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DISPOSAL OF CHEMOTHERAPEUTIC AGENT -- CONTAMINATED WASTE

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AFESC/RDVS has completed a project to determine the feasibility of incinerating chemotherapeutic agent-contaminated waste in a Phase I SBIR study project. Air Force base hospitals generate hazardous medical wastes in the form of infectious and chemotherapeutic agent-contaminated wastes. The Air Force is investigating methods of disposal of these hazardous wastes, of which incineration is one method. This study involved the development and design of an incineration unit capable of 99.99 percent destruction of these hazardous wastes. Design efforts have indicated that this unit is indeed feasible and economical. Also included in the study were hospital waste volumes and disposal practices. The study showed that current incineration equipment is not adequate for the difficult chemical compounds found in chemotherapeutic agent-contaminated wastes. As liabilities increase, more effective methods of waste disposal will need to be utilized.

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EXECUTIVE SUMMARY

Incineration is the only process which can safely and reliably dispose of most toxic wastes. Many hospital wastes are toxic in nature. Specifically, chemotherapeutic agent wastes (those compounds used in chemo-therapy treatment) are difficult wastes to breakdown into safe compounds. These agents require high temperatures for total destruction of the toxic compounds.

Chemotherapeutic agents contain compounds which contain chlorine and fluorine. Chemical bonds in chlorine and fluorine are very stable and are difficult to fracture. At extreme high temperatures (1800°F) the very strong bonds between organic substances and chlorine or fluorine can be broken. Therefore, high-temperature incineration can convert complex chemical compounds into fully reacted oxidation products. Chlorine and fluorine are converted into hydrochloric and hydrofluoric acids which can be removed easily by washing with alkaline solution. Fully oxidized compounds can be either discharged into the atmosphere, like water vapor and carbon dioxide, or can be disposed of in any landfill as fully oxidized, nonleachable ashes.

Proper destruction of chemotherapeutical agents by incineration requires equipment which will not emit partially reacted, intermediary reaction products and which will convert the entire waste into only harmless end products. The design of such equipment requires an intimate knowledge of incineration technology, reaction kinetics, combustion technology, flue gas cleaning, and high temperature construction.

The U.S. Air Force Engineering and Services Center at Tyndall AFB initiated a project under The Small Business Innovation Research (SBIR) program to develop an incineration system to dispose of chemotherapeutic agent-contaminated (CAC) waste. Phase 1 of this program included a feasibility study, concept development and preparation of assembly drawings of the proposed system. This final report summarizes the work carried out under Phase 1 of the SBIR program.

During Phase 1, a study was made to define types of hospital wastes, the role of CAC waste, and present methods for disposal. It was found that almost all health care facilities preferred incineration as the most desirable method of CAC waste disposal. Detailed specifications for CAC waste composition, quantities generated by a typical health care facility and preliminary economics were prepared. A concept and preliminary design for an incineration system was developed, then a set of assembly drawings for a test incineration system was prepared. The desired operating conditions for the typical compounds to be destroyed in the incineration system were defined by The University of Dayton Research Institute (UDRI) due to their intimate knowledge of thermal destruction of chemical compounds to assure that the CAC waste destruction efficiencies will be in excess of 99.99 percent.

Due to sealing considerations, the proposed design is based on a batch apparatus with a waste destruction chamber, which is hermetically sealed after the waste is loaded. The waste is heated to high temperatures which results in thermal decomposition. In a specially designed afterburner the gases are mixed with oxygen and completely oxidized at even higher temperatures. The entire destruction process is controlled by a supervisory computer which assures that the reaction conditions in every part of the waste disposal system are maintained at optimum conditions. Human interface is limited to manual loading and unloading to protect the operator and to prevent malfunction as a result of operator error.

The system design is based on scientific data for destruction of compounds in chemotherapeutic wastes. It is also suited for the thermal destruction of wastes with less difficult destruction properties. It can also be used for the disposal of biomedical wastes and wastes from oncological stations. Such wastes are not yet controlled but should be prevented from entering the drinking water recycling chain. These wastes contain halogenated hydrocarbons that are often very stable and not necessarily destroyed by anaerobic digestion or conventional oxidation. Traces of these halogenated hydrocarbons are accumulated in human and animal tissues where they can lead to future liabilities.

A concept design for chemotherapeutic waste disposal has been developed. This design is based on discussions and reviews with personnel from area health care facilities, the EPA (Environmental Protection Agency) and scientists working in hazardous waste incineration. The design also borrows heavily from the proposers experience with related equipment and processes. This design promises to safely dispose of these types of wastes. No technical problems were encountered which would prevent this disposal process from working.

In Phase 2 of this program, the detailed design must be translated to a bill of materials and followed by purchasing, fabrication, installation, and testing of a full size incineration system. These efforts will be complemented by an experimental investigation into closely defining those conditions which will assure complete destruction of agents. After initial tests with simulated, harmless substances the equipment will be subjected to extensive performance tests. After passing the most severe tests the unit will be used for the terminal disposal of chemotherapeutic wastes and other biomedical wastes.

At the end of Phase 2 a completely operational, full-size incineration system will be available which can be used for the disposal of chemotherapeutic and infectious wastes.

PREFACE

This report was prepared by Indugas, Inc., 5924 American Road East, Toledo OH 43612, under Contract Number F08635-88-C-0276, for the Air Force Engineering and Services Center, Engineering and Services Laboratory (AFESC/RDVS), Tyndall Air Force Base FL 32403-6001.

This report summarizes work done at Indugas, Inc., between September 1988 and February 1989. This work was performed under the direction of Dr K.H. Hemsath, principal investigator. The contributions of A.C. Thekdi and C.F. Andrews are acknowledged in the completion of this report. The HQ AFESC/RDVS project officer was Mr Surendra B. Joshi.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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LIST OF ABBREVIATIONS

CT	CHEMOTHERAPEUTIC
CAC	CHEMOTHERAPEUTIC AGENT CONTAMINATED
CDC	CENTER FOR DISEASE CONTROL
EPA	ENVIRONMENTAL PROTECTION AGENCY
JCAHCO	JOINT COMMISSION ON ACCREDITATION OF HEALTH CARE ORGANIZATIONS
OSHA	OCCUPATIONAL SAFETY AND HEALTH AGENCY
POC	PRODUCTS OF COMBUSTION
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
UDRI	UNIVERSITY OF DAYTON RESEARCH INSTITUTE

SECTION I

INTRODUCTION

A. OBJECTIVE

The primary objective of this program was to develop a safe and effective method and the associated equipment for the destruction of chemotherapeutic-agent-contaminated (CAC) wastes using thermal treatment (incineration) of the waste material.

The objectives of the first phase were: to familiarize the potential user with the expected performance capabilities of the thermal decontamination method and disposal unit; and to ascertain that the proposed equipment design meets demanding performance specifications in every respect.

These main objectives were to be achieved by using information from the following technical objectives discussed below.

- To study waste generation, handling and disposal methods used by hospitals to meet current and impending regulations. This includes development of data on types, characteristics, and quantities of different types of wastes generated in hospitals.

- To review available incineration technologies and equipment which have been used to meet local, state and federal environmental control regulations. Emphasis was placed on those technologies which have been used for hazardous waste disposal and to meet RCRA regulations.

- To predict and select process conditions (i.e., temperature, residence time, gas composition) which assure 99.99 percent destruction of the hazardous compounds present in the CAC wastes generated in hospitals. Specific agents were selected by the Air Force Engineering and Services Center (AFESC). Preliminary values were to be developed by the University of Dayton Research Institute (UDRI) based on their past experience, available data base and theoretical considerations. These preliminary values need to be confirmed or revised after execution of experiments during Phase 2.

- To develop necessary thermal treatment and flue gas cleaning or pollution control process schemes which will allow the user to meet all current and anticipated environmental regulations.

- To design a completely automated system, including all necessary equipment and components, to handle typical quantities of CAC waste produced by an average-size hospital. Assembly drawings of the proposed system were to be prepared to provide a "foot print" of the proposed system. These drawings were also to serve as reference to system size and to illustrate operating procedures.

- To prepare a detailed test plan for laboratory experiments to confirm or revise the assumed preliminary selected values of thermal parameters (temperature, residence time, process gas composition etc.) for selected chemotherapeutic (CT) agents and their critical products of combustion (POCs).

- To prepare a final report for Phase 1 work.

B. BACKGROUND

Air Force regional medical centers generate CAC waste from care and treatment of oncologic cases. This waste is in the form of syringes, tubing, bottles, gowns, and rags contaminated with small quantities of chemotherapeutic agents classified as carcinogenic, mutagenic and teratogenic drugs. The amount of waste is relatively small but the problems with disposal are exacerbated by the toxic or life threatening nature of the waste.

Although amounts of hospital waste in general and CAC waste in particular are rather small when compared to hazardous and toxic waste generated by industries, the social and political attention given to waste disposal makes this problem highly visible. This situation will become more serious as continuing publicity is given to uncontrolled disposal. Many of the problems of the past year have arisen out of poor disposal methods by hired contractors after the waste leaves the hospitals, leaving hospitals potentially liable, but helpless to find solutions. No state or federal guide lines are available to the Air Force or civilian health organizations to specify disposal of this waste.

Upon recommendations from the Center for Disease Control (CDC) and the Joint Commission on Accreditation of Health Care Organizations (JCAHCO) most hospitals have developed procedures to handle different types of wastes within health care facilities. Different types of wastes are defined as "solid waste" or general trash, "red bag" waste which includes infectious materials and "yellow bag" waste which contains chemotherapeutic waste and sharps (contaminated instruments).

The "solid waste" or general trash is not classified as hazardous waste and it is disposed of by using an incinerator or, in many cases, in a local landfill facility. Most of the incinerators used by health care facilities are relatively old and are not equipped with flue-gas cleaning systems.

However, both the red bag and the yellow bag wastes are considered as hazardous and cannot be disposed of as general wastes. Many organizations use waste hauling contractors or onsite incineration to dispose of the waste materials of this type. However, the long-term liability issue has forced these organizations to look for onsite disposal methods to assure ultimate disposal of these wastes.

Because the red bag waste contains mostly biological materials including pathogens, it is referred to as infecticus waste by many regulatory agencies. The main concerns are the effects of pathogens and contagious materials which are included in the waste. The Environmental Protection Agency has published a manual (Reference 1) which provides guidelines on handling and disposal of infectious waste from hospitals. Some of the methods recommended and accepted by EPA include landfilling of waste materials after their sterilization in an autoclave, or the chemical decontamination of pathogens followed by landfilling and incineration.

Most responsible hospitals do not accept the first two methods as satisfactory from the social and future legal liability point of view. As a result, they use outside contractors or utilize their existing thermal incinerators for the disposal of red bag wastes.

Yellow bag waste is separated at the hospital level from red bag waste, but no differing guidelines exist for its disposal.

Outside contract disposal is considered as too expensive and not fully reliable for red bag disposal. The hospitals have very little or no control on the ultimate destination of the waste, the paperwork is extensive and the cost is high. In some cases the disposal charges amount to as high as $1200 to $1600 per ton of waste and the total yearly cost to a hospital can be as high as $250,000 to $400,000.

In most cases, where onsite disposal is practiced, a general-purpose incinerator is used to burn almost everything generated as waste in a hospital. Recent studies (Reference 2) have shown that these incinerators do not have flue gas clean-up systems and perform only a very marginal function of "burning" the waste. Improper design and operating practices of these incinerators actually result in generation of air pollutants such as hydrocarbons generated from incomplete combustion, organic chlorides in the form of dioxins and furans and organic or inorganic particulates. These facilities are coming increasingly under review from local environmental regulatory agencies and may be forced to improve their operations to meet local air pollution regulations.

As mentioned earlier, most hospitals follow the guidelines provided by CDC and JCAHCO for segregation and in-house handling of CAC waste. They use yellow bags to collect this type of waste. Extreme care is taken for its isolation, storage and packaging. However, very little attention is given to the ultimate disposal of these bags. Very few, if any, hospitals try to dispose of this waste in their in-house incinerator facilities. The waste is generally handled by an outside contractor. Contacts and discussions with these contractors, however, indicated that they do not distinguish between the red bag and yellow bag waste in their disposal.

Recognizing that the current conditions and disposal methods are not fully acceptable to the Air Force, a number of studies were conducted by the Air Force to investigate the practices of waste disposal in Air Force hospitals and recommend possible methods for waste disposal of the CAC wastes. In one report (Reference 3) submitted to the Air Force the following methods were identified as possible means for disposal of this waste.

- Chemical Deactivation
- Sanitary Sewage Disposal
- Landfills
- Thermal Incineration

Chemical Deactivation of highly complex organics requires special reagents on a one-on-one basis. This method also requires separating these chemicals before final disposal. These reactions normally cannot offer the high destruction efficiency (greater than 99.99 percent). At the same time other issues such as the control and reliability of such a system dealing with a large number of materials in a mixture of waste, and the disposal of resultant materials make it very difficult to use this as a legally acceptable means for final disposal of this waste.

The sanitary sewage disposal is obviously not possible for bulk items. But even for materials such as liquid drugs, prior chemical deactivation is not always possible and the degree of neutralization achieved is always a question. The lack of reliability and potential consequences of a slight error in execution of this process can result in serious water toxicity problems. This method is also unacceptable.

Use of a landfill facility presents a number of problems related to the transportation, reliability of a second or third party for proper disposal and, above all, a long term liability problem for the originator of the waste. Many of the proposed state regulations (Reference 4) will not allow landfilling of this type of waste unless it is preprocessed and rendered nonhazardous before landfilling.

Thermal incineration, executed in a properly designed and operated incinerator is the only method for safe and reliable disposal of these wastes. In the past this method has been accepted and used for many highly toxic and hazardous materials such as chemical warfare agents for the U.S. Army. The thermal incineration process was selected in this application over alternatives such as chemical neutralization, sea dumping in a hermetically sealed concrete container, and discarding wastes into space (Reference 5).

During the execution of Phase 1 of this program Indugas, Inc. and University of Dayton Research Institute (UDRI) have studied different aspects of hospital waste and disposal methods and have concentrated on the thermal incineration of chemotherapeutic waste materials. As reported in later sections, it is possible to dispose of the chemotherapeutic waste and, if necessary, other types of wastes such as infectious waste, by using an automated and "intelligent" incineration system.

C. SCOPE/APPROACH

The program was divided into two phases. The scope of work during Phase 1 included the following activities.

- Review of the hospital wastes, characteristics, quantities and presently used disposal methods.
- Review of currently available thermal disposal methods and equipment for waste disposal and their performance.

- Concept development and analysis for an appropriate size incineration system.
- Process engineering.
- Preliminary equipment sizing.
- Concept finalization.
- Preliminary assembly drawings.
- Overview of operating procedures.
- Test plan preparation for Phase 2 activities.
- Final report.

Many sources including personal contacts and literature surveys were used to derive information on the hospital waste, presently used disposal methods and preliminary economics. Certain waste disposal companies were used to determine disposal methods used by outside contractors.

A data base developed by the Oak Ridge National Laboratory for The Environmental Protection Agency was used to identify different types of incineration equipment and their performance for disposal of hazardous waste during the last 5 years.

The UDRI personnel were retained as consultants to identify commonly used chemotherapeutical drugs and to define the thermal conditions necessary to obtain 99.99 percent destruction efficiency during their incineration.

All of the above information was used to develop a concept for the incineration system which can meet requirements of hazardous waste disposal process regulations such as RCRA. The pilot unit size and other specifications for an incinerator unit were determined on the basis of present and future (3 to 5 years from now) needs of a typical hospital (Air Force and civilian) with an oncological unit.

Process calculations included determination of process conditions such as temperatures, pressures, flows and gas analysis of the fluid streams at key locations in the proposed system. Values for operating temperatures, flue-gas composition and residence times for the incinerator modules were derived from the UDRI recommendations.

One of the most important parameters affecting the overall size and cost of the unit is the composition of waste material charged into the unit. In any hospital, it is almost impossible to precisely control the amount of organics, water and inert material content of the waste. The unit design has to handle a wide variety of materials in the discharge and still provide safe and efficient disposal. Two extreme situations were used in determining the size, design and operating procedure of the unit.

The two situations are:

- ° Waste consisting of 99 percent contaminated water.
- ° Waste containing 99 percent organic materials.

Obviously the real-world waste composition will be somewhere in between these two extremes. Normal operating times and utility requirements were calculated on the basis of composition of a "typical" waste, and predicted values for other types of waste were calculated to provide operating guidelines. The system and its controls are designed to automatically accomplish the necessary cycle time adjustments to assure total destruction of the varying wastes.

A number of assembly drawings were prepared to show the overall dimensions, location of major components and their relative size. The unit is small enough to be accommodated in a basement or other enclosed room where commonly used utilities such as electricity, natural gas (or other type of fuel) and water are available. The unit includes components to make it self-contained.

Although the system is designed to process chemotherapeutic wastes, it can handle any other type of hospital waste, including infectious waste. The operating condition requirements for wastes other than chemotherapeutic agents will be less strict. As a result, unit capacity, expressed in terms of pounds of waste processed per day, will increase greatly due to shorter residence times and lower temperatures (lower temperatures mean less time to reach operating temperature and shorter residence [length of time at a particular temperature] in the furnace chamber). For example, the above mentioned unit can process up to 300 pounds of infectious waste per day and still meet all the regulatory requirements (compared to 200 pounds per week for CAC waste). This capacity is sufficient for the disposal requirements of a typical Air Force hospital.

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SECTION II

HOSPITAL WASTE AND THE ROLE OF CHEMOTHERAPEUTIC AGENT-CONTAMINATED (CAC) WASTE

A. HOSPITAL WASTES: TYPES AND RATE OF GENERATION

Hospitals, both in the civilian and the military sector, generate a large variety of waste materials in a large quantity. The mix of wastes is also changing due to growth of patient population, advancements in therapeutic drugs, and increases in treatment facilities. For example, many hospitals, including Air Force hospitals, are opening special facilities for treatment of cancer and AIDS. As a result the waste stream will contain higher percentages of complex drugs which could be highly dangerous to hospital personnel and others if they are not disposed of properly. Recognition of this fact is leading many state and local governments to prepare legislation which will control waste handling and disposal of the hospital or medical wastes.

The wastes generated by hospitals are classified in many different ways. At this time there is no universally accepted classification. Terms such as pathological waste, infectious waste, and biomedical waste are commonly used. However none of them have been defined and accepted by any medical or government agency. In view of this and for the purpose of this report the waste is classified in three general and generic classes.

They are:

- General solid waste
- Infectious or biomedical waste
- Chemotherapeutic (toxic) waste

The amount of waste generated varies with type of hospital but some general statistics are available. The typical waste figures are expressed in terms of pounds of waste per day per patient(or bed). The total waste generated varies from 17 to 45 pounds/day-bed (Reference 6). An average number of 28 pounds is considered typical. This waste contains 89 (+/-0.5)percent general solid waste, 11 (+/-0.5)percent infectious or biomedical waste and less than 0.5 percent chemotherapeutical (or toxic) waste.

1. General Solid Waste

This type of waste includes wastes generated in offices (paper, cardboard, plastic etc.), kitchen and hospital floors. This constitutes the majority (more than 85 percent) of the hospital waste. It is collected in commonly used trash containers and it is handled as household waste, without any special precautions. The quantity of this type of waste is estimated to be approximately 20 pounds per day-per patient. The exact content of this type of waste contains varying amount of food and paper materials with plastics which may include chlorinated materials such as PVC.

The disposal methods for such wastes are:

- Onsite incineration in a "trash" incinerator.
- Contract hauling with ultimate disposal in a landfill or off-site incineration.

No special regulations exist with respect to the handling and disposal of such wastes. However, when an incinerator is used, its performance must meet local environmental regulations. The ashes from such incinerators are not classified as hazardous waste and are usually disposed of in a municipal or unprotected landfill.

Incineration equipment purchased 5 to 10 years ago did not include proper air pollution control equipment and cannot meet the current air pollution regulations.

2. Infectious or Biomedical Waste

The wastes which can transmit an infectious disease are considered infectious. For a specific waste to be identified as infectious waste it must contain pathogens of sufficient quantity and virulent materials to infect a host exposed to the waste. Extensive use of disposable items, listed later, which come in contact with patients or animals has increased the quantity of this type of waste in all health care facilities. This category can contain the following wastes (as identified by EPA).

- Isolation wastes
- Cultures and stocks of infectious agents and associated biologics
- Human blood and blood products
- Pathological wastes
- Contaminated sharps (instruments)
- Contaminated animal carcasses, body parts, and bedding

The quantity of infectious wastes generated by a hospital depends on the type of health care provided and, the method of classification used by the hospital. The estimates vary from 2 to 3 pounds per day-per bed of red and yellow bag wastes generated. With increasing awareness of the problem and stricter enforcement of handling regulations, classifications are expected to become more stringent and the quantity of wastes classified as hazardous will increase. In the near future (2 to 4 years) the rate of 3 pounds per day-per bed is a reasonable estimating figure.

Regulations regarding the infectious wastes have been formulated by a number of states and others will follow them within the next 1 to 3 years. There are no federal regulations and there is no general consensus among state or local regulations regarding the definition or method of disposal of these wastes.

Many states which have issued regulations on infectious wastes require that the wastes handling, movement and disposal must be properly documented to assure that it has been disposed of properly. The method of disposal can be classified in three categories.

- Land disposal after sterilization .
- Incineration in a municipal or general trash incinerator after sterilization.

° Incineration in an offsite hazardous waste incinerator facility.

At this time, many hospitals prefer the second option; however, the available incineration equipment performance does not meet many local air pollution regulations. Commonly reported performance problems are: emission of smoke, CO, unburned hydrocarbons, HCl and, in some cases, dioxins and furans formed due to uncontrollable combustion reactions due to poor design or operations. The third option is preferred by many hospitals, but many still hesitate because of its high cost and lack of total control over the final disposal methods.

3. Chemotherapeutic (Toxic) Waste

Many types of wastes generated in hospitals fall under the Resource Conservation and Recovery Act (RCRA) due to the nature and/or content of materials which are classified as hazardous by EPA. Typical materials or wastes containing these materials are given in Table 2. They must be disposed off in a RCRA permitted hazardous waste incineration system with proper permit. Strict operating control and reporting standards must be adhered to.

The quantity of this type of waste depends on the type of hospital (teaching, research, or general) and the type of care offered (oncological, geriatric, AIDS, etc.). For a general hospital the numbers given to Indugas during a survey of local civilian hospitals indicated that the rate of generation varies from 50 to 200 pounds per week.

A survey of Air Force medical facilities conducted by The Universal Energy Systems, Inc. (Reference 3) indicated that the waste amounts vary from 4 to 48 drums (55 gallons) per year. This amounts to 10 to 120 pounds per week. These quantities may double or triple in the next few years because of changing treatment methods, increased patient load, improved awareness and handling procedures, and stricter enforcement of the regulations.

The above figures make it safe to assume that the quantities of this type of wastes can be in the range of 50 to 200 pounds per week.

At this time many hospitals take special precautions and use well-planned waste tracking and handling systems. The waste is collected in a yellow plastic bag or in a special plastic container (mostly for sharp objects mentioned earlier). The bags and containers are placed in a card-board box which is hauled away by a contractor. In most cases the boxes and their contents are incinerated in a hazardous waste incinerator. Special paperwork is required for the offsite handling, transportation and disposal of the wastes. The cost of handling, transportation, disposal and associated paper work may be as high as $150,000 per year. Most hospitals are still concerned about the continuing future liability from contractor negligence during handling, transportation and disposal of the wastes.

B. NATURE OF CHEMOTHERAPEUTIC AGENTS

A large number of substances such as chemical reagents (acetone, alcohol, ether, etc.), and special drugs (anti-neoplastics, cytotoxic agents, etc.) are considered as hazards to human health. The degree of danger posed by these materials depends on their nature and exposure time. Relatively short exposures to antineoplastic drugs and other cytotoxic agents can cause dizziness, nausea, headache and dermatitis. Long-term exposure to these drugs may produce teratogenic (malformation of tissues or fetus) and carcinogenic (cancer causing) effects. In most cases, these types of drugs are contained in special glass or plastic containers and their administration and delivery to patients involve other items such as vials, syringes, needles, gloves, etc. These items also become contaminated and pose similar dangers. Because of the danger special precautions are required at all levels of their production, handling and administration to patients.

The antineoplastics, cytotoxic agents and other chemotherapeutic agents have highly complex molecular structures and contain hydrocarbons, chlorine, fluorine sulfur, etc. They interact with human body cells and cause the effects reported above. Chemically they are often extremely stable and their neutralization cannot be achieved to the acceptable levels (greater than 99.99 percent). They break down into a variety of compounds during heating. The products of decomposition depend on temperature history, types of gases present in the surroundings, and the temperatures to which they are subjected.

Limited testing has been carried out by UDRI, demonstrating that many of these materials have relatively low thermal stability in the presence of oxidation." When these materials are heated in absence of oxygen they form intermediate highly complex compounds of carbon-hydrogen-chlorine and sulfur. These intermediate products are considerably more stable and difficult to destroy at lower than 1800°F even with long residence times. It is usually necessary to mix the gases containing these compounds with air and raise the temperature into the range of 1800° to 2400°F to achieve the reduction efficiency in excess of 99.99 percent.

This can be done in the presence of proper incineration conditions. Well designed gas cleaning equipment makes it possible to destroy these harmful compounds and produce exhaust gases such as nitrogen, water vapor, and carbon dioxide.

At this time a limited amount of information is available (Reference 7) on the exact conditions under which the thermal treatment of CT compounds should be carried out. This information, however, indicates that greater than 99.99 percent destruction efficiency can be obtained by incinerating the reaction products at temperatures in the range of 1800° to 2400°F followed by a gas treatment process to remove acid gases such as HCl, SO_2, SO_3, etc. All other toxic substances, mentioned in a previous section, and plastic materials used during the drug administration will be destroyed, and metals or glass objects will become completely sterile under these high temperature, fully oxidizing conditions.

C. REGULATIONS

A typical hospital follows procedures intended to meet requirements of many different organizations. Some of these organizations recommend procedures without the authority or power to enforce them. However, government-controlled agencies such as OSHA and EPA are responsible for enforcement of certain regulations. Handling of toxic materials, including chemotherapeutic materials within a hospital is governed by OSHA regulations. In addition to OSHA two other organizations, CDC and JCAHCO, also provide guidelines and make recommendations on this subject.

According to generally followed practice, the toxic materials and items contaminated with them are collected in a yellow bag placed in a plastic or cardboard container. The bags and/or containers are collected at a central location and packed properly before being picked up by a contract hauler.

Although no federal or state regulations are specific to the chemotherapeutic waste disposal, these materials fall under the category of hazardous waste. Almost all contract waste-hauling companies incinerate the yellow bag waste in a hazardous waste incinerator. Operating conditions of these incinerators are neither defined nor controlled by EPA or any other local agency. There are no regulations or enforcement requirements to continuously monitor the presence and magnitude of harmful compounds such as dioxins, furans, etc., in the exhaust gases from the stack.

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SECTION III

INCINERATION PROCESS AND EQUIPMENT

A. INCINERATION PROCESS

The incineration process can be defined as the oxidation of organic materials at sufficiently high temperatures for a sufficient time to convert all organic materials (C, H, S, etc.) into its fully oxidized products (CO_2, H_2O, SO_2, etc.).

Incineration of waste materials offers several advantages:

- ° Oxidation of organic compounds into non harmful oxides or other compounds which can discharge into the atmosphere after removal of acidic compounds.
- ° Substantial reduction in volume of waste materials. The final volume is only a small fraction of the original material.
- ° Decontamination of infectious materials by destroying pathogens.
- ° Detoxification or decontamination of non-organic materials by removal or breakdown of the harmful toxic materials contained on the surface of non-organic materials.

The residue from a well-designed and properly operated incinerator system is free of organic contaminants and can usually be landfilled without any special provision. If the original waste and its residue contain certain heavy metals such as arsenic or chromium then it may still be necessary to dispose of it in a secured or permitted landfill. However, the mass and volume of such residue is usually a very small fraction of the original waste.

Many materials used by individuals and institutions are harmful to humans or the environment because of their complex molecular structures and their interaction with living things. During incineration, these materials are subjected to high temperatures in the presence or absence of oxygen or air. Depending on many factors, such as the composition and type of waste and presence or absence of oxygen, the necessary incineration temperature may vary from 1000° to 2400°F. It is often necessary to use additional energy in the form of fuel (natural gas, fuel oil, etc.) or electricity to supply the necessary heat to maintain the process temperature.

