AIR POLLUTION ASPECTS

OF

ODOROUS COMPOUNDS

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Prepared for the
National Air Pollution Control Administration
Consumer Protection & Environmental Health Service
Department of Health, Education, and Welfare
(Contract No. PH-22-68-25)

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September 1969

FOREWORD

As the concern for air quality grows, so does the concern over the less ubiquitous but potentially harmful contaminants that are in our atmosphere. Thirty such pollutants have been identified, and available information has been summarized in a series of reports describing their sources, distribution, effects, and control technology for their abatement.

A total of 27 reports have been prepared covering the 30 pollutants. These reports were developed under contract for the National Air Pollution Control Administration (NAPCA) by Litton Systems, Inc. The complete listing is as follows:

Aeroallergens (pollens)
Aldehydes (includes acrolein
  and formaldehyde)
Ammonia
Arsenic and Its Compounds
Asbestos
Barium and Its Compounds
Beryllium and Its Compounds
Biological Aerosols
  (microorganisms)
Boron and Its Compounds
Cadmium and Its Compounds
Chlorine Gas
Chromium and Its Compounds
  (includes chromic acid)
Ethylene
Hydrochloric Acid
Hydrogen Sulfide
Iron and Its Compounds
Manganese and Its Compounds
Mercury and Its Compounds
Nickel and Its Compounds
Odorous Compounds
Organic Carcinogens
Pesticides
Phosphorus and Its Compounds
Radioactive Substances
Selenium and Its Compounds
Vanadium and Its Compounds
Zinc and Its Compounds

These reports represent current state-of-the-art literature reviews supplemented by discussions with selected knowledgeable individuals both within and outside the Federal Government. They do not however presume to be a synthesis of available information but rather a summary without an attempt to interpret or reconcile conflicting data. The reports are

necessarily limited in their discussion of health effects for some pollutants to descriptions of occupational health exposures and animal laboratory studies since only a few epidemiologic studies were available.

Initially these reports were generally intended as internal documents within NAPCA to provide a basis for sound decision-making on program guidance for future research activities and to allow ranking of future activities relating to the development of criteria and control technology documents. However, it is apparent that these reports may also be of significant value to many others in air pollution control, such as State or local air pollution control officials, as a library of information on which to base informed decisions on pollutants to be controlled in their geographic areas. Additionally, these reports may stimulate scientific investigators to pursue research in needed areas. They also provide for the interested citizen readily available information about a given pollutant. Therefore, they are being given wide distribution with the assumption that they will be used with full knowledge of their value and limitations.

This series of reports was compiled and prepared by the Litton personnel listed below:

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ABSTRACT

Offensive odors provoke people into complaining about air pollution. They may cause both mental and physiological effects such as nausea, headache, loss of sleep, loss of appetite, impaired breathing, and in some cases allergic reactions. Community and personal pride and status may be adversely affected by obnoxious odors in the vicinity. Although some governmental agencies have enacted laws prohibiting air pollution that interferes with the reasonable enjoyment of life and property, no odor pollution standards have been established.

The most offensive odors come from kraft paper mills, animal rendering plants, chemical plants, petroleum refineries, diesel engines, sewers and sewage treatment plants, and metallurgical plants. Other sources include industrial, domestic, and natural odors. These smells often pollute an area 10 to 20 miles from the source.

Several methods have been developed for abating most odor pollution problems. The most generally accepted method is incineration at the source. However, this may be supplemented or replaced with any of several other methods such as adsorption, chemical scrubbing, containment, process changes, and masking or counteracting the odors.

Economically, odor pollution depresses property values. The cost of abatement depends on the odor pollution problem and the source.

The human nose is the only reliable detector, and several laboratory and field methods have been developed to quantify human observations.

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1. INTRODUCTION

Odorous compounds may have pleasant or unpleasant odors: an odor which is quite acceptable to one person may be unacceptable to another person. Although the quality of an odor is highly subjective, all healthy people are usually aware of odors and generally agree that some odorous compounds are obnoxious. Some of these offensive odors can be detected when the odorant is present in very low concentrations. For these reasons, malodors are one of the first manifestations of air pollution, and they frequently arouse extreme emotional reactions in people. Offensive odors are capable of producing nausea, vomiting, and headache; curbing the appetite, impairing nutrition, and curtailing water intake; disturbing sleep; upsetting the stomach; hampering proper breathing; offending the senses; and interfering with enjoyment of property. Most of all, bad odors can mar good dispositions and provoke emotional disturbances, mental depression, and irritability.[126]

Sociologically, such noxious odors can ruin personal and community pride, interfere with human relations in various ways, discourage capital improvements, lower socio-economic status, and damage a community's reputation. Economically, they can stifle growth and development of a

community. Both industry and labor prefer to locate in a desirable area in which to live, work, and play; and the natural tendency is to avoid communities with obvious odor problems. Tourists also shun such areas. The resulting decline in property values, tax revenues, payrolls, and sales can be disastrous to a community.[126]

No instrument has been developed with the sensitivity and versatility of the human nose for odor detection. Therefore, the methods currently used for odor measurement involve personal judgments by one or more people; results obtained are expensive and lack the desired precision.

The mode of expressing observation results is strictly of a qualitative nature. It is based largely upon the olfactory sense without any guide beyond human ability to associate and describe personal reaction. As a result, odors are often given such descriptive terms as dead-cat, wet-dog, manurial, rotten-egg, spoiled-fish, and others. In addition, the intensity of the odor is often rated on an arbitrary scale of 1 to 5. Such a system, of course, depends to a great degree upon the acuity of the observer's nose, his past experiences, and his ability to describe his reaction accurately. The most useful observation from an engineering point of view is to measure the number of dilutions which are necessary to reduce the odorant to the odor

threshold concentration.

Odor may be defined as the sensation of smell perceived as a result of olfactory stimulus.[65] An odorant is a substance or mixture of substances that produces the sensation of smell.[65]

The scope of this report is limited to the odor per se, not the toxic or chemical aspects of odorants. The reader is referred to the companion reports of this series for the toxic and chemical aspects of some odorous substances, such as hydrogen sulfide, aldehydes, chlorine, hydrochloric acid, ammonia, and ethylene.

2. EFFECTS

2.1 Effects on Humans

To keep alive man must breathe. A single sniff of air may delight him with the perfume of vanillin, may nauseate him with a fecal odor, may warn him of the presence of toxic quantities of hydrogen sulfide, or may start his digestive juices flowing with the aroma of a broiling steak. Thus, odors may affect man in various ways, depending not only on the characteristics of the odor, but also on the particular man and his environment.

2.1.1 Characteristics of Odors

2.1.1.1 Odor Intensity

The human nose is an extremely sensitive gaseous detector. It can respond to thousands of different odor stimuli and detect both low and high concentrations of gaseous materials simultaneously. Moreover, the odorants may originate from sources at relatively great distances away. The intensity of the odor is defined as the numerical or verbal indication of the strength of an odor.[294]

Experimental findings on discerning odor intensity show that an average observer can distinguish between three intensities--weak, medium, and strong--whereas a trained observer may distinguish between five degrees of intensity,[294]

and an expert can distinguish six.[190] Since 1920, experts

have been rating the intensity of various odors by using the

following scale:

Odor Intensity	Expert Description[140]
0	No odor
1	Very faint
2	Faint
3	Easily noticeable
4	Strong
5	Very strong

Trained observers have used[290,294] the following

scale to determine the odor intensity of tobacco smoke, as

well as of domestic and industrial odors:

Odor Intensity	Odor Description[22]
0	A concentration of an odorant which produces no sensation.
1	Concentration which is just detectable (the threshold dilution).
2	A distinct and definite odor whose unpleasant characteristics are revealed or foreshadowed (the recognition threshold).
3	An odor strong enough to cause a person to attempt to avoid it completely.

4   An odor so strong as to be overpowering and intolerable for any length of time.

The sensation of intensity of an odor varies exponentially with the concentration of the odorant. This phenomenon is described by the well-known Weber-Fechner Psychophysical Law, which states that the intensity of the sensation is proportional to the logarithm of the strength of the stimulus. For the sensation of odor this may be expressed as

$$I = k \ln C$$

where I is the intensity of the odor sensation

k is a constant

and C is the concentration of odorant.

The data for three odorants, ethyl mercaptan, butyl thioether, and crotonaldehyde, follow this law over extremely large changes in concentrations. The range of intensity from 0 to 5 covers eight log cycles for ethyl mercaptan, six for butyl thioether, and four for crotonaldehyde.[36]

The concentration of odorant that just gives an intensity of zero may be defined as the detection threshold concentration.[127,217] However, this odor threshold concentration is more commonly defined as the minimum concentration which

will result in the stimulation of the olfactory nerves. All people do not have the same sensitivity for detection of odors.[190] Therefore, an odor panel may be used to determine the odor threshold concentration.[26] As a result, the odor threshold may be reported as the "effective dosage" where 100 percent (ED_{100}), 50 percent (ED_{50}), or 0 percent (ED_0) of panelists perceive the odor. ED_{50} is the most commonly used. Tests are usually conducted to eliminate persons either highly sensitive or insensitive to odors from odor panels. (These tests are described in Section 6 .)

Two other bases of determining odor concentrations have been used: a recognition threshold concentration--the concentration at which the odor quality can be recognized; and the objectionability concentration--the concentration where the odor becomes objectionable. Leonardos et al.[154] have argued that the recognition sensation is more reproducible than the detection sensation.

Unfortunately, odor threshold measurements depend largely on the purity of the odorant. Therefore, odor threshold concentrations of "pure" odorants vary widely, often overlapping both detection and recognition threshold concentrations. For example, the reported odor threshold concentrations of hydrogen sulfide as shown in Table 1,

Appendix B, vary from 0.65 to 1,400 $\mu g/m^3$. Odor recognition threshold concentrations of odorants are listed in Table 2, Appendix B.

The intensities of a mixture of odorants may be independent, counteractive, additive, or synergistic.[236] For example, if odorants A and B are mixed, the odor intensity (I) may be

Independence
$$I_{AB} = k \ln (C_A \text{ or } C_B)$$

Counteraction
$$I_{AB} < k \ln (C_A \text{ or } C_B)$$

Addition
$$I_{AB} = k \ln (C_A + C_B)$$

Synergism
$$I_{AB} > k \ln (C_A + C_B)$$

Mixtures of butanol and pyridine showed an additive effect on the odor intensity at the odor threshold, whereas the addition of p-cresol to the mixture showed a synergistic effect, as shown in Table 3, Appendix B.

Tkach[281] reported that the odors of acetone and acetophenone are additive, and Stayzhkin[257] reported that the odors of hydrochloric acid and chlorine are additive.

Horstman et al.[116] have listed some of the factors which reportedly influence the olfactory sensitivity:

(1) The odor sensitivity of the individual observer varies from day to day, but the overall sensitivity of a group of observers is reasonably constant.

(2) The sense of smell becomes rapidly fatigued, though fatigue for one odor does not necessarily affect the perception of dissimilar odors.

(3) Responses to odors are not completely objective since psychological responses vary in different observers. What is unpleasant to one observer may be quite acceptable to another, and so may not be noted.

(4) The sensitivity of observers varies widely; some have extreme sensitivity while others are incapable of smelling an odor. The age of the observer seems to have an effect on sensitivity: sensitivity reaches a maximum at puberty and decreases with age.

(5) Meteorological factors influence reported odor levels; wind speed and vertical temperature gradient influence the dilution of odors. Temperature and humidity affect odor perception, but there is considerable disagreement about their precise influence.

2.1.1.2 Odor Quality

Odor quality is a verbal description of the odor. The quality may be described in terms of such familiar

odorants as coffee, onions, lemons (characteristic odors),

or by associating an unfamiliar odor with a familiar odor.

The observer often does not possess the vocabulary to des-

cribe the odor he smells. Summer[272] suggests that there may

be 2,500 olfactory receptors, each capable of detecting a

different quality of odor, and the combination of these

odors may produce hundreds of thousands of odor qualities.

As a result of the complexity of describing odors, various

systems have been devised to classify the odor quality, thus

providing an observer with a vocabulary for odor description.

Gruber[96] reported a "clock" chart attributed to Dean Foster.*

This chart is presented in Figure 1, Appendix A.

McCord and Witheridge[170] have listed three different

systems for classifying odor quality, as follows:

A.   Zwaardemaker's classification has nine categories:

(1)   Ethereal or fruity: characteristic in general
of fruits and due in most cases to the presence of various
esters; includes also beeswax and certain ethers, aldehydes,
and ketones

(2)   Aromatic

    a.   Camphoraceous: borneol, camphor, eucalyp-
         tole

    b.   Spicy: eugenol, ginger, pepper, cinnamon,
         cassia, mace

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    c.   Anise-lavender: anethole, lavender, menthol, thymol, safrole, peppermint

    d.   Lemon-rose: geraniol, citral, linalyl acetate, sandalwood

    e.   Amygdalin: benzaldehyde, oil of bitter almond, nitrobenzene, prussic acid, salicylaldehyde

(3) Fragrant or balsamic

    a.   Floral: jasmine, ilang-ilang, orange blossom, lilac, terpineol, lily of the valley

    b.   Lily: tuberose, narcissus, hyacinth, orris, violet, ionone, mignonette

    c.   Balsamic: vanillin, piperonal, coumarin, balsams of Peru and Tolu

(4) Ambrosial: musk and amber. Present in the flesh, blood, and excreta of certain animals

(5) Alliaceous or garlic: onion, garlic, and many compounds of sulfur, selenium, tellurium, and arsenic

    a.   Alliaceous: hydrides of sulfur, selenium, and tellurium, mercaptans, organic sulfides, thioacetone, asafetida

    b.   Cacodyl fish odors: hydrides of phosphorus and arsenic, cacodyl compounds, trimethyla-mine

    c.   Bromine odors: bromine, chlorine, quinone

(6) Empyreumatic or burnt: as in tar, baked bread, roasted coffee, tobacco, benzene, naphthalene, phenol, and products of the dry distillation of wood

(7) Hircine or goaty: due in the case of this animal to the caproic and caprylic esters contained in the sweat and typified also by perspiration and cheese

(8) Repulsive: such as given off by many of the narcotic plants and by acanthus

(9) Nauseating or fetid: such as given off by products of putrefaction (feces, etc.) and by certain plants

B. Henning's odor classification lists only six basic qualities:

(1) Spicy: conspicuous in cloves, cinnamon, nutmeg, etc.

(2) Flowery: conspicuous in heliotrope, jasmine, etc.

(3) Fruity: conspicuous in apple, orange oil, vinegar, etc.

(4) Resinous: conspicuous in coniferous oils and turpentine

(5) Foul: conspicuous in hydrogen sulfide and products of decay

(6) Burnt: conspicuous in tarry and scorched substances

C. The Crocker-Henderson classification is represented by four fundamental odor sensations:

(1) Fragrant or sweet

(2) Acid or sour

(3) Burnt or empyreumatic

(4) Caprylic, goaty, or oenanthic

These four fundamental odor sensations were ranked in intensity from 0 to 8 and expressed as four-digit numbers for each odorant. On this basis a substance without odor

would appear as 0000. Ethanol appears as 5414. The first digit represents the fragrant character; the second digit, acid; the third, burnt; and the fourth, caprylic. The odor standards listed in Table 4, Appendix B, serve to illustrate the numerical method of coding the odor quality.

Amoore[12] has determined the number of fundamental odors by arranging some 600 compounds into groups with similar odors. The odors that occurred most frequently were assumed to be the primary odors--the first seven odors listed in Table 5, Appendix B.

Moncrieff[190] has listed the odor quality of a large number of odorants. A representative number of these have been listed in Table 6, Appendix B.

The untrained observer has difficulty using any of the above systems for odor description and must resort to using common terms to describe the odor. Horstman et al.[116] allowed student observers to describe the odor quality in their own words and then reduced the odor qualities to the following:

Code	Odor Description
0	flowers
1	pulp mill
2	smoke, woodsmoke

3	burning leaves
4	mustiness
5	gasoline
6	rendering plant
7	rubbish burning
8	animal odors
9	miscellaneous odors
none	no odor

The odor quality may change with dilution. In mixtures of odorants this may be because one odorant is more pervasive than the other odorant. Single component systems may also exhibit quality changes on dilution. The reason for this is not fully understood.[272]

2.1.1.3 <u>Odor Acceptability</u>

An odor may be either acceptable or unacceptable depending on its intensity and quality. The odors of new-mown hay or honeysuckle and roses are indicative of acceptable odors at normal concentrations. However, obnoxious odors may be unacceptable at much lower concentrations and become acceptable only at very low intensities. At high intensities the normally acceptable perfumes can be unacceptable.[272]

Moncrieff[191] studied the acceptability of 132 odors and ranked them according to their acceptability. Those

compounds found least acceptable were mercaptans, sulfides, disulfides, amines, and aldehydes. He also observed that various people have odor preferences depending on age, sex, vocation, and environment. From these observations he wrote 124 rules of odor preference.

2.1.1.4 Odor Pervasiveness

Odor pervasiveness is the ability of an odor to pervade a large volume of air and still continue to possess a detectable intensity. Nadar[195] referred to it as odor potential or threshold dilution ratios. An odor unit* has been defined to describe the number of dilutions necessary to reduce the odor to the threshold concentration. A pervasive odor is one whose odor intensity changes very little on dilution. Mathematically, the pervasiveness is indicated by the slope (value of k) in the Weber-Fechner equation (Section 2.1.1.1). The pervasiveness increases as the value of k decreases. Of the three odorants mentioned in Section 2.1.1.1, ethyl mercaptan is more pervasive than butyl thioether, which in turn is more pervasive than crotonaldehyde.

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*The number of odor units is equal to the volumes (standard cubic feet) of air necessary to dilute the concentration of odorant in one volume (standard cubic foot) of air to the threshold concentration. For example, 100 odor units/scf require 99 cubic feet of dilution air to reduce the odorant in one cubic foot of air to the threshold concentration.

2.1.2 Physiological and Psychological Aspects of Odors

The influence of odors on the health and comfort of man is difficult to prove. Odors in themselves are usually not the cause of organic disease. However, the odorant may incite an allergic response. It is obvious that some highly toxic substances, such as hydrogen sulfide, are associated with offensive odors; but the dangerous properties of these types of substances do not derive from the odor itself. In fact, odor is valuable in serving as a warning of the presence of an injurious gas. Odor bears no relationship to toxicity, and some poisonous gases are odorless or have a rather pleasant odor. McCord and Witheridge[170] have indicated that foul odors may cause poor appetite for food, lowered water consumption, impaired respiration, nausea and vomiting, insomnia, and "mental perturbation."

Winslow and Palmer[301] exposed human subjects* to the ordinary air of an unventilated room containing whatever polluting substances were given off by their bodies and garments. These persons were exposed 4 to 7 hours daily. The chief findings were that there were differences in food consumption on test days and control days. About 5 percent more food was consumed when the supply of air was fresh. The authors concluded that breathing the stale air diminished food intake.

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*Number of persons exposed was not reported.

In another study, Winslow and Herrington[300] exposed
eight young men four or five mornings each week for several
winter months to an odor recognized as heated house dust.
The test odor was emitted into the room slowly so that sub-
jects were unaware of which days were test days. Olfactory
fatigue prevented them from perceiving the odor, while an
observer entering the test room would immediately recognize
the odor. The consumption of the noon meal was evaluated
as part of the test. There was no difference in the consump-
tion of potato salad on test and control days, but macaroni
and cheese showed a 13 percent rejection on odor test days.
As the test progressed, this rejection decreased to 6 percent.

McCord and Witheridge[170] report that odors appearing
in drinking water immediately cause a community to resort to
bottled drinks. However, at sulfur spring spas, people will
joyously drink the odoriferous liquid, at times relying on
the odors themselves to restore health.

McCord and Witheridge[170] also point out that respira-
tion may be impaired. When an unwanted odor is in the air,
the tendency is to engage in two or three deep appraising
sniffs. If the odor is deemed offensive, the person will
resort to shallow, slow breaths or mouth breathing to avoid
the odor. Where the odor is widespread in a community,

windows and doors may be sealed in an attempt to keep out the odor. The investigators state that in some cases odors may produce nausea and vomiting. Occasionally, the presence of continuous odors may induce persistent vomiting.

The most frequent effects of odors on human health, according to McCord and Witheridge,[170] are insomnia and mental perturbation. They point out that many people regularly have difficulty sleeping and that any disturbance may prevent sleep, often after the person has been aroused from a deep sleep by an offensive odor. They admit that the extent to which odors contribute to loss of sleep cannot be proved; but they assert that odors do cause loss of sleep and, therefore, affect the health of a community. Long continuous exposure to offensive odors arouses a person to anger. Otherwise calm persons may become mildly maniacal, hysterical, and capable of carrying out acts entirely foreign to their usual natures. Thus odors may affect the mental health of a person.

Petri[213] states that malodorous substances may cause headaches, nausea, and similar phenomena. Even inherently fragrant substances, such as flavorings and chocolates, can cause considerable discomfort with protracted exposure, or at high concentrations. According to Petri, the psycho-logical effects of an odor are highly subjective. Thus, the

nuisance value of an odor depends on the attitude of the person, his disposition, and the time of day.

Air pollution in the form of malodors has been cited as the reason for certain lawsuits, picketing, rioting, and even forceful closure of plants.[124]

2.1.2.1 Public Opinion

Opinion surveys often place offensive odors at the top of the list of air pollutants. However, this is not always the case but depends largely on the type of pollution within the city. Table 7, Appendix B, shows the results of some surveys which have been made. The data presented in Table 7 were taken from opinion surveys in which questions were asked such as "What do you think the words 'Air Pollution' mean to most people in this area?" Possible multiple choice answers were listed as "frequent bad smells," "too much dust," "frequent haze," etc. Jonsson[136] points out that the results of any opinion survey depend on how the question is worded and the groups surveyed--their socio-economic status, education, age, and sex. Therefore, it is difficult if not impossible to compare results of surveys taken in different areas using different questionnaires. Moreover, the problems of measuring reactions to odors have not been solved, nor have methods been developed for ade-quately measuring the odor exposure in an area. Some

examples of reactions to odors and attempts to assess the odor pollution effect on the health and welfare of the population are presented below.

Where a large percentage of the people are affected, concern about odors is often high. The frequent bad smells emanating from a pulp mill in Lewiston, Idaho--about 4 miles upwind from Clarkston, Wash.--resulted in a petition signed by 495 of the 7,000 residents of Clarkston. It read, in part, "This contamination of our air and its odor affects us from headaches, watery eyes, runny noses, and breathing difficulties, to paint corrosion or other property damages. This area has put up with this problem for 17 years, which is long enough." One resident states, "I believe the horrible, rotten stench coming from the smokestacks of the Potlatch pulp mill here in Lewiston is killing me; I am afraid to remain here; I don't want my family or myself to die premature deaths."[6]

A cooperative study[172,268] of the air pollution problem in the Clarkston-Lewiston Valley revealed that malodorous gases, including hydrogen sulfide, organic mercaptans, and organic sulfides emitted from the kraft pulp mill, were the major air pollution problem. Studies showed that 12 times during the 5-year period 1957 to 1961 (or

approximately twice each year) meteorological conditions
existed which may have caused air pollution episodes
lasting 48 hours or more.

Terre Haute, Ind., is another city where public
opinion has run high against odor pollution. Complaints of
odors causing health and property damage were received by
the mayor, the police, the Board of Health, and U.S. Public
Health Service representatives. The number of complaints
received in a 2-week period are given in Table 8, Appendix B.
These included claims of adverse effects on health (referring
to nausea, vomiting, headaches, diarrhea, and throat irrita-
tion), with or without additional complaints referring to
property damage (paint damage).[7]

A brief investigation[7] by a Public Health Service
physician failed to show any increase in illnesses being
treated by local physicians or admissions to the hospital.
However, when the Public Health Service physician and an
epidemiologist toured the affected areas, they themselves
experienced nausea and throat irritation, accompanied by the
obnoxious odors. Interviews with the complainants revealed
that

(1) Two out of three who complained were women.

(2) Nineteen of twenty persons interviewed reported
experiencing symptoms associated with odor air pollution.

Of a total of 65 individuals of all ages in the 20 house-
holds studied, 37 to 57 percent were reported to have
symptoms.

(3) Affected individuals usually complained of more
than one symptom: 13 complained of nausea, five complained
of being awakened at night, five reported burning eyes, and
four reported shortness of breath. Other symptoms reported
were cough, headache, anorexia, acute asthma attack,
nervousness, weight loss, diarrhea, fever, gagging, and
heaviness in the chest.

(4) Eight of twenty did not list any gastro-
intestinal symptoms.

(5) The symptoms were usually short in duration and
ceased when the odor became weaker or disappeared.

Ten local physicians who were consulted agreed that
the city's malodorous air caused nausea, sleep disturbances,
loss of appetite, and a distressing physical and emotional
environment in which to live.[7]

Hydrogen sulfide concentration measurements showed
good agreement between its concentration and the odor
episodes. The most likely source was a 36-acre lagoon used
for biodegradation of organic industrial wastes.[7]

Another odor episode occurred in St. Louis, Mo., on
November 24, 1963, during an odor survey of the city. Over

100 complaints were registered with the St. Louis Police Department and Laclede Gas Company before 8:00 p.m. Although odor surveys were taken at 8:00, 10:00, and 12:00 p.m., the exact cause of the trouble was not pinpointed. However, it was postulated that an industrial breakdown or spill must have taken place on the Illinois side of the Mississippi River.[131] Firemen made the odor survey, and their reports of pleasant and unpleasant odors reflect public opinion to some degree. The results of their surveys are given in Table 9, Appendix B.

Huey et al.[118] have studied effects of the day of the week, time of day, temperature, atmospheric pressure, humidity, and wind velocity on the number of complaints received from residents near an animal rendering plant. The odors emitted from the plant were described as offensive, nauseating, repulsive, and repugnant. The data shown in Tables 10-17, Appendix B, indicate that the number of complaints (1) increases on weekends, (2) increases during the day, (3) increases with rising temperature, (4) is higher when atmospheric pressure is above 28.84 inches mercury, (5) increases with decreasing humidity, (6) does not change with wind velocity, and (7) is highest in the summer months.

In its 1960 report, "National Goals in Air Pollution Research," the Surgeon General's ad hoc task group on air

pollution research goals states:[198] "The aspects of air pollution which are most apparent and of greatest personal concern to the individual are irritation to the eyes, nose, and throat; malodors; and reduction of visibility. The pollutants responsible for these effects are undesirable, whether or not they cause long-range health effects or economic losses, because they constitute an annoyance to people. The nuisance of these effects, together with those related to soiling, give rise to the greatest number of complaints received by air pollution control authorities. There is no doubt that a person's well-being is eventually affected by exposure to these sensory annoyances and that this may result in economic loss."

2.1.2.2 Allergies and Odors

Odors may cause attacks of asthma or other allergic conditions. In 1882 Salter[246] described asthmatic attacks produced by effluvium from hay, smell of mustard, odors from skins of animals, smell of a lucifer match, odors from fermenting foods, odors from cheese, smell of violets, burning wood, smoky air, sulfur fumes, smell of paint, foul air in crowded rooms, gas escape, camphor, tobacco smoke, smell of linseed, smell of horses, cattle, dogs, and rabbits. In 1932 Feinberg and Aries[80] described asthma resulting from odors of cooking shrimp, beans, and lentils.

