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AN EXPERIMENTAL PROCESS FOR DESTRUCTION OF HAZARDOUS WASTES USING SOLAR ENERGY

Phase I: Final Technical Report

December 1984

Work Performed Under Contract No. AC03-83SF11945

Babcock & Wilcox
A McDermott Company
Barberton, Ohio

Technical Information Center
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AN EXPERIMENTAL PROCESS FOR DESTRUCTION OF HAZARDOUS WASTES USING SOLAR ENERGY

FINAL TECHNICAL REPORT: PHASE I

REPORT NUMBER: BWPCB 1

DECEMBER 1984

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Prepared by:

BABCOCK & WILCOX
A McDermott Company
Nuclear Equipment Division
Barberton, Ohio 44203
NED Contract No. 894-0021-45

Submitted By:

BABCOCK & WILCOX
A McDermott Company
Contract Research Division
Barberton, Ohio 44203
CRD Contract No. 1118

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1.0 Abstract

Millions of tons of hazardous wastes are produced each year in the United States. Of these wastes, some are recycled or destroyed, while others are stored for subsequent disposal. The stored wastes are a hazard due to their potential for discharge into the environment. For many toxic organic wastes, detoxification using solar energy is a viable means for eliminating the environmental risks. In addition, it offers the potential for being more efficient and cost effective than the currently preferred method of disposal, incineration using fossil fuels.

This Phase I program provides an approach to the destruction of hazardous industrial wastes using solar energy. The approach makes use of both the photoreduction energy and thermal aspects of solar energy to destroy highly toxic hazardous wastes. This ultraviolet (UV) light energy is available in addition to the thermal energy in the detoxification process. The Phase I program has established poly-chlorinated biphenyls (PCB's) as the candidate material for the detoxification process due to their highly toxic nature and the large quantities which require disposal. The chlorine-carbon bonds that exist is PCBs are susceptible to photolytic reduction from intense solar flux in the UV range.

During Phase I, the feasibility of the concept was verified through an extensive literature search on photochemical effects. This search identified that the combined aspects of concentrated solar energy, photoreduction and thermal, could supply the required detoxification. Solar test facilities were also evaluated during this phase. In addition, candidate test materials were determined for a test burn using a photolytic detoxifier concept also established during Phase I.

For the Phase I workscope the Babcock & Wilcox Company assembled a team including Veda, Inc. and Woodward-Clyde Consultants. This team provided the project with a broad and diverse experience base in hazardous waste destruction, chemical and environmental engineering, optical analysis, and design and fabrication of solar thermal plant components and systems.

2.0 Program Summary

2.1 Objectives of Study

The objectives of the Phase I effort are:

- To design a device using concentrated, direct solar energy for the detoxification of hazardous wastes.
- To develop a program plan which includes the construction, installation, operation and evaluation of the test device at a solar facility.

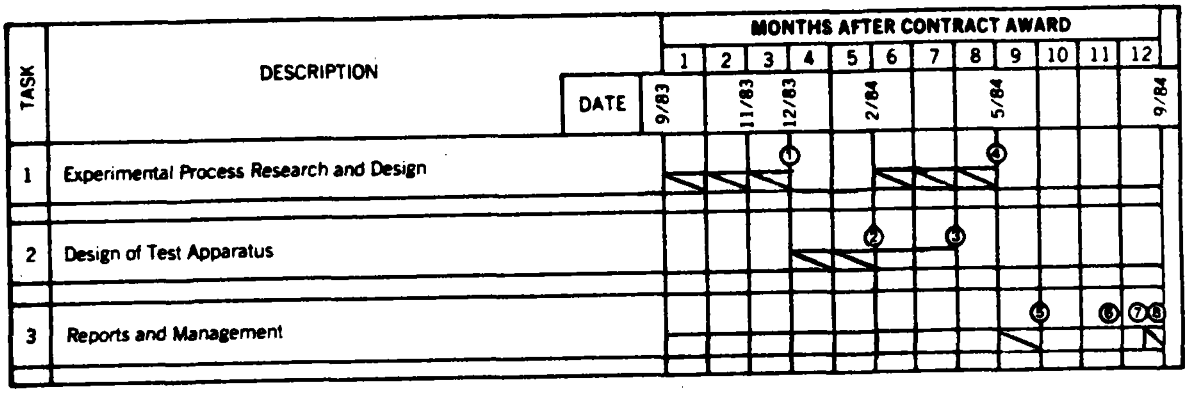
Specifically, this phase consists of the following work:

- Selection of candidate test burn material.
- Selection of solar test facility.
- Prediction of exhaust gas composition from detoxifying process.
- Design of a scale detoxifier system and detoxifier component.
- Establishment of test plans and requirements.

Also included in the Phase I effort is a literature search on the photochemical ultraviolet (UV) light effects on the detoxification process. The development of the program plan resulted in restructuring the program into four phases with Phase II being an added laboratory test prior to a solar facility test.

The three specific tasks and milestones associated with Phase I are identified in Figure 2-1. It is noted that Figure 2-1 is the original schedule as presented in the Phase I proposal. It does not reflect the actual required submittal date of May 30, 1984, for the Phase II Proposal - Milestone 6.

FIGURE 2-1 PHASE I SCHEDULE AND MILESTONES



MILESTONES

1. Chemical Process Design Complete
    a. W-C determine Candidate PCB's
    b. W-C provide optical properties to VEDA
    c. VEDA complete evaluation of test facilities
2. Solar reactor design complete
3. Arrangement drawings and cost estimate complete
4. Test plans complete
5. Summary report submitted
6. Phase 2 proposal complete
7. DOE review of summary report complete
8. Final report released

2.2 Technical Approach

Under Task 1, Experimental Process Research and Design, the definition of the reaction chemistry, which includes the selection of the candidate toxic materials for a future test burn, was established. Polychlorinated biphenyls (PCBs) and PCB-related substances in the form of a liquid or sticky resin have been selected as the candidate materials for the test burn. They were selected based on their prevalence in a wide range of industrial and commercial applications, the problems in characterizing both the compounds and the resulting detoxification effluents, and the difficulty in ensuring the complete detoxification of the material. Calculations of reaction chemistry were completed for several toxic compounds. The reaction chemistry studies determined the reaction temperatures, heats of release, and composition of the effluent for various air/waste mixtures for the following compounds: biphenyl, the non-chlorinated backbone of all PCBs; trichlorobenzene, a compound often found associated with PCBs in some applications; hexachlorobenzene, one of the most refractory of the combustion products from thermal incineration of PCB materials; the individual ten PCB isomers; and twelve commercial PCB mixtures (Aroclors) each containing from four to six of the individual isomers. Of these, eight candidate test burn materials were selected. They consist of trichlorobenzene, hexachlorobenzene and six Aroclor mixtures (1221, 1232, 1242, 1258, 1254, and 1260) . These particular Aroclors were selected based on their prevalence in industry. In addition, destruction data using only thermal energy is available for these materials based on the University of Dayton Research Institute (UDRI) development work. Therefore, a benchmark already exists for determining the photolytic destruction potential from solar energy.

An exhaustive literature search conducted during Task 1 provided valuable information concerning the mechanism of degradation of PCB-related materials, especially the photolytic effects of sunlight. It was confirmed that sunlight does produce photolytic reduction of toxic organic compounds. However, the data reported was for natural sunlight (no concentration), ambient temperatures, and several hours of exposure time. It was these findings that emphasized the need for a proof-of-principle experiment using high temperatures, residence times of 1-2 seconds, and concentrated solar flux. Thus the Phase II effort was structured to develop this data. The information resulting from the literature survey is presented in Appendix H.

During the course of the literature survey, familiarity was gained with the work of the University of Dayton Research Institute (UDRI). Through sophisticated laboratory experiments, they have fully characterized the thermal degradation properties of PCBs. This fundamental research is the basis for guidelines issued by the Environmental Protection Agency for incineration of PCBs. Therefore, UDRI has been included as a team member for Phase II due to their vast experience and current expertise in this field.

Also during Task 1, an in-depth investigation of solar collection/concentration facilities in the United States was conducted. The two primary candidates were the solar furnace at the Central Receiver Test Facility (CRTF) near Albuquerque, New Mexico, and the White Sands Solar Facility (WSSF) located on the White Sands Missile Range, New Mexico. Both sites offer adequate thermal power and peripheral facilities to conduct the planned prototype testing. However, the solar furnace at the Central Receiver Test Facility (CRTF) is currently equipped with second surface mirrors where most of the available ultraviolet radiation is absorbed by the protective glass. Since the need for UV radiation is a key element of the test program, the White Sands Solar Facility was selected as the test site due to their use of first surface reflectors which do not significantly degrade the UV portion of the solar spectrum. Appendix C provides the test selection evaluation.

A preliminary test plan was also prepared under Task 1 workscope. This test plan provides the preliminary test parameters for the proposed Phase II laboratory test. In addition, a generalized testing approach for a future site test using the photolytic detoxifier is also presented in the document. The plan defines the testing parameters required to quantify the destruction efficiency (DE) of the waste stream. The waste stream will be tested with variations to temperature, light intensity and residence time. The test results will be monitored by gas chromatographic/mass spectrometric (GC/MS) analysis. The test plan is presented in Appendix F.

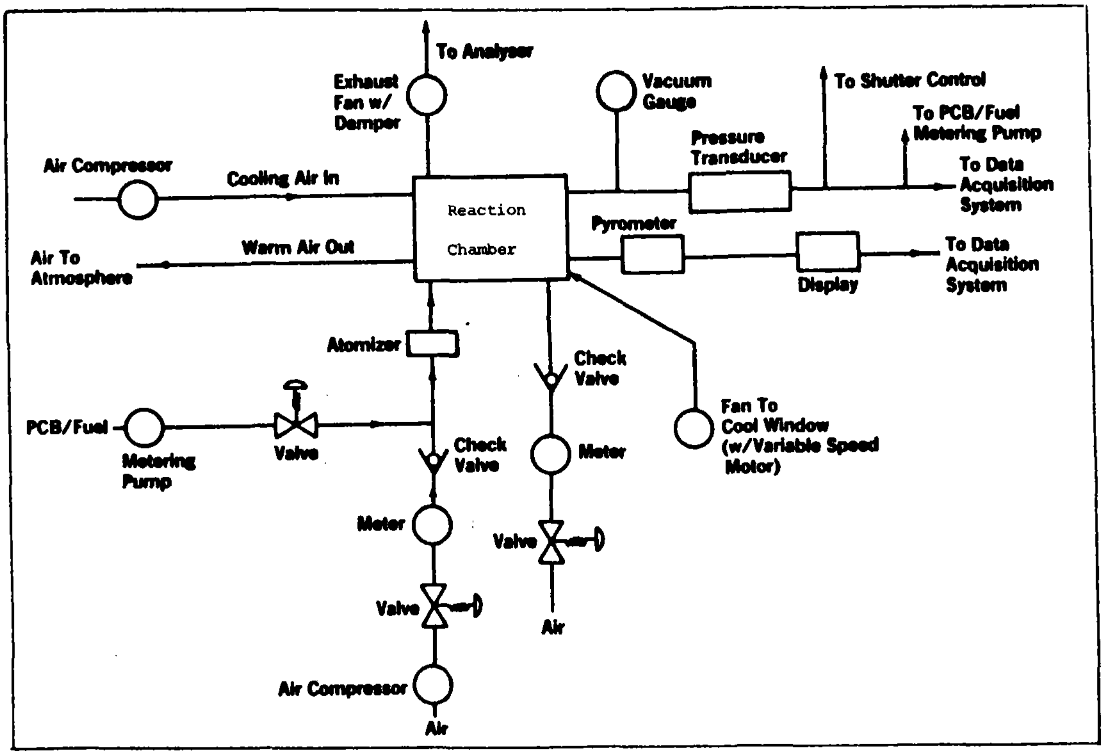
Preliminary designs of the prototype detoxification system and the detoxifier component have been completed. This comprises the majority of the Phase I - Task 2 effort.

Before the design of the detoxifier could begin, design requirements were established and are listed below.

- The detoxification chamber material must provide mechanical strength and corrosion resistance at temperatures up to 2500°F (1370°C).
- The aperture window material must allow high transmittance of both UV and infrared (IR) radiation.
- The product flow through the detoxification chamber must permit controlled exposure to incoming radiation.
- The residence time in the detoxifier must be sufficient to ensure complete destruction of the toxic compounds.
- Means must be provided for collection and analysis of the detoxifier effluent.
- The detoxifier overall size and weight must be compatible with the solar test facility.
- The detoxifier optics must be compatible with the flux distribution of the solar test facility.

The prototype detoxifier test system schematic is shown in Figure 2-2. The system incorporates controls and safeguards necessary for a successful field test of the solar detoxifier.

FIGURE 2-2 PROTOTYPE TEST SYSTEM SCHEMATIC



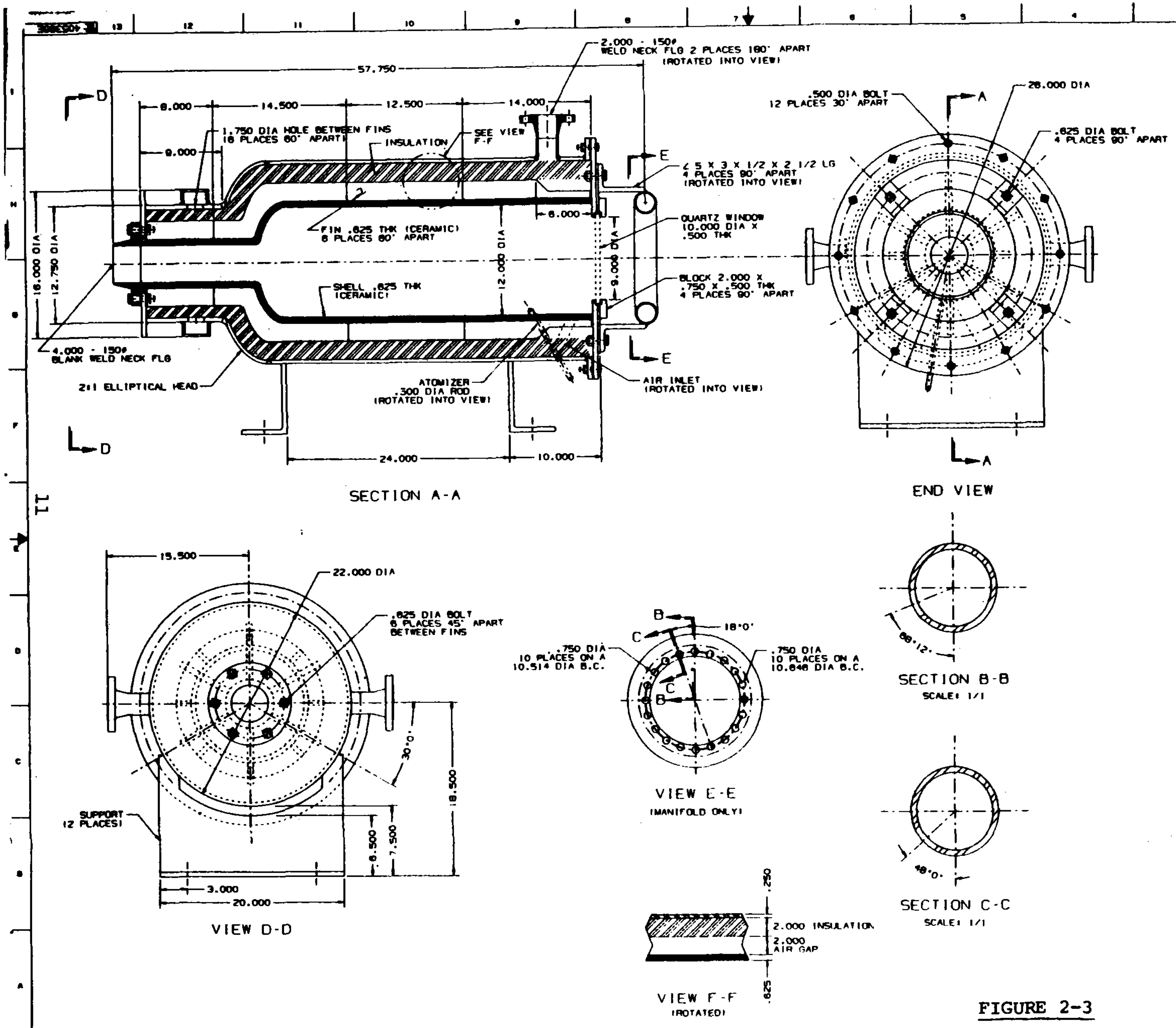
Several detoxifier designs were conceptualized using the design criteria as guidelines. Early designs utilized conventional furnace concepts and were found to be too bulky and heavy. A novel design, incorporating a round, four-piece reaction chamber liner, offered the advantages of compactness, weight reduction, and ease of assembly. After several rounds of refinements, the preliminary detoxifier design was completed. The details of this evaluation is provided in Appendix D. A general arrangement drawing of the unit is shown in Figure 2-3. The detoxification reaction is contained within a 12.0 in. I.D. ceramic cavity approximately 3.0 ft. in length. The toxic waste and air are injected into the cavity by an atomizer located near the front of the unit. Auxiliary air is introduced into the chamber from a slot beneath the aperture window. The auxiliary air creates an air curtain that shields the window from soot and other potentially undesirable reaction products. The exhaust pipe and ceramic liner are actively cooled by a flow of air which enters the rear of the unit and exits through a vent near the window. Cooling of the liner is enhanced by six integral, external fins which also serve to position the chamber within the containment vessel.