During the incineration, organic materials can react with oxygen or other gases present in waste material to form different compounds. The final products depend on three major parameters: temperature of reaction, composition or nature of gases reacting with the material, and the time allowed or available for the chemical reactions. The goal is to maintain proper values of these three parameters to form nonharmful compounds such as CO_2, H_2O, etc., which can be discharged into the environment.

If the incinerator is not designed or operated properly it can generate or form intermediate products of combustion which may be even more harmful than those originally present in the waste. For example, the lack of the proper amount of oxygen available for oxidation of hydrocarbons may cause formation of carbon monoxide, hydrogen and other complex hydrocarbons. Tests on a number of incinerator installations have indicated that a number of highly toxic compounds such as dioxins and furans are formed in the combustion chamber of an improperly operated unit.

A well-designed incineration system must include an afterburner to destroy the intermediate products of reactions by providing sufficient oxygen, temperature and residence time. However, operating conditions in the afterburners are often maintained at values obtained from experience or from laboratory experiments carried out on simple hydrocarbons such as carbon monoxide, methane, etc., Recent experiments and field experiences have shown that the intermediate products of combustion require good mixing of additional air, substantially higher reaction temperatures, and longer residence times in the afterburner than has been practiced to obtain acceptable levels of emissions.

The above mentioned facts have become widely known only during the last several years. Most equipment used at this time has been designed by using commonly used rules of thumb developed for the incineration of simple organic materials. In most cases these units were not tested at all or were tested for simple compounds such as CO, combustibles, SO_2, NO_x, etc. Additionally, the test equipment to detect the presence of complex gaseous compounds in trace quantities was not available. As a result, many of the currently operated units are based on past designs and cannot meet environmental regulations.

Over the last two decades a large amount of data has been developed on the behavior of commonly encountered compounds in the wastes. Several standard methods have been developed to obtain such data. The method used by research workers at UDRI has been successful in providing the information on the required incineration temperature and residence time for specific compounds. These data can be used to design a unit with acceptable performance.

B. INCINERATION SYSTEM AND EQUIPMENT

A typical incineration system (Figure 1) includes a heating chamber, an afterburner, a gas cooler in the form of a heat recovery device and/or a quench, a scrubber and a stack. Sometimes it is possible to combine or leave out one of these components.

The following comments apply to the design of typical systems used for hospital waste incineration. The system can be operated as a continuous or a batch unit. In either case the functional requirements of the components remain the same.

The material is charged or placed in the heating chamber or incinerator where it is heated by using auxiliary burners and/or by the heat generated from combustion of organics in the waste material. A large variety of chamber designs are used. The material is heated in the presence of gases which may contain varying amounts of oxygen, water vapor, carbon dioxide or other components. The chamber

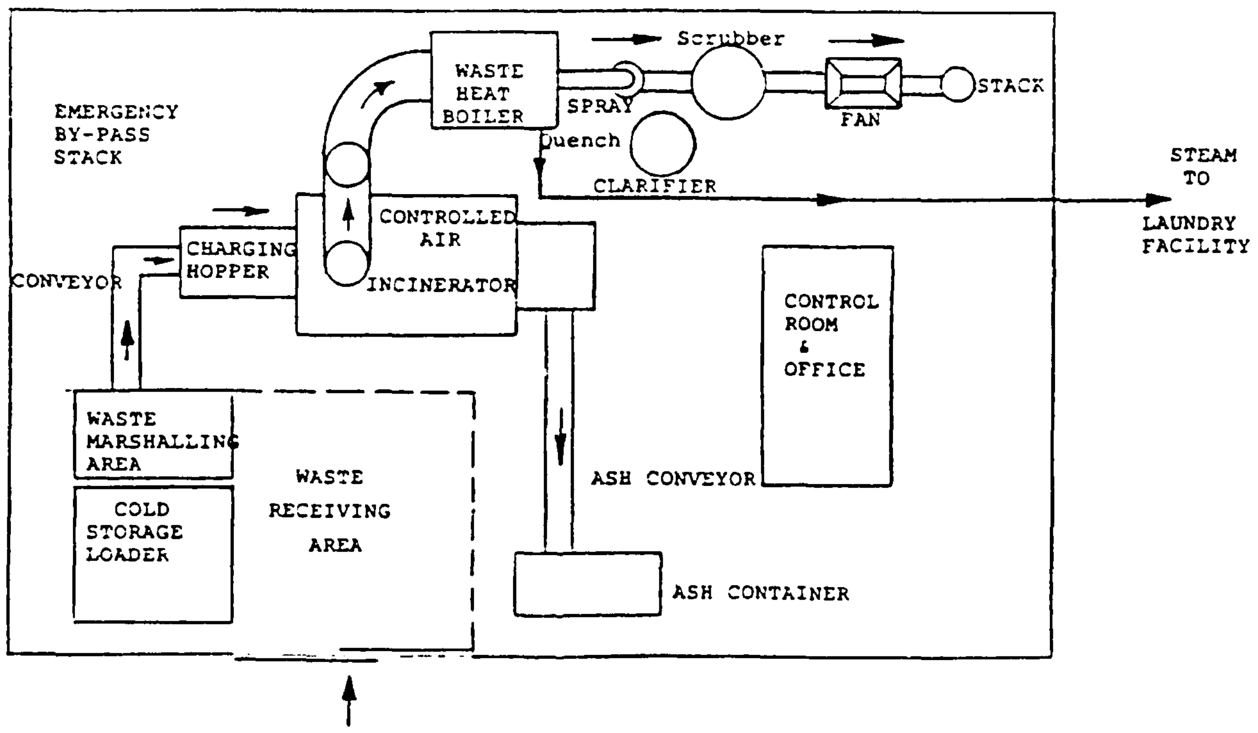

Figure 1. Typical Controlled Air Incineration System.

temperature is maintained between 800° to 1200°F. Depending on many factors related to air leakage, heat input, type of controls, charging cycle, etc., the temperature and gas composition may vary wide during the operating cycle.

The gases from the incinerator are taken to an afterburner and mixed with air to supply additional oxygen. The afterburner temperature is maintained at a certain value, usually between 1200° to 1400°F, by supplying additional heat if necessary. The afterburner dimensions are selected to provide sufficient volume and residence time for gases. A residence time of 0.25 to 0.5 seconds at maximum operating capacity for the system is often used to select the afterburner dimensions.

The flue products from the afterburner may be directly discharged into the atmosphere or may be further treated in a pollution control system. In the past the majority of the hospital units did not use any type of pollution control system.

The pollution control system is used to remove pollutants such as particulates, SO_2, HCl or other acid gases formed during the combustion. The gases are cooled by using a quench unit or a heat recovery device such as an air preheater, water heater or boiler prior to their scrubbing in a caustic scrubber. A solution of water and caustic compound such as NaOH or $Ca(OH)_2$ is used to neutralize the acid gases. Some particulates are also removed during this process. The solution is recirculated and its strength is maintained by proper controls. The gases are then passed through a mist eliminator to remove small droplets from the exhaust gases prior to their discharge into the atmosphere. Particulates are removed in a quench, if used, or in particulate removal equipment such as a baghouse located downstream of the scrubber.

As mentioned earlier most of the hospital incinerators designed before enforcement of pollution regulations specific to hospitals, did not use air pollution control equipment. At this time, many state and local governments require that the incineration system include such an air pollution system.

C. PRESENT STATUS OF EQUIPMENT AND DEVELOPMENT

Available incinerators were reviewed with special attention given to designs used by health care facilities. An attempt was made to obtain the results of performance characteristics of each of these designs used for hazardous waste disposal and used to meet RCRA requirements. Information was obtained from EPA through its contractor, Oak Ridge National Laboratory.

The incineration equipment presently in use has been classified into five types by EPA:

- Liquid Incinerator
- Rotary kiln
- Fixed Hearth or Multiple Hearth
- Fluidized Bed
- Miscellaneous Designs

For solid waste incineration the equipment selection narrows to only two types: Rotary Kiln and Fixed or Multiple Hearth units. Both of these are used by industries and institutions. An informal survey of units used by hospitals indicated that almost all hospitals use fixed-hearth type units; however, the rotary kiln type of units are being used by some large hospitals.

1. Fixed Hearth Incinerator.

A typical fixed hearth unit includes a primary and a secondary chamber. The waste material is packed in bags or other types of containers or is in bulk form. The material is charged periodically into the primary chamber by using a feeder. A fixed hearth is used to support the charge material. Combustion air, known as under-fire air, is introduced through the hearth and travels through the charged waste material. Auxiliary heat is supplied by burners to maintain the chamber temperature. The under-fire air may be used for combustion of some of the organic materials present in the waste. The gas composition in the chamber near the waste material varies greatly from an oxidizing atmosphere to a highly reducing atmosphere.

The gases from the primary chamber are led to the secondary chamber. The secondary chamber includes one or more burners which are operated at high excess air. The hot gases containing excess oxygen mix with the primary chamber gases to complete the incineration or oxidation of organic vapors.

The exhaust gases from the secondary chamber are discharged directly into a stack and from there into the atmosphere.

In most units, mixing of hot burner gases and organic volatiles from the waste material is poor, the residence time of gases in the secondary chamber is insufficient, and their temperature is too low during certain parts of the cycle. The primary chamber temperature drops rapidly during the charging period because of air leakage into the unit and due to the thermal loading of the wet and cold charge. These conditions may slow down reactions taking place in the bed of waste materials placed on the hearth. When the unit regains its normal operating temperature it is difficult to control the volatile release rate from the primary chamber. In both cases the secondary chamber heat demand or air demand may exceed the supply and it is difficult to control the incineration or oxidation process in the secondary chamber. In either case, the exhaust gases may contain unburned hydrocarbons, carbon monoxide or toxic gases such as dioxins, furans, etc. A recent survey (Reference 2) of a large number of incinerators in Canada showed that almost all units emitted excessive pollutants during the time period shortly after the waste charging. None of the units could meet the local air pollution control requirements.

The ash from such units is disposed of in a landfill.

The new regulations dealing with infectious wastes may force many users to install air pollution control devices, such as a scrubber and baghouse, to meet regulations.

2. Rotary Kiln Incinerator.

A rotary kiln is a refractory lined cylinder placed at a slight angle from horizontal which rotates about its axis. The speed of rotation is in the range of 1 to 3 rpm. The waste is charged continuously directly into the kiln by using a charger or feeder. The waste material travels along the axis of the kiln while coming in contact with flue gases from a burner fired at the opposite end of the kiln. The waste material is heated and oxidized or decomposed thermally during its travel. For a properly designed unit the waste material is discharged in the form of ashes free of all organics including carbon at the burner end of the kiln. The ashes can be disposed of in a landfill.

The gases from the kiln are directed into a secondary chamber. These gases may contain volatiles from the waste and organic and inorganic particulate matters. Additional air and hot gases from burners are introduced into the secondary chamber to complete combustion of volatiles and organic matter in the exhaust from the kiln.

Since the waste material is tumbled in the kiln, exhaust gases from the rotary kiln system contain large amounts of particulates which have to be removed before the gases are discharged into the atmosphere. Most rotary kiln installations include a particulate removal device such as a bag house.

The initial cost of rotary kiln units is substantially higher than that of the fixed hearth units. These units require special design efforts to keep them sealed so that the gases do not leak out of the unit during its operation. Because of higher equipment cost and relatively large unit capacity they are used by only a very few hospitals. They are widely used as centralized waste disposal facilities.

Rotary kiln installations may require the same type of air pollution control equipment for removing acid gases as any other type of installation.

D. INCINERATION OF CHEMOTHERAPEUTIC MATERIALS

Chemotherapeutic materials contain complex hydrocarbons and varying degrees of halogens, sulfur, etc. The stability and products of decomposition due to application of heat are greatly affected by the temperature and composition of surrounding gases.

Very little data are available on the behavior of these materials. During the execution of this program the University of Dayton Research Institute was retained as consultant to determine processing conditions to obtain higher than 99.99 percent destruction efficiency for CAC agents during the incineration process.

The research workers at UDRI reviewed a number of chemotherapeutic materials used by the health care community and selected 15 agents for the analysis. These agents were selected on the basis of their wide use in Air Force and civilian hospitals.

The agents analyzed are listed below.

metronidazol
isoniazid
4-aminobiphenyl
cyclophosphamide
3,3-dichlorobenzidine
alpha-naphthalamine
streptozocin
0-tolidine dihydrochloride
nitrofurantoin
furosemide
chlorambucil
daunomycin
ethylene thiourea
mechloroethamine HCl
acetozolamide

Only one agent, cyclophosphamide, has been tested to analyze its thermal decomposition characteristics at UDRI during an earlier unrelated project. Details of the test results are discussed later in this section.

Based on the experiences gained by testing of several waste materials during the last 10 years, UDRI has developed a method for making preliminary estimates and predictions regarding possible thermal decomposition behavior of different materials. This method was used to make predictions on the thermal decomposition products and the necessary thermal conditions to obtain greater than 99.99 percent destruction efficiency. The report containing findings of UDRI is attached as Appendix A.

The thermal decomposition characteristics of cyclophosphamide (CP) were studied at UDRI by using a Thermal Decomposition Analytical System (TDAS) using pyrolytic and oxidative atmospheres at several temperatures. Details of the equipment and test procedures used during these studies are described in Reference 7.

The studies indicated that a large number of products of decomposition are produced during the heating of CP. The nature and amount of intermediate products depends on the time, temperature and the composition of gases present in the vicinity of the material. For example, in presence of nitrogen at 1800°F and a 2-second residence time the thermal decomposition products included a large amount of aromatic compounds even though the parent compound is non-aromatic. On the other hand in presence of air at 1500°F and a 2-second residence time the decomposition products are completely destroyed. The results indicate the importance of oxygen during incineration.

It is expected that most of the chemotherapeutic materials will show similar behavior when subjected to heat during the incineration process. The UDRI report predicts temperature and residence times to obtain the degree of destruction (greater than 99.99 percent) necessary for these types of wastes. It is assumed that the equipment is designed properly to maintain the desired levels of oxygen through proper mixing of air with the intermediate products of thermal decomposition.

For most cases it may be necessary to maintain the reaction temperatures above 2000°F with 2 seconds residence time and sufficient oxygen to get destruction efficiency of greater than 99.99 percent.

E. SELECTED INCINERATION APPROACH

Any incineration equipment used in hospitals or similar institutions is expected to perform its function at the same efficiency irrespective of the nature or composition of the materials charged into it. The variability of composition will be reflected in its heating value which, in turn, depends on the amount of water, inert material or combustibles present in the waste charged.

In most incinerators it is difficult to control all the necessary parameters (temperature, residence time of gases and amount of oxygen) in one chamber. As a result, most incineration systems use at least two separate regions or chambers to achieve the desired destruction efficiency for the organics. The first region is used for heating and partial thermal treatment (pyrolysis or partial combustion) of waste. The gases from this region contain flue gases from the heating burners, intermediate products from combustion of organics in the waste, and water vapor. The composition, heating value and temperature of gases produced in this region depend on many factors which cannot be controlled precisely.

The second region or chamber, commonly known as the afterburner, is used to clean up the gases from the first region. The afterburner must be designed to deal with mostly unknown values of important thermal and chemical properties and yet assure that the gases leaving it meet the stringent air pollution control requirements. The operation and controls of each one of these regions or chambers are often independently adjusted and there is no "feed-back" loop between the control systems.

The proposed incineration system is designed to maintain the operating conditions of the primary chamber to permit one to control or limit the composition, heating value and mass flow of gases going to the afterburner. The design includes a "feed-back loop" between the two chambers to adjust the operating parameters of the primary chamber to meet the performance limitations of the afterburner.

The description of the system and its function are described in Section IV.

SECTION IV

PROCESS ENGINEERING

A. INCINERATION SYSTEM DESCRIPTION

The incineration system developed under this program consists of four major components (Figure 2).

- ° Destruction (Primary) Chamber
- ° Afterburner
- ° Quench
- ° Scrubber

The chemotherapeutic waste generated in a hospital contains varying amounts and types of materials. To accommodate all possible types of materials, the system is designed to handle any type of waste ranging from waste with very high percentage of water to waste which contains very large percentages of its organic materials such as plastic, solvents, etc. The total incineration cycle time depends on the type of waste charged. Because the cycl time is automatically adjusted to account for the waste type, the operator does not need to know anything about the type of waste and does not have to make any type of adjustments.

The demonstration unit, which can be considered as the smallest size commercial unit, is designed to handle 200 pounds of chemotherapeutic waste per week. A typical hospital with oncological treatment produces approximately 100 pounds of chemotherapeutic waste per week; however, this may double within 2 to 3 years.

In addition, the system can be used for infectious waste disposal with increased yield-over that possible for chemotherapeutic wastes. The exact yield/capacity depends on many factors which are discussed later.

The system is a batch-type unit in which a container loaded with the waste material can be charged at a certain frequency. The unit is designed to accept standard card-

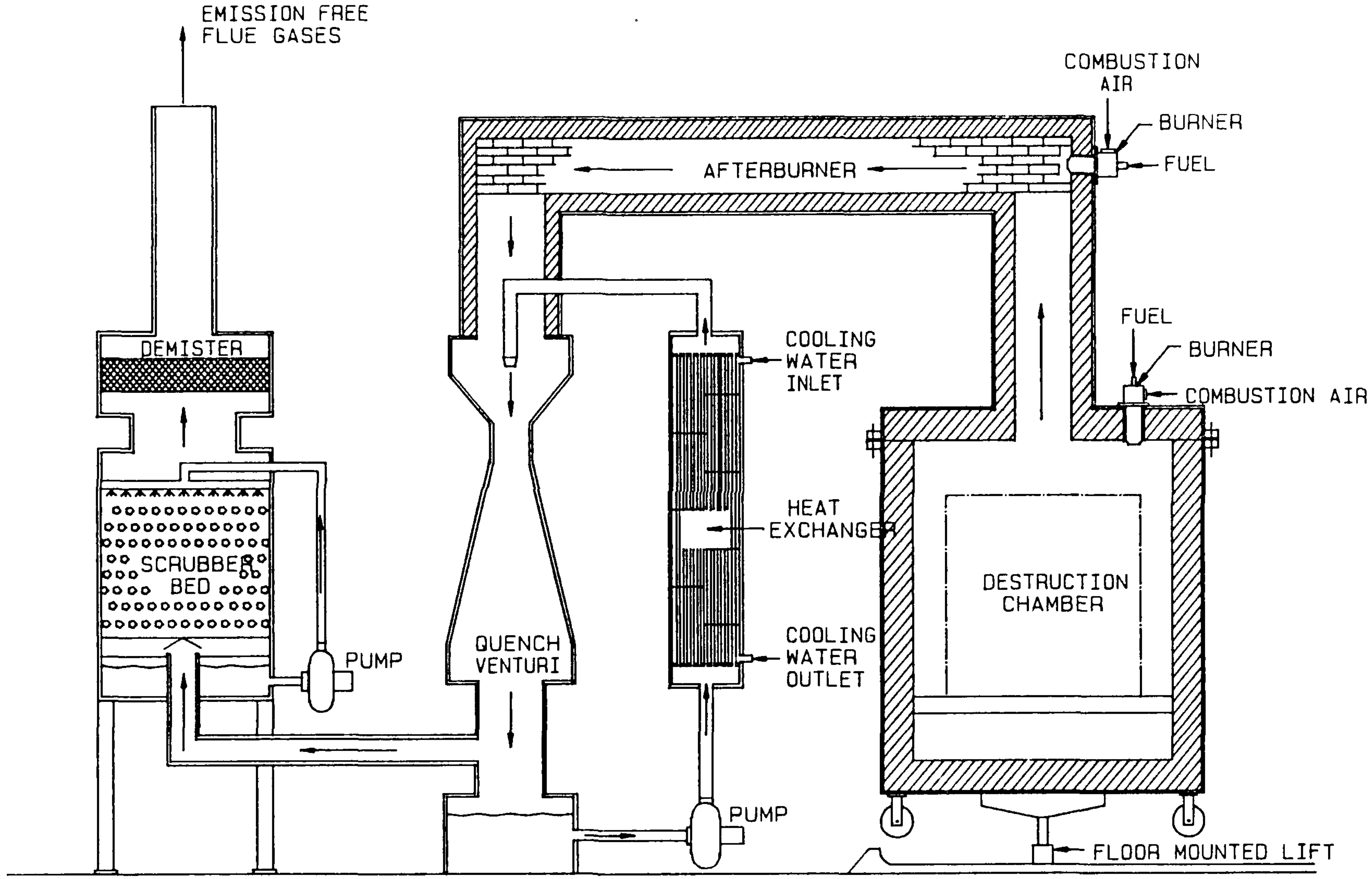

Figure 1 Chemotherapeutic Waste Thermal Destruction Disposal System.

board containers commonly used by the hospitals to store plastic bags containing the chemotherapeutic or infectious waste. It can be used for any other type of container if desired. Hospitals may use two different sizes of the containers: one with the capacity of 2 ft^3 and the other with 5 ft^3 capacity. The unit can be loaded with two large or four small containers in one batch.

The containers are placed on a charge table which is lifted from ground level into the destruction chamber. The charge table is placed inside the chamber during operation of the unit. Sealing occurs when the chamber is raised into its closed position.

The destruction chamber is heated by using combustion products from burners located at the top of the unit. These burners are operated at near stoichiometric combustion conditions to avoid the presence of excessive, uncontrolled amounts of oxygen in the destruction chamber. The chamber is heated at a controlled rate by the burners to deliver appropriate amount of heat for the evaporation of liquids and the heating of solids. The organics in the waste material break down to produce gases and carbon residue. The controlled amount of oxygen in the chamber allows combustion or burning of only a very small and predictable amount of organics in the destruction chamber. As a result, the heat release and, correspondingly, the temperature rise for the chamber is controlled to avoid damage to the chamber. At the same time, the heating value and mass of gases going to the afterburner are controlled. A feedback control loop from the afterburner is used to perform this function.

The gases from the destruction chamber are taken to an afterburner where they are mixed with air and the hot gases from pilot burners. The afterburner is designed to provide rapid and uniform mixing. The temperature of the afterburner exhaust gases can be maintained at any value between 1600° to 2400°F. The temperature will be higher (2400°F) while processing chemotherapeutic waste. For other types of wastes, such as infectious waste, it can be lowered if desired. The gases will have a residence time of up to 2 seconds at the design capacity of the unit.

The afterburner temperature is greatly affected by the heat content of flue gases from the destruction chamber. A large volume of high heating value gases will increase the afterburner temperature beyond the safe limit. The amount of gases from the destruction chamber is controlled by a temperature feedback loop from the afterburner. As the afterburner temperature increases beyond the set point the heat input to the destruction chamber is reduced. This reduces the amount of gases produced, thereby reducing the heat release in the afterburner.

The hot gases from the afterburner are quenched in a venturi scrubber by using water sprays. The gases come in intimate contact with the water spray in a venturi section. The particulate matter from the gases, if any, will also be collected in this section. The water temperature rise is maintained at approximately 30°F. The water is recirculated and cooled in a heat exchanger device where the heat is used for heating the cooling water which may be used in other facilities (laundry room, showers, etc.) of the hospital.

The quenched flue gases are passed through a spray tower where they are "washed" in a caustic solution to remove acid gases such as HCl, SO_2, etc. The alkalinity of the liquor as measured by its pH value is maintained by adding the required amount of caustic material in the storage tank. The overflow from the tank is neutralized and can be disposed of in the sewer.

The gases are then passed through a demister unit to eliminate droplets, or mist, of the solution from the gases. The gases are discharged to the atmosphere by an induced draft fan.

B. PILOT UNIT SPECIFICATIONS

The pilot unit is designed to meet the following performance and design specifications.

Charge:

Weight of the charge....................100 lbs/charge

Composition of charge material

Normal Operation

Organics (incl. plastic, paper etc.)....	40%
Liquid (Water).........................	50%
Inert (metal, ash etc.)................	10%
Volume (2 large or 4 small boxes).......	10 ft^3

Extreme values	High BTU	Low BTU
Organics	80%	10%
Liquid (Water)	10%	80%
Inert.	10%	10%

The connected thermal input, utility supplies and cycle time are designed to meet the extreme operating conditions.

Thermal System:

Fuel Type.........Natural Gas or Propane

Burners...........Stoichiometric and excess air capability, forced air, nozzle mix types

Number of Burners and Input Capacity:

	Burners	BTU/hr
Destruction Chamber	One	30,000
Afterburner.............	One	50,000

Turn Down

On-Ratio at stoichiometric................	10 to 1
At constant air (fuel T/D)................	15 to 1

Auxiliary cooling

Provision for cooling medium injection (i.e., water) in the destruction chamber.

Supply necessary combustion and auxiliary air in afterburner.

Insulation:

	Destruction chamber	After burner
Highest Temp.	1600°F	2600°F
Wall construction	composite insulation with inside metal	fibrous insulation
Outside wall temp. (not to exceed)	150°F	200°F

Performance:

Cycle time

standard waste	36 hours.
High BTU waste	up to 72 hours
Low BTU waste	up to 54 hours

Flue Gas composition at stack discharge:

At least to meet RCRA requirements of destruction efficiency of Chemo. waste >99.99 percent

Types of waste:

Red and Yellow bag hospital wastes

Operation:

- Push-button start-up,

- Automatic end of cycle announcement,

- Microprocessor based controls for all key variables such as temperature, pressure, pH control of scrubber fluids, etc.

- Manual loading of waste, unloading of ash, and discharge of neutralized liquor

C. HEAT AND MASS BALANCE

Heat and mass balance calculations for three cases, listed below, were carried out.

1. Cases analyzed:

   a. Chemotherapeutic waste

      - Normal waste loading at a rate of 100 pounds/charge

      - Possible cycle time for High and Low BTU wastes.

For these cases the afterburner temperature is assumed to be at 2400°F with 2 seconds residence time in afterburner.

   b. Infectious waste

      - Normal composition

For these cases the afterburner temperature is at 1600°F with 1 second residence time in the afterburner.

The heat and mass balance calculations are used to determine the cycle times, heat input rate for burners, the utilities, such as combustion/cooling air, cooling water, etc. The size of afterburner chamber, quench and scrubber are designed to handle the maximum loading conditions experienced during the destruction of CAC waste. The maximum loading conditions for different parts of the system occur under different operating conditions. For example, the heating system in the destruction chamber requires maximum input when the waste materials contain a large amount of water due to the large value of heat of evaporation for water. On the other hand the size of afterburner and other air pollution control system components should be sized to handle large amounts of flue gases generated during combustion of organic vapors when the waste contains large amounts of solvents or plastics.

The limiting values for which different components are sized are given below.

c. Destruction chamber:

Maximum water evaporation rate - 20 pounds/hr.
Maximum heat input rate - 30,000 BTU/hr.

d. Afterburner:

Maximum value of organics combustion - 3 pounds/hr.

Note: This means that the organics evolution in the destruction chamber has to be limited to 3 pounds/hr. to avoid overheating of afterburner chamber due to over temperature and to retain 2 seconds residence time.

e. Quench and Scrubber:

The size is determined for the maximum gas volume of 6300 actual cubic feet per hour (acfh), entering the quench unit at 2400oF. This may occur at limiting conditions of the water evaporation rate of 17 pounds/hr. or organics combustion rate of 3 pounds/hr.

f. Initial Heating Time:

The refractory lined components, destruction chamber and after burner have to be heated at a certain rate to avoid damage to the refractory insulating materials. The exact rates depend on the type of refractory and the final temperature. In this case light weight fibrous materials are used. For such materials a heating rate of 1000° to 1200°F per hour is considered safe. On this basis the minimum heating time of 2 hours, prior to starting the incineration cycle, should be allowed.

g. Total Cycle Time:

The incineration cycle time consists of the following components.

h. Afterburner preheating

This time is allowed to avoid damage to the refractories. As mentioned above it is 2 hours. This is fixed for all types of waste composition.

i. Destruction chamber heating

The chamber does not have to be preheated. However the heating rate should be maintained below 1000°F/h. In most cases, the waste will contain some amount of volatile liquids (water, solvents, etc.) which will start evaporating in the temperature range of 150 to 212°F range. The heating time will be then controlled by the limitations of burners to supply enough heat to the load or by the feedback control from afterburner to control its temperature. The heating time, until the organics and liquids are gone from the load, can be in the range of 6 hours (for low Btu load) to 26 hours (for high Btu load).