In many cases it is difficult to prove whether an allergic patient was affected by an odor or the odorant substance itself. Odorants from trees, shrubs, flowers, fabrics, animals, and household articles are ordinarily harmless to individuals not subject to allergies. However, these substances can, in small amounts under proper conditions, incite an allergic attack in sensitized individuals.[115]

Horesh[115] has reviewed the importance of nonspecific factors as provocateurs of allergic symptoms. He found odorous agents of etiological significance in asthma, allergic rhinitis, allergic croup and tracheitis, atopic dermatitis, urticaria, allergic headaches, and gastrointestinal allergy.

Odorous substances have been cited as causing allergic symptoms or illnesses by various authorities as follows:

Odorous Substance	Reference
Cleaning fluid	92
Cooking odors	92
Feces	130
Fish	60,64,79,288
Food	40,56,76,106,114,224, 226,240,262,271,275, 311
Formaldehyde	115,226
Fresh paint	59,60,92,279,288
Furniture polish	115

Gasoline	92
Lighter fluid	115
Moth balls	92
Newspaper print	84,115
Oils	33,262
Perfume	310
Rubber	115
Spices	115
Tobacco smoke	92,100,115,237,247, 276
Turpentine	288
Wood smoke	54,66,115,225

A questionnaire was devised by Brown and Colombo[34] to determine the number of their patients whose illnesses were significantly affected by odorants. A series of 200 patients in whom fumes, odors, and smells caused major symptoms was thus collected over a period of 10 years. Substances thought to be responsible were dimethyl sulfide, perfumes, cooking odors, gas, bleaching fluid, soap powders, deodorants, hair tonics, shaving lotions, fresh paint, kerosene, wood smoke, tobacco smoke, cleaning fluids, shoe polish, lighter fluid, spot removers, furniture polish, fluid insecticides, melting ironing wax, sweeping compounds and cedar dusts, freshly printed newspapers and typewriter ribbons, coal smoke from stoves or locomotives, pine wood, turpentine, moth balls, plastic furniture covers, floor wax, carbon paper, asphalt, chlordane, lindane, DDT, and weathered apples. A similar list of odors and fumes which cause directly or nonspecifically allergic reactions was

compiled by Deamer.[54] Included were such items as gasoline
odors, smoke from any source, gas, wood odors, paint odors,
household odors such as ammonia and floor wax, cosmetics,
and food odors.

Food odorants in low concentrations also commonly
excite allergic symptoms. Horesh[112] reported on allergy to
food odors and the role these odors play in the etiology of
infantile atopic dermatitis. Foods most frequently incrimi-
nated were eggs and fish, although chicken, pork, bacon, and
cabbage were also mentioned. Atopic dermatitis was reported
in a series of nine cases--the majority infants, but some,
older children. In these patients the allergic signs and
symptoms were provoked or aggravated by the mere presence
of the foods in the patient's environment.

Urbach[288] reviewed the effect of food odors on
allergic symptoms up to 1941. He reported that allergic
symptoms were elicited from the odors of the following
foods: fish, milk, egg, asparagus, coffee, garlic, onion,
sage, apple, and lemon.

That the odor rather than the pollen can be the
cause of allergic symptoms has been reported by other inves-
tigators. Biederman[28] described effects from a number of
flowers and presented experimental evidence to support his
views that odor, not pollen, was the cause of the symptoms.

Urbach[288] accepted the possibility that pollens head the list of

allergens responsible for most allergic rhinitis, but

called attention to the frequently forgotten fact that

plant odors can also be a cause. Urbach noted cases

in which nasal symptoms or asthma were produced by the

odors from roses, locust trees, linden trees, mock oranges,

carnations, privet, lilies, common elders, lilacs, lilies

of the valley, and violets. He also reported a patient who

developed asthma from the odor of a pine forest, pine needle

extract, and pine soap. Observations by Sticker,[262]

Mackenzie,[160] and Goodale[94] showed that the fragrance of

roses and certain other flowers can cause the symptoms of

hay fever, and experimental evidence was presented to con-

firm the fact that it was the odor and not the pollen that

produced the symptoms. Thus, instead of pollen, volatile

agents from trees, flowers, grass, and weeds may be the

cause of allergic symptoms and may produce their effects in

any season.

Horesh[115] found it impossible to prove whether

allergy is due to the odiferous substances from animal

dander or to some other volatile agent. A certain number

of his patients insisted that they were not bothered by all

dogs but only those that "smell doggy." DeBesche[55] studied

this subject by conducting experiments with the odorous
substance in horse urine. He was able to produce asthmatic
attacks in patients allergic to horses with this odorous
substance under circumstances in which horse hair and horse
dandruff were carefully excluded. DeBesche believed that
volatile allergens other than dander and hair were respon-
sible for some attacks of asthma suffered by persons
sensitive to horses or other animals. He reported patients
with allergic symptoms caused by the odors from cattle, dogs,
cats, monkeys, sheep, goats, hares, rabbits, guinea pigs,
rats, mice, hens, bees, toads, and eels. DeBesche accepted the
possibility that the dander of animals is the most important
carrier of the offending antigen, but believed that the odor
of animals is also an etiological factor. Many persons with
asthma caused by sensitivity to horses, according to
DeBesche, have asserted that it is the odor of the horse
which is the crucial factor, and it was sufficient to come
into the presence of a person who "smells horsey" to provoke
an attack.

Horesh[115] cautions that psychological factors can
incite allergic symptoms, but he believes that psychic
causes of allergic upsets should be accepted only after all
other factors have been considered and excluded. Many

so-called psychic causes for allergic upsets have vanished when odorous substances have been carefully evaluated.

2.1.3 Theories of Olfaction

Since 1870, about 30 theories have been proposed to explain olfaction; an excellent summary up to 1967 has been presented by Moncrieff.[190] These theories are summarized in Table 18, Appendix B. They are based on experimental correlation of odor with such physical and chemical properties as ultraviolet absorption, infrared absorption, Raman shifts, unsaturation, functional grouping, solubility in lipid, solubility in water, volatility, adsorption, oxidizability, and dipole moments. The greatest controversy is whether molecules of the odorant must come in contact with the olfactory receptors or whether the odorants emit waves which stimulate the receptors.[234] Thus, the numerous theories can be grouped into wave theories and contact theories.

Wave Theories. These theories are based on the fact that olfaction can occur at a distance from the odorous substance, and hence the molecules are assumed to emit radiation which travels to the olfactory receptors. These theories contradict two well-established characteristics of odor: namely, that to be odorous a substance must be

volatile and that odor cannot travel where air cannot.

The theory of Beck and Miles[178] deserves individual mention because of its novelty. Essentially this theory proposed that the olfactory apparatus was a tiny infrared spectrophotometer, emitting infrared radiation and measuring its absorption by molecules near it.

Roderick[234] maintains that contact of the odorant molecules with the olfactory receptors is definitely required, and therefore, all of the no-contact or wave theories may be rejected. However, he cautions that investigations should include the effects of radiation on the olfactory apparatus, since rats can detect X-rays by means of the olfactory apparatus.[120]

Contact Theories. Contact theories assume contact of odorant molecules with the olfactory receptors. Roderick[234] has divided these theories into two subgroups based on whether the contacting molecule is thought to stimulate the olfactory receptors by chemical or physical means. The theories involving chemical interaction are mainly ones based on correlations with functional groups. These chemical theories were popular from 1900 to 1920, the period during which data on structure-odor were first being collected. But by 1930 there were sufficient data to

establish that there is no simple relation of odor to molecular structure. Moncrieff[190] and Dyson[69] showed that compounds of very similar structure may have different odors, and compounds of very different structures may have similar odors. For example, the odor of macrocyclic compounds was shown to depend more on ring size than on functional groups, the odor of benzene derivatives depended more on the position of substituents than on their nature, and similar stereoisomers were found to have different odors.

From 1950 on, the major theories proposed recognized that the odor of a molecule could not be directly related to its functional groups but must be related to the molecule as a whole: i.e., odor is a "whole-molecule" property.[110] Beets[24] proposed in 1957 a profile-functional group theory in which odor was determined by two factors: the functional group with the highest hydration tendency determines the orientation of the molecule at the receptor, and the overall form or profile of the molecule also has some effect, which has not been specified.

The two major theories based on odor as a whole-molecule effect are discussed in Appendix C. These are the Dyson-Wright vibrational theory and the Moncrieff-Amoore stereochemical theory. These two theories appear to be the

only significant theories today, and much of the current

literature on theories of olfaction consists of a duel

between them.[234]

2.2 Effects on Animals

2.2.1 Commercial and Domestic Animals

No information on the effect of odor air pollution

on the health and behavior of commercial and domestic

animals was found in the literature reviewed. However,

there is considerable attention given to the sensitivity of

the noses of mammals--particularly of dogs--[169,190] but

these studies do not relate to air pollution.

2.2.2 Experimental Animals

No information was found on the effect of odor air

pollution on the health and behavior of experimental animals.

McCord and Witheridge[170] point out that it is impossible to

determine whether certain odors are repulsive to rats. The

investigators suggest that if left to their own devices,

rats might choose a dunghill in which to nest.

2.3 Effects on Plants

Odors per se have no known effects on plants. How-

ever, many odorous compounds such as sulfur dioxide, ethylene,

and ammonia are phytotoxic. The effects on the plants are

due to toxicity rather than to odor.

2.4 Effects on Materials

Molos[183] reported that obnoxious fishy odors emitted from a soap plant adhered to skin, hair, clothing, automobiles, and other materials for extended periods of time. People who had been in or near the plant could smell the odors miles away for many hours. Clothing required laundering or dry cleaning to completely remove the odor.

2.5 Environmental Air Standards

Stern[260] has listed air quality standards for approximately 100 odorants. Industrial standards for another 250 specific odorants have been listed by the American Conference of Governmental Industrial Hygienists.[46] Air quality standards for these odorous pollutants are based on toxicity rather than odor of the pollutants, and have not, therefore, been included in this report.

Some State, county, and city regulations have tried to limit odor pollution on the basis that air contaminants unreasonably interfere with the comfortable enjoyment of life or property. Those States which list odors specifically as an air pollutant are the following:[23,178]

Alaska	Florida
Arizona	Seminole County
California	Manatee County
Florida	Hillsborough County
Duval County	Orange County
Lake County	

Hawaii	New Hampshire
Iowa	Ohio
Kansas	Oregon
Maine	Rhode Island
Maryland	Texas
Massachusetts	Washington
Michigan	Wisconsin
Montana	

Some States, such as California, have been more aggressive than others in their action to control emissions of odorous compounds. The following California standard[39] for diesel odors and irritation exemplifies this fact:

(a) The average intensity of odor as determined by subjective appraisal shall be less than the intensity from diesel vehicles with horizontal exhaust pipes representative of the diesels in use in 1966 and whose odorant concentrations have been reduced by at least 80 percent.

(b) There shall be no detectable eye, nasal, or throat irritation to at least 75 percent of the panel.

(c) Exhaust odors that are different in quality from characteristic diesel odor shall be less objectionable to the panel than the odor from diesel vehicles with horizontal exhaust pipes representative of the diesels in use in 1966 and whose odorant concentrations have been reduced by at least 80 percent.

(d) The conditions for appraisal are:

1. The odor irritation panel shall consist of not less than 10 persons.

2. Appraisal of odor and irritation shall be made on a vertical plane ten feet distant from the exhaust outlet to either side of the motor vehicle parallel to the longitudinal axis. For vehicles with more than one exhaust outlet, the appraisal shall be made on a vertical plane parallel to the

longitudinal axis at a horizontal distance
ten feet from the midpoint of the exhaust
outlets.

3. The exhaust gas shall be evaluated during
the modes of idle and full throttle
acceleration.

4. Other methods of odor appraisal or measure-
ment may be used if approved by the
Department of Public Health.

In addition, the Los Angeles County Air Pollution
Control District[51] has several rules which limit the
emission of odorous compounds:

Rule 51 limits discharge of any air contaminants
which cause "injury, detriment, nuisance, or
annoyance."

Rule 52 limits the discharge of particulate matter.

Rule 53 limits the discharge of sulfur dioxide.

Rules 56,59,63, and 65 limit the discharge of gaso-
line, petroleum distillate, and petroleum products.

Rule 58 provides for proper incineration.

Rule 62 limits the discharge of hydrogen sulfide
from burning fuels.

Rule 64 limits emissions from animal rendering
plants.

Rule 66 limits emissions from evaporating solvents
and other organic liquids.

3. SOURCES

The most frequently reported sources of obnoxious odors in the ambient air were listed in 1958 by Kerka and Kaiser.[143] These are tabulated in Table 19, Appendix B. In New York State, Hilleboe[108] reported the number of odor sources along with other contaminants. In cities with populations over 5,000, the number of nonindustrial sources of odors (77) exceeded the industrial sources (26). In smaller communities (less than 5,000) the number of non-industrial sources (17) was less than the number of industrial sources (23), as shown in Table 20, Appendix B.

In 1955, the chief public officials responsible for control of air pollution in 67 major cities were surveyed.[211] The results of the survey showed that 78 percent received complaints of odors separately from other air pollution complaints, and 68 percent felt the public interest was increasing because of odor pollution. When asked to list the source of the odors in their communities, their replies were as follows:

Source	Percent*
Chemicals	62
Vehicles	52
Paint and varnish	49

*Percent of questionnaires in which the source was cited.

Food processing	47
Domestic (homes, etc.)	45
Rendering plants	43
Plastics	33
Oil refineries	31
Coke works	31
Rubber	27
Steel	25
Insulation	21
Fish	21
Gas works	19
Pharmaceuticals	19
Soaps and detergents	17
Breweries	15

The odor pollution of an area depends on the odor strength and quality. The odor unit has been defined thus: one odor unit is the amount of odorant necessary to contaminate one cubic foot of clean air to the odor threshold. For any one odorant, the number of odor units can be calculated by knowing the volume of odor released and the odor threshold. For example, dimethyl amine has an odor threshold of approximately 0.5 ppm (1,000 $\mu g/m^3$). A release of 10 pounds of this substance per hour would result in the release of 2,800,000 odor units per minute.[37] This number can then be used in atmospheric diffusion equations to calculate the distance the odor may travel. Any value above one would be detectable. Similar calculations are also useful to engineers in designing systems which will avoid or abate odor pollution. This method has been used by Benforado et al.[26] for the various applications shown in Table 21, Appendix B.

The mixture of two or more odorants may present complicating factors because the odorants may be additive, synergistic, counteractant, or independent.

3.1 Natural Occurrence

Odors are produced in nature primarily from the decomposition of proteinaceous material (vegetable and animal) by bacterial action.[192,212] They develop principally in stagnant and insufficiently aerated water--for example, in swamps and polluted stagnant water.[58,64,212] Odors from these sources, variously described as fishy, aromatic, grassy, and septic, have been reported most often after the peak of the blue-gree algae concentration has passed.[132,173] Dimethyl sulfide and methyl mercaptan either together or separately have been found among the volatile constituents of certain green, brown, and red algae.[132] Methyl sulfide has been found in marine algae; methyl mercaptan has been an odorant of algae; and dimethyl sulfide has been found in certain seaweeds. Microscopic animals also produce odorous compounds. Collins and Gains[47] reported that hydrogen sulfide was one of the odorous constituents of actinomycetes. As a result, the odors emanating from contaminated waters, including the oceans, are usually offensive. These odors may often be accompanied with the offensive odors of dead fish

found on the public beaches. Such an incident occurred in the Los Angeles area in 1964. Ocean water temperatures remained high (greater than 70°F) for several days, causing the "red tide" (plankton) to grow rapidly, thus creating a condition lethal to fish. Millions of fish washed onto the beaches, producing a stench along several miles of public beach. As a result, no people visited the beach for several weeks.

Robinson and Robbins[233] have estimated the annual worldwide production of some odorants. Hydrogen sulfide production in the middle sixties was about 90 to 100 million tons, with 60 to 80 million tons coming from land sources and 30 million tons from ocean areas. Other estimates of these figures ranged as high as 202 million tons from ocean areas and 82 million tons from land areas.[233] Data on background air concentrations of hydrogen sulfide arising from natural sources are scarce. However, concentrations, estimated to be between 0.15 and 0.46 $\mu g/m^3$, are below the odor threshold, or concentrations at which deleterious effects occur. Ammonia is also produced in large quantities by the biological processes,[233] mostly degradation of organic wastes. Approximately 3.7×10^9 tons of ammonia are released into the atmosphere annually.[85] Of this amount, only 4.2×10^6 tons

are emitted to the atmosphere as a result of industrial and urban processes.

Many kinds of fires--such as forest fires, brush fires, and open field burning--also contribute odorants to the environmental air.

The human body is also a source of unpleasant odors. Body odors have been studied extensively by the United States Armed Forces.[282] Some typical odorants collected on charcoal during a 30-day human experiment are given in Table 22, Appendix B.

3.2 Production Sources

Odorants are produced as by-products (usually un-wanted) in many industrial processes. Odorants are emitted during normal operations in the petroleum industry (re-fineries and natural gas plants), petrochemical plant com-plexes, chemical plants, coke-oven plants, kraft paper mills, chemical processing industry, dye manufacture, viscose rayon manufacture, sulfur production, manufacture of sulfur-containing chemicals, iron and metal smelters, cement plants, fertilizer plants, food processing plants, rendering plants, and tanneries.

3.2.1 Petroleum Industry

The stench of crude oil is evident near oil wells,

petroleum refineries, and in recent months, the Santa

Barbara Beach in California (which was contaminated from

an offshore oil well leak).

The main sources of odor pollution in refineries are

untreated gas stream leaks, vapors from crude oil and raw

distillates, and fumes from process and condensate sewers.[214]

The odorous emissions may contain hydrogen sulfide, mercap-

tans, phenolic compounds and naphthenic acids, organic

sulfides, organic amines, aldehydes, and aliphatic or

aromatic compounds.

The Petroleum Committee for the Air Pollution Control

Association[214] has listed the potential sources of odorous

compounds in a refinery as shown in Table 23, Appendix B.

Typical refinery processing systems that produce

malodorous emissions are cracking units, catalytic reforming

units,[177] and sulfur recovery units.[291] The cracking process

tends to convert the sulfur contained in crude oil into hydro-

gen sulfide in the heavier materials and mercaptans in the

gasoline fractions.[294] Measurements made in the El Paso,

Tex., area adjacent to an oil refinery showed the mean

hydrogen sulfide concentration to be 6 $\mu g/m^3$. The concentra-

tion varied from amounts too low to measure to a maximum of

91 $\mu g/m^3$.[5]

The main source of ammonia in oil refineries is from the catalyst regenerators in the catalytic cracking plants. The ammonia releases from oil refineries range up to 54 pounds per 100 barrels of feed.[17]

The ammonia emission from regenerator stacks in catalytic cracking units of Los Angeles area refineries was 4.2 tons per day from fluid bed cracking units and 0.2 tons per day from thermofor units.[17] At the time the data were compiled, there were 18 refineries in the Los Angeles area with a combined capacity of 700,000 barrels of crude oil per day.

In 1960 there were approximately 300 refineries distributed throughout the United States with a crude oil capacity of approximately 10 million barrels per day.[38] By 1969 there were about 263 refineries in the United States with a crude oil capacity of approximately 12 million barrels per day.[273] The States in which the refineries are located and their crude charge capacity in January 1969 are shown in Table 24, Appendix B. The crude capacity of refineries in the United States increased about 10 percent in the three years 1967 to 1969, and it is projected to increase another 10 percent in the next three years (1970 to 1972).[205]

The 14 oil refineries in Oklahoma were reported to cause air pollution problems of smoke, soot, and odors in 11 communities.[170]

Kropp and Simonsen[150] have reported odorous problems arising from fatty acids during grease-making processes, from vapor in asphalt production, and from sulfur oxides in acid treatment of lubricating oil. Mel'ster[176] also reported odor problems arising from asphalt production.

A common method of control of odorous emissions from petroleum plants is combustion of the waste gas. The combustion process oxidizes malodorous sulfides and amines to sulfur oxides and nitrogen oxides, which are also odorants but have a higher threshold odor concentration. Incomplete combustion results in odorous aldehydes.

A number of refineries and natural gas plants have installed units to recover sulfur from hydrogen sulfide. Sulfur plant installed capacities and yearly production rates are shown in Table 25, Appendix B.

Malodorous hydrogen sulfide occurs naturally in many areas associated with natural gas.[212] In some areas--for instance, Alberta, Canada--the sour natural gas can consist of over 50 percent hydrogen sulfide. The natural gas stream is treated to remove the hydrogen sulfide, which is generally

converted to sulfur. Distributing companies which sell natural gas for heating and power generation generally require that its hydrogen sulfide content be less than 23,000 $\mu g/m^3$.[249]

3.2.2 Petrochemical Plant Complexes

Malodorous gases are produced in petrochemical plants during cracking and other desulfurization reactions.[177] Krasovitskaya et al.[146] reported on atmospheric hydrogen sulfide concentrations around a petrochemical industrial complex in Russia. The complex consisted of three oil refineries, a synthetic alcohol plant, a chemical plant, and three power plants. Measurements in the industrial complex showed a concentration of 17 to 150 $\mu g/m^3$ of hydrogen sulfide; 2.5 km from the complex it was 8 to 70 $\mu g/m^3$; and 20 km from the complex it was 1 to 50 $\mu g/m^3$.

3.2.3 Chemical Industry

Odorous compounds are products of many chemical operations. In general, they are formed when nitrogen or sulfur compounds are associated with organic materials at high temperatures. In many operations the end products have a highly offensive odor (e.g., carbon disulfide, pyridine, and thiophene).

Sources of malodorants in the chemical industry are the manufacture of sulfur dyes[165] and the production of

viscose rayon, neoprene,[139] ethyl and methyl parathion

(pesticides),[269] organic thiophosphate,[175] ammonia, aldehydes,

and many other organic chemicals. Approximately 6 tons of

hydrogen sulfide are formed for every 100 tons of viscose

rayon produced.[192] Inorganic processes which evolve mal-

odorous compounds include the manufacture of barium

chloride (from barium sulfide), phosphorus compounds, pig-

ments, lithopone, and sodium sulfide. Hydrogen sulfide is

emitted during the manufacture of stove clay and glass.[142,212]

An odor problem in a soap plant was reported by

Molos.[183] Amine-like (fishy) odors were produced in unknown

areas in the plant. These obnoxious odors resulted in fre-

quent complaints from plant neighbors and were often detect-

able 5 to 6 miles from the plant. Although the actual source

within the plant was never located, continued public pressure,

picketing, and two public hearings forced the company to

install odor controls on storage tanks, and a centrifuging

operation, and to revise the exhaust system, including the

spray tower dryer.

Byrd et al.[37] reported an odor problem involving

dimethylamine in a synthetic detergent plant. No quantita-

tive data were given.

3.2.4 Pulp and Paper Mills

Hydrogen sulfide, mercaptans, organic sulfides, and organic disulfides are produced and released into the atmosphere in a number of processes in kraft pulp mills. Emission of such substances as these imparts the characteristic "rotten cabbage" or "rotten egg" odor in the vicinity of kraft paper mills and has been the cause of major air pollution problems. Over 50 percent of the pulp produced in the United States comes from the kraft or sulfate process.[141] Robinson and Robbins[233] estimated that in 1960, hydrogen sulfide emission from kraft paper mills throughout the world was about 64,000 tons.

In the kraft process, wood chips and a solution of sodium sulfide and sodium hydroxide (white liquor) are cooked in a digester for about 3 hours at elevated temperatures and pressures. The solution dissolves the liquor from the wood. The spent liquor (black liquor) is then separated from the cellulose fiber in the blow tank, after which the fiber is washed and processed into paper. The remainder of the process involves the recovery and regeneration of the cooking chemicals from the black liquor. The recovery process is initiated by concentrating the black liquor by evaporation. When the concentrated black liquor is burned in the recovery furnace, the inorganic chemicals collect on the floor of the furnace in a molten state (smelt).

Hot combustion gases from the recovery furnace are used in the direct contact evaporation to concentrate the black liquor. The smelt is removed from the recovery furnace, dissolved in the dissolving tank (where calcium hydroxide is added to convert the smelt from sodium carbonate to calcium hydroxide), and pumped to the causticizer, where the sodium carbonate is converted to sodium hydroxide by calcium hydroxide. The effluent liquor (white liquor) is used as feed to the digester. The precipitated calcium carbonate is then heated in a kiln to convert it to calcium oxide. The oxide is then slaked to calcium hydroxide for reuse in the causticizer.[141,260]

The major sources of odorant emission in kraft mills are the stack gases from the recovery furnace, including the direct contact evaporator; the stack gases from the lime kilns; and the noncondensibles from the digester relief, the blow tank, and the multieffect evaporator.[25,268] The concentration of odorous emissions from each source is given in Table 26, Appendix B. According to Sableski[242] investigations at the University of California have shown that 80 percent of the total gaseous sulfur appears as hydrogen sulfide and methyl mercaptan. The amount of these emissions that actually reaches the environment depends upon the efficiency of each of the abatement systems that are installed and

operating at each mill. Table 27, Appendix B, shows the emissions from a kraft mill in Lewiston, Idaho. The mill produces 450 tons per day of bleached paper board and 200 tons per day of market pulp.[268]

The single largest source of odorants in a kraft mill is the recovery furnace, and the amount of odor produced depends upon furnace loading. The hydrogen sulfide produced in the furnace rises very rapidly when the furnace is operated above design conditions.

During a 6-month period in 1961 and 1962, surveys were made of ambient odors in the Lewiston-Clarkston area, where the paper mill is the major contributor of gaseous pollutants.[42] The results are shown in Tables 28-29, Appendix B. During an incident in November 1961, peak 2-hour concentrations of 77 $\mu g/m^3$ of hydrogen sulfide were measured.

In 1957, about 12.8 million tons of pulp were made by the kraft process; the location of these kraft mills is shown in Figure 2, Appendix A. The United States production of pulp by the kraft process from the year 1957 to 1967 is shown in Table 30, Appendix B.

Sableski[242] reported in 1967 on government-funded research on kraft mill pollution. Research at the University of California has shown that pulping hardwoods produces more

methyl mercaptan and dimethyl sulfide than pulping soft woods and that methyl mercaptan is a primary product of pulp digestion. The mercaptan is partly consumed in the formation of dimethyl sulfide. At that time, the University of Washington was studying the kinetics of odor formation in the kraft process. A joint report from the Universities of Washington and Maine concluded thus:

(1) Although cooking soft woods at elevated temperatures for a short period of time reduces the amount of dimethyl sulfide formed as compared to cooking at lower temperatures for a longer period of time, it does not appreciably reduce the amount of the more obnoxious methyl mercaptan formed. Furthermore, any inadvertent lengthening of pulping times increases odors.

(2) The higher the sulfidity of the cooking liquors, the larger the amount of odorous compounds formed. Sulfidity should, therefore, be kept at the minimum practical for effective pulping.

(3) Recycling black liquor to the digester results in increased odor production, and this practice should be minimized.

(4) During the blow, the pH of the cooking liquor should not be allowed to drop below 12 in order to retain mercaptans and to reduce, by as much as 90 percent, hydrogen sulfide losses.

3.2.5 Coke Ovens and Coal

In 1966 about 66 million tons of coke, valued at $1,144,000 were produced per year in the United States in 66 coke oven plants.

Malodorants are produced in the coking operation. The effluent gas from coke ovens contains about 5,000 to 13,000 $\mu g/m^3$ of hydrogen sulfide (or about 6.7 pounds per ton of coal charged).[145] During cooling and scrubbing, approximately 50 percent of the hydrogen sulfide is removed. The remaining gas is either used as is for firing the coke ovens, purified further (partially desulfurized) and used for firing of coke ovens, or completely desulfurized and used for municipal gas.

