Wall) "HDIA"	Castings (One Hearth)		Refractory (One Hearth)	
	On-Site Material, 1969 $ "CAST"	Labor, Man-Hours "CLH"	On-Site Material, 1969 $ "REFR"	Labor, Man-Hours "RLH"
10.75	1907	10	913	192
14.25	2695	12	1661	288
16.75	3410	14	2365	336
18.75	4455	16	3542	480
22.25	5511	20	4950	640

TABLE 16

15 YEARS HEARTH REPLACEMENT HISTORY:
THREE MINEAPOLIS-ST. PAUL MHF'S
(Operating Since 1939)
Each MHF: 8 Hearths = 20 Arms + 138 Teeth

Year	MHF No. / Hearth No.	Castings: Rabble Teeth No.	Castings: Rabble Teeth Equiv.	Castings: Rabble Arms No.	Castings: Rabble Arms Equiv.	Castings: Total Hearth Equiv.	Refractory: Total Hearths
1951	All	20	0.50	2	0.50	1.00	
1952	All	2	0.05	2	0.50	0.55	
1953	All	24	0.60	5	1.25	1.85	
1954	3/2						1
	1/2						1
	1/3						1
	1/4						1
	All	81	2.00	6	1.50	3.50	
	2/2						1
	2/3						1
	2/4						1
1955	1/All	9	0.25	2	0.50	0.75	
	2/All	51	1.25	8	2.00	3.75	
	3/All	4	0.10	-	--	0.10	
1956	All	58	1.45	16	8.0	9.45	
	1/1						1
	1/3,4,6						1
	2/1						1
1957	All	55	1.40	12	6.0	7.40	
1958	All	--	--	2	0.5	0.50	
1959	All	18	0.50	3	0.75	1.25	
1960	All	44	1.10	11	5.00	6.10	
1961	1/	7	0.20	4	1.00	6.20	
	3/	2	0.05	3	0.75	0.80	
1962	3/	3	0.075	2	0.50	0.58	
	4/	-	--	2	0.50	0.50	
1963	1/	-	--	5	1.25	1.25	
1964	1/	-	--	2	0.5	0.50	
	2/	-	--	5	1.25	1.25	
	3/	-	--	4	1.0	1.00	
1965	1/	5	0.125	-	--	0.12	
15-Year Totals						42.90	10

	Castings	Refractories
Hearths replaced during years 11 through 25 (in 3 MHF's, each 8-hearth)	42.9	10
Equivalent MHF's replaced during years 11 through 25	1.79	0.42
Equivalent MHF's replaced during years 1 through 10 (at half rate of years 11 through 25)	0.60	0.14
Equivalent MHF's replaced during total 25-year life	2.39 (CRL)	0.56 (RRL)

Conditions at Minneapolis-St. Paul were relatively "mild", e.g., temperatures below 1600 F, primary sludge with high total solids, no sulfur in the auxiliary fuel, and, perhaps most important, 24 hr per day (HPD) operation. This meant few cooldown/heatup cycles and consequent low thermal stress. It was decided to use the replacement rates above (rounded off) for all 24 HPD furnaces, and a rate twice as high (to account for increased cycling) for all furnaces which operated less than 24 hr per day, i.e.:

$$\left.\begin{array}{l} \text{CRL} = 2.5 \text{ for HPD} = 24 \text{ and } 5.0 \text{ for HPD less than } 24 \\ \text{RRL} = 0.5 \text{ for HPD} = 24 \text{ and } 1.0 \text{ for HPD less than } 24 \end{array}\right\} \qquad (75)$$

NORMAL MAINTENANCE MATERIAL AND LABOR

Multiple hearth furnace maintenance has a periodic component (hearth replacement, see previous section) and a continuous component (normal maintenance). The latter involves for the most part regularly scheduled inspection (for wear, corrosion and failure), servicing, (e.g., lubrication of rotating machinery) and adjustment (e.g., of instrumentation) of all MHF components which may undergo changes as a result of operation and mere exposure to the environment.

The field survey produced sketchy and incomplete information. In particular, normal maintenance was sometimes lumped in with operation or hearth replacement. Frequently, labor and material (the latter called Parts and Supplies) were often reported as a combined dollar expenditure. The variables to be correlated were assumed to be expenditures per elapsed calendar time, rather than per operating time, because normal maintenance efforts and environmental deterioration are both related to calendar time. Physical size, expressed as hearth area was taken as the dependent variable, although its influence would be expected, and, in fact, was found to be minor.

Table 17 shows data from six MHF's for normal maintenance material and labor, Fig. 8 is a plot for Parts and Supplies, and Fig. 9 a similar plot for labor, both for annual expenditures as a function of hearth area. Least-square power law fits for these curves are as follows:

$$\text{Annual Parts and Supplies AMSY} = 570\ (\text{FHA})^{0.023},\ \text{1969 Dollars} \quad (76)$$

$$\text{Annual Labor} \quad \text{ANMM} = 120\ (\text{FHA})^{0.307},\ \text{Man-Hours} \quad (77)$$

OPERATING LABOR

Since this item is usually the second-largest component of the total annual cost (the first being capital charges), considerable effort was expended in obtaining realistic data. These are listed in Table 18 where the raw data are converted to Equivalent (i.e., considering supervision) Non-Supervisory Man-hours per MHF per 24 hr Operating Day (ØMD). In the absence of other information, the non-supervisory man-hours were increased by 10% to account for the cost of supervision. Where supervisory man-hours were available, a supervisory hourly rate 1-1/2 times the non-supervisory rate was adopted.

Fig. 10 is a plot of the 10 points of Table 18 on a ØMD vs FHA log-log graph. The data indicated that there was a minimum operating labor level in "small" plants, independent of the MHF size. This level was taken to be ØMD = 6. These plants, too, operated the MHF on 8-hr shifts (compared to round-the-clock operation for the other plants), contributing to higher specific labor costs. The remaining points (except two) were correlated by a 45° line (indicating direct proportionality) which met the minimum ØMD at FHA = 719. The correlation then becomes

$$\left.\begin{array}{ll}\text{For FHA equal to or less than 719 sq ft:} & \text{ØMD} = 6 \\ \text{For FHA greater than 719 sq ft:} & \text{ØMD} = 0.008343\ (\text{FHA})\end{array}\right\} \quad (78)$$

The two points which lie below the correlating line on Fig. 10 represent Saginaw and South Tahoe. In Saginaw, the incineration is continuous and requires no auxiliary fuel in view of the 45 w/o solids content; at South Tahoe two other MHF's (for lime recalcination and activated carbon regeneration) are part of the same plant and all three MHF's are operated jointly. Reduced operating labor would be expected in these two plants, and the dashed line parallel to the main line represents a 1/3 reduction, which is reasonable.

A direct proportion relationship means that no advantage in operating labor cost is gained by having fewer larger MHF's in a plant, i.e., there is no "large economy size". While at first this appears

TABLE 17

YEARLY NORMAL MAINTENANCE MATERIAL AND LABOR

MHF No.	Location	No. of MHF's	Hearth Area Sq.Ft./MHF "FHA"	Parts and Supplies			Labor		
				Year	All MHF's $/Yr.	Per MHF 1969 $/Yr. "AMSY"	Raw Data		Man-Hr./Yr. Per MHF "ANMM"
							Year	Expenditure	
2	Minn.-St. Paul	4	2084	1965	7,292	2,178	1965	$12,084 (4 MHF's)	880
3	Kansas City	3	2084	1969	5,000	1,667	1969	$18,000* (3 MHF's)	1,473
5	Battle Creek	1	1068	1969	3,000	1,500	1969	2,000 Man-Hr (2 MHF's)	1,000
6	Battle Creek	1	890			1,500			1,000
7	Saginaw	1	845	1969	2,400	2,400	1969	720 Man-Hr	720
9	Bridgeport	1	85	1969	2,000*	2,000	1969	*20% of Total Labor (6.3 Man-Hr/Day)	460

*Estimate

Correlating Equations:

Parts and Supplies: $AMSY = 570\ (FHA)^{0.023}$, 1969 $ per year

Labor: $ANMM = 120\ (FHA)^{0.307}$, Man-Hr per year

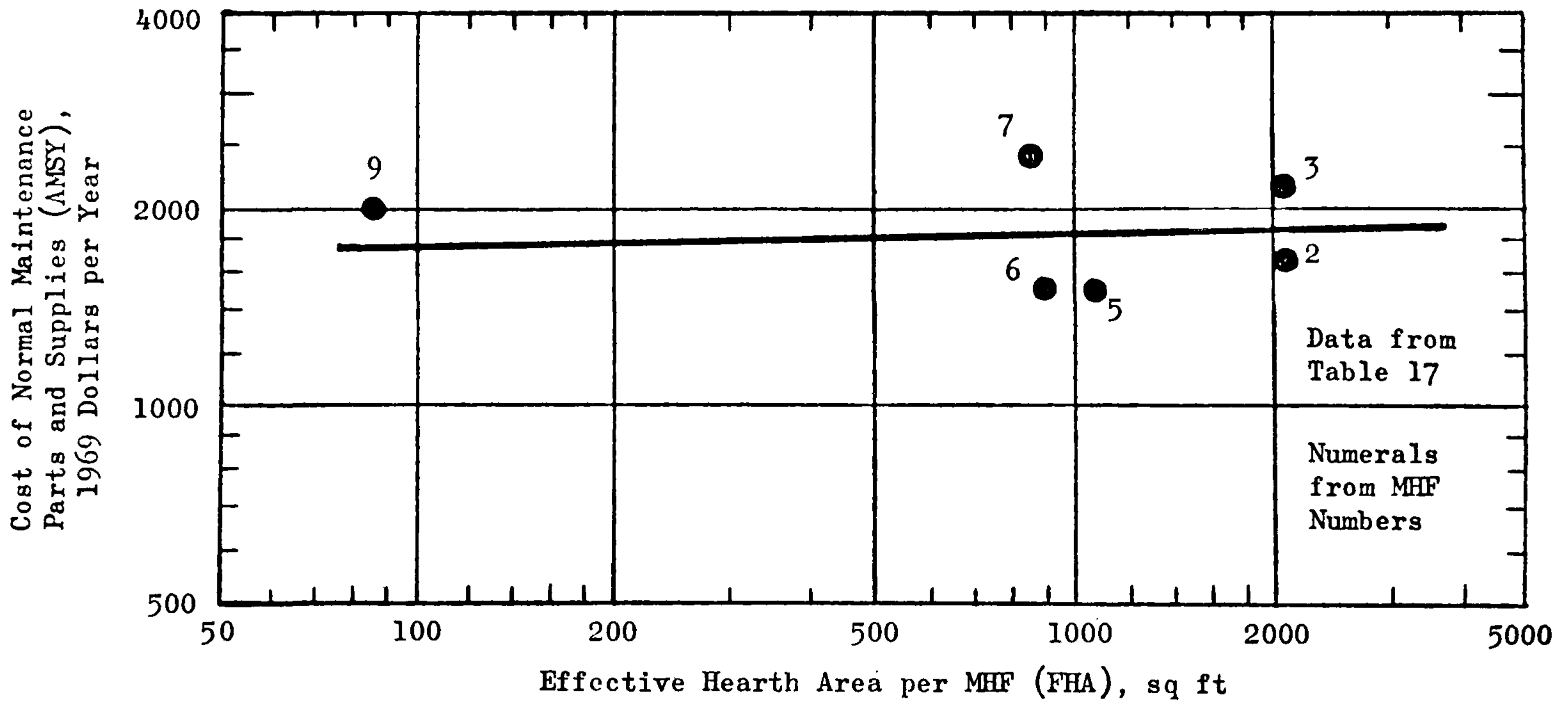


FIG. 8. COST OF NORMAL MAINTENANCE PARTS AND SUPPLIES

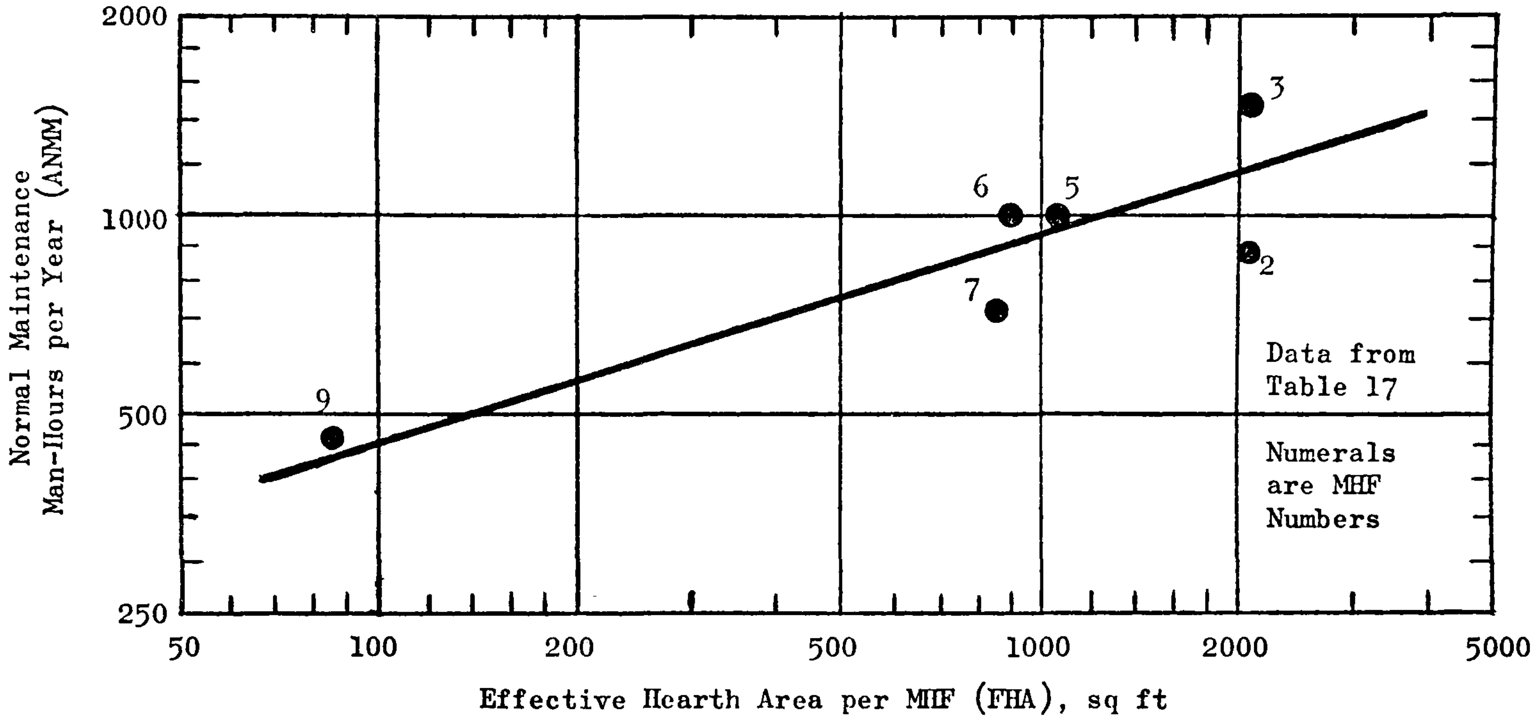


FIG. 9. NORMAL MAINTENANCE LABOR

TABLE 18

OPERATING LABOR

NMH = Non-supervisory Man-hours SMH = Supervisory Man-hours

MHF No.	Location	No. of MHF's	Hearth Area Sq Ft /MHF	Raw Data (for 24-Hr. Operating Day) 1969 Unless Stated	Equivalent NMH per MHF per 24-Hr. Operating Day
1	Cleveland	4	2327	(72 NMH + 8 SMH) per Day for 4 MHF's	21.0**
2	Minn.-St. Paul	4	2084	66 NMH per Day for 4 MHF's (1965)	18.2*
3	Kansas City	3	2084	40% (est.) of (Dewater + Incin.) Labor (80 Equivalent NMH/Day for 2 MHF's)	16.0
4	Cleveland	4	1425	40 NMH per Day for 4 MHF's (1958)	11.0*
5	Battle Creek	1	1068	8 NMH per Day	8.8*
6	Battle Creek	1	890	8 NMH per Day	8.8*
7	Saginaw	1	845	4 NMH per Day	4.4*
8	Hatfield	1	230	6.4 NMH per Day - No SMH	6.4
9	Bridgeport	1	85	80% (est.) of Total Labor (6.3 NMH per Day)-No SMH	5.0
10	South Tahoe	1	575	$19.93/Day at $5.65 Equivalent Hourly Rate	3.5

* Equivalent NMH (Est.) = 110% of Actual NMH (For Supervision)

**Supervisory Hourly Rate (Est.) = 150% of Non-supervisory Rate

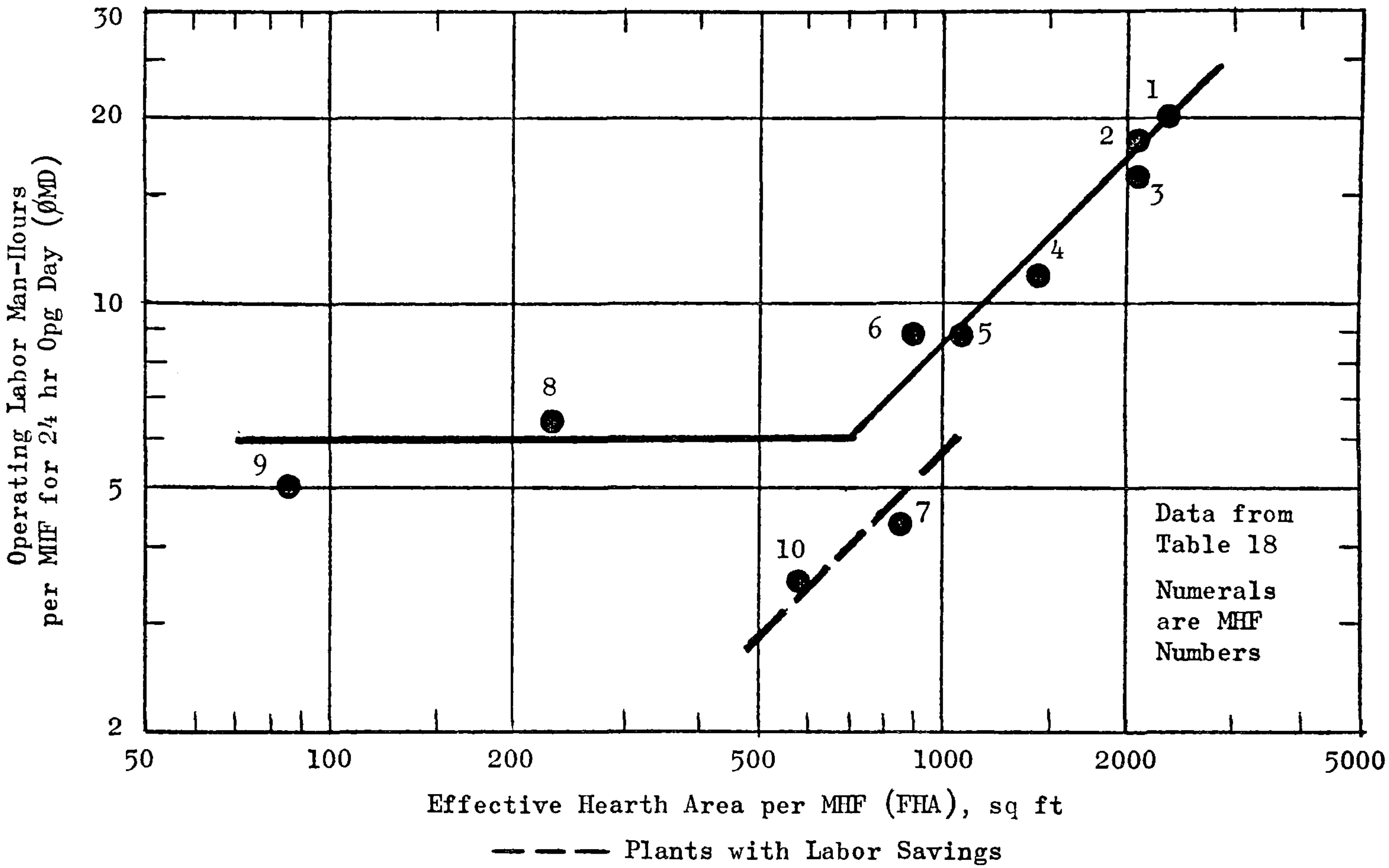


FIG. 10. OPERATING LABOR

unrealistic, it should be noted that a recent study of over 1500 U. S. treatment plants by Michel, Pelmoter and Palange (Ref. 32) was interpreted by Smith (Ref. 33) to indicate that the total labor (mainly operating) was almost directly proportional to the plant design capacity independent of plant size. Admittedly, this was the result of an overall statistical study of all types of conventional wastewater treatment plants; other overall plant studies (e.g., McMichael, Ref. 34) indicate a savings for larger plants. Obviously, the relation between operating labor and capacity for specific processes will vary with the process.

ELECTRICAL POWER CONSUMPTION

Good records are usually kept of electrical power consumption, by kilowatt-hour and dollar. Since power is consumed mainly during operating periods, a measure of cumulative power usage is the cumulative tonnage of treated sludge. The quantity kilowatt-hour per ton dry solids (PDS) was selected as the variable. Table 19 shows the data points which are plotted on Fig. 11 on a log-log plot vs FHA. The figure shows that PDS decreases as FHA increases. Ten of the eleven points were correlated (for FHA up to 2808 sq ft) by the function

$$PDA = 29.6 - 6.55 \times 10^{-9} (FHA - 2808)^3 + 4.94 \times 10^{-16} (FHA-2808)^5 \quad (79)$$

The one uncorrelated point is for the Minneapolis furnaces (No. 2) which employed natural draft and had no wet scrubber, thereby reducing power usage below the level of the forced draft, wet scrubber installations.

THERMAL CYCLING: YEARLY HOURS

When MHF's are not operated round the clock, the question arises of how best to schedule the on-off cycles, so that MHF life and operating time are not curtailed to the point of inefficiency. In addition to cycling as part of the operating schedule, at least one annual cold MHF inspection is advisable. Due to the inability of refractory to sustain tensile loads which may result from thermal stresses, it is important to limit the temperature differences within the material by limiting the heatup and cooldown rates. Although experts differ on details, there is a general consensus that somewhere in the temperature range from ambient to operating (say, 70 to 1500 F) a "soak" period should take place for reasons of stress equalization within refractories. In this study, 1200 F was chosen as the "soak" temperature, and also as the "standby" heating temperature, when the furnace is to be inactive for short time periods, such as overnight, or even weekends. This soaking should be carried out both during heatup and cooldown.