After the water or organics is gone the residue may contain carbon which must be burned or treated to high temperatures by using higher temperatures and higher oxygen concentrations in flue gases. The time for this process depends on many factors such as temperature, and nature and dimensions of the residue. For commonly used plastic materials found in the wastes the fixed carbon in the residue varies from 5 to 25 percent. The design is based on an average value of 15 percent residual carbon. For normally encountered waste containing 40 percent organics the residual carbon is estimated to be 6 pounds. The time to burn this amount of carbon at 1400°F is approximately 6 hours.

j. Cooling Time

The load and destruction chamber must to be cooled to a reasonable temperature before the chamber can be opened to remove the load. Cooling must be accomplished by using air and auxiliary cooling devices (such as water spray during the high temperature periods). The cooling time can range from 8 to 16 hours. A cooling period of 12 hours is used for estimating the total cycle.

k. Total Cycle Time

Estimated total cycle times for each type of chemotherapeutic contaminated waste are given below.

Typical hospital waste....	36 hours.
Low Btu waste.............	54 hours
High Btu waste............	72 hours

These cycle times will satisfy the needs of a typical civilian or military hospital which generates chemotherapeutical waste at a rate of 200 pounds/week.

Infectious waste disposal will require a few changes in the heat input capacity in the destruction chamber and increased capacity for the quench and the scrubber. However, physical size of the unit and its cost will not be affected significantly.

SECTION V

THE INCINERATION SYSTEM DESIGN

This section includes details of structural and mechanical design of various components of the system. During the design of this unit, the most important consideration was to maintain safety of personnel and equipment while achieving the required destruction efficiency for wastes contaminated with chemotherapeutical materials.

A. TOXICITY CONSIDERATIONS

Because chemotherapeutic materials in the waste are extremely dangerous, hospitals use extreme care in handling and transporting of the waste. The proposed unit is designed to assure that the waste material or its derivatives do not escape in the atmosphere in any form before their complete destruction in the unit. As a result, the following special considerations are given.

The unit is operated in the batch mode so that all parts of the unit which contact the waste materials during the thermal treatment are subjected to sufficiently high temperatures during the cycle. The waste container, all parts of the destruction chamber, and the afterburner will be heated to at least 1400°F and maintained at his temperature for at least 1 hour in the presence of oxygen during each cycle. It has been reported (Reference 5) that even the most dangerous chemicals such as the chemical warfare agents in possession of the U.S. Army have been proven to be decontaminated by treating them at 1000°F for 15 minutes. Studies by The University of Dayton Research Institute have concluded that chemotherapeutical materials are normally very unstable in presence of oxidizing conditions and do not require temperatures higher than 1000°F to obtain greater than 99.99 percent destruction efficiency. *In this design the selected temperatures and times of exposure are substantially higher than those required by the test results.*

The system is designed to maintain slightly negative pressure in all parts where the chemotherapeutic agents or their derivatives are present. This includes the destruction chamber, afterburner, quench and all ducts connecting them. This assures that no vapors or gases will escape from the system into the atmosphere at any time. If there is a possibility of leakage of gases, the air will leak into the system but this should not affect the system performance.

As mentioned earlier in the process engineering sections, several design features and operational controls are used to assure that the temperature and residence times in the afterburner are maintained at the design values during the entire cycle. The temperature feedback from the afterburner to the destruction chamber is used to control the amount of contaminated vapors. Without this, the thermal characteristics of boiling liquids may result in introducing an uncontrolled amount of contaminated vapors or gases into the afterburner, resulting in greatly reduced destruction efficiency or even formation of highly dangerous intermediate products of combustion.

The temperature and residence times in the afterburner are maintained at values (2400°F with 2 seconds residence time) above those suggested by UDRI to assure greater than 99.99 percent destruction of principle hazardous organic compounds (PHOCs).

B. MATERIAL HANDLING

The waste material is contained in sealed containers, in most cases card board boxes, of standard dimensions. As per established practice they are collected from the patient areas and stored in a secured area. It is assumed that this area will be near the area where the incinerator unit is housed.

The containers are hand-loaded into the destruction chamber. The chamber is moved under the heating chamber and moved up by using an electrically operated jack. In the "up" position it seals with the heating chamber. The seal is maintained by the jack during the entire incineration cycle.

After the completion of the cycle the destruction chamber is lowered on a track by using the motorized jack and moved away from the bottom of the heating chamber. The residues from the bottom of the chamber are removed by using a vacuum suction device and are collected in a bag. The bag containing sterile residue can be disposed of in a landfill. It is assumed that the materials in the bag will be acceptable for an unsecured landfill; however, it may be necessary to experimentally confirm this assumption.

C. HEATING AND DESTRUCTION CHAMBER

The heating and destruction chamber design is shown in Figure 2. The destruction chamber consists of a container made of high-temperature alloy steel which is placed into the heating chamber. The heating chamber is lined with high-temperature alloy lining at the inside. The outside casing is fabricated from carbon steel. The gap between the lining and casing is filled with high-temperature fibrous insulation. This type of construction assures that vapors from the waste liquids and the contaminated flue gases are not absorbed in the insulation and cannot migrate towards the outside of the wall where they may condense. The insulation is selected to maintain lower than 150°F temperature at the outside of the casing.

An annular gap between the destruction chamber and the heating chamber is used to supply hot combustion products to the load. The gases are generated by using a burner located on the top of the chambers. The gases travel in the annulus and are distributed into the destruction chamber to heat the load.

Such an arrangement allows uniform radiation heating of the load from the metal shell with very low mass and heat capacity. The heat transfer to the load can be controlled precisely by controlling the gas-flow rate which controls the shell temperature. This arrangement allows control of heat supply and rate of solvent or water evaporation or of the organic vapors generated in the destruction chamber.

The contaminated flue gases are directed to the afterburner burner by using a countercurrent heat-exchanger type system with the incoming burner gases.

D. AFTERBURNER

The afterburner is used to destruct the organics generated in the destruction temperature by subjecting them to high enough temperatures. The organics are mixed with hot combustion products from a burner and with supplementary air. The maximum burner capacity is 50,000 Btu/hr. and it can be turned down on ratio to at least one-fifth of the maximum heat release rate. The incinerator temperature is controlled by modulating the burner firing rate. The combustion air for organics is supplied in one of the two sources. Up to a certain point the air is supplied as excess air from the burner. Additional air is supplied from auxiliary air supply located very close to the burner.

The walls of the afterburner use high-temperature, high-density veneer refractory material with a maximum operating temperature of 2600°F This is backed by blanket insulation to maintain low heat storage capacity which allows fast heating and cooling. The afterburner inside diameter is 12 inches and the length is approximately 8 feet.

E. FLUE GAS TREATMENT

Flue gases from the afterburner are quenched with water in a venturi type quench unit. The water is injected from a wide angle spray nozzle and the gases are mixed with the spray in a venturi section. The water injection rate is maintained to raise the water temperature rise not more than 30°F As a result, the gas temperature is dropped from the incineration temperature to approximately 150°F The heated water is collected at the bottom of the quench unit and pumped to a water to water heat exchanger. The cooled quench water is recirculated through the system. The water level in the quench tank is controlled by either draining the excess water or by introducing make up water. The acidic venturi overflow is neutralized by mixing it with the mixture overflow from the scrubber which is alkaline in quality.

City water used for laundry or for general hot water supply within the hospital can be used as cooling medium in the heat exchanger. The water requirements for the heat exchanger are in the range of 3 to 5 gallons per minute (gpm). This arrangement allows recovery of a large percentage (greater than 75 percent) of all energy used as burner input and recovery of the heat content of the waste material.

The cooled flue gases from the quench section are taken to a scrubber where they are washed with alkaline solution to remove pollutants such as SO_2, HCl etc. The alkaline, $Ca(OH)_2$ or NaOH, solution is recirculated and its pH value is maintained between 7 and 9. The overflow is mixed with the quench water overflow in a tank. The mixture in the tank is neutralized before its discharge in the sewer.

The gases are passed through a demister, located on the upper section of scrubber, to separate liquid droplets from the gases before their discharge into the atmosphere. An exhaust fan, located between the scrubber, is used to discharge flue gases to the atmosphere. The suction created by the fan is used to maintain negative pressure throughout the system. This assures that the gases from the system do not leak to the outside.

F. ASSEMBLY DRAWINGS

A set of assembly drawings for the pilot test system is attached with this report in reduced size. One full set of these drawings in original size have been submitted to the Air Force.

A side view of the pilot test system is shown in Figure 3. The overall dimensions are 11.5 feet long, 10.5 feet high, and 5.5 feet wide.

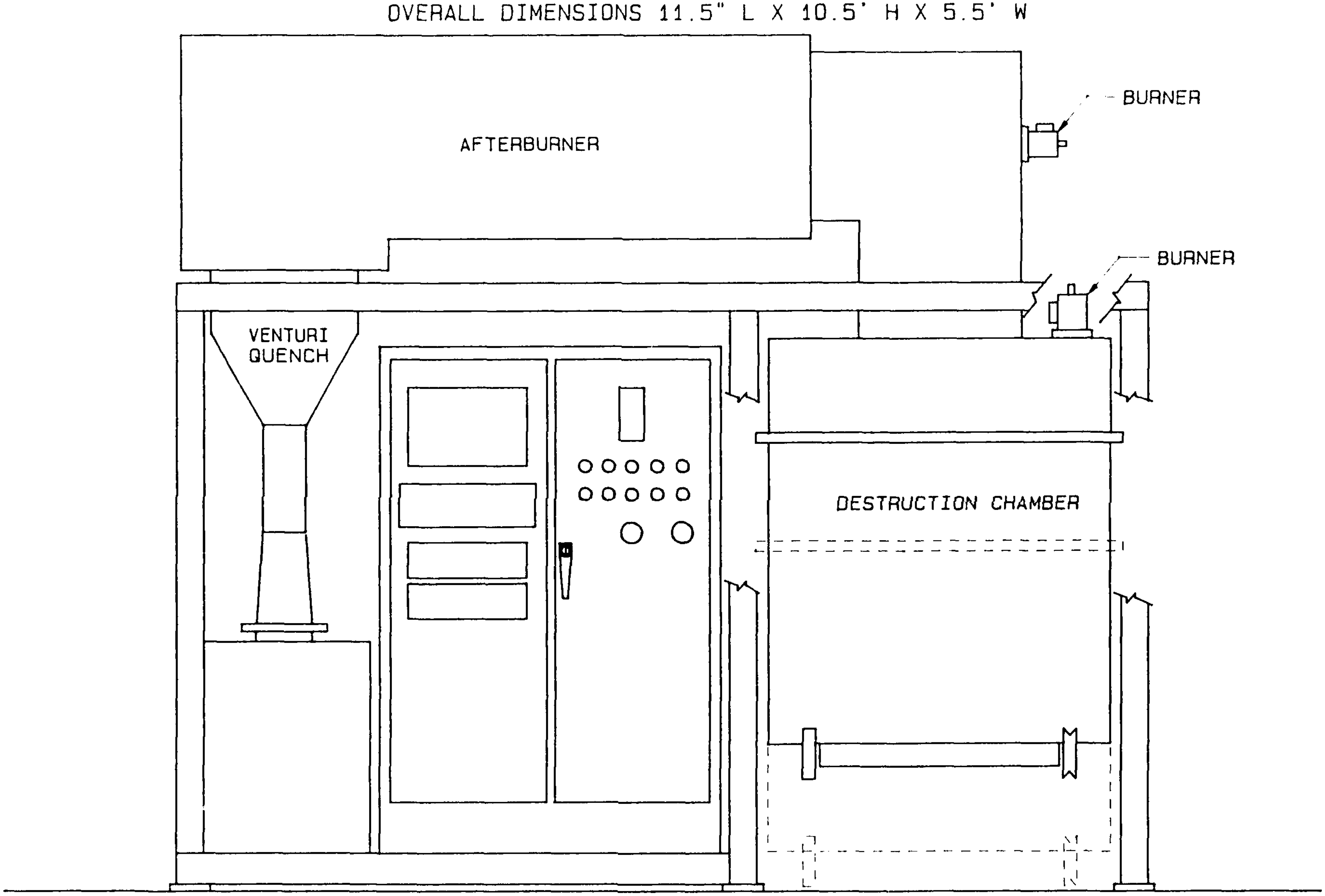

Figure 3 Front View of Incineration System for Disposal of Chemotherapeutic Waste.

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SECTION VI

OPERATING PROCEDURES AND INSTRUCTIONS

A. GENERAL

The incineration system is designed to be operated by one operator who has some working knowledge of operating a furnace, boiler or water heater. Although the system operation is carried out by the control system during its normal operation, it is necessary to perform loading, unloading and startup functions by an operator. It is not necessary for an operator to be present during the execution of the incineration cycle. Operator assistance may also be required during the occurrence of an abnormal operating situation which is displayed by the control unit.

The system design includes a rather sophisticated control system which performs all the necessary control functions after the unit has been loaded and the cycle has been started.

The operating procedure during a normal cycle involves the following steps. Most of them are executed and controlled by the control system.

The functions performed by an operator are:

- ° Loading and single push-button startup of the unit.
- ° Preparation and cleaning for next disposal run.
- ° Response to the signals indicating unusual operating conditions.

The following functions required during the operating cycle are performed by the control system.

- ° Preheating of afterburner.

- ° Startup of the burners in heating chamber.

- Heating of the waste material at controlled temperatures and heat input rates to maintain safe operating conditions.

- Operation of the afterburner to achieve required destruction efficiency.

- Operation of air pollution control system which includes the quench and scrubber.
- Cooling of the destruction chamber after completion of cycle.

The operation of burners, adjustment of set points etc., is controlled by the control system. Details of the control system operations are described later in this section.

At the end of the cycle, an audible and visual signal is given which informs the operator about the cycle completion. It is not absolutely necessary to take any immediate action. The operator can, at his convenience, lower the hearth of the heating chamber for unloading of the residues. The hearth is lowered by using a motor-operated jack, and moved to the loading-unloading station. The residue is expected to be in the form of ashes and discrete inorganic parts such as glass or metal objects. They can be picked up by a vacuum system or can be collected manually. The residue volume is expected to be small compared to the volume of original boxes. The residue can be collected in a plastic bag or other type of container and disposed of in a landfill.

Detailed operating instructions for the system will be developed during the next phase of this program.

B. OPERATING PROCEDURE

The system operates in batch mode. The waste material is loaded in the unit, and the operator starts the unit by depressing a button. The unit then operates automatically until the cycle is completed. The control system is designed to minimize operator involvement during the cycle.

Normal operating procedures for destruction of chemotherapeutic wastes in the unit are described in the following.

Before starting, the destruction chamber of the unit is located in the charging station. The cardboard waste containers are manually loaded into the chamber. Two large boxes or four small boxes can be loaded at one time. The chamber is manually moved to the bottom of the heating chamber by using tracks and raised by jacks to its operating position where it seals against the heating chamber. A "limit" switch will confirm the proper seal and will allow the initiation of the cycle. The operator will push a "cycle start" button to begin the cycle.

This initiation starts the induced draft fan, the liquid circulating pumps, and the combustion air blower. After these components are started, pilots for the burners in the afterburner are ignited. After the burner pilots are established, as indicated by a light on the panel, the operator is asked to open the gas safety valve to ignite the main burner for the afterburner. A flame supervision system will assure that the burners are ignited and are operating correctly. These burners are used to preheat the afterburner at a controlled rate within approximately 2 hours. The above sequence of operator actions assure safe starting of the system.

From this point, no further operator interaction is required until the cycle is completed. The series of activities going on during the complete cycle is described in the next section.

After the cycle is completed, an audible signal is given to the operator who should open the unit and remove the residue. The operator lowers the destruction chamber, and moves it on the tracks to the loading station. The residue is removed by using a vacuum system and is then collected in a bag, which is placed in a plastic bag, securely sealed and disposed of in a landfill.

C. THE OPERATING CYCLE.

After the afterburner temperature has reached the desired value (2200°F), heating chamber burners are ignited by the action of the cycle control system. The chamber temperature rise is controlled at a programmed rate. During the heating process the chamber and load are heated by flue gases from the burner.

As the cycle progresses, low boiling point liquid vapors or volatile products from the breakdown of organics mix with the burner flue gases and go to the afterburner where the mixture temperature is raised by its mixing with burner flue products. If the mixture contains gases with combustible gases they react with the oxygen contained in burner flue products and complete the oxidation reaction. The oxygen level of gases is maintained at a minimum value of 5 percent to assure oxidizing conditions within the afterburner. Additional air is introduced if the oxygen level drops below 5 percent.

The waste material may contain a large amount of volatile organic materials which may be released during the heating process. The volatilization or vaporization process takes place at a constant temperature and it is not possible to control it by simply controlling the chamber temperature. If not controlled properly, it may release a large amount of combustibles which may overload the afterburner capacity in terms of air supply and residence time. To avoid occurrence of these conditions, the system uses a temperature feedback loop to control the heat input into the heating chamber.

As the volatile content of heating chamber flue gases increases, the temperature in the afterburner increases beyond the set point. This signal is used to reduce heat input into the heating chamber. Since the heat transfer in the heating chamber is primarily by convection from gases and by radiation from destruction chamber wall which has very low thermal inertia, this should control the heat supply to the load and reduce the organics volatilization or vaporization of organics.

If the response is not fast enough to limit the temperature rise in the afterburner, an auxiliary cooling system will be used, consisting of a water spray in the heating chamber. The water spray has a tremendous heat absorption capacity caused by very high latent heat and specific heat of steam. The introduction of water will reduce heat supply to the waste container while increasing thermal load in the afterburner to control its temperature within the safe values.

The waste material continues to be heated until all liquids have been vaporized and all organics are decomposed into volatiles and fixed carbon. This should be completed prior to the chamber reaching 1000°F. The heating chamber is then heated to 1400°F at a relatively fast rate. After reaching 1400°F the burner air-fuel ratio is changed to increase the flue gas oxygen content up to 10 percent. This will supply additional oxygen to burnout all residual carbon.

After the carbon burnout is completed, the cooling cycle is started. Gas supply to the burners in the heating chamber is stopped while the combustion air supply is maintained through the burner. The afterburner is still maintained at the normal operating temperature until the heating chamber drops below 500°F after which the gas supply to burners is shut off and the supply of combustion air is continued. Auxiliary air may be introduced to accelerate the cooling rate.

The cycle is terminated when the heating chamber temperature drops below 250°F. The liquid's circulation is continued for a few more hours after the cycle is completed.

D. PROCESS CONTROL STRATEGY

The control system is designed to perform the following functions.

- ° Process control by maintaining proper values of process parameters such as temperatures, pressures, pH value of liquids, etc.

° Combustion system control to assure safe operation of main burners, afterburner, etc.

° Emergency shutoff system.

The process control system maintains proper values of important process parameters. It includes:

° Temperature control for the heating chamber,

° Temperature control for the afterburner,

° Pressure control in the heating chamber,

° Oxygen control for flue gases in the afterburner,

° Temperatures and pH value for quench and scrubber system liquids.

The heating chamber temperature is controlled by controlling the volume (or mass flow) of combustion products from the burner which is operated at near stoichiometric conditions. The firing rate is determined by the heat demand in the chamber as dictated by the temperature controller. The temperature set point is programmed to maintain uniform loading of the afterburner during the critical stage of the process. Under normal load processing the temperature is increased at a rate of 200°F/h. If this rate produces too high a rate of liquid vaporization or organic volatiles then the set point is held at a reduced value to retard volatile generation. During this time, the after-burner temperature rise determines the set point for heat input.

When the generation of volatiles is completed the programmed rate of temperature rise is resumed until the temperature reaches 1400°F. The temperature is then maintained at this value for approximately 1 hour, before the burner air-fuel ratio is changed to increase oxygen percentage in the flue gases. The heating chamber temperature is maintained at 1400°F for an additional 4 to 6 hours. The burners are then turned off and the chamber temperature is monitored to observe its drop. When the temperature reaches 250°F the operator is informed by an audible signal and a green light on the control panel.

An additional safety feature includes provision for water mist injection if the temperature of the afterburner does not respond fast enough during volatilization. Water injection starts when the afterburner temperature continues to rise above a second control point.

The afterburner temperature is controlled by controlling the firing rate of the burners in addition to the combustion of organic emissions from the load. These burners are operated at near stoichiometric conditions during this time. If the afterburner temperature falls below a set value, heat input is increased.

When the temperature increases because of excessive emissions of combustibles from the load, the burners are turned down until the minimum firing rate is reached. The burner firing rate is then maintained at the minimum value and additional cooling is achieved by introducing auxiliary air to the afterburner.

As the cooling air is introduced to maintain the desired temperature, the control system acts to reduce the generation of combustibles in the heating chamber. This is achieved by the actions described earlier.

A certain minimum value of oxygen should be maintained in the exhaust gases from the after burner. An oxygen probe is used to maintain this desired oxygen value. The auxiliary air volume is controlled to assure that the oxygen content is always above the selected set point.

The temperature of cooling water in quench section is achieved by controlling the water flow rate in the heat exchanger.

The pH values of scrubber liquor are maintained by adding alkaline (sodium or calcium hydroxide) solution to the liquor and maintaining the liquor level in the storage tank. A standard pH probe will be used.

Pressure in the system is maintained by adjusting a damper in the flue gas passages, located between the scrubber and exhaust fan. The pressure reading is taken in the destruction chamber and is maintained at slightly below atmospheric pressure, in the order of 0.5 inch w.c. This will also result in lower pressures in the afterburner, quench and scrubber.

The control system also includes provisions for protection of the system due to over temperature, flame failure, over pressure, etc. Design details of the entire system will be developed during the second phase of this program.

E. OPERATING INSTRUCTIONS

Final operating instructions for the entire system and its individual components will be developed after the detail design is completed. This will happen during Phase 2 of this program.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Incineration has been identified as the only available technology which can safely and reliably dispose of chemotherapeutic wastes. Chemotherapeutic agents contain compounds which contain chlorine and fluorine. Chemical bonds with chlorine and fluorine are very stable and are difficult to fracture. At extreme high temperatures (greater than 1800°F) the very strong bonds between organic substances and chlorine or fluorine can be broken. Therefore, high temperature incineration can convert complex chemical compounds into fully reacted oxidation products. Chlorine and fluorine are converted into hydrochloric and hydrofluoric acids which can be removed easily by washing with alkaline solution. Fully oxidized compounds can either be discharged into the atmosphere as water vapor and carbon dioxide, or can be disposed of in any landfill as fully oxidized, non leachable ashes.

Proper destruction of chemotherapeutical agents by incineration requires equipment which will not emit partially reacted, intermediary reaction products and which will with certainty convert the entire waste into only harmless end products. The design of such equipment requires an intimate knowledge of incineration technology, reaction kinetics, combustion technology, flue gas cleaning, and high temperature construction.

A typical health care facility with oncological facilities produces relatively small quantities (100 to 200 pounds/week) of CAC waste. A batch type incinerator unit was designed in which the waste is heated to high temperatures resulting in its thermal decomposition. In a specially designed afterburner the gases are mixed with oxygen and completely oxidized at very high temperatures. The entire destruction process is controlled by a supervisory computer which assures that the reaction conditions in every part of the waste disposal system are maintained at optimum conditions. Human interface is limited to manual loading and unloading to protect the operator and to prevent malfunction as a result of operator error.

The system design is based on scientific data for destruction of chemotherapeutic wastes. It is also suited for the thermal destruction of wastes with less demanding properties. It can especially be used for disposal of biomedical wastes and for wastes from oncological stations. Such wastes are not yet controlled but should be prevented from entering the drinking water recycling chain. Halogenated hydrocarbons are often very stable and are not necessarily destroyed by anaerobic digestion or conventional oxidation. Traces of these halogenated hydrocarbons are accumulated in human and animal tissues where they can lead to future liabilities.

In Phase 1 of this Air Force sponsored project, existing waste collection, waste disposal, and incineration practices were reviewed. Based on these reviews, supported by scientific inputs, and based on related equipment and process experience, a concept design for chemotherapeutic waste disposal has been developed. This design promises to safely dispose of these types of wastes.

Preliminary evaluations of thermal destruction of chemotherapeutic agents indicate that a large number of intermediate organic compounds are formed during the heating process. It is necessary to use an afterburner with sufficiently high temperature, excellent air-organics mixing and sufficiently long residence time to achieve the desired destruction efficiencies. Only one CT agent has been evaluated to define the necessary process parameters. It is necessary to test additional agents to define values of the process parameters to ascertain greater than 99.99 percent destruction efficiency of all hazardous organic compounds encountered during the incineration process.

B. RECOMMENDATIONS

During Phase 1 of this program, all parties dealing with hospital wastes in general and CAC waste in particular have expressed strong desires for an urgent need for a waste disposal system which can be used for onsite disposal of CAC wastes. The general agreement was that presently available systems cannot serve the special requirements of the CAC waste disposal system and it was recommended that a system should be designed and tested specifically for CAC wastes.

The incineration system design developed in Phase 1 will serve all needs of most health care facilities. However, it is necessary to test the unit to evaluate its performance using CAC and other types of biomedical wastes. Phase 2 of this program will accomplish these requirements. Funding of Phase 2 of the program, as described in a separate proposal to the Air Force is recommended to accomplish these requirements.

In Phase 2 of this program, the detailed design will be completed, followed by fabrication, installation, and testing of a full-size incineration system. These efforts will be complemented by an experimental investigation into closely defining those conditions which will assure complete destruction of agents. After initial tests with simulated, harmless substances, the equipment will be subjected to extensive performance tests. The unit will be used for the terminal disposal of chemotherapeutic wastes and other biomedical wastes only after passing the most severe tests.

At the end of Phase 2 a completely operational, full-size incineration system will be available for the disposal of chemotherapeutic and infectious wastes.

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APPENDIX A

ASSEMBLY DRAWINGS OF THE CHEMOTHERAPEUTIC AGENTS CONTAMINATED WASTE INCINERATION SYSTEM

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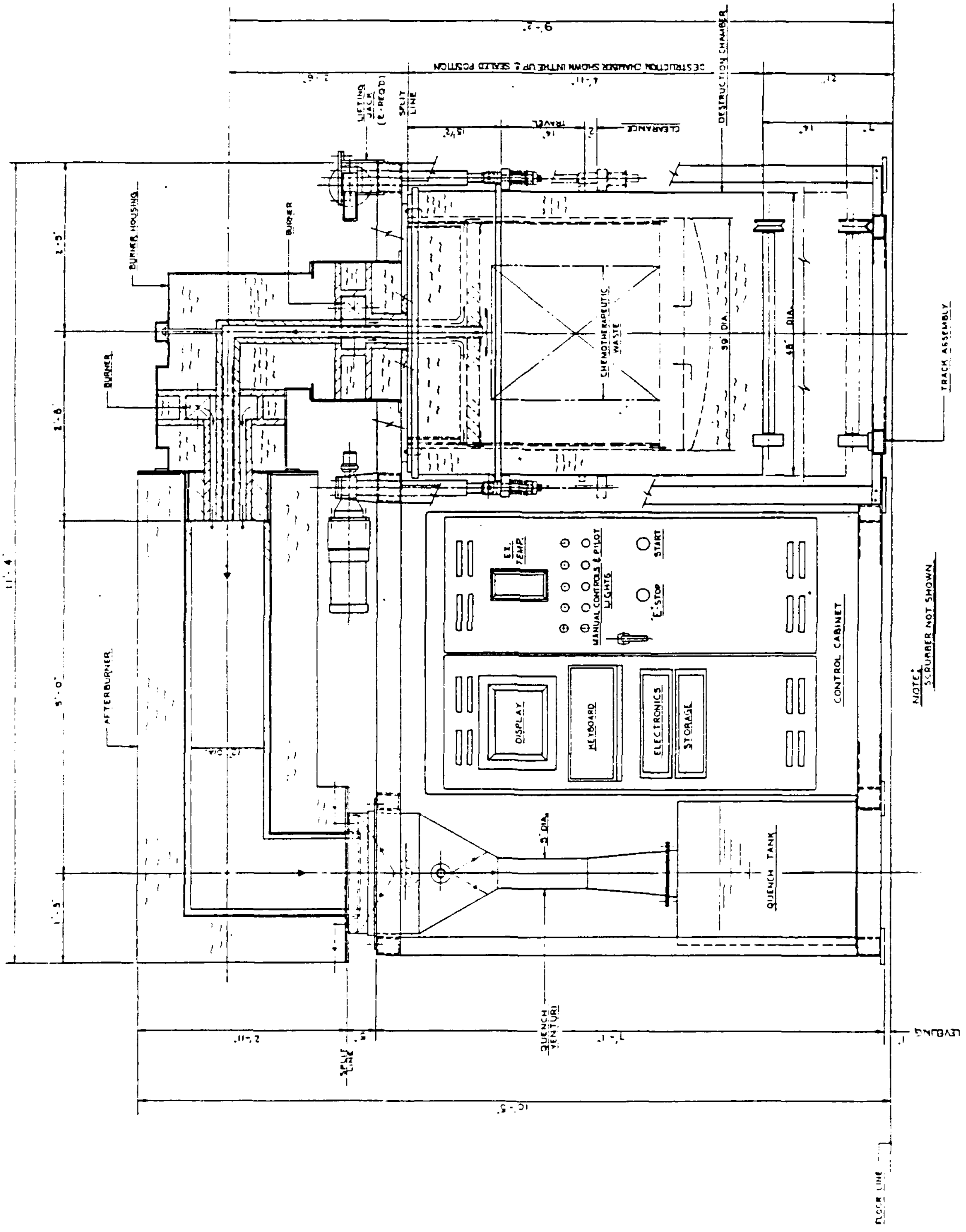

FIGURE A-1. CAC Waste Design Layout Elevation View.