Using the findings from the literature survey along with a knowledge of the potential by products of the destruction process, and the high temperature involved, fused quartz was chosen for the detoxifier aperture window. Of the wide variety of window materials examined, including quartz, sapphire, aluminum oxide, and magnesium-aluminum spinel, the fused quartz was selected because of its excellent UV transmission characteristics, its ability to tolerate a high temperature environment, and its immunity to chemical attack. Discussion with Energy and Materials researchers at the Georgia Institute of Technology confirmed that fused quartz was the best material for the proposed application.

Before embarking on the final design of the prototype field test component, further data is necessary on the effect of concentrated UV radiation on the detoxification reaction. The work proposed for Phase II and to be done at the University of Dayton Research Institute will provide quantitative design data required to refine the design to the point where a high degree of success is anticipated.

Also included in Task 2 is a budgetary cost estimate for the future testing of the photolytic detoxifier at the solar test site. Fabrication and test site costs have been estimated to be approximately $120,000. The basis for this cost estimate is provided in Appendix G.

The Task 3 effort consists of Babcock & Wilcox managment planning and control of the program. Also included is appropriate reporting documents, including monthly reports and a final report.



NOTES

1. PIPE: 22" SCH 10 , 2 1/4 Cr-1 Mo SPEC SA-335 GR P22.
2. CERAMIC: SILICON CARBIDE.
3. INSULATION: SAFFIL ALUMINA BLANKET
4. GASKET: KAOWOOL CERAMIC FIBER (PAPER FORM. 120/1000 AND 250/1000.
5. ALL OTHER STEEL AND BOLTS (EXCEPT ATOMIZER) 2 1/4 Cr STEEL.
6. ATOMIZER: 310 STAINLESS STEEL.

FIGURE 2-3

CONTRACT NO.
884-0021-45

PHOTOLYTIC
DETOXIFIER
FOR
HAZARDOUS
WASTE

1/4
405388E
0

2.3 Organization

The Babcock & Wilcox Company has assembled a team, as shown in Figure 2-4, which includes Veda, Inc. and Woodward-Clyde Consultants. This team brings to the program broad and diverse experience in design of solar thermal plant components and systems, optical analysis, chemical and environmental engineering, and mechanical design and construction. The specific responsibilities of each team member are summarized in the following paragraphs and identified in Figure 2-4.

Babcock & Wilcox

The Babcock & Wilcox Company accepts contracts for research and development through the Contract Research Division (CRD). This Division is responsible for the contractual and financial matters.

The Nuclear Equipment Division (NED) provided project management and coordination of subcontractors' activities. In addition, NED was responsible for the photolytic detoxifier conceptual design, design drawing, cost evaluation and preparation of the final report.

Veda, Inc.

Veda, Inc. had responsibility for all solar and optical requirements, including candidate solar test site selection and detoxifier window material determination. Preliminary test plan preparation for future program phases was also the responsibility of Veda, Inc.

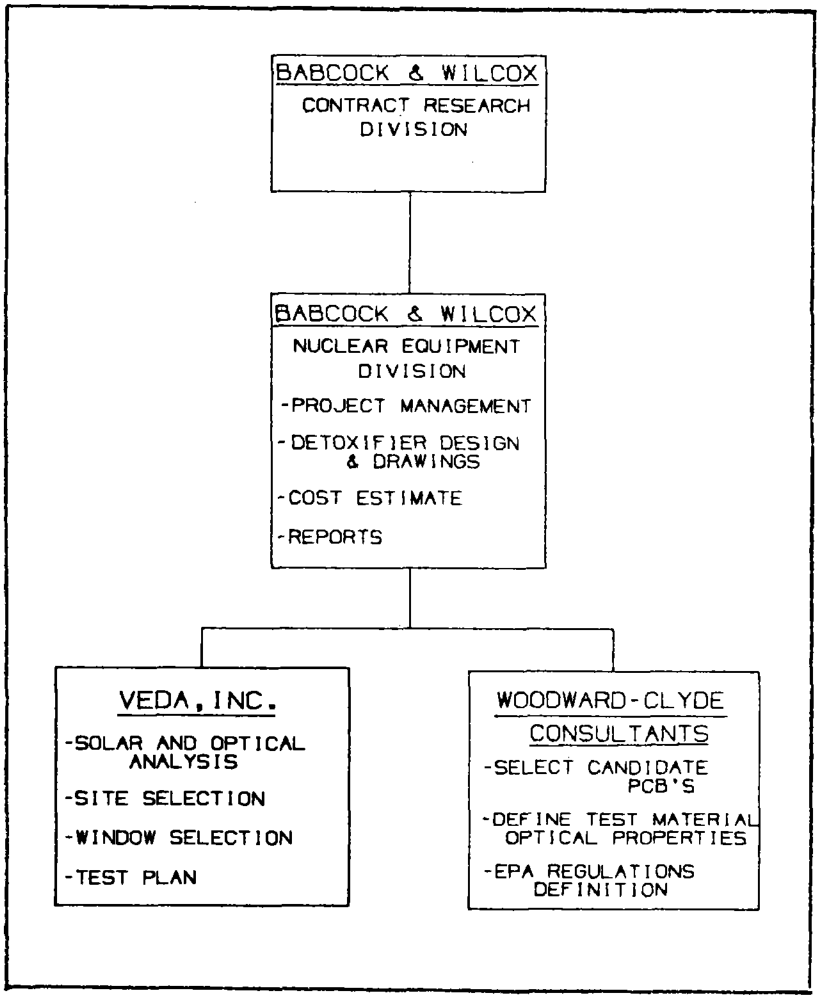
Woodward-Clyde Consultants

Woodward-Clyde Consultants provided the technical assessment of candidate hazardous wastes, specifically the PCB material selection for a future test burn. Also determined was the reaction chemistry associated with a test burn. Woodward-Clyde also provided familiarity with EPA regulations on hazardous wastes.

All of the subcontractors participated in the review and assessment of Task 1 and Task 2 workscopes.

FIGURE 2-4

PHASE I - TEAM MEMBER RESPONSIBILITIES



2.4 Overall Program Plan

The overall four-phase program as defined in the Phase I proposal has been restructured to incorporate a laboratory test program in Phase II. Therefore, the proposed restructured four-phase program consists of the following:

- Phase I - Definition of experimental test burn program and design of test apparatus (current contract)
- Phase II - Design and completion of laboratory proof-of-principle experiment
- Phase III - Design and completion of Subsystem Research Experiment (SRE) at solar test facility, and preliminary commercial design.
- Phase IV - Detailed commercial design and full system experiment.

The overall program schedule is illustrated in Figure 2-5. Phases I and IV are unchanged from the original plan. Phase II is now a laboratory experiment and Phase III consists of the SRE using the photolytic detoxifier design developed during Phase I and refined during Phase II. Phases I, II, and III are intended to bring the technology to the verge of commercialization, but as they are research oriented, they are not expected to attract private sector investors. The first three phases will, therefore, require DOE funding support.

The next phase of the program, Phase II, has two purposes. First, the effect of UV radiation on hazardous waste destruction efficiency will be quantified by conducting a laboratory test program. Second, the design for the prototype photolytic detoxifier will be refined based on the laboratory experimental results.

The laboratory experiment is designed to quantify the benefit of UV radiation in the overall detoxification process. An extensive literature search conducted during Phase I uncovered no quantitative data relating reaction temperature, UV effects, and residence time for the range of conditions expected in the commercial photolytic detoxifier. As a result of this, the original four-phase program outlined in the Phase I proposal has been restructured to include the laboratory test program.

FIGURE 2-5 OVERALL PROGRAM SCHEDULE

GFY

1984	1985	1986	1987
Phase I	**Phase II**	**Phase III**	**Phase IV**
• Investigation of UV effects • Prelim. design of site test unit • Select test site • Define Phase II & III test programs	• UV lab tests at U. Dayton • Lab test input to final design of site test unit	• Construct site test unit • Test at White Sands solar facility	• Commercial prototype design, construction and test

As stated previously, the proof-of-principle Phase II experiments are needed to quantify the effects of UV radiation on the waste destruction process. To do this, a Thermal/Photolytic Reactor system (TPRS) to be used in the laboratory tests will be designed and constructed to evaluate the amenability of toxic organic compounds to destruction by solar means. The decision to move these tests from the solar test facility to the laboratory was based on a number of factors including total program costs, ability to meet program objectives, and degree of confidence in the experimental methods and results. The major advantages of conducting the Phase II experiment in the laboratory are reduced costs, the greater controllability over the experimental parameters, the ready access to a variety of analytical instrumentation, and the vast experience of UDRI in performing degradation studies for toxic organic compounds. Although the solar flux intensity and reaction temperature will be lower in the laboratory tests than at the White Sands Solar Facility, the reaction kinetics follow well understood physical laws which allow the results to be scaled up to concentrated solar conditions.

It is important that the laboratory scale tests be conducted and evaluated prior to the construction of the prototype detoxifier to ensure the final design is based on quantitative data on the effects of UV. Therefore, the SRE has been included in Phase III.

The Phase III Program has been developed as a Prototype Subsystem Test using the photolytic detoxifier. The photolytic detoxifier design will be upgraded to include potential design advancements resulting from the Phase II laboratory test. Therefore, this phase will provide for design upgrade, construction and testing of the prototype photolytic detoxifier at the solar facility. Candidate test burn materials identified in Phase I will be used to further advance the program towards commercialization. Conceptual commercial designs will be developed which promote the solar detoxification benefit to the hazardous waste market.

Finalization of a commercial design in addition to a full system experiment is included in the Phase IV program.

2.5 Recommendations

Based on the Phase I technical approach and results, it has been established that the concept of detoxification of hazardous wastes using solar energy is feasible. Therefore, continuation of the overall program is recommended toward the goal of commercialization of the concept. This goal is achievable using a systematic approach as defined in the overall program schedule.

Specific recommendations for each phase are as follows:

Phase II - Laboratory Proof-of-Principle Experiment

- o Completion required to quantify destruction efficiency
- o Upgrade prototype detoxifier design and system

Phase III - Prototype Subsystem Tests

- o Fabricate prototype detoxifier
- o Photolytic detoxifier tests at the solar facility
- o Commercialization review

Phase IV - Commercilization Concept

- o Design of commercial concept
- o Fabricate commercial prototype
- o Test Program for commercialization prototype

During Phase III and Phase IV development, commercialization of the concept will be developed through direct involvement with the waste handling industry. This overall program can achieve the ultimate goal of developing the technology for design of a commercial process using concentrated solar energy to destroy toxic chloroaromatic wastes.

APPENDIX A

BACKGROUND / HISTORY

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A.0 Background/History

The need to detoxify hazardous wastes prior to their release to the environment, and to clean up existing landfills which contain toxic substances, is recognized as a critical problem in this country and throughout the world. The Phase I effort has established PCBs (polychlorinated biphenyls) as the test material for detoxification in this solar energy development program. PCBs have extremely high chemical and thermal stability which made them very useful in commercial applications. Due to this stability, PCBs are also very difficult to destroy. Therefore, the direct flux solar detoxifier may provide advantages over conventional disposal mechanisms. The advantages include:

-- The photochemical degradative effects of concentrated solar flux, which are not available from other energy sources, can be a signficant contributor to the overall detoxification process.

-- Solar energy also provides a clean energy source without decreasing the amount of fossil fuel required for the detoxification process.

-- Solar radiation can generate temperatures comparable to that of commercial incinerators.

-- The heat delivery capabilities of solar central receiver systems would allow the processing of large quantities of waste.

A.1 Regulations

In response to the dangerous accumulation of toxic wastes, Congress enacted the Toxic Substances Control Act and the Solid Waste Disposal Act, as amended by the Resource Conservation and Recovery Act of 1976. These laws require the EPA to establish a regulatory program for the manufacture, handling and disposal of those substances recognized as hazardous to human health and to the environment. These regulations defined the incineration process requirements for PCBs, including the monitoring requirements for off gases. Specifically, the combustion criteria shall be either of the following:

1. Maintenance of the introduced liquids for a 2-second dwell time at 1200°C (±100°C) and 3 percent excess oxygen in the stack gas.
2. Maintenance of the introduced liquids for a 1-1/2 second dwell time at 1600°C (±100°C) and 2 percent excess oxygen in the stack gas.

In addition, the combustion efficiency or Destruction Removal Efficiency (DRE) shall be at least 99.9 percent.

The design of the photolytic detoxifier has evolved based on these requirements as a minimum with the primary requirement for the detoxification process being the Destruction Removal Efficiency (DRE) where:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

W_{in} = mass feed rate of toxin

W_{out} = mass emission rate of toxin leaving reactor

A.2 Photolytic Methods

The photolytic process is based on the principal that ultraviolet (UV) radiation activates molecules which then undergo chemical reaction. This direct photolysis is therefore the rupture of molecular bonds by the absorption of light energy in the form of individual photons. Each molecule is characterized by an absorption curve in which photons of a particular wavelength are absorbed most readily.

Once absorbed, any reaction which results occurs instantaneously. The rupture of a specific chemical bond requires a definite amount of energy, which must be supplied by an individual photon. It cannot be supplied by cumulative photon absorption.

The energy available in a photon is inversely proportional to its wavelength. Due to atmospheric attenuation of solar energy, light of wavelength shorter than approximately 290 nanometers (nm) is not available at the earth's surface.

The aromatic carbon/chlorine bond requires an input of 97 Kcal/mole and the aliphatic carbon/hydrogen bond requires 94 Kcal/mole. Light of this amount of energy corresponds to 294 nm and 303 nm, respectively.