TABLE 19

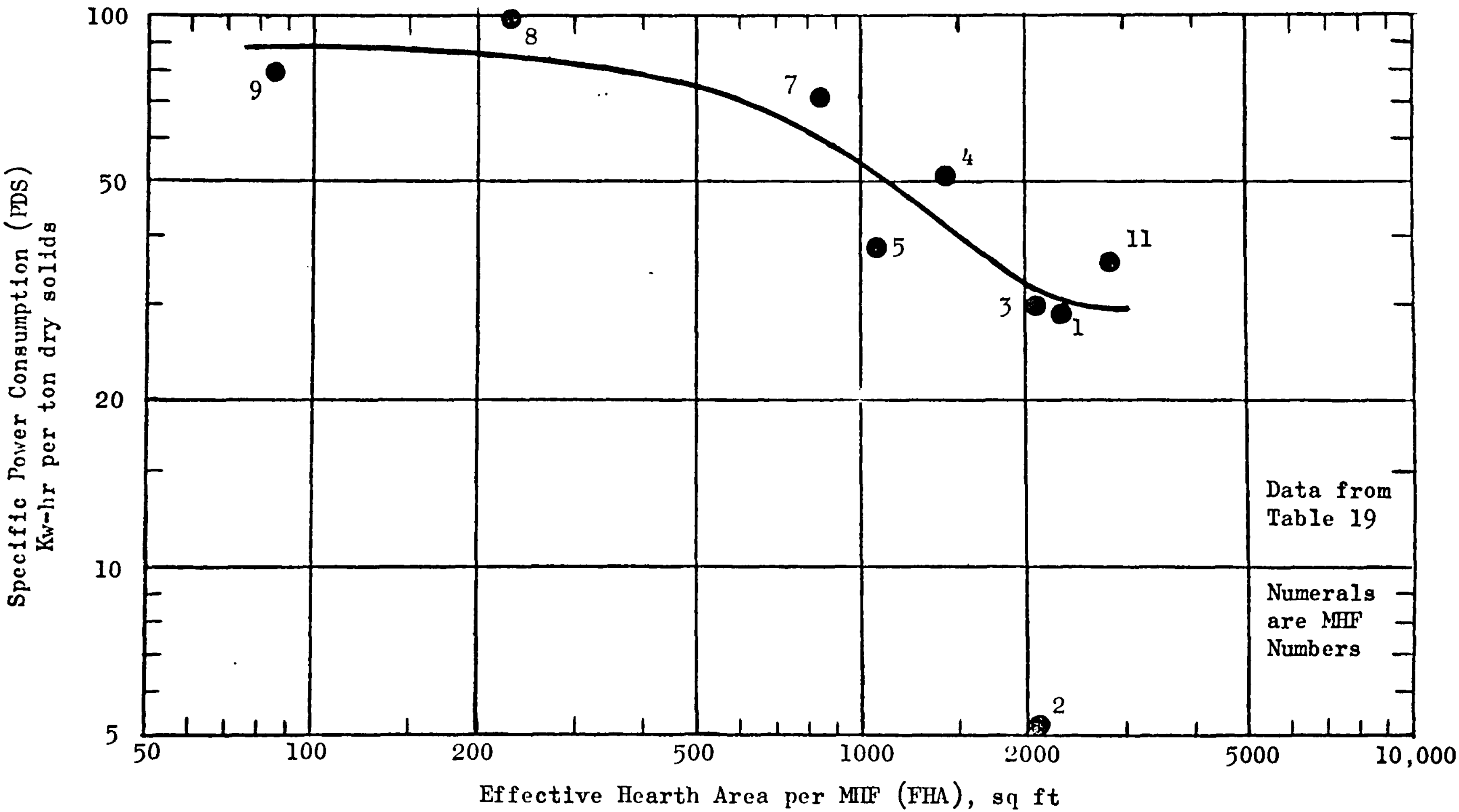
ELECTRICAL POWER CONSUMPTION

MHF No.	Location	Hearth Area/MHF Sq Ft "FHA"	No. of MHF's	Data Year	Actual Avg. per MHF		KWH per Ton Dry Solids
					1000's KWH per Year	Dry Solids Tons/Year	
1	Cleveland	2327	4	1967	94.7	3296	28.8
2	Minn.-St. Paul	2084	4	1967	--	--	5.2*
3	Kansas City	2084	3	'67-'69	216	7272	29.7
4	Cleveland	1425	4	'62-'65	205	4064	50.6
5	Battle Creek	1068	1	1968	229	6060	37.8
7	Saginaw	845	1	1969	541	7620	71.0
8	Hatfield	230	1	1969	--	--	98.9**
9	Bridgeport	85	1	1969	17.3	221***	78.4
11	Minn.-St. Paul	2808	3	1968	--	--	35.7

*Low Value: Natural Draft - No Wet Scrubber

**Estimated from HP and Sludge Flow Ratings

***Estimated from Ash Flow Rates



Note: MHF No. 2 not fitted, because plant
had no wet scrubber or induced draft fan.

FIG. 11. POWER CONSUMPTION

The allowable rates of change of temperature are lower for large hearth diameters and furnaces than for small ones, and are usually specified by the manufacturer. The field reports showed that the large furnaces, in Minneapolis-St. Paul and Cleveland, are limited to transient rates of 20 to 25 F per hr with soak periods of 1 to 2 days, so that it requires several days to heat up or cool down a furnace completely. The allowable temperature change rates increase to 150 F per hr for the smallest MHF's examined. The duration of the stated transients affects the steady-state annual MHF operating period and also the fuel requirements during transients. To limit the temperature change rates, it is sometimes necessary to apply heat to an MHF while it is cooling down. In this study, however, it was assumed that a furnace could be "bottled up" (i.e., all openings closed off) well enough to avoid the need for heating during cooldown. Moreover, the heat input rate (Btu/hr) was taken to be the same for (1) the pre-soak ambient-to-1200 F and (2) the post-soak 1200 F-to-1500 F periods.

A unified "optimum" operational scheme for all MHF's was developed with the help of the field data which suggested that the furnaces should be divided into three operational groups:

(A)	Hours per day HPD = 24	(Large cities)	
	Days per week DPW = 7	MHF Nos. 1, 2, 4 (also 7)	
(B)	HPD = 24	(Intermediate cities)	
	DPW < 7	MHF Nos. 3, 5, 6	
(C)	HPD < 24	(Small cities)	
	DPW = Any	MHF Nos. 8 & 9	

First, a Heatup Time (CYT), hr, (also equal to cooldown time) was developed as a function of furnace hearth area (FHA), based on typical temperature change rates soak times. Table 20 shows how CYT values were generated for several FHA levels, and Fig. 12 shows the resulting CYT vs FHA straight-line-segment graph.

Fig. 13 depicts the two types of cycle considered: a cold cycle for maintenance inspection for all three groups, and a hot cycle for standby at 1200 F applicable to groups (B) and (C). Periods during which fuel is used at the heatup rate, standby rate, or not at all are indicated on the figure.

Next, the total yearly cycling hours per MHF (YHUH) and yearly hot standby hours per MHF (YSBH) were established for each operational group in terms of CYT, NØF (total number of MHF's in plant) and SNØ (number of standby MHF's). This information is detailed in Table 21 which assumed two complete "cold cycle" inspections per year. To model standby units, it was assumed that the load was evenly distributed among all furnaces on an annual basis. Combination of the

TABLE 20

MHF HEATUP RATES AND TIMES

Note: Heatup hours = Cooldown hours, but no fuel used during cooldown

Effective Hearth Area, Sq Ft "FHA"	Assumed Allowable Heatup Rate, ^{o}F/Hr.	Hours for Portions of Complete Heatup (0-1500^{o}F)			Total Heatup, Hours "CYT"	Assumed Hours for Inspection (8/9) CYT
		0-1200^{o}F (4/9) CYT	1200^{o}F Soak (4/9) CYT	1200-1500^{o}F (1/9) CYT		
200 ± 200	150	8	8	2	18	16
600 ± 200	100	12	12	3	27	24
1100 ± 300	75	16	16	4	36	32
1700 ± 300	50	24	24	6	54	48
2000 +	25	48	48	12	108	96

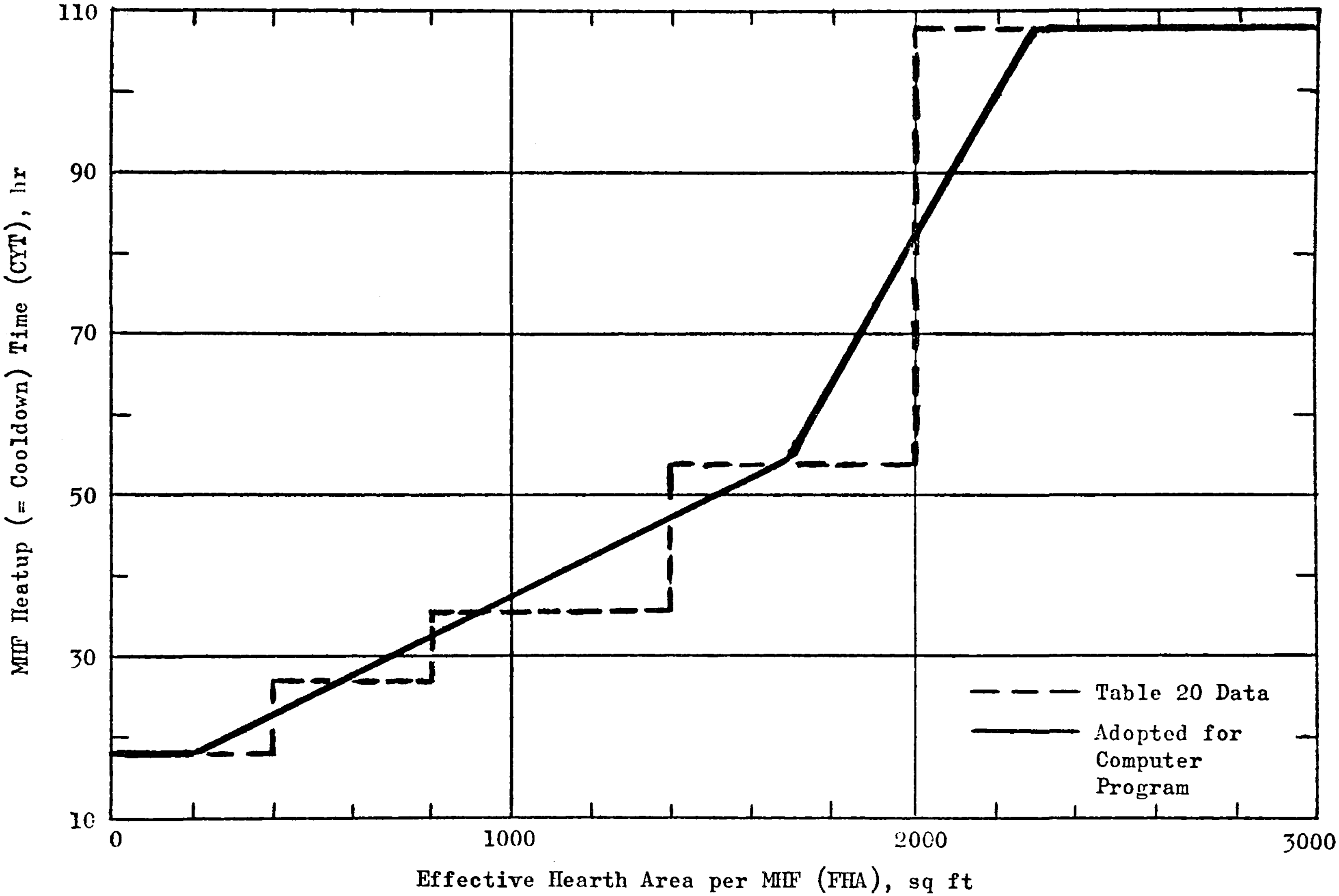


FIG. 12. MHF HEATUP TIME

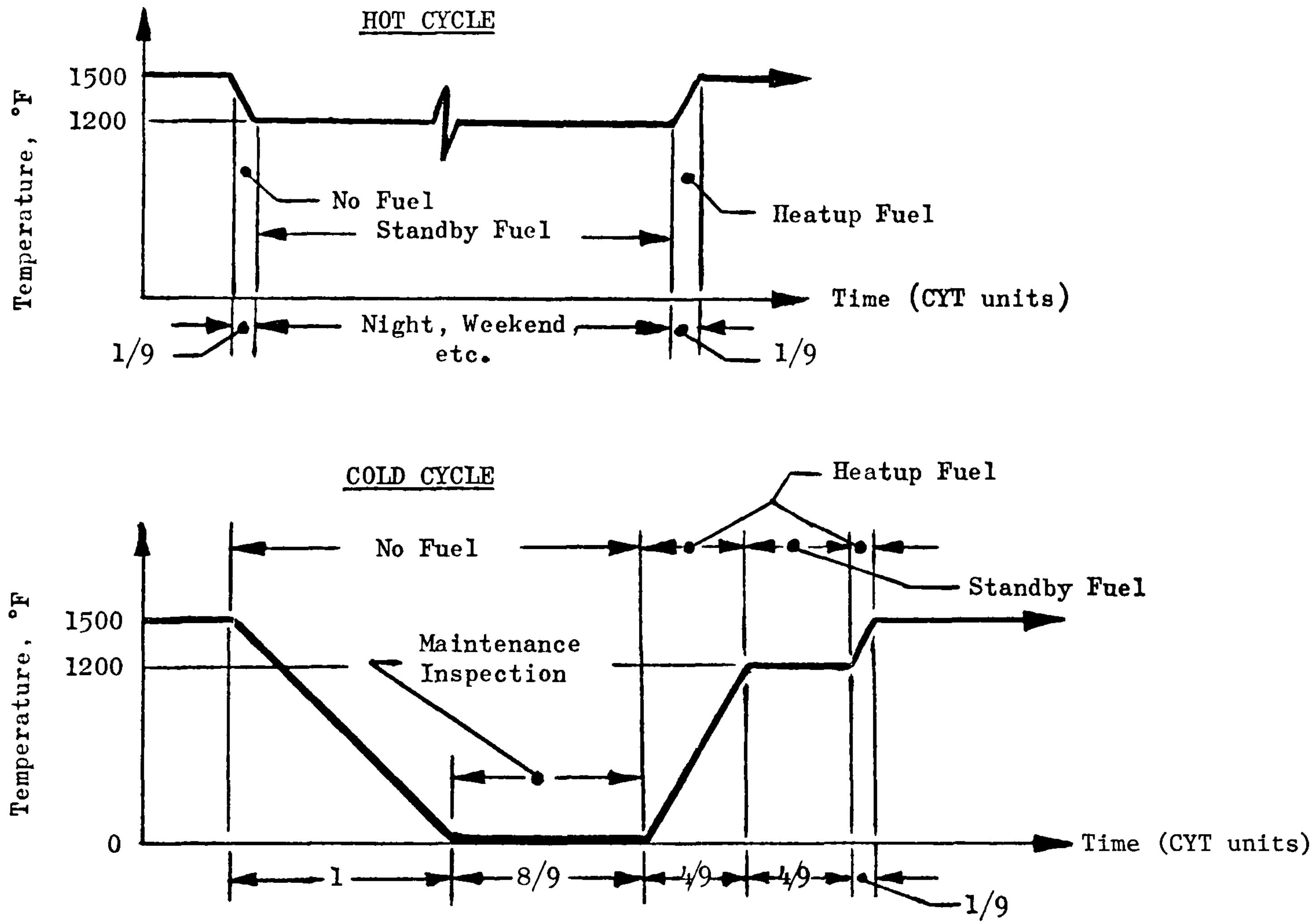


FIG. 13. ASSUMED MHF THERMAL CYCLES

TABLE 21

YEARLY COLD, HEATUP, AND STANDBY HOURS PER MHF

Assumption: Load evenly distributed among NØF on annual basis

Operational Group	Hr. per Day HPD	Days per Week DPW	Type of Cycle	Cold Hours (No Fuel Used): Hours per Cycle	Cold Hours: Cycles per Year	Cold Hours: Hrs. per Year	Heatup Hours (0-1200, 1200-1500^{o}F): Hours per Cycle	Heatup Hours: Cycles per Year	Heatup Hours: Hrs. per Year	Standby Hours (at 1200^{o}F): Hours per Cycle	Standby Hours: Cycles per Year	Standby Hours: Hrs. per Year
(A)	24	7	Cold	$\frac{17}{9}$ xy	2	$\frac{34}{9}$ xy	$\frac{5}{9}$ xy	2	$\frac{10}{9}$ xy	$\frac{4}{9}$ xy	2	$\frac{8}{9}$ xy
			Hot	--	--	None	--	--	None	--	--	None
(B)	24	<7	Cold	$\frac{17}{9}$ xy	2	$\frac{34}{9}$ xy	$\frac{5}{9}$ xy	2	$\frac{10}{9}$ xy	$\frac{4}{9}$ xy	2	$\frac{8}{9}$ xy
			Hot	$\frac{1}{9}$ xy	52	$\frac{52}{9}$ xy	$\frac{1}{9}$ xy	52	$\frac{52}{9}$ xy	(7-DPW) .24 y	52	1248 y ·(7-DPW)
(C)	<24	Any	Cold	$\frac{17}{9}$ xy	2	$\frac{34}{9}$ xy	$\frac{5}{9}$ xy	2	$\frac{10}{9}$ xy	$\frac{4}{9}$ xy	2	$\frac{8}{9}$ xy
			Hot	$\frac{1}{9}$ xy	52 DPW	$\frac{52}{9}$ xy .DPW	$\frac{1}{9}$ xy	52 DPW	$\frac{52}{9}$ xy .DPW	24 y(7-DPW) y(24-HPD)	52 52 DPW	y[8736 -52(HPD)(DPW)]

Abbreviations: x = CYT; y = (NØF-SNØ)/NØF .

YHUH and YSBH components in Table 21 leads to the following relationships for total hours:

$$\text{(A) } YSBH = (8/9)\ (CYT)\ (N\emptyset F - SN\emptyset)/(N\emptyset F) \quad (80)$$

$$YHUH = (10/9)\ (CYT)\ (N\emptyset F - SN\emptyset)/(N\emptyset F) \quad (81)$$

$$\text{(B) } YSBH = (N\emptyset F - SN\emptyset)\ [(8/9)\ (CYT) + 1248\ (7\text{-}DPW)]/(N\emptyset F) \quad (82)$$

$$YHUH = (62/9)\ (CYT)\ (N\emptyset F - SN\emptyset)/(N\emptyset F) \quad (83)$$

$$\text{(C) } YSBH = [(N\emptyset F - SN\emptyset)/(N\emptyset F)] \left\{[(8/9)CYT] + [8736-52(HPD)(DPW)]\right\} \quad (84)$$

$$YHUH = [(N\emptyset F - SN\emptyset)/N\emptyset F]\ (CYT/9)\ [10 + (52\ DPW)] \quad (85)$$

THERMAL CYCLING: HEAT AND FUEL REQUIREMENTS

From the field data, hourly standby and heatup heat requirements, in terms of million Btu per hour, were developed as functions of the effective hearth area. Table 22 shows the available data, reasonable on heatup and scant on standby. Linear least-square equations are fitted to the standby data, plotted on Fig. 14, and the heatup data, plotted on Fig. 15:

Standby Heat Requirement Btu per hr	SBQ = 315 (FHA)	(86)
Heatup Heat Requirement Btu per hr	HUQ = 1913 (FHA)	(87)

As might be expected, the standby requirement is a small fraction of the heatup requirement. The sum of the products (YSBH)·(SBQ) and (YHUH)·(HUQ) is the total annual heat requirement for thermal cycling. Division of this sum by the heating value (Btu per lb) of the fuel to be used then provides the annual fuel consumption for thermal cycling. The steady-state fuel consumption is found from the Thermal Analysis (Chapter IV) as explained in Chapter VII.

TOTAL MHF HEAT RELEASE

The basic energy balance, developed in detail in Chapter IV, matches the combined heat energy contained in the incoming sludge and auxiliary fuel to the sum of the outgoing heat flows. The latter are associated with the exhaust gases (including heat required for

TABLE 22

THERMAL CYCLING HEAT REQUIREMENTS PER MHF

MHF No.	Location	Hearth Area "FHA" Sq.Ft.	Opg. Year	Standby (Avg. per Year per MHF): Oil, Gal (Btu/Gal)	Standby: Gas, Cu Ft (Btu/Cu Ft)	Standby: Yearly Heat, 10^6 Btu	Standby: Stand-by, Day/Yr	Standby: Heat per Hr, 10^6 Btu	Heatup (Avg. per MHF): Fuel Qty. (Btu/Unit)	Heatup: Heat Rate, 10^6 Btu	Heatup: Cy/Yr (Hr/Cy)	Heatup: Heat per Hr, 10^6 Btu
1	Cleveland	2327	1966	16,535 ($1.39x10^5$)	207.5 (600)	2298	130.5	.734				
2	Minn.-St. Paul	2084	1959						25,700 Gal/Yr ($1.39x10^5$)	3572 per Year	15 (60)	3.97
3	Kansas City	2084	1969						25,000 Cu Ft/Wk (880)	22 per Week	1 per Week (5)	4.4
4	Cleveland	1425	62-65 (Avg)	204 ($1.39x10^5$)	$3.15x10^6$ (600)	506	55.1	.383				
5,6	Battle Creek	1068, 890	1969	--	400/Hr (896)	--	--	.358	14,000 Cu Ft/Wk (896)	12.54 per Week	1 per Week (9)	1.39
7	Saginaw	845	1969						900 Gal/Cy ($1.4x10^5$)	126 per Cycle	8 (72)	1.75
8	Hatfield	230	1969						6100 Cu Ft/Cy (936)	5.71 per Cycle	(12)	0.475
9	Bridgeport	85	1969						200 Gal/Cy ($1.4x10^5$)	1.4 per Cycle	(3)	0.467

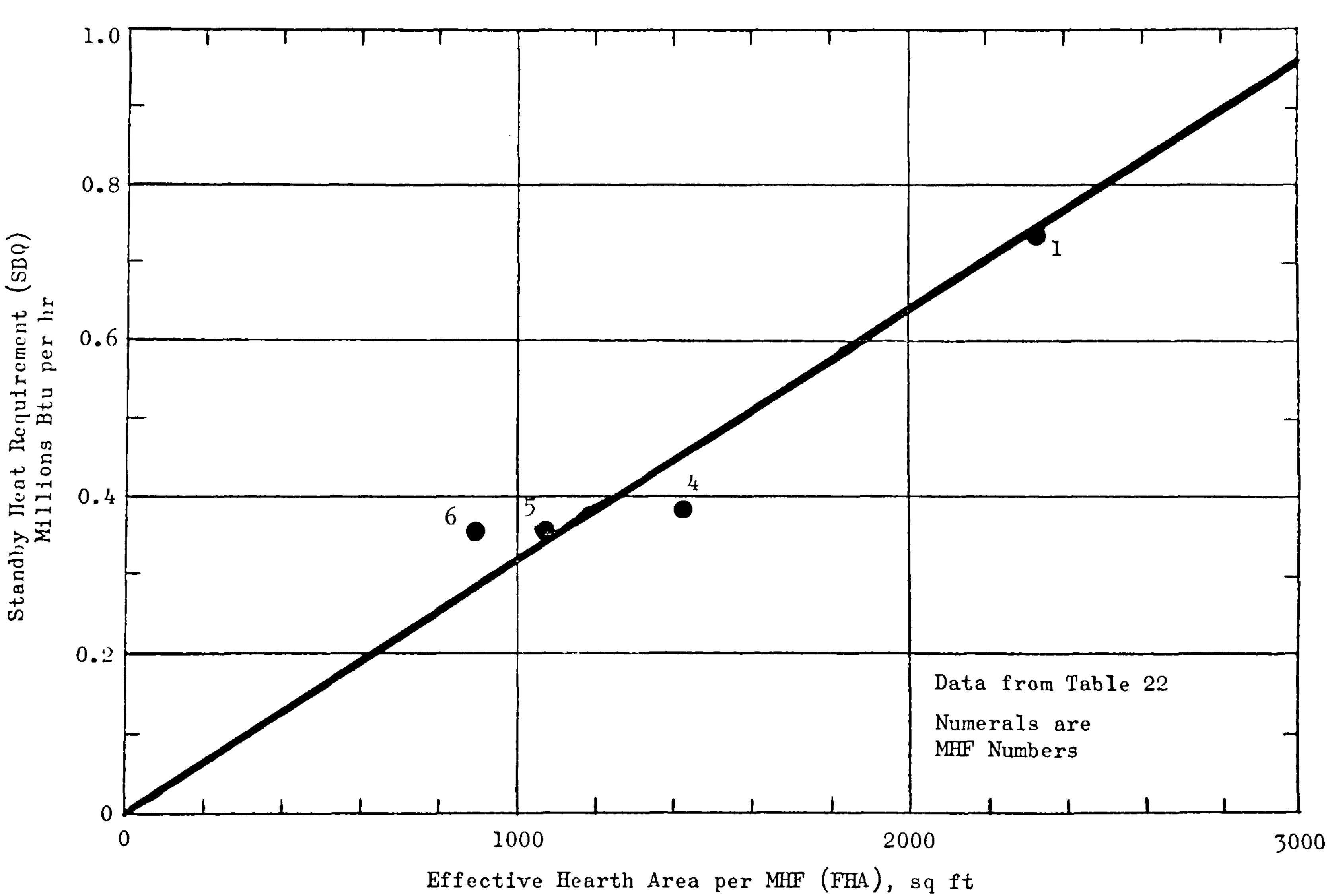


FIG. 14. MHF STANDBY HEAT REQUIREMENT

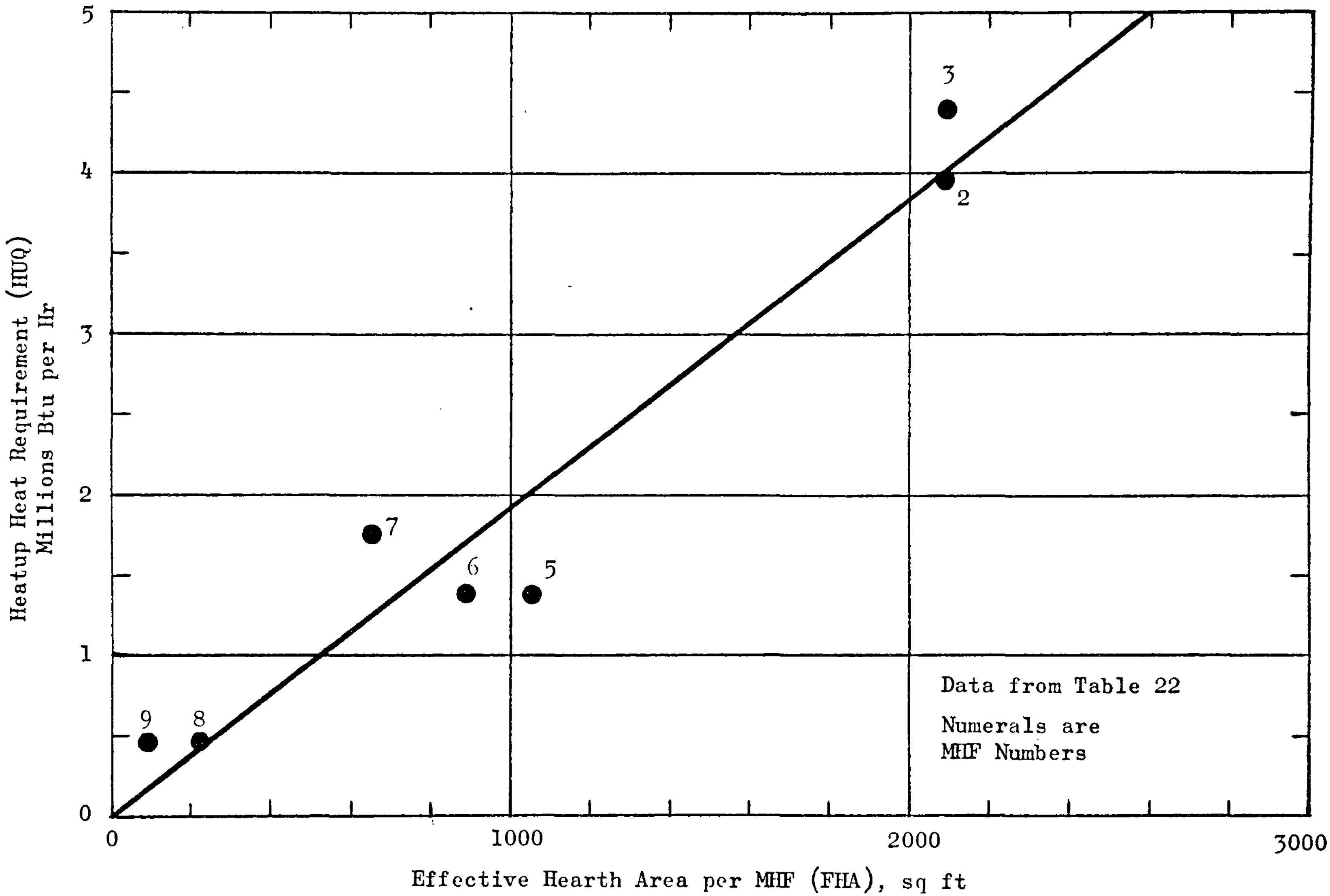


FIG. 15. MHF HEATUP HEAT REQUIREMENT

evaporation of the water content of the sludge), the ash, the part of the cooling air rejected to the atmosphere, and the furnace heat losses to the environment. The Thermal Analysis described in Chapter IV calculates the steady-state fuel requirements when sludge properties, minimum percent excess air, temperatures of the exhaust stream, and some minor parameters are specified.