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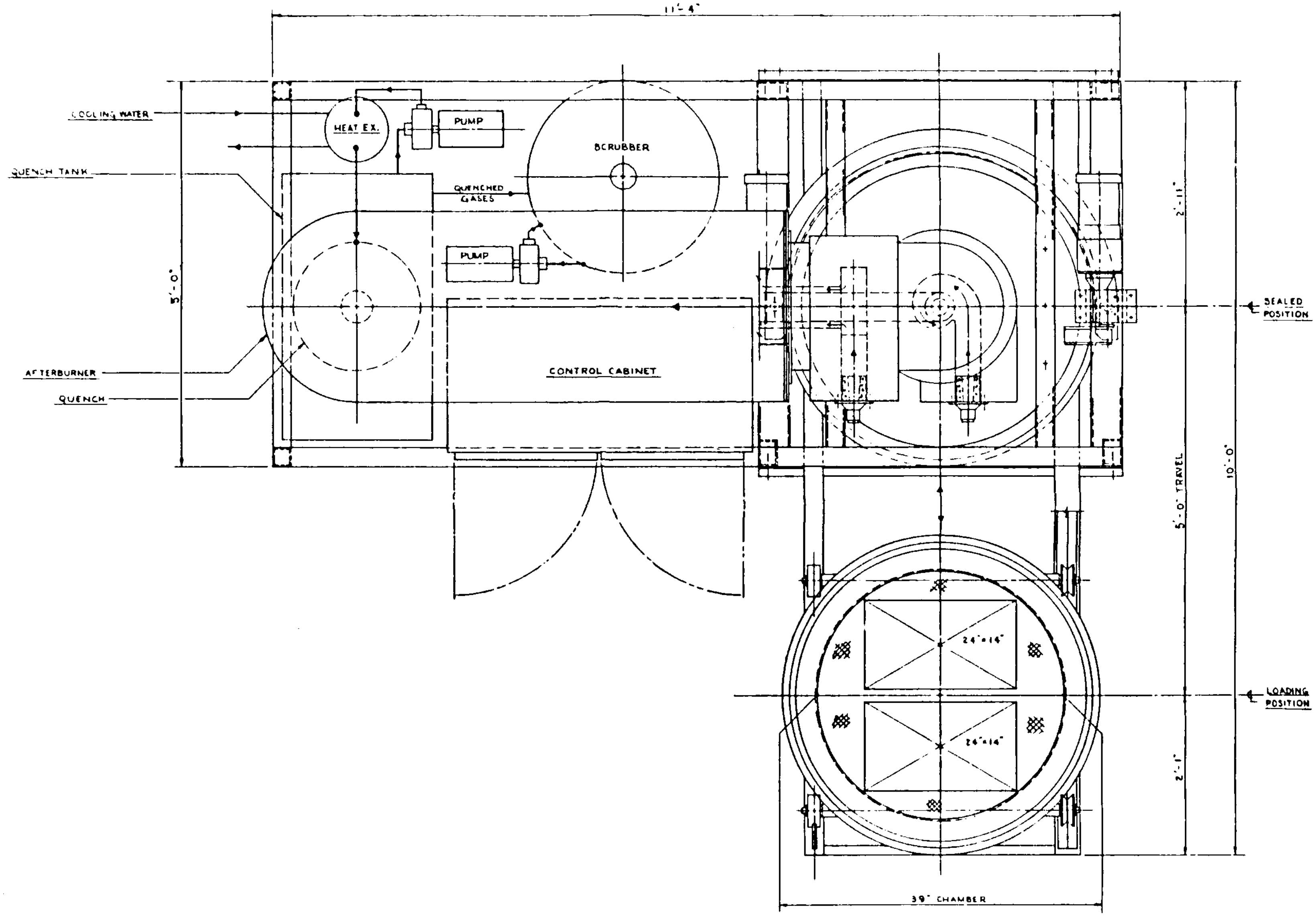

Figure A-2. CAC Waste Design Layout Plan View.

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APPENDIX B

THE UNIVERSITY OF DAYTON RESEARCH INSTITUTE REPORT

"INPUT FOR PRELIMINARY DESIGN OF THE INCINERATOR FOR THE DISPOSAL OF CHEMOTHERAPEUTIC AGENT-CONTAMINATED WASTE"

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INPUT FOR PRELIMINARY DESIGN OF INCINERATOR FOR THE: DISPOSAL OF CHEMOTHERAPEUTIC AGENT-CONTAMINATED WASTE

submitted by:

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December 15, 1988

INTRODUCTION:

The purpose of this report is to provide input for design criteria for a hospital waste incinerator being designed by Indugas, Inc. The chemotherapeutic agents specified by the Air Force in their Request for Proposal include:

metronidazol
isoniazid
4-aminobiphenyl
cyclophosphamide
3,3-dichlorobenzidine
alpha-naphthalamine
streptozocin
o-tolidine dihydrochloride
nitrofurantoin
furosemide
chlorambucil
daunomycin
ethylene thiourea
mechloroethamine .HCl
acetozolamide

In addition to the chemotherapeutic (CT) agents described above, it seems prudent to also investigate the effects of other materials that may be involved in any incineration process along with the chemotherapeutic agents. These materials include, for example, polyvinylchloride (PVC) and polyethylene which may be used for handling and transporting CT agents.

Thus, in this project, we concentrated on predicting the thermal stability of the CT agents at higher temperatures in order to give some guidance to those involved with incinerator design. Actual laboratory-generated thermal decomposition information is currently available for only one CT agent - cyclophosphamide (This report is included as Appendix A). The rest of these materials were evaluated using kinetic theory, information in the literature, etc, and by applying our own experience with similar compounds. As many as 320 compounds have been assigned an incinerability ranking in a recent project performed for the US-EPA. This information, generated from laboratory data for about 68 of the 320 Appendix A compounds, was used to decide what temperatures were necessary to destroy each CT agent to at least 99% destruction.

In addition, preliminary predictions of products of thermal decomposition were made from our experience with similar compounds in thermal decomposition studies. Overall, one may speculate that any material which has chlorine in its structure may show nearly quantitative conversion to HCl as a thermodynamically stable end product. Similarly, NOx will be formed as the ultimate end products from nitrogen containing compounds. SO2 is likely to be produced from sulfur containing compounds. Polynuclear aromatics (PNAs) are likely to form from any aromatic-containing compound as a product of incomplete combustion, as is naphthalene and benzene. Additional products of thermal reaction are outlined in the discussions that follow.

This report has two parts. In Part 1, the incinerability of the CT agents will be discussed, i.e., how difficult are these materials to incinerate, what are their products of incomplete combustion. Physical properties and structures of each of these materials will also be provided in this first section, along with toxicity information about each of the CT agents.

Part 2 of this report will outline an experimental plan to be conducted at the University of Dayton Research Institute to evaluate the incinerability of selected CT agents. Laboratory studies using quartz flow reactors will investigate the formation of products of thermal decomposition of CT agents and waste products contaminated with CT agents. The effect of oxygen concentration on the incinerability and product formation from the CT agents will also be determined as will the effect of residence time. This information will be related to the full scale operation of an actual hospital waste incinerator with the lab data providing guidance on what conditions to efficiently operate the incinerator.

CHEMOTHERAPEUTIC AGENTS FOR CONSIDERATION IN HOSPITAL WASTE INCINERATION

Part 1: Physical Properties and Incinerability Estimates of Each Chemotherapeutic Agent

Summary:

In this section, the physical properties of each chemotherapeutic agent are listed, along with the structure of the compound. With the information known about each CT agent, the incinerability of each was assessed in light of our experience with the hazardous waste incinerability ranking. In many cases, the temperature for 99% destruction of the parent material was less than 300 degrees C, indicating a very unstable compound. A summary of the stability of the pure component chemotherapeutic agents is given in Table 1 below:

Table 1

Stabilities of the Chemotherapeutic Agents
(Data taken from Incinerability Ranking given in Appendix B;
Ranking for experimentally determined compounds - Appendix C)

Chemotherapeutic Agent	T99 if available	Approximate position in the ranking (0-320)
metronidazol (*)	< 380 C	> 287

nitrofurantoin (*)	< 380 C	> 267
isoniazid (*)	< 380 C	> 287
furosemide (*)	< 380 C	> 287
acetozolamide (*)	< 380 C	> 287
4-aminobiphenyl	845 C	51
chlorambucil	655 - 680 C	142
cyclophosphamide	< 380 C	273 - 276
daunomycin	< 380 C	291 - 292
3,3-dichlorobenzidine	785 - 815 C	67
ethylene thiourea	< 380 C	291 - 292
alpha-naphthalmine	835 - 880 C	52 - 53
mechloroethamine salt (**)	860 - 880 C	132 - 134
streptozocin	< 380 C	302
o-tolidine salt (**)	785 - 815 C	~ 78

(*) signifies that parent compound is not in the Appendix VIII list from the EPA. As such, it was not ranked using experimental or theoretical information. However, all of these compounds are likely to be very unstable.

(**) this compound is fairly stable in its salt form; however, the mechloroethamine.HCl and o-tolidine .2HCl are very unstable compounds in that they lose hydrochloride functionality readily. We would propose to examine the more stable salts. From this point forward, any discussion of mechloroethamine.HCl and o-tolidine .2HCl will refer more appropriately to the more stable salt.

The incinerability ranking consisted of a series of experiments using quartz flow reactors in which temperature, residence time, oxygen concentration, etc were precisely controlled. 68 of the 320 Appendix VIII compounds were evaluated experimentally for $\phi = 3$ (1/3 of stoichiometric oxygen) at 2.0

seconds residence time. The other compounds in the Appendix VIII listing were ranked according to structure and available information in the literature. Thus, a ranking was developed which included an estimated or experimentally determined "T99" or temperature necessary for 99% destruction of the parent material, in addition to a ranking out of 320 compounds. This information was quite useful in determining the relative stability of each of the hospital wastes.

It is important to keep in mind that nine of the fifteen compounds in this study are specifically mentioned in the EPAs Appendix VIII list of hazardous wastes. Thus, the majority of these compounds are controlled under Resource Conservation and Recovery Act (RCRA) as far as their disposal, transport, control, etc.

It is apparent from table 1 that there are a few materials which stand out with regard to parent stability. The 4-aminobiphenyl, alpha-naphthalamine and 3,3′-dichlorobenzidine and o-tolidine salt are very stable parent materials with T99s of 800 C or greater. Incidently, three of these four chemotherapeutic agents are regulated as Appendix VIII hazardous wastes.

When compounds are thermally fragmented, products of incomplete combustion usually form to some extent. These products of incomplete combustion (PICs) may be the source of any organic emissions from a high temperature incineration process. Incineration processes must be prepared to address the destruction of PICs which are generally more thermally stable than the parent materials. Some of the very unstable parent materials may produce PICs which are stable several hundred degrees C above the stability of the associated parent. <u>In this case, to state that a compound would be easy to incinerate because it has a T99 temperature less than 300 C is not entirely correct.</u>

For this reason, we evaluated each compound as to what products of incomplete combustion were likely to form and what stability each of these would have. It is important to note that the stabilities given for each PIC are Principal Organic Hazardous Constituents (POHC) or parent stabilities. This means that eeach compound had been evaluated, not as a thermal reaction product, but as a parent material. Because the formation of PICs take a finite amount of time at temperature, residence times for PIC destruction would not be as long as residence times for POHCs in the same incinerator. Therefore, T99 temperatures for PICs may well be higher than T99 temperatures for POHCs, which have been exposed to longer residence times. The information in table 2 does present, however, a good estimate of the relative incinerability of PICs from each of the chemotherapeutic agents.

Table 2

Summary of Anticipated PIC Formation and the Relative Stability of Each PIC

Parent Compound	Suspected Stable PICs	T99 as a POHC (*)
metronidazol	hydrogen cyanide (HCN)	>> 1100 C

	acetonitrile	1000 C
	acrylonitrile	985 C
nitrofurantoin	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
isoniazid	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
	pyridine	785 C
furosemide	hydrogen chloride	(*)
	benzene	1150 C
	chlorobenzene	990 C
	sulfur dioxide	(*)
	hydrogen cyanide	>> 1100 C
	poly nuclear aromatics (PNAs)	1000-1070C
acetozolamide	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
4-aminobiphenyl	benzene	1150 C
	aniline	~ 850 C
	poly nuclear aromatics (PNAs)	1000-1070C
chlorambucil	hydrogen chloride	(*)
	naphthalene	1070 C
	toluene	895 C
	benzene	1150 C
	styrene	N.D.
	poly nuclear aromatics (PNAs)	1000-1070C
cyclophosphamide	benzonitrile	N.D.
	benzodinitrile	N.D.
	ethynlbenzene	N.D.
	hydrogen chloride	(*)
daunomycin	benzene	1150 C
	phenol	~ 765 C
	poly nuclear aromatics (PNAs)	-
3,3′-dichlorobenzidine	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
	benzene	1150 C
	hydrogen chloride	(*)
	aniline	~ 860 C
	chlorobenzene	990 C
	biphenyl	N.D.
	poly nuclear aromatics (PNAs)	1000-1070C

ethylene thiourea	hydrogen cyanide (HCN)	>> 1100 C
	sulfur dioxide	(*)
mechloroethamine*HCl	possible chloroalkanes	----
	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
	diethylmethylamine	N.D.
alpha-naphthalamine	naphthalene	1070 C
	benzene	1150 C
	poly nuclear aromatics (PNAs)	1000-1070C
streptozocin	hydrogen cyanide (HCN)	>> 1100 C
	acetonitrile	1000 C
	acrylonitrile	985 C
o-tolidine *2HCl	hydrogen chloride	(*)
	toluene	895 C
	acetonitrile	1000 C
	acrylonitrile	985 C

(*) is a thermodynamically stable product of complete combustion

N.D. - not determined

In summary of table 2, some of the products that will form in the highest concentrations are the thermodynamically stable products like hydrochloric acid, in the case of chlorinated parent material, and SO2 for sulfur containing parents. (Of course, CO, CO2, H2O, NOx, etc., will be formed in large amounts, but they are not of particular concern for this study). These compounds (SO2 and HCl) must be scrubbed out of any effluent from a thermal reaction. HCN, benzene, naphthalene, chlorobenzene, acetonitrile, acrylonitrile and polynuclear aromatics (PNAs) are extremely stable organic PICs and they would be expected to form most readily.

Thus, any incineration process must deal, not only with the materials to be incinerated, but also with the products which may form when these materials are combusted. In this regard, the incineration of the chemotherapeutic agents is every bit as difficult as incinerating hazardous wastes; indeed, more than half of these materials are, themselves, hazardous wastes. Thus, no compromises can be made with incinerator design, operating temperature, residence time, oxygen concentrations or any other operating parameter - these must all meet or exceed the operating conditions necessary for the incineration of hazardous wastes. Only through this attention to proper operating conditions and incinerator design can hospital waste incineration be properly carried out.

Individual Description of Each CT Agent

Metronidazole

EPA Classification (Ref 1): Laboratory Chemical

Use (Refs 2,3,4): Antitrichomonal; drug that inhibiits pathogenic protozoa (trichomonas vaginalis) which are the causative agent of trichomonal vaginitis.

Synonyms (Refs 2,3,4): Flagyl, Acromona, Anagiardil, Atrivyl.

IUPAC Name (Refs 2,3,4): 1-(2-hydroxethyl)-2-methyl-5-nitromidazole

Produced by (Refs 1,2):

Searle Laboratories
Division of Searle Pharmaceuticals, Inc
PO Box 5110
Chicago, IL 60680

Toxicity (Refs 3,4):

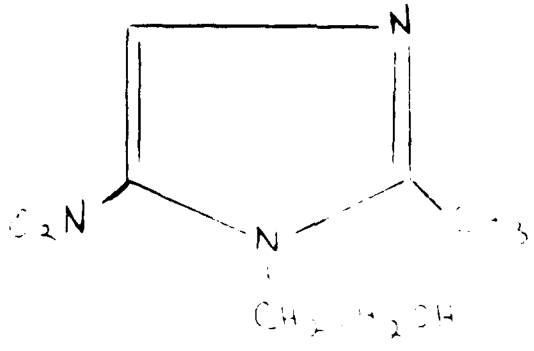
Cancer Suspect Agent, Mutagen
bfa-hmn/sat 10 mg/kg
oral-man TDLo: 3570 ug/kg/D
oral-man TDLo: 1030 mg/kg/8W

animal carcenogenicity - positive

Physical Data: CAS #: 443-48-1
MW: 171.18
Merck: 10,6033
mp: 160-162

Formula: C6-H9-N3-O3

Structure:



DISCUSSION:

This material will have extremely low thermal stability; thus one should be concerned about the products of thermal reaction from this material moreso than the original material. Metronidazole will probably degrade at temperatures below 300 degrees C.

The products that are likely to form from this material, using our laboratory experience with similar compounds will be as follows:

hydrogen cyanide (HCN) - extremely stable, very toxic. This material is the second most toxic material in the ranking with a temperature of 99% destruction (T99) of greater than 1100 C

acetonitrile - high stability, relatively low yields. This product of incomplete combustion has a T99 of approximately 1000 C.

acrylonitrile - another high stability, low yield compound with a T99 of 985 C.

Nitrofuratoin

EPA Classification (Ref 1): Laboratory Chemical

Use (Refs 2,3,4): Antibacterial for urinary tract infections

Synonyms (Refs 2,3,4): Berkfurin, Furadantin, Urantoin

IUPAC Name (Refs 2,3,4): N-(5-nitro-2-furfurylidene)-1-aminohydantoin

Produced by (Refs 1,2): Norwich-Eaton, Lannett, Vortech, Star, Kenyon, Saron, Mckesson, Scruggs

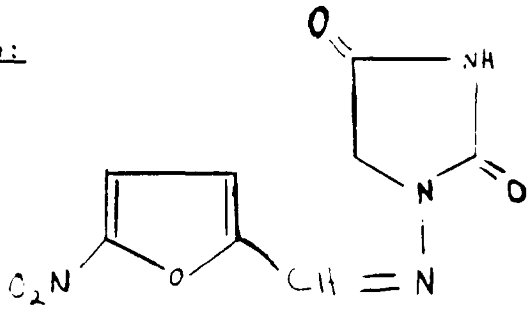
Toxicity (Refs 3,4): Toxic, Mutagen RTECS# MU2800000
bfa-hmn/sat: 1400 mg/kg
orl-hmn: TDLo: 80 mg/kg
unk-hmn: TDLo: 80 mg/kg

Carcenogenicity not known

Physical Data (Refs 3,4): CAS# 67-20-9
MW 238.18
mp: 268
Merck: 10,6445

Formula: C8-H6-N4-O5

Structure:



DISCUSSION:

This material will have extremely low thermal stability; thus one should be concerned about the products of thermal reaction from this material moreso than the original material. Nitrofuratoin will probably degrade at temperatures below 300 degrees C.

The products that are likely to form from this material, using our laboratory experience with similar compounds will be as follows:

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - high stability, low yield, toxic

acrylonitrile - high stability, low yield, toxic

Isoniazid

<u>EPA Classification (Ref 1):</u> none

<u>Use (Refs 2,3,4):</u> Antibacterial, tuberculostatic

<u>Synonyms (Refs 2,3,4):</u> Cotinazin, Mybasan, Pycacide, USAF CB-2

<u>IUPAC Name (Refs 2,3,4):</u> Isonicotinic acid hydrazide

<u>Produced by (Refs 1,2):</u> Parke-Davis, Merrell Dow, Ciba, Squibb

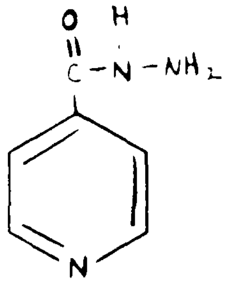
<u>Toxicity (Refs 1,2):</u> Suspected Cancer Agent, Toxic

dns-hmn:fbr 500 umol/L
dni-hmn:fbr 10 mmol/L
cyt-hmn:leu 5 gm/L
cyt-hmn:bmr 5 gm/L
orl-hmn LDLo: 100 mg/kg
orl-man TDLo: 430 mg/kg
orl-man TDLo:5628 mg/kg/2.5Y
orl-man TDLo: 100 mg/kg/3W-C

<u>Physical Data (Refs 1,2):</u> MW: 137.16
mp: 171-173
Merck: 10, 5032
RTECS: NS1750000

<u>Formula:</u> C6-H7-N3-O

<u>Structure:</u>



DISCUSSION:

Because of the relative instability of the N-N bond in this structure, this material will be also be unstable even at relatively low temperatures (greater than 300 degrees C).

Again, the products of thermal reaction from this material will obviously be more stable the parent material. The first obvious product is likely to result from the loss of the imide functionality to form pyridine. Other thermally stable products will form as before.

pyridine - somewhat high stability with T99 of 785 C

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - high stability, low yield, toxic

acrylonitrile - low stability, low yield, toxic

Furosemide:

EPA Classification (Ref 1): Natural Products

Use (Refs 2,3,4): Diuretic

Synonyms (Refs 2,3,4): Lasix, Furosemid, Urex

IUPAC Name (Refs 2,3,4): 4-chloro-N-furfuryl-5-sulfamoylanthranilic acid)

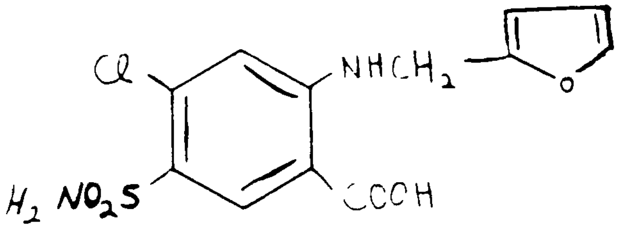
Produced by (Refs 1,2): Hoechst-Roussel, Abbott

Toxicity (Ref 3,4): ivn-man: TDLo: 29 mg/kg
currently testing for carcenogenesis (1983)

Physical Data (Refs 3,4):
MW: 330.75
CAS #54-31-9
RTECS: CB2625000
Merck: 10, 4186
Hygroscopic, light sensitive
mp 220 (dec.)

Formula: C12-H11-C1-N2-O5-S

Structure:



DISCUSSION:

This aromatic material will also be very fragile, at least as far as the parent material is concerned. As is the case with any aromatic compound, the formation of stable aromatic products such as benzene and chlorobenzene is likely to be observed. Any time sulfur is present in an air atmosphere, SO_2 is a likely product and it is thermodynamically very stable. Similarly, chlorine will scavenge any hydrogen available to form the stable HCl which must be scrubbed out of any incineration process if produced in excess of regulated levels.

benzene - extremely stable, in fact, is the third most stable compound in the incinerability ranking with a T99 of 1150 degrees C

chlorobenzene - high stability, low yield; the T99 for this compound is given as 990 C

hydrogen cyanide - trace levels, extremely stable

Acetozolamides:

EPA Classification: Laboratory Chemical

Use: Carbonic Acid Inhibitor, treatment for glaucoma, also used as a diuretic.

Synonyms: Diomox, Hydrazol, Acetazide

IUPAC Name: (5-sulfamoyl-1,3,4-thiadiazol- 2-yl) acetamide OR 5-acetamido-1,3,4-thiadiazole- 2-sulfonamide

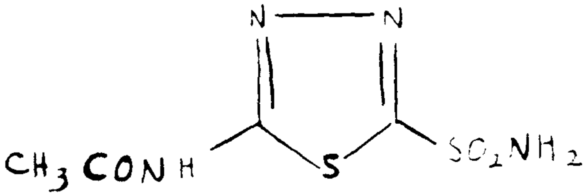
Produced by: Lederle, Softcon,

Toxicity: No information
orl-rat TDLo: 6600 mg/kg (1-22D preg)
orl-rat TDLo: 240 mg/kg (9-10D preg)
other information given on rat toxicity in RTECS

Physical Data: MW: 222.25
Merck: 10, 45
mp: 258-259
CAS # 59-66-5
RTECS: AC8225000

Formula: C4-H6-N4-O3-S2

Structure:



DISCUSSION:

Acetozolamide is also a very fragile compound as a parent material. Thermal degradation mechanisms are as before with probable product formation as follows:

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - high stability, low yield, toxic

acrylonitrile - high stability, low yield, toxic

4-aminobiphenyl

EPA Classification: Laboratory Chemical

Use: Unknown

Synonyms: 4-biphenylamine

IUPAC Name: 4-aminobiphenyl

Produced by: Unknown, can be purchased from Aldrich

Toxicity: Cancer Suspect Agent, OSHA Regulated
Carcen. Determination (human)-positive
Carcenogenic Determ. (animal)-negative
orl-rat TDLo: 3850mg/kg/35W-C
orl-rat LD50: 500 mg/kg
orl-dog LD50: 25 mg/kg

Physical Data: MW: 169.23
mp: 52-54
bp: 191/15mm
fp: >110
Merck: 10, 1233
RTECS: DU8925000
CAS # 92-67-1

Formula: C12-H11-N

Structure:

DISCUSSION:

Unlike the other materials described to this point, the 4-aminobiphenyl is suspected to be a very stable compound as a parent material. In fact, in an incinerability ranking prepared for the US-EPA, this compound was ranked 51st out of over 300 organic materials specified on the EPAs Appendix VIII list of hazardous compounds. Thus, this compound is in the top 1/6 of the most stable compounds in which the EPA is most concerned.

In the incinerability ranking described, a temperature necessary to achieve 99% destruction of the parent material was either determined by experiments with laboratory flow reactors, or estimated from kinetics and physiochemical relationships. In this ranking, the temperature of 99% decomposition was assigned for this compound as 845 degrees C. All of the other parent compounds quoted thus far have been relatively unstable with 99% decomposition temperatures less than 300 degrees C.

In addition to being very stable as a parent material, this compound would predictably form benzene and aniline upon thermal decomposition of the parent material:

benzene - extremely stable

aniline - moderate stability; ranked (theoretically) 46-50 out of 320 compounds.

Chlorambucil:

EPA Classification: Alkylating Agents (Nitrogen Mustard)

Use: antineoplastic, haemoblastoses (a form of leukemia)

Synonyms: Leukeran, CB 1384, Ecloril, NSC-3088

IUPAC Name: p-N,N-di-(beta-chloroethyl)- aminophenylbutyric acid

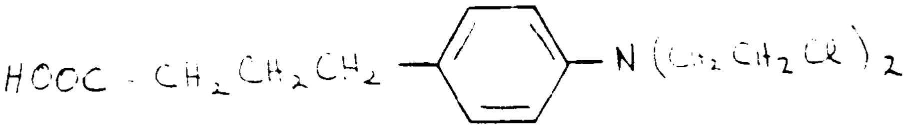
Produced by: Burroughs-Wellcome

Toxicity: Carcenogenic Determination Animal - postive; Carcenogenic Determination Human - suspected, indefinite
unk-wmn TDLo: 161 mg/kg/3Y-I
ipr-rat LD50: 14 mg/kg
scu-rat LDLo: 32 mg/kg

Physical Data: RTECS # ES7525000
CAS # 305-03-3
MW: 304.24
human dosage is .1 to .2 mg/kg daily

Formula: C14-H19-Cl 2-N-O2

Structure:



DISCUSSION:

This particular compound is a fairly stable parent material but not nearly as stable as the aminobiphenyl. This compound was also ranked in the incinerability ranking with a 99% decomposition temperature of 659 degrees C. The ranking would be significantly higher if not for the HCl elimination reactions.