Odorous emissions can occur throughout the complete coking cycle from coke-oven charging to hydrogen sulfide removal (desulfurization).[231] The sources of these emissions other than charging and discharging emissions, and their causes are shown in Table 31, Appendix B. No data were found on the magnitude of odorant concentrations in the atmosphere in or around coke ovens. However, it is often of sufficient magnitude to create problems or evoke complaints from nearby residents.[171]

Coal refuse piles have been burning and causing odor pollution since coal mining first started.[274] Approximately

20 to 50 percent of the raw anthracite processed in cleaning

plants is rejected as refuse. At many operations the refuse

discarded amounts to about 33 percent of the tonnage produced.

This refuse over the years has accumulated in coal refuse

piles, some of which contain millions of tons.[260] The piles

ignite either through spontaneous combustion, carelessness,

or deliberate action. A recent survey indicated that there

are approximately 500 burning piles in 15 States.[260] The

odorants generated during combustion emanate from the piles

and disperse into the atmosphere. Significant concentrations

of hydrogen sulfide gas have been measured in communities

adjacent to burning piles. Sussman[274] reported that hydrogen

sulfide measurements made in July 1960 adjacent to a large

burning anthracite refuse pile showed an hourly maximum

average of 600 $\mu g/m^3$. The minimum hourly average was

140 $\mu g/m^3$.

3.2.6 Iron-Steel Industry and Foundries

Malodorants are given off in many metallurgical

processes.[248] Wohlbier and Rengstorff[303] showed by experi-

ments that the amount of hydrogen sulfide formed in slag

granulation is proportional to the amount of hydrogen formed

during the quenching process. Typical hydrogen sulfide

exhaust emissions from foundries range from 4 to 100 pounds

per 500 tons of castings produced per day.

3.2.7 <u>Food Processing</u>

Odors from food processing evoke frequent complaints. Food processing includes operations such as slaughtering, smoking, drying, cooking, baking, frying, boiling, dehydrating, hydrogenating, fermenting, distilling, curing, ripening, roasting, broiling, barbecuing, canning, freezing, enriching, and packaging. Some of these processes produce very obnoxious odors, while others produce quite pleasant odors. Because of the odor problems associated with meat processing, it is discussed separately.

McHard and Wromble[171] reported in 1965 that 538 manufacturing establishments in Oklahoma were processing food and related products. Odors from these processes and septic sewage resulting from plant operations caused the chief air pollution problems.

In South Dakota, 24 of 32 air pollution appraisal questionnaires mentioned food processing odors as sources of air pollution. Complaints included odors from milk and cheese processing, livestock pens, alfalfa dehydration, and grain elevators.[41]

Coffee processing produces four types of emissions: dust, chaff, odor, and smoke. The odor and smoke are combinations of organic constituents volatilized at roasting

temperatures. Coffee roasting odors are attributed to alcohols, aldehydes, organic acids, and nitrogen and sulfur compounds. During decaffeination, odors can be traced to trichloroethylene, the solvent used in extracting caffeine from the green coffee beans. The odor-laden smoke presents the most difficult problem in emission control.[210]

3.2.8   Meat Industry

3.2.8.1   Feedlots

The keeping of cattle, sheep, hogs, and poultry in feedlots often produces a noxious odor problem. Feeding on farms may produce odor problems, but the number of people affected is relatively small. Commercial feeding produces odors on a much larger scale, since a community may surround the feedlots.

According to Faith,[78,260] 10 million cattle are on feed in the United States. Commercial feedlots may contain 3,200 to 32,000 head during peak seasons. These cattle are normally kept on feed for 150 days, during which each animal eats 25 pounds of balanced ration every day. The animal will gain about 1 pound for each 8 to 10 pounds of feed. A 1,000-pound animal will produce approximately 26 pounds of total excreta per day, 15 pounds of which is urine. Thus a large potential for odor pollution exists where many animals are kept.

Odor problems develop in two ways.[260] One is the
typical range odor of fresh excreta. The odor is rapidly
dissipated as the excrement cools. This odor is not
particularly offensive. If the manure remains wet, a second
and more offensive odor develops as the bacteria multiply
rapidly and putrefaction begins. Such highly odorous sub-
stances are produced as ammonia, hydrogen sulfide, and
organic amines. These odors may be confined in manure piles
where a crust has formed and will not be released until the
crust is broken, usually during manure removal.

Similar problems arise in feedlots for hogs, sheep,
and poultry (usually in egg production). In one instance,
the urine and droppings were collected underneath the
slotted floor of a pigsty, and the manure was agitated prior
to removal. This agitation allowed malodorous gases to
escape, and within an hour all the pigs lay dead in their
pens.[53]

The physical conditions which cause odor problems in
feedlots have been listed by Moorman[193] as these:

(1) Poor drainage allowing water or wet manure to
stand for long periods of time.

(2) Spilled feed from feed trucks or around feed
mills.

(3)   Improper carcass disposal.

(4)   Accumulation of manure in feeding pens.

(5)   Improper management of manure disposal operations.

3.2.8.2   Livestock Slaughtering

Slaughtering operations have traditionally been associated with odorous air contaminants, though many odorants are due to by-product operations rather than to slaughtering and meat dressing itself. Slaughtering is considered to include only the killing of the animal and the separation of the carcass into edible meat and inedible by-products.

Cattle-, sheep-, and hog-killing operations are necessarily more extensive than those concerned with poultry, though poultry houses usually handle appreciably larger numbers of animals.

In the slaughtering operation, the animal is stunned, bled, skinned, eviscerated, and trimmed. Blood is drained and collected in a holding tank. Entrails are removed, sliced in a "gut hasher," and washed to separate the partially digested food, termed "paunch manure." Many slaughterers have heated reduction facilities in which blood, intestines, bones, and other inedible materials are processed to recover tallow, fertilizer, and animal feeds. Other slaughterers usually sell their offal to scavenger plants that

deal exclusively in by-products. Hides are almost always shipped to leather-processing firms. Dressed beef, normally about 56 percent of the live weight, is refrigerated before it is shipped.

Odors emitted from slaughtering operations can be differentiated as (1) those released from the animal upon killing and cutting, and upon exposure of blood and flesh to air; and (2) those resulting from the decay of animal matter spilled on exposed surfaces or otherwise exposed to the atmosphere. Odors from the first source are not appreciable when healthy livestock are used. Where nuisance-causing odors are encountered from slaughtering, they are almost always attributable to inadequate sanitary measures. These odors probably result from breakdown of proteins. Amines and sulfur compounds are considered to be the most disagreeably odorous breakdown products.[51]

In addition to these sources, odors arise from slaughterhouse stockyards and from the storage of blood, intestines, hides, and paunch manure before their shipping or further processing.[51]

3.2.8.3 Inedible Rendering of Animal Matter

Animal matter not suitable as food for either humans or pets is nevertheless converted into salable products by

rendering. Animal rendering plants are the principal outlets for disposal of wastes from slaughterers, butchers, poultry dressers, and other processors of flesh foods. In addition, rendering plants dispose of whole animals (such as cows, horses, sheep, poultry, dogs, and cats) that have died from natural or accidental causes. The principal products of the reduction processes are proteinaceous meals, which find primary use as poultry and livestock feeds, and tallow.

In the normal reduction process, the raw animal materials are picked up from individual sources and trucked to the rendering plant, usually in open-bodied trucks with canvas covers. The raw material is dumped into a receiving bin, from which it is conveyed to a grinder (breaker) where the meat and bones are ground (hashed), and then conveyed to the cooker. The cooker is either a steam-jacketed vessel (dry-rendering process) or live-steam-heated vessel (wet-rendering process). The cooker may handle from 6,000 to 12,000 pounds of raw material in batch processes, and some may handle as much as 40,000 pounds. More recently built plants use a continuous process. Temperatures of 300°F are required to digest bones, hooves, hides, and hair. Process times range from 1 to 4 hours. Most of the moisture is evaporated and exhausted from the cooker. This exhaust steam

contains extremely odorous gases. Tallow is drained and pressed from the cooked meal. The tallow is then filtered and further dehydrated by centrifuging, settling, or air blowing.[293]

Some materials, such as blood and feathers, that do not contain tallow are also digested and dehydrated in dry-rendering cookers.

Malodors are the principal complaint around rendering plants. These odors arise mainly from the raw materials (especially during the grinding operation), cooker drier, percolator, and press.[277] Many factors may significantly influence the offensiveness and quantity of odors:[126]

(1) The age and condition of raw material.

(2) Overcooking.

(3) Overheating the drier.

(4) Excess air flow through the drier.

(5) Inadequate control equipment.

(6) Overtaxing the capacity of condensers and scrubbers.

(7) Improper disposal and inadequate treatment of liquid wastes.

(8) Insufficient temperature or residence time in incinerator.

(9) Poor housekeeping.

(10) Failure to collect all emissions for deodorization before release to the atmosphere.

Summer[272] stresses that once the carcass is fly-blown and maggot-infested, the obnoxious trimethylamine is produced rapidly. Chemicals which are responsible for the offensive odors have been reported by Strauss[265] and Ronald[235] as ammonia, monoethylamine, diethylamine, triethylamine, hydrogen sulfide, and in lesser quantities skatole, other amines, sulfides, and mercaptans. Aldehydes and organic acids are derived from fats. Putrescine, $NH_2(CH_2)_4NH_2$, and cadaverine, $NH_2(CH_2)_5NH_2$, are two extremely offensive odorants associated with decaying flesh.

The odor concentration and production rate have been measured in rendering plants. These data are shown in Table 32, Appendix B. Mills et al.[179] have estimated the odor emissions in the Los Angeles Metropolitan Area for 1966 from rendering refuse from beef cattle. The average cattle kill was 28,000 per week. He assumed that 15 percent offal and 5.5 percent raw blood were derived from an average 1,000-pound steer. He calculated that rendering plants would produce 3.15×10^{11} odor units per day from offal and 5.24×10^{11} odor units per day from blood. The figures show that the 26 percent of blood of the total rendered material

produced 62 percent of total quantity of odorants. The total quantity of odorants was 8.39×10^{11} odor units per day. He points out that he did not include swine, sheep, poultry, or horses in his calculations, and also that the odor emissions would have been considerably higher if the offal and blood had been allowed to putrefy.

Mills et al.[179] have also reported that most odor emissions take place during the first hour of cooking in the batch process. Their results are summarized in Figure 3, Appendix A. However, the emission rate depends largely on the operating mode. The above data are for a system operating at ambient pressure. In a system operating under vacuum or pressure, the odor would be emitted faster or slower depending on the mode. On the other hand, a continuous system would have a continuous emission of odors.[51]

3.2.8.4 Fish Processing

In the fishing industry, odors are unavoidable because of the nature of the species. Objectionable odors can be detected in fishing wharfs, canneries, and reduction plants. Heavy odor emissions that cause nuisance complaints can usually be traced to poor sanitation. Trimethylamine is the principal compound identified with fish odors.[51]

Reduction of inedible wastes from fish to fish meal is carried out in about the same manner as the animal rendering process described above. This reduction process is capable of producing large quantities of odorants. Mills <u>et</u> <u>al.</u>[179] have reported some typical odor emissions, which are presented in Table 33, Appendix B.

3.2.8.5 <u>Edible Meats</u>

Odors are also emitted from edible meat processing. However, compared to emissions from inedible-rendering processes, the odors from edible-rendering processes are relatively minor. In the Los Angeles area, only 10 percent of the total animal material rendered is from edible meat, and the rates of odor emissions are low. The concentration in the exhaust gas is only about 3,000 odor units per scf.* The main reason for this is that edible materials are kept scrupulously clean.[51]

3.2.8.6 <u>Tanneries</u>

Offensive odors often arise from tanneries. Summer[272] states that the main cause of these odors stems from skins which have become infested with maggots. Sinitsyna[251] claims that the air of tanneries becomes polluted with ammonia.

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*scf—standard cubic foot.

3.2.9 Miscellaneous Production Sources

There are many other production sources of odors which may cause complaints. Some of these include the paint industry,[51] varnish kettle cookers,[51] wire reclamation,[51] electroplating,[294] cement production,[147] cotton ginning,[48] and breweries.[143]

3.3 Product Sources

Odorous product sources fall into four categories: perfumes and cosmetics, masking agents, counteracting agents, and warning agents. All of these products are purposely emitted into the air. Complaints have arisen only when the product is improperly used. Examples of improper use of masking agents and counteractants have been discussed in the previous section. Warning agents consist of small quantities of malodorous gases added to nonodorous lethal gases to warn people of gas leaks.

3.4 Other Sources

3.4.1 Combustion Processes

Odorants are released when wood, coal, oil, or gas are burned.[272] The quantity of odorant will depend upon the amount of sulfur in the fuel and the efficiency of the combustion process. In an efficient combustion system the hydrocarbons, sulfur, and nitrogen compounds will be oxidized to

carbon dioxide, water, sulfur dioxide, and nitric oxide. However, if the combustion is incomplete, malodorants such as hydrogen sulfide and aldehydes are released.[272] In studies[8,238,253] of sulfur released from domestic boilers, hydrogen sulfide was found to be given off during heavy smoke emission, mainly just after refueling.

Williams[299] points out that the most frequent cause of odorant production in fuel-burning operations is incomplete combustion. This also produces smoke, and thus smoke and odors are often associated.

The tepee burner[73] is another source of odor complaints. Incineration of plastic products, garbage, and rubber products is accompanied by extensive and often nauseating odors.

Refuse burning is reported to be a common cause of odor complaints, both from open burning in garbage dumps and incineration.[171] Odors emitted from the incineration of refuse collected overnight in an apartment house were measured by Kaiser et al.[138] Their observations (tabulated in Table 34, Appendix B) showed emission concentrations of 2.5 to 100 odor units per cubic foot and emission rates of 4,900 to 145,000 odor units per minute.

Gasoline and automobile exhaust are frequent sources

of odor complaints. Automobile exhaust odorants are not as offensive as diesel exhaust odors. Therefore, they have not been studied to the same extent as diesel odors. There are numerous studies on the emission of several individual odorants, such as aldehydes, sulfur oxides, and nitrogen oxides, but no studies were found on odors per se.

3.4.1.1 Diesel Engine Odors

Exhaust constituents and odors have been related to aldehyde concentrations in diesel exhaust because aldehydes have a characteristic odor and cause irritation in exceedingly low concentrations. Table 35, Appendix B, shows the **approximate relationships** of total aldehyde concentrations to odor intensities of diesel exhaust as estimated from the results of three separate studies.[72,239,297]

Although each investigative group found a definite relationship of aldehydes to odor, the relationships differed somewhat. Much of the difference is due to the subjective evaluation methods and to the analytical procedures. In addition, the quality of odor may change with different fuels, engines, load and rpm, and other factors.[227]

Rounds and Pearsall[239] tested correlations of odors from diesel engines with formaldehyde, higher aldehydes, and oxides of nitrogen, as well as with total aldehydes. They

found that formaldehyde and oxides of nitrogen did not correlate as well with odor as did total aldehydes. They concluded, "The concentrations of the exhaust gas constituents measured in the present study cannot be used to predict reliably the changes in odor or irritation intensity which would accompany changes in factors such as engine operating conditions, the engine design, the fuel, or the lubricant. Further, the data suggest either that constituents other than those measured are contributing significantly to odor and irritation or that the chemical methods used are not measuring accurately the constituents they are intended to measure."

The concentrations of acrolein, formaldehyde, and total aldehydes appear to be about the same from gasoline engines as from diesels,[73,119,121,156,239] thus indicating that other compounds must contribute to odor and irritation from diesels. Objectionable diesel odors have occurred at a time when aldehydes were present in the air only at extremely low concentrations.[72]

In another study,[156] the concentrations of nitrogen dioxide, formaldehyde, acrolein, and hydrocarbons in the diesel exhaust gases were compared with the odor threshold concentrations. The concentrations of nitrogen dioxide,

hydrocarbons, acrolein, and formaldehyde present in the diesel exhaust at the threshold dilution (Table 36, Appendix B) show that (1) under the 1,600 rpm*, full-load condition, the average concentration of nitrogen dioxide present in the threshold dilution of diesel exhaust is 38 percent of the average threshold for pure nitrogen dioxide; (2) under the 500 rpm, no-load condition, the average concentration of nitrogen dioxide present in the threshold dilution of diesel exhaust is 51 percent of the average threshold for pure nitrogen dioxide; (3) for both types of exhaust, the average concentration of acrolein and formaldehyde present at the threshold dilution of the exhaust is only one-tenth to one-hundredth of the thresholds for the pure compounds; and (4) the average concentration of hydrocarbons at the threshold dilution of 500 rpm, no-load diesel exhaust is larger than for the 1,600 rpm, full-load exhaust. Tentative conclusions were as follows:

(1) At the odor threshold dilution of diesel exhaust, acrolein and formaldehyde were present in such small concentrations, in relation to the threshold concentration for the pure compounds, that it is unlikely that

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*rpm: revolutions per minute.

they were major factors in the odor of diesel exhaust.

(2) Under load conditions, the amount of nitrogen dioxide present in the odor threshold dilution of diesel exhaust was large enough, in relation to the odor threshold for pure nitrogen dioxide, that nitrogen dioxide was more likely to be a major factor in the odor detectability of diesel exhaust than were acrolein and formaldehyde. The data in Table 37, Appendix B, support this conclusion.

(3) At ideal conditions, hydrocarbons, as measured by infrared carbon and hydrogen absorption, were present in such large concentrations in relation to nitrogen dioxide, acrolein, and formaldehyde, that the unburned diesel fuel was a likely suspect as the major factor in the odor of diesel exhaust produced under these conditions. The data in Table 38, Appendix B, support this conclusion.

A number of investigators have suggested that smoke or particulate matter also contributes to odor.[82,155,157,239] In one study, removal of smoke by filtration greatly reduced odor intensity, although electrostatic precipitation was ineffective in doing so.[239] In another study, particulate matter collected on glass fiber filters was extracted with benzene, and upon evaporation of the benzene, an oily yellow residue with a "heavy diesel odor" remained.[156]

Reckner et al.[227] observed that nearly all of the odor was removed from diesel exhaust when the gas was bubbled through a 5 percent aqueous sodium bicarbonate solution.

There is considerable evidence that the most pronounced and objectionable odors and the highest aldehyde concentrations in diesel exhausts occur at conditions of no load, idle, and deceleration or acceleration after idle.[27,72,297] These odors have been described as very pungent, sharp, acrid, and objectionable. Under load conditions, odors were strong and heavy but not particularly objectionable.[297] Berger and Artz[27] reported only faint odor when a diesel mine locomotive (GM 6-71) was operating upgrade under load. When the locomotive was descending the grade, considerable odor and eye irritation were evident. The high aldehyde and odor intensity may be caused by chilling of the combustion chamber and substances reacting with the great excess of air under no-load conditions.[27,72,232]

However, Rounds and Pearsall[239] found much higher concentrations of aldehydes at full load than at no load with a two-cycle engine. Concentrations were lowest at

intermediate loads. The data indicated that diesel exhaust gas was most odorous and irritating at either no load or at full load. At intermediate loads the intensities were less, although this effect was not as pronounced with odors as with irritation. The effect of engine rpm was small compared to that of load.

Rounds and Pearsall[239] also compared the odor intensities produced by three different engine makes, a two-cycle and two four-cycle engines. They found that at intermediate loads, the odor intensities from all three engines were practically the same. At full load, one of the four-cycle engines had less odor than the other two, which had about the same odor intensities. At no load the other four-cycle engine had the least odor.

Another factor which influenced the odor production of diesel engines was the mechanical condition of the engine. Rounds and Pearsall[239] found that an engine in poor mechanical condition except for the fuel injection system produced slightly higher odor intensities, but only when partially loaded. The engine tested produced excessive smoke, which indicates that odor and smoke are not necessarily related. Roberts[232] indicates that leaking valves can reduce the temperature of the combustion chamber and increase smoke and

odors. Leaking injectors or maladjusted governors increase aldehyde concentrations and probably also affect odor intensity. [111,239,297]

There are conflicting reports on the effects of fuel on odor. Reckner et al.[227] and Young[309] believe that a fuel produces two separate effects: odor and lacrimation. Furthermore, light diesel fuels, such as kerosenes, are satisfactory with respect to odor (and smoke), but the lacrimation effect may be greater than for fuels with higher boiling points. Reckner et al.[227] suggest that the differences they observed in odors of two unburned diesel fuels and the exhausts from burning these fuels might be explained by their differing volatility. Grunder[98] stated that city-type buses using kerosene-like fuel had a characteristic odor which is pungent, sometimes irritating to the eyes, and objectionable in heavy traffic to many people. He also stated that these buses introduced a distinctly different odor easily distinguishable from the odor from gasoline engines or four-cycle diesel engines operating on regular grade diesel fuel. According to Rounds and Pearsall,[239] the odor (and irritation) from a low endpoint fuel was only slightly more than from a high

endpoint fuel (the cetane number and initial boiling points of the fuels were about the same). Roberts[232] thought that the highly volatile fractions in the diesel oil were prone to cause partially oxidized fuel in the exhaust gases.

A number of investigators have found that cetane number influences aldehyde concentrations and odor only during no-load conditions and immediately after: the lower the cetane number, the higher the aldehyde concentra-tion.[72,239,297,309] With respect to odor, Wetmiller and Endsley[297] state that offensive odor depends only on cetane number. Young[309] says that cetane number has some bearing on odor; and Rounds and Pearsall[239] state that it has but a slight effect. Sinks[252] reported that no marked change in odor resulted from varying the volatility and cetane number of the fuel over a wide range. Additives or impurities may also affect the odor of diesel exhaust gases. Young states that the addition of amyl nitrate tends to improve exhaust odor by increasing cetane number, but may slightly increase the tendency for the eyes to water.[309] There is good evidence that high sulfur content fuels increase odor and irritation.[239,267]

Studies show that the oil type has no effect on odor intensity but does affect odor quality.[239,252] It was

found that in all conditions, a polyalkane glycol oil pro-
duced more offensive exhaust odors than a mineral oil. At
low speeds and loads, a diester oil gave a less offensive
smelling exhaust gas than did the mineral oil, whereas at
high speeds and loads the opposite was true.

The National Air Pollution Control Administration is
presently funding diesel odor studies at the U.S. Bureau of
Mines at Bartlesville, Okla.; the Southwest Research Insti-
tute at San Antonio, Tex.; and the A.D. Little Laboratory
in cooperation with Illinois Institute of Technology.

3.4.1.2 Aircraft Odors

Lozano et al.[159] have reported the odor dilution
threshold concentrations for jet aircraft. These data are
summarized in Table 39, Appendix B. The authors point out
that the odor dilution threshold concentration is highest
for fan-jet engines at idle, and this concentration (1,000
odor units per scf) is approximately three times higher
than diesel engine exhaust at idle. Conventional jets and
turbojets were 10 to 100 times lower at idle than in the
cruise and take-off mode.

A 10-day odor survey was conducted near the John F.
Kennedy International Airport in New York[201] in 1964
(October 5th through 9th and October 19th through 23rd) to

determine the major types of odors in the area, particularly those that can be attributed to jet aircraft exhaust. An untrained corps of odor observers was used, consisting of about 100 seventh- and eighth-grade science students residing in the study area. The students were tested for sensitivity by means of the "triangle" test, using odorant solutions of vanillin, methyl salicylate, and butyric acid. All students tested were found acceptable as observers. Students were instructed in the manner of making odor observations, and observations were made three times daily at 7 a.m., 4 p.m., and 8 p.m. Observers noted the strength of the odor, if observed, and described the odor in their own words on a data form provided. The data subsequently were punched onto cards and analyzed by use of a card sorter.

The number, type, and location of odor observations made are given in Table 40, Appendix B. All communities surveyed are within 3 miles of the airport. The greatest percentage of positive odor responses occurred in the Rosedale area (Zone 3), followed by South Ozone Park (Zone 4). No odors were described by the students as jet exhaust smoke or odor. To determine whether odors described as "gasoline and diesel engine exhaust" or "oily or fuel odor"

could have possibly originated at the airport, these obser-
vations were compared with wind direction. Six of these
observations were made at a time when odor originating at
the airport could have been carried by wind to the observer,
and 20 of these observations were made when odors from the
airport were being carried away from the observer. These
data indicated that gasoline and diesel exhaust and oily
or fuel odors were not specifically related to jet aircraft
emissions in this instance, and that sources other than the
airport were the main contributors.

The possibility that emissions from jet aircraft do
create an odor problem should not be ruled out. Odors from
these sources may be apparent during other seasons of the
year or during more adverse meteorological conditions.

3.4.2 Sewage

Complaints of odors have come from the immediate
vicinity of some sewage treatment plants, especially during
the summer months when the daytime temperatures are high
and there is little or no air movement. In most cases,
these odor problems are experienced only in areas imme-
diately adjacent to sewage treatment plants[229,295] or open
manholes.[229]

In Chicago, Ill., the sewer system in the city has been cited[229] as a frequent source of offensive odors emanating from manholes. Such problems are not unusual in communities where domestic sewage is discharged to a sewer system which was originally designed to carry off storm water. Since storm sewers normally handle large volumes of water over short time periods, they are laid on a grade less than that required for a system handling only domestic sewage. As a result, solid sewage deposits often remain in the sewer where they generate odors in the process of decomposition.[229]

Malodorous gases are produced biologically in sewers and treatment plants from organic compounds formed by hydrolysis of materials like cystine and methionine and by reduction of sulfates. A survey of odors emitted most frequently at some 300 sewage treatment plants in the U.S. shows that the methyl mercaptans, methyl sulfides, and amines are leading causes, followed by indoles and skatoles, and last of all the notorious hydrogen sulfide.[219] Factors that influence odorant generation in sewers include temperature, content, age, and pH value of sewage; flow velocity; and ventilation of the sewer.

In the Washington, D.C. metropolitan area about
1,000,000 cubic feet of sewage sludge gas is produced each
day by various sewage treatment plants. This gas is used
as fuel for certain types of engines or for heating purposes,
or is wasted by flaring.[295] Atmospheric measurements made
at a sewage treatment plant in El Paso, Tex., in 1958 showed
that the hydrogen sulfide atmospheric concentration varied
between 24 $\mu g/m^3$ and 2,120 $\mu g/m^3$, with the average concen-
tration 610 $\mu g/m^3$. At a sampling station 100 yards from
the sewage plant, the maximum hydrogen sulfide concentration
was 205 $\mu g/m^3$.[5]

At the Stickney treatment plant in southwestern
Chicago, a source of frequent odor complaint is believed to
be the storing or disposal of sewage sludge in lagoons at
the plant site on those occasions when the plant cannot use
non-odor-producing processes.[229]

3.4.3 Miscellaneous Other Sources

Many other sources of odors may cause complaints,
such as the use of fertilizers, insecticides, paint solvents,
and other solvents.

A characteristic pungent odor is associated with
photochemical smog. Ozone is the acrid component of this
odor.[129]

3.5 Environmental Air Concentrations

No quantitative data have been reported on the odor concentration in ambient air even though a number of odor surveys have been made. These surveys have shown detectable disagreeable odors, but their intensity was not reported.

4. ABATEMENT

Odor abatement has been reviewed by Turk,[284]
von Bergen,[292] and Summer.[272] The abatement methods
employed depend largely on the odor-producing process, the
odorant, and other substances in the waste gas stream.
These abatement methods fall into several categories:
combustion, absorption, adsorption, odor masking, odor
counteraction, dilution, source elimination, particulate
removal, chemical control, biological control, and contain-
ment. Often two or more of these processes may be combined
to eliminate an odor problem.