Another approach to finding fuel requirements is to examine the records of operating sludge incinerators for historical sludge and fuel flows and properties. The sum of the heat energies released by the sludge and fuel, normalized on the basis of some MHF capacity variable, might be proven of value as an empirical guideline. Of several tried, the quantity Total (Fuel + Sludge) Heat Release in Million Btu per Ton Wet Sludge appeared to be the most useful. Table 23 gives average annual fuel and sludge data for all the furnaces visited in the field. The Total Heat Release computed from these data appears in the last column, with values varying between 3 and 7.

The Total Heat Release is between 3.5 and 4.5 for most of the furnaces investigated. Values much above 4.5 are probably excessive (since they are out of step with the current practice) and could indicate either higher exhaust stream temperatures than in most incinerators, or excessive use of cooling or combustion air. The highest value listed in Table 23, 7.0 for Saginaw, is the result of (1) the high calorific value of the sludge volatiles and (2) the high concentration of solids in the sludge. The Saginaw MHF could be operated quite well with a much wetter sludge, thereby reducing filtration costs or could be used as a source of thermal energy for other tasks.

The Kansas City MHF plant also appears to operate at a high heat usage per ton of sludge. Since the Kansas City sludge has about an average solids content and heat release, the reason here would appear to be the use of excess fuel perhaps accompanied by enough excess air to maintain a reasonable exhaust temperature.

The Cleveland MHF's, on the other hand, have a Total Heat Release of about 3. This is quite low and indicates a colder exhaust temperature than the average operating MHF or perhaps a smaller amount of excess air and cooling air than is in use elsewhere.

It is realized that the suggested criterion is empirical. It should be tested against operating data from other MHF's to establish the extent of its validity.

TABLE 23

TOTAL MHF HEAT RELEASE

MHF No.	Location	Year or Period	Sludge (Yr. Avg.) Btu/Lb Volatiles	Wt.% Volatiles	"X" 10^6 Btu Per Ton Dry Sol.	"Y" All Fuel (Yr. Avg.) 10^6 Btu per Ton Dry Sol.	"Z" Avg. Tot. Solids, Wt.% in Sludge	"Z(X+Y)" Avg. Total (Fuel + Sludge) 10^6 Btu per Ton Wet Sludge
1	Cleveland	1966	9,530	43.7	8.33	5.4	23.0	3.16
		1967		43.3	8.25	4.25	23.4	2.92
2	Minn.-St. Paul	1966	10,000	71.8	14.4	0.375	27.5	4.06
		1967		69.5	13.9	0.50	28.2	4.06
3	Kansas City	67-69	10,500	59.9	12.6	4.0	29.4	4.88
4	Cleveland	62-65	10,070	43.9	9.4	4.0	23.4	3.14
5	Battle Creek	1968	10^4*	57.0	11.4	4.46	26.0	4.47
		1969		54.8	11.0	6.15	26.1	4.12
6	Battle Creek	1964	10^4*	56.5	11.3	7.60	24.7	4.67
		1965		58.4	11.7	3.45	26.6	4.03
		1967		63.7	12.7	4.18	24.75	4.17
7	Saginaw	1966	13,970	44.8	12.5	None	45.9	5.74
		1967		46.7	13.0		47.	6.1
		1968		48.2	13.2		47.	6.2
		1969		51.1	14.3		48.	6.92
8	Hatfield	1969	10^4*	65(est.)	13.0	--	20.(est.)	--
9	Bridgeport	1969	7000/Lb. Dry Sol. (est.)		14.0	14.0	13.5(est.)	3.78

* Assumed value

VII. DESCRIPTION OF SUBROUTINE

SUBROUTINE OPTIONS

The subroutine developed is a single computer program with two options:

1. Thermal Analysis Option (NCASE = 0)
2. Design Cost Option (NCASE > 0)

These options are specified by the value assigned to the variable NCASE (number of cases) on the first input data card. The subroutine was written in Fortran IV computer language and is compatible with the IBM 1130 and IBM System 360 digital computers. The Fortran IV subroutine listing is enclosed in the Appendix. Chapter VIII is a User's Guide to Input Selection wherein each input variable (to both options) is listed and discussed. Chapter IX describes the mechanics of the input format and contains a set of sample input data cards, as well as printouts for a numerical example of each option.

The Thermal Analysis Option (TAO) essentially performs the calculations detailed in Chapter IV, "Thermal Analysis". For a unit MHF supplied with a sludge flow of given magnitude and characteristics TAO finds the steady-state flows of combustion air and auxiliary fuel to maintain a specified excess air percentage for combustion of sludge volatiles and specified temperatures of cooling air, exhaust gas and ash at discharge. The TAO is useful for checking an existing or planned incinerator from a technical performance standpoint. The Design and Cost Option (DCO) performs the task of designing and costing an incinerator system (which may consist of one or more MHF's) to incinerate a given sludge flow considering operating schedule, maintenance factors, and costs. The DCO includes the TAO in its entirety. The DCO features a variable "MHF Selection Input" which the user should employ for the design and costing of a number of differently operated incineration systems for the purpose of choosing an optimum system.

The interrelationship between the two options may be seen from the respective calculation outlines depicted in the schematics of Fig. 16 for the TAO and Fig. 17 for the DCO. The rectangular boxes on these figures contain all the individual inputs in the groupings discussed in Chapter VIII. On the TAO Schematic (Fig. 16), there are 5 boxes of technical inputs: for Sludge Stream, Air Data and Stream Temperatures, Auxiliary Fuel Burner, Chemicals Reaction Data, and Environment. Only the remaining box (MHF Data Input) is non-technical. The entire TAO computation (detailed in Chapter IV) is given the designation "B".

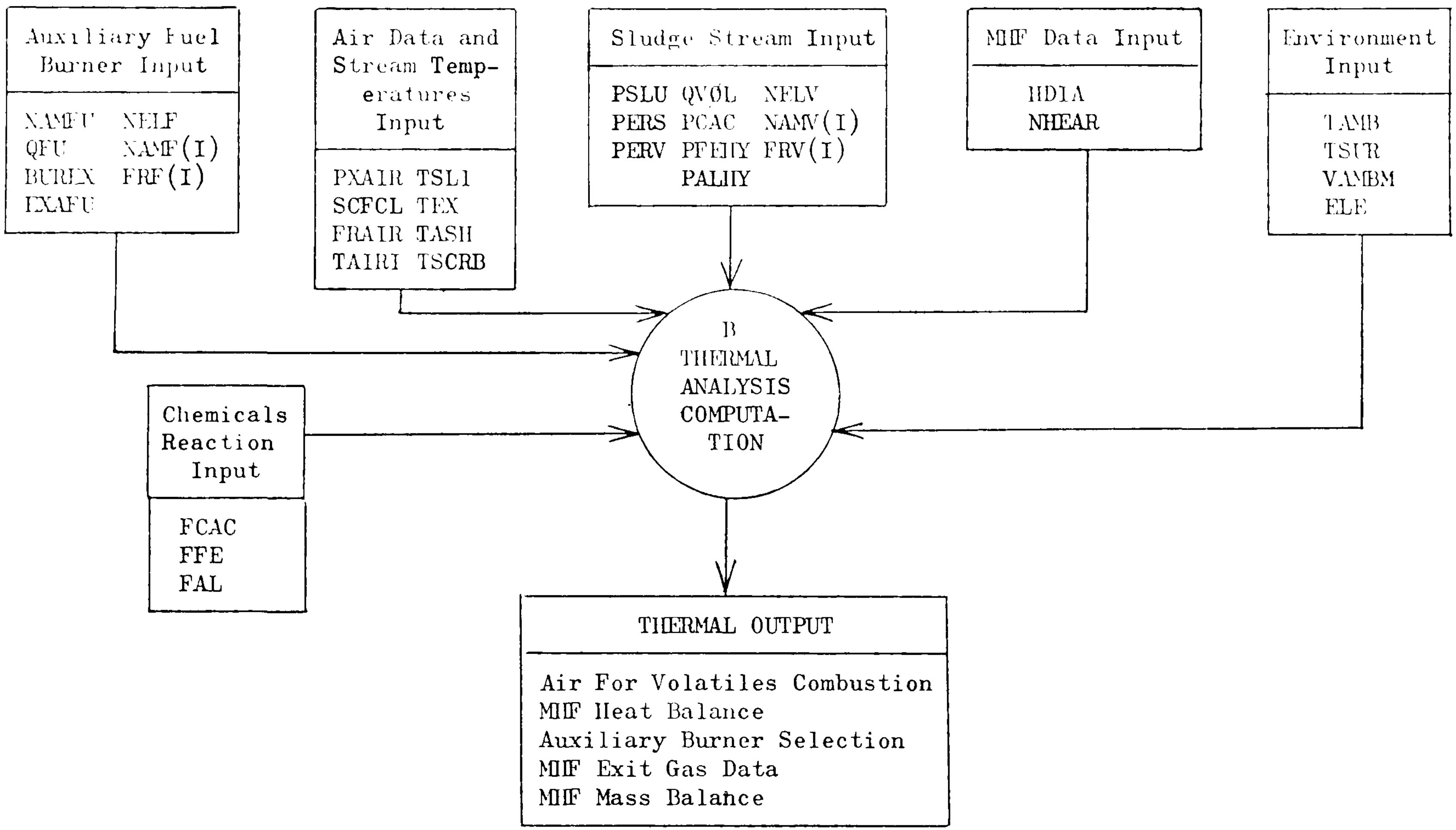


FIG. 16. SCHEMATIC OF THERMAL ANALYSIS OPTION (NCASE = 0)

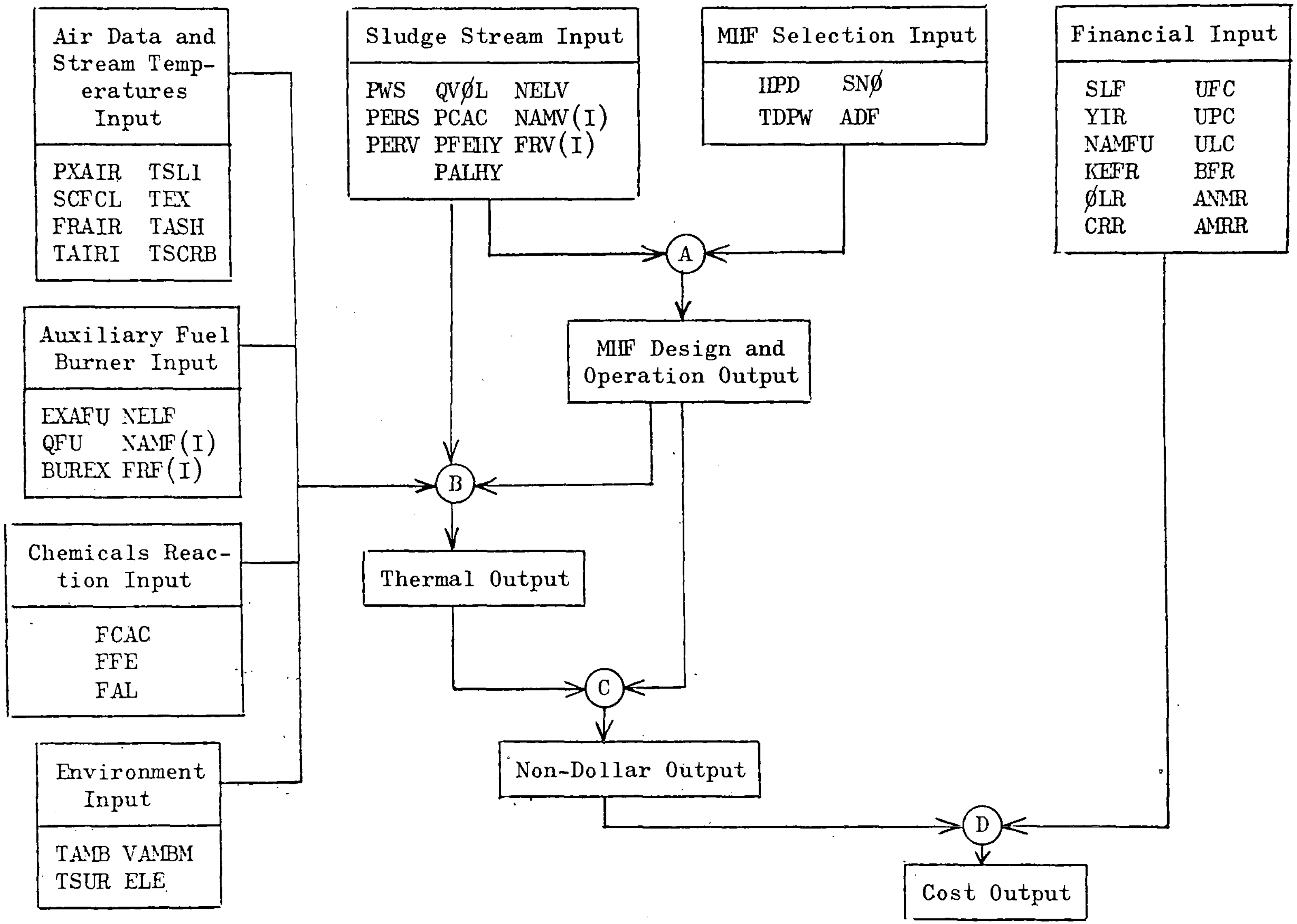


FIG. 17. SCHEMATIC OF DESIGN AND COST OPTION (NCASE > 0)

Reference to the DCO schematic (Fig. 17) reveals that it, too, features the same 5 technical input groups, but, in addition, has a Financial input and an MHF Selection input. Four sets of computations are involved, designated "A" through "D"; of these "B" is the TAO computation. Before describing these computations in detail, mention should be made of some ground rules which were evolved based on the nature of the field data (Chapter V) and the results of the data correlation (Chapter VI).

GROUND RULES

1. The MHF selection input is made variable to provide numerous incinerator designs from which an optimum may be chosen. The MHF Selection input consists of four quantities, two indicative of the operating schedule (hours per day and days per week), and two indicative of the reliability to be built into the system (number of standby units and number of units above the minimum required). As these four quantities assume different values, different incineration system designs and costs will be generated, and the optimum will be the one which satisfies the most important criteria of the user. If this is minimum cost, then a smaller number of larger furnaces, associated with zero standby and excess units, would probably result, but at a sacrifice in reliability and flexibility. Alternatively, the schedule inputs may be varied to find the optimum for a plant yet to be built, or to adjust the changes in operation of an existing plant.

2. Incineration is assumed to take place only during all or part of regular operating hours for the treatment plant as a whole. It was considered definitely too costly to operate the incinerator outside of regular plant hours by itself. Incineration takes place 52 weeks in the year, except for 2 yearly shutdowns for maintenance inspection. For incinerators which do not operate continuously, hot standby operation at 1200 F is assumed, e.g., for a weekend period or portions of every day. Further, the heatup and cooldown is taking place according to the temperature change rates (which vary with incinerator size) in Chapter VI. Implicit in these assumptions is the ability of the dewatering and any sludge storage equipment to adapt to the incineration flowrates and schedules.

3. Each incineration system was considered to consist of one or more standard furnaces of the same size (some of them on standby) so that the entire plant sludge load could be incinerated in steady-state operation, excluding the cycling operations referred to in 2. above. The furnace sizes were limited to standard dimensions

as used in practice, varying in hearth area from 85 to 3120 sq ft, representing 59 discrete furnaces from 6 to 12 hearths and 6.75 to 22.25 ft outer diameter, all with a wall thickness of 13.5 inches (Table 9). From Fig. 3 and Table 1, incinerator sizing was based on a loading rate nearest to 2 lb dry solids per hr per sq ft effective hearth area. The approach was only made from the high side because the more recent recommendations of manufacturers are slightly greater than 2 lb/hr sq ft.

4. The correlation of field data (Chapter VI) showed that the cost per MHF for equipment and operating labor was unaffected by the number of MHF's operating in parallel. Therefore, as far as possible, the technical and cost computations are carried out for a single MHF first, and then extended to an incineration system consisting of several furnaces.

5. Auxiliary fuel consumption and combustion air flow during steady-state MHF operation were based on the Thermal Analysis computations ("B") and not on field data. Air flowrates and excess percentages were generally not accurately measured in the field, and estimates were regarded as inferior to calculation. Fuel consumption, of course, was measured, but since it is a function of air flow, good correlation was not possible.

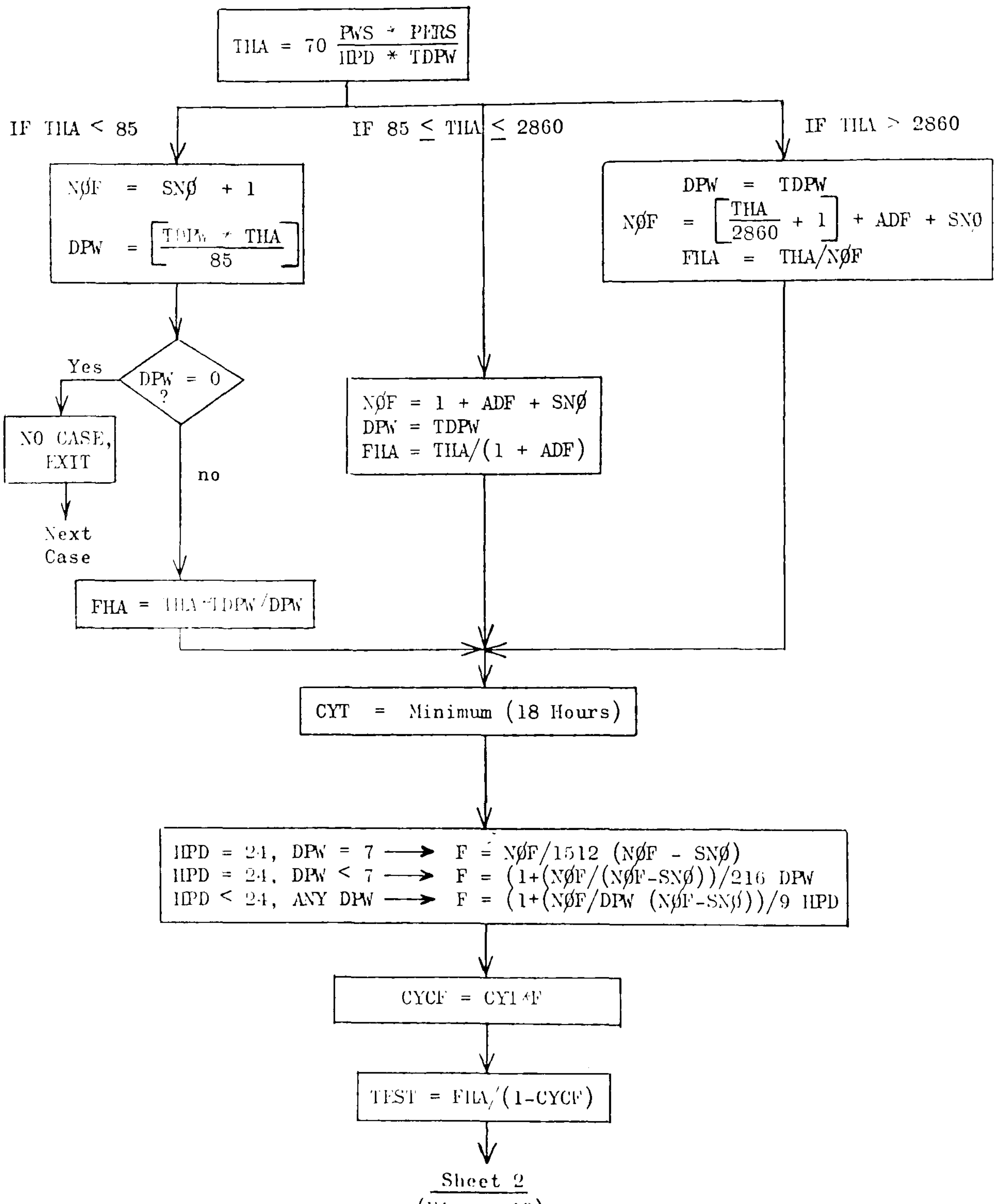
6. The user may choose to include one or more of the following components of capital cost: building, land, and engineering fee, in addition to the installed equipment.