The products formed from this material include the extremely stable naphthalene:

naphthalene - extremely stable

styrene - somewhat stable, low yields

toluene - high stability, ranked 35th

benzene - extremely stable

Cyclophosphamide:

<u>EPA Classification:</u> Alkylating Agent, Nitrogen Mustard

<u>Use:</u> antineoplastic

<u>Synonyms:</u> Cytoxan, B 518, Endoxan

<u>IUPAC Name:</u> N,N-bis(beta-chloroethyl) N'O-propylene phosphoric ester diamide

<u>Produced by:</u> Bristol Meyers

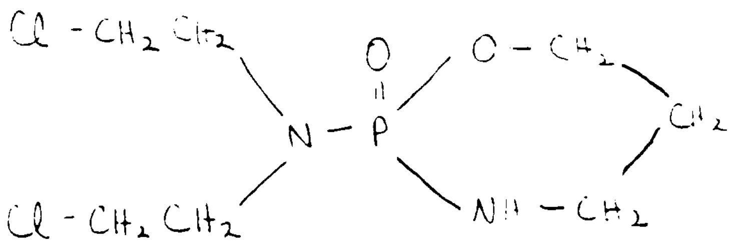
<u>Toxicity:</u> Carcenogenic Determination both humans and animals - positive

orl-wmn: TDLo: 45 mg/kg
orl-hmn: TDLo: 20 mg/kg
unk-man: TDLo: 10 mg/kg
orl-rat: LD50: 94 mg/kg
ipr-rat: LD50: 40 mg/kg

<u>Physical Data:</u> RTECS: RP5950000
CAS # 50-18-0
MW: 279.13

<u>Formula:</u> C7-H15-Cl 2-N2-O2-P *H2O

<u>Structure:</u>



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DISCUSSION:

Cyclophosphamide is a material which was also evaluated as part of the incinerability ranking. It had an extremely low stability with T99 at approximately 300 C (rank 273-276). This compound was actually investigated in a similar project (Appendix C) dealing with the thermal decomposition of hospital waste products; in this study, the cyclophosphamide was introduced to flow reactor experiments to determine products of incomplete combustion that might be formed upon incineration. Benzonitrile, ethynylbenzene and benzodinitrile were observed as thermal reaction products at 1000 C with 2.0 seconds residence time in nitrogen. Oxidative experiments would probably have destroyed these materials.

In addition to these products, we suspect that benzene and HCl will form. In addition some extremely toxic combinations of phosphorus and chlorine may be generated under specific conditions.

benzonitrile - low yields, somewhat stable

ethynyl benzene - low yields, somewhat stable

benzodinitrile - low yields

Daunomycin:

EPA Classification: Natural Products - Antibiotics

Use: antineoplastic

Synonyms: Daunorubicin, DM, NSC-82151, Streptomyces

IUPAC Name:

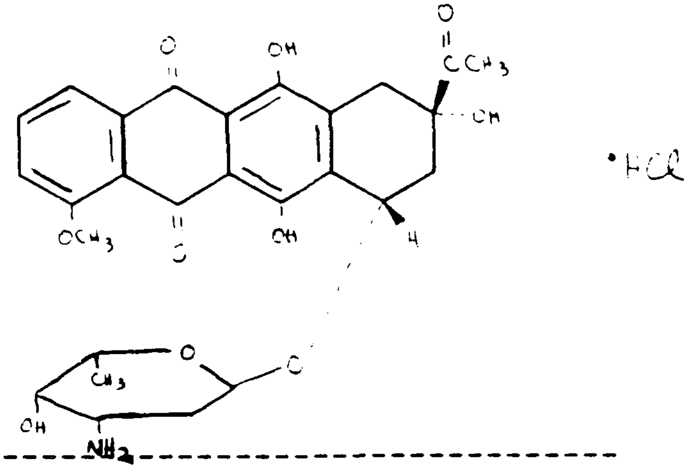
Produced by: Ives

Toxicity: Carcenogenicity Determination, animal - positive
orl-hmn: LDLo: 6 mg/kg
ipr-rat: LD50: 20 mg/kg

Physical Data: RTECS: HB7875000
CAS# 20830-81-3
MW: 527.57

Formula: C27-H29-N-010

Structure:



DISCUSSION:

This compound, being one of the largest in the group of consideration, is probably one of the least stable as a parent. The thermal stability ranking of this material is T99 = 230 C (ranked approximately at 291-292).

The products of interest are:

benzene - extremely stable

phenol - relatively stable (T99 ~775 C)

3,3-dichlorobenzidine

EPA Classification: Laboratory Chemical

Use: Active against cancer of the bladder

Synonyms: Curithane, DCB, C.I. 23060

IUPAC Name: (1,1′-biphenyl) -4,4′diamine, 3,3′dichloro-

Produced by: unknown

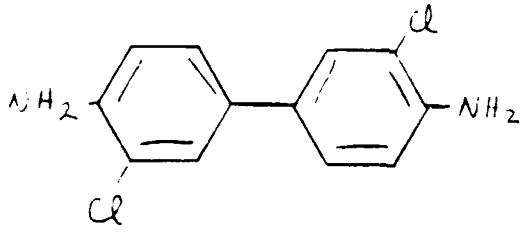
Toxicity: OSHA Carcenogen
Carcenogenic Determination Animal - postive; Carcenogenic Determination Human - indefinite

orl-rat: LD50: 7070 mg/kg

Physical Data: RTECS: DD0525000
CAS # 91-94-1
MW: 253.14

Formula: C 12-H10-Cl 2-N2

Structure:



DISCUSSION:

This material is the third most stable in this group and was assigned an incinerability measure of T99 equal to 810 degrees C. Again, the aromatic, biphenyl structure is quite stable as a parent material.

Product formation from this compound would most likely show a variety of compounds formed from the progressive stripping of the substituents from the biphenyl; in addition, other compounds are likely to form:

benzene - extremely stable

aniline - somewhat stable

chlorobenzene - moderately stable

biphenyl - somewhat stable

trace HCN, acetonitrile and acrylonitrile

Ethylene thiourea:

EPA Classification: Laboratory Chemical

Use: Unknown

Synonyms: N,N'-ethylenethiourea, Pennac CRA

IUPAC Name: 2-Imidazolidinethione

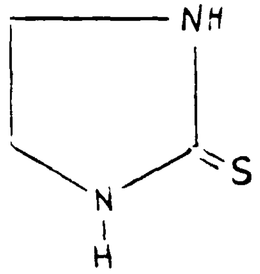
Produced by: Unknown, available through aldrich

Toxicity: RTECS: NI9625000
Cancer Suspect Agent - Teratogen
Carcenogenic Determination Animal - positive
orl-rat LD50: 545 mg/kg
orl-mus LD50: 3000 mg/kg

Physical Data: MW: 102.17
CAS# 96-45-7
mp: 197-200
Merck: 10, 4812

Formula: C3-H6-N2-S

Structure:



DISCUSSION:

Another of the compounds in this grouping that are among the most unstable with a T99 of 230 C (same ranking as daunomycin). The only products of concern would be:

hydrogen cyanide - trace, extremely stable, toxic

Mechlorethamine hydrochloride:

EPA Classification: Alkylating Agent, Nitrogen Mustard

Use: Antineoplastic

Synonyms: Trituration, Dichloren, Mustargen

IUPAC Name: 2,2′-dichloro-n-methyl-diethylamine Hydrochloride

Produced by: Merck, Sharp and Dohme

Toxicity: Highly Toxic, Cancer Suspect Agent
RTECS: IA2100000
ivn-hmn: LDLo: 400ug/kg
orl-rat: LD50: 10 mg/kg
orl-mus: LD50: 20 mg/kg

Physical Data: MW: 192.52
CAS# 55-86-7
Merck 10, 5598
mp: 108-110

Formula: C5-H11-Cl 2-N .Cl-H

Structure:

$CH_3N(CH_2CH_2Cl)_2 \cdot HCl$

DISCUSSION:

Again, because this material has a HCl functionality, we limit our discussion to the material remaining after the HCl has been lost - in this case, the C5-H11-Cl 2- N cation.

The products that are likely to form from this material, using our laboratory experience with similar compounds will be as follows:

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - trace, high stability

acrylonitrile - trace, high stability

diethyl-methyl-amine - somewhat stable

Alpha-naphthalamine:

EPA Classification: Laboratory Chemical

Use: Unknown

Synonyms: 1-aminonaphthalene

IUPAC Name: 1-aminonaphthalene

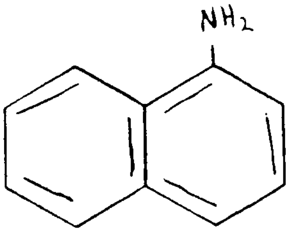
Produced by: Unknown

Toxicity: RTECS: QM1400000
Cancer Suspect Agent
OSHA Regulated Carcenogen
orl-rat: LD50: 779 mg/kg
orl-man: LDLo: 4000 mg/kg
Carcenogenic Determination Human - Suspected; Carcenogenic Determination Animal - indefinite

Physical Data: MW: 143.19
mp: 48-50
bp: 301
d: 1.114
FP: > 230
CAS # 134-32-7
Merck: 10,6250

Formula: C 10-H7-N-H2

Structure:



DISCUSSION:

This material is the 2nd most stable compound in this list of 15 compounds to be investigated. The T99 for this compound is assigned to be 840 degrees C with a ranking of 52. Loss of the amine to form naphthalene and the possible degradation of naphthalene to form benzene are the only reaction pathways forseeable for this material.

naphthalene - extremely stable with a T99 temperature of 1070 C.

benzene - extremely stable

Streptozocin:

EPA Classification: Nitrosoureas

Use: antineoplastic

Synonyms: Streptozoticin

IUPAC Name: Glucopyranose,
2-deoxy-2-(3-methyl-3-nitrosoureido)-D-

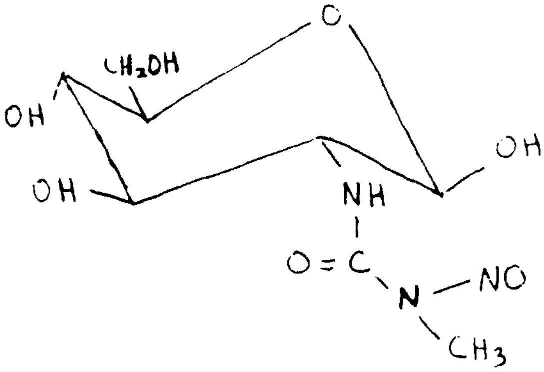
Produced by: Upjohn

Toxicity: RTECS: LZ5775000
orl-hmn: TDLo: 1044 mg/kg/5D
inv-wmn: TDLo: 170 mg/kg/3W
ivn-wmn: LDLo: 440 mg/kg/65W-I
inv-rat: LD50: 138 mg/kg
orl-mus: LD50: 284 mg/kg

Physical Data: MW: 265.26
CAS # 18883-66-4

Formula: C8-H15-N3-O7

Structure:



DISCUSSION:

This completely saturated material is the least stable compound in the list of 15 with a T99 of about 155 degrees C. This material would be difficult even to chromatograph before it degraded to its byproducts. The products that are likely to form from this material, using our laboratory experience with similar compounds will be as follows:

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - trace, high stability

acrylonitrile - trace, high stability

o-tolidine dihydrochloride:

EPA Classification: Laboratory Chemical

Use: Analgesic

Synonyms: 3,3′-dimethylbenzidine dihydrochloride

IUPAC Name: same

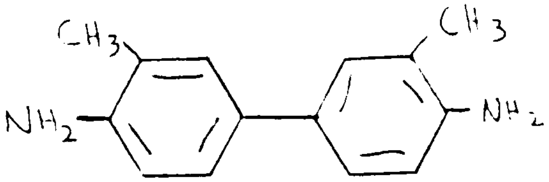
Produced by: Parke Davis

Toxicity: Cancer Suspect Agent
RTECS: DD1226000
mma-sat 50 ug/plate

Physical Data: MW: 285.22
CAS# 612-82-8
mp: > 340

Formula: C14-H16-N2 .2Cl-H

Structure:



DISCUSSION:

This material, like the other benzidine material in this list, is quite stale at higher temperatures with this compound having a T99 temperature between 785 and 815 C. As we have seen before, the dihydrochloride functionality decreases the stability of the parent as well as providing an abundant source of HCl. Again, we are ranking the stability of the compound after the HCl has been eliminated from the parent.

Stable products that may form are:

hydrogen cyanide (HCN) - extremely stable, very toxic

acetonitrile - high stability

acrylonitrile - high stability

toluene - moderately stable

Part 2: Technical and Cost Proposal for Thermal Decomposition Studies for CT Agency - Contaminated Wastes

Summary:

The University of Dayton proposes to evaluate the incinerability of selected CT agents. The proposed technical effort and cost information are outlined in detail in University of Dayton Proposal No. R-7098.

References

1. EPA classifications for Chemotherapeutic Agents, provided in RFP.
2. Drugs, 1987
3. Aldrich Catalog, Aldrich Chemical Co., 1987.
4. Registry of the Toxic Effects of Chemical Substances (RTECS) Manual, NIOSH Publication 1983.
5. C. Sellei, Chemotherapy of Neoplastic Diseases, Hungarian Academy of Sciences, 1970.

APPENDIX A

THERMAL DESTRUCTION OF ANTINEOPLASTIC AGENTS

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I. INTRODUCTION

The thermal decomposition characteristics of three samples: methylene chloride, a methylene chloride/toluene/p-xylene mixture, and cyclophosphamide were studied using the Thermal Decomposition Analytical System (TDAS). Thermal decomposition data were generated for each of these samples in both pyrolytic and oxidative atmospheres.

In addition to this overall characterization, the major products resulting from the decomposition of each of the samples were identified. As appropriate, these products were profiled by weight percent remaining versus temperature curves with their formation and destruction relatively quantified.

Based upon the information obtained in this study, the gas-phase thermal stabilities of the sample materials as well as the conditions under which products are formed are discussed. Possible mechanisms for product formation are also addressed.

II. EXPERIMENTAL

A. Instrumentation

Laboratory investigations of the thermal decomposition behavior of methylene chloride, a methylene chloride/toluene/p-xylene mixture, and cyclophosphamide were conducted with the Thermal Decomposition Analytical System (TDAS). The TDAS is comprised of a closed, in-line thermal decomposition flow reactor unit which sophisticated analytical instrumentation through which analysis of effluent products is accomplished. The following discussion presents a detailed description of the TDAS so as to establish a firm basis for understanding the experimental procedure.

The design concept of the TDAS incorporated several fundamental objectives [1]. Within the scope of providing precise thermal decomposition information, this system is capable of determining the effects of the prominent variables related to incinerability studies. It can accommodate a wide range of organic samples -- gases, liquids, solids, and polymers. The identification of thermal decomposition effluent products is facilitated by its advanced analytical features.

The TDAS may be described as the integration of two sections, the thermal section and the analysis section. It is depicted in block diagram form in Figure 1. Reference to this figure greatly simplifies visualization of the overall process. Upon insertion of the sample, the vaporized compound is carried by a stream of flowing gas into a reactor where it is subjected to a controlled high-temperature exposure.

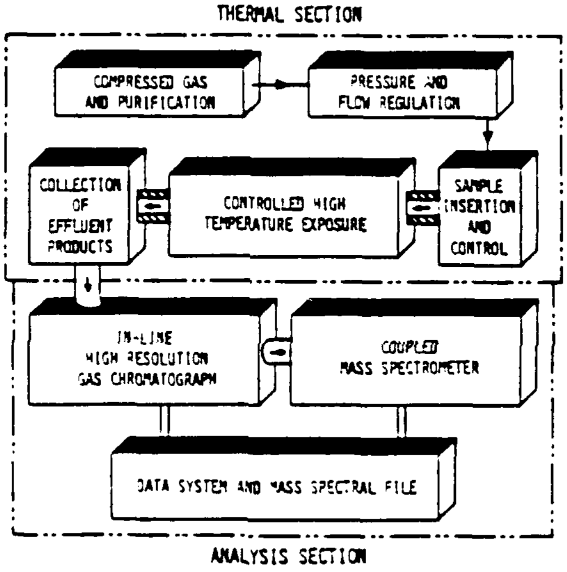


Figure 1. Block Diagram of the TDAS.

The compounds that emerge are cryogenically trapped and subsequently separated by a high-resolution gas chromatograph. Analysis and identification is then achieved by an in-line mass spectrometer and associated data reduction equipment. A more detailed description of the two sections comprising this instrumentation system follows.

Thermal Section. This section consists of the gas supply tanks, sample insertion chamber, transfer lines, high-temperature reactor, effluent collection, and a control console to monitor the process variables. Key components are discussed in the following paragraphs.

1. Sample Handling and Insertion. The versatility of the sample insertion region is reflected by its ability to handle different types of organic samples. However, all material transported into the reactor must be in the gas phase. In the case of liquid and solid samples, volatilization is achieved through controlled heating of the insertion chamber with a Theall Engineering TP-2000 temperature programmer. This enables the use of linear temperature programs ranging from -100°C to +700°C as well as the maintenance of isothermal conditions. The temperature programmer is not exclusively for volatilization purposes, but serves to heat the inlet for ease of transport in nearly all experimentation.

2. Transport Lines. Proper transport of gas-phase compounds is another important aspect of the thermal decomposition analyses. Most of the tubing material is fabricated from fused quartz because of its inert properties. The inside diameter of these lines is generally 1.0 mm or less in order to ensure high linear velocities and a continual flow of sweeping gas.

An outer jacket of quartz tubing encloses the small bore transfer tube and it is the larger diameter glass which experiences direct heating. Thermocouples are attached at various locations along the outer tube and woven glass tape from Ware Apparatus Company is used to electrically insulate the conductors. This is followed by a layer of high-temperature heating tape known as Electrothermal flexible tape. Finally, the assembly is wrapped once again with the woven glass tape.

3. Quartz Tube Reactor. The high temperature reactor is one of the most fundamental components of the entire Thermal Decomposition Analytical System [1,2]. After careful and

detailed consideration of the design factors, a 1.0 mm ID, multiple-fold quartz tube reactor of race track configuration was selected. Construction of the reactor was accomplished through the scientific glassblowing expertise of the University Glass Shop.

This design affords several advantages. Although the overall length of the main portion of the reactor is relatively short, the multiple folds and the cycle arrangement effectively eliminate any existing temperature gradients. This translates into a controlled, isothermal exposure of the sample. The narrowness of the gas flow path accounts for very low Reynolds numbers and laminar flow characterization. Even at high linear gas velocities, the pressure drop across the reactor remains low. Also attributable to the diameter size is the fact that back diffusion is nearly impossible. Furthermore, the flow path dimensions permit a variation in mean residence time between 0.25 and 5.0 seconds.

The mean residence time is determined from a study of the physical relationships within the gas flow path of the thermal decomposition unit as illustrated in Figure 2. The ideal gas low applies as follows:

$$\frac{V_2 p_2}{\bar{T}_2} = \frac{V_o p_o}{T_o} \tag{1}$$

where V is volume, p is pressure, and T is temperature with the bar indicating an average over the length of the reactor. The subscript "2" denotes the quartz tube interior and "o" refers to ambient conditions. Utilizing the defining expressions,

$$p_d = p_2 - p_o \tag{2}$$

$$F_o = \frac{V_o}{\bar{t}_r} \tag{3}$$

$$V_2 = \pi r^2 L \tag{4}$$

where p_d is differential pressure, F_o is volumetric flow rate, $\bar{t}_r$ is mean residence time, and r and L are the tube radius and length, respectively, substitution into equation (1) and manipulation of the variables yields:

$$\bar{t}_r = \left(\frac{\pi r^2 L}{F_o}\right) \left(\frac{T_o}{\bar{T}_2}\right) \left(1 + \frac{p_d}{p_o}\right) \qquad (5)$$

By maintaining the pressure, temperature, and linear gas velocity within the reactor at constant values, each molecule of the sample is subjected to essentially the same thermal conditions. This results in the generation of a normal or Gaussian residence time distribution.

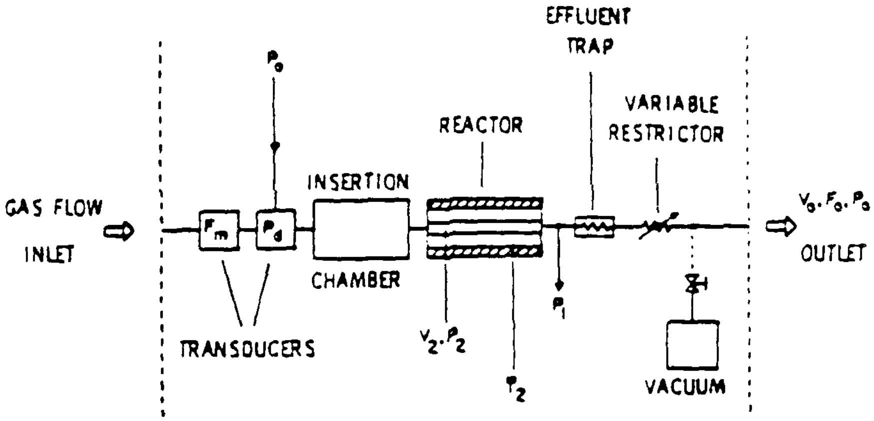


Figure 2. Schematic Showing Physical Relationships of TDAS Gas Flow Paths.

The quartz tube reactor is fitted into a three-zone Lindberg furnace (Model 54357) capable of continuous operation to a practical upper limit of 1150°C. This tubular furnace is equipped with its own control mechanism for individual regulation of the temperature within each of the three zones. Although only the central portion is actually used to heat the reactor, the entire length is held at a uniform temperature.

This section may be visualized by reference to three separate gas flow paths. The main stream carries the vaporized sample from the insertion chamber through the transfer lines and into the controlled, high-temperature reactor. The remaining parent compound and the various products formed during the decomposition process are then swept downstream through the exit transfer tubing and cryogenically collected for chromatographic analysis.

The other two gas streams serve to cool the entrance and exit regions of the quartz tube assembly and an adjustable flow of heat transfer air. The incoming gas containing the sample is thus maintained at a nondestructive level up to the point of entry and immediately upon leaving the reactor. Fine-bore connecting tubes at these transition points increase the linear gas velocity fivefold at the inlet with a corresponding decrease at the outlet so as to produce a square-wave temperature profile. This ensures that the molecules experience the desired thermal exposure for the appropriate mean residence time.

Process Monitoring. Most of the measurement devices pertaining to the thermal decomposition unit have been incorporated into an instrumentation console for convenient control of the experimental variable.

The pressure and flow readout is achieved with a Hewlett-Packard 3465A digital multimeter. Both the mass flow and differential pressure transducers display a DC voltage output, but the former is expressed in volts whereas the latter is in the millivolt range. Calibrations on these components allow for gas flows up to 50 cm^3/min and a maximum differential pressure of 2.0 absolute atmospheres.

Eighteen electrically shielded thermocouples are brought together in the temperature measurement section and this parameter is monitored at different positions throughout the TDAS with the turn of a selector switch (Omega MTG-OSW3-18). There are two digital temperature indicators, one of which is exclusively assigned to the quartz tube reactor.

The gas flow control module is comprised of the gas input connections, a carrier gas filter from Applied Science Laboratory, a valve for switching from one reaction gas to another (Carle Instruments 5511), and needle valves that adjust the flow of heat transfer air within zones one and three of the Lindberg furnace. In addition, a variable flow controller (Porter Instruments VCD 1000) which regulates the main gas stream into the reactor and the electronics of the flow and pressure transducers are included on this panel.

There are a few other significant points with regard to monitoring instrumentation. A number of variacs, adjustable power supplies, temperature controllers, and assorted fuses and switches are housed in a separate unit within the console for heating the transport lines. Ambient temperature and barometric pressure must also be measured during the course of conducting a test in order to calculate the necessary gas flow to attain a particular mean residence time. A mercury-in-glass thermometer located inside the cabinet and a Sargent-Welch S-4565 vernier rack barometer are available for these measurements.

Analysis Section. This section consists of a high resolution gas chromatograph coupled to a mass spectrometer with associated data acquisition and reduction peripherals. Key aspects of the analysis section are discussed in the following paragraphs.

1. Collection of Effluent. As the gas-phase sample and its associated decomposition products emerge from the high-temperature reactor, they are carried through the heated transfer line to the high-resolution gas chromatograph. Column overloading is an important consideration because of the capillary tubing utilized in the analytical treatment. For this reason, a splitter-restrictor installed between the furnace and the GC direct only a small fraction of the effluent into the column where it is cryogenically trapped. The remainder is diverted into a piece of plastic tubing and filtered through activated charcoal before being vented to the atmosphere.

2. Chromatographic Separation. Separation of the constituents of the collected effluent is accomplished by a modified Varian Aerograph Model 2400 Gas Chromatograph (GC). It is equipped with a flame ionization detector (FID) and separate fine metering valves for adjustment of the hydrogen and air flows. The column oven linear temperature programmer has been calibrated for subambient operation as low as -70°C. This temperature is achieved through the use of an auxiliary coolant, liquid nitrogen, and serves to trap low molecular weight species at the head of the column. This is an essential step in the separation process because of the applicability of the principle of cryogenic focusing, especially in the case of a complex mixture. It is necessary that the condensable compounds be concentrated in the inlet region of the gas chromatograph. The combination of this thermal focusing technique and a fused silica capillary column promotes the efficient elution of a set of components with good resolution and sensitivity.

The coiled fused silica capillary tube is coated with a stationary phase. As the column is heated, the vaporized sample in a helium carrier make up the gas phase from which solutes dissolve into the stationary phase to produce an equilibrium state. The rate of transport for an individual substance depends on the solute partition between the flowing gas-phase and the stationary phase.

3. Sample Detection and Data Reduction. Although the GC used for this work is equipped with an FID, only the LKB 2091 mass spectrometer was used for these analyses. This mass spectrometer is a 90° magnetic sector instrument with an electron impact ion source. The interface of the mass spectrometer with the gas chromatograph is via a single stage all-glass molecular jet separator from Scientific Glass Engineering, specially modified for use on the TDAS.

A total ion current detector outputs a chromatographic signal that represents the ionized effluent at the exit of the ion source. It is displayed on a potentiometric recorder from Fisher Scientific. By switching the electrical connections, this recorder is also capable of receiving the corresponding information from the flame ionization detector.

The data reduction equipment that supports the mass spectrometer is an LKB 2130 data system. Included in this set-up is a Digital Electronics Corporation PDP 11/04 Minicomputer, a Tektronix 4012 graphics terminal and a Versatec 800 line printer/plotter. The package is completed with an LKB applications software manual.

B. Sample Preparation

All standards from which samples were prepared were obtained from Aldrich Chemical Company as follows:

- HPLC Grade Methylene Chloride Lot # 1208BM
- HPLC Grade Toluene Lot # 9817LL
- Gold Label (99+% purity) p-Xylene Lot # 04610PL
- Cyclophosphamide Monohydrate (98+% purity) Lot # 00907HM

In addition, HPLC Grade (99.9%) methanol used to prepare a cyclophosphamide solution was obtained from Fisher Scientific.

The methylene chloride sample as well as the methylene chloride/xylene/toluene mixture were gas-phase samples prepared in one liter gas sampling spheres. For experiments conducted in air, liquid samples were injected into air filled sampling spheres. For pyrolytic studies (i.e., experiments in 100% N_2) air was purged from the sampling spheres using a stream of N_2 gas prior to plugging the sphere and making the liquid injections.

The liquid injection sizes utilized for preparation of the gas-phase samples were:

- 54 μl for methylene chloride pure compound studies, and
- 4 μl methylene chloride, 18 μl toluene, and 21 μl p-xylene for the mixture studies.

Following liquid injections, evaporation of the liquids occurred in the spheres to achieve a final equilibrium vapor pressure for each of the sample constituents which did not exceed 50% of the saturation vapor pressure.