Complete combustion is generally accepted as the
best way to deodorize malodorous gases. However, it may
not be the most economical method. Complete oxidation of
odorants converts hydrocarbons to odorless carbon dioxide
and water, and sulfur and nitrogen compounds to sulfur
oxides and nitrogen oxides that usually have higher odor
thresholds than the parent compounds. Partial oxidation
may increase the odor problem by the formation of malodorous
aldehydes.[292]

Oxidation at 1,200°F or above has been recommended
and usually gives satisfactory results. The temperatures

may be lower (500 to 800°F) when a catalyst is used. This will depend on the odorants and the possible catalytic poisons in the gas stream.[292]

Reed and Truitt[228] point out that the control of odors emitted from incinerators can take place either in the combustion chamber or in the stack just before release to the atmosphere. They propose an auxiliary gas burner with a flame temperature of at least 1,500°F.

Benforado[26] has reported on measurements of odor concentrations made before and after incineration in a number of plants. These results are tabulated in Tables 41 and 42, Appendix B.

Odor-laden smoke from the coffee roasting industry is most effectively controlled with afterburners, but fuel requirements are increased 100 to 150 percent over those for a conventional roaster.[210]

Where odorants are soluble in water or some other liquid or solution, absorption may be used. For example, ammonia may be removed by spraying water through a chamber containing the ammonia. Hundreds of methods have been devised for contact between vapor and liquid. Some of those used include simple vertical spray towers in single or multiple stages and cascade vertical towers packed with

partition rings, Raschig rings, spiral rings, Berl saddles, hollow balls, helical packers, hexahelix blocks, double spirals, cyclohelix blocks, prismic packings, centrifugal or cyclone scrubbers, and bubble and sieve trays.[274]

Some solids will adsorb odorant compounds and thus remove them from the system. This process requires that adsorbent and odorant be matched. Activated charcoal has the particular advantage that it will adsorb all types of materials under almost any conditions. However, the efficiency of any adsorbent system is dependent on the temperature, pressure, and flow rate of the gas stream.[272]

Odor masking is the process of eliminating the perception of one odor or group of odors by superimposing another odor or group of odors on it to create a new odor sensation, preferably pleasant. Odor-masking chemicals are usually synthetic aromatic compounds or a mixture of these compounds.[292] Some examples of these are vanillin, methyl ionones, eugenols, benzyl acetate, phenyethyl alcohol, and heliotropin. The proper masking agent does not alter the composition of the preexisting odorant, but has a pleasant smell that is strong enough to overpower the offensive odorant.[272]

All smells cannot be masked. In particular, strong acids, even in traces, will defy masking because the agents used decompose under acid conditions.[272]

Masking agents may be applied directly to raw material (sewage, animal or vegetable waste, blood), drip-fed into process lines, added to scrubbing waters, injected into gas streams, soaked into covers for small leaks, or sprayed as a fog.[272]

The chief advantage of this method of control is that little or no capital costs are involved. Masking may be used as a temporary measure while other control methods are developed.[292] Odor counteractants are often used together with masking agents in a single application.[292]

The effect of odor counteraction is to reduce both the odor of the counteractant and the odor of the malodorant. When the two odors are sniffed together, both odors are diminished. This is often confused with odor masking, in which equal strengths of two odorants may both be distinguished and the masking agent concentration must be increased to overpower the malodors.[292]

Moncrieff[190] has cited the following examples of

counteractant pairs:

> Cedarwood and rubber
> Wax and rubber
> Wax and balsam of tolu
> Paraffin and rubber
> Rubber and balsam of tolu

When benzene, toluene, xylene, pseudo-cumene, and durene are mixed in small quantities, their odor strengths are additive. However, at higher concentrations, the odor becomes faint. Another example of counteraction is the pair, butyric acid and oil of juniper. When air is bubbled through a butyric acid solution, the characteristic strong, unpleasant odor is perceived. Oil of juniper also has an unpleasant odor, but a mixture of the vapors has a faintly pleasant odor.[190]

Odor dilution will obviously result in odor-free air as an odorant is diluted below the threshold concentration. Such a method is feasible to remove an odor problem from a plant area provided the weather conditions are favorable. However, unfavorable meteorological conditions may cause the odorant concentration to increase above the odor threshold. Thus, the odor emission rate (odor units per minute) must be weighed against the possibility of adverse meteorological conditions in order to prevent odor pollution.[272,292]

Another method of odor control is to eliminate or reduce the odor-producing substance. This type of control is being practiced by using low sulfur fuels.[272]

Many odorants are adsorbed on particulates, and the removal of these particulates may also reduce the odor.[49]

Chemical control of odors is possible in many industries. Chemical oxidation or combination may change an odorant to a nonodorous compound. Frequently, chlorine or potassium permanganate is added to a scrubbing solution to oxidize the odorants.[272] Other reactions result in ammonium acetate products that have no odor--for example, the reaction of acetic acid with ammonia which produces odorless ammonium acetate. Ozonation, catalytic chemical oxidation, silent electric discharge, and ultraviolet radiation will all result in chemical conversion of some odorants to compounds with a less offensive odor.[272]

Biological control may be possible in some operations. The biological degradation of sewage produces odorous gases. However, it is known that some microorganisms (Beggiatoa alba) oxidize hydrogen sulfide to water and sulfur, and this method has been suggested for sewage odor control.[272]

Containment offers a means of odor abatement in some situations. Covers on fuel tanks, sewage ponds, and other open storage areas will reduce the emissions of odor.[272]

4.1 Petroleum Industry

Odor pollution control methods used most frequently in the petroleum industry are scrubbing and combustion.[177,214] Mercaptans are often removed in alkaline scrubbers or converted to disulfides. Hydrogen sulfide is often treated with an amine (diethanolamine) in a scrubber. These malodorous gases may be recovered from the scrubber in a regeneration step for disposal by combustion in a waste gas furnace. Aldehydes do not present problems with proper incinerator temperature.[214]

Kropp and Simonsen[150] have described a fog-filter-type scrubber that was successful in removing fatty-acid odors, hydrogen sulfide, and sulfur dioxide.

4.2 Chemical Industry

Abatement of odors in the chemical industry depends entirely on the nature of the chemical process and the odorant, each group requiring a specific control.

Ilgenfritz et al.[122] of Dow Chemical Company emphasize that a large chemical complex such as their

Midland, Mich., operation requires continual surveillance by
odor panels and immediate response to complaints. Response
to complaints from in-plant personnel prevents out-of-plant
complaints by a ratio of 14 to 1.

Sandomirsky et al.[244] reported on an "intolerable
odorous fume condition" produced by a rubber processing
plant (B. F. Goodrich Company). These odorants were non-
soluble and, therefore, could not be removed with a scrubber.
Incineration at 1,300°F was found to solve the problem.
Tests at lower temperatures showed that satisfactory inciner-
ation was achieved at temperatures down to 1,100°F, but smoke
and odor appeared as the temperature was lowered to 800°F.
The 1,300°F incineration resulted in a concentration of 50
odor units per standard cubic foot, approximately 205,000
odor units per minute.

4.3 Pulp and Paper Mills

Sableski[243] has summarized the odor control methods
for kraft mills as follows:

Source	Methods of Control
Pulp digestion	Condensation of vapors followed by incineration
Multiple-effect evaporation	Condensation of vapors followed by scrubbing or incineration

Source	Methods of Control (Continued)
Direct-contact evaporators and recovery furnace	Black liquor oxidation accompanied by strict process control
Dissolving tank	Scrubbing
Condensate disposal	Stream stripping followed by incineration
Lime kilns	Improved mud washing and use of scrubbing fluids without sulfides

The greatest reduction of odorant emissions was achieved by the black liquor oxidation process. The process consists of oxidizing the sulfides in the weak black liquor (before going through the multiple-effect evaporators) or strong black liquor (after going through the multiple-effect evaporators) by contacting it with air in a packed tower or thin film or porous plate black liquor oxidizing unit. The oxidation converts the sulfides to less volatile compounds which are less odorous and have less tendency to escape.[141] This has the effect of reducing the odorant emissions from the direct-contact evaporator and the recovery furnace stack by 80 to 95 percent.[104,140,151] The weak black liquor oxidizing process also reduces emission from the multiple-effect evaporators.

The majority of the black liquor oxidizing systems installed in the United States, which are based on oxidizing

weak liquor, are located in the Western part of the country.
In the South, the woods used in kraft processes cause
excessive foaming problems in the weak black liquor oxidiz-
ing process.[151,207] To alleviate this, a few southern mills
have installed an oxidizing process based on oxidizing the
strong black liquor.[207,208]

The key to minimizing odorous emissions from the
recovery furnace even in those systems employing black
liquor oxidizing systems is proper furnace operating condi-
tions. For minimum emissions from the recovery furnace
the furnace should not be operated above design conditions.
There should be 2 to 4 percent excess oxygen leaving the
secondary burning zone (i.e., leaving the furnace), and
there should be adequate mixing (turbulence) in the secondary
combustion zone.

In the direct-contact evaporator, where flue gases
from the recovery furnace are used to concentrate the black
liquor, the carbon dioxide in the flue gases reacts with
the sulfite in the black liquor to release hydrogen sulfide.[207]
As noted before, this is substantially reduced by the black
liquor oxidizing process. However, some sulfite remains even
after the oxidation. Therefore, removal of the direct-contact

evaporator from the stream would further reduce hydrogen sulfide emissions.[207]

To reduce recovery furnace particulate emissions, some mills have installed a secondary wet scrubber following the primary scrubber (direct-contact evaporator). Limited pilot plant studies and experience in some plants have shown that weak wash (weak caustic solutions) has removed hydrogen sulfide from the stack gases. In other instances, no hydrogen sulfide removal has been obtained in such a system. In general, the removal of hydrogen sulfide from flue gases containing 11 to 14 percent carbon dioxide with a caustic solution has not been developed.[30,31,151]

Clement and Elliott[45] have emphasized that the formation of malodorous gases in kraft mills takes place during incomplete oxidation in both the contact evaporator and recovery furnace. They recommend the elimination of the direct-contact evaporator by replacing it with a multiple-effect evaporator. This step--together with complete combustion in the upper part of the furnace by thorough mixing of additional air admitted through secondary and tertiary air ports--has resulted in reducing the hydrogen sulfide to less than 1 ppm and organic malodorous compounds to nondetectable concentrations. Clement and Elliott further point out that

in 1968, 45 plants in Sweden and 3 in the United States were using such as arrangement.

Hochmuth[109] has reported that Combustion Engineering, Inc. has developed a heat exchanger to use the recovery furnace gases to preheat air for the direct-contact evaporation. Gases leaving the direct-contact evaporator are then incinerated. This method eliminates the contact evaporator as an odor source.

Another source of odorous emissions from kraft mills is provided by the noncondensible gases released for digesters and multiple-effect evaporators. These emissions have been minimized by various systems, generally based on collecting the noncondensible gases in a gas holder, then oxidizing or burning them at a constant flow rate. The various methods used are the following:

(1) Burning the gases in the recovery furnace or lime kiln.[250]

(2) Oxidizing the gases in a separate catalytic oxidizing furnace or a direct-flame incinerator.[151,245]

(3) Oxidizing the gases in an absorption tower with aqueous chlorine solutions, such as chlorine bleach water from the bleach plant, waste chlorine, hypochlorite, etc. Sometimes this is followed by passing them through

another absorption tower, where the absorbent is either a weak chlorine solution or a caustic solution.[134,250,296]

(4) Absorbing the gases with a caustic solution in a scrubber.[134]

Sableski[243] mentions that the gases can be collected in a floating roof tank rather than the Vaporsphere, thus avoiding the problem of diaphragm leakage.

In the lime kiln, odorous emissions may be substantially reduced through the use of wet scrubbers with an alkaline absorbent, efficient control of cumbustion, and proper washing of lime mud. Scrubbing smelt tank gaseous emissions with weak wash or green liquor in an absorption tower will reduce odorous emissions from this source.[250]

Around 1951, masking of odors by adding aromatic compounds to the digester, the black liquor, and the stack gases was tried in the United States. This strictly make-shift approach did not solve the basic pollution problem and is not used at the present time.[296]

4.4 Coke Ovens and Coal

In coke-oven plants, gases are often removed by passing the gases through iron-oxide-impregnated wood shavings.[10,145,266] This process is generally nonregenerative, although methods for regenerating the iron oxide have

recently been developed.[161] Regenerative liquid absorption systems using such absorbents as ammonium carbonate, sodium thioarsenate, and sodium arsenate solutions have also been used.[89,145]

4.5 <u>Diesel Engine Odors</u>

The similarity between smoke- and odor-causing factors in diesel exhaust suggests that the same methods to control one will control the other to some extent. This is further indicated by Rounds and Pearsall[239] in their summary: "Several special approaches to exhaust gas odor reduction were tried, but no panacea was found. For the present, close attention should be given to factors such as improved engine and injector design, proper fuel and oil, good maintenance, and avoidance of overloading."

Some work is being done to develop exhaust converters to reduce diesel odor. However, numerous engineering problems remain to be solved. The sulfur content of fuel and the type of lubricating oil used appear to be more important with respect to odor and irritation than to smoke. Decreasing the scavenging air of two-stroke engines has improved fuel economy, decreased exhaust volume, and presumably decreased odor intensity.[252] Along the same lines, London[158]

has suggested, "Possibly the light load stench can be re-
duced by intake air throttling so as to reduce the air-to-
fuel ratio from 80 to 90 down to 50 to 60."

Odorants or masking agents offer a different approach
to the diesel odor problem. In this connection, the Cleveland
Transit System, General Motors Diesel Coach Division, Sindar
Corporation, and Rhodia Company, Inc. conducted tests for
approximately 1 year on the effects of masking agents. They
concluded at the end of that time that:[158,252]

(1) The main combustion products have not been
altered by the additives tested.

(2) Normal engine life is not affected.

(3) Additives can be completely soluble in the
fuel and do not form deposits before or after combustion.

(4) There was little, if any, reduction of odor
intensity or of eye, nose, or throat irritation.

(5) Odor quality was changed and improved.

The cost of the additive increased the price of
diesel fuel by about 0.2 cent per gallon.

4.6 Meat Industry

4.6.1 Feedlots

Control of feedlot odors depends primarily on sani-
tation and housekeeping. If the pens are paved with either

concrete or asphalt, daily cleaning and manure removal may be necessary. According to Moorman[193] and Faith,[78,260] it is important that there be adequate drainage so that manure will dry. If the manure can dry before putrefaction takes place, then manure need only be removed two or three times per year. One method of accelerating the drying process is to scarify the manure with a spring-tooth harrow to enhance evaporation.

The use of odor counteractants have proven to be more successful than the use of a masking agent. Moorman[193] points out that in some cases more complaints were received when masking agents were used than when the manure odor was untreated. Another common method of control is with potassium permanganate. The treatment consists of spraying a 1 percent solution of potassium permanganate (20 pounds per acre) in the corrals.

Removal of manure in commercial feedlots presents a problem because there is considerably more supply than demand for the raw material. Therefore, manure dehydrators have in many cases been installed adjacent to feedlots to package manure for shipment and sale. Storage and handling become important in relation to both the odor problem and the cost of operation. An odor control agent such as

potassium permanganate is usually all that is necessary to prevent odor problems during storage. The application of counteractants prior to bagging can serve to deodorize the bagged material and plant exhaust.[193]

4.6.2 Livestock Slaughtering

As has been explained, odorous air contaminants are emitted from several points in a slaughtering operation. Installing control equipment at each source would be difficult if not impossible. Methods of odor control available include (1) rigid sanitation measures to prevent the decomposition of animal matter, and (2) complete enclosure of the operation to capture the effluent and exhaust it through a control device.[51]

When slaughtering is government-inspected, the operators are required to wash their kill rooms constantly, clean manure from stock pens, and dispose of all by-products as rapidly as possible. These measures normally hold plant odors to tolerable levels.[51]

When a slaughterhouse is located in a residential area, the odor reduction afforded by strict sanitation may not be sufficient. In these instances, full-plant air conditioning may be necessary. Filtration with activated carbon has been cited[51] as the only practical means of

controlling the large volume of exhaust gases from a plant of this type. The latter method has not yet been employed at slaughterhouses in the United States. Nevertheless, activated-carbon filtration of the entire plant has been employed to control similar odors at animal matter by-product plants. With increasing urbanization, this method of control may conceivably be used in the near future.[51]

4.6.3 Inedible Rendering of Animal Matter

The principal devices used to control odorant emissions from rendering plants are afterburners and con-densers, installed separately or in combination. Adsorbers and scrubbers are also used. Selection of the odor control equipment depends largely on the moisture content of the malodorous stream. Steam-laden streams can be controlled by condensation, while those from air driers and auxiliary processes require incineration, scrubbing, or adsorption.[51] Walsh[293] claims that combinations of condensers and incinera-tion devices have been utilized to achieve odor removal efficiencies greater than 99.99 percent. He suggests that surface condensers are more desirable than contact conden-sers because the odor-laden water cannot be run through a cooling tower.

Mills _et al._[180] have reported odor removal efficiencies from a dry rendering cooker. These data are tabulated in Table 43, Appendix B.

Exhaust gases from air drying processes must be incinerated, according to Walsh,[293] because they contain about 80 percent air and other noncondensible gases. The recommended incineration temperature is 1,200°F.

Carbon adsorbers are as efficient as afterburners.[51] Strauss[265] has reported that the use of activated charcoal adsorbers following a surface condenser-cooling tower arrangement has virtually eliminated odors from a rendering plant in Australia. The surface area of the carbon bed is large enough to give a linear velocity of 40 ft/min, and the usable life of the carbon is 6 months.

Scrubbing solutions of both sodium hypochlorite[197] and potassium permanganate[51] have been used to oxidize odorants from rendering plants. Mills _et al._[180] claim that an afterburner is more efficient than a chlorinator. However, the chlorinator-scrubber has been successful in removing odors from fish meal driers[179] and a glue factory.[197] Posselt and Reidies[218] have reported odor reduction by oxidation with potassium permanganate. The results of their

experiments are shown in Table 44, Appendix B.

Use of odor counteractants and masking agents have shown limited success in the local area of the rendering plant but are of little use in abating the odor pollution.[51,260]

4.7 Sewage

Santry[245] has reviewed the odor control methods for sanitary sewers and claims that control methods fall into these categories: physical control, chemical control, biological control, and a combination of these.

In sewage plants, the most comprehensive elimination of odors is accomplished by enclosing the process and venting the gases to an incinerator.[153] Odorous gases are piped from critical points in the plant and burned at temperatures of 1,100 to 1,500°F.[86] Afterburners are also employed to control odor emissions from sewage treatment plants.

Other methods of removing odors are absorption or chemical oxidation of the gas. The oxidation process is utilized in New York City and in Sarasota, Fla.[235] Ullrich and Ruff[286] reported on a catalytic oxidation unit that was used to control sewer odors in Austin, Tex.

In sewers, the production and release to the atmosphere of sewage gas can be minimized by maintaining

sufficient velocities of sewage to avoid buildup, minimizing pressure lines, minimizing points of high turbulence, insuring adequate ventilation, injecting air to maintain aeration, cleaning sewers to remove slime and silt, using chemicals such as chlorine and ozone to suppress biological activity,[182] and adding specific biota to suppress the development of organisms producing hydrogen sulfide.[245] A method of preventing release of odorous gas to the atmosphere that has had some degree of success is trapping the gas in laterals, branches, and mains by use of specially designed junctions, followed by incineration.[245] A method utilized by the County Sanitation District of Los Angeles to control hydrogen sulfide is to add lime slurry periodically in relatively large quantities.[245]

5. ECONOMICS

Economically, the impact of odors is far-reaching.
Because noxious and foul odors can ruin personal and commu-
nity pride, interfere with human relations, discourage
capital investment, lower socioeconomic status, and damage
a community's reputation, the economics of a community may
be closely related to any odor pollution problem. Both
people and industry desire to locate in a desirable area
in which to live, work,and play; the natural tendency is to
avoid communities and localities with obvious odor problems.
Tourists shun polluted areas. The resulting decline in
market and rental property values, tax revenues, payrolls,
and sales can be disastrous to a community.[126,166,263]

However, industries which cause odor pollution may
be an economic advantage to a community, since they provide
job opportunities both in the industry itself and in
businesses which service the industry and its employees.

There are many socioeconomic aspects to odors which
are difficult to assess. However, some incidents are easily
evaluated. For example, a downtown theater in Washington
D.C., was once evacuated because of some odor which penetrated

the theater, requiring the manager to refund the price of admission. The exact source of the odor was not reported, but sewer gas was suspected.[302]

The cost of odor control by an industry is economically important. Often the cost is offset by economic benefits gained through the control methods or from recovery of waste products. For example, odorous compounds are often controlled by incineration, and the heat generated by incineration used to provide heat for some industrial process. Good examples are the heat from the recovery furnace in kraft pulp mills, heat recovered from incineration of odorous gases in rendering plants, and heat produced from sewage gas burners.

Typical costs of control equipment installed in Los Angeles County are listed in Table 45, Appendix B. Byrd and Phelps[36] have presented a method of arriving at what may be the most economical approach to odor control. They suggest determining the emission rate (odor units per minute) at each source of emission in a plant and the cost for its control. The cost per 1,000 units reduction can then be computed, thus allowing management to assess the costs of making improvements prior to expenditure of funds.

According to the American Petroleum Institute, as reported by Elkin,[71] odor control costs in the petroleum industry increased by a factor of eight in the 10-year period 1956 through 1966. This represented an increase of from 6 percent of total air pollution abatement expenditures by the industry in 1956 to 28 percent in 1966 (see Table 46 in Appendix B).

Kasparick[139] stated in 1965 that duPont had spent nearly $100,000 on odor control for a neoprene chemical plant, and furthermore, that the company had to abandon some promising projects that could have saved thousands of dollars annually because these projects would have contributed to an odor pollution. In the same report, this author states that the B.F. Goodrich Co. estimated that the annual fuel cost for incineration of odorant effluents from their rubber plant could be reduced from $26,600 to $10,650 by installing a recovery heat exchanger.[139]

Reed and Truitt[228] suggest that the cost of operating an auxiliary gas burner to control odors in a 100-unit apartment building will cost $490 per year for each unit and about 41 cents per month for each suite served.

The pulp and paper industry has spent about $75 million to date to control air pollution emissions. This figure

includes $40 million spent over the last 4 years. In the next 4 years, the industry expects to spend $60 million. The cost includes the amounts spent for all phases of air pollution, including process changes in kraft mills.[85]

Because of the large volumes of gases exhausted from animal rendering plant driers, afterburner fuel requirements are a major consideration in odor pollution control. A drier emitting 3,000 scfm[a] requires about 4,800 scfh[b] of natural gas for 1,200°F incineration. Means of recovering the waste heat include using a steam generator and pre-heating the drier air.[51]

Strauss[265] examined the economics of three control systems for a rendering plant, as shown in Table 47, Appendix B. He concluded that the air-cooled unit (being a single unit) was cheaper to install than the surface condenser and cooling tower combinations which became less economical for operating periods greater than 3 years. The operating costs of the direct spray condenser eliminated it from further consideration in comparison with the other two units. The cost of scrubbing rendering plant gas with potassium permanganate is reported to be $8.40 per day on a

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[a]scfm-standard cubic feet per minute.
[b]scfh-standard cubic feet per hour.

20,000 cfm scrubber using a 1 to 2 percent solution of potassium permanganate.[260]

Many cities in the United States may be faced with sewer-odor problems similar to those in Chicago (see Section 3.4.2). To eliminate the odors emanating from the manholes would be very expensive. The Chicago Sanitary District serves approximately 5,000,000 people and produces industrial wastes equivalent to wastes from 3,000,000 people. Their sewage systems, covering an area of 900 square miles, drain into five major treatment plants. To modernize even one of these--such as the Stickney treatment plant--to handle sewage in a nonoffensive manner would cost over $5,000,000.[229]

6. METHODS OF ANALYSIS

Methods of odor analysis may be divided into two groups: organoleptic, and chemical or instrumental. The organoleptic methods, which rely on detection with the human nose, are completely subjective, but other methods are available to convert the subjective measurements into some meaningful objective results. Chemical or instrumental methods for analyzing odorants--which are numerous--usually suffer from lack of sensitivity. Sensitive noses can detect odors in quantities impossible to identify and monitor with commercially available instrumentation or chemical methods.[164]

6.1 Sampling Methods

Samples may be collected in 250-ml Pyrex gas collecting tubes. The air sample is aspirated with a rubber squeeze bulb into the tube and isolated with stopcocks at both ends of the tube.[26,97]

6.2 Qualitative Methods

Only the nose can measure odor quality, and even then, results are strictly qualitative. The odor surveys that have been conducted are examples of qualitative odor analyses. In these surveys, high school students, firemen, and panelists have been asked to sniff ambient air or air samples and describe the odor quality, strength, and acceptability.[26,97]

6.3 Quantitative Methods

6.3.1 Organoleptic Methods

The most common method used is the vapor dilution technique. With this method, a sample is usually taken at the sampling station (in ambient air, a plant waste-gas stream, or any other desired sampling point) with a gas sampling tube. The sample is then returned to the laboratory, where it is diluted, usually by means of a syringe, and presented to a panel of observers for evaluation of the odor threshold dilution.[26,162,164,256]

A modification of this method is the syringe dilution technique. The sample is collected in a syringe and removed in part to another syringe for dilution to produce a test dilution for human appraisal. Sensitivity limits this method to use with nonambient odors. However, it has the advantage of being simple and easily portable. Benforado et al.[26] consider removal of the samples to the laboratory for analysis an advantage, but Gruber et al.[97] believe this to be a disadvantage.

The vapor dilution method may be a static method, a continuous method, or a volatilization technique. Some instruments that have been based on the vapor dilution

method, using the human nose as the detector, are listed below:

> (1) <u>Static Method</u>
> Checkovich-Turner Osmometer[164]
> Barail Osmometer[21]
> Elsberg-Levy Olfactometer[74,75]
> Fair-Wells Osmoscope[202]
>
> (2) <u>Continuous Method</u>
> Allison-Katz Odorimeter[83]
> Zwaardemaker Olfactometer[312]
> Procter and Gamble Osmo[102]
> Scentometer[97]
> Nader Odor Evaluation Apparatus[196]
>
> (3) <u>Volatilization Technique</u>
> Flask Dilution Method[135]
> Enclosed Sniff-Blotter Technique[164]

Of these instruments, the scentometer requires special mention because it is portable, inexpensive, and requires only one man for its operation. However, this last advantage may become a disadvantage when it is desirable to have the opinion of an odor panel rather than a single person. The instrument has several ports which allow air to pass through activated charcoal to provide "clean" air for dilution with the odorous air sample. By opening and closing the ports, the operator can adjust the dilution threshold concentration. Moreover, he can breathe "clean" air to allow his nose to recover from olfactory fatigue, the main problem associated with sniffing.

Other methods, based on such properties as vapor adsorption, liquid dilution, and diffusion, are the following:

(1) The <u>vapor adsorption and breakthrough method</u> is based upon the time required for odor to "break through" an adsorber column of known volume. The Moncrieff Adsorption Unit is based on this technique.[187]

(2) The <u>liquid dilution method</u> uses an odorless solvent to dilute the odorous material, and the human appraisal is made on either the flask of diluent or on fractions of the diluent. The Elsberg-Levy Olfactometer[74,75] and Foster-Smith-Scofield Stimulator[83] use this technique.