PCBs, as a subset of chloroaromatic compounds, generally absorb light weakly around 300 nm and not at all at the more prevalent longer wavelengths. To maximize photolytic degradation of chloroaromatic compounds (PCBs) the greatest possible amount of high energy solar radiation that can be obtained is required.

A.3 Comparison of Alternate Disposal Methods

A.3.1 Reuse and Treatment Methods

The PCBX process, developed by Sunohio, is a chemical destruction process. The chemical reactions involved are proprietary information; probably sodium organics in an amine solvent convert the chlorine in the PCBs to sodium chlorides. The organic portion of the PCB molecule, i.e., the biphenyl nucleus, is converted to the polymeric solids. The polymer product is insoluble in water and only slightly soluble in solvents such as alcohol and hydrocarbons. A large tractor/trailer truck, rigged to carry out the complete reaction, can travel to the site of a contaminated transformer, flush out the oil, clean it of PCBs and other contaminants, and return the oil to the transformer. The mobile unit is self-contained, and can be hooked up without shutting down the transformer. Present costs are estimated at from $3/gal to $20/gal of oil.

Goodyear Tire and Rubber Company, in Akron, Ohio, developed a chemical treatment process for highly toxic PCB transformer and heat transfer fluids. The treatment (which is also applicable to other halogenated contaminants, such as polybrominated biphenyls, DDT, and tetrachlorobenzodioxin pesticides and herbicides) extracts the toxic ingredients and converts them into a nontoxic residue that can be safely incinerated in conventional equipment. The contaminant-free fluids can be recovered for reuse.

In the Goodyear process, the PCB-contaminated fluid reacts with an organosodium reagent, sodium napthalide. The reaction destroys the carbon-chlorine chemical bonds to produce sodium chloride and hydrogen ions. The reaction takes less than 5 minutes under an inert atmosphere (nitrogen) at room temperature in glass or steel vessels.

Goodyear has no plans for a mobile unit, so due to process set-up costs, it may be restricted to treating large lots of oil (10,000 gallons or more) if it is to be competitive with PCBX. A patent has been granted for the process and Goodyear has donated the process to the public with no commercial gain accruing to itself.

The NaPEG^{TM} (molten sodium metal dispersed in polyethylene gycols - peg) process is based on the properties of a new family of chemicals, called in general, NaPEG^{TM} reagents. These substances are made from readily available raw materials that are reacted together at a supplier's location; the resulting agent is shipped to various users to process their own oils using "home-made" equipment. The reactant products are purified oil, nontoxic oxygenated organics, and sodium chloride. The NaPEG^{TM} reagent is stable, and can be stored for at least two years at room temperature in closed but not necessarily sealed containers. It is a thick brown liquid or semi-solid that flows readily when warmed. Chemically, it is insensitive to moisture or air.

Plasma arc technology is a PCB destruction process in which an electrical current is passed through low pressure gas. In passing through the gas, electrical energy is absorbed by the gas molecules and converted to thermal energy. The gas molecules are activated into ionized atomic states with equivalent temperatures of about 50,000^{o}K. The process is one of molecular fracture rather than a chemical oxidation reaction typical of incineration. Products that result are simple because the activated states are atomic, reflecting the much more energetic nature of radiation supplied by the plasma discharge compared to the oxidation processes involved in combustion. Most carbon in the feedstock is converted to carbon black. Because combustion air is not required, the effluent gas stream is considerably smaller than that from an oxidation process. This makes the process equipment compact, eases off-gas treatment, and simplifies monitoring. The small volume of gas can be scrubbed easily to remove hydrochloric acid.

An evaluation of plasma-arc technology reveals some advantages over other methods considered for PCB destruction. The plasma torch and reactor assembly can handle solids as well as liquids. This removes the need for either rotary kilns or solvent washing of contaminated solids (large transformers will still have to be drained and flushed.)

Atlantic Research Corporation recently announced it had stopped work on the LARC (Light Activated Reduction of Chemicals) process. LARC is a patented process which uses ultraviolet light in the 1850-4000 A region in combination with hydrogen gas and optimized photochemical conditions to affect the dehalogenation of complex chlorinated and brominated organic molecules. The ultraviolet light initiates the photochemical process by homolytic cleavage of the carbon-halogen bonds. The hydrogen gas plays a significant role in the photoreduction process, since the same reactions with nitrogen substituted for hydrogen proceed at much slower rates.

Before LARC can be successfully used for degradation of PCBs in oils such as transformer and heat exchanger fluids, several basic problems associated with photochemical destruction of PCBs in mineral and silicone oils must be overcome. These problems include: ultraviolet absorbing degradation products are present in many transformer fluids; most of the oils are not good hydrogen sources; some of the oils are too viscous for adequate dispersion of the hydrogen gas; and the PCB degradation product is a yellow-brown polymer substance which also absorbs ultraviolet light.

A.3.2 Incineration Methods

Landfilling and incineration are approved methods for the disposal of PCBs and PCB-contaminated materials. Historically, landfilling has been the dominant method of PCB disposal. However, recent attention has focused on incineration because it provides a means to actually destroy PCBs.

There are eight land dispoals sites currently permitted by the EPA to receive PCB materials. However, for large quantities of waste (notably liquids and oils with PCB concentration greater than 500 ppm and capacitors) land disposal is not an approved method, and incineration is the only option available. Incineration is a relatively new disposal option. The nations's first commercial PCB incineration facility was not approved by the EPA until January 1981.

J. M. Huber Technology Group in Borge, Texas, developed an Advanced Electric Reactor (AER) for destroying PCBs. A key design feature of the reactor is a fluid barrier that keeps toxic materials from contacting the vessel walls. This allows the reactor to treat toxic liquids and gases, as well as contaminated solids. Intense infrared radiation, rather than convection or conduction based heating is used to obtain temperatures of 4000 to 4500°F (2200 to 2480°C). For a large site (containing more than 100,000 tons of material), the cost is estimated to be between $365 and $565/ton processed.

The incineration facility at Rollins Environmental Services, Inc. (RES) in Deer Park, Texas, was the first commercial chemical waste incinerator in the nation to be approved for PCB destruction. The incinerator is a rotary kiln system and is capable of destroying liquid, solid, and gaseous wastes. At the present time, it is permitted for incineration of PCB liquids but not PCB solids.

The EPA approved the Energy Systems Company (ENSCO) incinerator in El Dorado, Arkansas, for disposal of PCBs on January 18, 1981 (effective March 12, 1981), making it the second commercial chemical-waste incinerator to be approved for PCB destruction. The facility has approval for the destruction of liquids as well as solids (capacitors, transformers, and other PCB articles).

The M/T Vulcanus is an at sea incineration vessel that had been approved by the U.S. for test burns. The vessel, originally chartered by Ocean Combustion Services, B. V. Rotterdam, the Netherlands, has successfully incinerated European wastes in the North sea since 1972. The vessel was bought by a U.S. company, Chemical Waste Management, in 1980 and received approval to incinerate PCBs in January, 1982.

Incineration costs are much higher than landfilling. ENSCO's prices vary between $200 and $700 per drum depending on the number of drums, PCB concentration, and other factors. Rollins charges different rates for bulk-shipped and drum-packed liquids. Prices for incinerating liquids in drums range from $600 to $980 per drum. These cost estimates do not include transportation costs, which can be significant. Although transportation costs vary, figures in the area of $3 per mile were quoted in a recent survey. High transportation costs are one of the reasons mobile incinerators are so attractive.

APPENDIX B

HAZARDOUS WASTE SELECTION

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PAGE

B.0 Introduction

As part of the Phase I study, candidate PCB materials to be considered for use in a future Phase III photolytic detoxifier prototype test have been identified.

B.1 Candidate Test Burn Materials

Based on previous work in the field of hazardous waste disposal and the desire to establish a comparative scientific basis for the solar detoxification process, the following candidate materials are recommended for a test-burn program at the solar facility:

1. Trichlorobenzene
2. Hexachlorobenzene
3. Aroclor 1221
4. Aroclor 1232
5. Aroclor 1242
6. Aroclor 1248
7. Aroclor 1254
8. Aroclor 1260

Aroclors 1221, 1232, 1242, and 1248 are colorless mobile liquids; 1254 is a viscous liquid; and 1260 is a sticky resin. These Aroclors are commercially available as electrical transformer oils, hydraulic fluids, adhesive chemicals, and dedusting agents.

Section B.2 presents reaction chemistry calculations for these materials.

B.2 Reaction Chemistry Calculations

Table B-1 shows the major combustion equations with material balances for biphenyl, trichlorobenzene, hexachlorobenzene, and the ten chlorinated forms of biphenyl.

Table B-2 gives the reaction chemistry for twelve Aroclor mixtures. For each mixture the table shows: the weight of each chlorinated biphenyl form present in 1,000 gms of feed; the weight of air needed to burn that much compound (with no excess); the weight of CO_2, H_2O, HCl, and Cl_2 formed in the combustion; and the amount of N_2 carried through the air.

TABLE B-1

Material Balances

1) Biphenyl Basis 1000 gm

$$\O - \O + 14 \frac{1}{2} O_2 \longrightarrow 12\ CO_2 + 5\ H_2O$$

M.W.	154.2129	31.9988	44.0099	18.0153
gm	1000	3008.6952	3424.586	584.101
moles	6.4845	94.02525	77.814	32.4225

Air required = 12,968.51 gm N_2 added = 9959.82 gm

2) Trichlorobenzene Basis 1000 gm

$$\O - Cl_3 + 6\ O_2 \longrightarrow 6\ O_2 + 0\ H_2O + 3\ HCl$$

M.W.	181.4495	31.9988	44.0099	36.46097
gm	1000	1058.1107	1455.2842	602.8311
moles	5.5112	33.0672	33.0672	16.5336

Air required = 4560.82 gm N_2 = 3502.71 gm

3) Hexachlorobenzene Basis 1000 gm

$$\O - Cl_6 + 6\ O_2 \longrightarrow 6\ CO_2 + 3\ Cl_2$$

M.W.	284.7846	31.9988	44.0099	70.906
gm	1000	674.168	927.245	746.943
moles	3.5114	21.069	21.069	10.534

Air required = 2905.90 gm N_2 added = 2231.73 gm

4) Monochlorobiphenyl Basis 1000 gm

$$\O - \O - Cl + 14\ O_2 \longrightarrow 12\ CO_2 + 4\ H_2O + 1\ HCl$$

M.W.	188.658	31.9988	44.0099	18.0153	36.46097
gm	1000	2374.579	2799.346	381.968	193.265
Moles	5.3006	74.208	63.607	21.202	5.3006

Air required = 10,235.254 gm N_2 added = 7860.675 gm

TABLE B-1 (Continued)

5) Dichlorobiphenyl Basis 1000 gm

$$\text{Ø-Ø-Cl}_2 + 13\frac{1}{2}\ O_2 \longrightarrow 12\ CO_2 + 3\ H_2O + 2\ HCl$$

M.W.	223.103	31.9988	44.0099	18.0153	36.46097
gm	1000	1936.253	2367.153	242.246	326.853
Moles	4.4822	60.5102	53.787	13.447	8.964

Air required = 8345.92 gm N_2 added = 6409.67 gm

6) Trichlorobiphenyl Basis 1000 gm

$$\text{Ø-Ø-Cl}_3 + 13\ O_2 \longrightarrow 12\ CO_2 + 2\ H_2O + 3\ HCl$$

M.W.	257.548				
gm	1000	1615.172	2050.564	139.899	424.709
Moles	3.8828	50.476	46.593	7.766	11.6483

Air required = 6961.95 gm N_2 added = 5346.78 gm

7) Tetrachlorobiphenyl Basis 1000 gm

$$\text{Ø-Ø-Cl}_4 + 12\frac{1}{2}\ O_2 \longrightarrow 12\ CO_2 + 1\ H_2O + 4\ HCl$$

M.W.	291.993				
gm	1000	1369.844	1808.669	61.698	499.477
Moles	3.4247	42.809	41.097	3.4247	13.699

Air required = 5904.5 gm N_2 added = 4534.66 gm

8) Pentachlorobiphenyl Basis 1000 gm

$$\text{Ø-Ø-Cl}_5 + 12\ O_2 \longrightarrow 12\ CO_2 + 0\ H_2O + 5\ HCl$$

M.W.	326.438				
gm	1000	1176.289	1617.822		558.467
Moles	3.0634	36.7604	36.7604		15.3168

Air required = 5070.21 gm N_2 added = 3893.92 gm

TABLE B-1 (Continued)

9) Hexachlorobiphenyl Basis 1000 gm

$$\phi\text{-}\phi\text{-}Cl_6 \quad + \quad 12\ O_2 \longrightarrow 12\ CO_2 \quad + \quad 4\ HCl \quad + \quad Cl_2$$

M.W.	360.883	31.9988	44.0099	36.46097	70.906
gm	1000	1064.017	1463.407	404.1306	196.479
Moles	2.7710	33.2518	33.2518	11.0839	2.77110

Air required = 4586.28 gm N_2 added = 3522.26 gm

10) Heptachlorobiphenyl Basis 1000 gm

$$\phi\text{-}\phi\text{-}Cl_7 \quad + \quad 12\ O_2 \longrightarrow 12\ CO_2 \quad + \quad 3\ HCl \quad + \quad 2\ Cl_2$$

M.W.	395.328				
gm	1000	971.3086	1335.900	276.689	358.720
Moles	2.5295	30.3545	30.3545	7.5886	5.0591

Air required = 4186.68 gm N_2 added = 3215.37 gm

11) Octachlorobiphenyl Basis 1000 gm

$$\phi\text{-}\phi\text{-}Cl_8 \quad + \quad 12\ O_2 \longrightarrow 12\ CO_2 \quad + \quad 2\ HCl \quad + \quad 3\ Cl_2$$

M.W.	429.773				
gm	1000	893.461	1228.832	169.675	494.954
Moles	2.3268	27.9217	27.9217	4.6536	6.9804

Air required = 3851.125 gm N_2 added = 2957.66 gm

12) Nonachlorobiphenyl Basis 1000 gm

$$\phi\text{-}\phi\text{-}Cl_9 \quad + \quad 12\ O_2 \longrightarrow 12\ CO_2 \quad + \quad HCl \quad + \quad 4\ Cl_2$$

M.W.	464.218				
gm	1000	827.166	1137.652	78.543	610.9713
Moles	2.1542	25.8499	25.8499	2.1542	8.6166

Air required = 3565.37 gm N_2 added = 2738.20 gm

TABLE B-1 (Continued)

13) Decachlorobiphenyl Basis 1000 gm

	$\phi\text{-}\phi\text{-}Cl_{10}$ +	12 O_2 $\longrightarrow$	12 CO_2 +	5 Cl_2
M.W.	498.6632	31.9988	44.0099	70.906
gm	1000	770.030	1059.069	710.961
Moles	2.0054	24.064	24.064	10.027

Air required = 3319.09 gm

N_2 added = 2549.06 gm

TABLE B-2

REACTION CHEMISTRY

Basis 1,000 gm of Compound

Compound	Air	CO_2	H_2O	HCl	Cl_2	N_2
Biphenyl	12,968.51	3,424.59	584.10	0	0	9,959.82
Tricholorobenzene	4,560.82	1,455.28	0	602.83	0	3,502.71
Hexachlorobenzene	2,905.90	927.24	0	0	746.94	2,231.73
PCBS						
o mono	10,235.25	2,799.35	381.97	193.26	0	7,860.68
o di	8,345.92	2,367.15	242.25	326.85	0	6,409.67
o tri	6,961.95	2,050.56	139.90	424.71	0	5,346.78
o tetra	5,904.5	1,808.67	61.70	499.48	0	4,534.66
o penta	5,070.21	1,617.82	0	558.47	0	3,893.92
o hexa	4,586.28	1,463.41	0	404.13	196.48	3,522.26
o hepta	4,186.68	1,335.90	0	276.69	358.72	3,215.37
o octa	3,851.12	1,228.83	0	169.68	494.95	2,957.66
o nona	3,565.37	1,137.65	0	78.54	610.97	2,738.20
o deca	3,319.09	1,059.07	0	0	710.96	2,549.06

I. Aroclor 1221 (1) Basis 1,000 gm

No. of Cl's	gms	gms Air	CO_2	H_2O	HCl	Cl_2	N_2
0	110	1,426.54	376.70	64.25	0	0	1,095.58
1	510	5,219.98	1,427.67	194.80	98.57	0	4,008.94
2	320	2,670.69	757.49	77.52	104.59	0	2,051.09
3	40	278.48	82.02	5.60	16.99	0	213.87
4	20	118.09	36.17	1.23	9.99	0	90.69
5	5	25.35	8.09	0	2.79	0	19.47

II. Aroclor 1221 (2) Basis 1,000 gm

No. of Cl's	gms	Air	CO_2	H_2O	HCl	Cl_2	N_2
0	70	907.10	239.72	40.89	0	0	697.19
1	510	5,219.98	1,427.67	194.80	98.57	0	4,008.94
2	380	3,171.45	899.52	92.05	124.20	0	2,435.67
3	30	208.86	61.52	4.20	12.74	0	160.40

TABLE B-2 CONT.