In as much as the cyclophosphamide (CP) is a low vapor pressure solid at normal ambient conditions, this sample was prepared to be run as a solid. To facilitate constant sampling of this material, it was decided to prepare the CP in solution with a volatile solvent. Methanol was selected as the solvent and a 3.95 μg CP/μg solution was prepared in a Pierce Chemical Company 14 ml. screw cap septum vial. Because of the clearly established toxicity of CP, the CP solution was prepared in the Environmental Sciences Group's Hazardous Materials Laboratory.

C. Procedures

Insertion of samples into the TDAS was accomplished either by direct injection of gas-phase samples (methylene chloride and mixture) or by injection of the CP/methanol solution onto a solids probe and allowing the solvent to evaporate prior to inserting the probe into the TDAS insertion region.

The gas-phase injections were made through a septum (Supelco Inc., Thermogreen LB-1) directly into a preheated isothermal (250°C) insertion region. The gas samples were then swept directly from the insertion region into the reactor by the appropriate flowing gas stream. Injection sizes were 150 μl (10.7 μg) for the methylene chloride sample and 500 μl (2.76 μg of methylene chloride, 7.92 μg of toluene, and 9.13 μg of p-xylene) for the mixture. Gas-tight syringes (Precision Sampling Corp., Pressure-Lok) were used for these injections.

The CP sample was admitted to the TDAS via a solids sampling probe which is placed into the insertion region and sealed by viton O-rings (Anchor Rubber Co.). With the solids probe removed and in an exhaust hood, 5 μl of the CP/methanol solution was injected onto the probe tip using a liquid syringe (Hamilton Co., Microliter). The methanol was allowed to evaporate leaving the

CP (19.7 μg) deposited on the probe tip. The probe was then placed into the insertion chamber which was then heated from ambient temperature to 200°C at a rate of 15°C per minute to volatilize the sample for transport to the reactor. The insertion region was held at 200°C for approximately eight minutes to assure quantitative mass transport of the volatilized species from the insertion region.

Since the effect of both oxidative (excess oxygen) and pyrolytic (oxygen starved) conditions on the thermal decomposition characteristics of the samples were of interest, two different flowing gas streams were used to sweep the samples from the insertion region, into and through the reactor. Oxidative studies were conducted using breathing quality compressed air (Air Products) with residual moisture removed by a Hydropurge (Coast-Engineering). Pyrolytic studies were conducted in nitrogen (Air Products) which received additional deoxygenation by an Oxyclear prefilter (Labclear) in combination with an Indicating Oxy-Trap (Alltech Associates). The nitrogen was also demoisturized using a Hydropurge.

Experimental gas flow rates were established to provide a mean gas-phase residence time ($\bar{t}_r$) of 2.0 seconds for all samples. In addition, because of the extraordinary thermal fagility of the CP (see Results and Discussion), a limited amount of data was taken at a $\bar{t}_r$ of 0.5 seconds. A wide range of reactor temperatures were used in these experiments, from 175°C to 1000°C.

Chromatographic techniques used in these analyses also varied widely. For the methylene chloride sample as well as the mixture, analyses were accomplished with a 30 meter fused silica capillary column containing a 0.25 μm DB-5 film (J & W Scientific). The column was maintained at -50°C to capture the reactor effluent (following thermal exposure of the sample) and hold the effluent species during changeover to the helium carrier gas which was used for chromatographic analyses. Following changeover to helium, and establishing a linear gas velocity of approximately 30 cm/s, the GC oven was programmed up to 300°C at 12°C per minute.

The CP chromatographic analyses were conducted using a short (four meter) fused silica capillary column containing a 0.25 μm film of moderately polar 75% cyanopropyl silicone (Quadrex Corp.). An undetermined (but extremely high) helium linear gas velocity was used in combination with a GC oven temperature program beginning at -20°C and heating at 45°C per minute to 230°C, at which point the temperature was held about 10 minutes. This unusual chromatographic technique was the best compromise of numerous methods tried to analyze CP and its thermal reaction products. None of the methods were entirely successful or satisfactory (see additional discussion in results section).

Depending on whether quantitative or qualitative information was desired from the particular experiment, different mass spectrometer (MS) detection methods were used. For quantitative information the total ion current (TIC) detector was used with output to the chart recorder. Ions were generated in the MS source using 70 eV electron impact, 50 μA trap current, and accelerated from the source by a 3.5 kV voltage. When qualitative information was desired, the MS was scanned in the mass range of 45 to 492 amu at approximately 2.5 s per scan. Ionization parameters were as described above and output from the electron multiplier was directed to the PDP 11/04 Minicomputer for assimilation and reduction.

III. RESULTS AND DISCUSSION

The results of the thermal decomposition experiments involving methylene chloride; a mixture of methylene chloride/toluene/p-xylene; and cyclophosphamide follow. For clarity, results have been divided according to sample make-up and pertinent discussion of each set of results is included.

A. Methylene Chloride

The thermal decomposition profiles for the methylene chloride sample are shown in Figure 3. These profiles were generated at a mean gas-phase residence time at temperature ($\bar{t}_r$) of 2.0 sec. in a pyrolytic atmosphere (100% N_2) and in an oxidative atmosphere (air). Values for weight percent remaining are calculated by dividing the detector response value for a given temperature by the detector response value at a non-degradative temperature and then multiplying this number by 100.

From these thermal decomposition curves it is readily apparent that methylene chloride is thermally stable as a pure compound in the gas-phase. For a $\bar{t}_r$ = 2.0 sec., 99% destruction of the parent material is possible in the temperature range of 760 to 840°C depending on the oxygen content of the reaction atmosphere. Excess oxygen levels affect the decomposition of methylene chloride by reducing the 99% destruction level approximately 80°C relative to the oxygen starved pyrolytic conditions. Although this is not a high level of oxygen dependence (e.g., 200°C difference in the temperature required for 99% destruction of pentachlorobiphenyl in air versus N_2 [31]), it does indicate decomposition pathways involving reactive oxygen containing species such as O_2, O, or OH are available to this compound.

A higher level of oxygen dependence is observed for the formation and subsequent destruction of thermal reaction products. As shown in Figure 4, the area of maximum thermal reaction product yield (products normalized to non-decomposed methylene chloride) is shifted approximately 100°C by the oxidative versus the pyrolytic atmospheres. In addition, the slopes of the destruction

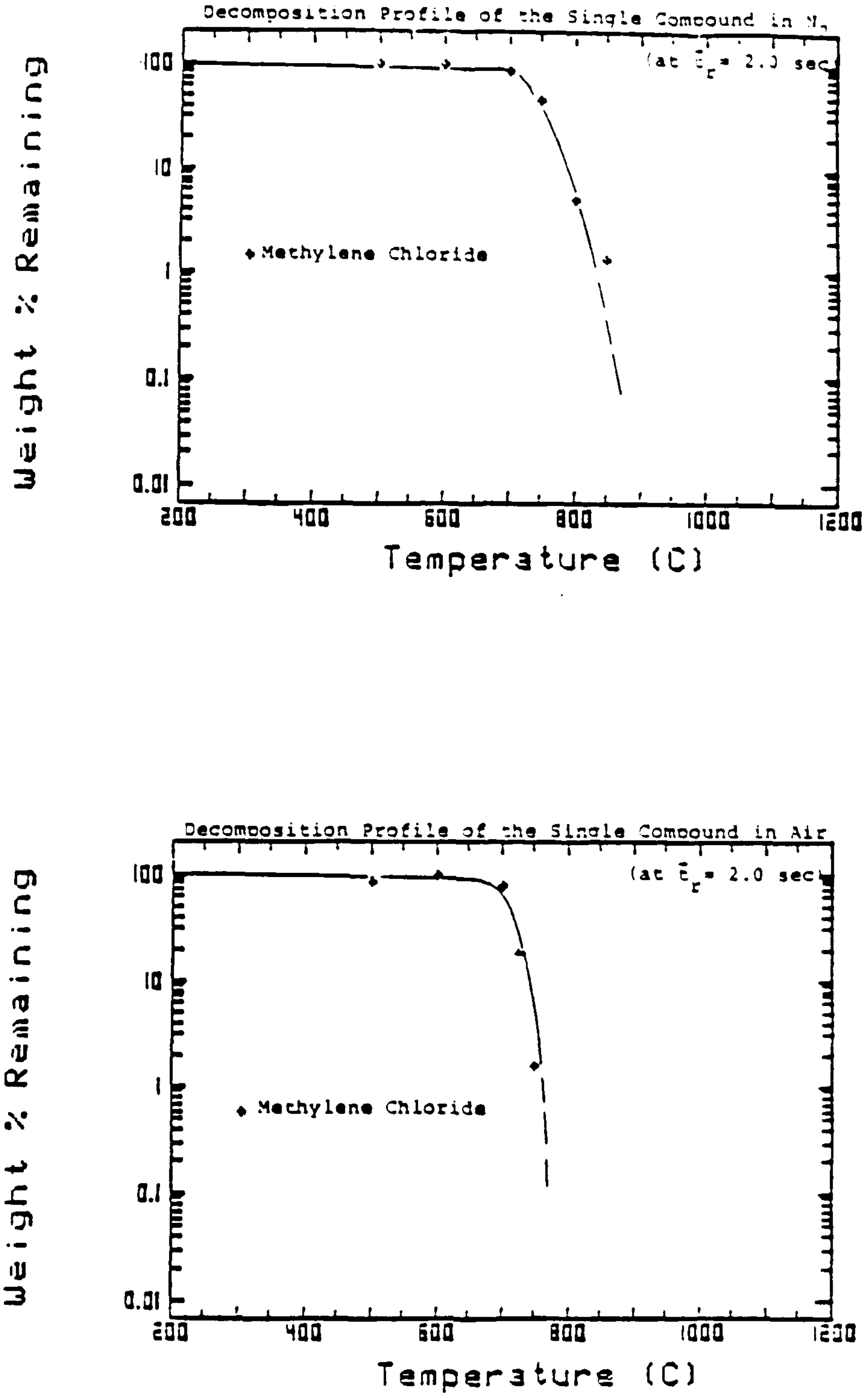


Figure 3. Composite of the Thermal Decomposition Profiles of Methylene Chloride in Nitrogen and Air.

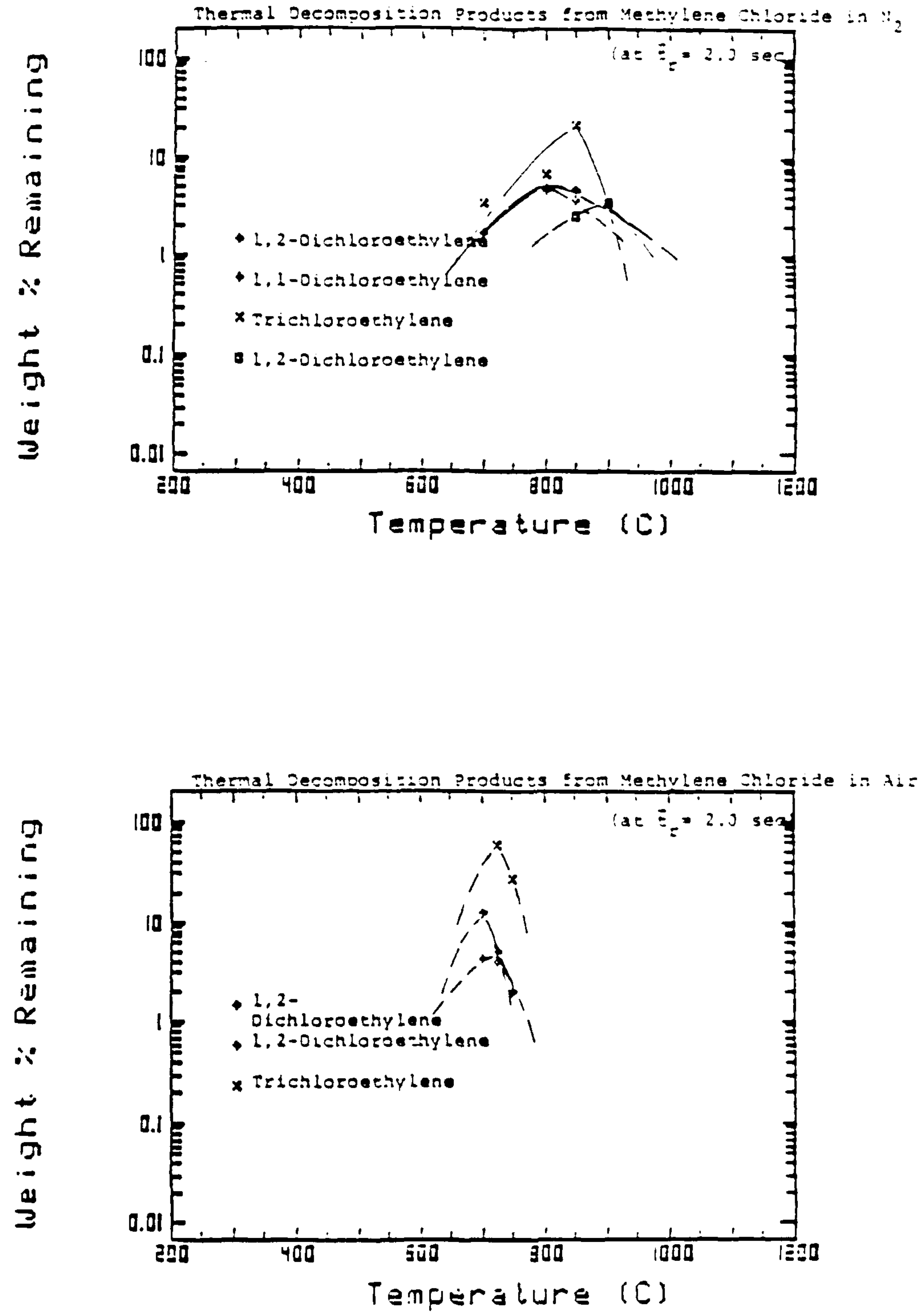


Figure 4. A Composite of the Appearance/Disappearance Profiles of Some Major Thermal Decomposition Products of Methylene Chloride in both Nitrogen and Air (Weight Percent Remaining Normalized to Non-Decomposed Methylene Chloride).

portion of the appearance/disappearance curves for many of the reaction products are much shallower in the N_2 atmosphere. This would lead one to suspect that the oxygen required for efficient thermal decomposition of the parent methylene chloride is amplified by the greater oxygen dependence of its thermal reaction products, particularly the dichloroethylene isomers.

Qualitatively the change in reaction atmosphere had little impact on the product formation. In both pyrolytic and oxidative atmospheres the major product was trichloroethylene. Trichloroethylene could be formed by the recombination of dichloromethyl radicals formed as a result of hydrogen being abstracted from methylene chloride. A subsequent concerted elimination of hydrogen chloride from the recombination product tetrachloroethane, would lead to the formation of trichloroethylene. Since the yield of trichloroethylene was observed to be somewhat higher in air than in N_2, one would suspect that OH radicals participate in the hydrogen abstraction process. In the oxygen starved system OH radicals are minimized and hydrogen abstraction would be expected to result from the presence of other reactive species such as chlorine atoms leading to the formation of hydrogen chloride. Chlorine atoms could originate from the parent methylene chloride by simple chlorine to carbon bond homolysis.

Another possible route for the decomposition of methylene chloride is through the concerted elimination of hydrogen chloride to form a chlorocarbenyl radical. Recombination of two of these biradicals would lead directly to the formation of 1,2-dichloroethylene. This is a likely pathway in both oxidative and pyrolytic conditions and is indicated by the presence of both 1,2-dichloroethylene isomers as products in air and pyrolytic conditions.

The third dichloroethylene isomer, 1,1-dichloroethylene was observed under pyrolytic conditions but not under oxidative conditions. This is somewhat surprising since dichloromethyl radicals formed in processes such as hydrogen loss by OH abstraction would be expected to play a major role in

1,1-dichloroethylene formation. Further study would be required to fully explain this phenomenon.

Overall, it is clear from the results of the methylene chloride studies that, while the methylene chloride is a stable compound, toxic thermal reaction products may also be formed during its decomposition. The destruction of the thermal reaction products would appear to be especially challenging under oxygen starved conditions.

B. Methylene Chloride/Toluene/p-Xylene Mixture

Thermal decomposition profiles were generated for a mixture of methylene chloride, toluene and p-xylene which was prepared and studied at a molar ratio of 16:42:42, respectively. The mixture was studied in oxidative conditions (air) as well as pyrolytic conditions (100% N_2). Thermal decomposition profiles of the mixture's components were determined by calculating the weight percent remaining values as previously described. Product appearance/disappearance curves are plotted with weight percent remaining values normalized to the non-decomposed toluene detector response for the mixture.

Figure 5 shows the thermal decomposition profiles for each of the mixtures constituents in air and N_2 at a $\bar{t}_r$ of 2.0 sec. Clearly, the influence of oxygen is significant in terms of the overall decomposition of this mixture. The most stable component under both oxidative and pyrolytic conditions is toluene, however, the temperature required for 99% destruction of toluene is decreased over 200°C in air versus that in nitrogen. The p-xylene also exhibits a significant level of oxygen dependence as shown by the shift in temperature required for 99% destruction of nearly 200°C in air versus N_2.

Methylene chloride exhibits a lesser oxygen dependence of the 99% destruction temperature than either the toluene or p-xylene. However, the shift of the 99% destruction temperature in the mixture (approximately 130°C) exceeds that previously discussed for the pure compound (approximately 30°C) under the two conditions.

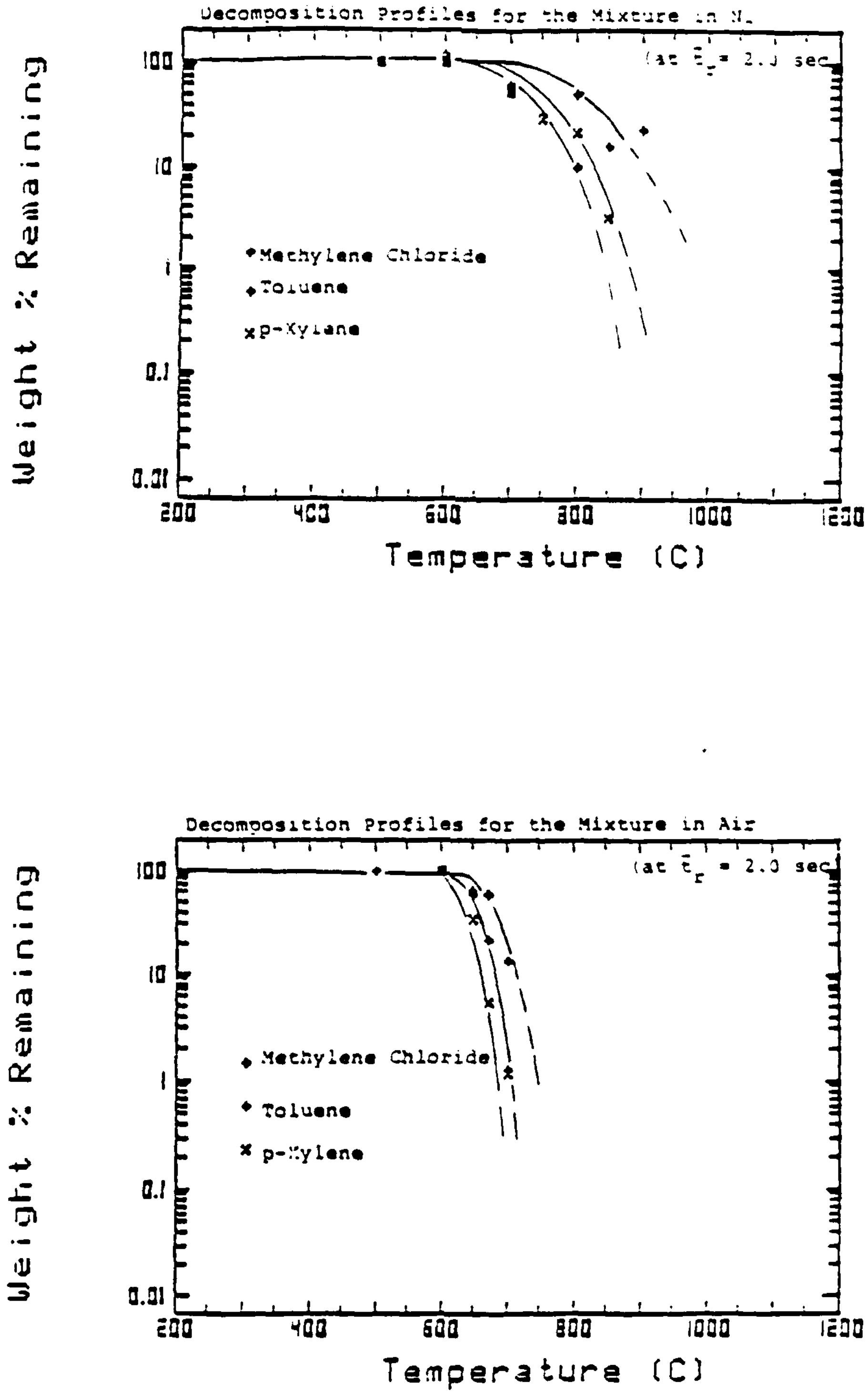


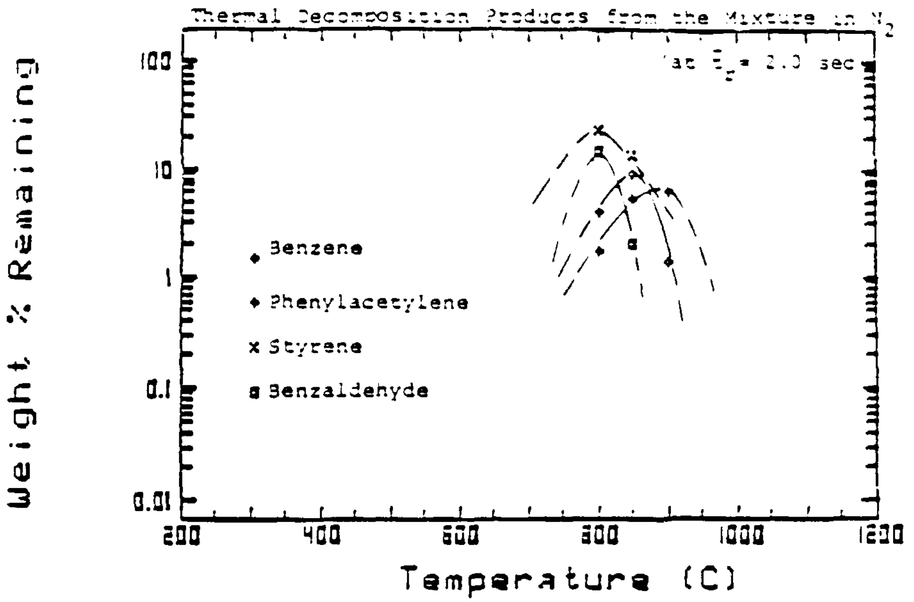
Figure 5. Composite of the Thermal Decomposition Profiles for the Mixture in Nitrogen and Air.

This can be attributed to reactive species generated by the thermal decomposition of the other components of the mixture which may attack the methylene chloride. The change in relative thermal stabilities of the components of the mixture provides a key to further understanding this situation.

Under pyrolytic conditions, methylene chloride is the least stable of the components. Under oxidative conditions, p-xylene is the least stable. As previously mentioned, toluene and p-xylene have a greater oxygen dependence than methylene chloride so their curves shifted to a greater degree toward lower temperatures in the presence of excess oxygen than is the curve for methylene chloride. This results in a change in the relative thermal stabilities. Since p-xylene becomes less stable than methylene chloride, the products of p-xylene decomposition will be available to attack by the methylene chloride resulting in an apparently greater oxygen dependence for the methylene chloride in the mixture than as a pure compound.

The high degree of oxygen dependence exhibited by p-xylene and toluene is probably related to the ease with which benzylic hydrogens may be abstracted from these compounds. Oxygen containing species, such as OH, could be the principal reactive species for this mechanism.

The role of oxygen species in the thermal decomposition of the mixture is evidenced by the products observed, tentatively identified, and plotted in Figure 6. Under oxidative conditions three of the four major products are partially oxidized. The presence of benzaldehyde in the pyrolytic runs is most likely the result of trace levels of oxygen entering the system in gas streams, with the sample, or through a punctured septum. Again, as was the case for the pure compound, methylene chloride studies, pyrolysis products formed in oxygen starved environments are likely to challenge the efficient thermal destruction of this mixture. Phenylacetylene, formed in the pyrolytic mode, appears likely to compete with the thermal stability of the toluene, an



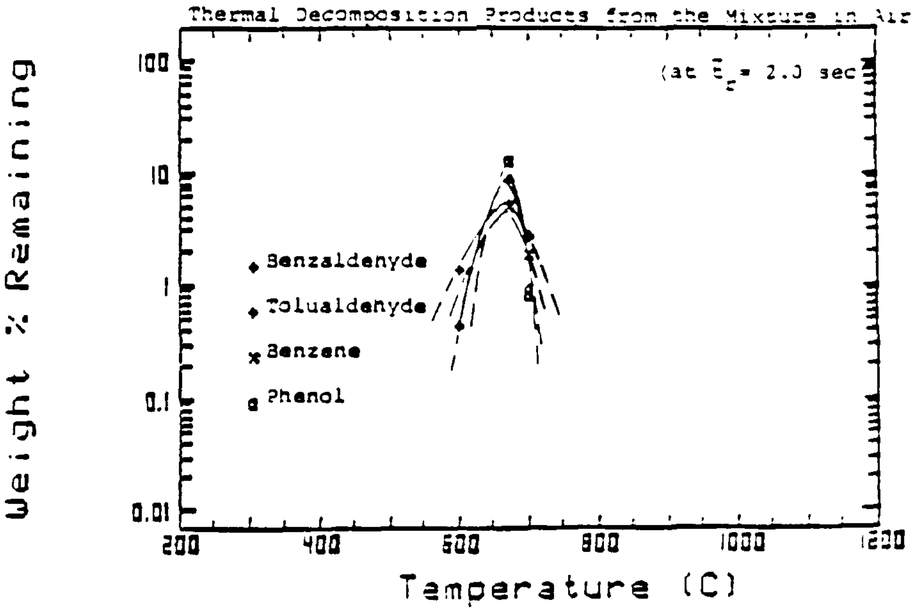


Figure 6. A Composite of the Appearance/Disappearance Profiles of Some Major Thermal Decomposition Products of the Mixture in Both Nitrogen and Air (weight percent remaining normalized to non-decomposed toluene).

original constituent of the mixture. There is however, some ambiguity in this assertion due to scatter in the high temperature toluene data.

C. Cyclophosphamide

Due to its low thermal stability, analysis of the thermal decomposition behavior of cyclophosphamide was focused on its thermal decomposition products. Mean gas-phase residence times ($\bar{t}_r$) of 0.5 sec. and 2.0 sec. were used in these experiments to provide additional information about thermal reaction products.

Figure 7 is a reconstructed total ion current chromatogram of the compound entering the mass spectrometer following vaporization and transport of a cyclophosphamide sample at approximately 175°C. The large amount of "tailing" of this peak indicates that this compound is of marginal chromatographability, possibly due to thermal instability of the gas-phase species. In fact, mass spectral analysis of this compound indicated that it was not cyclophosphamide but actually a fragile decomposition product of the cyclophosphamide (CP).

Figure 8 is a comparison of the CP mass histogram to the mass histogram of the compound transported at 175°C. The CP mass histogram was obtained by admitting a few CP crystals to the mass spectrometer vacuum system via the direct inlet. The product transported through the TDAS to the mass spectrometer is obviously different from the CP admitted to the direct inlet. The shift in both the molecular ion as well as the base peak of the transported material, indicate a loss of hydrogen chloride from the parent CP. The hydrogen chloride would presumably be lost through concerted elimination from one of the CP alkylating side chains.