(3) The <u>rate of diffusion method</u> requires the odorant to be placed on an adsorptive surface at the end of a diffuser column which encloses odorless, static air. Rates of diffusion may be measured by determining the time required by the odorant to diffuse through the full length of the tube (Ramsey Unit[223]) or the diffusion time may be detected as the odorant passes sniff ports along the length of the tube (Snell Laboratory Air Force Unit[90]).

Turk[285] has described a method for determining the intensity and character of diesel exhaust odors. In this

method an odor panel is screened by giving each person a triangle test and intensity test. The triangle test consists of allowing each person to sniff five sets of three samples. Two of three samples are identical, while the third is different. He must detect which sample is different. The intensity test requires the person to rank in intensity a solution of odorant with a series of dilutions of the same odorant. Panelists selected are then asked to compare diesel exhaust gases with standards. In Turk's method, the standards were 32 liquids contained in polyethylene bottles. The head gas expelled by squeezing the bottles served as the reference odors. Overall exhaust odor intensity was rated on a 1 to 12 scale, and the qualities "burnt," "oily," "pungent," and "aldehyde/aromatic" were each rated on a 0 to 4 scale representing the following intensities: none, slight, moderate, strong, and extreme.

Duffee[65] reports that Battelle has developed a sniff kit for rendering plant odors. Methyl disulfide is presented to a human odor panel at five concentrations, ranging from 0.001 to 10 percent, for comparison with the rendering odors. He claims that the kit may be used by a single untrained observer to determine the effectiveness of odor control systems for rendering odorants or to compare odorant

sources within or between plants.

6.3.2 Instrumental Methods

Gas chromatography has been exploited by several investigators[16,32,81,243] as a means of measuring odorants in the range of the odor threshold concentration of the mercaptans. Applebury and Schaer[16] have reported successful results. They used a 40-ml sample and a Porapak Q column (1/4" x 6') at 90°C. The detector was a coulometric cell with platinum electrodes similar to a design recommended by Adams et al.[3] The reported minimum detectable concentrations were the following:

Hydrogen sulfide	0.1 ppm,	150 $\mu g/m^3$
Methyl mercaptan	0.5 ppm,	1,000 $\mu g/m^3$
Sulfur dioxide	0.5 ppm,	650 $\mu g/m^3$

Stevens et al.[261a] have developed a gas chromatography method which they claim can be used to determine the concentration of sulfur dioxide and other odorous gases produced in kraft paper mills. Polyphenyl ether was coated (4 percent) on 30-40 mesh teflon powder containers and packed in 24 feet of teflon tubing. A small amount (0.05 percent) of phosphoric acid was also added. It was found that sulfur dioxide, hydrogen sulfide, methyl mercaptan, and carbon disulfide could be separated by this column with very little loss. A flame photometric detector was used to measure concentrations down to 0.01 ppm.

7. SUMMARY AND CONCLUSIONS

Offensive odors in the air are a major air pollution problem in some areas. These malodors cause many complaints, provoking emotional disturbances, mental depression, and irritability. In some instances health effects such as nausea, vomiting, headache, loss of sleep, loss of appetite, and impaired breathing are induced. Contact with odorants may cause varying degrees of reactions in allergic individuals, particularly children.

Sociologically, odor pollution can interfere with human relations in many ways. It can damage personal and community pride, discourage capital investment, and lower the socioeconomic status of both the individual and the community. Some State, county, and city governments have enacted laws that prohibit the emission of air pollutants which unreasonably interfere with the enjoyment of life and property. However, no odor standard has been established.

No information has been found on the effects of odor air pollution on animals. Odors per se have no effect on plants or materials. However, some odorants such as hydrogen sulfide and sulfur dioxide may affect animals, plants, and materials.

The sources of odors are numerous and include pulp and paper mills, animal rendering plants, sewers and sewage

treatment plants, garbage dumps and incinerators, chemical plants, petroleum refineries, metallurgical plants, and internal combustion engines, particularly diesel and air-craft engines. The most offensive odors come from plants or processes which produce low molecular weight sulfur and nitrogen compounds, such as ethyl- and methyl-mercaptans, hydrogen sulfide, ammonia, and dimethylamine. Environmental air concentrations of obnoxious odorants frequently exceed the odor threshold concentration in some local areas, and the odor has on occasions been recognized 20 miles from the source.

The most generally accepted method of abatement of odors is incineration at the source. However, improper incineration may in itself be a source. Other abatement methods include adsorption, absorption, particulate removal, source elimination, process changes, chemical control, containment, odor masking, odor counteraction, biological control, and dilution.

Economically, noxious odors may stifle the development and growth of a community. Both people and industry desire to locate in a place where it is pleasant to work, live, and play. Tourists shun polluted areas, and rental and real estate property values may decrease. The control

of odor pollution is often very costly to an industry,

depending on the odor problem and the type of industry.

This cost may be reduced by economic benefits derived from

recovered heat or waste products. About $75 million have

been spent for air pollution control in the kraft paper

industry alone.

Both laboratory and field methods have been developed

for measurement of odors at the source and in the ambient

air. The human nose is the only valid odor detector, and

all methods rely on the judgment of one or more people who

make up the odor panel. Only gas chromatography has been

developed to measure hydrogen sulfide, methyl mercaptan, and

sulfur dioxide at concentrations near the odor threshold.

Based on the material presented in this report,

further studies are suggested in the following areas:

(1) Development of odor emission recommendations,

based on the effect of meteorological conditions on rate of

odor emission (odor units per minute).

(2) Measurement of the odor concentrations at

various distances from sources.

(3) Study of the pervasive character of the most

offensive odorants.

(4) Development of methods for detecting the most offensive odorants so that these odorants may be monitored below the odor threshold.

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APPENDIX A
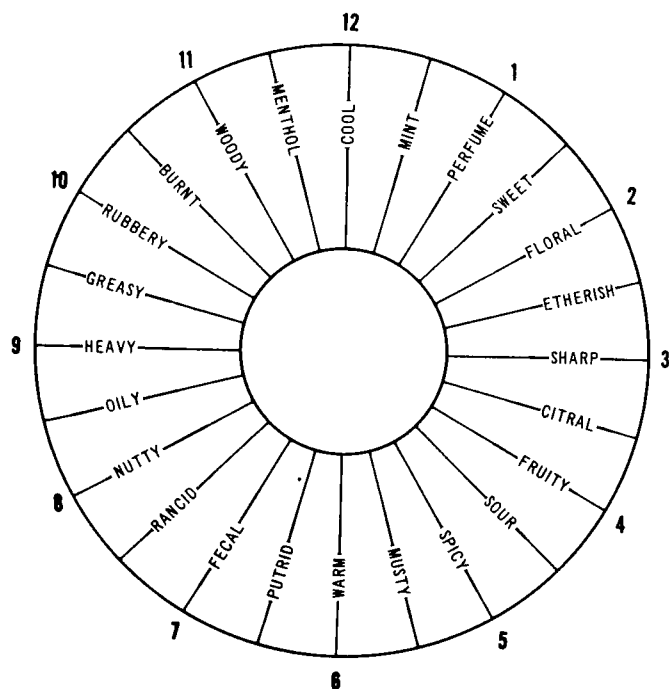
FIGURE 1

Odor Quality Chart 96
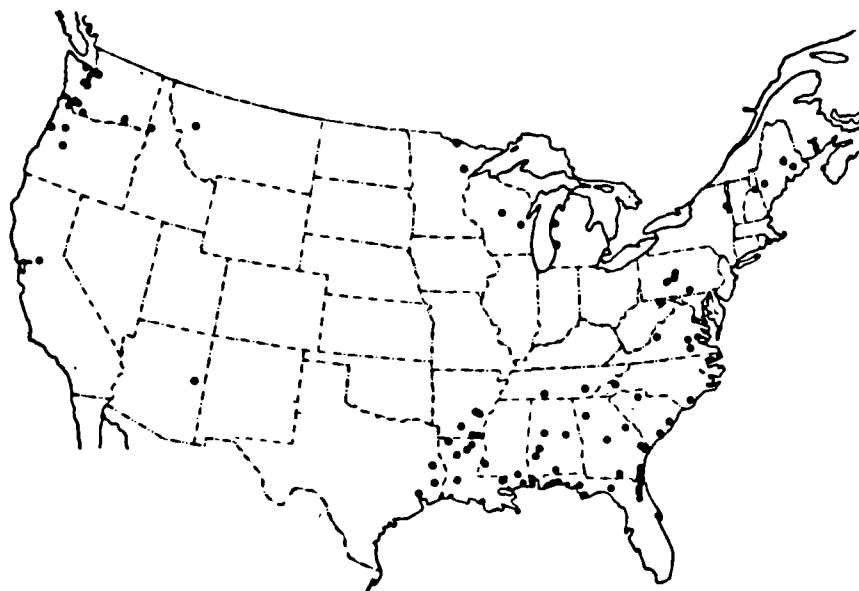
FIGURE 2

Location of Kraft Mills in the United States (1957)[141]
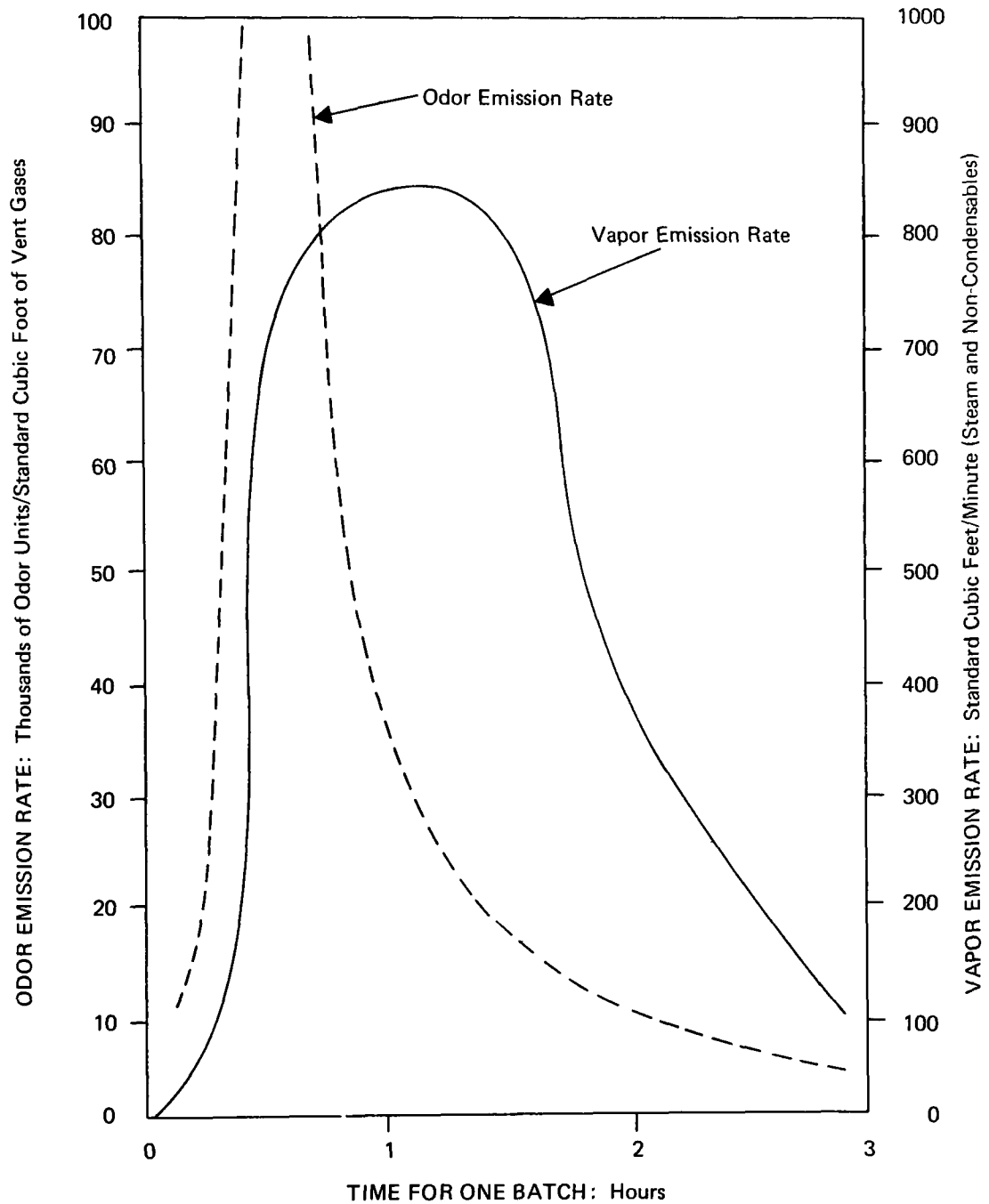
APPENDIX A

FIGURE 3

Typical Rates of Odor Emissions and of Vapor
Emissions from a Batch-Type Rendering Cooker
Reducing Inedible Animal Matter[179]

APPENDIX B

TABLE 1

REPORTED ODOR THRESHOLD CONCENTRATIONS OF HYDROGEN SULFIDE

ppm	$\mu g/m^3$	Reference
0.0011	1.5	125
0.13-1.0	180-1,400	294
0.0047 (from Na_2S)	6.5	134
0.00047 (gas)	0.65	134
0.0072	10	254
0.072	100	4

TABLE 2

RECOGNITION ODOR THRESHOLD OF ODORANTS[154]

Odorant	$\mu g/m^3$	ppm
Acetaldehyde	380^u, 130^v, 400^f	0.066^m, 0.21^u, 0.21 0.07^v, 0.07
Acetephenone	10^d	
Acetic acid		1.0
Acetone	100^d; $770,000^a$	100.0, 320^a
Acrolein	820^v; $4,500^v$; $3,500^j$; 520^v; 800^d; $38,000^f$	$1.8^{r,v}$, 0.21, 0.33^v 1.5^j, 0.21^v
Acrylonitrile		1.56^n, 21.4
"Aktol"	$10,000^f$	
Allyl alcohol	$17,000^f$	
Allyl amine	$67,000^f$	6.2^m
Allyl chloride		0.47
Allyl disulfide	100^f; 0.07^j	0.0001^j
Allyl isocyanide	$4,300^f$	
Allyl isothiocyanate	$1,700^f$	
Allyl mercaptan	500^f, 0.15^j	0.00005^j, 0.0015^m
Allyl sulfide	50^f	
Amine dimethyl		0.047
Amine monomethyl		0.021
Amine trimethyl		0.00021
Ammonia	26^j; 500^d; $37,000^f$	0.037^j; 46.8 53^n
Amyl acetate	$600^{d,f}$	

(continued)

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Amyl alcohol	35,000[a]	10[a]
Amyl isovalerate (iso)	800[f]	
Amyl mercaptan (iso)	300[f]	
Amyl sulfide (iso)	300[f]	
Amylene	6,600[f]	
Amylenes and pentenes		1.8[d]
Anethole	140[o]	
Aniline	370[d]	1.0
Apiole	57[j]	0.0063[j]
Arsine		0.5[r]
Benzaldehyde	3,000[f]; 430[o]	1.3[f], 0.042[m]
Benzene	180,000[a]	3.0[c], 4.68, 60[a]
Benzyl chloride	1,600[f]	0.047
Benzyl mercaptan	190[f]	0.0026[m]
Benzyl sulfide	600[f]	0.0021
Bromacetone	500[f]	
Bromacetophenone	640[f]	
Bromine		0.047
Bromoform		530[l]
i-Butanol	120,000[a]	40[a]

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
1-Butanol		1.00^p
n-Butanol	$33,000^a$	
n-Butyl acetate	$35,000^a$	7^a 0.6^c
i-Butyl acetate	$17,000^a$	4^a
n-Butyl formate	$70,000^a$	17^a
i-Butyl mercaptan		0.00097^e
n-Butyl mercaptan	$40,000^b$; $1,400^f$	0.00072^e
n-Butyl sulfide	$1,100^f$	
t-Butyl mercaptan		0.00009^e
Butylene (beta)	$59,000^f$	
Butylene (gamma)	$50,000^f$	
Butyric acid	1^j	
Camphor	$10,000^j$	1.6^j, 120^l
Carbon disulfide	$80-500^y$; $2,300^j$, 50^d; $2,600^f$	0.21, 0.77^j
Carbon monoxide	d	
Carbon tetrachloride (Chlorination of CS_2)		21.4
Carbon tetrachloride (Chlorination of CH_4)	$1,260,000^a$	100.0, 200^a
Carvone	550^e	
Chloracetophenone	$8,500^f$	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Chloral		0.047
Chlorine	0.01^j; $1,000^d$; $10,000^f$	29^j, 0.314, 3.5^r
Chlorobenzil	400^d	
Chlorophenol	180^f	
Chloropicrin	$7,300^f$	
Chloroprene	400^d	
B-Chlorvinyldi-chlorarsine	$14,000^f$	
Chromium (hexavalent)	d	
Citral	300°	
Coumarine	340^f	
m-Cresol		0.25^p
o-Cresol		0.26^p
p-Cresol	900°	
Creosote		0.031^n
Crotonaldehyde	$21,000^f$	
Crotyl mercaptan	29^f	
Cyclohexanol	d	160^l
Cyanogen chloride	$2,500^f$	
Cyclohexanone	d	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Cycloheptanone		130^l
Diacetyl	88^j	0.025^j
Dichlordiethyl sulfide	$1,300^f$	
1,2-Dichloroethane	$450,000^a; 23,200^d$	110^a
Dichlorethylene (trans)	$4,300^f$	
Diethyl disulfide		.0046
Diethyl ketone	$33,000^a$	
Diethyl sulfide		0.003^k, $.0059^e$
Diethyl trisulfide		$.00085^e$
Diketene	19^d	
Dimethylamine	$1,100^j$	0.6^j
Dimethylacetamide		46.8
Dimethyl disulfide		$.0076^c$
Dimethyl formamide	880^d	100.0
Dimethyl sulfide	51^j	0.004^k, $.0025^e$, 0.001, 0.02^j
Dimethyl trisulfide		$.0014^e$
Dimethyl trithio- carbonate	180^f	
Dinitro-o-cresol	d	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Dinyl	80^d	
Dioxane	$620,000^a$	170^a
Diphenyl chlorarsine	300^f	
Diphenyl ether (perfume grade)	69^f	0.1
Diphenyl cyanarsine	300^f	
Diphenyl oxide	69^o	
Diphenyl sulfide	48^f	0.0047
Diphenylamine chlorarsine	$2,500^f$	
Diphosgene	$8,800^f$	
Di-n-propyl sulfide		$.023^e$, 0.01^k
Di-i-propyl sulfide		$.0038^e$
Dithio-ethylene glycol	$1,600^f$	
Epichlorohydrin	300^d	
Ethanol (synthetic)	93^a	10.0, 50^a
Ethyl acetate	600^d; $180,000^a$	50^a
Ethyl acrylate		0.00047
Ethyl dichlorarsine	$1,000^f$	
Ethyl glycol	$90,000^a$	25^a

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Ethyl isothiocyanate	38,000[f]	
Ethyl mercaptan	30,000[b]; 190[f]; 0.04[j]	0.002[k], 0.0033[k], 0.001, .0004[e], 0.000016[j]
Ethyl methyl disulfide		.014[e]
Ethyl selenide	62[f], 0.35[j]	0.000062[j]
Ethyl seleno mercaptan	1.8[f], 0.008[j]	0.0000018[j], 0.00030[m]
Ethyl sulfide	250[f], 0.92[j]	0.00025[j]
Ethylene dichloride	25,000[f]	
Ethylene oxide	1,500[d]	
Eugenol	3,900[o]	
Fluorides	d	
Formaldehyde	1,200[u]; 60[t]; 70[d]; 72-108[s]	0.06-0.09[s], 1.0, 1.0[u], 0.4-6.6[s,k], 0.05[t]
Furfural	1,000[d]	
Gasoline		10.0[d]
Gasoline (thermal cracked)		3.120[n]
Gasoline-shale	300[bb]	0.3[d]
Heptane	930,000[a]	220[a]
n-Heptyl alcohol		20[l]

(continued)

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Hexamethylenediamine	d	
Hydrochloric acid gas		10.0
Hydrogen chloride	100^d	
Hydrogen cyanide	$1,000^f$	1^r
Hydrogen fluoride	30^d	
Hydrogen selenide	$1,000^j$	0.3^j
Hydrogen sulfide	$14-30^{aa}$; $12-30^z$; 1.5^j; 10^d; $1,100^f$	$.01^y$, 0.00110^j, $0.13-1.0^n$
Hydrogen sulfide (from Na_2S)		0.0047
Hydrogen sulfide gas		0.00047
15-Hydroxy Pentadecanoic acid lactone		270^l
Iodoform	6.1^j	0.00037^j
Ionone	0.0046^j	0.000000059^j
Isopropyl benzene	60^d	0.029^d
Isoamyl isovalerate	800^o	
Isoborhylacetate	440^o	
Isopropyl hydro-peroxide	30^d	
Lead	d	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Lead sulfide	d	
Linalyl acetate		10^l
Maleic anhydride	$1,000^d$	
Mercury	d	
Methanol	$7,800,000^a$; $4,300^d$	100.0; $5,900^a$
Methyl acetate	500^d; $550,000^a$	200^a
Methyl anthranilate	370^f	
Methyl chloride		(Above 10 ppm)
Methyl dichlorarsine	800^f	
Methyl ethyl ketone	$80,000^a$	10.0, 25^a
Methyl formate	$5,000,000^a$	$2,000^a$
Methyl glycol	$190,000^a$	60^a
Methyl isobutyl ketone	$32,000^a$	0.47, 8^a
Methyl mercaptan	$1,100^f$; 2.2^j	0.0011^j, 0.04^k, 0.041^m, 0.0021, $.00099^e$
Methyl methacrylate		0.21
Methyl n-nonyl ketone		500^k
Methyl propyl ketone	$27,000^a$	8^a
Methyl salicylate	$120,000^O$	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Methyl sulfide	1,100[f]	
Methyl thiocyanate	9,600	
Methylene chloride	550,000[a]	214.0, 150[a]
Mineral spirits	150,000[a]	30[a]
Monochlorobenzene		0.21
Musk, synthetic	0.005[j]	0.00000042[j]
Nitrobenzene	18.2[d]; 30,000[f]	0.0047
Nitrogen dioxide		4.0, 1-3[x]
Nitrogen oxides	d	
Octane	710,000[a]	150[a]
Oxidized oils	1,100[f]	
Ozone	200[j]; 1,000[f]	0.02-0.05[r], 0.02[g], 0.005[h], 2.0[h], 0.5[h], 0.012[h], 0.01[i], 0.1[j]
Paracresol		0.001
Paraxylene		0.47
Perchloroethylene		4.68
Phenol	1,200[j]; 184[d]	4.2[p], 15[l], 0.047, 0.3[j]
Phenyl isocyanide	29[f]	
Phenyl isothiocyanate	2,400[f]	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Phosgene	4.400^f	5.6^r, 1.0
Phosphine		0.021
Polychloroprene suspension		0.025^n
n-Propanol	$80,000^a$	30^a
i-Propanol	$90,000^a$	40^a
Propionaldehyde	$2,000^f$	
n-Propyl acetate	$70,000^a$	20^a
i-Propyl acetate	$140,000^a$	30^a
n-Propyl mercaptan	$30,000^a$; 75^f; 0.23^j	0.000075^j, $.00075^e$. 0.02^k
i-Propyl mercaptan		$.00045^e$
b-Propyl sulfide	810^f	
Pyridine	40^j; 210^d; $3,700^f$	0.82^p, 0.021, 0.012^j, 0.23^m
Skatole	0.0004^j; $9,000^f$	0.000000075^j, 0.019^m
Styrene (inhibited)		0.1
Styrene (uninhibited)		0.017^n, 0.047
Styrol	36^d	
Sulfur dichloride		0.001
Sulfur dioxide	$7,900^j$; 870^d	$.03-1.0^r$, 0.47, 3.0^j

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Sulfuric acid	600[d]	
Tetrachloroethylene	320,000[a]	50[a]
Tetradodecyl mercaptan	9,000,000[b]	
Tetrahydrofurane	90,000[a]	30[a]
Thiocrespol	100[f]	
Thiophane		.00077[e]
Thiophenol	62[f]	
Thiophenol mercaptan		0.00026[m]
Tolvene		0.25[n]
Tolvene (from coke)	140,000[a]	4.68, 40[a]
Tolvene (from petroleum)		2.14
Tolvene diisocyanate	200[d]	
1,1,1-Trichloroethane	2,100,000[a]	400[a]
Trichloroethylene	135,000[j]; 440,000[a]	21.4, 80[a], 25[j]
Trimethylamine	9,600[j]	0.4[j]
Trinitro butyl xylene	10[f]	
Valeric acid vapor	d	
Valeric acid	2.6[j]	0.00062[j]
Vanadium pentoxide	d	

TABLE 2 (Continued)

RECOGNITION ODOR THRESHOLD OF ODORANTS

Odorant	$\mu g/m^3$	ppm
Vanillin	0.0002[j]	0.000000032[j]
Vinyl acetate	1,000[d]	
m-Xylene		1.1[p]
o-Xylene		1.8[o]
p-Xylene		0.53[p]
Xylene	100,000[a]	
Xylol	730[d]	

[a]Reference 167.
[b]Reference 10.
[c]Reference 259.
[d]Reference 260.
[e]Reference 298.
[f]Reference 4.
[g]Reference 128.
[h]Reference 289.
[i]Reference 35.
[j]Reference 125.
[k]Reference 81.
[l]Reference 166.
[m]Reference 272
[n]Reference 255.

[o]Reference 93.
[p]Reference 236.
[r]Reference 294.
[s]Reference 174.
[t]Reference 264.
[u]Reference 36.
[v]Reference 137.
[w]Reference 36.
[x]Reference 209.
[y]Reference 63.
[z]Reference 87.
[aa]Reference 19.
[bb]Reference 308.

TABLE 3

ODOR ADDITION OR SYNERGISM IN MIXTURES[236]

| Test | Fraction of Odor Threshold Concentration When Odor Could Be Perceived in the Mixture | | | |
	Butanol[a]	p-Cresol[a]	Pyridine[a]	Mixture Total[b]
1	0.46		0.53	0.99
2	0.37	0.14	0.42	0.93
3	0.35	0.40		0.75
4	0.24	0.19	0.29	0.72
5	0.18	0.21	0.21	0.60
6	0.15	0.09	0.26	0.50
7	0.12	0.21	0.07	0.40

[a]Fraction $= \dfrac{\text{measured concentration}}{\text{odor threshold concentration}}$

[b]Mixture Total $= \dfrac{\text{total measured concentration}}{\text{additive odor threshold concentration}}$
when the odor of the mixture could be perceived.

TABLE 4

CROCKER-HENDERSON ODOR CLASSIFICATION STANDARDS*[170]

Fragrant
    1112   n-Butyl phthalate
    2424   Toluene
    3336   a-Chlornaphthalene
    4344   a-Naphthyl methyl ether
    5645   Cymene
    6645   Citral
    7343   Safrole
    8453   Methyl salicylate

Acid
    7122   Vanillin
    7213   Cinnamic acid
    5335   Resorcinol dimethyl ether
    2424   Toluene
    5523   Isobutyl phenylacetate
    5626   Methyl phenylacetate
    5726   Cincole
    3803   Acetic acid (20 percent solution)

Burnt
    5414   Ethyl alcohol
    7423   Phenylethyl alcohol
    5335   Resorcinol dimethyl ether
    4344   a-Naphthyl methyl ether
    4355   Veratrole
    6665   Thujone
    4376   Paracresyl acetate
    7584   Guaiacol

Caprylic
    ----   No suitable standard found
    7122   Vanillin
    7343   Safrole
    5624   Phenylacetic acid
    5615   Cymene
    3336   a-Chlornaphthalene
    2577   Anisole
    3518   2,7-Dimethyl octane

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*A single substance may serve for several standards. The substances included in this table have been chosen because they are reasonably reproducible in odor from lot to lot, safe to breathe in quantities required for comparison, readily available from chemical sources, and reasonably stable against changes in use or on standing.