COMPUTATIONS

A. <u>Design and Operation Output</u> (Three sheets: Fig. 18, Fig. 19, and Table 24). The aim of this computation is to design an incineration system satisfying (1) the MHF Selection input as to scheduling and standby capacity, (2) the Sludge Stream input as to total load, and (3) the Table (Table 9) of standard MHF sizes available. Basically, the imposed scheduling determines the time fraction of steady-state operation which requires a furnace of larger hearth area than with full-time operation, since sludge flow is directly proportional to hearth area FHA (Eq. 68). However, a larger furnace gives rise to a smaller steady-state operating fraction (Fig. 12). A search is carried out among the table of MHF hearth area sizes until the inequality

$$FHTAB(K) * (1 - CYCF(K)) \leq FHA \leq FHTAB(K+1)*(1-CYCF(K+1)) \quad (88)$$

FIG. 19. COMPUTATION A: MHF DESIGN AND OPERATION OUTPUT
(SHEET 1 of 3)



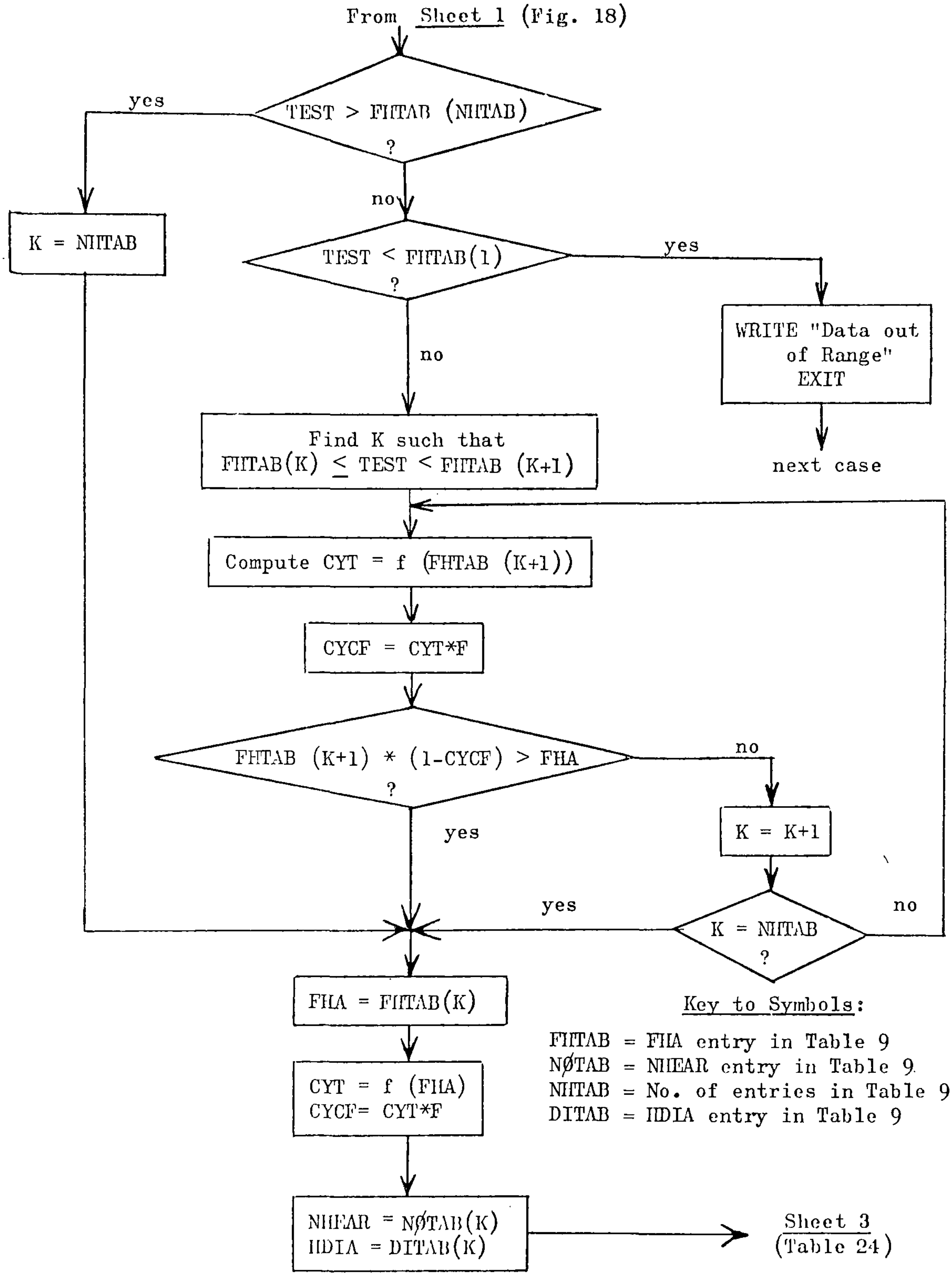


FIG. 19. COMPUTATION A: MHF DESIGN AND OPERATION OUTPUT (SHEET 2 of 3)

TABLE 24

COMPUTATION A: MHF DESIGN AND OPERATION OUTPUT (SHEET 3 OF 3)

NOTE: Sheet 1 = Fig. 18

Sheet 2 = Fig. 19

PSLU = 14,000 PWS/(1 - CYCF) (HPD) (DPW)

CYCF from Sheet 2

DPW from Sheet 1

DSF = (PSLU) (PERS)

HLD = DSF/FHA (FHA from Sheet 1)

YHF = 52 (HPD) (DPW) (NØF - SNØ)/NØF

NØF from Sheet 1

CRL from Eq. 75

RRL from Eq. 75

WØH = (HPD) (DPW)

SCFCL (scfm) = 36 PWS from Chapter VI

is satisfied where

FHTAB(K) is the Kth entry (in ascending order) of FHA in Table 9

CYCF(K) is the non-steady-state operating time fraction corresponding to FHTAB(K) according to Fig. 12

When more than one furnace size satisfies the inequality, the lowest FHA is chosen, giving a higher hearth loading. This is done because there is a tendency to design furnaces for too low a hearth loading. The iterations necessary to make the FHA (and, therefore, MHF) selection are shown in detail on Figs. 18 and 19. Once FHA is found, the remaining design and operation output variables are calculated in a straightforward fashion as shown on Table 24.

B. Thermal Output: This is fully discussed in Chapter IV.

C. Non-Dollar Output: Calculations are listed in Table 25.

D. Cost Output: Calculations are listed in Table 26.

TABLE 25

COMPUTATION C: NON-DOLLAR OUTPUT PER MHF

LAND AREA: (acres)
ALA = 0.7854 * KLA * (HDIA)^2/43,560
KLA = 4.938 (Chapter VI)

YEARLY FUEL: (lb/year)
FCY = (WGTF * YHF * (1-CYCF)) + (YSBH * SBQ/QFU) + (YHUH * HUQ/QFU)
WGTF from Eq. (50)
YHF from Output A
CYCF from Output A
YSBH from Eq. 80, 82, or 84
SBQ from Eq. 86
YHUH from Eq. 81, 83, or 85
HUQ from Eq. 87

YEARLY POWER: (KW-hr/year)
PCY = PDS * DSF * (1-CYCF) * YHF/2000
DSF from Output A
PDS from Eq. 79

YEARLY OPG. LABOR: (man-hr/yr)
ØLM = ØMD * YHF/24
ØMD from Eq. 78 (FHA from Output A)

YEARLY NORMAL MAINT. LABOR: (man-hr/yr)
ANMM from Eq. 77 (FHA from Output A)

YEARLY CASTING REPLACEMENT LABOR: (man-hr/yr)
CRM = CLH * NHEAR * CRL/SLF
CLH from Eq. 73
NHEAR from Output A
CRL from Eq. 75

YEARLY REFRACTORY REPLACEMENT LABOR: (man-hr/yr)
AMRM = RLH * NHEAR * RRL/SLF
RLH from Eq. 74
RRL from Eq. 75

TABLE 26

COMPUTATION D: COST OUTPUT, DOLLARS

All Quantities From Output C, Except FHA, HDIA, NHEAR are From Output A

1. CAPITAL COSTS PER MHF

Installed Capital Cost: CCI, from Eq. 69

Optional Building Cost: BGC = BFR * CCI

Optional Land Cost: CLD = ALA * ULC

Optional Engineering Fee: EFC from Eq. 70

Total Capital Cost: TCC = CCI + BGC + CLD + EFC

2. CAPITAL COSTS FOR ALL MHF's

CCI, BGC, CLD: Multiply values (1.) by NØF

EFC: Apply Eq. 70 to new (CCI + BGC)

TCC: New (CCI + BGC + CLD + EFC)

3. TOTAL COST BREAKDOWN PER YEAR PER MHF (Averaged over SLF)

Total Capital Charges $TCY = \frac{(TCC)(YIR)/100}{1 - (1 + (YIR/100))^{-SLF}}$

Replacement Parts $RPY = (NHEAR/SLF)\left[(CRL.CAST) + (RRL.REFR)\right]$

CRL, RRL from Eq. 75

CAST from Eq. 71

REFR from Eq. 72

Materials and Supplies: AMSY from Eq. 76

Fuel: FUY = FCY * UFC

Power: PØY = PCY * UPC

Operating Labor: ØLY = ØLM * ØLR

Normal Maintenance Labor: ANMY = ANMM * ANMR

Replacement Maintenance Labor RMY = (CRM * CRR) + (AMRM * AMRR)

Total Cost: TCST = TCY + RPY + AMSY + FUY + PØY + ØLY + ANMY + RMY

TABLE 26 (Concluded)

4. <u>TOTAL COST BREAKDOWN PER YEAR FOR ALL MHF's</u> (Averaged over SLF)

TCY: Multiply value (3.) by (TCC (2.) /TCC (1.))

All Others: Multiply values (3.) by NØF

Total Cost: Summation as in 3.

5. <u>COST PER TON DRY SOLIDS</u>

Divide values in 4. by [(DSF) (NØF) (YHF) (1 - CYCF)/2000]

6. <u>COSTS AS PERCENTAGE OF TOTAL</u>

Multiply values in 4. by (100/TCST)

VIII. USER'S GUIDE TO INPUT SELECTION

This Chapter discusses every single input to the Design & Cost Option and Thermal Analysis Option to assist the user in making rational selections when he is called upon to use his judgment. For every input, a standard numerical value is also provided, in the event that insufficient background information exists to make a rational selection. The mechanics of the input format are described in detail in the next Chapter (IX) in which a set of input data cards is reproduced, with instructions on how to enter the numerical values. In the rest of this Chapter, the symbol (D) following the Fortran name of an input or a group of inputs designates an input only needed for the Design & Cost option, and the symbol (T) an input only needed for the Thermal Analysis Option. Where no symbol appears, the input is common to both options.

INFORMATION INPUT

<u>LØC</u> (location: The user may use up to 48 letters (including numerals, punctuation and spaces) for the title. This could be the city, plant, or other designation desired.

<u>NCASE</u> (number of cases): Any finite number of cases (1,2,3,....) may be run for (D). The value zero (0) denotes that (T) is being run.

MHF DATA INPUT (T)

<u>HDIA</u> (outer diameter, ft): An input for Thermal Analysis only.

<u>NHEAR</u> (number of hearths): An input for Thermal Analysis only.

SLUDGE STREAM INPUT

<u>PWS</u> (D) (plant wet sludge flow, ton/day): Primary input (per 24 hr day), using the value of the design flowrate exiting from the sludge dewatering equipment immediately upstream of the incinerator. It is assumed that PWS may be divided into any number of MHF's without restriction, as indicated by optimization. If unknown, use PWS = 0.0004·(Population Served), per Ref. 7.

<u>PSLU</u> (T) (steady state wet sludge flow per MHF, lb/hr): This is the rate for one MHF.

PERS (total dry solids concentration, w/o): Also from upstream process. If unknown, use PERS = 25, typical for well-operating vacuum filters and centrifuges.

PERV (volatiles concentration in solids, w/o): This is the portion which burns, determined from analysis of the sludge. Typically, it varies between 65 and 85. If unknown, use PERV = 75.

QVØL (higher heat value of volatiles, Btu per lb): This must be determined from a bomb calorimeter. If the percentages by weight of carbon (C), (atomic) hydrogen (H), and (atomic) oxygen (Ø) in the volatiles are known, the DuLong formula may be used for a reasonably good approximation to the calorimeter value:

$$QVØL = 14{,}600\ C + 62{,}000\ (H - Ø/8) \tag{89}$$

If the sludge type and the percentage by weight in the solids of precipitating or conditioning chemicals (PERC) are known, Fair, Geyer, and Okun (Ref. 35) give what amounts to:

$$QVØL = 100\ a - (ab(100 - PERC)/PERV) \tag{90}$$

where a = 131 and b = 10 for plain-sedimentation municipal wastewater solids (fresh and digested)

a = 107 and b = 5 for fresh activated sludge

The general range of values is 8500 to 11,000. If not otherwise estimable, use QVØL = 10,000.

PCAC (calcium carbonate in dry solid, w/o):
PFEHY (ferric hydroxide in dry solid, w/o):
PALHY (aluminum hydroxide in dry solid, w/o): All three quantities are presumed known from the composition of the sludge stream leading the dewatering equipment.

NELV (number of elements in the volatiles): Provision is made for 5 elements.

NAMV(I) (name of Ith element in volatiles)
FRV(I) (mass fraction of Ith element in volatiles): The numbers are 1 for carbon C, 2 for elemental hydrogen H, 3 for elemental oxygen Ø, 4 for elemental nitrogen N, and 5 for sulfur S. The up to five mass fractions are to be taken from ultimate analysis of the sludge volatiles. If no data are available

use this typical composition:

FRV(1)	0.55
FRV(2)	0.06
FRV(3)	0.35
FRV(4)	0.03
FRV(5)	0.01
	1.00

AIR DATA AND STREAM TEMPERATURES INPUT

PXAIR (minimum excess air for combustion of volatiles, percent): Most sludge incinerators run with 50 percent excess air, some as high as 150. The value chosen should provide the desired exhaust gas temperature and ensure complete volatiles combustion, but not incur unduly high auxiliary fuel consumption. In absence of specific considerations, use PXAIR = 75.

SCFCL (shaft cooling air flow, in scfm for entire plant (D), or in scfh per MHF (T)): From correlation of operating MHF's a rate of 36 scfm for each ton of wet sludge per 24 hr day in suggested (Chapter VI).

FRAIR (fraction of cooling air recycled): The fraction of cooling air recycled should be so chosen that the temperature rise in the cooling air does not exceed 200 to 300 F so that adequate cooling exists at the top of the shaft. At the same time, the recycled cooling air is the principal source of air for combustion of volatiles. General practice seems to be to recycle 60 to 80 percent of the cooling air. In absence of other considerations, use FRAIR = 70.

TAIRI (exit temperature of cooling air, F): In line with the remarks immediately above, a value in the 275 to 375 F range is indicated. In absence of specific considerations, use TAIRI = 325.

TSL1 (sludge inlet temperature, F): Usually this is close to ambient temperature. If unknown, use TSL1 = 60.

TEX (combustion gas exhaust temperature, F): Based on the discussion in Chapter III, a range of 500 to 1100 F has been used. A lower TEX would reduce the scrubber capacity needed, but possibly tend toward incomplete combustion. A higher TEX would lead to an increase in auxiliary fuel. In the absence of specific considerations, use TEX = 800.

TASH (ash discharge temperature, F): Operating MHF's show a variation from 150 to 850 F. The optimum depends on the temperature of the incoming combustion air. If the latter is mainly recycled cooling air, at say 325 F, TASH must be above this level to avoid the impossible situation of ash leaving at a lower temperature than the incoming cooling air. If the incoming air is mainly ambient, TASH should be lower for good heat exchange. In the absence of specific considerations, use TASH = 400.

TSCRB (scrubber exit gas temperature, F): The main consideration here is formation of steam plumes. The temperature should be low enough to avoid formation of such plumes, but high enough for scrubber water flows not to become excessive. In absence of specific considerations, use TSCRB = 175.

CHEMICALS REACTION INPUT

FCAC (fraction of calcium carbonate calcined): The recalcination of limestone in an MHF requires a minimum temperature of 1650 F (900 C), or higher, according to some sources. The extent to which this reaction takes place as a function of MHF parameters is not known. Since the reaction is endothermic, the higher the value of FCAC, the more conservative the furnace design. Therefore, if no data are available, use FCAC = 1.

FFE (fraction of ferric hydroxide reacting): There is a lack of information here, too. In the absence of data, for a conservative design (this reaction is also endothermic) use FFE = 1

FAL (fraction of aluminum hydroxide reacting): This is also an endothermic reaction with no MHF data known. In the absence of data, for a conservative design, use FAL = 1.

AUXILIARY FUEL BURNER INPUT

NAMFU (name of fuel): Twelve spaces are allotted. Designations like No. 2 Fuel Oil or Natural Gas are possible.

QFU (higher heat value of fuel, Btu per lb): This must be determined from a bomb calorimeter. There are three common fuels: fuel oil, natural gas and sludge digester gas. If no data are available, use typical values for these fuels, as follows:

QFU = 19,000 for fuel oil
QFU = 21,000 for natural gas
QFU = 12,000 for digester gas

BUREX (percent excess auxiliary fuel burner capacity): It is customary to provide excess capacity in case there is an overload on the burner due to large excess air flow or a very wet sludge. In the absence of specific considerations, use BUREX = 25.

EXAFU (percent excess air for auxiliary fuel burner): Most burners operate close to theoretical (stoichiometric) air/fuel mixture ratio. This variable may be used for leaner mixtures (EXAFU positive, percent excess air) or richer mixtures (EXAFU negative, percent air deficiency). In the absence of specific considerations, use EXAFU = 0.

NELF (number of elements in the fuel): Provision is made for 5 elements.

NAMF(I) (name of Ith element in fuel):
FRF(I) (mass fraction of Ith element in fuel): The numbers are 1 for carbon C, 2 for elemental hydrogen H, 3 for elemental oxygen Ø, 4 for elemental nitrogen N, and 5 for sulfur S. The up to five mass fractions are to be taken from ultimate analysis of the fuel. If no data are available, use these typical compositions:

	Fuel Oil	Natural Gas	Digester Gas
FRF(1)	0.86	0.67	0.50
FRF(2)	0.11	0.22	0.12
FRF(3)	0.00	0.01	0.38
FRF(4)	0.00	0.10	0.00
FRF(5)	0.03	0.00	0.00
	1.00	1.00	1.00

ENVIRONMENT INPUT

TAMB (ambient temperature, F): In the absence of specific data, use TAMB = 60

TSUR (temperature of outer surface of MHF, deg F): The heat loss from the MHF to the environment by radiation and convection depends on TSUR. With good insulation (13.5 inches) and typical heat releases, TSUR can be kept about 100 F above ambient. In the absence of specific data, use TSUR = TAMB + 100.

VAMBM (ambient air velocity, miles/hr): The convective heat loss from the MHF increases with VAMBM. For conservative design, average annual wind speed in vicinity of MHF, if exposed to environment should be chosen. In the absence of specific data, use VAMBM = 5 for outdoor location, VAMBM = 0 for indoor location.

ELE (elevation above sea level, ft): Since the MHF operates at ambient pressure, which affects gas density and saturation conditions, it is important to use the value at the MHF location.

FINANCIAL INPUT (D)

SLF (MHF system life, years): Not all components of the MHF have the same physical life, of course. However, public wastewater treatment plants have generally been considered to have a life equal to the repayment period of the bond issue financing them. Most bond issues have a 25-year period. In the absense of specific data, use SLF = 25.

YIR (yearly interest rate, percent):
UFC (unit fuel cost, \$ per lb):
UPC (unit power cost, \$ per kw-hr):
For these three input parameters, use information pertaining to the MHF locality.

NAMFU (name of auxiliary fuel): See under Auxiliary Fuel Burner Input, above.

KEFR (engineering fee code): If it is desired to include the fee in the capital costs, put KEFR = 1; if not, put KEFR = 0.

ULC (unit land cost, \$ per acre): If it is desired to include the land in the capital costs, use value for MHF locality; if not, use ULC = 0.

BFR (building/MHF installed cost ratio, \$ per \$): This study only found two data points (BFR = 0.513, 0.667 est.). Depending on the quality of the building, BFR can vary widely. In the absence of any data, for a crude estimate, use BFR = 0.5. If building cost is not to be included, use BFR = 0.

ØLR (operating labor rate, \$ per man-hr):
ANMR (normal maintenance labor rate, \$ per man-hr):
CRR (castings replacement labor rate, \$ per man-hr):
AMRR (refractory replacement labor rate, \$ per man-hr):
Local labor rates at the time of MHF operation should be used. If no data available, the averages given in Chapter VI may serve, i.e., in 1969 dollars:

ØLR =	3.88
ANMR = CRR =	4.07
AMRR =	4.91

MHF SELECTION INPUT (D)

This input permits the user to explore the effect of variations in operating schedules and standby units on costs, because the subroutine considers the "down time" as a function of operating schedule, furnace size, standby units, etc. Many variations can be tried out, and the optimum chosen from them.

HPD (hours per day MHF operation): This should be the period for which operating personnel is paid, e.g., an 8-hr shift, 24-hr (round the clock, 3 shifts), and other arrangements. For large plants, one should use HPD = 24. For smaller plants, HPD from 8 to 24 should be explored.

TDPW (trial days per week MHF operation): Generally, the output DPW (days per week) computed by the subroutine will be equal to or less than TDPW, but never larger. In the field survey, actual DPW values were 2, 5, and 7 in different plants.

SNØ (number of standby MHF's): Most plants surveyed had no standby units, one had one standby unit, and another (in effect) more than one. The benefits of standby units include (1) no interruption or reduction in capacity in case of a failure requiring MHF shutdown, (2) longer calendar life per unit, if all the MHF's in the plant are operated in regular rotation, and (3) greater flexibility in operation (load distribution, labor scheduling). These benefits must be balanced against greater initial capital outlay. It is recommended that SNØ = 0 and 1 (even 2 in large plants) be explored.

ADF (number of MHF's above minimum): The subroutine computes out a number of MHF's, each incinerating at a certain steady-state rate. It may be desired to obtain greater reliability by spreading the load over a larger number of smaller units (regardless of standby units). Possibly, there may be a limitation on the size or capacity of a unit MHF. In either event, one may use ADF = 1,2, etc.

IX. USE OF SUBROUTINE

This Chapter describes the mechanics of using the Subroutine, in both the Design and Cost and Thermal Analysis options, with a numerical worked example for each option. Computer time expenditures are also indicated.

INPUT FORMAT

After the user has decided on all the numerical inputs, guided by Chapter VIII, he enters them on 80-column data punch cards. For the Design and Cost Option, there are 13 cards, as shown on the four sheets of Design and Cost Input (pp. 104 through 107). For the Thermal Analysis Option, there are 11 cards, as shown on the three sheets of Thermal Analysis Input (pp. 108 through 110). On each card, there are listed

(a) the Fortran names of the input variables (see Glossary for definitions and units);
(b) next to each input variable, in parentheses, the columns in which the numerical value is entered; and
(c) in the upper right-hand corner of the description field the format specification of that card.