Because of the apparent instability of the CP, there was concern that it was also decomposing in the methanol solution. The direct inlet of the mass spectrometer was used to confirm that the material in solution was indeed undecomposed CP. The major thermal decomposition product formed during vaporization

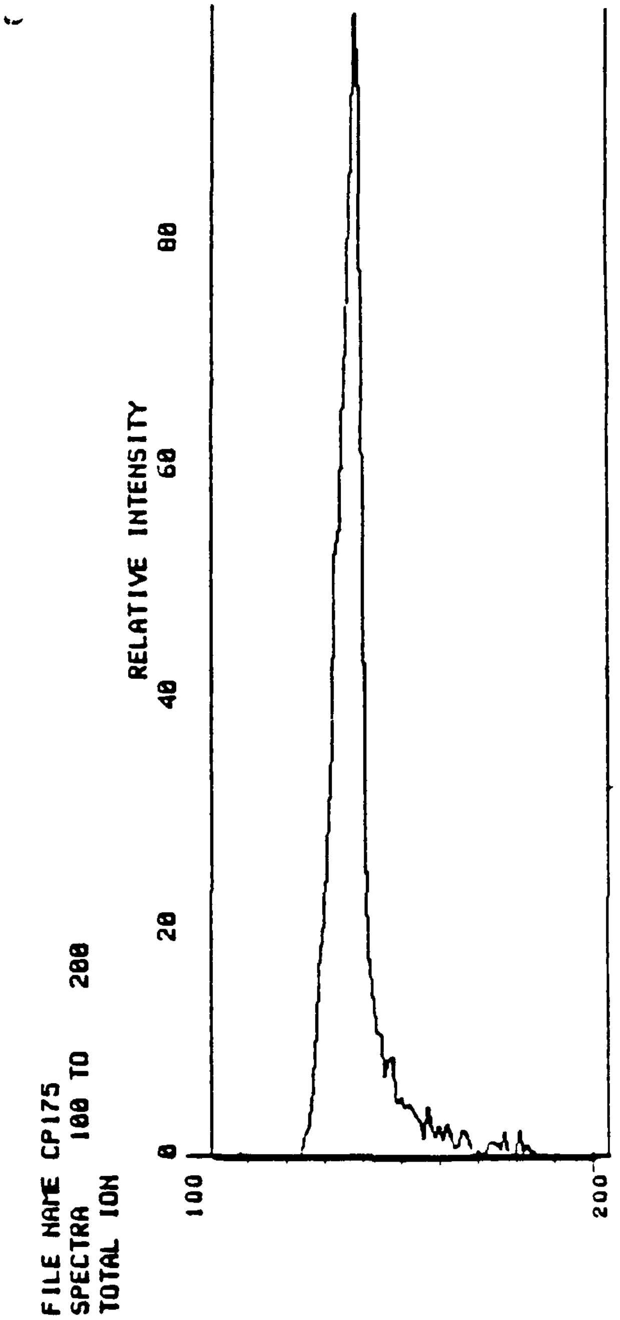
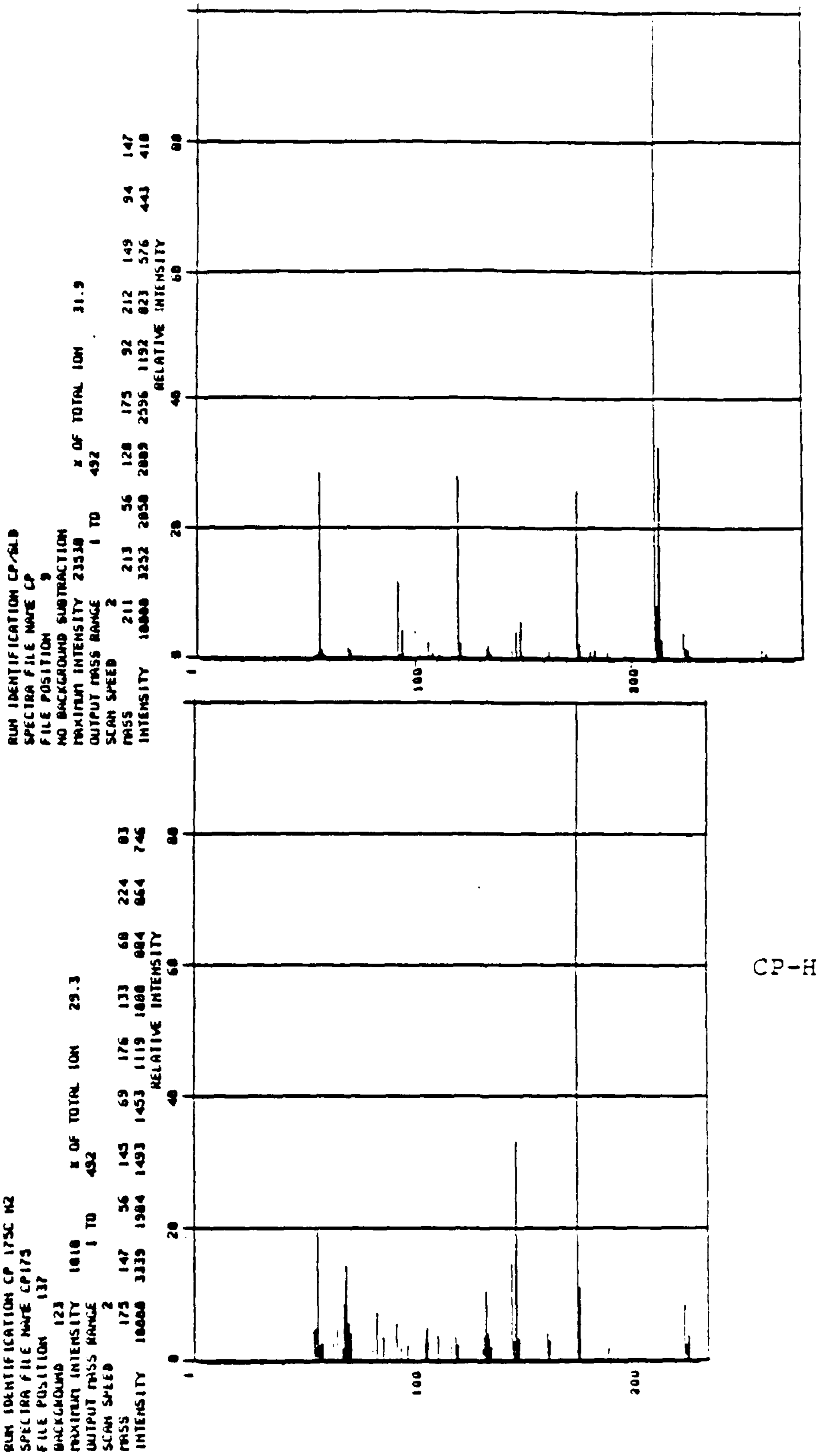


Figure 7. Reconstructed Total Ion Current Chromatogram Showing Unusual Peak Shape of CP Decomposition Product.



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FILE POSITION      9
NO BACKGROUND SUBTRACTION
MAXIMUM INTENSITY  23530
OUTPUT MASS RANGE      1 TO     492
SCAN SPEED         2                   % OF TOTAL ION    31.9
MASS        211   213    56   120   175    92   212   149    94   147
INTENSITY 10000  3252  2050  2009  2596  1192   823   576   443   418
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CP

```
RUN IDENTIFICATION CP 175C N2
SPECTRA FILE NAME CP175
FILE POSITION     137
BACKGROUND     123
MAXIMUM INTENSITY   1010
OUTPUT MASS RANGE      1 TO     492
SCAN SPEED         2                   % OF TOTAL ION    29.3
MASS        175   147    56   145    69   176   133    60   224    83
INTENSITY 10000  3335  1984  1493  1453  1119  1000   984   864   746
```

CP-HCl

Figure 8. Mass Histograms of CP (top) and Decomposition Product (CP-HCl) Detected Following Vaporization and Transport of CP at Temperatures less than 200°C.

and transport of the CP was designated CP-HCl. No thermal decomposition profiles were generated in these studies due to the inability to quantify the parent material.

The product CP-HCl also proved to be a thermally labile compound, although not nearly as labile as its parent CP. Figure 9 is a compilation of three ion current chromatograms obtained at three temperatures in an atmosphere of 100% N_2. The $\bar{t}_r$ for these three runs was reduced to 0.5 sec. to minimize decomposition to the greatest extent possible. Despite these experimental conditions, the CP-HCl was destroyed to levels below the detection limit before the reactor temperature reached 500°C. However, as shown by the chromatograms, a large number of thermal reaction products were detected.

Since the methylene chloride and the mixture were studied at a $\bar{t}_r$ of 2.0 sec, additional experiments were conducted to determine the destructability of the thermal reaction products at $\bar{t}_r$ = 2.0 sec. Figure 10 allows a comparison of the product yields at 0.5 sec. and 2.0 sec. in an N_2 atmosphere at 500°C. Although the atmosphere was pyrolytic, a net reduction in the product yields is observed by a four-fold increase in the mean gas-phase residence time at temperature.

As shown in Figure 11, the oxygen content of the reaction atmosphere has an effect far greater than the increased residence time at temperature. The chromatogram obtained for an air atmosphere at 800°C for $\bar{t}_r$ = 2.0 sec., demonstrates almost complete destruction of the CP thermal decomposition products. In a pyrolytic atmosphere at 800°C, numerous products are still detected.

In order to determine what products would be most likely to challenge the thermal destruction of CP, qualitative and quantitative data was obtained at 1000°C for 2.0 sec in an N_2 atmosphere. The total ion current chromatogram for the reactor effluent at these conditions is shown in Figure 12. A substantial number of products still remained undecomposed at this temperature in a pyrolytic atmosphere, whereas with excess oxygen present,

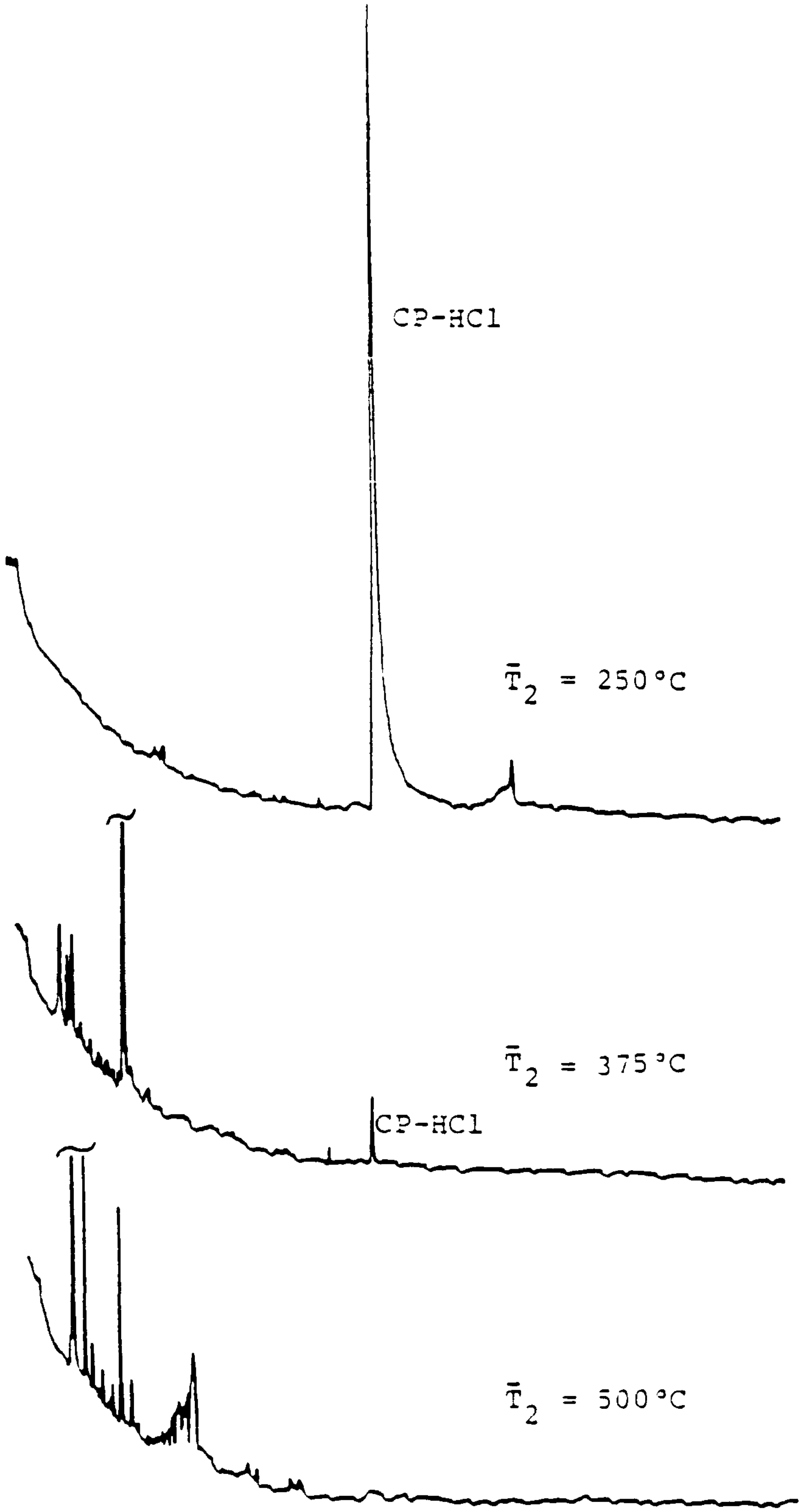

Figure 9. Chromatograms Showing Progressive Destruction of Cyclophosphamide Thermal Decomposition Product (CP-HCl) with Increasing Reactor Temperature ($\bar{T}_2$) at a Mean Gas-Phase Residence Time of 0.5 sec. in 100% N_2.

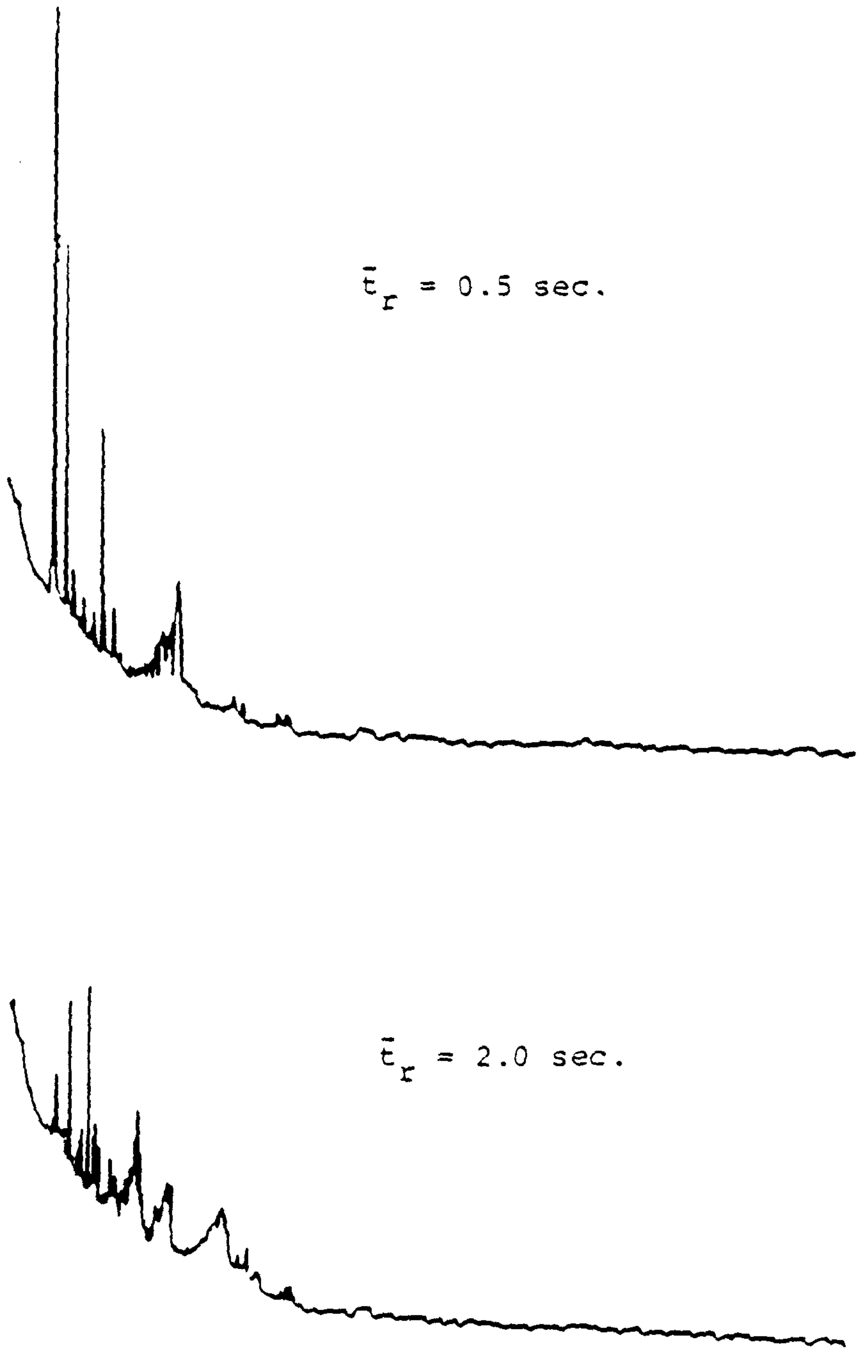

Figure 10. Chromatograms for Comparison of Reactor Effluents Resulting from Changes in the Mean Gas-Phase Residence Time at Temperature ($\bar{t}_r$) at 500°C in 100% N_2 atmosphere for cyclophosphamide.

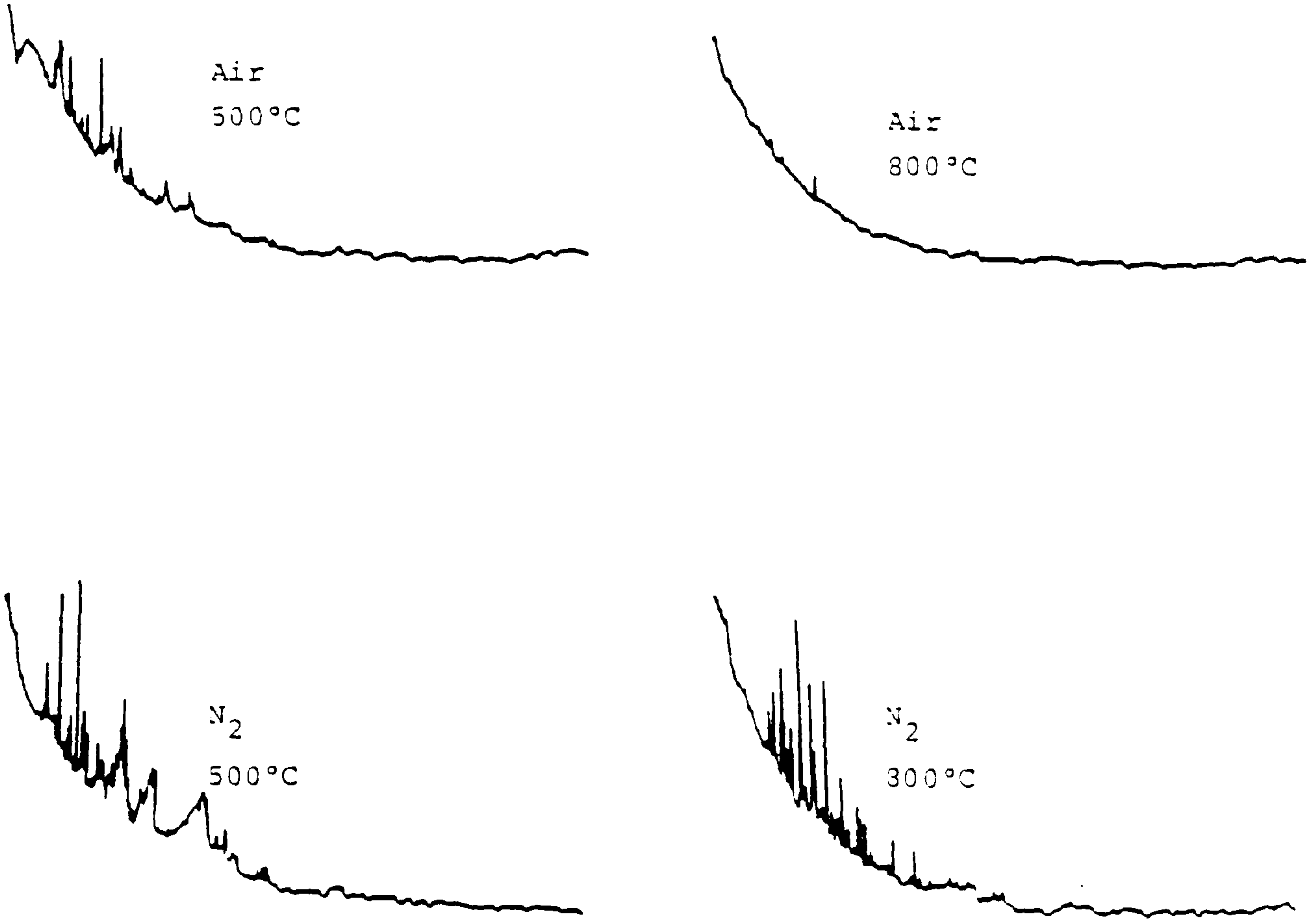

Figure 11. Selected Chromatograms Resulting from CP Decomposition for Comparison of the Effect of Reaction Atmosphere at 2.0 sec. Mean Gas-Phase Residence Time.

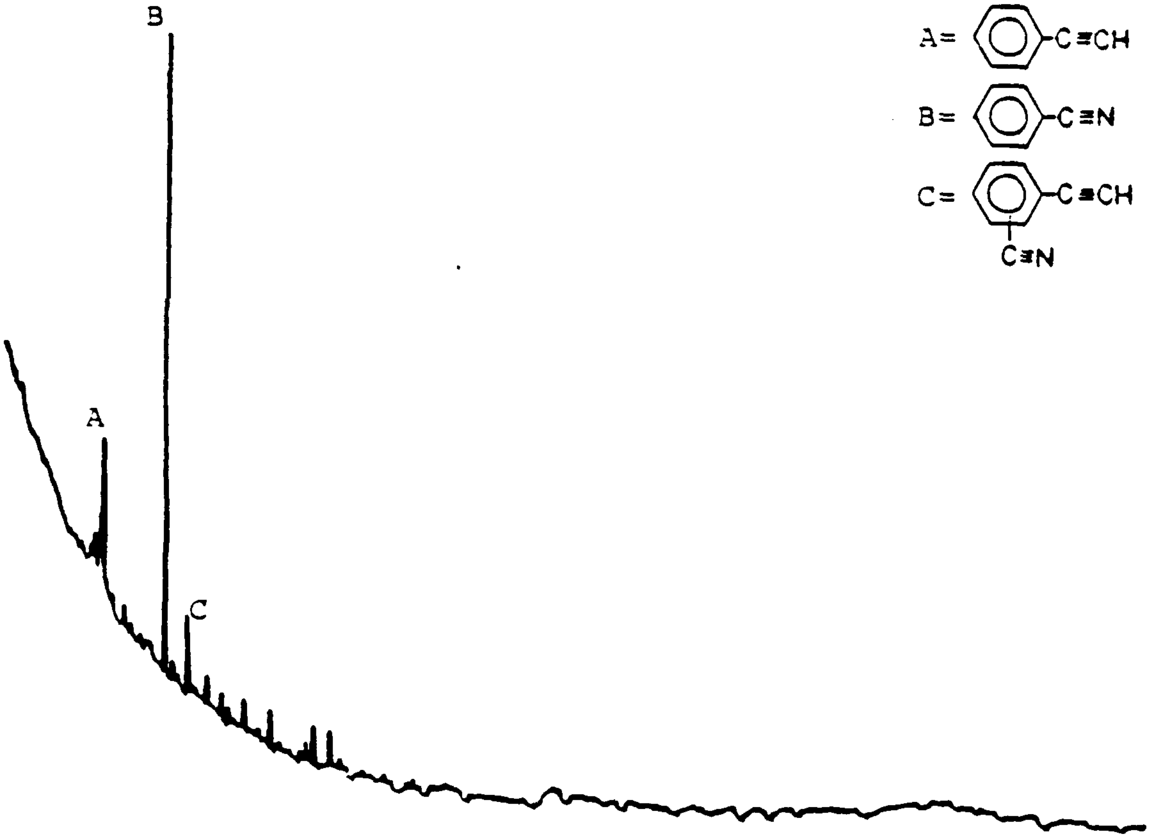

Figure 12. Reactor Effluent Following Exposure of Cyclophospha
to 1000°C in N_2 for a Mean Gas-Phase Residence Time
($\bar{t}_r$) of 2.0 sec. (Product Identifications are Tentat

greater levels of destruction were achieved at temperatures 200°C lower. The three major products remaining have been tentatively identified and their structures are shown on the Figure. The aromatic nature of these products is not unexpected, but their formation from a non-aromatic parent compound is unequivocal evidence of the complexity of thermal decomposition mechanisms.

IV. CONCLUSIONS AND RECOMMENDATIONS

The thermal decomposition characteristics of the three samples studied in this research effort illustrate the enormous variability in thermal stabilities of toxic compounds. Toluene, which was a component of the mixture studied, requires exposure for 2.0 seconds to temperatures approaching 1000°C to achieve 99% destruction in an oxygen starved environment. Cyclophosphamide, on the other hand, cannot even be transported in N_2 at temperatures of less than 200°C without decomposition occurring.

The unifying phenomenon of all three samples studied is the formation of thermally stable, potentially toxic, thermal reaction products which are as difficult or more difficult to destroy than the materials originally transported into the reactor. The most dramatic example of this is the cyclophosphamide and its products. While the parent material is extremely fragile, undecomposed thermal reaction products were still detected at 1000°C in a pyrolytic atmosphere. This emphasizes the need to monitor the destruction of products in addition to the destruction of input materials for safe field-scale thermal destruction of any of these materials.

The oxygen dependence of the thermal decomposition of the samples was investigated in air and nitrogen atmospheres. The use of air and nitrogen for the laboratory studies "brackets" the range of oxygen conditions possible in a field-scale incinerator. In these studies, air provides several thousand times the theoretical stoichiometric oxygen requirement with respect to combustion. Nitrogen, with the trace level of oxygen removed, provides none of the oxygen required for combustion.

The concentration of oxygen in the thermal decomposition atmosphere had a significant impact on the degradation of the samples studied in this effort. In most cases, a change from oxygen starved conditions to excess oxygen conditions shifted the decomposition of the samples to significantly lower temperatures.

Some compounds showed a much greater thermal decomposition dependence on oxygen concentration than others, namely toluene and xylene were highly dependent while methylene chloride was only moderately dependent. This variation in oxygen dependence may appear to somewhat cloud the designation of relative thermal stabilities. As shown in the mixture study, the relative order of thermal stabilities may change depending on the oxygen concentration of the decomposition environment.

In addition, despite a nearly constant level of oxygen in the stack gas of a field-scale unit, it is likely that transients occur in which extreme oxygen conditions exist. Flare-ups may lead to momentary depletion of the oxygen, leading to oxygen-starved conditions. On the other hand, combustion may prevail in areas near air inlets which are rich in oxygen. Clearly, in terms of potential emissions, the oxygen depleted condition is the most serious. In fact, a recently completed comparison of laboratory and field results indicates that laboratory studies under pyrolytic conditions are an effective means of predicting stability of waste feed components in full-scale systems. (Included as Appendix A.)

Increasing the time at temperature experienced by the target substance was also shown to impact the decomposition process. Although only limited data were obtained in this effort, a decrease in the high temperature yield of thermal reaction products was observed with an increase in the time at temperature from 0.5 to 2.0 sec. This is to be expected since thermal decomposition in flowing systems is generally believed to be kinetically controlled.

Based on our laboratory studies, we feel that toluene represents the most stable waste tested and will most seriously challenge the incinerator. However, thermal reaction products present an even more severe challenge. For example, benzonitrile and the other reaction products from cyclophosphamide are the most likely compounds to be emitted during its incineration. Phenylacetylene rivals the thermal stability of toluene and should be monitored during incineration of wastes comparable to the study mixture. Trichloroethylene and the various isomers of dichloroethylene represent the potentially major emissions from methylene chloride incineration.

Quantitative extrapolation of these laboratory data to full-scale systems must be done with great care. Approximately 14 orders of magnitude separate the mass feed rate in our precisely controlled laboratory system from those common in poorly controlled field units. High yield, thermally stable products observed in the laboratory, may be anticipated during full-scale thermal treatment on the same materials, but product yields and emission rates in the field will depend heavily on the range of conditions experienced by the waste feed. A precise quantitative correlation between laboratory-scale product formation and field-scale product formation has not therefore, as of yet, been developed. The development of additional data at intermediate pilot-scale facilities and comparison of lab and field results (as may occur in this study) will lead to increased confidence in quantitative extrapolation of laboratory data to field-scale systems and in the not-to-distant future. A further discussion of the differences in laboratory and full-scale systems and how to best extrapolate laboratory data is given in the appendicies.