TABLE 5

AMOORE CLASSIFICATION OF ODOR QUALITY[12]

Odor	No. of Compounds
1. Camphoraceous	106
2. Pungent	95
3. Ethereal	53
4. Floral	71
5. Pepperminty	77
6. Musky	69
7. Putrid	49
8. Almond	30
9. Aromatic	27
10. Aniseed	12
11. Lemon	7
12. Cedar	7
13. Garlic	7
14. Rancid	6
Total	616

TABLE 6

ODOR QUALITIES OF SELECTED ODORANTS[190]

Compound	Formula	Odor Quality
INORGANIC COMPOUNDS		
Ammonia	NH_3	Ammoniacal
Antimony compounds		Garlic
Arsine	AsH_3	Garlic
Bismuth compounds		Garlic
Carbon dioxide	CO_2	Odorless
Carbon disulfide	CS_2	Strong objectionable odor
Carbon monoxide	CO	Faint, garlic
Chlorine monoxide	Cl_2O	Chlorine
Chlorine peroxide	ClO_2	Unpleasant
Cyanogen	C_2N_2	Faint, peach
Hydrochloric acid	HCl	Halogen
Hydrochromic acid	HBr	Halogen
Hydrofluoric acid	HF	Halogen
Hydrogen cyanide	HCN	Bitter almonds

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Hydrogen peroxide	H_2O_2	Odorless
Hydrogen persulfide	H_2S_2	Pungent, irritating odor
Hydrogen selenide	H_2Se	Garlic
Hydrogen sulfide	H_2S	Rotten eggs
Hydroiodic acid	HI	Halogen
Hydroxylamine	NH_2OH	Odorless
Hydrozoic acid	N_3H	Penetrating, unpleasant
Monocloramine	NH_2Cl	Penetrating
Nitrogen dioxide	NO_2	Strong, irritating
Nitrous oxide	N_2O	Faint, pleasant odor
Phosgene	$COCl_2$	Faint, musty hay
Phosphine	PH_3	Decayed fish
Phosphorus compounds		Garlic
Selenium compounds		Garlic
Silicon fluoride	SiF_4	Pungent

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Stannic chloride	$SuCl_4$	Pungent
Sulfur chloride	S_2Cl_2	Pungent
Thiophosgene	$CSCl_2$	Powerful fetid smell
Titanic chloride	$TiCl_4$	Pungent
	HYDROCARBONS	
Methane	CH_4	Odorless
Ethane	C_2H_6	Practically odorless
Propane	C_3H_8	Practically odorless in concentrations below inflammable limits
Butane	C_4H_{10}	
Hexane	C_6H_{14}	Easily noticeable
Heptane	C_7H_{16}	Easily noticeable
Octane	C_8H_{18}	Powerful gasoline odor
Nonane	C_9H_{20}	Powerful gasoline odor
Decane	$C_{10}H_{22}$	Powerful gasoline odor
Ethylene	C_2H_4	Ethereal

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Acetylene	C_2H_2	Garlic
Cyclohexane	C_6H_{12}	Bland, fatty benzene
Cyclohexene	C_6H_{10}	Pungent
1,3-Cyclohexadiene	C_6H_8	Strong, pungent
1,4-Cyclohexadiene	C_6H_8	Weak, pungent
Benzene	C_6H_6	Odor of dry-cleaning agent
Naphthalene	$C_{10}H_8$	Odor of mothballs
Diphenylmethane	$(C_6H_5)_2CH_2$	Odor of geraniums when dilute; also said to resemble oranges
Dibenzyl	$C_6H_5CH_2CH_2CH_5$	Fragrant
Limonene	$CH_2CH_2C(CH_3)CH\ CH_2CH\ C(CH_2)CH_3$	Agreeable lemonlike odor

OFFENSIVE ODORANTS

Ammonia	NH_3	Ammoniacal
Methyl amine	CH_3NH_2	Fishy
Dimethyl amine	$(CH_3)_2NH$	Fishy

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Trimethyl amine	$(CH_3)_3N$	Fishy
Ethyl amine	$CH_3CH_2NH_2$	Fishy
Diethyl amine	$(CH_3CH_2)_2NH$	Fishy
Triethyl amine	$(CH_3CH_2)_3N$	Fishy
Putrescine	$NH_2(CH_2)_4NH_2$	Decayed flesh
Cadaverine	$NH_2(CH_2)_5NH_2$	Decayed flesh
Hydrogen sulfide	H_2S	Rotten eggs
Methyl mercaptan	CH_3SH	Skunk
Ethyl mercaptan	CH_3CH_2SH	Skunk
n-Propyl mercaptan	$CH_3CH_2CH_2SH$	Skunk
n-Butyl mercaptan	$CH_3(CH_2)_3SH$	Skunk
Dimethyl sulfide	$(CH_3)_2S$	Rotten cabbage
Diethyl sulfide	$(CH_3CH_2)_2S$	Rotten cabbage
Methyl ethyl sulfide	$CH_3SCH_2CH_3$	Rotten cabbage
Dimethyl disulfide	CH_3SSCH_3	Rotten cabbage

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Diethyl disulfide	$(CH_3CH_2S)_2$	Rotten cabbage

<div align="center"><u>ALCOHOLS AND PHENOLS</u></div>

Compound	Formula	Odor Quality
Geraniol	$(CH_3)_2C:CH \cdot CH_2 \cdot CH_2 \cdot C(CH_3):CH \cdot CH_2OH$	Roses
Linalool	$(CH_3)_2C:CH \cdot CH_2 \cdot CH_2 \cdot C(CH_3)OH \cdot CH:CH_2$	Fragrant
p-Cresol	$CH_3-C_6H_4-OH$	Strong
o-Cresol	$CH_3-C_6H_4OH$	Intermediate
m-Cresol	$CH_3-C_6H_4OH$	Weak
2-4 Xylen-1-ol	$(CH_3)_2C_6H_3OH$	Faint
2-5 Xylen-1-ol	$(CH_3)_2C_6H_3OH$	Mild cresolic odor
3-5 Xylen-1-ol	$(CH_3)_2C_6H_3OH$	Strong cresolic odor
3-4 Xylen-1-ol	$(CH_3)_2C_6H_3OH$	Dull, musty
2-6 Xylen-1-ol	$(CH_3)_2C_6H_3OH$	Oil of wintergreen
Ethanol	C_2H_5OH	Sweet spiritous odor
Nonanol	$C_9H_{19}OH$	Strong, disagreeable
Cetyl alcohol	$C_{16}H_{33}OH$	Faint, ethereal, waxy

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Allyl alcohol	$CH_2:CH\ CH_2OH$	Irritating
Propargyl alcohol	$CH=C \cdot CH_2OH$	Agreeable
Oleyl alcohol	$CH_3(CH_2)_7CH:(CH_2)_7CH_2OH$	Faint, waxy
Glycol	$CH_2OH\ CH_2OH$	Odorless
Glycerol	$CH_2OH \cdot CHOH \cdot CH_2OH$	Odorless
Benzyl alcohol	$C_6H_5CH_2OH$	Faint aromatic odor
Phenylethyl alcohol	$C_6H_5CH_2CH_2OH$	Constituent of rose perfume
Cinnamyl alcohol	$C_6H_5CH:CH\ CH_2OH$	Weak, pleasant hyacinth odor
Menthol	$(CH_2)_2CH(CH_3)CH_2CH(OH)CH\ CH(CH_3)$	Peppermint odor
Terpineol	$(CH_2)_2C(CH_3)CHCH_2CH\ C(CH_3)_2OH$	Lilac odor
Phenol	C_6H_5OH	Carbolic, disinfectant odor
Xylenol	$C_6H_3(CH_3)_2OH$	Similar, less sharp
Resorcinol	$1 \cdot 3 \cdot C_6H_4(OH)_2$	Odorless

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
	ETHERS	
Heptyl hexyl ether	$C_7H_{15}OC_6H_{13}$	Odor like bluebell stalks
Heptyl heptyl ether	$C_7H_{15}OC_7H_{15}$	Odor like wet wool
Heptyl undecyl ether	$C_7H_{15}OC_{11}H_{23}$	Fugitive odor of fatty aldehydes
Heptyl phenyl ether	$C_7H_{15}OC_6H_5$	Odor of opoponax
3,7-Dimethyl-e-methoxy-oct-6-en-1-yn		Bergamot
3,7-Dimethyl-3-ethoxy-oct-6-en-1-yn		Bergamot
3,7-Dimethyl-3-amyloxy-oct-6-en-1-yn		Jasmine
3,7-Dimethyl-3-allyloxy-oct-6-en-1-yn		Jasmine and fruity
3,7-Dimethyl-3-benzyloxy-oct-6-en-1-yn		Cinnamon
3,6,7-Trimethyl-6-methoxy-oct-6-en-1-yn		Nutmeg
3,7-Dimethyl-3-propargyloxy-oct-6-en-1-yn		Rosewood
3,7,11-Trimethyl-3-methoxy-dodeca-6,10-dien-1-yn		Lily
3,7,11-Trimethyl-3-allyloxy-dodeca-6,10-dien-1-yn		Lily, fruity

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
3-Methyl-3-methoxy-6-cyclohexyliden-hex-1-yn		Vetiver
3-Methyl-3-allyloxy-6-cyclohexyliden-hex-1-yn		Coriander
Diethyl ether	$C_2H_5OC_2H_5$	Sweet spiritous
Heptyl hexyl ether	$C_7H_{15}OC_6H_{13}$	Bluebell stalks
Anisole	$CH_3OC_6H_5$	Fragrant, overpowering
Phenetole	$C_2H_5OC_6H_5$	Fragrant, aromatic
Diphenyl ether	$C_6H_5OC_6H_5$	Geraniums when dilute
CARBOXYLIC ACIDS		
Formic acid	$H \cdot COOH$	Pungent, irritating
Acetic acid	$CH_3 \cdot COOH$	Penetrating; vinegar when dilute
Butyric acid	$CH_3(CH_2)_2 \cdot COOH$	Disagreeable
Isobutyric acid	$(CH)_2CH \cdot COOH$	More disagreeable
Palmitic acid	$C_{15}H_{31} \cdot COOH$	Odorless

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(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Acrylic acid	$CH_2:CH \cdot COOH$	More pungent than acetic
Crotonic acid	$CH_3 \cdot CH:CH \cdot COOH$	Acrid, butyric
Oleic acid	$CH_3 \cdot (CH_2)_7 \cdot CH:CH \cdot (CH_2)_7 \cdot COOH$	Odorless
Propiolic acid	$CH=C \cdot COOH$	Acrylic
Lactic acid	$CH_3 CHOH \cdot COOH$	Odorless
Succinic acid	$COOH \cdot (CH_2)_2 \cdot COOH$	Odorless
Tricarballylic acid	$COOH \cdot CH_2 \cdot CH \ COOH \cdot CH_2 COOH$	Odorless
Phenylacetic acid	$C_6H_5 \cdot CH_2 COOH$	Weak civet
Benzoic acid	$C_6H_5 \cdot COOH$	Odorless
Hexahydrobenzoic acid	$C_6H_{11} \cdot COOH$	Rancid

ESTERS

Propyl acetate	$C_3H_7 \cdot O \cdot CO \cdot CH_3$	Like pears
Amyl acetate	$C_3H_{11} O \cdot CO \cdot CH_3$	Like Jargonelle pears
Isoamyl acetate	$(CH_3)_2 CH \cdot CH_2 \cdot CH_2 \cdot O \cdot CO \cdot CH_3$	Like pears

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Ethyl butyrate	$C_2H_5 \cdot O \cdot CO \cdot C_3H_7$	Like pineapples
Isoamyl isovalerate	$(CH_3)_2CH \cdot C_2H_4 \cdot O \cdot CO \cdot C_4H_9$	Like apples
Heptyl formate	$C_7H_{15} \cdot O \cdot CO \cdot H$	Fruity
Heptyl acetate	$C_7H_{15} \cdot O \cdot CO \cdot CH_3$	Fruity
Heptyl isobutyrate	$C_7H_{15} \cdot O \cdot CO \cdot C_3H_7$	Cyclamen-camomile
Heptyl caproate	$C_7H_{15} \cdot O \cdot CO \cdot C_5H_{11}$	Bruised green leaves
Heptyl undecylate	$C_7H_{15} \cdot O \cdot CO \cdot C_{10}H_{21}$	Smoke, ink
Heptyl salicylate	$C_7H_{15} \cdot O \cdot CO \cdot C_6H_4OH$	Steel
Heptyl geranate	$C_7H_{15} \cdot O \cdot CO \cdot C_9H_{15}$	Hawthorn, mimosa
Methyl acetate	$CH_3OCO\ CH_3$	Fragrant
Ethyl acetate	$C_2H_5OCO\ CH_3$	Fragrant
Octyl acetate	$C_8H_{17}OCO\ CH_3$	Orange
Diethyl adipate	$C_2H_5OCO\ (CH_2)_4 \cdot OCOC_2H_5$	Fruity
Ethyl hydrogen adipate	$C_2H_5OCO\ (CH_2)_4COOH$	Fruity

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Triethyl citrate	$(C_2H_5OCOCH_2)_2C(OH)COOC_2H_5$	Fruity
Melissyl palmitate	$C_{30}H_{61}OCO\ C_{15}H_{31}$	Odorless
Benzyl acetate	$C_4H_5CH_2OCO\ CH_3$	Jasmine
Methyl salicylate	$CH_3OCO\ C_6H_4OH$	Oil of wintergreen
Amyl salicylate	$C_5H_{11}OCO\ C_6H_4OH$	Clover

<div align="center">ALDEHYDES</div>

Compound	Formula	Odor Quality
Alpha-methyl cinnamaldehyde	$C_0H_5\ CH:C(CH_3)CHO$	Gentle cinnamon, grassy
Alpha-ethyl cinnamaldehyde	$C_6H_5\ CH:C(C_2H_5)CHO$	Mild cinnamon, nasturtium
Alpha-n-propyl cinnamaldehyde	$C_8H_5\ CH:C(C_3H_7)CHO$	Sweet, faintly animal
Alpha-n-butyl cinnamaldehyde	$C_8H_5\ CH:C(C_4H_9)CHO$	Strong, fatty, green
Alpha-n-amyl cinnamaldehyde	$C_8H_5\ CH:C(C_5H_{11})CHO$	Very powerful, jasmine
Alpha-n-hexyl cinnamaldehyde	$C_6H_5\ CH:C(C_6H_{13})CHO$	Less powerful, jasmine, green
Alpha-n-heptyl cinnamaldehyde	$C_6H_5\ CH:C(C_7H_{15})CHO$	Sweet
Alpha-n-octyl cinnamaldehyde	$C_6H_5\ CH:C(C_8H_{17})CHO$	Faint, almond, no longer green

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Alpha-n-decyl cinnamaldehyde		Very faint
Formaldehyde	$H \cdot CHO$	Pungent formalin
Paraformaldehyde	$(CH_2O)_n$	Mild formalin
Acetalehyde	CH_3CHO	Pungent
Acrolein	$CH_2:CH\ CHO$	Irritating, snuffed candle
Propiolaldehyde	$CH\equiv C \cdot CHO$	Irritating
Stearaldehyde	$C_{17}H_{35}CHO$	Faint waxy
Geranial (citral)	$(CH_3)_2C:CH\ C_2H_4C(CH_3):CH\bullet CHO$	Lemon
Glycollic aldehyde	$CH_2OH \cdot CHO$	Odorless
Benzaldehyde	C_6H_5CHO	Bitter almonds
Cinnamic aldehyde	$C_6H_5CH:CH\ CHO$	Cinnamon
Piperonal	$CH_2O_2C_6H_3CHO$	Heliotrope
Phenylethyl aldehyde	$C_6H_5CH_2CHO$	Hyacinth
Salicylaldehyde	$o-HO\ C_6H_4CHO$	Spirea

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Aubepine	$p-CH_3O\ C_6H_4CHO$	Hawthorn
Vanillin	$CHO-C_6H_3-OH\ OCH_3$	Vanilla
Furfural	$C_4H_3O \cdot CHO$	New bread
Alpha-Amyl cinnamic (jasmine) aldehyde	$C_6H_5-CH:C(C_5H_{11})CHO$	Jasmine

ACETALS

Alpha, beta-dihydroxypropane	$CH_2OH \cdot CHOH \cdot CH_3$	The acetal smells of fresh roses
Alpha, beta-dihydroxybutane	$CH_2OH \cdot CHOH \cdot C_2H_5$	The acetal smells of hyacinths
Alpha, gamma-dihydroxybutane	$CH_2OH \cdot CH_2 \cdot CHOH \cdot CH_3$	The acetal smells of hyacinths
2:4 dihydroxy-4-methylpentane	$CH_3 \cdot CHOH \cdot CH_2C(OH)CH_3 \cdot CH_3$	Mignonette

HALIDES

Methyl chloride	CH_3Cl	Ethereal
Methylene chloride	CH_2Cl_2	Ethereal

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Chloroform	$CHCl_3$	Sweet, ethereal
Iodoform	CHI_3	Saffron
Chlorobenzene	$C_6H_5 \cdot Cl$	Mild
p-Dichlorbenzene	$C_6H_4-Cl_2$	Camphor, naphthalene
Benzyl chloride	$C_6H_5 \cdot CH_2Cl$	Stupefying
Hexachlorethane	C_2Cl_6	Camphoraceous
	AMINES	
Methylamine	$CH_3 \cdot NH_2$	Ammonia, boiled lobsters
Trimethylamine	$(CH_3)_3 \cdot N$	Herring brine
Triethanolamine	$(C_2H_4OH)_3N$	Oily, slightly fishy
Tetraethylammonium hydroxide	$(C_2H_5)_4N \cdot OH$	Odorless
Aminovaleric acid	$NH_2 \cdot (CH_2)_4COOH$	Odorless
Cadaverine	$NH_2 \cdot (CH_2)_5NH_2$	Decaying flesh
Benzylamine	$C_6H_5 \cdot CH_2 \cdot NH_2$	Ammoniacal

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Aniline	$C_6H_5 \cdot NH_2$	Gas, lime
Diphenylamine	$(C_6H_5)_2NH$	Floral
Anthranilic acid	$C_6H_4NH_2-COOH$	Odorless
Methyl anthranilate	$C_6H_4NH_2- COOCH_3$	Orange blossom, jasmine
	NITROGEN COMPOUNDS	
Methyl nitrate	$CH_3 \cdot O \cdot NO_2$	Pleasant ester
Methyl nitrite	$CH_3 \cdot O \cdot NO$	Powerful, oppressive
Nitromethane	$CH_3 \cdot NO_2$	Pleasant
Beta-Nitrohexane	$CH_3 \cdot (CH_2)_3 \cdot CH(NO_2) \cdot CH_3$	Aniseed
Nitrobenzene	$C_6H_5 \cdot NO_2$	Coarse, bitter almonds
Acetamide	$CH_3 \cdot CO \cdot NH_2$	"Mice" usually, odorless if pure
Methyl cyanide	$CH_3 \cdot CN$	Agreeable, reminiscent of prussic acid
Sebacic dinitrile	$CN(CH_2)_8CN$	Unpleasant, nutty

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Ethyl carbylamine	$C_2H_5N:C$	Offensive, nauseating
Phenylhydrazine	$C_6H_5 \cdot NH \cdot NH_2$	Pleasant, aromatic
Diazomethane	CH_2N_2	Odorless
Tetraethyl tetrazine	$(C_2H_5)_2N \cdot N:N \cdot N(C_2H_5)_2$	Alliaceous

SULFUR COMPOUNDS

Compound	Formula	Odor Quality
Allyl sulfide	$(CH_2:CH \cdot CH_2)_2S$	Garlic
Allyl isothiocyanate	$CH_2:CH \cdot CH_2N:CS$	Mustard
Ethyl isothiocyanate	$C_2H_5 \cdot N:CS$	Mustard
Ethyl thiocyanate	$C_2H_5 \cdot S \cdot C:N$	Onions
Ethyl sulfite	$(C_2H_5O)_2 \cdot SO$	Peppermint
Diethyl sulfate	$(C_2H_5O)_2 \cdot SO_2$	Heavy, sweet, ethereal
Amyl mercaptan	$C_5H_{11} \cdot SH$	Powerful, unpleasant
Mustard gas	$(ClCH_2 \cdot CH_2)_2S$	Horseradish

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Phenyl thiocarbimide	$C_6H_5N:CS$	Mustard
p-Thiocarbimide benzaldehyde	$CHO-C_6H_4-N:CS$	Cherry pie
m-Tolyl thiocarbimide	$CH_3-C_6H_4NCS$	Pungent
p-Tolyl thiocarbimide	$CH_3-C_6H_4-N:CS$	Sweet anise

HETEROCYCLIC COMPOUNDS

Compound	Formula	Odor Quality
Ethylene oxide	$(CH_2)_2O$	Sweet, ethereal
Ethylene imine	$(CH_2)_2NH$	Ammoniacal
Succinic anhydride	$(CH_2CO)_2O$	Suffocating
Butyrolactone	$CH_2CH_2CH_2OCO$	Faintly aromatic
Furfular	C_4H_3OCHO	New bread
Thiophen	C_4H_4S	Faint, neutral
Pyrrol	C_4H_4NH	Chloroform
Pyridine	C_5H_5N	Rank, unpleasant

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Quinoline	C_9H_7N	Aromatic, aniseed
Piperidine	$C_5H_{10}NH$	Ammoniacal, pungent
Dioxane	$C_4H_8O_2$	Faint, sweet, ethereal
Morpholine	C_4H_8ONH	Faint, ammoniacal
Piperazine	$C_4H_8(NH)_2$	Bitter odor like dandelions, slightly ammoniacal
Alpha-Phenylpropyl pyridine	$C_6H_5(CH_2)_3-C_6H_5N$	Roses
Gamma-Propyl pyridine	$C_3H_7C_5H_5N$	Violets
Indole	C_8H_6NH	Alpha-Naphthylamine when concentrated, but jasmine when dilute
Skatole	$C_8H_5NH(CH_3)$	Fecal
Coniine	$C_3H_7C_5H_7NH$	Stupefying
Nicotine	$C_5H_4NC_4H_7NCH_2$	Rank, tobacco
Thiazole	C_3H_2NS	Pyridine

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Benzothiazole	C_6H_4NSCH	Quinoline
2-Phenylbenzothiazole	$C_6H_4NSC \cdot C_6H_5$	Tea rose
Benzoxazole	C_6H_4NOCH	Tobacco
Pyridazine	$C_4H_4N_2$	Pyridine
	MACROCYCLIC COMPOUNDS	
Compounds with	9-12 atom rings	Camphor or mint
"	13 atom rings	Woody or cedar-like
'	14-15-16 atom rings	Musk
" "	17-18 atom rings	Civet
" '	More than 18-19 atom rings	Odor practically disappears
Decamethylene oxalate (14-atom ring)	$(CH_2)_{10}O_2(CO)_2$	Fresh, musk-like
Undecamethylene oxalate (15-atom ring)	$(CH_2)_{11}O_2(CO)_2$	Musk odor

(continued)

TABLE 6 (Continued)

ODOR QUALITIES OF SELECTED ODORANTS

Compound	Formula	Odor Quality
Decamethylene malonate (15-atom ring)	$(CH_2)_{10}O_2(CO)_2CH_2$	Faint musk
Ethylene sebacate (14-atom ring)	$(CH_2)_{10}O_2(CO)_2$	Musk-like
Ethylene undecanedioate (15-atom ring)	$(CH_2)_{11}O_2(CO)_2$	Musk-like
Tetraethylene carbonate (14-atom ring)	$(CH_2)_8O_5CO$	Fresh, faint, musk-like

TABLE 7

PUBLIC OPINION SURVEYS RELATING ODORS TO AIR POLLUTION

Location	Year	Persons Responding to Survey Number	Persons Annoyed by Odors[a] Number	Percent
Nashville, Tenn.[254]	1959	2,835	742	26.2
Clarkston, Wash.[172]	1962	104	95	91
Moerrum, Sweden[43]	1963	394	351	89
Terre Haute, Ind.[1]	1964	20[b]	19	95
St. Louis, Mo.[131,221]	1965	400	214	53.5
St. Louis, Mo.[131,221]	1965	600	269	44.8
Steubenville, Ohio[124]	1967	936	288	30.8

[a]These people described air pollution in their location as "bad smells."

[b]These people complained of air pollution with all but one mentioning odors.

TABLE 8

COMPLAINTS RELATING ODORS TO PROPERTY DAMAGE
AND HEALTH IN TERRE HAUTE, IND.[1]

Date	Number of Complaints Property/odor	Health/odor	Total
May 20, 1964	1	15	16
May 21, 1964	1	4	5
May 24, 1964	14	14	28
May 26, 1964	6	0	6
May 27, 1964	4	0	4
June 3, 1964	14	8	22

TABLE 9

ODORS BY TIME OF DAY IN THE ST. LOUIS METROPOLITAN AREA[131]
(November 18 to December 1, 1963)

Area	7 a.m.	2 p.m.	8 p.m.	10 p.m.	12 M
St. Louis					
Positive observations	126	136	192	176	157
Total observations	483	494	490	491	488
% positive	26.1	27.5	39.2	35.8	32.2
St. Louis County					
Positive observations	66	85	119	106	74
Total observations	371	370	372	360	311
% positive	17.8	23.0	32.0	29.4	23.8
Illinois					
Positive observations	43	39	54	56	56
Total observations	164	161	162	161	144
% positive	26.2	24.2	33.3	34.8	38.9
Metropolitan Area					
Positive observations	235	260	365	338	287
Total observations	1,018	1,025	1,024	1,012	943
% positive	23.1	25.4	35.6	33.4	30.4

TABLE 10

EFFECT OF THE DAY OF THE WEEK
ON ODOR NUISANCE OCCURRENCES[118]

Day of Week*	Number of Complaints	Number of Nuisance Occurrences
Sunday	19	7
Monday	15	11
Tuesday	8	6
Wednesday	10	7
Thursday	17	10
Friday	34	11
Saturday	41	18

*During the middle of the week fewer occurrences and complaints happened. Saturday is the day of most frequent complaints and most numerous odor occurrences.

TABLE 11

EFFECT OF THE TIME OF DAY
ON ODOR NUISANCE OCCURRENCES[118]

Time of Day*	Number of Complaints	Number of Nuisance Occurrences
0000 to 0600	12	9
0600 to 1200	29	23
1200 to 1800	44	24
1800 to 2400	53	32

*Only 8.7 percent of complaints and only 10 percent of the odor occurrences came during the first quarter of the day.

APPENDIX B

TABLE 12

EFFECT OF TEMPERATURE ON ODOR NUISANCE OCCURRENCES[118]

Temperature Range*	No. of Complaints During 1958 & 1959	No. of Hours at Temperature	Ratio: No. Hours/ No. Complaints
0 to 44	0	6,184	∞
45 to 49	2	1,262	631
50 to 54	3	1,121	374
55 to 59	4	1,118	280
60 to 64	5	1,493	299
65 to 69	26	1,795	69
70 to 74	33	1,957	59
75 to 79	34	1,228	36
80 to 84	13	817	63
85 to 89	10	472	47
90 to 94	4	73	18
95 to 100	0	0	-

*The critical temperatures for these odor nuisances are above 65°F. Higher temperatures result in more frequent complaints and nuisances.