III. Aroclor 1232 (2) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
0	60	778.11	205.48	35.05	0	0	597.59
1	260	2,661.17	727.83	99.31	50.25	0	2,043.78
2	290	2,420.32	686.47	70.25	94.79	0	1,916.80
3	150	1,044.29	307.58	20.98	63.71	0	802.02
4	5	29.52	9.04	0.31	2.50	0	22.67

IV. Aroclor 1016 (1) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
1	10	102.35	27.99	3.82	1.93	0	78.61
2	200	1,669.18	473.43	48.45	65.37	0	1,321.93
3	570	3,968.31	1,168.82	79.74	242.08	0	3,047.66
4	210	1,239.95	379.82	12.96	104.89	0	952.28
5	10	50.70	16.18	0	5.58	0	38.94

V. Aroclor 1242 (1) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
1	10	102.35	27.99	3.82	1.93	0	78.61
2	160	1,335.35	378.74	38.76	52.30	0	1,057.55
3	490	3,411.36	1,004.78	68.55	208.11	0	2,619.92
4	250	1,476.13	452.17	15.42	124.87	0	1,133.67
5	80	405.62	129.43	0	44.68	0	311.51
6	10	45.86	14.63	0	4.04	1.96	35.22

VI. Aroclor 1242 (2) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
1	10	102.35	27.99	3.82	1.93	0	78.61
2	170	1,418.81	402.42	41.18	55.57	0	1,123.64
3	400	2,784.78	820.23	55.96	169.88	0	2,138.71
4	320	1,889.44	578.77	19.74	159.83	0	1,451.09
5	100	507.02	161.78	0	55.85	0	389.39
6	5	22.93	7.32	0	2.02	.98	17.61

VII. Aroclor 1242 (3) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
2	40	333.84	94.69	9.69	13.07	0	264.39
3	390	2,715.16	799.72	54.56	165.64	0	2,085.24
4	420	2,479.89	759.64	25.91	209.78	0	1,904.56
5	140	709.83	226.50	0	78.19	0	545.15

TABLE B-2 CONT.

VIII. Aroclor 1248 (2) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
2	10	83.46	23.67	2.42	3.27	0	66.10
3	230	1,601.25	471.63	32.18	97.68	0	1,229.76
4	500	2,952.25	904.33	30.85	249.74	0	2,267.33
5	200	1,014.04	323.56	0	111.69	0	778.78
6	10	45.86	14.63	0	4.04	1.96	35.22

IX. Aroclor 1248 (1) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
2	5	41.73	11.84	1.21	1.63	0	33.05
3	10	69.62	20.51	1.40	4.25	0	53.47
4	210	1,239.95	379.82	12.96	104.89	0	952.28
5	480	2,433.70	776.55	0	268.06	0	1,869.08
6	230	1,054.84	336.58	0	92.95	45.19	810.12
7	60	251.20	80.15	0	16.60	21.52	192.92

X. Aroclor 1254 (2) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
4	160	944.72	289.39	9.87	79.92	0	725.55
5	600	3,042.13	970.69	0	335.08	0	2,336.35
6	230	1,054.84	336.58	0	92.95	45.19	810.12
7	10	41.87	13.36	0	2.77	3.59	32.15

XI. Aroclor 1254 (3) Basis 1,000 gm

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
3	5	34.81	10.25	0.70	2.12	0	26.74
4	360	2,125.62	651.12	22.21	179.81	0	1,632.48
5	450	2,281.59	728.02	0	251.31	0	1,752.26
6	180	825.53	263.41	0	72.74	35.37	634.01
7	10	41.87	13.36	0	2.77	3.59	32.15

XII. Aroclor 1260 (2) Basis 1,000

No. of Cl's	gm	Air	CO_2	H_2O	HCl	Cl_2	N_2
5	120	608.43	194.14	0	67.02	0	467.27
6	460	2,109.69	673.17	0	185.90	90.38	1,620.24
7	360	1,507.20	480.92	0	99.61	129.14	1,157.53
8	60	231.07	73.73	0	10.18	29.70	177.46

APPENDIX C

TEST SITE SELECTION

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C.0 Test Site Selection

C.1 Introduction

The purpose of this appendix is to compare the candidate test sites on a technical basis and to recommend the site which is best suited to our "proof of principle" photolytic detoxifier tests. These tests would be completed during Phase III.

The candidate test facilities are:

1. The solar furnace at Central Receiver Test Facility (CRTF), Sandia National Laboratories, Albuquerque, NM.
2. The White Sands Solar Facility (WSSF), U.S. Army White Sands Missile Range, NM.

C.2 Site Requirements

C.2.1 Solar Energy

The most important site characteristic to be considered is the quality of the solar radiation reaching the focal zone. The process being tested requires the maximum amount of ultraviolet (UV) energy obtainable, even to the extent of sacrificing the other segments of the solar spectrum (see Appendix H). The maximum ultraviolet energy obtainable should be the overriding criteria for site selection.

The prototype detoxifier has been designed with both sites in mind as regards the solar energy available at the focal zone. Yet, from a more subjective point of view, the availability of a larger quantity of energy is always desirable to ensure an adequate margin is available under less than optimal insolation conditions.

The flux profile is another important aspect of the solar energy available at each site. Here again, the prototype detoxifier has been designed with this in mind.

Excessive beam drift due to either heliostat tracking ability or wind loading is undesirable. While no specific criteria has been generated, the most stable system is obviously desired.

C.2.2 Specialized Instrumentation Data Acquisition

The prototype detoxifier is very self-contained with respect to process instrumentation. The test site must provide real time solar constant and focal plane flux measurement data.

C.2.3 Space Usability

The prototype tests, as yet, have no proximity requirements for associated equipment or personnel. In general, it is usually advantageous and more efficient to have personnel close enough to make direct observations and adjustments. Future refinements to test and equipment definition will be used to define specific space requirements.

C.2.4 Utilities and Equipment

The prototype tests will be self-contained with respect to equipment. Modest amounts of electrical power will be required for the various pumps and fans used for testing and for instrumentation and analysis equipment. A 220 Volt AC power source should be sufficient for any equipment required. Future refinements to test and equipment definition will be used to provide specific electrical power requirements.

A support fixture at the focal zone will be required for the tests. Current estimates of the detoxifier weight put it at approximately 800 pounds.

C.2.5 Environmental Protection Agency Requirements

These experiments will allow the photolytic detoxifier excess effluent to enter the environment. As such, the tests must be conducted under strict adherence to EPA regulations concerning toxic waste disposal. The ramifications of these regulations, as well as any procedures required by the selected test site, are currently under investigation and may significantly alter the manner in which these tests are performed.

Specifically, the application for the series of tests using the prototype photolytic detoxifier should be made to the Regional Administrator, Region 6, Dallas, Texas, if less than 500 pounds of PCB contaminated material will be tested. If more than 500 pounds is used, the application should go to the Assistant Administrator of the Office of Pesticides and Toxic Substances in Washington.

The requirements for this application for approval to conduct research and development on the solar powered PCB detoxifier are outlined in the March 30, 1983 Federal Register Notice (48FR 13181). They include the following:

1. Name, address, and phone number of the unit's principal manager.
2. The location of the facility where the unit will be tested and the location where the unit will be stored and serviced when not engaged in testing.
3. A detailed description of the unit, including general plans and design drawings.
4. An engineering report or other information on the anticipated performance of the unit.
5. A sampling plan and quality assurance plan, including sampling and monitoring equipment and available facilities.

6. Waste volumes expected to be handled, process design capacity, process control, reagent-to-waste feed ratios, and safety features.
7. Any local, state or federal permits or approvals.
8. Schedules and plans for complying with the approval requirements.
9. A contingency plan which describes steps taken in case of process failure, spill or overflow.
10. Environmental impact, including process emissions, toxicity, and disposal of process products, site relationships, and steps taken to protect the health of operators.

These requirements must be met whichever site is chosen for the prototype test program.

C.3 Site Comparison

C.3.1 General Layout

Simple diagrams and descriptions of both prospective test sites are included in Appendix I. Both sites are similar in that they have a tracking heliostat for gathering the solar energy and a segmented parabolic dish concentrator. The attenuator for both sites operates on the heliostat reflected light and not the concentrated beam.

The principle difference in the two layouts is the focal zone test area. The CRTF has the data system and control room located remotely from the focal zone test area, off to the side of the building housing the concentrator. The WSSF has the data system and control room located at the focal zone.

The WSSF heliostat and concentrator are relatively larger than those at the CRTF, giving it a greater energy availability.

C.3.2 Data Acquisition and Instrumentation

The lists of available instrumentation at each site are given in Appendix I. The CRTF has a more advanced data acquisition system primarily due to the use of a mini-computer. Both sites have the equipment required for solar constant measurement and focal zone flux characterization.

C.3.3 Utilities and Equipment

The WSSF has electrical power available at 110, 220, and 440 volts AC. The CRTF has power at 110 an 220 volts AC. Both sites have shop air, the CRTF at 100 psi and WSSF at 150 psi. Both sites have water available.

Both sites use automated positioning tables to support and accurately position test hardware. The CRTF positioning table is 2 ft x 4 ft (major dimension perpendicular to optical axis) and is rated at approximately 1,000 pounds. The prototype detoxifier's length of 52" would probably require an additional support fixture. The WSSF table cannot support 800 pounds. Therefore the detoxifier will have to be supported from the floor of the test chamber which can support as much as 1,000 pounds.

C.3.4 Space Usability

The WSSF test area is a room 16 ft x 8 ft x 8 ft high and approximately 20 feet above the ground. It is located at the focal zone of the concentrating mirror. This room contains the test area and controls for facility operation. Any equipment that has to enter the room must pass through an 84-1/2" x 29" doorway or a 36" x 36" window. There is not much extra room available. Testing will be cramped, but it should be feasible based on past site experience. Even though the detoxifier is large, most of the support equipment need not be close to the detoxifier chamber. There is unlimited space at the base of the support structure up to a height of 111" at which point the light reflected from the heliostat is intersected. A van or small truck with equipment already set up could be driven in and parked at the base of the test room support structure.

The CRTF presents an entirely different situation. Only the test table is positioned at the focal zone and the control room is located remotely, outside the building housing the concentrating mirror. During testing, the table is raised about 13 feet in the air. The closest a manned piece of equipment could be positioned is about 20 feet away from the table. This restriction would make prototype testing extremely difficult. Equipment can be placed on the floor directly below the table. However, the equipment cannot extend higher than 2 feet above the floor or it will interfere with energy reflected from the heliostat.

C.3.5 Solar Energy

At the focal plane, WSSF can put 26 KW through a 6" diameter circle and the CRTF can put 16 KW through the same area. The flux profiles for both sites are similar (Appendix I), the WSSF profile having a more uniform control flux. The peak densities are approximately the same, 100 cal/cm^2-sec. This maximum value, however, depends on weather conditions, time of year, cleanliness of mirrors, etc. After passing through the focal plane, both beams start to diverge, WSSF beam in an approximate 20 degree solid angle and the CRTF in an approximate 92 degree solid angle.

Beam drift at the CRTF is about 0.25 cm due to the heliostat incremental tracking and with a 7 mph wind is as large as 0.5 cm due to wind loading. The WSSF can keep beam excursions within 0.25 cm in winds up to 10 mph. At about 15 mph the facility is usually shut down to wait for a decrease in wind velocity.

Of paramount importance is the quantity of UV-B (ultraviolet in the 280 to 320 nm range) radiation delivered to the focal zone. In this aspect the two sites are significantly different. A direct comparison of the two sites could be made if focal plane spectral scans were available in the wavelength range of interest. The CRTF does not currently have that information, although they do plan to generate it sometime in the summer of 1984. The WSSF has a scan available, however, it does not cover the range of interest. The net ultraviolet transmission must be derived from available information.

At both sites, the incident solar energy is reflected off of two surfaces before it reaches the focal zone. The characteristics of these two surfaces establish the percentage of available solar ultraviolet energy delivered to the test area as follows:

CRTF - The heliostat used at this site is manufactured by ARCO and is composed of double strength Gardner float glass with a silvered reflecting surface on the back side of the glass. This is a "second surface reflector", which requires the light to pass through the glass twice to be reflected. The specifications for the glass are not available. Appendix I shows the reflectance of both silver and aluminum versus wavelength. While silver has a better reflectance in the higher wavelength regions, its reflectance in the 0.3 micron (300 nm) area drops dramatically to below 10%. Aluminum, for the same region has a reflectance of over 90%.

The concentrating elements at the CRTF are also second surface mirrors with silvered back surfaces. The specifications for this glass are also given in Appendix I, which also includes a transmission calculation from absorption data given. The transmission qualities of the glass are very poor in the 300 nm wavelength region, the transmission being less than .209 (this corresponds to an absorption coefficient of 2.41 cm^{-1}, assuming 100% theoretical transparency). It may be safely concluded that there is very little ultraviolet radiation in the UV-B range reaching the focal zone with the current CRTF reflecting surfaces.

WSSF - This facility uses first surface mirrors on both the heliostat and the concentractor. The mirror segments are made up of glass panes with a mylar overlay adhered to the front surface. The mylar is 3M product no. ECP-91A. The reflecting material is aluminum. The term "first surface" is a slight misnomer here in that the aluminum surface is coated with a 0.0002 inch thickness of acrylic to prevent oxidation. Specifications from 3M Corporation are given in Appendix I. The numbers given for percent of total reflected radiation are a combination of aluminum reflectance and acrylic transmission. At 300 nm the total reflectance is greater than 78%. The percent of available ultraviolet energy reaching the focal zone after being reflected off of 2 such surfaces is, thus, on the order of 56%.