Regardless of the difficulty in extrapolating quantitative information from laboratory to field-scale, a number of examples exist in which qualitative predictions of emissions (based on laboratory data), have been successful. A number of these studies have been compiled and are included in Appendix B. The success of laboratory studies in predicting field-scale emissions suggests that laboratory studies are a useful tool in establishing a test burn protocol and monitoring program to assure the greatest margin of safety for operation of the field unit.

APPENDIX B

APPENDIX VIII THERMAL STABILITY INDEX

PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
CYANOGEN {ETHANEDINITRILE}	1
HYDROGEN CYANIDE {HYDROCYANIC ACID}	2
BENZENE [2]	3
SULFUR HEXAFLUORIDE [3]	4
NAPHTHALENE	5
FLUORANTHENE {BENZO[j,k]FLUORENE}	6
BENZO[j]FLUORANTHENE {7,8-BENZOFLUORANTHENE}	7
BENZO[b]FLUORANTHENE {2,3-BENZOFLUORANTHENE}	8
BENZANTHRACENE (1,2-) {BENZ[a]ANTHRACENE}	9
CHRYSENE {1,2-BENZPHENANTHRENE}	10
BENZO[a]PYRENE {1,2-BENZOPYRENE}	11
DIBENZ[a,h]ANTHRACENE {1,2,5,6-DIBENZANTHRACENE}	12
INDENO(1,2,3-cd)PYRENE {1,10-(1,2-PHENYLENE)PYRENE}	13
DIBENZO[a,h]PYRENE {1,2,5,6-DIBENZOPYRENE}	14
DIBENZO[a,i]PYRENE {1,2,7,8-DIBENZOPYRENE}	15
DIBENZO[a,e]PYRENE {1,2,4,5-DIBENZOPYRENE}	16
CYANOGEN CHLORIDE {CHLORINE CYANIDE}	17-18
ACETONITRILE {ETHANENITRILE}	17-18
CHLOROBENZENE	19
ACRYLONITRILE {2-PROPENENITRILE}	20
DICHLOROBENZENE {1,4-DICHLOROBENZENE}	21-22
CHLORONAPHTHALENE (1-)	21-22
CYANOGEN BROMIDE {BROMINE CYANIDE}	23-24
DICHLOROBENZENE {1,2-DICHLOROBENZENE}	23-24
DICHLOROBENZENE {1,3-DICHLOROBENZENE}	25
TRICHLOROBENZENE (1,3,5-TRICHLOROBENZENE) [4]	26-27
TRICHLOROBENZENE (1,2,4-TRICHLOROBENZENE)	26-27
TETRACHLOROBENZENE (1,2,3,5-TETRACHLOROBENZENE) [4]	28
CHLOROMETHANE {METHYL CHLORIDE}	29-30
TETRACHLOROBENZENE (1,2,4,5-TETRACHLOROBENZENE)	29-30
PENTACHLOROBENZENE	31-33
HEXACHLOROBENZENE	31-33
BROMOMETHANE {METHYL BROMIDE}	31-33
TETRACHLORODIBENZO-p-DIOXIN (2,3,7,8-) {TCDD}	34
TOLUENE {METHYLBENZENE}	35
TETRACHLOROETHENE	36
CHLOROANILINE {CHLOROBENZENAMINE}	37
DDE{1,1-DICHLORO-2,2-BIS(4-CHLOROPHENYLETHYLENE}	38
FORMIC ACID {METHANOIC ACID}	39-40

APPENDIX VIII THERMAL STABILITY INDEX

PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
PHOSGENE {CARBONYL CHLORIDE}	39-40
TRICHLOROETHENE	41
DIPHENYLAMINE {N-PHENYLBENZENAMINE}	42-44
DICHLOROETHENE (1,1-)	42-44
FLUOROACETIC ACID	42-44
DIMETHYLBENZ[a]ANTHRACENE (7,12-)	45
ANILINE {BENZENAMINE}	46-50
FORMALDEHYDE {METHYLENE OXIDE}	46-50
MALONONITRILE {PROPANEDINITRILE}	46-50
METHYL CHLOROCARBONATE {CARBONOCHLORIDIC ACID, METHYL ESTER}	46-50
METHYL ISOCYANATE {METHYLCARBYLAMINE}	46-50
AMINOBIPHENYL (4-) {[1,1'-BIPHENYL]-4-AMINE}	51
NAPHTHYLAMINE (1-)	52-53
NAPHTHYLAMINE (2-)	52-53
DICHLOROETHENE (trans-1,2-)	54
FLUOROACETAMIDE (2-)	55-56
PROPYN-1-OL (2-) {PROPARGYL ALCOHOL}	55-56
PHENYLENEDIAMINE (1,4) {BENZENEDIAMINE}	57-59
PHENYLENEDIAMINE (1,2-) {BENZENEDIAMINE}	57-59
PHENYLENEDIAMINE (1,3-) {BENZENEDIAMINE}	57-59
BENZIDINE {[1,1'-BIPHENYL]-4,4'DIAMINE}	60-64
ACRYLAMIDE {2-PROPENAMIDE}	60-64
DIMETHYLPHENETHYLAMINE (alpha, alpha-)	60-64
METHYL METHACRYLATE {2-PROPENOIC ACID, 2-METHYL-,METHYL ESTER}	60-64
VINYL CHLORIDE (CHLOROETHENE)	60-64
DICHLOROMETHANE {METHYLENE CHLORIDE}	65-66
METHACRYLONITRILE {2-METHYL-2-PROPENENITRILE}	65-66
DICHLOROBENZIDINE (3,3'-)	67
METHYLCHOLANTHRENE (3-)	68
TOLUENEDIAMINE (2,6-) {DIAMINOTOLUENE}	69-77
TOLUENEDIAMINE (1,4-) {DIAMINOTOLUENE}	69-77
TOLUENEDIAMINE (2,4-) {DIAMINOTOLUENE}	69-77
TOLUENEDIAMINE (1,3-) {DIAMINOTOLUENE}	69-77
TOLUENEDIAMINE (3,5-) {DIAMINOTOLUENE}	69-77
TOLUENEDIAMINE (3,4-) {DIAMINOTOLUENE}	69-77
CHLORO-1,3-BUTADIENE (2-) {CHLOROPRENE}	69-77
PRONAMIDE {3,5-DICHLORO-N-[1,1-DIMETHYL-2-PROPYNYL] BENZAMIDE}	69-77
ACETYLAMINOFLUORENE (2-) {ACETAMIDE,N-[9H-FLUOREN-2-YL]-}	69-77
DIMETHYLBENZIDINE (3,3'-)	78

APPENDIX VIII THERMAL STABILITY INDEX

PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
n-PROPYLAMINE (1-PROPANAMINE)	79
PYRIDINE	80
PICOLINE (2-) (PYRIDINE,2-METHYL-)	81-84
DICHLOROPROPENE (1,1-)	81-84
THIOACETAMIDE (ETHANETHIOAMIDE)	81-84
TRICHLORO(1,2,2-)TRIFLUOROETHANE(1,1,2-) (FREON 113) [4]	81-84
BENZ[c]ACRIDINE (3,4-BENZACRIDINE)	85-88
DICHLORODIFLUOROMETHANE (FREON 12)	85-88
ACETOPHENONE (ETHANONE,1-PHENYL-)	85-88
TRICHLOROFLUOROMETHANE (FREON 11)	85-88
DICHLOROPROPENE (trans-1,2-)	89-91
ETHYL CYANIDE (PROPIONITRILE)	89-91
BENZOQUINONE (1,4-CYCLOHEXADIENEDIONE)	89-91
DIBENZ[a,h]ACRIDINE (1,2,5,6-DIBENZACRIDINE)	92-97
DIBENZ[a,j]ACRIDINE (1,2,7,8-DIBENZACRIDINE)	92-97
HEXACHLOROBUTADIENE (trans-1,3)	92-97
NAPHTHOQUINONE (1,4-) (1,4-NAPHTHALENEDIONE)	92-97
DIMETHYL PHTHALATE	92-97
ACETYL CHLORIDE (ETHANOYL CHLORIDE)	92-97
ACETONYLBENZYL-4-HYDROXYCOUMARIN (3-alpha-) (WARFARIN)	98-99
MALEIC ANHYDRIDE (2,5-FURANDIONE)	98-99
PHENOL (HYDROXYBENZENE)	100-101
DIBENZO[c,g]CARBAZOLE (7H-) (3,4,5,6-DIBENZCARBAZOLE)	100-101
CHLOROPHENOL (2-)	102
CRESOL (1,3-) (METHYLPHENOL)	103
CRESOL (1,4-) (METHYLPHENOL)	104-105
CRESOL (1,2-) (METHYLPHENOL)	104-105
ACROLEIN (2-PROPENAL)	106-107
DIHYDROXY-ALPHA-[METHYLAMINO]METHYL BENZYL ALCOHOL (3,4-)	106-107
METHYL ETHYL KETONE (2-BUTANONE)	108-109
DIETHYLSTILBESTEROL	108-109
BENZENETHIOL (THIOPHENOL)	110
RESORCINOL (1,3-BENZENEDIOL)	111
ISOBUTYL ALCOHOL (2-METHYL-1-PROPANOL)	112
CROTONALDEHYDE (2-BUTENAL)	113-115
DICHLOROPHENOL (2,4-)	113-115
DICHLOROPHENOL (2,6-)	113-115
METHYLACTONITRILE (2-) (PROPANENITRILE,2-HYDROXY-2-METHYL)	116-118
ALLYL ALCOHOL (2-PROPEN-1-OL)	116-118

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PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
CHLOROCRESOL (4-CHLORO-3-METHYLPHENOL)	116-118
DIMETHYLPHENOL (2,4-)	119
CHLOROPROPENE (3-) (ALLYL CHLORIDE)	120
DICHLOROPROPENE (cis-1,3-)	121-125
DICHLOROPROPENE (trans-1,3-)	121-125
TETRACHLOROETHANE (1,1,2,2-)	121-125
TRICHLOROPHENOL (2,4,5-)	121-125
TRICHLOROPHENOL (2,4,6-)	121-125
CHLOROETHANE (ETHYL CHLORIDE) [4] [5]	126
DICHLOROPROPENE (2,3-)	127-130
HYDRAZINE (DIAMINE)	127-130
BENZYL CHLORIDE (CHLOROMETHYLBENZENE)	127-130
DIBROMOMETHANE (METHYLENE BROMIDE)	127-130
DICHLOROETHANE (1,2-)	131
MUSTARD GAS (bis[2-CHLOROETHYL]-SULFIDE)	132-134
NITROGEN MUSTARD	132-134
N,N-BIS(2-CHLOROETHYL)2-NAPHTHYLAMINE (CHLORNAPHAZINE)	132-134
DICHLOROPROPENE (3,3-)	135
DICHLORO-2-BUTENE (1,4-)	136-140
TETRACHLOROPHENOL (2,3,4,6-)	136-140
TETRACHLOROMETHANE (CARBONTETRACHLORIDE)	136-140
BROMOACETONE (1-BROMO-2-PROPANONE)	136-140
HEXACHLOROPHENE (2,2'-METHYLENEbis[3,4,6-TRICHLOROPHENOL])	136-140
DIOXANE (1,4-) (1,4-DIETHYLENE OXIDE)	141
CHLORAMBUCIL	142
NITROBENZENE	143-144
CHLOROPROPIONITRILE (3-) (3-CHLOROPROPANENITRILE)	143-144
DICHLORO-2-PROPANOL (1,1-)	145-146
DDD (DICHLORODIPHENYLDICHLOROETHANE)	145-146
DICHLORO-2-PROPANOL (1,3-)	147
PHTHALIC ANHYDRIDE (1,2-BENZENEDICARBOXYLIC ACID ANHYDRIDE)	148-150
METHYL PARATHION	148-150
NITROPHENOL (4-)	148-150
CHLORODIFLUOROMETHANE (FREON 22) [4]	151-153
PENTACHLOROPHENOL	151-153
HEXACHLOROCYCLOHEXANE (LINDANE)	151-153
DICHLOROFLUOROMETHANE (FREON 21) [4]	154-157
DINITROBENZENE (1,3-)	154-157
NITROANILINE (4-NITROBENZENAMINE)	154-157

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PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
PENTACHLOROETHANE	154-157
DINITROBENZENE (1,4-)	158-161
DINITROBENZENE (1,2-)	158-161
TRICHLOROETHANE (1,1,2-)	158-161
TRICHLOROMETHANE (CHLOROFORM)	158-161
ISODRIN	162-164
DIELDRIN	162-164
ALDRIN	162-164
DICHLOROPROPANE (1,3-)	165
NITROTOLUIDINE (5-) (BENZENAMINE,2-METHYL-5-NITRO-)	166-167
CHLOROACETALDEHYDE	166-167
TRICHLOROPROPANE (1,2,3-)	168-173
DINITROTOLUENE (2,4-)	168-173
DINITROTOLUENE (2,6-)	168-173
HEXACHLOROCYCLOPENTADIENE	168-173
BENZAL CHLORIDE (ALPHA,ALPHA-DICHLOROTOLUENE)	168-173
DICHLORO-1-PROPANOL (2,3-)	168-173
ETHYLENE OXIDE (OXIRANE)	174
DICHLOROETHANE (1,1-) (ETHYLIDENE DICHLORIDE)	175-178
DIMETHYLCARBAMOYLCHLORIDE	175-178
GLYCIDYALDEHYDE (1-PROPANOL-2,3-EPOXY)	175-178
DDT (DICHLORODIPHENYLTRICHLOROETHANE)	175-178
DICHLOROPROPANE (1,2-) (PROPYLENE DICHLORIDE)	179
AURAMINE	180-181
HEPTACHLOR	180-181
DICHLOROPROPANE (1,1-)	182
CHLORO-2,3-EPOXYPROPANE (1-) (OXIRANE,2-CHLOROMETHYL-)	183-186
DINITROPHENOL (2,4-)	183-186
bis(2-CHLOROETHYL)ETHER	183-186
TRINITROBENZENE (1,3,5-TRINITROBENZENE)	183-186
BUTYL-4,6-DINITROPHENOL (2-sec-) (DNBP)	187-188
CYCLOHEXYL-4,6-DINITROPHENOL (2-)	187-188
bis(2-CHLOROETHOXY)METHANE	189-192
CHLORAL (TRICHLOROACETALDEHYDE)	189-192
TRICHLOROMETHANETHIOL	189-192
DINITROCRESOL (4,6-) (PHENOL,2,4-DINITRO-6-METHYL-)	189-192
HEPTACHLOR EPOXIDE	193
DIEPOXYBUTANE (1,2,3,4-) (2,2'-BIOXIRANE)	194
BENZOTRICHLORIDE (TRICHLOROMETHYLBENZENE)	195-196

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PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
METHAPYRILENE	195-196
PHENACETIN {N-[4-ETHOXYPHENYL]ACETAMIDE}	197-198
METHYL HYDRAZINE	197-198
DIBROMOETHANE (1,2-) {ETHYLENE DIBROMIDE}	199
AFLATOXINS	200
TRICHLOROETHANE (1,1,1-) {METHYL CHLOROFORM}	201
HEXACHLOROETHANE	202-203
BROMOFORM {TRIBROMOMETHANE}	202-203
CHLOROBENZILATE	204-207
ETHYL CARBAMATE {URETHAN} {CARBAMIC ACID, ETHYL ESTER}	204-207
ETHYL METHACRYLATE {2-PROPENOIC ACID, 2-METHYL-, ETHYL ESTER}	204-207
LASIOCARPINE	204-207
AMITROLE {1H-1,2,4-TRIAZOL-3-AMINE}	208-209
MUSCIMOL {5-AMINOMETHYL-3-ISOAZOTOL}	208-209
IODOMETHANE {METHYL IODIDE}	210
DICHLOROPHENOXYACETIC ACID (2,4-) {2,4-D}	211-213
CHLOROETHYLVINYLETHER (2-) {ETHENE, [2-CHLOROETHOXY]-}	211-213
METHYLENE BIS(2-CHLOROANILINE) (4,4-)	211-213
DIBROMO-3-CHLOROPROPANE (1,2-)	214
TETRACHLOROETHANE (1,1,1,2-)	215
DIMETHYLHYDRAZINE (1,1-)	216-217
N,N-DIETHYLHYDRAZINE {1,2-DIETHYLHYDRAZINE}	216-217
CHLOROMETHYLMETHYL ETHER {CHLOROMETHOXYMETHANE}	218-220
DIMETHYL-1-METHYLTHIO-2-BUTANONE,O-[(METHYLAMINO)-CARBONYL] OXIME (3,3-) {THIOFANOX}	218-220
DIMETHYLHYDRAZINE (1,2-)	218-220
CHLORDANE (ALPHA AND GAMMA ISOMERS)	221
bis(CHLOROMETHYL)ETHER {METHANE-OXYbis[2-CHLORO-]}	222-223
PARATHION	222-223
DICHLOROPROPANE (2,2-)	224
MALEIC HYDRAZIDE {1,2-DIHYDRO-3,6-PYRIDAZINEDIONE}	225
BROMOPHENYL PHENYL ETHER (4-) {BENZENE,1-BROMO-4-PHENOXY-}	226
bis(2-CHLOROISOPROPYL)ETHER	227-228
DIHYDROSAFROLE {1,2-METHYLENEDIOXY-4-PROPYLBENZENE}	227-228
METHYL METHANESULFONATE {METHANESULFONIC ACID, METHYL ESTER}	229
PROPANE SULFONE (1,3-) {1,2-OXATHIOLANE,2,2-DIOXIDE}	230
SACCHARIN {1,2-BENZOISOTHIAZOLIN-3-ONE,1,1-DIOXIDE}	231
METHYL-2-METHYLTHIO-PROPIONALDEHYDE-O-(METHYLCARBONYL)OXIME (2-)	232-233
METHYOMYL	232-233

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PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	RANK
HEXACHLOROPROPENE	234
PENTACHLORONITROBENZENE (PCNB)	235-239
DIALLATE (S-(2,3-DICHLOROALLYL)DIISOPROPYL THIOCARBAMATE)	235-239
ETHYLENEIMINE (AZIRIDINE)	235-239
ARAMITE	235-239
DIMETHOATE	235-239
TRICHLOROPHENOXYACETIC ACID (2,4,5-) (2,4,5-T)	240-241
TRICHLOROPHENOXYPROPIONIC ACID (2,4,5-) (2,4,5-TP) (SILVEX)	240-241
tris(2,3-DIBROMOPROPYL)PHOSPHATE	242
METHYLAZIRIDINE (2-) (1,2-PROPYLENIMINE)	243-244
METHOXYCHLOR	243-244
BRUCINE (STRYCHNIDIN-10-ONE,2,3-DIMETHOXY-)	245-246
KEPONE	245-246
ISOSAFROLE (1,2-METHYLENEDIOXY-4-ALLYLBENZENE)	247-249
SAFROLE (1,2-METHYLENE-4-ALLYLBENZENE)	247-249
tris(1-AZRIDINYL) PHOSPHINE SULFIDE	247-249
DIMETHOXYBENZIDINE (3,3'-)	250
DIPHENYLHYDRAZINE (1,2-)	251
O,O-DIETHYLPHOSPHORIC ACID, O-p-NITROPHENYL ESTER	252
n-BUTYLBENZYL PHTHALATE	253
O,O-DIETHYL-O-2-PYRAZINYL PHOSPHOROTHIOATE	254
DIMETHYLAMINOAZOBENZENE	255
DIETHYL PHTHALATE	256-257
O,O-DIETHYL-S-METHYL ESTER OF PHOSPHORIC ACID	256-257
O,O-DIETHYL S-[(ETHYLTHIO)METHYL]ESTER OF PHOSPHORODITHIOIC ACID	258-259
CITRUS RED No. 2 (2-NAPHTHOL,1-[(2,5-DIMETHOXYPHENYL)AZO])	258-259
TRYPAN BLUE	260
ETHYL METHANESULFONATE (METHANESULFONIC ACID, ETHYL ESTER)	261-265
DISULFOTON	261-265
DIISOPROPYLFLUOROPHOSPHATE (DFP)	261-265
O,O,O-TRIETHYL PHOSPHOROTHIOATE	261-265
Di-n-BUTYL PHTHALATE	261-265
PARALDEHYDE (2,4,6-TRIMETHYL-1,3,5-TRIOXANE)	266
Di-n-OCTYL PHTHALATE	267
OCTAMETHYLPYROPHOSPHORAMIDE (OCTAMETHYLDIPHOSPHORAMIDE)	268
bis(2-ETHYLHEXYL)PHTHALATE	269-270
METHYLTHIOURACIL	269-270
PROPYLTHIOURACIL	271
STRYCHNINE (STRYCHNIDIN-10-ONE)	272

APPENDIX VIII THERMAL STABILITY INDEX

PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	**RANK**
CYCLOPHOSPHAMIDE	273-276
NICOTINE {(S)-3-[1-METHYL-2-PYRROLIDINYL]PYRIDINE}	273-276
RESERPINE	273-276
TOLUIDINE HYDROCHLORIDE {2-METHYL-BENZENAMINE HYDROCHLORIDE}	273-276
TOLYLENE DIISOCYANATE {1,3-DIISOCYANATOMETHYLBENZENE}	277
ENDRIN	278
BUTANONE PEROXIDE (2-) {METHYL ETHYL KETONE, PEROXIDE}	279
TETRAETHYLPYROPHOSPHATE	280
NITROGLYCERINE [{TRINITRATE-1,2,3-PROPANETRIOL}	281
TETRAETHYLDITHIOPYROPHOSPHATE	282
ETHYLENEbisDITHIOCARBAMIC ACID	283
TETRANITROMETHANE	284
URACIL MUSTARD {5-[bis(2-CHLOROETHYL)AMINO]URACIL}	285
ACETYL-2-THIOUREA (1-) {ACETAMIDE,N-[AMINOTHIOXOMETHYL]-}	286-290
CHLOROPHENYL THIOUREA (1-) {THIOUREA,[2-CHLOROPHENYL]-}	286-290
N-PHENYLTHIOUREA	286-290
NAPHTHYL-2-THIOUREA (1-) {THIOUREA,1-NAPHTHALENYL-}	286-290
THIOUREA {THIOCARBAMIDE}	286-290
DAUNOMYCIN	291-292
ETHYLENE THIOUREA {2-IMIDAZOLIDINETHIONE}	291-292
THIOSEMICARBAZIDE {HYDRAZINECARBOTHIOAMIDE}	293-294
MELPHALAN {ALANINE,3-[p-bis(2-CHLOROETHYL)AMINO] PHENYL-,L-}	293-294
DITHIOBIURET (2,4-) {THIOIMIDODICARBONIC DIAMIDE}	295-296
THIURAM {bis[DIMETHYLTHIOCARBAMOYL]DISULFIDE}	295-296
AZASERINE {L-SERINE,DIAZOACETATE [ESTER]}	297
HEXAETHYL TETRAPHOSPHATE	298
NITROGEN MUSTARD N-OXIDE	299-300
NITROQUINOLINE-1-OXIDE (4-)	299-300
CYCASIN {beta-D-GLUCOPYRANOSIDE, [METHYL-ONN-AZOXY]METHYL-}	301
STREPTOZOTOCIN	302
N-METHYL-N'-NITRO-N-NITROSOGUANIDINE	303-318
N-NITROSO-DI-ETHANOLAMINE {[2,2'-NITROSOIMINO]bisETHANOL}	303-318
N-NITROSO-DI-N-BUTYLAMINE {N-BUTYL-N-NITROSO-1-BUTANAMINE}	303-318
N-NITROSO-N-ETHYLUREA {N-ETHYL-N-NITROSOCARBAMIDE}	303-318
N-NITROSO-N-METHYLUREA {N-METHYL-N-NITROSOCARBAMIDE}	303-318
N-NITROSO-N-METHYLURETHANE	303-318
N-NITROSODIETHYLAMINE {N-ETHYL-N-NITROSOETHANAMINE}	303-318
N-NITROSODIMETHYLAMINE {DIMETHYLNITROSAMINE}	303-318
N-NITROSOMETHYLETHYLAMINE {N-METHYL-N-NITROSOETHANAMINE}	303-318

APPENDIX VIII THERMAL STABILITY INDEX

PRINCIPAL ORGANIC HAZARDOUS CONSTITUENT	RANK
N-NITROSOMETHYLVINYLAMINE (N-METHYL-N-NITROSOETHENAMINE)	303-318
N-NITROSOMORPHOLINE	303-318
N-NITROSONORNICOTINE	303-318
N-NITROSOPIPERIDINE (HEXAHYDRO-N-NITROSOPYRIDINE)	303-318
N-NITROSOSARCOSINE	303-318
NITROSOPYRROLIDINE (N-NITROSOTETRAHYDROPYRROLE)	303-318
DI-n-PROPYLNITROSAMINE (N-NITROSO-DI-n-PROPYLAMINE)	303-318
OXABICYCLO[2.2.1]HEPTANE-2,3-DICARBOXYLIC ACID (7-) (ENDOTHAL)	319
ENDOSULFAN	320

FOOTNOTES:

1. UNITS OF TEMPERATURE ARE DEGREES CELSIUS.
2. BOLDFACE PRINT INDICATES THERMAL STABILITY IS 'EXPERIMENTALLY EVALUATED;' RANKING BASED ON UDRI EXPERIMENTAL DATA COUPLED WITH REACTION KINETIC THEORY.
3. NON-APPENDIX VIII COMPOUND.
4. N.O.S. LISTING; RANKING BASED ON EITHER UDRI OR LITERATURE EXPERIMENTAL DATA COUPLED WITH REACTION KINETIC THEORY.
5. ITALICIZED PRINT INDICATES COMPOUND THERMAL STABILITY IS RANKED BASED ON LITERATURE EXPERIMENTAL DATA COUPLED WITH REACTION KINETIC THEORY

APPENDIX C

TABLE 3

THERMAL STABILITY INDICES FOR EXPERIMENTALLY EVALUATED COMPOUNDS

HAZARDOUS ORGANIC COMPOUND	$T_{99}(2)$(°C)
Hydrogen Cyanide	>> 1100
Benzene	1150
Naphthalene	1070
Acetonitrile	1000
Chlorobenzene	990
Acrylonitrile	985
Chloronaphthalene	975
1,2-Dichlorobenzene	970
1,3-Dichlorobenzene	960
1,2,4-Trichlorobenzene	955
1,3,5-Trichlorobenzene	955
1,2,3,5-Tetrachlorobenzene	955
1,2,4,5-Tetrachlorobenzene	950
Chloromethane	950
Bromomethane	935
Pentachlorobenzene	935
Hexachlorobenzene	935
Toluene	895
Tetrachloroethene	890
Trichloroethene	865
1,1-Dichloroethene	860
1,2-Dichloroethene	835
Dichloro methane	815
Methacrylonitrile	815
Pyridine	785
1,1-Dichloropropene	780
1,2,2-Trichloro-1,1,2-Trifluoroethane	780
Dichlorodifluoromethane	775
Acetophenone	775
Trichlorofluoromethane	775
Ethyl Cyanide	770
Hexachlorobutadiene	765
Dimethyl phthalate	765

TABLE 3 (CONT.)

HAZARDOUS ORGANIC COMPOUND	$T_{99}(2)$(°C)
Acetyl Chloride	765
p-Cresol	745
Methyl Ethyl Ketone	730
Benzenethiol	725
Isobutyl Alcohol	715
Crotonaldehyde	710
3-Chloropropene	695
1,1,2,2-Tetrachloroethane	690
Benzyl Chloride	685
Dibromomethane	685
1,2-Dichloroethane	680
1,4-Dioxane	660
Nitrobenzene	655
3-Chloropropionitrile	655
Tetrachloromethane	645
Chlorodifluoromethane	645
Hexachlorocyclohexane	645
Dichlorofluoromethane	640
Pentachloroethane	640
Trichloromethane	635
1,1,2-Trichloroethane	635
1,2,3-Trichloropropane	625
Benzal Chloride	625
bis-(2-Chloroethyl)ether	615
1,1-Dichloroethane	610
Tribromomethane	585
Hexachloroethane	580
2-Chloroethylvinylether	565
1,1,1,2-Tetrachloroethane	560
1,1,1-Trichloroethane	545
Hexachloropropene	505
n-Butyl Benzyl Phthalate	415
Di-n-Octyl Phthalate	380

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