TABLE 13

EFFECT OF ATMOSPHERIC PRESSURE ON ODOR NUISANCE OCCURRENCES[118]

Pressure Range* (Inches Hg)	No. of Complaints During 1958 & 1959	No. of Hours at Pressure	Ratio: No. Hours/ No. Complaints
0 to 28.84	1	1,234	1,234
28.85 to 28.89	6	790	132
28.90 to 28.94	21	1,424	68
28.95 to 28.99	9	1,714	190
29.00 to 29.04	18	2,032	113
29.05 to 29.09	25	2,260	90
29.10 to 29.14	18	2,090	116
29.15 to 29.19	15	1,770	118
29.20 to 29.24	9	1,720	191
29.25 to 29.29	5	844	170
29.30	4	1,622	406

*Very few complaints were received when the atmospheric Pressure was below 28.84 inches Hg.

TABLE 14

EFFECT OF RELATIVE HUMIDITY
ON ODOR NUISANCE OCCURRENCES[118]

Relative Humidity Range*	No. of Complaints During 1958 & 1959	No. of Hours at R.H.	Ratio: No. Hours/ No. Complaints
0 to 30	0	453	∞
30 to 49	27	2,974	110
50 to 69	47	5,186	110
70 to 79	24	3,184	132
80 to 89	18	3,007	167
90 to 100	18	2,698	150

*Hours of low relative humidity (R.H.) have more frequent complaints per hour.

TABLE 15

EFFECT OF WIND VELOCITY ON ODOR NUISANCE OCCURRENCES[118]

Range Wind Velocity* (mph)	No. of Complaints During 1958 & 1959	No. of Hours at Velocity	Ratio: No. Hours/ No. Complaints
0 to 4	25	3,584	143
5 to 14	95	11,105	117
15 to 24	17	2,740	161
25 to ∞	0	91	∞

*Wind velocity had no effect on the number of hours per complaint.

APPENDIX B

TABLE 16

EFFECT OF CHANGING TEMPERATURE, PRESSURE, AND
RELATIVE HUMIDITY ON ODOR NUISANCE OCCURRENCES[118]

Type of Change*	Temperature		Pressure		Relative Humidity	
	No. of Complaints	% of Total	No. of Complaints	% of Total	No. of Complaints	% of Total
Increasing	34	26	64	49	69	52
Static	19	14	37	28	15	11
Decreasing	79	60	30	23	48	37

*On a percentage basis, decreasing temperature, increasing pressure, and increasing relative humidity cause more frequent complaints to be received.

TABLE 17

EFFECT OF TIME OF YEAR ON ODOR NUISANCE OCCURRENCES[118]

Month	Number of Complaints	Number of Nuisance Occurrences*
January	0	0
February	0	0
March	1	1
April	6	4
May	9	4
June	14	9
July	28	16
August	44	18
September	34	18
October	2	2
November	1	1
December	0	0

*The number of nuisance occurrences refers to the number of different days on which complaints occurred. Note that 86 percent of the complaints and 84 percent of the occurrences happened during the months of June, July, August, and September.

TABLE 18

THEORIES OF OLFACTION[195,234]

Author	Date	General Class	Salient Features
Ogle[203]	1870	Vibrational	Vibrations affected nasal pigment, which gave out heat which excited the olfactory cells
Woker[304]	1906	Chemical	Unsaturation main cause of odor, but not essential if substance very volatile
Fabre[77]	1911	Vibrational	Limited to insects. Not known by man. Human olfaction due to material particles
Marchand[163]	1915	Chemical	Unsaturation (including carbonyl bonds). Having two points of unsaturation reduces odor
Henning[105]	1916	Chemical	Osmophore groups are important, but their relative position determines the type of odor
Heyninx[107]	1917	Vibrational	Vibrations causing absorption in the ultra-violet band also cause odor
Backman[18]	1917	Chemical	Water solubility and lipoid solubility essential
Teudt[278]	1919	Vibrational	Electronic vibrations of sensory nerves increased by reasonance with similar vibrations of odorants
Durrans[67]	1920	Chemical	Residual affinity. Addition reaction on the olfactory epithelium
Heller[103]	1920	Chemical	Direct chemical action on nerve-ending
Ruzicka[241]	1920	Chemical	Osmophore and osmoceptor
Tschirch[283]	1921	Chemical	Substance must be soluble in air. Loose compound formed with plasma of the olfactory cell

TABLE 18 (Continued)

THEORIES OF OLFACTION[195,234]

Author	Date	General Class	Salient Features
Zwaardemaker[313]	1922	Chemical-vibrational	Odorous substances possess odoriphores, are volatile, have lower surface tension, and are lipoid soluble. Odoriphore depends on vibrations in molecule
Ungerer and Stoddard[287]	1922	Vibrational	Intramolecular vibrations within definite frequency range. Unsaturation helpful. Interference and resonance effects
Delange[57]	1922	Chemical	Unsaturation
Missenden[181]	1926	Chemical	Intensity depends on number of molecules making contact with nose. Quality depends on nature of reaction between odorous molecules and lipoid tissues
Nicol[200]	1926		Function of sinuses
Pirrone[215]	1929	Chemical	Two smophore groups; one determines type of odor, the other the variety
Niccolini[199]	1933	Chemical	Volatility. Solubility in nasal mucosa. Oxidizability
Krisch[149]	1934	Vibrational	Insects
Muller[194]	1936	Physical	Odorous substances are dipolar. Irritate the molecular fields of the osmoceptor in nose
Dyson[70]	1937	Vibrational	Volatility. Lipoid solubility Raman shift between 1,400 and 3,500 cm^{-1}
Beck and Miles[23]	1947	Vibrational	Infra-red radiation from receptors absorbed by odorants
McCord and Witheridge[170]	1949	Electro-chemical	Change in bonding angle of odorant molecules on solution in mucosa

TABLE 18 (Continued)

THEORIES OF OLFACTION[195,234]

Author	Date	General Class	Salient Features
Baradi and Bourne[20]	1951	Enzyme	Inhibition of enzyme action by odorants
Hainer[99]	1953	Information	30 levels of intensity; 24 kinds of primary odor
Wright[305]	1954	Vibrational	Raman shift of frequency lower than 800-1,000 cm^{-1}
Davies[52]	1954	Physico-chemical	Puncturing of olfactory cell membrane and exchange of Na^+ and K^+
Moncrieff[188]	1961	Physical	Volatility, adsorbability, and customary absence from olfactory region
Amoore[12]	1962	Stereo-chemical	Whole-molecule theory. Developed size and shape of each receptor site
Moncrieff[190]	1967	Stereo-chemical	Whole-molecule theory. Extended 1961 theory

TABLE 19

MOST FREQUENTLY REPORTED ODOR SOURCES[143]

Source of Odor	Number Reported
Animal odors	
Meat packing and rendering plants	12
Fish oil odors from manufacturing plants	5
Poultry ranches and processing	4
Odors from combustion processes	
Gasoline and diesel engine exhaust	10
Coke-oven and coal-gas odors (steel mills)	8
Poorly adjusted heating systems	3
Odors from food processing	
Coffee roasting plants	8
Restaurants	4
Bakeries	3
Paint and related industries	
Manufacturing of paint, lacquer, and varnish	8
Paint spraying	4
Commerical solvents	3
General chemical odors	
Hydrogen sulfide	7
Sulfur dioxide	4
Ammonia	3
General industrial odors	
Burning rubber from smelting and debonding	5
Odors from dry-cleaning shops	5
Fertilizer plants	4
Asphalt odors (roofing and street paving)	4
Asphalt odors (manufacturing)	3
Plastic manufacturing	3
Foundry odors	
Core-oven odors	4
Heat treating, oil quenching, and pickling	3
Smelting	2
Odors from combustion of waste	
Home incinerators and backyard trash fires	4
City incinerators burning garbage	3
Open-dump fires	2

(continued)

TABLE 19 (Continued)

MOST FREQUENTLY REPORTED ODOR SOURCES[143]

Source of Odor	Number Reported
Refinery odors	
Mercaptans	3
Crude oil and gasoline	3
Sulfur	1
Odors from decomposition of waste	
Putrefaction and oxidation (organic acids*)	3
Organic nitrogen compounds (decomposition of protein*)	2
Decomposition of lignite (plant cells)	1
Sewage odors	
City sewers carrying industrial waste	3
Sewage treatment plants	2

*Probably related to meat processing plants.

TABLE 20

NATURE OF AIR CONTAMINANTS EMANATING FROM VARIOUS TYPES OF SOURCES[108]

Source	Communities Over 5,000 Population[a]					Communities under 5,000 Population				
	Total No.	%	Smoke	Odors	Other	Total No.	%	Smoke	Odors	Other
All sources	409	100	258	103	48	167	100	99	40	28
Industrial (total)[b]	123	30	49	26	48	100	60	49	23	28
Nonindustrial (total)	286	70	209	77	0	67	40	50	17	0
Apartment houses	28	10	21	7		5	7	3	2	
Office buildings	15	5	15			2	3	1	1	
Stores	10	3	8	2		1	2	1		
Bakeries	9	3	6	3						
Laundries	21	7	18	3		1	2	1		
Schools	18	6	18			7	10	7		
Hospitals	12	4	12			1	2	1		
Hotels	11	4	10	1		1	2	1		
Theaters	9	3	7	2		1	2	1		
Public buildings	18	6	18			4	6	4		
Incinerators	33	12	16	17		3	4	2	1	
Railroads	16	6	13	3		4	6	4		
Dumps	60	21	36	24		32	48	21	11	
Auto and bus exhaust	16	6	5	11		3	4	2	1	
Other	10	3	6	4		2	3	1	1	

[a]Surveys did not include New York City.

[b]No breakdown is available on types of industrial establishments.

TABLE 21

ODOR CONCENTRATION MEASURED IN VARIOUS PLANTS[26]

Application	Exhaust Flow (scfm)	Average* Odor Concentration (odor units/scf)	Average Emission Rate (odor units/min)	Remarks
Rubber processing	6,900	50	350,000	Controlled by direct fume incinerator
Coffee roaster	3,600	2,000	7,200,000	Uncontrolled effluent from roasters
Rendering plant	29,000	1,500-25,000	55,000,000 730,000,000	Uncontrolled effluent from dryer
Pulp mill	200,000	<10	2,000,000	Controlled by recovery furnace
Pulp mill	200,000	17	3,400,000	Controlled by recovery furnace
Pulp mill	200,000	2,000	400,000,000	Recovery furnace intentionally upset
Pulp mill	200,000	2,500-11,000	500,000,000 2,200,000,000	Effluent from cascade evaporator

*Based on syringe dilution technique.

TABLE 22

ATMOSPHERIC CONTAMINANTS* RECOVERED FROM CHARCOAL AFTER 30-DAY MANNED EXPERIMENT[282]

1.	Carbon dioxide	16.	Hydrocarbon
2.	Ethylene	17.	Ethyl acetate
3.	Acetylene	18.	Benzene
4.	Propylene	19.	Hydrocarbon
5.	Butene-1	20.	Trichloroethylene
6.	Isobutylene	21.	Toluene
7.	n-Butane	22.	Tetrachloroethylene
8.	Saturated hydrocarbon	23.	Butanol
9.	Freon-11	24.	Acetone
10.	Acetaldehyde	25.	Hydrocarbon
11.	Isoprene	26.	Acetic acid
12.	Hydrocarbon	27.	Proprionic acid
13.	Ethyl formate	28.	Butyric acid
14.	Hydrocarbon	29.	Formaldehyde
15.	Ethyl alcohol		

*Detected in the unseparated desorbate mixture of hydrocarbons.

TABLE 23

POTENTIAL SOURCES OF ODOROUS EMISSIONS FROM OIL REFINERIES[214]

Emissions	Sources
Oxides of sulfur	Combustion of fuels containing sulfur, flares, catalytic cracking unit regenerators, treating units, decoking operations
Hydrocarbons	Gasoline storage tanks and loading facilities, turnarounds (blow-down systems, blind changing), leakage (pumps, valves, cooling towers, sampling), sewers and oil recovery facilities, vacuum jets and/or barometric condensers, catalyst regenerators, and compressor engines
Oxides of nitrogen	Combustion processes, gas fired compressor engine exhausts, catalyt regenerators, flares
Mercaptans	Cracking units, caustic regeneration units, some asphalt plants
Hydrogen sulfide	Untreated gas stream leaks; vapor from crude oil and raw distillates, process condensate sewers
Phenolic compounds and naphthenic acids	Movement and storage of the caustic solutions used in scrubbing straight run and cracked distillates
Organic sulfides and nitrogen bases	Movement and storage of the acid solutions used in scrubbing organic sulfides and nitrogen bases, if they are present, from straight run or cracked distillates or lubricating oil fractions
Aldehydes	Air-blowing of asphalts, incomplete combustion of fuel

TABLE 24

CRUDE OIL CAPACITY IN THE UNITED STATES AS OF JANUARY 1969[273]

State	No. Plants	Crude Capacity[a]	
		b/cd[b]	b/sd[c]
Alabama	6	34,620	36,820
Alaska	1	20,000	21,000
Arkansas	6	93,500	94,985
California	32	1,529,075	1,606,985
Colorado	4	42,900	46,235
Delaware	1	140,000	150,000
Florida	1	3,100	3,150
Georgia	2	9,500	11,000
Hawaii	1	35,000	NR
Illinois	11	704,100	732,300
Indiana	10	565,700	588,800
Kansas	12	389,300	407,300
Kentucky	3	128,500	132,600
Louisiana	16	1,190,850	1,230,000
Maryland	2	19,400	20,500
Michigan	8	146,050	152,000
Minnesota	3	138,300	144,000
Mississippi	4	168,700	181,500
Missouri	1	83,000	84,700
Montana	9	128,200	137,500
Nebraska	1	4,000	4,500
New Jersey	6	523,500	555,000
New Mexico	6	42,610	44,400
New York	2	76,900	81,000
North Dakota	2	55,000	57,000
Ohio	11	491,600	525,900
Oklahoma	14	449,367	464,250
Oregon	1	11,000	12,000
Pennsylvania	13	628,920	659,100
Rhode Island	1	7,500	10,000
Tennessee	1	28,500	29,750
Texas	47	3,118,250	3,244,300
Utah	5	11,950	116,400
Virginia	1	43,600	45,000
Washington	6	219,000	226,000
West Virginia	2	8,570	9,100
Wisconsin	2	29,500	30,600
Wyoming	9	132,900	146,686
Total	263	11,522,512	12,079,201

[a]State totals include figures converted to calendar-day or stream-day basis.
[b]b/cd = barrels per calendar day.
[c]b/sd = barrels per stream-day.

APPENDIX B

TABLE 25

SULFUR PRODUCTION FROM HYDROGEN SULFIDE
IN THE UNITED STATES[95,204]
(Long Tons per Year)

Year	Plant Capacity	Actual Production
1961	1,659,000	858,000
1967	2,737,000	1,244,000
1968	3,036,000	1,400,000

TABLE 26

RANGE OF SULFUR GAS CONCENTRATIONS ENCOUNTERED IN KRAFT MILL SAMPLING[243]

Source	Gas Concentration (ppm by volume)				
	Sulfur Trioxide	Hydrogen Sulfide	Methyl Mercaptan	Dimethyl Sulfide	Dimethyl Disulfide
Digester vent		16-18,800	0-4,370	3,850-65,000	0-65,000
Blow gases		0-782	0-9,840	522-46,900	0-10
Pulp washer	0.1-0.2	0-12	0-79	0	0.1-0.4
Evaporator, noncondensible		907-32,600	455-36,700	0-27,600	0-1,278
Recovery furnace	4-798	14-1,140	0-489	0-260	0-17
Smelt dissolving tank	0.5-70	10-44	0-212	0-91	0-4
Lime kiln	0-169	0-254	0-128	0-60	0-18
Tall oil cooking	2-822	5,400-101,000	0-4,660	0	103-7,693

TABLE 27

ESTIMATED EMISSIONS FROM KRAFT PULP MILL IN LEWISTON, IDAHO[268]
(Pounds per Day)

Process or Equipment Source	Hydrogen Sulfide	Methyl Mercaptan	Dimethyl Sulfide	Solid Particulates	Combustibles[a]	Sulfur Oxides as SO_2	Nitrogen Oxides as NO_2	Aldehydes as Formaldehydes	Organic Acids as HAc	Hydrocarbons	Water Vapor
Digester gases	9	69	50	e	e	e	e	e	e	e	e
Evaporators	390	20	neg	e	e	e	e	e	e	e	e
Recovery furnaces	3,120	neg	neg	12,310	141,400	1,180	c	e	e	e	2,778,000
Smelt tanks	c	c	c	1,100	e	e	e	e	e	e	e
Lime kilns	737	c	c	6,269	147,700	6[b]	847	8	20	e	1,850,000
Oxidation towers	c	c	60	e	e	e	e	e	e	e	e
Plant boilers[d]	e	e	e	397	neg	28[b]	2,910	141	92	1,285	2,550,000
Paper machines	e	e	e	e	e	e	e	e	e	e	1,782,000
Pulp dryer	e	e	e	e	e	e	e	e	e	e	320,000
Total	4,256	89	110	20,076	289,100	1,214	3,757	149	112	1,285	9,280,000

[a]Combustible emission probably consists of carbon monoxide and other organic materials.
[b]Assumed sulfur content of natural gas, 0.4 grain per 100 ft^3.
[c]Indicated pollutant present in emissions, but amount is unknown.
[d]Emissions include those from burning waste wood.
[e]Material below detection or not measured.

TABLE 28

NOVEMBER ODOR SURVEY IN LEWISTON-CLARKSTON AREA[268]

Odor Type	Clarkston 51 Students		Clarkston Heights 7 Students		Lewiston 32 Students		Lewiston Orchards 30 Students	
	Positive Responses	Total Positive Response, %	Positive Responses	Total Positive Response, %	Positive Responses	Total Positive Response, %	Positive Responses	Total Positive Response, %
Pulp mill	238	31.2	45	30.4	107	48.2	52	26.5
Wood smoke	228	30.0	41	27.7	76	34.2	78	39.8
Burning leaves	92	12.1	8	5.4	19	8.6	22	11.2
Wet grass, misty	41	5.4	5	3.4	3	1.3	11	5.6
Gasoline, oil, tar	23	3.0	4	2.7	3	1.3	5	2.6
Rotten flesh	12	1.6	8	5.4	1	0.5	2	1.0
Rubbish	66	8.6	12	8.1	5	2.3	12	6.1
Animal odors	19	2.5	11	7.4	0	0.0	8	4.1
Miscella-neous	43	5.6	14	9.5	8	3.6	6	3.1
Total	762	100.0	148	100.0	222	100.0	196	100.0

TABLE 29

APRIL ODOR SURVEY IN LEWISTON-CLARKSTON AREA[268]

Odor Type	Clarkston 37 Students		Clarkston Heights 6 Students		Lewiston 37 Students		Lewiston Orchards 30 Students	
	Positive Responses	Total Positive Response, %	Positive Responses	Total Positive Response, %	Positive Reponses	Total Positive Response, %	Positive Responses	Total Positive Response, %
Pulp mill	134	51.6	5	10.6	63	27.7	31	19.5
Wood smoke	28	10.8	14	29.8	39	17.2	41	25.8
Burning leaves	7	2.7	0	0.0	4	1.8	10	6.3
Wet grass, misty	2	0.8	7	14.9	12	5.3	9	5.7
Gasoline, oil, tar	4	1.5	0	0.0	28	12.3	4	2.5
Rotten flesh	6	2.3	0	0.0	1	0.4	1	0.6
Rubbish	42	16.2	5	10.6	10	4.4	4	2.5
Animal odors	5	1.9	2	4.3	5	2.2	12	7.5
Miscella-neous	32	12.3	14	29.8	65	28.6	47	29.6
Total	260	100.0	47	100.0	227	100.0	159	100.0

TABLE 30

KRAFT PULP PRODUCTION IN THE UNITED STATES[222]

Year	Million Tons/Year
1957	12.8
1958	13.1
1959	14.9
1960	15.3
1961	16.1
1962	17.4
1963	18.7
1964	20.4
1965	22.3
1966	24.4
1967	23.9

TABLE 31

SOURCES OF ODOROUS EMISSIONS IN COKE PLANTS[231]

Source of Emission	Cause of Emission
Condensation	
Unburnt gases escaping from the gas torches	
In normal operation with torch shut off	Leakage at stop valves
With torch open during operational failures	Failure of ignition device
Gases escaping from water seals	Defective seals
Outflow collectors on coolers; collector and separator tanks	Gas escape from liquids
Ammonia Scrubber	
Outflow collectors and collector tanks	Gas escape from washing of fluid
Secondary coolers for primary-cooler outflow (in semi-direct process)	Escape of hydrogen sulfide with the cooling-tower vapors
Benzol Scrubber and Plant	
Outflow receivers of scrubbers and washing oil tanks	Gas escape from washing fluid
Cooler-ventilating lines	Escape of sulfur-containing compounds with low boiling point, together with ventilating gases
Desulfurization of Gas	
Outflow receivers and tanks for scrubbing fluid	Gas escape from washing fluid

TABLE 32

ODOR CONCENTRATIONS AND EMISSION RATES FROM INEDIBLE REDUCTION PROCESSES[51]

Source	Odor Concentration (odor unit/scf)		Typical Moisture Content of Feeding Stocks (%)	Exhaust Products (scf/ton of feed[a])	Odor Emission Rate	
	Range	Typical Avg			Odor unit/ ton of feed	Odor unit/ min
Rendering cooker, dry-batch type[b]	5,000 to 500,000	50,000	50	20,000	$1,000 \times 10^8$	25,000,000
Blood cooker, dry-batch type[b]	10,000 to 1 million	100,000	90	38,000	$3,800 \times 10^6$	
Feather drier, steamtube[c]	600 to 25,000	2,000	50	77,000	153×10^6	50,000,000
Blood spray drier[c,d]	600 to 1,000	800	60	100,000	80×10^6	25,000,000
Grease-drying tank, air blowing 156°F 170°F 225°F		4,500 15,000 60,000	<5	100 scfm per tank		

[a]Assuming 5 percent moisture in solid products of system.
[b]Noncondensible gases are neglected in determining emission rates.
[c]Exhaust gases are assumed to contain 25 percent moisture.
[d]Blood handled in spray drier before any appreciable decomposition occurs.

TABLE 33

TYPICAL ODOR EMISSIONS FROM ROTARY FISH MEAL DRIERS
WITHOUT ODOR CONTROL[179]

Drier	Feed Rate (tons per hour)	Type of Scrap	Temp at Drier Discharge $^{\circ}$F	Exhaust Gas Volume (scf per min[a])	Odor Concentration (odor units per scf[b])	Odor Emission Rate (odor units per min)	Odor Emission Rate (odor units per ton of feed)
A	10	Tuna	220	18,500	1,500	27.8×10^6	167×10^6
A	15	Mackerel	220	18,500	1,500	27.8×10^6	111×10^6
B	7	Tuna	220	9,000	700	6.3×10^6	54×10^6
B	10	Tuna	240	10,000	1,500	15×10^6	90×10^6
B	14	Tuna	300	8,000	4,000	32×10^6	137×10^6
C	9	Tuna	200	17,000	2,500	42.5×10^6	284×10^3
D	6	Tuna	180	9,800	2,000	19.6×10^6	196×10^6

[a] Standard cubic feet per minute.
[b] Odor units per standard cubic foot (70°F and 14.7 psia).

TABLE 34

ODOR EMISSIONS FROM APARTMENT HOUSE INCINERATORS[138]

	Test Number				
	1	2	3	4	5
Odor units per scf	2.5	14	5	100	8
Dry flue gas, scf x 1,000	263	211	618	131	144
Total odor units x 1,000	657	2,950	3,090	13,100	1,150
Odor units x 1,000 per 100 lb refuse	240	1,070	755	5,000	930
Burning rate, 100 lb/hr	1.22	1.38	0.546	1.74	0.620
Odor units x 1,000 per min	4.90	24.7	6.92	145	9.63

TABLE 35

ODOR INTENSITY OF DIESEL EXHAUST AND CONCENTRATION
OF ALDEHYDES (AS FORMALDEHYDE)

Odor Strength	Odor Intensity	Aldehyde Concentration, ppm (as HCHO)*		
		Reference 239	Reference 72	Reference 297
0	No odor			7.1
1	Very faint	.52	.95	12
2	Faint	5.5	4	21
3	Easily noticeable	48	18	35
4	Strong	420	80	60
5	Very strong			100

*Smoothed values.

TABLE 36

COMPUTED CONCENTRATIONS AT ODOR THRESHOLDS OF DILUTED DIESEL EXHAUST[156]

Subject	Trials	Odor Units/scf[a] of Diesel Exhaust	ppm NO_2[b]	ppm CH[b,c]	ppm Acrolein[b]	ppm Formaldehyde[b]
		I. 500 rpm, ZERO LOAD				
A	4	215	0.20	0.27	0.019	0.021
B	4	385	0.11	0.15	0.010	0.012
C	3	205	0.21	0.28	0.020	0.022
D	4	140	0.31	0.42	0.029	0.033
E	6	190	0.23	0.31	0.021	0.024
F	5	360	0.12	0.16	0.011	0.013
Avg		249	0.20	0.26	0.018	0.021
		II. 1,600 rpm, FULL LOAD				
A	7	450	0.89	0.10	0.018	0.034
B	8	475	0.84	0.09	0.017	0.032
C	4	215	1.85	0.21	0.038	0.072
D	4	175	2.28	0.26	0.046	0.088
E	6	195	2.05	0.23	0.042	0.079
F	3	320	1.25	0.14	0.025	0.048
Avg		305	1.53	0.17	0.031	0.059

[a]Volume of dilution air per volume of raw diesel exhaust at the odor threshold.

[b]Computed by dividing concentration values by the odor units/scf. Odor thresholds of nitrogen dioxide, acrolein, and formaldehyde are 4.0, 0.4-6.6, and 0.2-1.8, respectively.

[c]Calculated from 3.4 μ infrared band as hexane.

TABLE 37

ANALYSIS OF DIESEL ENGINE EXHAUST[61]

		Engine A[a] Exhaust				Engine B[b] Exhaust			
		Idle		Half Load		Idle		Full Load	
		Fuel E[d]	Fuel F[e]	Fuel E	Fuel F	Fuel E	Fuel F	Fuel E	Fuel F
Formaldehyde, ppm	Avg	34.9	32.3	9.2	12.1	12.6	10.4	19.3	23.3
	SD[c]	2.0	4.5	1.0	1.2	1.6	2.1	3.7	2.0
Acrolein, ppm	Avg	8.0	8.4	2.1	2.8	3.9	3.7	4.1	5.0
	SD	0.9	1.4	0.5	0.4	0.5	0.7	0.6	1.0
Total aldehydes, ppm	Avg	56.4	58.8	13.8	17.3	18.3	15.2	30.3	25.3
	SD	3.0	3.9	0.8	1.4	1.6	3.6	1.0	5.4
Total carbonyls, ppm	Avg	165.0	149.3	270.0	220.7	49.5	56.5	93.6	97.0
	SD	20.2	13.6	36.3	20.4	10.4	11.2	4.5	9.0
Total unsaturation, ppm	Avg	75.5	54.5	130.8	111.2	18.2	19.0	43.2	56.6
	SD	6.4	6.1	16.3	26.2	3.2	3.9	9.9	19.1
NO_x, ppm	Avg	288	256	1,635	1,651	130	142	1,121	1,159
	SD	21	18	42	47	10	17	108	84
Color, ml	Avg	15.0	16.1	1.9	2.0	4.7	4.5	5.0	4.5
	SD	1.0	2.2	0.3	0.0	0.4	0.5	0.2	0.6
ODOR AT DILUTION, ODOR UNITS									
Threshold		8,000	6,900	7,800	7,200	7,900	7,500	8,800	8,400
Diesel identification		4,400	3,550	4,180	3,700	4,100	2,650	4,500	4,800
Objectional		1,650	1,650	1,380	1,650	1,300	800	1,450	1,780

[a]Engine A: four-cycle engine.
[b]Engine B: two-cycle engine.
[c]SD: Standard deviation.
[d]Fuel E: No. 1 grade.
[e]Fuel F: No. 2 grade.