The input is sub-divided by card number as follows:

	Design & Cost Option	Thermal Analysis Option
Information	Card 1	Card 1
Sludge Stream	2,3,4	2,3,4,5 (with MHF data)
Financial	5,6	-
Air Data and Stream Temperatures	7,8	6,7
Reaction of Chemicals	9	8
Auxiliary Fuel Burner	10,11	9,10
Environment	12	11
MHF Selection Input, repeated for each Case	13 & on	-

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DESIGN AND COST INPUT

	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH	
1			LØC (1-48)	(12A4, I12)
13	CHECKØUT ØF			
25	SAMPLE INPUT			
37				
49	1	73 80	NCASE (49-60)	
61		1		
1	1000.		PWS (1-12)	(6E 12.8)
13	30.		PERS (13-24)	
25	70.		PERV (25-36)	
37	10000.		QVØL (37-48)	
49	18.	73 80	PCAC (49-60)	
61	6.	2	PFEHY (61-72)	
1	4.		PALHY (1-12)	(E 12.8, I12)
13	5		NELV (13-24)	
25				
37				
49		73 80		
61		3		
1	C .550		$NAMV_1$ (1-4), FRV_1 (5-12)	(6(A4, F 8.5))
13	H .074		$NAMV_2$ (13-16), FRV_2 (17-24)	
25	Ø .334		↓ ↓	
37	N .031			
49	S .011	73 80	$NAMV_{NELV}$, FRV_{NELV}	
61		4		

114-C-17 VELLUM

DESIGN AND COST INPUT

	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	25.		SLF (1-12) (2E12.8, I12, 3A4, 2E12.8)
13	7.		YIR (13-24)
25	1		KEFR (25-36)
37	FUEL ØIL		NAMFU (37-48)
49	20000.	73 80	ULC (49-60)
61	.025	5	UFC (61-72)
1	.010		UPC (1-12) (6E12.8)
13	4.		ØLR (13-24)
25	4.5		ANMR (25-36)
37	4.25		CRR (37-48)
49	5.	73 80	AMRR (49-60)
61	.4	6	BFR (61-72)
1	75.		PXAIR (1-12) (4E12.8)
13	36000.		SCFCL (13-24)
25	.7		FRAIR (25-36)
37	300.		TAIRI (37-48)
49		73 80	
61		7	
1	60.		TSL1 (1-12) (4E12.8)
13	800.		TEX (13-24)
25	400.		TASH (25-36)
37	70.		TSCRB (37-48)
49		73 80	
61		8	

114-C-17 VELLUM

DESIGN AND COST INPUT

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1.		FCAC (1-12) (3E12.8)
.8		FFE (13-24)
.6		FAL (25-36)
	9	
20000.		QFU (1-12) (3E12.8, I12)
25.		BUREX (13-24)
5.		EXAFU (25-36)
5		NELF (37-48)
	10	
C .861		$NAMF_1$ (1-4), FRF_1 (5-12) (6(A4, F8.5))
H .103		$NAMF_2$ (13-16), FRF_2 (17-24)
Ø .008		↓ ↓
N .001		
S .027		$NAMF_{NELF}$ FRF_{NELF}
	11	
100.		TSUR (1-12) (4E12.8)
5.		VAMBM (13-24)
50.		TAMB (25-36)
5000.		ELE (37-48)
	12	

114-C-17 VELLUM

DESIGN AND COST INPUT

	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	24.		HPD (1-12) (4F12.6)
13	5.		TDPW (13-24)
25	1.		SNØ (25-36)
37	1.		ADF (37-48)
49		73 80	
61		13	
1			
13			
25			
37			
49		73 80	
61			
1			
13			
25			
37			
49		73	
61			
1			
13			
25			
37			
49		73	
61			

114-C-17 VELLUM

THERMAL ANALYSIS INPUT

Col.	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	CHECKØUT ØF		LØC (1-48) (12A4, I12)
13	NCASE EQUAL		
25	TØ ZERØ .		
37			
49	0	73 … 80	NCASE (49-60)
61		1	
1			(12X, 5E12.8)
13	17.1		PERS (13-24)
25	67.		PERV (25-36)
37	10000.		QVØL (37-48)
49	29.2	73 … 80	PCAC (49-60)
61	.5	2	PFEHY (61-72)
1	.5		PALHY (1-12) (E12.8, I12)
13	5		NELV (13-24)
25			
37			
49		73 … 80	
61		3	
1	C .550		$NAMV_1$ (1-4), FRV_1 (5-12) (6(A4, F8.5))
13	H .074		$NAMV_2$ (13-16), FRV_2 (17-24)
25	Ø .334		↓ ↓
37	N .031		
49	S .011	73 … 80	$NAMV_{NELV}$, FRV_{NELV}
61		4	

114-C-17 VELLUM

THERMAL ANALYSIS INPUT

Col.	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1	NATURAL GAS		NAMFU (1-12) (3A4, F12.6, I12, F12.6)
13	14.3		HDIA (13-24)
25	6		NHEAR (25-36)
37	2228.3		PSLU (37-48)
49		73 80	
61		5	
1	100.		PXAIR (1-12) (4E12.8)
13	30000.		SCFCL (13-24)
25	0.		FRAIR (25-36)
37	330.		TAIRI (37-48)
49		73 80	
61		6	
1	57.		TSL1 (1-12) (4E12.8)
13	700.		TEX (13-24)
25	540.		TASH (25-36)
37	70.		TSCRB (37-48)
49		73 80	
61		7	
1	1.		FCAC (1-12) (3E12.8)
13	.5		FFE (13-24)
25	.5		FAL (25-36)
37			
49		73 80	
61		8	

114-C-17 VELLUM

THERMAL ANALYSIS INPUT

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH	
20880.		QFU (1-12)	(3 E 12.8, I12)
25.		BUREX (13-24)	
0.		EXAFU (25-36)	
4		NELF (37-48)	
	73 … 80 / 9		
C .739		$NAMF_1$ (1-4), FRF_1 (5-12)	(6(A4, F8.5))
H .237		$NAMF_2$ (13-16), FRF_2 (17-24)	
Φ .003		↓ ↓	
N .021		$NAMF_{NELF}$, FRF_{NELF}	
	73 … 80 / 10		
170.		TSUR (1-12)	(4 E 12.8)
0.		VAMBM (13-24)	
65.		TAMB (25-36)	
6265.		ELE (37-48)	
	73 … 80 / 11		
	73 … 80		

There are several input variables which require clarification; these are listed below, by input card number:

Design & Cost Card 1 and Thermal Analysis Card 1:	NCASE = 0 means Thermal Analysis Option only. NCASE = positive integer means number of MHF Selection Inputs for Design & Cost Option only. There is no limit on NCASE for Design & Cost Option.
Design & Cost Cards 4 and 11 and Thermal Analysis Cards 4 and 10:	Variables NAMV(I) and NAMF(I) must take on values from the following set (C⊙⊙⊙, H⊙⊙⊙, Ø⊙⊙⊙, N⊙⊙⊙, S⊙⊙⊙) where ⊙ (circle dot) indicates a blank, C is carbon H is (atomic) hydrogen Ø is (atomic) oxygen N is (atomic) nitrogen, and S is (atomic) sulfur.
Design & Cost Card 5:	KEFR = 0 means no engineering fee KEFR = 1 computes engineering fee per formula, Chapter VI.
Design & Cost Card 7:	SCFCL is in scfm (standard cu ft per min, for entire plant with wet sludge flow PWS).
Thermal Analysis Card 6:	SCFCL is in scfh (standard cu ft per hr, for the one MHF with wet sludge flow PSLU).
Design & Cost Card 8 and Thermal Analysis Card 7:	TSL1 (TSL-one) is correct .

FORTRAN PROGRAM

The program, incorporating both the Design & Cost Option and the Thermal Analysis Option, was coded in Fortran IV compatible with both the IBM 1130 and IBM System 360 digital computers. The Fortran IV listing of the program, with its permanent data, appears in the Appendix. The permanent data (26 lines, sequence numbers 99900010 thru 99930050 in listing) are read in by the program before it considers the user's input. The listing in the Appendix includes system cards for IBM System 360 after the main program immediately before the permanent input data (4 lines, sequence numbers 99800000 thru 99990000 in listing), and also at the end of the listing (1 card, sequence number 99999999). When the IBM 1130 is used, these cards must be replaced by their appropriate counterparts.

In order to permit easy conversion between computer systems, the program uses integer variables for the input and output device numbers. The variable IN is used for the input device while the variable IØ is used for the output device. IBM System 360 uses device number 5 (five) for input and device number 6 (six) for output. These specific values have been given for the variables IN and IØ at card numbers 00000980 and 00000990, respectively. These cards must be changed for systems using device numbers other than five and six.

The program, together with the necessary system library routines, occupies 52,000 bytes on the IBM System 360. On the IBM 1130 an overlay procedure may be necessary. A list of the subroutines constituting the program, with a cross-reference of the subroutines that call them, is given below:

Subroutine	Sequence Number of First Card	Called From
Main Program	00000010	--
INPUT	10000010	Main Program
HEAT	20000000	Main Program
BLØCK	30000000	Main Program
TITL	40000000	Main Program, INPUT, PRINT
PRINT	50000010	Main Program
GETDH	68000100	HEAT
LØCAT	69200000	Main Program

The execution time for the program (one case for the Design & Cost Option, and one case for the Thermal Analysis Option, see Numerical Examples below) was 0.01 minute on the IBM System 360.

NUMERICAL EXAMPLES

One numerical example (NCASE = 1) was run for the Design & Cost Option and another (NCASE = 0) for the Thermal Analysis Option. The numerical input variables were entered in the number fields of the data cards shown on the 7 input sheets (pp. 104 through 110) discussed in the Section on Input Format earlier in this Chapter. The last page of the Fortran IV listing in the Appendix contains the numerical inputs from the 7 input sheets (24 lines, Sequence numbers 00001000 through 10000011.

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

(NUMBER OF CASES TO BE RUN 1)

*** SLUDGE STREAM INPUT ***

PLANT WET SLUDGE FLOW	1000.0	TON/DAY
TOTAL DRY SOLIDS CONCENTRATION IN SLUDGE	30.00	WEIGHT O/O
VOLATILE SOLIDS CONCENTRATION IN D.S.	70.00	WEIGHT O/O
HEAT VALUE OF VOLATILES	10000.	BTU/LB
CACO3 IN DRY SOLID	18.00	WEIGHT O/O
FE(OH)3 IN DRY SOLID	6.00	WEIGHT O/O
AL(OH)3 IN DRY SOLID	4.00	WEIGHT O/O
NUMBER OF ELEMENTS IN VOLATILES	5	
MASS FRACTION OF C IN VOLATILES	0.550	
MASS FRACTION OF H IN VOLATILES	0.074	
MASS FRACTION OF O IN VOLATILES	0.334	
MASS FRACTION OF N IN VOLATILES	0.031	
MASS FRACTION OF S IN VOLATILES	0.011	

*** FINANCIAL INPUT ***

SYSTEM LIFE OF MHF	25.0	YRS
YEARLY INTEREST RATE	7.00	O/O
ENGG FEE RATE CODE (1=FORMULA,0= ZERO RATE)	1	
UNIT LAND COST	20000.00	$/ACRE
AUXILIARY FUEL NAME	FUEL OIL	
UNIT FUEL COST	0.025	$/LB
UNIT POWER COST	0.010	$/KWH
OPERATING LABOR RATE	4.00	$/MAN-HR
NORMAL MAINTENANCE LABOR RATE	4.50	$/MAN-HR
CASTINGS REPLACEMENT LABOR RATE	4.25	$/MAN-HR
REFRACTORY REPLACEMENT LABOR RATE	5.00	$/MAN-HR
BUILDING/MHF RATIO	0.400	$/$

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

*** TECHNICAL INPUT ***

MINIMUM EXCESS AIR FOR COMB OF VOLATILES	75.00	0/0
SHAFT COOLING AIR FLOW (ALL MHF'S)	36000.	SCFM
FRACTION OF COOLING AIR RECYCLED	0.700	
EXIT TEMPERATURE OF COOLING AIR	300.	DEG F
INLET TEMPERATURE OF SLUDGE	60.	DEG F
EXIT TEMPERATURE OF COMBUSTION GASES	800.	DEG F
EXIT TEMPERATURE OF ASH	400.	DEG F
EXIT TEMPERATURE OF SCRUBBER GAS	70.	DEG F
FRACTION CACO3 CONVERTED TO CAO	1.000	
FRACTION FE(OH)3 CONVERTED TO FE2O3	0.800	
FRACTION AL(OH)3 CONVERTED TO AL2O3	0.600	
HEAT VALUE OF AUXILIARY FUEL	20000.	BTU/LB
EXCESS BURNER CAPACITY	25.00	0/0
EXCESS AIR FOR AUXILIARY FUEL	5.00	0/0
NUMBER OF ELEMENTS IN AUXILIARY FUEL	5	
MASS FRACTION OF C IN AUXILIARY FUEL	0.861	
MASS FRACTION OF H IN AUXILIARY FUEL	0.103	
MASS FRACTION OF O IN AUXILIARY FUEL	0.008	
MASS FRACTION OF N IN AUXILIARY FUEL	0.001	
MASS FRACTION OF S IN AUXILIARY FUEL	0.027	
MHF SURFACE TEMPERATURE	100.	DEG F
AMBIENT AIR VELOCITY	5.0	MPH
AMBIENT AIR TEMPERATURE	50.	DEG F
ELEVATION OF PLANT	5000.	FT

```
MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

*** MHF SELECTION INPUT FOR CASE  1 ***

DAILY INCINERATION SCHEDULE                 24.00 HR/DAY
MAX. WEEKLY INCINERATION SCHEDULE            5.00 DAYS/WK
NUMBER OF STANDBY MHF UNITS                     1
NUMBER OF MHF'S ABOVE MINIMUM                   1


*** MHF DESIGN AND OPERATION ***

NUMBER OF MHF'S                                          9
MHF OUTER DIAMETER (13.5 INCH WALL)                  20.25 FT
NUMBER OF HEARTHS PER MHF                               12
EFFECTIVE HEARTH AREA PER MHF                       2464.0 SQ FT
STEADY STATE WET SLUDGE RATE PER MHF               16460.9 LB/HR
STEADY STATE DRY SOLIDS RATE PER MHF                4928.3 LB/HR
HEARTH LOADING (DRY SOLIDS)                           2.00 LB/HR-SQ FT

YEARLY OPERATING HOURS PER MHF                      5546.7 HR/YR
WEEKLY INCINERATION SCHEDULE                          5.00 DAYS/WK
WEEKLY INCINERATION HOURS                           120.00 HR/WK
CYCLING AS FRACTION OF OPERATION                     0.212 HR/HR
CYCLE TIME (HEATUP)                                 106.00 HR
MHF CASTING SETS REPLACED DURING LIFE                 2.50
MHF REFRACTORY SETS REPLACED DURING LIFE              0.50
SHAFT COOLING AIR PER MHF                          270000. SCFH


*** AIR FOR VOLATILES COMBUSTION ***

FLOWRATE OF COOLING AIR SENT TO FURNACE      189000. SCFH
FLOWRATE OF AMBIENT AIR ENTERING FURNACE     746662. SCFH
THEORETICAL AIR REQUIRED FOR VOLATILES        25660. LB/HR
PERCENT EXCESS AIR FOR VOLATILES              177.47
TOTAL AIR USED FOR VOLATILES                  71199. LB/HR
```

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

CASE 1

*** MHF HEAT BALANCE ***
(SIX SIGNIFICANT DIGITS)

HEAT REQUIREMENTS		
HEAT FOR SLUDGE COMBUSTION PRODUCTS	16710948.	BTU/HR
HEAT FOR SLUDGE MOISTURE EVAPORATION	16105299.	BTU/HR
HEAT REMOVED IN ASH	67272.	BTU/HR
RADIATION AND CONVECTION HEAT LOSS	372526.	BTU/HR
SHAFT COOLING HEAT LOSS	1236273.	BTU/HR
HEAT FOR INCOMING AMBIENT AIR	133995.	BTU/HR
HEAT FOR CALCINING CACO3	676444.	BTU/HR
HEAT FOR DECOMPOSING FE(OH)3	53333.	BTU/HR
HEAT FOR DECOMPOSING AL(OH)3	45132.	BTU/HR
TOTAL HEAT REQUIREMENT	35395152.	BTU/HR
HEAT INPUT		
HEAT FROM VOLATILES	34567904.	BTU/HR
HEAT FROM INCOMING SHAFT COOLING AIR	827274.	BTU/HR
NET HEAT REQUIRED FROM BURNER	0.	BTU/HR
TOTAL HEAT INPUT	35395152.	BTU/HR

*** AUXILIARY BURNER SELECTION ***

PERCENT AVAILABLE HEAT FROM BURNER(CALC)	0.0	
GROSS HEAT REQUIRED FROM BURNER	0.	BTU/HR
TOTAL BURNER CAPACITY(25.00 O/O EXCESS)	0.	BTU/HR
REQUIRED BURNER FUEL FLOWRATE	0.0	LB/HR
BURNER HEAT PER STD CUBIC FT OF AIR	0.0	BTU/SCF
REQUIRED BURNER AIR VOLUMETRIC FLOWRATE	0.	SCFH
REQUIRED BURNER AIR MASS FLOWRATE	0.0	LB/HR

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

CASE 1

*** MHF EXIT GAS DATA ***

SPECIES	FLOWRATES MASS(LB/HR)	VOLUME(ACFH)
CO2	7358.	182830.
H2O	13915.	844330.
O2	10611.	362615.
N2	54717.	2136162.
SO2	76.	1297.
TOTALS	86671.	3527131.

DENSITY OF FURNACE EXIT GAS	0.02457	LB/FT3
SCRUBBER EXIT VOLUME/LB OF DRY GAS	16.002	FT3/LB
SCRUBBER SATURATED EXIT GAS FLOWRATE	19405.	ACFM
WATER FLOWRATE TO SATURATE EXIT GAS	0.	GPM

*** MHF MASS BALANCE ***
(SIX SIGNIFICANT DIGITS)

MASS INFLOWS		
WET SLUDGE FEEDRATE	16460.9	LB/HR
REQUIRED BURNER FUEL FLOWRATE	0.0	LB/HR
AMBIENT AIR TO VOLATILES	56817.2	LB/HR
TOTAL COOLING AIR	20545.6	LB/HR
REQUIRED BURNER AIR FLOWRATE	0.0	LB/HR
TOTAL MASS INFLOW	93823.8	LB/HR
MASS OUTFLOWS		
TOTAL MHF EXIT GAS FLOWRATE	86670.8	LB/HR
ASH DISCHARGE RATE	989.3	LB/HR
REJECTED COOLING AIR	6163.7	LB/HR
TOTAL MASS OUTFLOW	93823.8	LB/HR

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF SAMPLE INPUT

CASE 1

*** NON-DOLLAR OUTPUT PER MHF ***

LAND AREA	0.04 ACRE
YEARLY FUEL	245279. LB/YR
YEARLY POWER	322136. KWH/YR
OPERATING LABOR	4751.2 MAN-HR/YR
NORMAL MAINTENANCE LABOR	1234.7 MAN-HR/YR
CASTINGS REPLACEMENT LABOR	21.1 MAN-HR/YR
REFRACTORY REPLACEMENT LABOR	127.7 MAN-HR/YR

*** MHF CAPITAL COST BREAKDOWN, DOLLARS ***

	ONE MHF	ALL MHF'S
INSTALLED CAPITAL COST	593482.	5341340.
BUILDING COST	237393.	2136535.
LAND COST	730.	6572.
ENGINEERING FEE	51083.	327862.
TOTAL CAPITAL COST	882688.	7812309.

*** MHF TOTAL COST BREAKDOWN ***

	$/YR,ONE MHF	$/YR,ALL MHF'S	$/TON DRY SOLIDS	PERCENT
TOTAL CAPITAL CHARGES	75744.	670379.	6.91	63.28
REPLACEMENT PARTS	6703.	60327.	0.62	5.69
MATERIALS AND SUPPLIES	1877.	16890.	0.17	1.59
FUEL	6132.	55188.	0.57	5.21
POWER	3221.	28992.	0.30	2.74
OPERATING LABOR	19005.	171044.	1.76	16.15
NORMAL MAINTENANCE LABOR	5556.	50005.	0.52	4.72
REPLACEMENT MAINTENANCE LABOR	728.	6553.	0.07	0.62
TOTAL COST	118966.	1069378.	10.91	100.00

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF NCASE EQUAL TO ZERO .

(THERMAL ANALYSIS ONLY)

*** SLUDGE STREAM INPUT ***

```
TOTAL DRY SOLIDS CONCENTRATION IN SLUDGE   17.10 WEIGHT O/O
VOLATILE SOLIDS CONCENTRATION IN D.S.      67.00 WEIGHT O/O
HEAT VALUE OF VOLATILES                  10000.  BTU/LB
CACO3 IN DRY SOLID                         29.20 WEIGHT O/O
FE(OH)3 IN DRY SOLID                        0.50 WEIGHT O/O
AL(OH)3 IN DRY SOLID                        0.50 WEIGHT O/O
NUMBER OF ELEMENTS IN VOLATILES                5
MASS FRACTION OF C     IN VOLATILES        0.550
MASS FRACTION OF H     IN VOLATILES        0.074
MASS FRACTION OF O     IN VOLATILES        0.334
MASS FRACTION OF N     IN VOLATILES        0.031
MASS FRACTION OF S     IN VOLATILES        0.011
```

*** TECHNICAL INPUT ***

```
AUXILIARY FUEL NAME                       NATURAL GAS
MHF OUTER DIAMETER (13.5 INCH WALL)        14.30 FT
NUMBER OF HEARTHS PER MHF                      6
STEADY STATE WET SLUDGE RATE PER MHF     2228.3 LB/HR

MINIMUM EXCESS AIR FOR COMB OF VOLATILES  100.00 O/O
SHAFT COOLING AIR FLOW PER MHF          30000.  SCFH
FRACTION OF COOLING AIR RECYCLED           0.0
EXIT TEMPERATURE OF COOLING AIR              330. DEG F

INLET TEMPERATURE OF SLUDGE                   57. DEG F
EXIT TEMPERATURE OF COMBUSTION GASES         700. DEG F
EXIT TEMPERATURE OF ASH                      54[illegible]. DEG F
EXIT TEMPERATURE OF SCRUBBER GAS             7[illegible]. DEG F
```

THERMAL ANALYSIS PRINTOUT (SHEET 1 OF 4)

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF NCASE EQUAL TO ZERO .

*** TECHNICAL INPUT ***

FRACTION CACO3 CONVERTED TO CAO	1.000	
FRACTION FE(OH)3 CONVERTED TO FE2O3	0.500	
FRACTION AL(OH)3 CONVERTED TO AL2O3	0.500	
HEAT VALUE OF AUXILIARY FUEL	20880.	BTU/LB
EXCESS BURNER CAPACITY	25.00	O/O
EXCESS AIR FOR AUXILIARY FUEL	0.0	O/O
NUMBER OF ELEMENTS IN AUXILIARY FUEL	4	
MASS FRACTION OF C IN AUXILIARY FUEL	0.739	
MASS FRACTION OF H IN AUXILIARY FUEL	0.237	
MASS FRACTION OF O IN AUXILIARY FUEL	0.003	
MASS FRACTION OF N IN AUXILIARY FUEL	0.021	
MHF SURFACE TEMPERATURE	170.	DEG F
AMBIENT AIR VELOCITY	0.0	MPH
AMBIENT AIR TEMPERATURE	65.	DEG F
ELEVATION OF PLANT	6265.	FT

*** AIR FOR VOLATILES COMBUSTION ***

FLOWRATE OF COOLING AIR SENT TO FURNACE	0.	SCFH
FLOWRATE OF AMBIENT AIR ENTERING FURNACE	49810.	SCFH
THEORETICAL AIR REQUIRED FOR VOLATILES	1895.	LB/HR
PERCENT EXCESS AIR FOR VOLATILES	100.00	
TOTAL AIR USED FOR VOLATILES	3790.	LB/HR

THERMAL ANALYSIS PRINTOUT (SHEET 2 of 4)

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF NCASE EQUAL TO ZERO .

*** MHF HEAT BALANCE ***
(SIX SIGNIFICANT DIGITS)

HEAT REQUIREMENTS		
HEAT FOR SLUDGE COMBUSTION PRODUCTS	850094.	BTU/HR
HEAT FOR SLUDGE MOISTURE EVAPORATION	2496213.	BTU/HR
HEAT REMOVED IN ASH	7361.	BTU/HR
RADIATION AND CONVECTION HEAT LOSS	265659.	BTU/HR
SHAFT COOLING HEAT LOSS	145312.	BTU/HR
HEAT FOR CALCINING CACO3	84673.	BTU/HR
HEAT FOR DECOMPOSING FE(OH)3	214.	BTU/HR
HEAT FOR DECOMPOSING AL(OH)3	363.	BTU/HR
TOTAL HEAT REQUIREMENT	3849885.	BTU/HR
HEAT INPUT		
HEAT FROM VOLATILES	2552999.	BTU/HR
HEAT FROM INCOMING AMBIENT AIR	7157.	BTU/HR
HEAT FROM INCOMING SHAFT COOLING AIR	0.	BTU/HR
NET HEAT REQUIRED FROM BURNER	1289730.	BTU/HR
TOTAL HEAT INPUT	3849885.	BTU/HR

*** AUXILIARY BURNER SELECTION ***

PERCENT AVAILABLE HEAT FROM BURNER(CALC)	74.59	
GROSS HEAT REQUIRED FROM BURNER	1728988.	BTU/HR
TOTAL BURNER CAPACITY(25.00 O/O EXCESS)	2161235.	BTU/HR
REQUIRED BURNER FUEL FLOWRATE	103.5	LB/HR
BURNER HEAT PER STD CUBIC FT OF AIR	96.24	BTU/SCF
REQUIRED BURNER AIR VOLUMETRIC FLOWRATE	22457.	SCFH
REQUIRED BURNER AIR MASS FLOWRATE	1708.9	LB/HR

THERMAL ANALYSIS PRINTOUT (SHEET 3 of 4)

MULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATION

CHECKOUT OF NCASE EQUAL TO ZERO .

*** MHF EXIT GAS DATA ***

SPECIES	FLOWRATES MASS(LB/HR)	VOLUME(ACFH)
CO2	844.	20279.
H2O	2236.	131217.
O2	442.	14590.
N2	4228.	159573.
SO2	6.	93.
TOTALS	7755.	325742.