C.4 Other Considerations

In addition to the technical requirements identified, a current cost evaluation has been completed for each facility for a projected detoxifier test span. This test span is provided for comparative purposes and the actual test span will be defined after finalization of the test plan. A cost evaluation was also completed to upgrade the Central Receiver Test Facility solar furnace to "first surface" mirrors. These evaluations are presented in the following sections.

C.4.1 Estimated Cost for Upgrading UV Capabilities of CRTF

Purchase of ECP-91A (3M Mylar overlay)	
3 rolls at $404/roll	$ 1,212
Installation:	
2 men, 4 weeks at $1,000/day	20,000
Removal:	
2 men, 2 weeks at $1,000 day	10,000
TOTAL	$31,212

NOTE: Installation costs based on CRTF estimate

C.4.2 Test Site Cost Comparison

The following comparison was prepared based on an assumed ten (10) day test period for the prototype photolytic detoxifier at the solar test facility. An additional three (3) day set-up time and a one (1) day removal span was also assumed.

CRTF

Daily cost = $1,000/day

Therefore, Set-up (3 days) = $3,000

Tests (10 days) = $10,000

Removal (1 day) = $1,000

UV Upgrade Costs (Section C.4.1) = $31,212

TOTAL = $45,212

WSSF

Daily costs = $3,400/day

Therefore, Set-up (3 days) = $10,200

Tests (10 days) = $34,000

Removal (1 day) = $3,400

TOTAL = $47,600

C.5 Conclusion

The WSSF is recommended as the test site for the following reasons:

1. Dramatically superior ability to supply the desired solar ultraviolet energy to the test area.
2. More suitable test area configuration which allows at least some equipment and personnel to be immediately adjacent to the focal zone test area.

It should be noted that in the near future the WSSF intends to start converting all of its mirror surfaces to first surface vacuum deposited aluminum. The aluminum will be specifically doped to significantly increase ultraviolet energy transmission. This will make the facility even more desirable for the planned experiments.

As identified, the CRTF mirrors could be upgraded at a cost of about $31,000 to provide an ultraviolet wavelength profile comparable to that of the WSSF, though not of as high an intensity.

A comparison was made of test costs, using currently available information for the two test sites. Conducting the tests at the CRTF would cost $45,212 (including minor upgrades), whereas the WSSF would cost $47,600.

APPENDIX D

DETOXIFIER DESIGN

APPENDIX D - TABLE OF CONTENTS

D.0 Detoxifier Design

D.1 Introduction

This appendix identifies the design progression used to establish the final conceptual design of the photolytic detoxifier. Design requirements were established based on detoxifying requirements in addition to concerns for compatibility with the solar test facilities. Specifically, the major design requirements are listed below.

- The detoxification chamber material must provide mechanical strength and corrosion resistance at temperatures up to 2500°F (1370°C)
- The aperture window material must allow high transmittance of both UV and IR radiation in addition to being compatible with the operating temperatures.
- The product flow through the detoxification chamber must permit controlled exposure to incoming radiation.
- The residence time in the detoxifier must be sufficient to ensure complete destruction of the toxic compounds.
- The detoxifier overall size and weight must be compatible with the solar test facility.
- The detoxifier optics must be compatible with the flux distribution of the solar test facility.
- Means must be provided for collection and analysis of the detoxifier effluent.
- Design must promote component safety.

Several design concepts were considered and evaluated. Heat transfer and fluid flow calculations were performed for the various designs. Section D.2 identifies the established conceptual design of the photolytic detoxifier. The system description is provided in section D.3. The additional developmental design concepts reviewed are presented in section D.4.

D.2 Final Conceptual Detoxifier Design

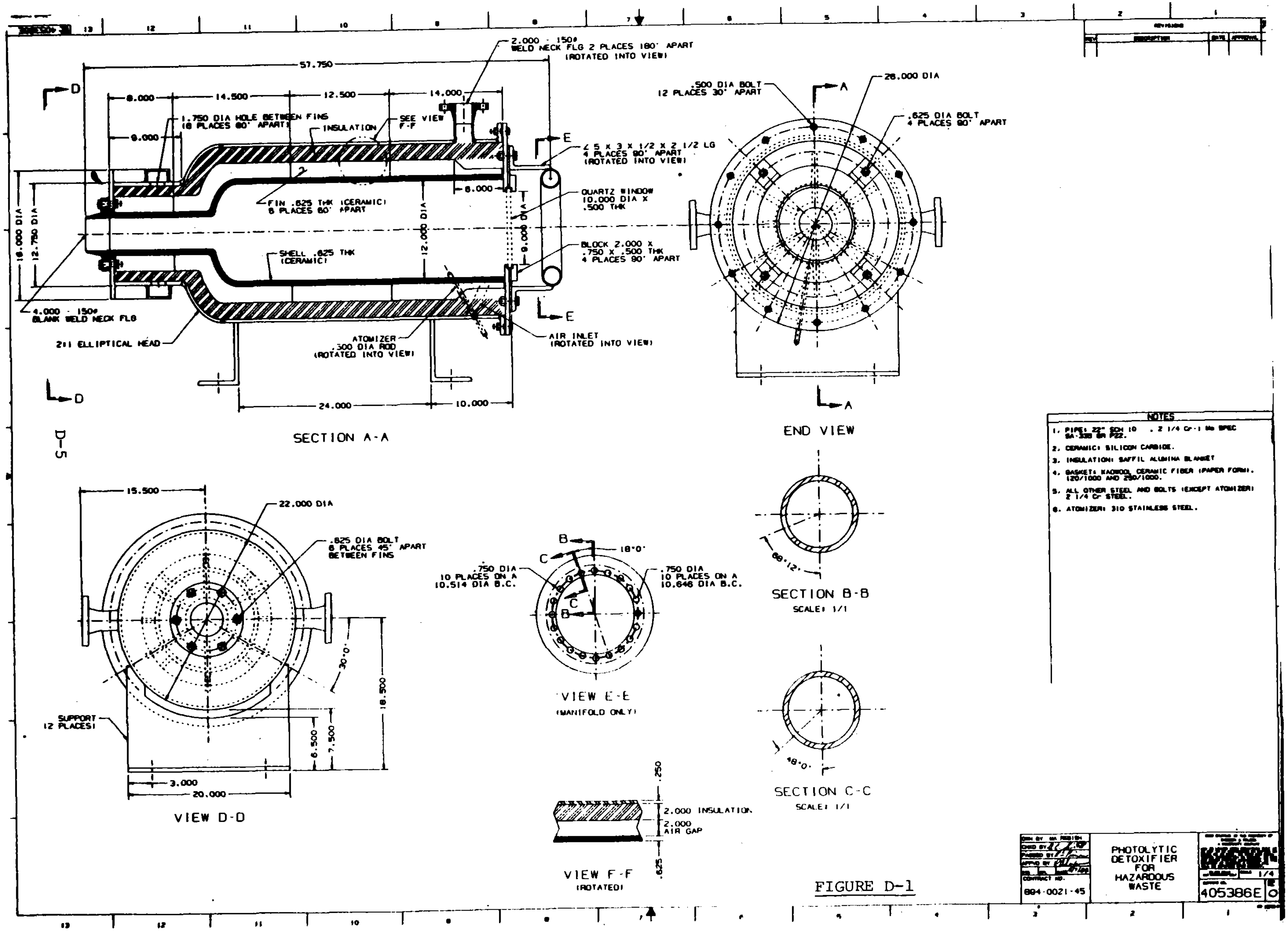
The final conceptual design concept was established based on compatibility with the design requirements. The design consists of a 12.0" I.D. ceramic shell which defines the reaction chamber. The chamber incorporates a fused quartz window for entrance of the solar energy. The reaction chamber is subsequently enclosed in a 22" O.D" 2 1/4 CR-1 Mo steel cylinder which provides a cooling annulus to the assembly. The basic assembly is provided in Figure D-1.

A 5/8" thick ceramic liner concept was established based on the high operating temperatures in addition to the need to satisfy reaction chamber chemical environmental concerns. The castable liner also incorporates six ceramic fins to aid in cooling the ceramic shell by increasing the heat transfer surface. In addition, the fins direct the cooling air which is provided between the line and insulated steel cylinder. The annulus cooling air flow is approximately 220 cfm.

Because the temperature inside the reaction chamber will be in excess of 2400^{o}F (2400^{o}F is needed for the combustion) and the fused quartz window material is only capable of withstanding temperatures up to approximately 1600^{o}F, additional window cooling is required. Therefore, cooling air is introduced on the outside of the window through a manifold which provides an even distribution of air flow at the rate of 300 cfm across the window. This is expected to keep the outside temperature of the window at 800^{o}F. Also, on the inside, a jet of air is directed on the window to assist in cooling the window from the inside. This internal cooling air also helps to provide a shield curtain between the products of reaction and the window to reduce waste product deposition on the window. The inside air enters the combustion chamber near the window through two rectangular penetrations at a rate of 7 cfm. This air will also supplement the air needed for the reaction process.

An atomizer is located on the bottom of the reaction cylinder near the window. The atomizer sprays the mixture of air and fuel toward the center of the cavity where it is in direct contact with the concentrated solar beam.

As was stated before, during the detoxification process, the temperature inside the vessel (at the point of combustion) will be at least 2400°F. A slight drop of about 35°F will occur across the ceramic lining. The ceramic material was chosen specifically with a high thermal conductivity in order to dissipate as much heat as possible to the cooling air. The cooling air enters at ambient temperature and in the process of cooling the ceramic shell heats up to approximately 1100°F. Although insulation has also been included in the annulus, the steel shell temperature has been conservatively estimated to be approximately 1100°F also due heat transfer by conduction. A 6" insulation blanket on the outside provides the necessary temperature drop from 1100°F to 150°F to protect personnel in the vicinity of the system.



NOTES

1. PIPE: 22" SCH 10 , 2 1/4 Cr-1 Mo SPEC SA-335 GR P22.
2. CERAMIC: SILICON CARBIDE.
3. INSULATION: SAFFIL ALUMINA BLANKET
4. GASKET: KAOWOOL CERAMIC FIBER (PAPER FORM). 120/1000 AND 250/1000.
5. ALL OTHER STEEL AND BOLTS (EXCEPT ATOMIZER) 2 1/4 Cr STEEL.
6. ATOMIZER: 310 STAINLESS STEEL.

DRN BY MA REDISH
CHKD BY
PASSED BY
APPVD BY
CONTRACT NO.
894-0021-45

PHOTOLYTIC
DETOXIFIER
FOR
HAZARDOUS
WASTE

SCALE 1/4
405386E
0

FIGURE D-1

D.2.1 Mechanics of the Detoxifier Operation

The basic system schematic is presented in Figure D-2. The mixture of PCB and fuel oil (Grade 2 diesel) is pumped in the ceramic cavity through the atomizer using a positive displacement metering pump with an adjustable pumping rate (air to fuel ratio). The atomizer discharges the hazardous waste into the solar beam entering the window.

An exhaust fan is supplied with a damper to control the speed of the exhaust gases and therefore control the pressure inside the ceramic combustion chamber. The exhaust fan is used to draw out the gases and maintain a vacuum of 5" of water (approximately 0.2 psig) in the cavity. The purpose of the vacuum is to insure that no gases will escape to the atmosphere. Check valves located on the incoming excess air lines assure one direction flow.

D.2.2 Thermal Hydraulic Design Calculations

The following is an example of the calculations performed for the final conceptual design discussed in Section D.2. Similar calculations were done for the other four preliminary designs. The calculations include estimates of the gas temperature inside the cavity, the heat losses by radiation and convection to the walls and window, and the cooling requirements for the window and walls receiving the solar flux.

The flow mass rate of reactants entering the detoxifier will be the following:

4.23 lb/hr of fuel and PCB's is burned with 100% excess air (57.33 lb/hr) under the highest solar flux available, Q_s = 86.547 Btu/hr:

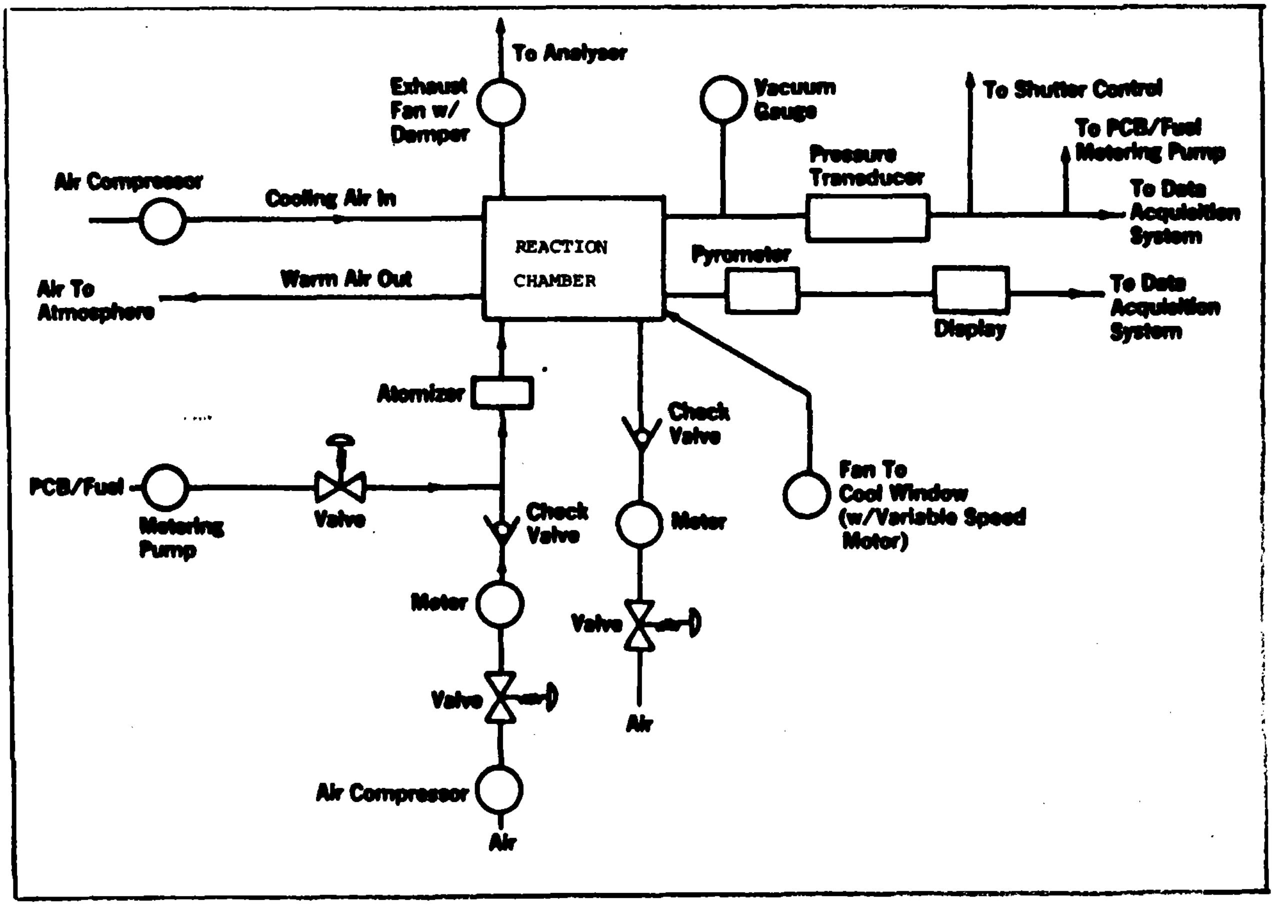
$$Q_{comb} = 4.23\ (9200\ \text{Btu/lb}) \quad = 38{,}916\ \text{Btu/hr}$$

$$\dot{m}_{CO_2} = 8.49274\ \text{lb/hr},\ \dot{m}_{H_2O} = .535307,\ \dot{m}_{HCl} = 1.8440$$

$$\dot{m}_{CL_2} = .0082908\ \text{lb/hr},\ \dot{m}_{N_2} = 22.15031,\ \dot{m}_{air} = 28.665$$

FIGURE D-2

Component Test Arrangement



D.2.2.1 Heat Balance on Gas

The mixture of air and PCB/fuel is burned inside the cavity and heat is released by combustion. Other sources of heat to the gas are a fraction of the solar heat that the gas absorbs and the enthalpies of the incoming air/fuel mixture. The gas loses heat to the walls, window and exhaust as seen from the Figure D-3.

$$Q_{comb} + (\text{air} + \text{fuel})\ \text{enthalpies} + \alpha_g Q_s = Q_{exhaust} + Q_{walls} + Q_{window} \qquad \text{(D.1)}$$

where: Q_{comb} is the heat released by combustion of the PCB/fuel

Q_s is the solar flux entering the cavity

$Q_{exhaust}$ is the enthalpy of the exhaust gases

Q_{wall} is the heat loss to the walls by convection and radiation

Q_{window} is the heat loss to the window by convection and radiation

α_g is the gas absorptivity

Equation D.1 is solved iteratively to obtain the gas and wall temperatures. A first estimate of the gas temperature is the adiabatic flame temperature which is found by balancing the enthalpies of the reactants and the products.

$$\Delta H_r = \Delta H_p \qquad \text{(D.2)}$$

By trial and error this temperature was found to be 2500°F.