TABLE 38

DIESEL EXHAUST EMISSIONS AND PERCENT OF TIME AT EACH POWER
SETTING FOR TWO-CYCLE DIESEL BUS OPERATING IN DETROIT[159]

Power Setting	Exhaust Flow (scfm)	Percent of Time	CO (ppm)	Hydrocarbons as CH_4 (ppm)	Nitrogen Oxides as NO_2 (ppm)	Odor Dilution Threshold[a]	Odor Emission Rate[b]
Idle	120	57.5	160	340	160	330	39,500
32 mph, 25 hp	408	21.5	145	457	305	440	180,000
35 mph, 65 hp	630	7.7	617	570	650	540	340,000
51 mph, 122 hp	640	13.3	850	750	810	790	505,000

[a]Odor units/scf.

[b]Odor units/min.

APPENDIX B

TABLE 39

ODOR EMISSIONS FROM JET AIRCRAFT EXHAUST [159]

Engine Type	Power(%)	Normal Use	Odor Units/scf
T-56-A7 (Turboprop)	100	Take-off	100
	75	Cruise and approach	
	65	Idle	75
T-57-19W (Conventional jet)	100	Take-off	600
	75	Cruise	660
	65	Idle	15
TF-33-P5 (Fan jet)	100	Take-off	75
	75	Approach	500
	65	Idle	1000

TABLE 40

NUMBER, TYPE, AND LOCATION OF ODOR OBSERVATIONS
NEAR JOHN F. KENNEDY AIRPORT [201]

Type of Odor	Total Observations by Zones[a]			
	1	2	3	4
Total number of observations	238	260	335	198
Total number of positive observations	62	65	146	61
Percentage of positive observations[b]	26.1	25.0	43.6	30.8
1. Chemical odors (including chemical, sulfurous, soap or detergent, refinery, medicinal, vanilla or coumarin, bleach or chlorine, ammonia, other)	1	3	1	2
Percentage of positive observations[c]	1.6	4.6	0.68	3.3
2. Food processing odors (including coffee roasting, bakery, brewery, restaurant, grain, smoking fish, other, unknown)	1	1	1	1
Percentage of positive observations[c]	1.6	1.5	0.68	1.6
3. Combustion odors including the following:	10	36	46	22
Gasoline and diesel engine exhaust	0	0	11	5
Coke-oven and coal gas odors (steel mills)	2	0	0	6
Maladjusted heating systems	0	3	2	0
Coal smoke	6	0	1	0
Smokey	0	13	23	8
Other	2	4	0	3
Unknown	0	15	9	0
Jet exhaust smoke or odor	0	0	0	0
Percentage of positive observations[c]	16.1	55.4	31.5	36.1
4. General industrial odors (including asphalt, plastics, solvents, fertilizer plants, paint and related industries, oily, fuel odor, other, unknown)	11	2	0	8
Percentage of positive observations[c]	17.7	3.1	0	13.1

TABLE 40 (Continued)

NUMBER, TYPE, AND LOCATION OF ODOR OBSERVATIONS
NEAR JOHN F. KENNEDY AIRPORT

Type of Odor	Total Observations by Zones[a]			
	1	2	3	4
5. Animal odors (including rendering, stockyards, poultry, fish, organic fertilizer, meat processing plant, other, unknown)	0	1	3	7
Percentage of positive observations[c]	0	1.5	2.1	11.5
6. Odors from combustible waste (including open-dump fires, city incinerators burning garbage, home incinerators, backyard trash fires and wood smoke, burning rubber, other, unknown)	14	5	14	6
Percentage of positive observations[c]	22.6	7.7	9.6	9.8
7. Decomposition odors (including sewage, nonburning garbage, other, unknown)	2	1	1	9
Percentage of positive observations[c]	3.2	1.5	0.68	14.9
8. Vegetation odors (including general, freshly cut wood, flowers and/or flowering shrubs, marshland odor, fresh fruit odors, plowed or excavated soil)	22	11	14	4
Percentage of positive observations[c]	35.5	16.9	9.6	6.6
9. Miscellaneous odors (including general, foul--not specified, putrid--source not specified, not pleasant, smog, clean or fresh, ocean smell, dust, tobacco)				
Percentage of positive observations[c]	1.6	7.7	45.2	3.3

a. Zones 1, 2, 3, and 4 are all within 3 miles of the airport premises and in a northerly direction from the airport. Zones 1 and 4 are in NNW direction, zone 2 in a N direction, and Zone 3 in a NNE direction.

b. $\frac{\text{Total number of positive observations}}{\text{Total number of observations}}$ x100

c. $\frac{\text{Number of odor types observed}}{\text{Total number of positive observations}}$ x100

TABLE 41

CONTROL OF ODORS BY INCINERATION[26]

Application	Incinerator Temperature (°F)	Average Odor Concentration* in Incinerator (odor units/scf)		Exhaust Gas Flow (scfm)	Effect of Incineration on Odor Strength (% reduction)
		Inlet	Outlet		
Wire enameling	1,000	1,300	2,100		-61
Oven, portable unit	1,200	2,500	350		86
Field test	1,400	1,300	70		97
Glass fiber	1,009	550	625	14,000	-14
Curing-oven field	1,250	380	53	14,000	86
	1,352	255	25	14,000	90
Abrasive wheel	1,200	800	10		98
Curing-oven laboratory test	1,400	1,600	32		98
Test 1					
Automobile paint	1,350	260	14		95
Bake-oven field test	1,450	170	10		94
Test 2	1,350	650	10		93
	1,450	680	18		97
Hard-board curing	1,400	1,000	40		96
Oven laboratory test	1,500	1,400	15		98

*Based on syringe dilution technique.

TABLE 42. ODOR EMISSIONS FROM TYPICAL INDUSTRIAL EQUIPMENT AND ODOR CONTROL DEVICES[137]

Type of Equipment or Operation	Odor Levels and Emission Rates, Uncontrolled		Odor Levels and Emission Rates, Controlled			
	Vent Gas Odor Concentration Range (ou/scf[a])	Model Odor Emission Rate (ou/min[b])	Type of Odor Control Equipment	Vent Gas Odor Concentration (ou/scf[a])	Odor Emission Rate (ou/min[b])	Temperature[c] and Efficiency[d]
Rendering cooker (Inedible charge) Dry batch type	5,000 to 500,000[e]		Direct-Fired(DF)*	100 to 150 (Mode 120)	90,000	1,200°F 99+%
			Surface condenser**	100,000 to 10,000,000[f] (Mode 500,000)	12,000,000	80°F Negative[f]
			Jet condenser followed by a D-F after-burner*	20 to 50 (Mode 25)	2,000	1,200°F 99+%
	(Mode 50,000)	25,000,000	Surface condenser followed by a D-F after-burner*	50 to 100 (Mode 75)	6,000	1,200°F 99+%
			Jet (or contact condenser)**	2,000 to 20,000 (Mode 10,000)	70,000	80°F 80%
Rendering Cooker (Blood drying) Dry batch type	10,000 to 1,000,000[g]	Not measured				
Rendering cooker (Edible charge) Dry batch type Wet batch type Continuous type	2,500[h] 350[h] 650 to 7,000[h,i]	70,000[h]				

TABLE 42. ODOR EMISSIONS FROM TYPICAL INDUSTRIAL EQUIPMENT AND ODOR CONTROL DEVICES[137] (Continued)

Type of Equipment or Operation	Odor Levels and Emission Rates, Uncontrolled		Odor Levels and Emission Rates, Controlled			
	Vent Gas Odor Concentration Range (ou/scf[a])	Model Odor Emission Rate (ou/min[b])	Type of Odor Control Equipment	Vent Gas Odor Concentration (ou/scf[a])	Odor Emission Rate (ou/min[b])	Temperature[c] and Efficiency
Fish-meal drier	1,000 to 5,000 (Mode 2,000)	50,000,000	Packed column type scrubber**	200 to 1,000 (Mode 400)	10,000,000	70°F 80%
			Chlorination[k] plus packed column scrubber**	30 to 50 (Mode 40)	1,000,000	70°F 98%
Air blowing of fish oils	10,000 to 70,000 (Mode 50,000) (Estimated)	30,000,000	Direct-fired afterburner*	25 to 75 (Mode 50) (Estimated)	50,000[l]	1,200°F 99+%
Air blowing of linseed oil	120,000[h]	Not measured	Direct-fired afterburner*	2,000	Not measured	1,200°F 97.5%
Varnish cooker batch type	10,000 to 200,000[e] (Mode 25,000)	10,000,000	Recirculating spray contact scrubber followed by a DF afterburner*	10 to 25 (Mode 20)	10,000	1,200°F 99+%
			Recirculating spray (contact) scrubber**	20,000	Not measured	
			Direct fired afterburner*	100 to 400 (Mode 250)	100,000	1,200°F 99%
			Recirculating spray (contact) scrubber**	100,000[h]	Not measured	

(continued)

TABLE 42. ODOR EMISSIONS FROM TYPICAL INDUSTRIAL EQUIPMENT AND ODOR CONTROL DEVICES (Continued)

Type of Equipment or Operation	Odor Levels and Emission Rates, Uncontrolled		Odor Levels and Emission Rates, Controlled			
	Vent Gas Odor Concentration Range (ou/scf^a)	Model Odor Emission Rate (ou/min^b)	Type of Odor Control Equipment	Vent Gas Odor Concentration (ou/scf^a)	Odor Emission Rate (ou/min^b)	Temperature^c and Efficiency
Lithographing oven metal decorating	700 to 10,000^j (Mode 3,000)	15,000,000	Direct-fired afterburner*	50 to 500 (Mode 200)	1,200,000	1,200°F 95%
			Catalytic afterburner*	450^h 3,000^h	2,300,000	1,000°F^m 800°F
Coffee roaster batch type	300 to 30,000^e	3,000,000^h (Estimated)	Direct-fired afterburner*	150 to 15,000^h	1,700,000^j (Estimated)	1,100°F 50%
Coffee roaster continuous type	500 to 1,000^j (Mode 1,000) (Estimated)	3,000,000^j	Direct-fired afterburner*	300 to 1,000 (Mode 350) (Estimated)	1,200,000^j	900°F 65%
Bread baking oven	1,000^h	Not measured				
Tallow hydrolyzer ("Fat splitter")	Not measured	Not measured	Surface condenser^o followed by a direct-fired afterburner*	2,000,000 2,000 750 150 70	Not measured	940°F 1,100°F 1,200°F 1,300°F 1,400°F
			Surface condenser**	6,000	Not measured	

TABLE 42. ODOR EMISSIONS FROM TYPICAL INDUSTRIAL EQUIPMENT AND ODOR CONTROL DEVICES (Continued)

Type of Equipment or Operation	Odor Levels and Emission Rates, Uncontrolled		Odor Levels and Emission Rates, Controlled			
	Vent Gas Odor Concentration Range (ou/scf[a])	Model Odor Emission Rate (ou/min[b])	Type of Odor Control Equipment	Vent Gas Odor Concentration (ou/scf[a])	Odor Emission Rate (ou/min[b])	Temperature[c] and Efficiency
Phthalic anhydride manufacturing unit	1,800 to 3,500[j] (Mode 2,500)	15,000,000	Direct-fired afterburner*	45 to 120 (Mode 75)	500,000	1,200°F 97%
			Catalytic afterburner*	1,800	11,000,000	745°F 27%
			Catalytic afterburner*	180	1,100,000	815°F[m] 93%

*Afterburner odor control devices.

**Nonafterburner odor control devices.

[a]Odor units per standard cubic foot (at 70°F and 14.7 psia).

[b]Odor units discharged per minute, based on average volumetric discharge rate and modal odor concentration.

[c]Temperature of gases after leaving flame-contact zone (afterburners); temperature of vent gases in other cases.

[d]Odor control efficiency, on a modal odor concentration basis.

[e]Odor concentrations in batch processes vary with materials charged and phase of operation.

[f]Surface condensers increase odor concentrations in the vent gases but reduce total odor emission rates.

[g]Hundred-fold increase from beginning to end of cycle.

[h]One test only.

[i]Samples collected from several points of odor emissions.

[j]In continuous processes, odor concentrations vary with temperatures maintained and materials charged.

[k]Chlorine (20 ppm) mixed with drier off-gases, which are then scrubbed. More or less chlorine increases odor concentrations.

[l]Estimated from two tests only.

[m]Maximum temperature at which this catalytic unit can operate.

[n]Outlet odor concentration rises and falls with inlet odor concentration.

[o]The surface condenser is an integral part of the hydrolyzing unit. Note that low temperature incineration increases odor concentration above condenser vent level.

APPENDIX B

TABLE 43

ODOR REMOVAL EFFICIENCIES OF CONDENSERS OR AFTERBURNERS,
OR BOTH, VENTING A TYPICAL DRY RENDERING COOKER*[180]

Concentration (odor units/scf)	Emission Rate (odor units/min)	Condenser Type	Condensate Temperature (^{O}F)	Afterburner Temperature (^{O}F)	Concentration (odor units/ scf)	Modal Emission Rate (odor units/min)	Odor Removal Efficiency (%)
50,000	25,000,000	None		1,200	100 to 150 (Mode 120)	90,000	99.40
		Surface	80	None	100,000 to 10 million (Mode 500,000)	12,500,000	50
		Surface	140	1,200	50 to 100 (Mode 75)	6,000	99.98
		Contact	80	None	2,000 to 20,000 (Mode 10,000)	250,000	99
		Contact	140	1,200	20 to 50 (Mode 25)	2,000	99.99

*Based on a hypothetical cooker that emits 500 scfm of vapor containing 5 percent noncondensible gases.

TABLE 44

ODOR REDUCTION IN POLLUTED AIR BY POTASSIUM PERMANGANATE[213]

Pollutant	Odorant Concentration Odor Units/scf	
	Solution 1[b]	Solution 2[c]

MERCAPTANS

Butanethiol	200,000	33[a]
Pentanethiol	>100,000	16[a]
Hexanethiol	85,000	10.5[a]
Heptanethiol	3,200	20[a]
Octanethiol	3,500	6.5[a]

OTHER SULFUR COMPOUNDS

Mercaptoacetic acid	65	1
2-Mercaptoethanol	30	1
Allyl isothiocyanate	2,500	1
Thiophenol	1,300	13[a]
Thiophene	4,000	13[a]

AMINES

Dimethylamine	1,300	20
Trimethylamine	2,700	20
Triethylamine	60-70	50-65[a]
Cadaverine	20	1
Indole	5	1
Skatole	60-100	1

PHENOLS

Phenol	11	1
o-Cresol	20	1
o-Chlorophenol	200	1
m-Chlorophenol	45	25[a]
p-Chlorophenol	5	1

MISCELLANEOUS ORGANIC COMPOUNDS

Styrene	2,000	10[a]
Allyl acetate	1,700	25[a]
Acrolein	140,000	1
Benzaldehyde	80	1
Acetaldehyde	1,700	200
1-Butanol	150	40[a]
Off-gas of bone elevators (rendering plant)	100-140	20-25[a]
Cooker condensate (rendering plant)	4,000	250[a]
Off-gas of asphalt plant	15-20	1

[a]Residual odor characteristics much improved.
[b]Malodorous air bubbled through water, pH 8.5.
[c]Malodorous air bubbled through 1% solution of potassium permanganate, pH 8.5.

TABLE 45

TYPICAL COSTS OF BASIC AND CONTROL EQUIPMENT INSTALLED IN LOS ANGELES COUNTY[44]

Source	Size of Equipment	Cost of Basic Equipment	Type of Control Equipment	Cost of Control Equipment
Airblown asphalt system	500 bl/batch	$ 10,000	Afterburner	$ 3,000
Bulk gasoline loading rack	667,000 gal/day	88,000	Vapor control system	50,000
Catalytic reforming unit	2,400 bl/day	265,000	Flare and sour water oxidizer	6,000
Chip dryer	2,500 lb/hr	3,000	Afterburner	3,000
Chrome plating	4 by 5 by 5 ft	2,000	Scrubber	800
Coffee roaster	3 tons/hr	35,000	Cyclone and after-burner	8,000
Core oven	8 by 8 by 12 ft	4,000	Afterburner	1,500
Crude oil distillation unit	37,000 bl/hr	3,060,000	Vapor control system	10,000
Debonder	500 brake shoes/hr	1,800	Afterburner	300

(continued)

TABLE 45 (Continued)

TYPICAL COSTS OF BASIC AND CONTROL EQUIPMENT INSTALLED IN LOS ANGELES COUNTY

Source	Size of Equipment	Cost of Basic Equipment	Type of Control Equipment	Cost of Control Equipment
Deep fat fryer, food	1,000 lb/hr	$ 15,000	Afterburner	$ 1,500
Delayed coker unit	9,300 bl/day	4,000,000	Scrubber (serving 3 cokers)	385,000
Drum reclamation incinerator	60 bl/hr 200 bl/hr	10,000 25,000	Afterburner Afterburner	2,000 5,000
Fixed roof storage tank for gasoline	80,000 bl	50,000	New floating roof tank	132,000
Flue-fed incinerator	Most sizes	4,000-7,000	Afterburner	2,500
Insulation production, including cupola, blow chamber, and curing oven	5,000 lb/hr	13,000	Baghouse, scrubber and afterburner	30,000
Lithographing oven	240 ft/min	78,000	Afterburner	15,000
Multiple-chamber incinerator, industrial and commercial	50 lb/hr 500 lb/hr 6,000 lb/hr	800 6,500 75,000		

TABLE 45 (Continued)

TYPICAL COSTS OF BASIC AND CONTROL EQUIPMENT INSTALLED IN LOS ANGELES COUNTY

Source	Size of Equipment	Cost of Basic Equipment	Type of Control Equipment	Cost of Control Equipment
Multiple-chamber incinerator, pathological	50 lb/hr 200 lb/hr	$ 1,000 4,500		
Multiple-chamber incinerator, wire reclamation	100 lb/hr 1,000 lb/hr	1,200 15,000		
Multiple-chamber incinerator, with continuous feed bin	250 lb/hr 3,000 lb/hr	5,000 45,000		
Natural gas plant	20,000,000 ft^3/ day	220,000	Vapor manifold and flare	$ 5,000
Oil-water separator	300,000 bl/day	170,000	Floating roof	80,000
Phthalic anhydride manufacturing plant	25,000,000 lb/yr	1,200,000	Afterburner and baghouse	195,000
Pot furnace, type metal	16,000 lb	9,000	Afterburner	3,000

TABLE 45 (Continued)

TYPICAL COSTS OF BASIC AND CONTROL EQUIPMENT INSTALLED IN LOS ANGELES COUNTY

Source	Size of Equipment	Cost of Basic Equipment	Type of Control Equipment	Cost of Control Equipment
Rendered grease processing	6 tons/day	$ 10,000	Contact condenser and afterburner	$ 2,500
Rendering cooker and drier (batch)	4 tons/batch	10,000	Surface condenser and afterburner	15,000
Rendering cooker system (continuous)	15 tons/hr	100,000	Surface condenser and afterburner	25,000
Rotogravure press	5-color, 44-inch web	340,000	Activated carbon filter	40,000
Sewage treatment digestion	900,000 gal/day	800,000	Water seals and flares	7,000
Sewage treatment headworks	250,000,000 gal/day	550,000	Covers	20,000
Sewage water reclamation	17,000,000 gal/day	1,500,000	Covers and aeration tanks	25,000

TABLE 45 (Continued)

TYPICAL COSTS OF BASIC AND CONTROL EQUIPMENT INSTALLED IN LOS ANGELES COUNTY

Source	Size of Equipment	Cost of Basic Equipment	Type of Control Equipment	Cost of Control Equipment
Smoke generator and smokehouse	11 by 14 by 11 ft	$ 18,000	Precipitator, scrubber, and afterburner	$ 42,000
Sulfur recovery plant	2 parallel units, 65 tons/day each	1,400,000	Incinerator	30,000
	10 tons/day	265,000	Incinerator	5,000
	2,840 lb/day	30,000	Incinerator	1,000
	8,000 lb/day	60,000	Incinerator	1,000
Synthetic rubber manufacturing	30,000 tons/year	1,600,000	Vapor manifold and flare	250,000
Synthetic solvent dry cleaner	60 lb/batch	14,000	Activated carbon filter	3,000
Varnish cookers (2)	250 gal/each	4,000	Afterburner	5,500

TABLE 46

CONTROL EXPENDITURES BY TYPES OF EMISSIONS IN THE PETROLEUM INDUSTRY[71]
(Thousands of Dollars)

| Year	Sulfur Compounds	Hydrocarbons (Combustion)	Hydrocarbons (Recovery)	Smoke and Particulates	Odors and Fumes	Total
1956	$ 6,154	$ 4,977	$ 5,325	$ 2,150	$ 1,171	$ 19,777
1957	6,154	4,977	5,325	2,150	1,171	19,777
1958	4,087	2,235	7,628	449	981	15,380
1959	2,693	3,640	3,124	2,780	1,091	13,328
1960	4,495	2,230	7,152	780	1,047	15,704
1961	5,560	1,501	6,497	3,437	4,381	21,376
1962	1,474	6,143	2,501	5,257	3,046	18,421
1963	2,191	3,829	4,012	2,109	2,711	14,852
1964	4,230	4,515	2,421	3,868	2,030	17,064
1965	1,795	5,497	2,700	3,840	2,101	15,933
1966	7,901	6,959	3,821	5,361	9,368	33,410
Total	$46,734	$46,503	$50,506	$32,181	$29,098	$205,022

TABLE 47

ECONOMIC ANALYSIS OF THREE TYPES OF CONDENSERS FOR RENDERING PLANTS[265]

Condenser Type	Basic Cost	Capital Charges (U.S. Dollar Equivalent) Installation	Total
Direct-spray condenser			$2,000
Surface condenser with cooling tower	$3,550	$1,550	5,050
Air-cooled condenser	4,320	1,000	5,320
		Operating Charges[a]	
	Water Cost[b]	Electricity Cost[c]	Total Cost
Spray condenser	$850	$ 56	$906
Surface condenser	29.75	168	198
Air-cooled condenser		280	280

[a]Based on a 2,500-hour working year.

[b]Water: 17 cents/1,000 gal.

[c]Electricity: 2 cents/unit.

APPENDIX C

OLFACTION THEORIES

The Dyson-Wright Vibration Theory

In 1937, Dyson[69] proposed three requirements for an odorous substance: volatility, lipid solubility, and intramolecular vibrations which give rise to Raman shifts in the region 3,500 to 1,400 cm^{-1}. Dyson[68] had actually proposed the essential factor of vibrations in 1928, the year the Raman effect was discovered; then in 1937 he suggested that the vibrational frequencies of molecules could be assessed from the Raman shifts. Based on limited data, he proposed the region 3,500 to 1,400 cm^{-1} as the region of "osmic frequencies" to which the nose was sensitive. Because the senses of hearing and vision involve sensitivities to vibrations of certain frequencies, a theory of olfaction based on an analogous mechanism is logically appealing. This theory attracted much interest, but it was quickly discarded for the simple reason that there is no correlation between frequencies in the 3,500 to 1,400 cm^{-1} range and odors. Because the Raman and infrared spectra are related, the correlation between odor and frequencies of 3,500 to 1,400 cm^{-1} would have to be correlated with the functional groups now known to give rise to absorptions in this range.

Dyson's theory was ignored for 20 years until it was resurrected by Wright in 1956.[307] Wright believed that the basic idea of vibrational frequencies to which the olfactory receptors are sensitive is correct, but that Dyson's selection of the range of osmic frequencies was wrong. It is known that infrared absorption resulting from the molecular vibrations occurs in the low frequency region (the fingerprint region of infrared spectra), and Wright proposed the region 500 to 50 cm^{-1}, in the far infrared, for osmic frequencies. In his theory, the vibrational frequencies determine the quality of an odor, whereas such factors as volatility, adsorbability, and water-lipid solubility determine the intensity of the odor. The olfactory pigment is proposed as having all its molecules in an electronically excited state; the molecules do not return to the ground state unless triggered. The odorous molecule combines with a pigment molecule whose vibrational frequency it matches, thereby changing the frequency of vibration of the pigment molecule and triggering the return of the electronically excited molecule to the ground state. To account for the variety of odors, there must be a number of types of olfactory pigments.

From the generalization that no instances are known in which one of a pair of optical isomers has an odor and the other does not,* Wright[306] infers that the primary process of olfaction must be a physical rather than a chemical interaction. He thinks that the slight differences reported in the odors of some optical isomers may result from different levels of purity. The change in quality of an odor upon dilution is probably due to the odors consisting of several odors having different thresholds, so that at lower concentrations only certain components are detected. Wright[307] acknowledges three exceptions to his theory-- ammonia, hydrogen sulfide, and hydrogen cyanide--none of which has low frequency vibrations.

Experimentally, Wright's vibrational theory was at the same state in 1966 as Dyson's theory was in 1937; namely, there were few data to test the theory.[234]

The Moncrieff-Amoore Stereochemical Theory

In 1944, Moncrieff[184] proposed a new theory: namely, that the only prerequisites for odor were volatility and suitable solubility. According to this theory, differences

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*Moncrieff[190] has reported dihydrocamphenol as an exception to this generalization.

in intensity of odors were due to variations in volatility, whereas differences in quality were due to different solubilities in the lipoproteins of the various types of receptor cells, with each type sensitive to some fundamental odor. In 1949 he presented a revised theory[185] in which the two prerequisites were volatility and a molecular configuration complementary to the sites of the receptors. The latter is an example of the lock-and-key concept well known in enzyme and drug theory. He suggested that there are probably between 4 and 12 types of receptor sites, each corresponding to a fundamental odor. No further details were specified. It was claimed that this theory incorporated the good features of most of the earlier theories and could explain most of the important characteristics of olfaction, including the different odors of stereoisomers.[234] Moncrieff's[186,189,190] recent work has been concerned with demonstrating that odorous compounds are readily adsorbed on the olfactory epithelium and with emphasizing the theoretical importance of adsorption in concentrating the molecules and thereby enabling detection of such small amounts of substances.

Amoore[11,12,14,15] has developed a detailed theory based on Moncrieff's outline. Two refinements were needed:

first, to determine how many types of receptor sites exist;
second, to determine the size and shape of each of the
receptor sites. The theory successfully accounts for the
identical odors of isotopic molecules and the different
odors of stereoisomers, the two chief contradictions to
Wright's theory. The change in quality of odor upon dilu-
tion can be readily explained by preferential adsorption in
various sites. An odorous molecule may fit several sites
but have a greater affinity for some of them. At high
concentrations all sites will be occupied, whereas at low
concentrations only the preferred sites will be occupied.