DENSITY OF FURNACE EXIT GAS	0.02381 LB/FT3
SCRUBBER EXIT VOLUME/LB OF DRY GAS	16.642 FT3/LB
SCRUBBER SATURATED EXIT GAS FLOWRATE	1531. ACFM
WATER FLOWRATE TO SATURATE EXIT GAS	0. GPM

*** MHF MASS BALANCE ***
(SIX SIGNIFICANT DIGITS)

MASS INFLOWS	
WET SLUDGE FEEDRATE	2228.3 LB/HR
REQUIRED BURNER FUEL FLOWRATE	103.5 LB/HR
AMBIENT AIR TO VOLATILES	3790.3 LB/HR
TOTAL COOLING AIR	2282.8 LB/HR
REQUIRED BURNER AIR FLOWRATE	1708.9 LB/HR
TOTAL MASS INFLOW	10113.9 LB/HR
MASS OUTFLOWS	
TOTAL MHF EXIT GAS FLOWRATE	7754.8 LB/HR
ASH DISCHARGE RATE	76.2 LB/HR
REJECTED COOLING AIR	2282.8 LB/HR
TOTAL MASS OUTFLOW	10113.9 LB/HR

The Design & Cost Printout appears in 6 sheets (pp. 113 through 118). The input data are printed out on sheets 1, 2 and part of 3; and the outputs on the remaining sheets. In particular, the MHF Design and Operation output is on sheet 3, the Heat Balance on sheet 4, the Mass Balance on sheet 5, and the expenditures and costs on sheet 6.

The Thermal Analysis Printout appears in 4 sheets (pp. 119 through 122). The input data are printed out on sheets 1 and part of 2, and the outputs on the remaining sheets. In particular, the combustion air requirement is on sheet 2, the heat balance and auxiliary burner selection on sheet 3, and the exit gas composition and mass balance on sheet 4.

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The authors of this final report are W. Unterberg, R. J. Sherwood and G. R. Schneider.

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XII. GLOSSARY

ADF	Number of MHF's above minimum
ALA	Incinerator land area per MHF - acres
AMRM	Yearly refractory replacement labor per MHF - man-hr/yr
AMRR	Refractory replacement labor rate - $ per man-hr
AMSY	Yearly normal maintenance material cost per MHF - $ per year
ANMM	Yearly normal maintenance labor per MHF - man-hr/yr
ANMR	Normal maintenance labor rate - $ per man-hr
ANMY	Yearly cost of normal maintenance labor per MHF - $/yr
BFR	Building/MHF cost ratio - $ per $
BGC	Cost of incinerator building - $
BRN(I)	Species formed from combustion of 1 lb of burner fuel - lb
BTUV	Burner heat output per unit air flow - Btu/scf
BURAI	Air for fuel burner - lb per lb fuel
BUREX	Excess fuel burner capacity - percent
BURNØ	Theoretical (stoichiometric) oxygen for burner - lb per lb fuel
C	Carbon
CAST	On-site cost of castings for one hearth - $
CCI	Installed Capital cost - $
CLD	Land cost per MHF - $
CLH	Castings replacement labor for one hearth - man-hr
CPA	Specific heat of air - Btu per lb ^{o} F
CPASH	Specific heat of ash (= 0.2) - Btu/lb ^{o} F
CP(I)	Specific heat of Ith species - Btu per lb ^{o} F
CPS	Specific heat of water vapor (steam) - Btu/lb ^{o} F
CPWAT	Specific heat of liquid water (= 1.0) - Btu/lb ^{o} F
CRL	Complete MHF castings replaced during MHF life (SLF)-number
CRM	Yearly casting replacement labor per MHF - man-hr/yr
CRR	Castings replacement labor rate - $ per man-hr
CYCF	Non-steady state (cycling) fraction of total operation - hr per hr
CYT	Total heatup cycle time - hr
(D)	Applies only to Design & Cost Option
DCO	Design & Cost Option
DHBUR	Heat to raise burner gases to TEX - Btu/lb-fuel
DPC	Castings material cost per hearth - $
DPR	Refractory material cost per hearth - $
DPW	Weekly incineration schedule - days/wk
DRYMØ	Molecular weight of dry exhaust gas
DSF	Steady-state dry solids rate per MHF - lb/hr

ELE Elevation above sea level, or altitude-feet
EFC Engineering fee - $
ELMW(I) Elemental weight of Ith element - number
ELMW(I = 1,2,3.4,5) = 12.011, 2.016, 32.0, 28.0134, 32.064
EXAFU Excess air for auxiliary fuel burner percent

FAL Fraction $Al(OH)_3$ converted to Al_2O_3
FCAC Fraction $CaCO_3$ converted to CaO
FFE Fraction $Fe(OH)_3$ converted to Fe_2O_3
FCY Yearly fuel consumption per MHF - lb/yr
FHA Effective hearth area per MHF - sq ft
FRAIR Fraction of cooling air recycled
FRF(I), FRFU(I) Mass fraction of Ith element in fuel (I=1, NELF)
FRV(I), FRVØ(I) Mass fraction of Ith element in volatiles (I=1, NELV)
FUY Yearly fuel cost per MHF - $/yr

GDRY Total dry exhaust flow, including burner products - lb/hr
GTØT Total exhaust gas flow, including burner products - lb/hr

H Hydrogen
HASH Heat removed in ash - Btu/hr
HC MHF heat transfer coefficient by free and forced convection-Btu/hr ft^2 F
HDIA MHF outer diameter (13.5 inch wall) - feet
HLD Hearth loading (dry solids) - lb per hr per sq ft
HPD Daily incineration schedule - hr per day
HR MHF heat transfer coefficient by thermal radiation - Btu/hr ft^2 F
HUQ Heatup heat requirement per MHF for 0-1200 F and 1200-1500 F heating-Btu/hr
HWGAS Heat for gas phase heating of sludge moisture - Btu/hr
HWSEN Heat for liquid phase heatup of sludge moisture - Btu/hr
HWSL Heat for sludge moisture evaporation and heating - Btu/hr
HWVAP Heat for evaporation of sludge moisture - Btu/hr

I	Elements	Species
1	C (carbon)	CO_2 (carbon dioxide
2	H_2 (molecular hydrogen)	H_2O (water)
3	O_2 (molecular oxygen)	O_2 (oxygen)
4	N_2 (molecular nitrogen)	N_2 (nitrogen)
5	S (elemental sulfur)	SO_2 (sulfur dioxide)

KASE Number of case (MHF Selection Input)
KEFR Engineering fee code formula or omit
KLA Land area constant (Chapter VI)

LØC Title information - alpha-numeric

MHF	Multiple hearth furnace
N	Nitrogen
NCASE	Number of cases
NAMV(I)	Name of element in volatiles (I=1, NELV)
NELV	Number of elements in volatiles
NAMFU	Name of auxiliary fuel
NELF	Number of elements in fuel
NØF	Total number of MHF's
NHEAR	Number of hearths per MHF
NAMF(I)	Name of element in fuel (I=1, NELF)
NUMSP	Number of species in exhaust gas
Ø	Oxygen
ØLM	Yearly operating labor per MHF - man-hr/yr
ØLR	Operating labor rate - $ per man-hr
ØLY	Yearly operating labor cost per MHF - $ per yr
ØMD	Daily operating labor per MHF - man-hr/24 hr-operating day
PAIRA	Ambient combustion air rate - lb/hr
PAIRC	Total shaft cooling air rate - lb/hr
PAIRS	Shaft cooling air per MHF - lb/hr
PAIRT	Total air flow for combustion of volatiles - lb/hr
PALHY	Aluminum Hydroxyde $Al(OH)_3$ in dry solid - w/o
PASH	Ash flow rate - lb/hr
PCAC	Calcium Carbonate $CaCO_3$ in dry solid - w/o
PSCRE	Atmospheric pressure at given altitude - lb/sq in, abs.
PCY	Yearly electrical power consumption per MHF - Kw-hr/yr
PDS	Electrical power consumption rate - Kw-hr/ton dry solids
PERS	Total dry solids concentration - w/o
PERV	Volatiles concentration in solids - w/o
PERW	Water concentration in sludge - w/o
PFEHY	Ferric Hydroxide $Fe(OH)_3$ in dry solid - w/o
PØ2S	Theoretical (stoichiometric) oxygen flowrate for sludge combustion-lb/hr
PØY	Yearly power cost per MHF - $/yr
PSLU	Steady state wet sludge rate per MHF - lb/hr
PSØL	Dry sludge flowrate per MHF - lb/hr
PSWAT	Water vapor pressure - lb/sq in, abs.
PVØL	Volatiles flowrate per MHF - lb/hr
PWAT	Sludge moisture flowrate - lb/hr
PWS	Plant wet sludge flow - ton/day
PXAIR	Minimum excess air for combustion of volatiles - percent

QALHY	Heat for decomposing $Al(OH)_3$ - Btu/hr
QAMBA	Heat from incoming ambient air - Btu/hr
QARIN	Heat from recycled shaft cooling air - Btu/hr
QBUR	Total burner heat requirement - Btu/hr
QCAL	Heat for calcining of $CaCO_3$-Btu/hr
QCØØL	Shaft cooling heat loss - Btu/hr
QFE	Heat for decomposing $Fe(OH)_3$ - Btu/hr
QFU	Higher heat value of Fuel - Btu/lb
QGRØS	Gross burner heat requirement - Btu/hr
QIN	Total heat supplied - Btu/hr
QNET	Net heat supplied - Btu/hr
QREQ	Total heat required - Btu/hr
QSEN	Heat for sludge combustion products - Btu/hr
QTRAN	MHF radiation and convection heat loss - Btu/hr
QVØL	Higher heat value of volatiles - Btu/lb
QVØLT	Heat from combustion of volatiles - Btu/hr
REFR	On-site cost of refractory for one hearth - $
RLH	Refractory labor for one hearth - man-hr
RMY	Yearly hearth replacement labor cost per MHF - $/yr
ROEX	Exhaust gas density at entry to scrubber - lb/cu ft
RPY	Yearly cost of hearth replacement parts - $/yr
RRL	Complete MHF refractories replaced during MHF system lifetime (SLF)
S	Sulfur
SAREA	MHF cylindrical outer area for heat loss - sq ft
SBQ	Hot standby (1200 F) heat requirement per MHF - Btu/hr
SCFAI	Burner air flowrate - scfh
SCFCL	Shaft cooling air flow DCO: std cu ft per min, for whole plant TAO: std cu ft per hr, for one MHF
SHYF	Hot standby (1200 F) time - hr per yr per MHF
SLF	MHF system life - years
SNØ	Number of standby MHF units
SPMW(I)	Molecular weight of Ith species - number

SPMW(I=1,2,3,4,5) = 44.011, 18.016, 32.0, 28.0134, 64.066

T	Temperature - deg F
(T)	Applies only to Thermal Analysis Option
TAIRI	Exit temperature of cooling air - deg F
TAMB	Ambient air temperature - deg F
TAO	Thermal Analysis Option
TASH	Exit temperature of ash - deg F
TCC	Total capital cost per MHF - $
TCST	Total annual cost per MHF - $/yr
TCY	Yearly total capital charges per MHF - $/yr