$Q_{comb} = 38{,}916$ Btu/hr

(air + fuel) enthalpies = 316.4 Btu/hr

$\alpha_s Q_s = .0306(86{,}547) = 2648$ Btu/hr

$Q_{exhaust} = \Sigma H_p$ enthalpies of products

$Q_{walls} = \sigma A_{walls}(\varepsilon_g T_g^4 - \varepsilon_g T_{wall}^4) + h_c\, A_{wall}(T_g - T_{wall})$ walls

$Q_{window} = \sigma A_w \quad w(\varepsilon_g T_g^4 - \varepsilon_g T_w^4) + h_c\, A_w(T_g - T_w)$ window

The window was kept at its normal service temperature $T_w = 1642^oF$ and the gas and wall temperatures were obtained iteratively until both sides of Equation D.1 were balanced. T_g was found to be 2440^oF and T_{walls} was 2400^oF. Q_{walls} was found to be 2937 Btu/hr and Q_{window} had a value of 395 Btu/hr from the gas. It is noted that the gases absorb only a small fraction of the solar flux (3 to 5%) and the rest of the flux impinges on the walls.

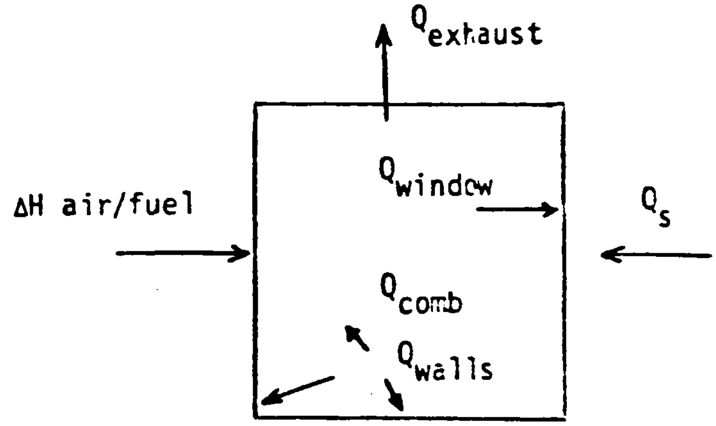


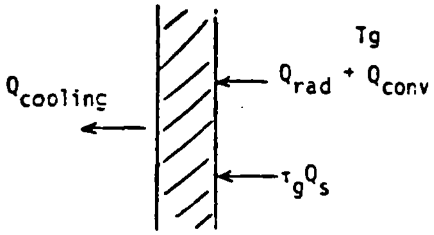
FIGURE D-3 - HEAT BALANCE ON GAS

D.2.2.2 Heat Transfer to Walls

The walls receive heat by radiation and convection from the gas and the rest of the solar heat that was transmitted through the gas assuming no soot formation. The walls lose heat to the coolant as shown in the diagram below.

$$Q_{rad} + Q_{conv} + \tau_g Q_s = Q_{cooling} \qquad (D.3)$$

where:	Q_{rad}	is the heat by radiation from the gas
	Q_{conv}	is the heat by convection from the gas
	τ_g	is the transmittancy of the gas $\tau_g = 1 - \alpha_g$
	$Q_{cooling}$	is the heat removed by cooling



Equation D.3 was used to obtain the rate of cooling required and to decide on the material of the walls and the cooling medium. The heat received by the walls directly from the solar flux is $Q_s\ (1-\alpha_g) = 86{,}547\ (1-.0306)$ $= 83{,}899$ Btu/hr, which is much larger than the heat received from the gas by radiation and convection (2937 Btu/hr). The total heat to be removed from the walls by cooling is about 86,000 Btu/hr. Using 5/8" thick silicon carbide ceramic, a temperature drop of 2400^oF to 2365^oF is obtained across the lining. The heat transfer area is 17 ft^2; it includes the six fins and the outer surface of the ceramic in contact with the cooling fluid (air in this case). The convective heat transfer coefficient between the air and the ceramic was found iteratively.

The bulk temperature was found to be at 1100^oF with $\bar{h} = 3.95$. The air velocity was calculated from the following equation for a flow in a duct.

$$\bar{N}u_{D_H} = .023\ Re_{D_H}^{\ .8}\ Pr^{.33} \qquad (D.4)$$

Each space between two fins forms a duct with a hydraulic diameter D_H = .27 ft. The velocity was found to be 37 ft/sec and the air volume flow rate of air needed to remove 86,000 Btu/hr was 220 CFM. The heat loss through the ducts was calculated from the following equation.

$$h_L = f\ \frac{L}{D_H}\ \frac{V^2}{2g} \qquad (D.5)$$

and had a value of 16 ft (0.1" water).

The temperature distribution along the fins was found as follows:

$$T = T_\infty + (T_S - T_\infty)\left[\frac{\cos h\ m\ (L - X)}{\cos h\ m\ L}\right] \qquad (D.6)$$

where: L = the length of the fin

$m^2 = \bar{h}P/k\ A_c$

P is the fin perimeter

A_c is the fin cross-sectional area

T_S is the ceramic surface temperature

T_∞ is the air bulk temperature

The temperature at the end of the fin ($X = L$) was found to be 1500°F.

Due to the high temperatures involved, the steel casing has to be protected using an insulating material such as Saffil Kaowool Blanket which has a low thermal conductivity and can handle temperatures up to 3000°F. The insulation thickness depends on the temperature of the steel casing. Keeping the steel casing at 1400°F requires about 1" of insulation. Keeping the steel casing at 800°F would require 3.5" of insulation. Therefore, using 2" of insulation, the steel casing will remain at about 1100° maximum.

D.2.2.3 Heat Transfer to Window

The main source of heat to the window is the solar flux. Additional heat is received by radiation from the walls and gas and by convection from the gas. Heat is removed from the window by impinging a jet of air on it.

$$\alpha_w Q_s + Q_{rad\ gas} + Q_{conv\ gas} + Q_{rad\ walls} = Q_{jet} \qquad (D.7)$$

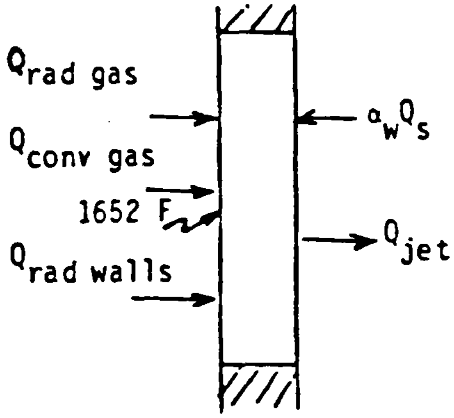
where: Q_s is the solar flux

$Q_{rad\ gas}$ is the heat by radiation from the gas

$Q_{conv\ gas}$ is the heat by convection from the gas

$Q_{rad\ walls}$ is the heat received by radiation from the walls

α_w is the window absorptivity in the solar spectrum (.05 for Fused Silica)



Q_{jet} is the heat removed by cooling to keep the hot face of the window at or below its normal operation temperature (1652°F for fused quartz). The solar heat flux makes the largest contribution to the window.

Cooling from the hot face of the window would introduce a large volume of air into the combustion chamber which would constitute a lot of excess air (much higher than 200%), therefore, cooling of the window has to be done from the outside using an impinging jet.

The window absorbs 4327 Btu/hr from the highest solar heat flux of 86,547 Btu/hr and receives 1355 Btu/hr by radiation from the walls and gas and by convection from the gas.

A 9" diameter, 1/2"-thick fused quartz window at 1652°F on the hot face, would have a temperature of 1226°F on the cold face and requires 160 CFM of air at 100°F to cool it. A 9" diameter, 1"-thick Fused Silica window at 1652°F on the hot face would be at 800°F on the cold face and requires 300 CFM of air to cool it. Since a thinner window is easier to cool, a 1/2"-thick fused quartz will be used, cooled by 300 CFM of air on the outside.

D.2.2.4 Exhaust Flow Rate

The exhaust gases in this case are made up mainly of air and nitrogen and therefore have a density close to air at that temperature. The exhaust gases flow at a rate of 61.6 lb/hr and have a density of .0133 lb/ft^3 at 2440°F and 14.5 psi (a slight vacuum of 5" water) which gives a volume flow rate of 76 ft^3/min of exhaust gases. An estimate of the residence time can be obtained by dividing the volume of the cylinder by the exhaust flow rate, i.e.,

$$t \approx \frac{2.36 \text{ ft}^3}{76/60 \text{ ft}^3/\text{sec}} = 1.86 \text{ sec}$$

It can be seen here that the residence time can be controlled by varying the exhaust fan speed. An average velocity of the gases inside the chamber of 1.6 ft/sec was obtained by dividing the gas volume flow rate by the cross-sectional area.

D.2.2.5 Thermal Expansion

One potential problem that may be encountered putting the vessel together would be the differential expansion of the two difference materials (silicon carbide and steel) at different temperatures.

To find a proper seal we need to examine the thermal expansion.

γ = coefficient of thermal expansion

γ steel at 1100°F is 7.9×10^{-6}

γsilicon carbide at 2400°F is 2.7×10^{-6}

ε= linear expansion

Because restriction will occur mainly in one dimension, assume linear expansion

ΔT for steel is 1100°F - 100°F = 1000°F

ΔT for ceramic is 2400°F - 100°F = 2300°F

for steel $\varepsilon = 7.9 \times 10^{-6} \times 50'' \times (1100 - 100) = .395''$

for ceramic $\varepsilon = 2.7 \times 10^{-6} \times 50'' \times (2400 - 100) = .3105$

$\Delta\varepsilon = .395'' - .3105'' = .0845''$

Therefore, the gaskets used will be able to absorb .0845" strain when they are preloaded originally.

D.2.3 Stress Calculations

Stress calculations were performed for the prototype detoxifier to assure that all components were adequate for the intended service. These calculations evaluated the proposed materials for the anticipated operating conditions with particular emphasis on the effect of the operating temperature. The metal container around the ceramic liner in addition to the component supports were evaluated. The effect of the thermal expansion of the ceramic cavity versus the metal container was also evaluated to assure that thermal restraint was not a concern. As a result of this evaluation, the final design concept as shown in Figure D-1 was established.

D.2.4 Assembly Procedure and Weight Evaluation

D.2.4.1 Assembly Procedure

The final design was conceived keeping in mind several basic aspects: safety, ease of fabrication and handling. Complicated procedures in component design were avoided where possible to the extent that would insure structural stability. During assembly, the following procedure should be followed:

After fabricating the steel shell, the inside insulation is installed as a 2" thick layer on the inside of the main shell and 1.25" thick layer on the inside of the exit nozzle. The insulation needs to be contoured to insure the circulation of the cooling air through the entrance, overall annulus and exit passages.

The ceramic shell is put in place, piece by piece, ensuring proper seal between every two connecting pieces and also at each end where the ceramics shell comes in contact with the steel shell. 2). Gaskets are used at each end of the ceramic liner to account for manufacturing tolerances in the length of the ceramic and the steel shell, and to assure that a compressive load is applied between the steel shell and the ceramic liner in order to maintain alignment. Gaskets are also put between the outer steel shell flange and the front cover plate to minimize cooling air leakage andprovide for assembly tolerances. Finally, the end plate containing the window and the manifold assembly, is bolted in place.

After the control instrumentation (thermocouple and pyrometer) and external connections are mounted on the vessel, the outside insulation is installed. This insulation may be wrapped with aluminum lagging to avoid deterioration.

This detoxifier assembly is subsequently supported on the two saddle type supports.

D.2.4.2 Weight Evaluation

The weight of the basic prototype detoxifier is of importance in order to assure compatibility with the positioning table available at the solar furnace test facility. In addition, the weight is important from the handling and assembly standpoint. As a result, the weight determined for the basic prototype detoxifier design is approximately 800 pounds assembled. The design has been established in a manner that allows component assembly using a building block approach resulting in subassembly weights that are manageable at the test facilities.

D.2.5 Instrumentation and Control System

A preliminary assessment of the instrumentation and control system has been made. Additional development of the system will be required in subsequent phases.

D.2.5.1 Temperature Consideration

In order to monitor the temperature at various points of the assembly, the following instrumentation needs to be supplied:

a. Pyrometer inside the combustion chamber

b. Thermocouple at the entrance window

c. Thermocouple at the exit nozzle

d. Thermocouple at the outside of the steel shell close to the point where the process is taking place.

Specific upper limit temperatures are assigned for the various positions:.

Location	Upper Limit Temperature
a. Ceramic Chamber	2500°F
b. Entrance Window	1600°F
c. Exit Nozzle	1500°F
d. Outer Steel Shell	1200°F

The temperature can increase at any point for a number of reasons, including:

1. Malfunction of pump for ceramic liner cooling air and/or cooling air on window (inside, outside)
2. Uncontrolled solar intensity
3. Malfunction of exhaust fan
4. Uncontrolled fuel feeding

If the temperature at any point approaches the temperature limit, the following actions should be taken instantaneously (automatically):

1. Shut off the fuel feeding
2. Shut off the solar beam
3. Increase the exhaust fan speed

It is recommended that all the thermocouples and the pyrometer are connected to the same control panel rather than in separate, so all of the above steps will occur simultaneously.

Also, it may be advisable to have two independent control systems in case one fails.

D.2.5.2 Pressure Consideration

To sense the pressure, a pressure transducer is needed inside the combustion chamber connected to the same control system that regulates the temperature. If the pressure inside the combustion chamber exceeds 14.7 psia (or 0 psig), the same action will be taken as in the temperature increase case, in order to avoid leakage from inside the detoxifier to the outside environment.

D.3 Conceptual Detoxifier System Design

As previously defined in Section D.2.1, the conceptualized detoxifier system (Figure D-2) is designed for a continuous feed of waste material into the ceramic chamber. Provisions have been made for adequate instrumentation and safeguards for successful operation as defined in Section D.2.5.