TDPW	Maximum weekly incineration schedule - days/wk
TEX	Exit temperature of combustion gas - deg F
TØT(I)	Total flow of Ith specie in exhaust gas, including burner products-lb/hr
TSCRB	Exit temperature of scrubber gas - deg F
TSL1	Inlet temperature of sludge - deg F
TSUR	MHF surface temperature - deg F
TVØL	Total exhaust gas flow, including burner products - lb/hr
UFC	Unit fuel cost - $ per lb
ULC	Unit land cost - $ per acre
UPC	Unit power cost - $ per Kw-hr
VAMBF	Ambient air velocity - ft/sec
VAMBM	Ambient air velocity - mph
VDRY	Total dry gas flow of exhaust gases, including burner products at TEX - cu ft/hr
VØL(I)	Total flow of Ith specie in exhaust gas, including burner products - cu ft/hr
VSAT	Specific volume of scrubber exit gases - cu ft per lb dry gas
VSCEX	Saturated total exit flowrate from scrubber - acfm
VWATS	Water flow to saturate scrubber exit gas - gal/min
WATSC	Water flow to saturate scrubber exit gas - lb/hr
WBAIR	Burner air flowrate - lb/hr
WGTF	Burner fuel flowrate - lb/hr
WØH	Weekly incineration hours - hrs/wk
WS(I)	Flowrate of Ith species (excluding auxiliary burner) - lb/hr
YHF	Yearly total operating hours per MHF
YHUH	Yearly heatup hours per MHF
YIR	Yearly interest rate - percent
YSBH	Yearly standby hours hours per MHF

```
C
C.......................................................................
C
C      MULTIPLE HEARTH SLUDGE INCINERATOR PROGRAM
C        CHEMICAL TECHNOLOGY AND APPLIED MATHEMATICS UNIT, ROCKETDYNE
C
C.......................................................................
C
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59),FCYT(5),FHACY(5)
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX
     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE
     2,NHEAR,NOTAB,NRTAB,NUMEL,NUMSP
     3 , IN,IO
      DATA  FCYT / 18.,18.,54.,108.,108. /
      DATA FHACY/ 0., 200., 1700., 2300. , 3500. /
      DATA NHTAB /59/
C      DEFINE STATEMENT FUNCTIONS
      FALA(X) = 4.938303 * .7853982 * X**2 / 43560.
```

```
      FCCI(X) =  5463.8 * X ** .6002739
      FCLH(X) =  7.47457 - 0.104711*X +0.0298929*X**2
      FOMD(X) =  0.0083434* X
      FPDS(X) = 29.6041 - 6.5523 E-09 *(X-2808.)**3+4.93916E-16
     X         *(X-2808.)**5
      FRLH(X) = 69.0762 + .105219*X + .529646*X**2.25
      FCAST(X) = 1080.95 - 219.732*X +89.4829*X**1.5
      FREFR(X) = 458.024 - 120.287*X +14.5823*X**2
      FEFC(X,Y) = .50065678*(X+Y)**.84613605
      FMSY(X)  =  1569.7036 * X**.02287259
      FANMM(X)  = 111.8621 * X ** .30748408
C       SET CONTROL INTEGERS FOR INPUT AND OUTPUT DEVICE NUMBERS
      IN = 5
      IO = 6
C        READ INPUTDATA AND PRINT
      CALL BLOCK
    5 CALL INPUT
      IF ( NCASE ) 6,6,10
C        THERMAL ANALYSIS ONLY
    6 CALL HEAT (IER)
      IF ( IER) 5,7,5
    7 CALL PRINT
      GO TO 5
C          REPEAT MAIN PROGRAM FOR EACH SELECTION INPUT
   10 DO 1000 KASE = 1,NCASE
C
C        READ AND PRINT SELECTION DATA
C
      CALL TITL (2)
      READ (IN,8100) HPD,TDPW,SNO,ADF
 8100 FORMAT ( 4F12.6)
      ISNO = SNO
      IADF= ADF
      WRITE (IO,9100) KASE,HPD,TDPW,ISNO,IADF
 9100 FORMAT (1HO/ 31X,32H*** MHF SELECTION INPUT FOR CASE,I3,4H ***
```

```
     X  /// 26X,27HDAILY INCINERATION SCHEDULE,3X,F11.2,7H HR/DAY       00002310
     X /26X,33HMAX. WEEKLY INCINERATION SCHEDULE  ,F8.2,8H DAYS/WK      00002320
     X /26X, 27HNUMBER OF STANDBY MHF UNITS, I14                         00002330
     X /26X, 29HNUMBER OF MHF'S ABOVE MINIMUM, I12 )                     00002340
C                                                                        00002700
C.......................................................................00002800
C                                                                        00002900
C        COMPUTE DESIGN REQUIREMENTS                                     00003000
C                                                                        00003100
C                                                                        00003200
      THA =   70.*PWS*PERS/ (HPD*TDPW)                                   00003300
      IF ( THA -85.)  50,80,80                                           00003320
   50 NOF  = 1.+SNO + 0.0001                                             00003340
      N = TDPW*THA/85. + 0.0001                                          00003360
      DPW = N                                                            00003380
      IF ( DPW) 60,60,70                                                 00003400
   60 WRITE (IO,9900) KASE,TDPW,THA                                      00003420
 9900 FORMAT ( 1H1,9X, 8H*** CASE,I3,6H   *** / 8X,                      00003440
     X  20HTRIAL DAYS PER WEEK, , F6.1,37H , IS TOO SMALL FOR TOTAL HEAR00003460
     XTH AREA , F11.2  )                                                 00003480
      WRITE (IO,9910)                                                    00003500
 9910 FORMAT ( 8X,30HCASE IS NOT CONSIDERED FURTHER )                    00003520
      GO TO 1000                                                         00003540
   70 FHA =  THA*TDPW/DPW                                                00003560
      GO TO 120                                                          00003580
   80 IF ( THA-2860.) 100,100,90                                         00003600
   90 DPW = TDPW                                                         00003620
      NOF = THA/2860. + 1.00001                                          00003640
      NOF = FLOAT(NOF) + ADF+SNO + .0001                                 00003660
      FHA = THA/ FLOAT(NOF)                                              00003680
      GO TO 120                                                          00003700
  100 NOF = 1. + ADF + SNO + 0.00001                                     00003720
      DPW = TDPW                                                         00003740
      FHA =  THA/(1.+ADF)                                                00003760
  120 CYT = FCYT(1)                                                      00003780
```

```
      ANOF = NOF
      IF ( HPD - 23.99 ) 140,125,125
  125 IF ( DPW - 6.99 )  130,135,135
  130 F = ( 1. + ANOF/(ANOF-SNO))/(216.*DPW)
      GO TO 145
  135 F = ANOF/((ANOF-SNO)*1512.)
      GO TO 145
  140 F = (1.+ ANOF/(DPW*(ANOF-SNO)))/(9.*HPD)
  145 CYCF = CYT * F
      TEST = FHA/(1.0 -CYCF)
      CALL LOCAT ( TEST,FHTAB, NHTAB,IERR,K )
      GO TO ( 160,170,150,150,150 ),IERR
  150 WRITE (IO,9920) KASE,THA,NOF
 9920 FORMAT( 1H1,9X,8H*** CASE,I3,6H   *** / 8X,
     X  18HTOTAL HEARTH AREA,,F11.2,24H, OR NUMBER OF FURNACES,,I5,1H,,
     X17H IS OUT OF RANGE.  )
      WRITE (IO,9910)
      GO TO 1000
  160 CALL LOCAT ( FHTAB(K+1), FHACY,5, IERR,L)
      CYT = FCYT(L)+(FCYT(L+1)-FCYT(L))*(FHTAB(K+1)-FHACY(L))
     X    /(FHACY(L+1)-FHACY(L))
      CYCF = CYT*F
      IF (FHTAB(K+1)*(1.0-CYCF)-FHA)165,165,170
  165 K = K+1
      IF ( K - NHTAB ) 160,170,170
  170 FHA = FHTAB(K)
      CALL LOCAT ( FHA,FHACY,5,IERR,L)
      CYT = FCYT(L)+(FCYT(L+1)-FCYT(L))*(     FHA    -FHACY(L))
     X     /(FHACY(L+1)-FHACY(L))
      CYCF = CYT*F
      NHEAR = NOTAB(K)
      HDIA  = DITAB(K)
      PSLU = 14000.*PWS /( (1.0-CYCF)*HPD*DPW*ANOF )
      DSF = PSLU*PERS/100.
      SCFCL  =  SCFCL*60. / ( ANOF-SNO)
      HLD = DSF/FHA
```

```
                                                                                    00004400
      YHF = 52.*HPD*DPW*(ANOF-SNO)/ANOF                                             00004440
      IF ( HPD - 23.99)  175,174,174                                                00004480
  174 CRL = 2.5                                                                     00004485
      RRL = 0.5                                                                     00004490
      GO TO 176                                                                     00004495
  175 CRL = 5.0                                                                     00004500
      RRL = 1.0                                                                     00004510
  176 WOH = HPD*DPW                                                                 00004520
C                                                                                   00006000
C       COMPUTE HEAT AND MASS BALENCE                                               00006100
C                                                                                   00006200
      CALL HEAT(IER)                                                                00006300
      IF ( IER)  1000,177,1000                                                      00006320
C                                                                                   00006400
C     COMPUTE NON-DOLLAR REQUIREMENTS                                               00006500
C                                                                                   00006600
  177 ALA = FALA( HDIA)                                                             00006800
      SBQ =  315.0639  * FHA                                                        00006900
      HUQ =  1912.7905 * FHA                                                        00006950
      F =(ANOF-SNO)/ANOF                                                            00006960
      IF ( HPD - 23.99)  6140,6125,6125                                             00006970
 6125 IF ( DPW - 6.99) 6130,6135,6135                                               00006980
 6130 YSBH =           F*( 8.*CYT/9. + 1248.*(7.-DPW) )                             00006990
      YHUH =  62.*CYT/ 9. * F                                                       00007000
      GO TO 6145                                                                    00007010
 6135 YSBH =  8.*CYT/9. * F                                                         00007020
      YHUH = 10.*CYT/9.* F                                                          00007030
      GO TO 6145                                                                    00007040
 6140 YSBH =  F*(8.*CYT/9. + 8736.-52.*HPD*DPW )                                    00007050
      YHUH =              F* CYT/9. * (10. + 52.*DPW)                               00007060
 6145 FCY =  WGTF*YHF*(1.-CYCF) + (YSBH*SBQ + YHUH*HUQ)/ QFU                        00007070
      IF (FHA - 2808.) 180,178,178                                                  00007100
  178 PDS = 29.6041                                                                 00007120
      GO TO 185                                                                     00007140
```

```
  180 PDS = FPDS (FHA)
  185 IF( FHA- 719.13) 191,192,192
  191 OMD = 6.0
      GO TO 193
  192 OMD = FOMD(FHA)
  193 PCY = PDS*DSF*(1.-CYCF)*YHF/2000.
      OLM = OMD*YHF/24.
      ANMM = FANMM(FHA)
      CLH = FCLH(HDIA)
      CRM = CLH*CRL*FLOAT(NHEAR)/SLF
      RLH = FRLH(HDIA)
      AMRM = RLH*FLOAT(NHEAR)*RRL/SLF
C
C       COMPUTE COST REQUIREMENTS
C
      CCI = FCCI(FHA)
      BGC = BFR* CCI
      CLD = ALA*ULC
      IF (KEFR) 200,200,210
  200 EFC = 0.0
      GO TO 220
  210 EFC = FEFC(CCI,BGC)
  220 TCC = CCI + BGC + CLD + EFC
      ANOF = NOF
      CCIAL = CCI*ANOF
      BGCAL = BGC*ANOF
      CLDAL = CLD*ANOF
      IF(KEFR) 230,230,240
  230 EFCAL = 0.0
      GO TO 250
  240 EFCAL = FEFC(CCIAL,BGCAL)
  250 TCCAL = CCIAL + BGCAL + CLDAL + EFCAL
      TCY =  TCC*YIR/100. /( 1.0 -(1.+YIR/100.)**(-SLF))
      RPY = (FLOAT(NHEAR)/SLF)*( CRL*FCAST(HDIA) + RRL*FREFR(HDIA) )
      AMSY = FMSY(FHA)
```

```
      FUY = FCY* UFC
      POY = PCY*UPC
      OLY = OLM*OLR
      ANMY = ANMM*ANMR
      RMY = CRM*CRR + AMRM*AMRR
      TCST = TCY + RPY + AMSY + FUY + POY + OLY + ANMY + RMY
      TCYAL = TCY*TCCAL/TCC
      RPYAL = ANOF*RPY
      AMSYA = ANOF*AMSY
      FUYAL = ANOF*FUY
      POYAL = ANOF*POY
      OLYAL = ANOF*OLY
      ANMYA = ANOF*ANMY
      RMYAL = ANOF*RMY
      TCSTA = TCYAL+RPYAL+AMSYA +FUYAL+POYAL+OLYAL+ANMYA+RMYAL
      F = 2000./ (ANOF*DSF*YHF*(1.0-CYCF))
      TCYPT = TCYAL*F
      RPYPT = RPYAL*F
      AMYPN = AMSYA*F
      FUYPT = FUYAL*F
      POYPT = POYAL*F
      OLYPT = OLYAL*F
      ANYPN = ANMYA*F
      RMYPT = RMYAL*F
      TCTPN = TCYPT+RPYPT+AMYPN+FUYPT+POYPT+OLYPT+ANYPN+RMYPT
      F =  100./TCSTA
      TCYPC = TCYAL*F
      RPYPC = RPYAL*F
      AMSYP = AMSYA*F
      FUYPC = FUYAL*F
      POYPC = POYAL*F
      OLYPC = OLYAL*F
      ANMYP = ANMYA*F
      RMYPC = RMYAL*F
      TCSTP =TCYPC+RPYPC+AMSYP+FUYPC+POYPC+OLYPC+ANMYP+RMYPC
```

```
C
C     WRITE OUT ANSWERS
C
      CALL PRINT
 1000 CONTINUE
      GO TO 5
      END
      SUBROUTINE INPUT
C
C     THIS ROUTINE READS AND PRINTS TITLE INPUT, NUMBER OF CASES,
C      SLUDGE STREAM INPUT, FINANCIAL INPUT, AND TECHNICAL INPUT
C
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59)
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX
     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE
     2,NHEAR,NOTAB,NRTAB,NUMEL,NUMSP
     3 , IN,IO
C
```

```
C.................................................................
C
C         READ TITLE , NO. OF CASES
      READ (IN,8000) LOC,NCASE
 8000 FORMAT(24A2,I12)
C        READ SLUDGE STREAM INPUT
      READ (IN,8100) PWS,PERS,PERV,QVOL,PCAC,PFEHY,PALHY,NELV
 8100 FORMAT ( 6E12.8/ E12.8,I12)
      READ(IN,8200) (NAMV(I),FRV(I),I=1,NELV)
 8200 FORMAT(6(A2,F10.6))
      IF ( NCASE )  10,10,20
C        HEAT BALANCE RUN ONLY
   10 READ (IN,8250) NAMFU,HDIA,NHEAR,PSLU
 8250 FORMAT( 6A2,F12.6,I12,F12.6)
      GO TO 30
C         READ FINANCIAL INPUT
   20 READ (IN,8300) SLF,YIR,KEFR,NAMFU,ULC,UFC
 8300 FORMAT( 2E12.8,I12,6A2,2E12.8)
      READ (IN,8400) UPC,OLR,ANMR,CRR,AMRR,BFR
 8400 FORMAT ( 6E12.8)
C        READ TECHNICAL INPUT
   30 READ (IN,8400) PXAIR,SCFCL,FRAIR,TAIRI
      READ (IN,8400) TSL1,TEX,TASH,TSCRB
      READ (IN,8400) FCAC,FFE,FAL
      READ (IN,8500) QFU,BUREX,EXAFU,NELF
 8500 FORMAT ( 3E12.8,I12)
      READ (IN,8200) (NAMF(I),FRF(I),I=1,NELF)
      READ (IN,8400) TSUR,VAMBM,TAMB,ELE
C
C.................................................................
C
C         OUTPUT THE INPUT DATA
      CALL TITL(2)
      IF ( NCASE ) 40,40,50
   40 WRITE (IO,9005)
```

```
      WRITE (IO,9010)                                                   10003630
      WRITE (IO,9015)                                                   10003635
      GO TO 60                                                          10003640
   50 WRITE (IO,9000) NCASE                                             10003700
      WRITE (IO,9010)                                                   10003800
      WRITE (IO,9020) PWS                                               10003850
   60 WRITE (IO,9025) PERS,PERV,QVOL,PCAC                               10003900
      WRITE (IO,9026) PFEHY,PALHY,NELV                                  10003910
      WRITE (IO,9030) (NAMV(I),FRV(I),I=1,NELV)                         10004000
      IF ( NCASE ) 70,70,80                                             10004010
   70 WRITE (IO,9070)                                                   10004015
      WRITE (IO,9140) NAMFU,HDIA,NHEAR,PSLU                             10004020
      WRITE (IO,9080) PXAIR                                             10004030
      WRITE (IO,9082) SCFCL                                             10004040
      WRITE (IO,9085) FRAIR,TAIRI                                       10004050
      WRITE (IO,9090) TSL1,TEX,TASH,TSCRB                               10004060
      CALL TITL(2)                                                      10004070
      WRITE (IO,9070)                                                   10004075
      GO TO 90                                                          10004080
   80 WRITE (IO,9040)                                                   10004100
      WRITE (IO,9050) SLF,YIR,KEFR,ULC                                  10004200
      WRITE (IO,9051) NAMFU,UFC,UPC                                     10004210
      WRITE (IO,9060) OLR,ANMR,CRR,AMRR,BFR                             10004300
      CALL TITL(2)                                                      10004400
      WRITE (IO,9070)                                                   10004500
      WRITE (IO,9080) PXAIR                                             10004600
      WRITE (IO,9083) SCFCL                                             10004640
      WRITE (IO,9085) FRAIR,TAIRI                                       10004650
      WRITE (IO,9090) TSL1,TEX,TASH,TSCRB                               10004700
   90 WRITE (IO,9100) FCAC,FFE,FAL                                      10004800
      WRITE (IO,9110) QFU,BUREX,EXAFU,NELF                              10004900
      WRITE (IO,9120) (NAMF(I),FRF(I),I=1,NELF)                         10005000
      WRITE (IO,9130) TSUR,VAMBM,TAMB,ELE                               10005100
 9000 FORMAT (1H0/34X,27H( NUMBER OF CASES TO BE RUN,I5,2H ) )          10005200
 9005 FORMAT (1H0/ 38X,25H( THERMAL ANALYSIS ONLY ) )                   10005250
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```
 9010 FORMAT ( 1H0,36X,27H*** SLUDGE STREAM INPUT *** )
 9015 FORMAT  (  1H  )
 9020 FORMAT (1H0, 23X,21HPLANT WET SLUDGE FLOW ,14X,F12.1,8H TON/DAY
     X        )
 9025 FORMAT(24X,40HTOTAL DRY SOLIDS CONCENTRATION IN SLUDGE, F7.2 ,
     X 12H WEIGHT 0/0 /24X,37HVOLATILE SOLIDS CONCENTRATION IN D.S.,
     X F10.2, 12H WEIGHT 0/0 ,
     X/24X,23HHEAT VALUE OF VOLATILES, 12X, F12.0,7H BTU/LB
     X/24X,18HCACO3 IN DRY SOLID,17X,F12.2, 12H WEIGHT 0/0   )
 9026 FORMAT(24X,20HFE(OH)3 IN DRY SOLID,15X,F12.2,12H WEIGHT 0/0 ,
     X/24X,20HAL(OH)3 IN DRY SOLID,15X,F12.2,12H WEIGHT 0/0
     X/24X,31HNUMBER OF ELEMENTS IN VOLATILES,4X,I12
     X    )
 9030 FORMAT(24X,17HMASS FRACTION OF ,A2,15H  IN VOLATILES ,F13.3)
 9040 FORMAT ( 1H0/ 39X, 23H*** FINANCIAL INPUT ***  )
 9050 FORMAT (1H0, 23X,18HSYSTEM LIFE OF MHF,17X,F12.1,4H YRS
     X/24X,20HYEARLY INTEREST RATE,15X,F12.2,4H 0/0
     X/24X,42HENG FEE RATE CODE (1=FORMULA,0= ZERO RATE), I5
     X/24X,14HUNIT LAND COST , 21X,F12.2, 7H $/ACRE
     X)
 9051 FORMAT(24X,19HAUXILIARY FUEL NAME,16X,6A2
     X/24X,14HUNIT FUEL COST , 21X, F12.3, 5H $/LB
     X/24X,15HUNIT POWER COST, 20X, F12.3, 6H $/KWH
     X   )
 9060 FORMAT ( 1H0,23X,20HOPERATING LABOR RATE,15X,F12.2,9H $/MAN-HR
     X/24X,29HNORMAL MAINTENANCE LABOR RATE,6X,F12.2,9H $/MAN-HR
     X/24X,31HCASTINGS REPLACEMENT LABOR RATE, 4X,F12.2,9H $/MAN-HR
     X/24X,33HREFRACTORY REPLACEMENT LABOR RATE,2X,F12.2,9H $/MAN-HR
     X/24X,18HBUILDING/MHF RATIO, 17X,F12.3, 4H $/$  )
 9070 FORMAT ( 1H0 /39X,23H*** TECHNICAL INPUT *** )
 9080 FORMAT (1H0,23X,40HMINIMUM EXCESS AIR FOR COMB OF VOLATILES
     X      , F7.2, 4H 0/0
     X   )
 9082 FORMAT( 24X,30HSHAFT COOLING AIR FLOW PER MHF,F17.0,5H SCFH )
 9083 FORMAT( 24X,34HSHAFT COOLING AIR FLOW (ALL MHF'S),F13.0,5H SCFM )
 9085 FORMAT(24X,32HFRACTION OF COOLING AIR RECYCLED , 3X, F12.3
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```
     X/24X,31HEXIT TEMPERATURE OF COOLING AIR , 4X,F12.0,6H DEG F         10008300
     X      )                                                             10008400
 9090 FORMAT(1H0,23X,27HINLET TEMPERATURE OF SLUDGE,8X,F12.0,6H DEG F     10008500
     X/24X,36HEXIT TEMPERATURE OF COMBUSTION GASES,F11.0, 6H DEG F        10008600
     X/24X,23HEXIT TEMPERATURE OF ASH ,12X, F12.0, 6H DEG F               10008700
     X/24X,32HEXIT TEMPERATURE OF SCRUBBER GAS,3X,F12.0,6H DEG F          10008800
     X      )                                                             10008900
 9100 FORMAT (1H0,23X,31HFRACTION CACO3 CONVERTED TO CAO,4X,F12.3         10009000
     X/24X,35HFRACTION FE(OH)3 CONVERTED TO FE2O3,F12.3                   10009100
     X/24X,35HFRACTION AL(OH)3 CONVERTED TO AL2O3,F12.3                   10009200
     X    )                                                               10009300
 9110 FORMAT (1H0,23X,28HHEAT VALUE OF AUXILIARY FUEL , F19.0,            10009400
     X     7H BTU/LB                                                      10009500
     X/24X,22HEXCESS BURNER CAPACITY,13X, F12.2, 4H 0/0                   10009600
     X/24X,29HEXCESS AIR FOR AUXILIARY FUEL ,6X,F12.2,4H 0/0              10009700
     X/24X,36HNUMBER OF ELEMENTS IN AUXILIARY FUEL, I11 )                 10009800
 9120 FORMAT(24X,17HMASS FRACTION OF ,A2,19H  IN AUXILIARY FUEL,F9.3)     10010000
 9130 FORMAT (1H0,23X,23HMHF SURFACE TEMPERATURE ,12X,F12.0,6H DEG F      10010100
     X/24X,20HAMBIENT AIR VELOCITY,15X,F12.1, 4H MPH                      10010200
     X/24X,23HAMBIENT AIR TEMPERATURE, 12X, F12.0, 6H DEG F               10010300
     X/24X,18HELEVATION OF PLANT , 17X, F12.0, 3H FT                      10010400
     X     )                                                              10010500
 9140 FORMAT(1H0,23X,19HAUXILIARY FUEL NAME,16X,6A2                       10010600
     X/24X,35HMHF OUTER DIAMETER (13.5 INCH WALL),F12.2,3H FT             10010700
     X/24X,25HNUMBER OF HEARTHS PER MHF,10X,I12                           10010800
     X/24X,36HSTEADY STATE WET SLUDGE RATE PER MHF, F11.1,6H LB/HR        10010900
     X  )                                                                 10011000
      RETURN                                                              10020000
      END                                                                 10020100
      SUBROUTINE  HEAT (IER)                                              20000000
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)         20000080
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)            20000085
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59)                            20000090
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA         20000100
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX       20000110
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     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB         20000120
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC           20000130
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT            20000140
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT        20000150
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV            20000160
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO           20000170
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR         20000180
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS             20000190
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC          20000200
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL       20000210
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1           20000220
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT          20000230
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS           20000240
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR                                20000250
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE        20000260
     2,NHEAR,NOTAB,NRTAB,NUMEL,NUMSP                                      20000270
     3 , IN,IO                                                            20000280
      DIMENSION SPMW(5),ELMW(5),WS(5),DH(6),BRN(5),QX(5)                  20001800
      DATA SPMW,ELMW/ 44.011,18.016,32.,28.0134,64.066,12.011,2.016       20002100
     X,32.,28.0134,32.064/                                                20002200
      IER   = 0                                                           20002700
      QCAL = 0.                                                           20002800
      QFE = 0.                                                            20002900
      QALHY = 0.                                                          20003000
      PCACO = 0.                                                          20003100
      PFEWA = 0.                                                          20003200
      PALWA = 0.                                                          20003300
      PSLT = 24.*PSLU/2000.                                               20003800
      NUMEL =5                                                            20007100
      NUMSP =5                                                            20007200
      NPX =0                                                              20007300
      PSOL = PERS*PSLU/100.                                               20007400
      PERW = 100. - PERS                                                  20007500
      PWAT = PERW/100.*PSLU                                               20007600
      PERA = 100. - PERV                                                  20007700
```

```
      PVOL = PERV/100.*PSOL
      PASH = PERA/100.*PSOL
      IF(PCAC) 210,210,211
  211 PMEL   =  PCAC/100.*PSOL
      PCACO =  PMEL/100.08*44.054*FCAC
      PASH = PASH - PCACO
      QCAL = PMEL*FCAC*761.
  210 IF(PFEHY) 212,212,213
  213 PMEL = PFEHY/100.*PSOL
      PFEWA = PMEL/106.87*27.*FFE
      PASH = PASH - PFEWA
      QFE = PMEL*FFE*225.
  212 IF(PALHY) 214,214,215
  215 PMEL = PALHY/100.*PSOL
      PALWA = PMEL/78.003*27.*FAL
      PASH = PASH - PALWA
      QALHY = PMEL*FAL*380.8
  214 DO 168 I=1,NUMEL
      FRFU(I)=0.
  168 FRVO(I)=0.
      DO 130 I=1,NUMSP
  130 BRN(I) =0.
      DO 165 J=1,NELV
      DO 164 I=1,NUMEL
      IF(NAMV(J) - NAMEL(I)) 164,166,164
  164 CONTINUE
      WRITE (IO,167) NAMV(J)
  167 FORMAT(1H1/ 5X,16HNAME OF ELEMENT  ,A4,23H INCORRECT - CASE ENDED)
      IER = 1
      RETURN
  166 FRVO(I) = FRV(J)
  165 CONTINUE
      DO 171 J=1,NELF
      DO 172 I=1,NUMEL
      IF(NAMF(J) - NAMEL(I)) 172,173,172
```

```
  172 CONTINUE
      WRITE (IO,167) NAMF(J)
      IER = 1
      RETURN
  173 FRFU(I) = FRF(J)
  171 CONTINUE
      IF(BUREX) 230,230,231
  230 BUREX = 25.
  231 PI = 3.14159
      GASR =10.73
      TEXR = TEX + 460.
      TARIR = TAIRI + 460.
      TAMBR = TAMB + 460.
      TSURR = TSUR + 460.
      TSL1R = TSL1 + 460.
      PSCRE = 14.696 - 4.2/9000.*ELE
      TSCRR = TSCRB + 460.
      PSWAT = 1.78885*EXP(15.9014*(TSCRR-581.58)/TSCRR)
      AIRM = 28.84
      AMOL = 1./AIRM*(1.+ PSWAT/(PSCRE-PSWAT))
      CPWAT =1.
      CPSL =1.
C     INLET TEMPERATURE OF SLUDGE USED AS BASE TEMPERATURE FOR ENTHALPY
      HWSEN = CPWAT*(212.-TSL1)*PWAT
      HWVAP = 970.*PWAT
      HWGAS = PWAT*(1.102*(TEXR-672.) - 66.2*(SQRT(TEXR) -SQRT(672.))
     X + 416.*ALOG(TEXR/672.))
      HWSL = HWSEN + HWVAP + HWGAS
      CPASH = .2
      HASH = PASH*CPASH*(TASH-TSL1)
      VAMBF = 1.46667*VAMBM
      HR =.1713*((TSURR/100.)**4 - (TAMBR/100.)**4)
      HR= HR/(TSURR-TAMBR)
      HC = .29*((TSUR-TAMB)/HDIA)**.25
      HC = HC*(1. + .225*VAMBF)
```

```
      QTRAN =(HR+HC)*(TSUR-TAMB)*PI*(HDIA**2/2.+FLOAT(NHEAR)*4.*HDIA)
      DO 12 I=1,NUMSP
   12 WS(I)  = PVOL*FRVO(I)/ELMW(I)*SPMW(I)
      WS(1)  = WS(1)  + PCACO
      WS(2)  = WS(2)  + PFEWA + PALWA
      PO2S = PVOL*(FRVO(1)/ELMW(1)*SPMW(3) + FRVO(2)/ELMW(2)*SPMW(3)/2.
     X + FRVO(5)/ELMW(5)*SPMW(3) - FRVO(3))
      PAIRC = SCFCL/379.*AIRM
      PAIRS = PAIRC*FRAIR
      SCFCF = FRAIR*SCFCL
   20 PAIRT = PO2S/.233*(1. + PXAIR/100.)
      PAIRA = PAIRT - PAIRS
      SCFAM = PAIRA*379./AIRM
      PAIR = PO2S/.233
C     CALCULATE HEAT REQUIRED TO HEAT SLUDGE COMBUSTION PRODUCTS TO TEX
      CALL GETDH(DH,TSL1R,TEXR)
      DH(2) = DH(2) + 1048.
      DO 14 I=1,NUMSP
   14 QX(I) = WS(I)*DH(I)
      QX(3) = PO2S*PXAIR/100.*DH(3)
      QX(4) = QX(4) + .767*PAIRT*DH(4)
      QARIN = PAIRS*(.219*(TARIR-TSL1R) + .171E-4*(TARIR**2-TSL1R**2)  -
     X .293E-8/3.*(TARIR**3 -TSL1R**3))
      QCOOL =  PAIRC*(.219*(TARIR - TAMBR) + .171E-4*(TARIR**2 -      TA
     XMBR**2) - .293E-8/3.*(TARIR**3 - TAMBR**3))
      QAMBA = PAIRA*(.219*(TAMBR-TSL1R) + .171E-4*(TAMBR**2-TSL1R**2)
     X- .293E-8/3.*(TAMBR**3 - TSL1R**3))
      QREQ = HWSL + HASH + QCOOL + QLAL
      QREQ = QREQ + QFE + QALHY + QTRAN
      QSEN =0.
      DO 16 I=1,NUMSP
   16 QSEN = QSEN + QX(I)
      QREQ = QREQ + QSEN +     AMAX1(0.,-QAMBA)
      QVOLT = PVOL*QVOL
      QIN = QVOLT  + QARIN +  AMAX1(0., QAMBA)
```

```
      QNET = QIN - QREQ
      IF(NPX) 122,122,121
  122 IF(QNET - 200. ) 50,50,60
   60 NPX = NPX + 1
      PXS = PXAIR
      QNS = QNET
      PXAIR = PXAIR + 10.
      GO TO 20
  121 IF(ABS(QNET) - 200.) 123,123,124
  124 NPX=NPX + 1
      IF(NPX - 10) 125,125,126
  126 WRITE (IO,127) PXAIR,QNET
  127 FORMAT(1H1/5X,55HITERATION NUMBER EXCEEDED IN CALCULATION FOR EXCE
     XSS AIR ,/5X, 8HPXAIR = ,F8.2, 9H  QNET = ,F8.1 )
      GO TO 123
  125 PXSAV = PXAIR
      PXAIR = PXAIR - (PXAIR-PXS)/(QNET-QNS)*QNET
      PXS = PXSAV
      QNS = QNET
      GO TO 20
  123 WGTF = 0.
      QNET = 0.
      PEFF = 0.
      QGROS =  0.
      QBUR = 0.
      BTUV = 0.
      SCFAI = 0.
      WBAIR = 0.
      GO TO 140
   50 CONTINUE
      QNET = ABS(QNET)
      BURNO = FRFU(1)/ELMW(1)*SPMW(3) + FRFU(2)/ELMW(2)*SPMW(3)/2. +
     XFRFU(5)/ELMW(5)*SPMW(3) - FRFU(3)
      BURAI =  BURNO/.233*(1.+EXAFU/100.)
      BRN(1) = FRFU(1)/ELMW(1)*SPMW(1)
```

```
      BRN(2) = FRFU(2)/ELMW(2)*SPMW(2)
      BRN(3) = BURNO*EXAFU/100.
      BRN(4) = FRFU(4) + .767*BURAI
      BRN(5) = FRFU(5)/ELMW(5)*SPMW(5)
      CALL GETDH(DH,TSL1R,TEXR)
      DH(2) = DH(2) + 1048.
      DHBUR = 0.
      DO 18 I=1,NUMSP
   18 DHBUR = DHBUR + BRN(I)*DH(I)
      FEFF =(QFU-DHBUR)/QFU
      PEFF = 100.*FEFF
      QGROS = QNET/FEFF
      QBUR = (1. + BUREX/100.)*QGROS
      WGTF = QBUR/QFU
      WBAIR = WGTF*BURAI
      SCFAI = WGTF*BURAI/AIRM*379.
      BTUV = QBUR/SCFAI
  140 TOT(1) = WS(1) + BRN(1)*WGTF
      TOT(2) = PWAT + WS(2) + BRN(2)*WGTF
      TOT(3) = PO2S*PXAIR/100. + BRN(3)*WGTF
      TOT(4) = WS(4) + .767*PAIRT + BRN(4)*WGTF
      TOT(5) = WS(5) + BRN(5)*WGTF
      GTOT = 0.
      TVOL = 0.
      DO 22 I=1,NUMSP
      VOL(I) = TOT(I)/SPMW(I)*GASR/PSCRE*TEXR
      TVOL =  TVOL + VOL(I)
   22 GTOT = GTOT + TOT(I)
      GDRY = GTOT - TOT(2)
      VDRY = TVOL - VOL(2)
      ROEX = GTOT/TVOL
      DRYMO = SPMW(1)*VOL(1)/VDRY
      DO 150 I=3,NUMSP
  150 DRYMO = DRYMO + SPMW(I)*VOL(I)/VDRY
      VSAT = 10.73/DRYMO*(1.+PSWAT/(PSCRE-PSWAT))/PSCRE*TSCRR
      WATSC =  PSWAT/(PSCRE-PSWAT)*SPMW(2)/DRYMO*GDRY - TOT(2)
```

```
      VWATS = WATSC/8.3451/60.
      VSCEX = GDRY*VSAT/60.
      RJAIR = PAIRC - PAIRS
      TOTMF =  PSLU+WGTF+PAIRA+PAIRC+WBAIR
      RETURN
      END
      SUBROUTINE BLOCK
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59)
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX
     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE
     2,NHEAR,NOTAB,NRTAB,NUMFL,NUMSP
     3 , IN,IO
      READ (IN,10) NAMEL,ANAMS
   10 FORMAT(5A2,2X,5A4)
      READ (IN,20) FHTAB
      READ (IN,20) DITAB
   20 FORMAT(6F12.6)
      READ (IN,30) NOTAB
```

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   30 FORMAT(12I6)                                                        30001800
      RETURN                                                              30001900
      END                                                                 30010000
      SUBROUTINE TITL( I )                                                40000000
C                                                                         40000010
C       ROUTINE TO WRITE HEADING                                          40000020
C                                                                         40000030
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)         40000080
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)            40000085
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59)                            40000090
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA         40000100
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX       40000110
     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB         40000120
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC           40000130
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT            40000140
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT        40000150
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV            40000160
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO           40000170
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR         40000180
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS             40000190
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC          40000200
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL       40000210
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1           40000220
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT          40000230
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS           40000240
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR                                40000250
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE        40000260
     2,NHEAR,NOTAB,NRTAB,NUMEL,NUMSP                                      40000270
     3 , IN,IO                                                            40000280
      WRITE (IO,9000)                                                     40001000
 9000 FORMAT(1H1,25X,50HMULTIPLE HEARTH FURNACE SEWAGE SLUDGE INCINERATI40001100
     XON  )                                                               40001110
      WRITE (IO,9010) LOC                                                 40001200
 9010 FORMAT(1H0,26X,24A2)                                                40001300
      IF ( NCASE ) 20,20,5                                                40001350
```

```
    5 GO TO ( 10,20),I
   10 WRITE (IO,9020) KASE
 9020 FORMAT ( 1H0, 46X, 4HCASE , I3 )
   20 RETURN
      END
      SUBROUTINE PRINT
C
C
       DIMENSION ANAMS(5) , NAMEL(5) , FRVO(5) , FRFU(5) , TOT(5)
     X , VOL(5),NAMFU(6),FRV(5),FRF(5),NAMV(5),NAMF(5),LOC(24)
       DIMENSION DITAB(59),FHTAB(59),NOTAB(59)
      COMMON ACF,ADF,ALA,ALKX,AMRM,AMRR,AMSY,ANMM,ANMR,ANMY,AMSYA
     1,AMSYP,AMYPN,ANAMS,ANMYA,ANMYP,ANYPN,BFR,BGC,BTUV,BGCAL,BUREX
     2,CCI,CLD,CLH,CRL,CRM,CRR,CYT,CYCF,CCIAL,CLDAL,DPW,DSF,DITAB
     3,EFC,ELE,EFCAL,EXAFU,FAL,FCY,FFE,FHA,FPC,FRF,FRV,FUY,FCAC
     4,FRFU,FRVO,FHTAB,FRAIR,FRCO2,FUYAL,FUYPC,FUYPT,GDRY,GTOT
      COMMON  HLD,HPD,HASH,HDIA,HWSL,OLM,OLR,OLY,OLYAL,OLYPC,OLYPT
     1,PCY,PDS,POY,PWS,PAIR,PASH,PCAC,PEFF,PERA,PERC,PERS,PERV
     2,PERW,PSLT,PSLU,PAIRA,PAIRC,PAIRS,PAIRT,PALHY,PALWA,PCACO
     3,PFEHY,PFEWA,POYAL,POYPC,POYPT,PSCRE,PXAIR,QFE,QFU,QIN,QBUR
     4,QCAL,QNET,QREQ,QSEN,QVOL,QALHY,QAMBA,QARIN,QCOOL,QGROS
      COMMON  QTRAN,QVOLT,RLH,RMY,RPY,RRL,ROEX,RJAIR,RMYAL,RMYPC
     1,RMYPT,RPYAL,RPYPC,RPYPT,SLF,SNO,SMGD,SCFAI,SCFAM,SCFCF,SCFCL
     2,SCWAT,SLDEN,TCC,TCY,TEX,TMF,TOT,TAMB,TASH,TCST,TDPW,TSL1
     3,TSUR,TVOL,TAIRI,TCCAL,TCSTA,TCSTP,TCTPN,TCYAL,TCYPC,TCYPT
     4,TOTMF,TSCRB,UFC,ULC,UPC,VOL,VSAT,VAMBM,VAREA,VSCEX,VWATS
      COMMON  WOH,WGTF,WATSC,WBAIR,YHF,YIR
     1,KASE,KEFR,LOC,NOF,NPX,NAMF,NAMV,NELF,NELV,NAMEL,NAMFU,NCASE
     2,NHEAR,NOTAB,NRTAB,NUMEL,NUMSP
     3 , IN,IO
      IF ( NCASE) 20,20,10
C
C        PRINT DESIGN AND OPERATION OUTPUT
   10 WRITE (IO,9000)
 9000 FORMAT ( 1H0/35X,32H*** MHF DESIGN AND OPERATION *** )
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```
      WRITE (IO,9010) NOF,HDIA,NHEAR
      WRITE(IO,9011) FHA,PSLU,DSF,HLD
 9010 FORMAT(1H0,22X,15HNUMBER OF MHF'S,21X, I14
     X/ 23X,35HMHF OUTER DIAMETER (13.5 INCH WALL),1X,F14.2,3H FT
     X/ 23X,25HNUMBER OF HEARTHS PER MHF,11X,I14
     X )
 9011 FORMAT(23X,29HEFFECTIVE HEARTH AREA PER MHF ,7X,F14.1,6H SQ FT
     X/ 23X,36HSTEADY STATE WET SLUDGE RATE PER MHF,F14.1,6H LB/HR
     X/ 23X,36HSTEADY STATE DRY SOLIDS RATE PER MHF,F14.1,6H LB/HR
     X/ 23X,27HHEARTH LOADING (DRY SOLIDS),9X, F14.2,12H LB/HR-SQ FT
     X    )
      WRITE(IO,9020) YHF,DPW,WOH,CYCF
      WRITE(IO,9021) CYT,CRL,RRL
 9020 FORMAT(1H0,22X,30HYEARLY OPERATING HOURS PER MHF,6X,F14.1,6H HR/YR
     X/ 23X,28HWEEKLY INCINERATION SCHEDULE ,8X, F14.2,8H DAYS/WK
     X/ 23X,25HWEEKLY INCINERATION HOURS , 11X,F14.2, 6H HR/WK
     X/ 23X,32HCYCLING AS FRACTION OF OPERATION,4X, F14.3, 6H HR/HR
     X )
 9021 FORMAT( 23X,19HCYCLE TIME (HEATUP), 17X,F14.2, 3H HR
     X/ 23X,37HMHF CASTING SETS REPLACED DURING LIFE, F13.2
     X/ 23X,40HMHF REFRACTORY SETS REPLACED DURING LIFE, F10.2
     X   )
      WRITE(IO,9025) SCFCL
 9025 FORMAT (23X,25HSHAFT COOLING AIR PER MHF, 11X, F14.0, 5H SCFH )
   20 WRITE(IO,9030)
 9030 FORMAT ( 1H0/ 33X,36H*** AIR FOR VOLATILES COMBUSTION *** )
      WRITE(IO,9040) SCFCF,SCFAM,PAIR
      WRITE(IO,9041) PXAIR,PAIRT
 9040 FORMAT(1H0,22X,39HFLOWRATE OF COOLING AIR SENT TO FURNACE,F11.0
     X    , 5H SCFH
     X/ 23X,40HFLOWRATE OF AMBIENT AIR ENTERING FURNACE,F10.0,5H SCFH
     X/ 23X,38HTHEORETICAL AIR REQUIRED FOR VOLATILES, F12.0,6H LB/HR
     X )
 9041 FORMAT(23X,32HPERCENT EXCESS AIR FOR VOLATILES ,4X, F14.2
     X/ 23X,28HTOTAL AIR USED FOR VOLATILES , 8X, F14.0, 6H LB/HR
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     X    )                                                             50004200
      CALL TITL(1)                                                      50004300
      WRITE(IO,9050)                                                    50004400
 9050 FORMAT(1HO/ 39X,24H*** MHF HEAT BALANCE ***                       50004500
     X / 39X,24H(SIX SIGNIFICANT DIGITS)                                50004550
     X    // 20X,17HHEAT REQUIREMENTS  )                                50004600
      WRITE(IO,9060) QSEN,HWSL                                          50004700
      WRITE(IO,9061) HASH,QTRAN,QCOOL                                   50004710
 9060 FORMAT(23X,35HHEAT FOR SLUDGE COMBUSTION PRODUCTS,1X,F14.0,       50004800
     X    7H BTU/HR                                                     50004900
     X/23X,36HHEAT FOR SLUDGE MOISTURE EVAPORATION, F14.0,7H BTU/HR     50005000
     X )                                                                50005010
 9061 FORMAT(23X,19HHEAT REMOVED IN ASH,17X, F14.0, 7H BTU/HR           50005100
     X/23X,34HRADIATION AND CONVECTION HEAT LOSS,2X,F14.0,7H BTU/HR     50005200
     X/23X,23HSHAFT COOLING HEAT LOSS ,13X,F14.0,7H BTU/HR              50005300
     X    )                                                             50005350
      IF ( QAMBA ) 100,100,110                                          50005400
  100 QAMA = ABS(QAMBA)                                                 50005500
      WRITE(IO,9070) QAMA                                               50005600
 9070 FORMAT (23X,29HHEAT FOR INCOMING AMBIENT AIR , 7X,F14.0,7H BTU/HR)50005800
  110 WRITE(IO,9080) QCAL,QFE,QALHY,QREQ                                50005850
 9080 FORMAT (23X,24HHEAT FOR CALCINING CACO3,12X,F14.0,7H BTU/HR       50005900
     X/23X,28HHEAT FOR DECOMPOSING FE(OH)3,8X, F14.0,7H BTU/HR          50006100
     X/23X,28HHEAT FOR DECOMPOSING AL(OH)3,8X, F14.0,7H BTU/HR          50006200
     X/23X,22HTOTAL HEAT REQUIREMENT  , 14X,F14.0, 7H BTU/HR            50006300
     X    )                                                             50006400
      WRITE(IO,9090)                                                    50006500
 9090 FORMAT ( 1HO,19X,10HHEAT INPUT )                                  50006600
      WRITE(IO,9100) QVOLT                                              50006700
 9100 FORMAT ( 23X,19HHEAT FROM VOLATILES , 17X, F14.0,7H BTU/HR )      50006800
      IF (QAMBA) 125,125,120                                            50006900
  120 WRITE(IO,9110) QAMBA                                              50007000
 9110 FORMAT ( 23X,30HHEAT FROM INCOMING AMBIENT AIR,6X,F14.0,7H BTU/HR)50007100
  125 WRITE(IO,9120) QARIN,QNET,QREQ                                    50007200
 9120 FORMAT(23X,36HHEAT FROM INCOMING SHAFT COOLING AIR,F14.0,7H BTU/HR50007300
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     X/23X,29HNET HEAT REQUIRED FROM BURNER,7X,F14.0,7H BTU/HR          50007400
     X/23X,16HTOTAL HEAT INPUT , 20X, F14.0, 7H BTU/HR                  50007500
     X )                                                                50007600
      WRITE(IO,9130)                                                    50007700
 9130 FORMAT( 1H0/ 34X,34H*** AUXILIARY BURNER SELECTION *** )          50007800
      WRITE(IO,9140) PEFF,QGROS,BUREX,QBUR                              50007900
      WRITE(IO,9141) WGTF,BTUV,SCFAI,WBAIR                              50007910
 9140 FORMAT (1H0,22X,40HPERCENT AVAILABLE HEAT FROM BURNER(CALC),F10.2 50008000
     X/23X,31HGROSS HEAT REQUIRED FROM BURNER,5X, F14.0,7H BTU/HR       50008100
     X/23X,22HTOTAL BURNER CAPACITY( F6.2 ,                             50008200
     X            12H O/O EXCESS) ,F10.0, 7H BTU/HR                     50008300
     X )                                                                50008310
 9141 FORMAT(23X,29HREQUIRED BURNER FUEL FLOWRATE,7X,F14.1, 6H LB/HR    50008400
     X/23X,35HBURNER HEAT PER STD CUBIC FT OF AIR,1X,F14.2,8H BTU/SCF   50008500
     X/23X,39HREQUIRED BURNER AIR VOLUMETRIC FLOWRATE,F11.0,5H SCFH     50008600
     X/23X,33HREQUIRED BURNER AIR MASS FLOWRATE,3X,F14.1,6H LB/HR       50008700
     X  )                                                               50008800
      CALL TITL(1)                                                      50008900
      WRITE(IO,9150)                                                    50009000
 9150 FORMAT (1H0/ 38X,25H*** MHF EXIT GAS DATA ***                     50009100
     X  // 32X,7HSPECIES,11X, 9HFLOWRATES                               50009200
     X  /  41X,11HMASS(LB/HR) 5X, 12HVOLUME(ACFH)   )                   50009300
      DO 130 I = 1,NUMSP                                                50009400
  130 WRITE(IO,9160) ANAMS(I),TOT(I),VOL(I)                             50009500
 9160 FORMAT ( 33X, A4, F12.0, F16.0  )                                 50009600
      WRITE(IO,9170) GTOT,TVOL                                          50009700
 9170 FORMAT ( 31X, 6HTOTALS, F12.0,F16.0  )                            50009800
      VWATS = AMAX1( VWATS,0.0)                                         50009850
      WRITE(IO,9180) ROEX,VSAT,VSCEX,VWATS                              50009900
 9180 FORMAT (1H0/23X,27HDENSITY OF FURNACE EXIT GAS,9X,F14.5,7H LB/FT3 50010000
     X/23X,34HSCRUBBER EXIT VOLUME/LB OF DRY GAS,2X,F14.3, 7H FT3/LB    50010100
     X/23X,36HSCRUBBER SATURATED EXIT GAS FLOWRATE,F14.0,5H ACFM        50010200
     X/23X,35HWATER FLOWRATE TO SATURATE EXIT GAS,1X,F14.0,4H GPM       50010300
     X  )                                                               50010400
      WRITE(IO,9190)                                                    50010500
 9190 FORMAT (1H0/39X,24H*** MHF MASS BALANCE ***                       50010600
```

```
     X / 39X,24H(SIX SIGNIFICANT DIGITS)
     X    // 20X,12HMASS INFLOWS )
      WRITE(IO,9200) PSLU,WGTF,PAIRA
      WRITE(IO,9201) PAIRC,WBAIR,TOTMF
 9200 FORMAT(23X,19HWET SLUDGE FEEDRATE,17X,F14.1,6H LB/HR
     X/23X,29HREQUIRED BURNER FUEL FLOWRATE,7X,F14.1,6H LB/HR
     X/23X,24HAMBIENT AIR TO VOLATILES,12X,F14.1,6H LB/HR
     X )
 9201 FORMAT(23X,17HTOTAL COOLING AIR ,19X,F14.1, 6H LB/HR
     X/23X,28HREQUIRED BURNER AIR FLOWRATE,8X,F14.1, 6H LB/HR
     X/23X,17HTOTAL MASS INFLOW,19X,F14.1, 6H LB/HR
     X  // 20X, 13HMASS OUTFLOWS  )
      WRITE(IO,9210) GTOT,PASH,RJAIR,TOTMF
 9210 FORMAT(23X,27HTOTAL MHF EXIT GAS FLOWRATE,9X,F14.1,6H LB/HR
     X/23X,18HASH DISCHARGE RATE,18X, F14.1, 6H LB/HR
     X/23X,20HREJECTED COOLING AIR , 16X,F14.1,6H LB/HR
     X/23X,18HTOTAL MASS OUTFLOW , 18X, F14.1, 6H LB/HR
     X        )
      IF ( NCASE) 200,200,140
  140 CALL TITL(1)
      WRITE(IO,9220)
 9220 FORMAT (1H0/34X,33H*** NON-DOLLAR OUTPUT PER MHF ***  )
      WRITE(IO,9230) ALA,FCY,PCY
 9230 FORMAT ( 1H0,22X,9HLAND AREA,27X,F14.2,5H ACRE
     X/23X,11HYEARLY FUEL,25X,F14.0, 6H LB/YR
     X/23X,12HYEARLY POWER,24X,F14.0,7H KWH/YR
     X    )
      WRITE(IO,9240) OLM,ANMM,CRM,AMRM
 9240 FORMAT(1H0,22X,15HOPERATING LABOR,21X,F14.1,10H MAN-HR/YR
     X/23X,24HNORMAL MAINTENANCE LABOR,12X,F14.1,10H MAN-HR/YR
     X/23X,26HCASTINGS REPLACEMENT LABOR,10X,F14.1,10H MAN-HR/YR
     X/23X,28HREFRACTORY REPLACEMENT LABOR,8X,F14.1,10H MAN-HR/YR
     X   )
      WRITE(IO,9250)
 9250 FORMAT(1H0/29X,43H*** MHF CAPITAL COST BREAKDOWN, DOLLARS ***
     X // 55X, 7HONE MHF , 13X,9HALL MHF'S  )
```

```
      WRITE(IO,9260) CCI,CCIAL,BGC,BGCAL,CLD,CLDAL,EFC,EFCAL,
     X    TCC,TCCAL
 9260 FORMAT(19X,22HINSTALLED CAPITAL COST , 1X, 2F21.0
     X/19X,13HBUILDING COST,10X,2F21.0
     X/19X,9HLAND COST ,14X,2F21.0
     X/19X,15HENGINEERING FEE,8X,2F21.0
     X/19X,18HTOTAL CAPITAL COST,5X, 2F21.0 )
      WRITE(IO,9270)
 9270 FORMAT(1H0/35X,32H*** MHF TOTAL COST BREAKDOWN *** /
     X/38X,58H$/YR,ONE MHF    $/YR,ALL MHF'S    $/TON DRY SOLIDS    PERCENT
     X       )
      WRITE(IO,9280) TCY,TCYAL,TCYPT,TCYPC,RPY,RPYAL,RPYPT,RPYPC,AMSY
     X,AMSYA,AMYPN,AMSYP,FUY,FUYAL,FUYPT,FUYPC                    ,POY ,POYAL
     X,POYPT,POYPC
      WRITE(IO,9281) OLY,OLYAL,OLYPT,OLYPC,ANMY,ANMYA,ANYPN
     X,ANMYP,RMY,RMYAL,RMYPT,RMYPC                         ,TCST,TCSTA,TCTPN,TCSTP
 9280 FORMAT (7X,21HTOTAL CAPITAL CHARGES,10X,F10.0,F16.0,F17.2,F14.2
     X/7X,17HREPLACEMENT PARTS,14X,F10.0,F16.0,F17.2,F14.2
     X/7X,22HMATERIALS AND SUPPLIES,9X,F10.0,F16.0,F17.2,F14.2
     X/7X,4HFUEL,27X,F10.0,F16.0,F17.2,F14.2
     X/7X,5HPOWER,26X,F10.0,F16.0,F17.2,F14.2)
 9281 FORMAT(7X,15HOPERATING LABOR ,16X,F10.0,F16.0,F17.2,F14.2
     X/7X,24HNORMAL MAINTENANCE LABOR,7X,F10.0,F16.0,F17.2,F14.2
     X/7X,29HREPLACEMENT MAINTENANCE LABOR,2X,F10.0,F16.0,F17.2,F14.2
     X/7X,10HTOTAL COST,21X,F10.0,F16.0,F17.2,F14.2
     X     )
  200 WRITE(IO,400)
  400 FORMAT(1H1)
      RETURN
      END
      SUBROUTINE GETDH(DH,T1,T2)
      DIMENSION DH(6)
      DH(1) = .368*(T2-T1) - 148.4*ALOG(T2/T1) -32000.*(1./T2-1./T1)
      DH(2)=1.102*(T2-T1)-66.2*(SQRT(T2)-SQRT(T1)) + 416.*ALOG(T2/T1)
      DH(3) =.36*(T2-T1)-10.75*(SQRT(T2)-SQRT(T1)) + 47.8*ALOG(T2/T1)
```

```
      DH(4)=.338*(T2-T1)-123.8*ALOG(T2/T1) - 41400.*(1./T2-1./T1)
      DH(5)= .1875*(T2-T1) +.472E-5*(T2**2-T1**2)+13360.*(1./T2-1./T1)
      DH(6)=.219*(T2-T1)+.171E-4*(T2**2-T1**2)-.293E-8/3.*(T2**3-T1**3)
      RETURN
      END
      SUBROUTINE LOCAT ( Y,YT,NY,IERR,ISUB )
C
C     ROUTINE TO FIND ISUB  S.T.
C      YT(ISUB).LE. Y .LT. YT(ISUB+1)
C      IF   IERR = 1 , O.K.
C                = 2 , EXTRAP HI
C                = 3 , EXTRAP LO
C                = 4 , Y TO LARGE
C                = 5 , Y TO SMALL
C
      DIMENSION  YT(1)
      IERR = 1
      ISUB = 1
      R =  ( YT(NY)-YT(1))/ 3.
      IF ( Y - (YT(1)-R)) 9,9,10
    9 IERR = 5
      RETURN
   10 IF ( Y - (YT(NY)+R)) 20,19,19
   19 ISUB = NY - 1
      IERR = 4
      RETURN
   20 IF ( Y - YT(1)) 29,30,30
   29 IERR = 3
      RETURN
   30 NY1 = 2
      IF ( NY-12) 50,49,49
   49 DO 40 I = 7,NY,7
      IF ( Y - YT(I) ) 50,80,40
   40 NY1 = I+1
   50 DO 60 I = NY1,NY
```

```
      IF ( Y-YT(I)) 70,60,60
   60 CONTINUE
      ISUB = NY-1
      IERR = 2
      RETURN
   70 ISUB = I - 1
      RETURN
   80 ISUB = I
      IF (I - NY) 85,81,85
   81 ISUB = ISUB-1
   85 RETURN
      END
      FUNCTION AMAX1(X,Y)
      IF(X-Y) 2,1,1
    1 AMAX1 = X
      GO TO 5
    2 AMAX1 = Y
    5 CONTINUE
      RETURN
      END
/*
//S2   EXEC AFLINK
//G.SYSABEND DD SYSOUT=A
//G.SYSIN  DD *
C H O N S   CO2 H20 O2  N2  SO2
    95.        98.       112.       125.       126.       140.
   145.       166.       187.       193.       208.       225.
   256.       276.       288.       319.       323.       351.
   364.       383.       411.       452.       510.       560.
   575.       672.       760.       845.       857.       944.
   988.      1041.      1068.      1117.      1128.      1243.
  1260.      1268.      1400.      1410.      1483.      1540.
  1580.      1591.      1660.      1675.      1752.      1849.
  1875.      1933.      2060.      2084.      2090.      2275.
  2350.      2464.      2600.      2860.      3120.
```

```
      6.75           6.75           6.75           7.75           6.75           6.75    99920010
      7.75           7.75           7.75           9.25           7.75           9.25    99920020
      9.25          10.75           9.25           9.25          10.75           9.25    99920030
     10.75           9.25          10.75          10.75          10.75          10.75    99920040
     14.25          14.25          14.25          16.75          14.25          14.25    99920050
     16.75          14.25          18.75          16.75          14.25          18.75    99920060
     16.75          20.25          16.75          18.75          20.25          16.75    99920070
     22.25          18.75          20.25          16.75          18.75          22.25    99920080
     20.25          18.75          20.25          22.25          18.75          20.25    99920090
     22.25          20.25          22.25          22.25          22.25                   99920100
      6       7      8       6      9      10      7       8      9       6      10     799930010
      8       6      9      10      7      11      8      12      9      10      11    1299930020
      6       7      8       6      9      10      7      11      6       8      12     799930030
      9       6     10       8      7      11      6       9      8      12      10     799930040
      9      11     10       8     12      11      9      12     10      11      12      99930050
              CHECKOUT OF SAMPLE INPUT                               1                00001000
     1000.          30.            70.          10000.          18.            6.     00001001
      4.                   5                                                          00001002
C     .55     H     .074    O     .334    N     .031    S     .011                    00001003
     25.            7.                    1    FUEL OIL    20000.          .025       00001004
     .01          4.0            4.5          4.25          5.00            .4        00001005
     75.        36000.           .7          300.                                     00001006
     60.          800.         400.           70.                                     00001007
     1.0           .8            .6                                                   00001008
    20000.          25.          5.                   5                               00001009
C     .861    H     .103    O     .008    N     .001    S     .027                    00001010
     100.           5.           50.          5000.                                   00001011
     24.            5.           1.           1.                                      00001012
CHECKOUT OF NCASE EQUAL TO ZERO .                                                     10000001
                17.1           67.0       10000.          29.2            .5          10000002
       .5                  5                                                          10000003
C      0.55   H      0.074 O      0.334 N      0.031 S      0.011                     10000004
 NATURAL GAS    14.3                     6 2228.33333                                 10000005
    100.        30000.           0.          330.                                     10000006
     57.          700.         540.           70.                                     10000007
```

```
      1.0             .5              .5                                                     10000008
     20880.          25.              0.                 4                                   10000009
C      .739   H       .237   O        .003   N       .021                                    10000010
      170.            0.             65.            6265.                                    10000011
/*                                                                                           99999999
```

1 Accession Number	2 Subject Field & Group	
W	05 D	**SELECTED WATER RESOURCES ABSTRACTS** INPUT TRANSACTION FORM

5 *Organization*

Rocketdyne, a Division of North American Rockwell Corporation
Canoga Park, California 91304

6 *Title*

COMPUTERIZED DESIGN AND COST ESTIMATION FOR MULTIPLE-HEARTH SLUDGE INCINERATORS

10 *Author(s)*

Unterberg, Walter
Sherwood, Robert J.
Schneider, George R.

16 *Project Designation*

FWQA Contract 14-12-547, Project No. 17070 EBP

21 *Note*

22 *Citation*

23 *Descriptors (Starred First)*

*Computer Programs, *Cost Estimate, Capital Costs, Operating Costs

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*Sewage Sludge, *Multiple-Hearth Furnace, *Incineration, *Design, Heat Balance, Mass Balance, Fuel Consumption, Power Consumption, Maintenance Costs, Hearth Replacement

27 *Abstract*

A digital computer program was developed for the preliminary design and cost estimation of an optimum multiple-hearth-furnace system for sewage sludge incineration. The program was primarily based on field data from nine operating plants, each having one to four furnaces. The individual furnaces covered a range in capacity from 200 to 4500 lb dry solids per hour, in number of hearths from 5 to 11, in outer diameter from 6 to 22 feet, and in hearth area from 85 to 2327 square feet. Operating schedules and thermal cycling were considered, the field data were correlated by least-square curve fits, and costs were normalized to 1969 dollars. The computer program provides the number, dimensions and ratings of components; expenditures of labor, fuel and power; and all the cost elements for an incineration system which is to process a given flow of sludge having specified characteristics. Cost breakdowns are calculated for capital, total cost per annum and total cost per ton dry solids incinerated. The computer program may also be used for the thermal analysis (air and fuel requirements, heat balance, and mass balance) of a multiple-hearth furnace incinerator without design and cost features. (Unterberg - Rocketdyne)

Abstractor Walter Unterberg | *Institution* Rocketdyne, A Division of North American Rockwell Corp.

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