Design upgrades may be required to incorporate refinements necessitated to assure compatibility with the final prototype subsystem test plan. These upgrades include consideration of the following:

- Preheating the PCBs to various controlled temperatures prior to their injection into the cavity.
- Introducing the PCB mixture in a vapor state into the cavity.
- Include an air dryer in the air supply line to guard against devitrification of the window material.
- Varying the axial distance of the flame front relative to the ejection nozzle for better evaluation of the ratio of photolytic to thermal destruction efficiencies.

D.4 Developmental Design Concepts

Many different designs of incinerators were considered and analyzed. Heat transfer and fluid calculations were performed to various shapes ranging from rectangular to cylindrical. A brief review of some of these concepts follows.

D.4.1 Design I

At an early stage of this study, steps were taken toward the design of a solar detoxifier by incorporating conventional furnace design concepts keeping in mind the special application at hand. Figure D-4 shows the first design of the detoxifier and the arrangement of its components. This design was based on the understanding that a 6.57" fused silica window would be used with the highest solar heat flux available at White Sands Solar Facility where the solar beam has a 6" focal plane diameter with a 20^{o} solid angle of divergence. The solar beam would impinge on the back wall which was selected to be a high conductivity ceramic. Cooling with water was found to be adequate.

A mixture of PCB, fuel and air is injected into the detoxifier cavity through an atomizer. The mixture is sprayed into the incident solar beam. Additional air enters the detoxifier below the window to keep it clear from any soot that may develop in the detoxification process. Due to the heat transfer properties of the window material, a stream of air is also used to cool the window from the outside.

D.4.2 DESIGN II

The second design is an amelioration of Design I and incorporates more details and specifications of materials used and their sizes. Figure D-5 shows the second design. The window was enlarged from 6.5" to 9" to prevent

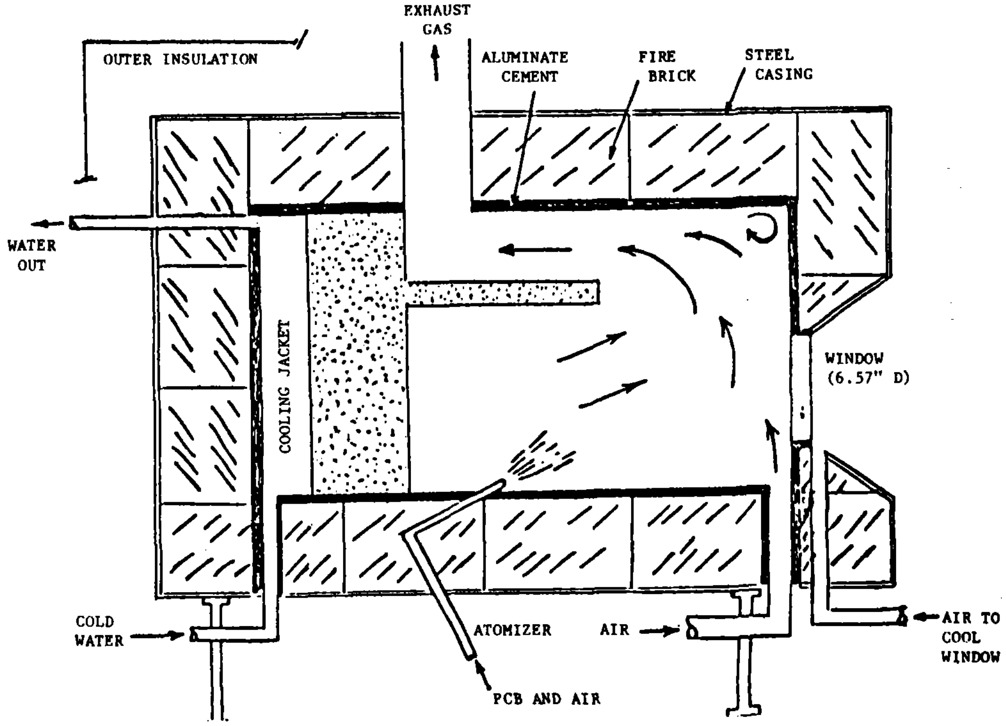


FIGURE D-4 DESIGN I

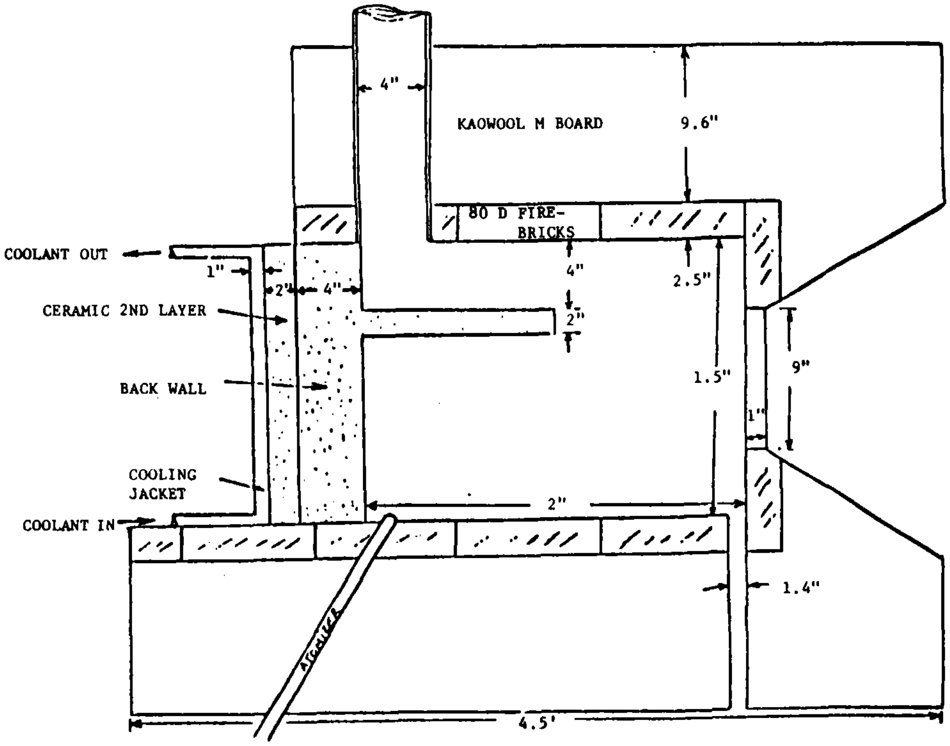


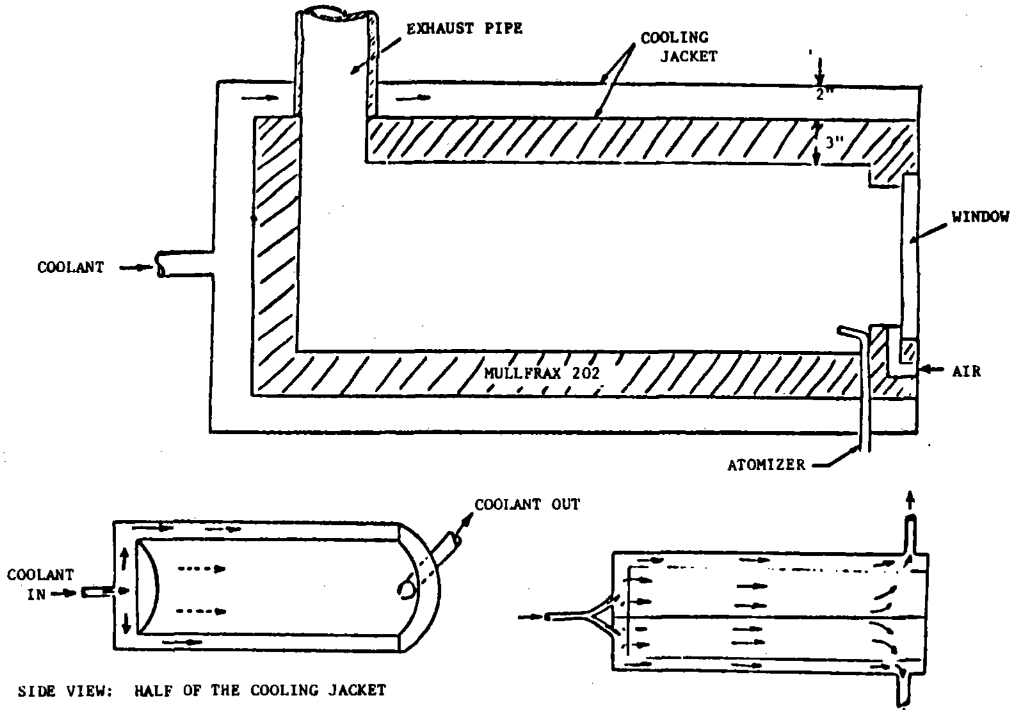
FIGURE D-5 DESIGN II

the edges of the solar beam from falling on the casing. A 9" window was found to be easier to cool than a smaller window because of the larger area available for the heat transfer and is therefore recommended for use. Cooling of the window is achieved by impinging atmospheric air from a round pipe manifold which surrounds the window. B&W Insulating Product Division Firebrick 80-D was selected to be at the hot face because of its ability to handle high temperatures up to 3000°F and resist hydrochloric acid and chlorine. High temperature ceramics such as Crystolon CN 163 (Norton Company) and CN 178 were chosen for the back wall. Cooling the wall with air was not possible because of the large heat flux (86,000 Btu/hr) and the relatively small area of the wall (1.5' x 1'). Dowtherm was considered as a coolant, but it has a limited working temperature range (200-700°F) which was not enough to cover a potential wide range of varying solar heat flux. A solution to that problem was provided by adding ceramic slabs behind the back wall which then could be cooled with Dowtherm. The aim of adding the slabs was to maintain the cavity at 2400°F and the cooled walls at 500°F as the solar heat flux is reduced. Otherwise, reducing the heat flux would cause the gas temperature to drop, which is undesirable.

This apparatus was estimated to weigh a minimum of 800 lb and had outer dimensions of 4.5' x 3.6' x 3.1'. The weight, size and assembly techniques were regarded as highly undesirable.

D.4.3 DESIGN III

The third design, shown in Figure D-6, has the concept of making the detoxifier simpler to assemble. The inner cavity was designed as a one-piece 3"-thick castable material. Mullfrax 202, a ceramic with a low thermal conductivity, was used to obtain a temperature drop from 2400°F to 450°F, a temperature that can be handled by a coolant such as Dowtherm. The coolant



SIDE VIEW: HALF OF THE COOLING JACKET

TOP VIEW OF COOLING JACKET

FIGURE D-6 DESIGN III

flows in a cylindrical shell that covers the ceramic piece. The dimensions of this detoxifier were chosen in such a way as to comply with space limitations at the test sites and to obtain roughly the same mass flow rates of fuels and air inside the incinerator.

This design is limited by the working range of Dowtherm (200-700°F), which does not allow a wide variation of the solar heat flux.

D.4.4 DESIGN IV

The fourth design is a one-piece castable ceramic cavity with six fins. The ceramic is a 1/2"-thick Alfrax 201 (Carborundum Co.), a high temperature material that can handle hydrochloric acid and chlorine. This design is potentially lighter and uses air as a coolant. The ceramic piece is estimated to weigh about 50 lb. Figure D-7 shows the ceramic piece details. Figure D-8 shows the ceramic and the casing assembly. A 9" window is placed at one end of the finned cylinder and the exhaust pipe at the other. The exhaust pipe is cemented to the ceramic cylinder using Alfrax mortar (Carborundum Co.). The atomizer is located near the bottom of the window and sprays the air and fuel mixture toward the center of the cavity. Auxiliary air is introduced into the chamber from a 9" x 1-1/4" slot beneath the window.

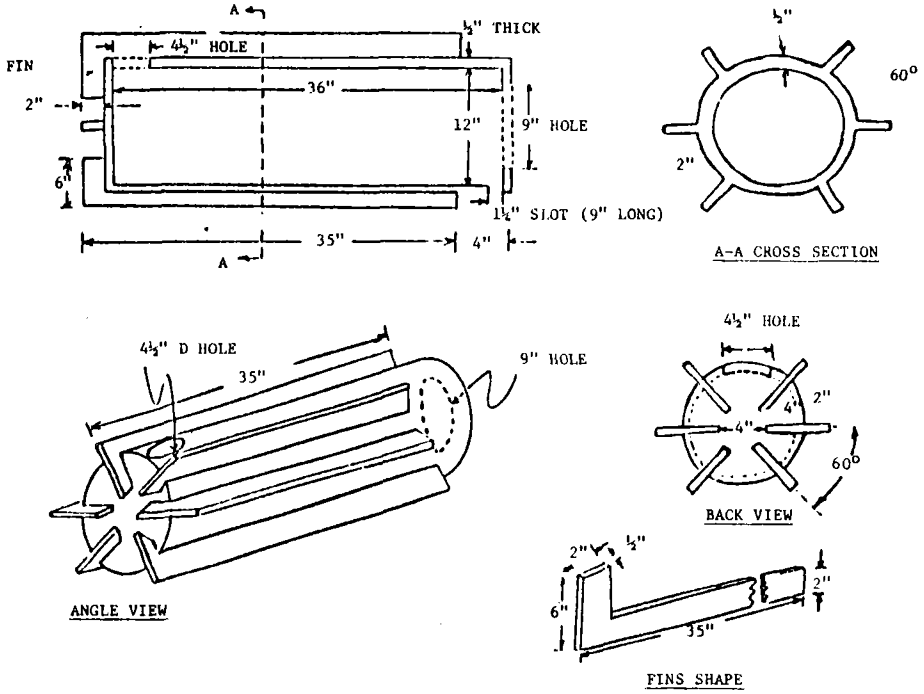


FIGURE D-7 DESIGN IV

DETAILS OF CERAMIC CYLINDER

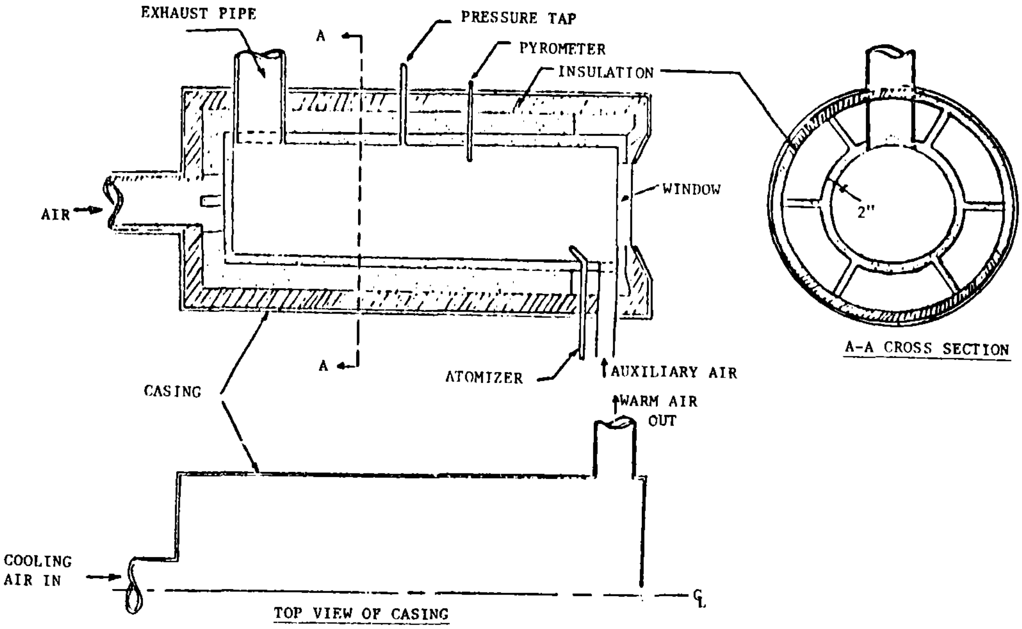


FIGURE D-8 DESIGN IV

CERAMIC AND CASING ASSEMBLY

APPENDIX E

OPTICAL REQUIREMENTS FOR THE PHOTOLYTIC DETOXIFIER

APPENDIX E - TABLE OF CONTENTS

E.0 Optical Requirements for the Photolytic Detoxifier

This appendix presents the evaluation used to select the optical and window material to be used in the prototype photolytic detoxifying reactor.

E.1 Design Constraints and Assumptions

In determining optical design requirements, the following constraint factors must be evaluated:

- Two solar furnace test sites are currently being considered for the prototype tests. The design must be able to accommodate both.
- Normal steady state combustion of the compounds and mixtures we will be testing will not create smoke. This is fortunate since smoke would act as an optical barrier and possibly settle on the window's inner surface. The products of combustion will include carbon dioxide, water, hydrochloric acid, chlorine gas, nitrogen gas, and oxides of nitrogen.
- The reactor operating temperature will be between 1,200 and 1,500 degrees C. (If the photolytic effect can be maximized, lower temperatures may be possible.)

E.2 Design

Having considered these factors, the following recommendation is made:

E.2.1 Window Material

A premium grade of ultraviolet fused quartz (amorphous silicon dioxide) was selected. This was chosen primarily for its transparency to the ultraviolet portion of the solar spectrum. Other properties leading to the selection of fused quartz are its resistance to chemical attack, size availability, and low thermal conductivity.

The primary reference influencing this selection is "Georgia Tech Solar Thermal Ceramics Research", by S. H. Bomar, September 1983. This paper documents actual tests made in six materials:

Fused Quartz (standard grade)
Vycor
Pyrex
Sapphire
Vistal
Spinel

These materials were tested as a function of flux, operating temperature, and atmosphere. Note, however, that for the prototype test a "premium" grade of quartz is specified which results in a significantly higher ultraviolet transmittance than the "standard" grade. The following chart gives the top three candidates and their relevant characteristics:

Material	Melting Temp. (Degrees C)	Transmittance (300 nm)	Remarks
Fused Quartz	1700	.92	Premium Grade UV
Sapphire	2030	.83	Single Crystal AL203
Vycor	1500	.75	95% Silica Glass

Suggested materials are Corning 7940, Dynasil 1000. Section E.2.11 presents the specification sheets for this material.

E.2.2 Window Finishing

Of the three properties: index of homogeneity, total inclusion cross-section and surface finish, the last two are of most concern. Total inclusion cross-section should be as low as possible. This will allow the maximum amount of ultraviolet radiation to pass through the window and will decrease window cooling requirements. Surface finish is important insofar as it affects scattering and reflection of the incident solar energy. This is particularly critical with the ultraviolet end of the spectrum due to its short wavelength. Surface finishing specification is:

Mil-0-13830A - Transmitted wavefront lambda/4
- Surface quality 80-50
- Parallel 2 arc min.
- 95% central clear area

The transmittance of the finished window shall be checked using a 300 nm wavelength source to verify the manufacturer's specification.

E.2.3 Window Size

The thickness of the window, in the range we are considering, has an insignificant effect on the optics and should be chosen solely on the basis of structural and thermal requirements. The reactor design should incorporate some method of varying the effective window diameter. Due to reradiation out of the cavity, net energy capture is a function of window size. A variable window diameter will allow optimization of performance as testing experience is accumulated. It will also ensure the ability to adapt optimally to the test site finally chosen. Because roughly 100% of the available power is projected through a six-inch diameter circle at the focal plane, this is the maximum effective diameter from a purely optical or energy balance point of view. Other design aspects of the reactor may favor a larger window diameter (such as fringe effects or window stress due to differential expansion of the reactor body and the window). However, any increase in window diameter beyond six inches will necessarily decrease the available energy in the reactor due to reradiation losses through the window. The system used to alter diameter should have two simultaneous, yet separate effects. First, it should block a portion of the incoming radiation so that it does not reach the reactor/window outside of the desired area. Second, and of greater importance, the system should keep energy from reradiating out of the cavity, except through the desired area. This might be accomplished by the use of removable interior and exterior orifice plates. If this type of arrangement is chosen, the interior plate should be of such a nature as to reflect the energy back into the reactor interior.

E.2.4 Window Temperature

The window itself must be kept below 900 degrees C. This is the maximum recommended temperature for normal continuous service. Also, thermal cycling of the window with this temperature as an upper bound will prevent devitrification (a recrystallization effect) of the window's inner surface, should any of the chemical species within the reactor inadvertently come in contact with it. Any method used to keep the window cool should not interfere with or filter the solar beam. For example, should a cooling system be selected which uses a liquid or gas stream flowing over the window, the fluid chosen should not tend to absorb ultraviolet radiation.

E.2.5 Window Placement

Window should be at or close to the focal plane of the facility for maximum energy capture.

E.2.6 Window Protections

None of the chemicals to be tested or their reaction products should come into direct contact with the window. Design of the reactor should prevent any conceivable contamination from being deposited on the inner surface of the window. If this were to happen, the results could be a rather dramatic destruction of the window caused by the almost instantaneous high temperature generated at the window's inner surface. This, if nothing else, could present a significant safety hazard even with the slight negative design pressure in the chamber.

E.2.7 Energy Flux

In using the solar facility flux data, apply a 10% drop in peak flux to allow a design margin for atmospheric or facility conditions.

E.2.8 Irradiation of Reactants

After the flux has passed through the window, it must be allowed to irradiate the chemicals being tested in their mist/vapor state. This is critical for energy absorption and the resulting photolytic degradation. Nothing should interfere with this process, including (if possible) the flame front of the combustion reaction. Test compounds should tend to be injected toward the axis of the focal zone so as to be irradiated with as high a flux density as is available.

E.2.9 Combustion Control

Depending on the reactor design, there needs to be an ignition point for the combustion of the test chemicals. This will be some part of the reactor (perhaps a matrix area) or some "seed" objects entrained in the gas flow. The "seed" will absorb enough light energy to be raised above the ignition temperature of the test chemicals.

E.2.10 Detoxifying Reactor Design

The interior areas of the reactor which will be directly irradiated by the incoming solar energy should be made of appropriate materials and/or situated far enough behind the focal plane so that the energy density will not cause failure. Also, these areas should be of such a configuration as to minimize direct reflection back out through the window. It may be desirable to configure this area so as to distribute flux more evenly throughout the reactor.

E.2.11 SPECIFICATION SHEETS - CORNING 7940 AND DYNASIL 1000

E. 2.11.1 DYNASIL 1000

Dynasyl 1000

Optical Properties

Glass Type Number (MIL-G-174A) **458-678**

Abbe Constringent Coefficient

Helium $V_d = \dfrac{n_d - 1}{n_F - n_C} = 67.8 \pm .5$

Sodium $V_D = \dfrac{n_D - 1}{n_F - n_C} = 67.8 \pm .5$

d = 5876 Å
D = 5893 Å
F = 4861 Å
C = 6563 Å

Temperature Coefficient of Refractive Index

$\dfrac{\Delta n}{\Delta t}$ (20°C to 30°C)

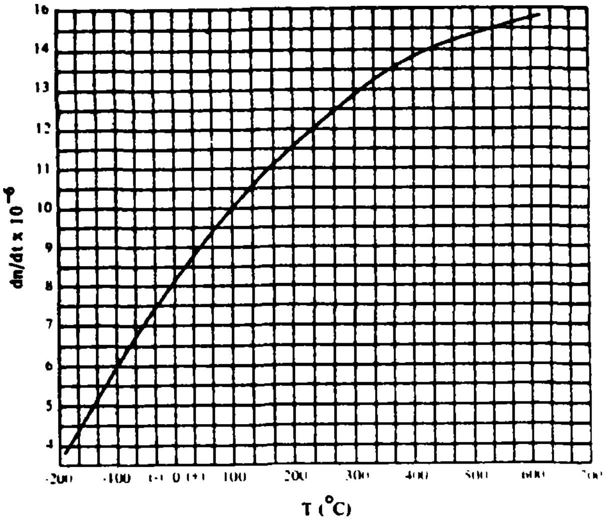
at	0.21 microns	15 X 10^{-6}
	.3650	10.7
	.4047	10.1
	.5461	9.9
	.5876	9.9
	.6328	9.9
	.6563	9.9
	2.0	12
	3.7	10

Birefringence Constant: 3.46 mμ cm^{-1}/Kg cm^{-2}

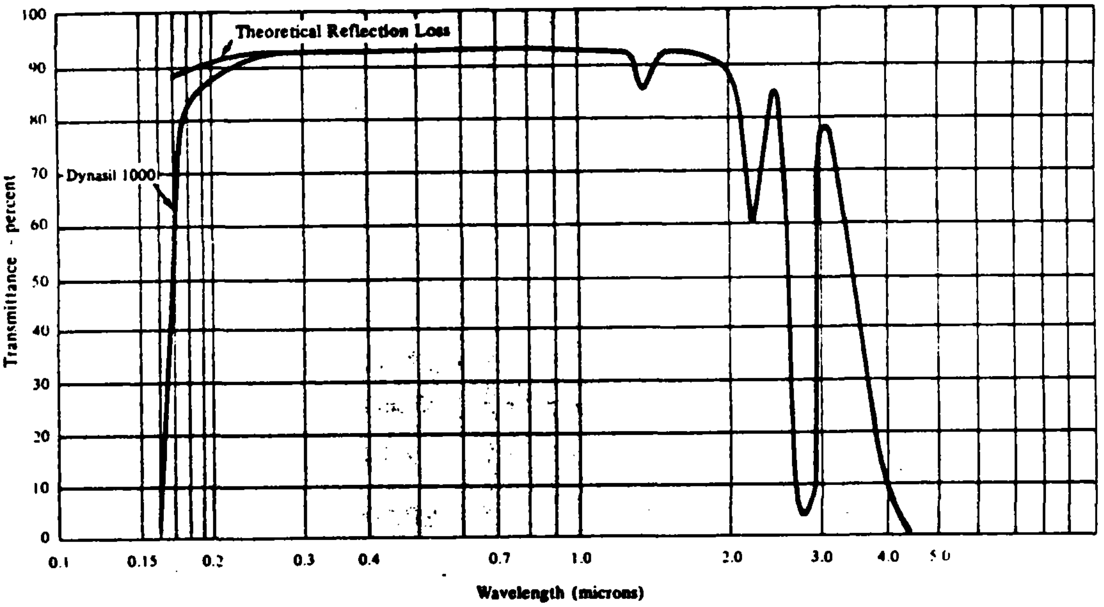
Dispersion equation at 20°C (1)

$$n^2 - 1 = \frac{0.6961663\lambda^2}{\lambda^2 - (0.0684043)^2} + \frac{0.4079426\lambda^2}{\lambda^2 - (0.1162414)^2} + \frac{0.8974794\lambda^2}{\lambda^2 - (9.896161)^2}$$

Refractive Index
Change with Temperature (λ = 587.6 mμ)



Transmittance (10 mm Thickness - Reflective Losses Included)



Note: Above transmittance curve is typical of stock materials.

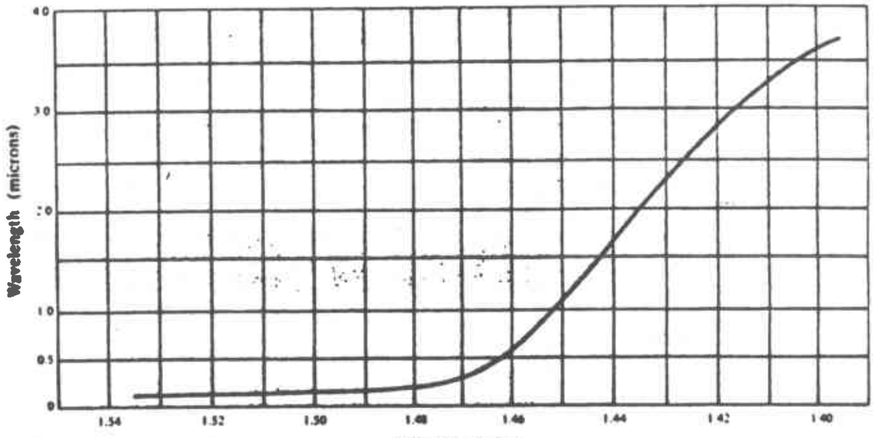
Dynasil 1000

REFRACTIVE INDICES OF Dynasil (20°C) (2)

WAVELENGTH (MICRONS)	SPECTRAL SOURCE	INDEX	WAVELENGTH (MICRONS)	SPECTRAL SOURCE	INDEX
0.213856	Zn	1.534265	0.643847	Cd	1.456708
0.214438	Cd	1.533701	0.656272	H	1.456372
0.226747	Cd	1.522818	0.667815	He	1.456073
0.230209	Hg	1.520050	0.706519	He	1.455157
0.237833	Hg	1.514752	0.852111	Cs	1.452468
0.239938	Hg	1.513369	0.894350	Cs	1.451840
0.248272	Hg	1.508397	1.01398	Hg	1.450245
0.265204	Hg	1.500004	1.08297	He	1.449406
0.269885	Hg	1.498043	1.12866	Hg	1.448877
0.275278	Hg	1.495921	1.3622	Hg	1.446198
0.280347	Hg	1.494030	1.39506	Hg	1.445840
0.289360	Hg	1.491012	1.4695	Cs	1.444984
0.296728	Hg	1.488722	1.52952	Hg	1.444274
0.302150	Hg	1.487192	1.6606	TCB[a]	1.442651
0.330259	Zn	1.480549	1.681	Poly[b]	1.442404
0.334148	Hg	1.479762	1.6932	Hg	1.442254
0.340365	Cd	1.478586	1.70913	Hg	1.442060
0.346620	Cd	1.477456	1.81307	Hg	1.440692
0.361051	Cd	1.475120	1.97009	Hg	1.438531
0.365015	Hg	1.474524	2.0581	He	1.437215
0.404656	Hg	1.469617	2.1526	TCB	1.435744
0.435835	Hg	1.466694	2.32542	Hg	1.432925
0.467816	Cd	1.464295	2.4374	TCB	1.430933
0.486133	H	1.463131	3.2439	Poly	1.413147
0.508582	Cd	1.461864	3.2668	Poly	1.412535
0.546074	Hg	1.460079	3.3026	Poly	1.411565
0.576959	Hg	1.458849	3.422	Poly	1.408222
0.579065	Hg	1.458775	3.5070	Poly	1.405656
0.587561	He	1.458462	3.5564	TCB	1.404145
0.589262	Na	1.458407	3.7067	TCB	1.399375

[a] TCB = 1, 2, 4 - Trichlorobenzene [b] Poly = Polystyrene

WAVELENGTH (MICRONS)	LASER SOURCE	INDEX(3)	WAVELENGTH (MICRONS)	LASER SOURCE	INDEX
0.4880	A	1.463015	0.840	GaAs	1.452655
0.5682	Kr	1.459177	1.060	CO_2	1.449679
0.6328	HeNe	1.457018	1.060	Nd in glass	1.449679
0.6943	Ruby	1.455424	1.0648	N-YAG	1.449621



(1), (2), (3) Malitson, I. H. "Interspecimen Comparison of the Refractive Index of Fused Silica," *Journal of the Optical Society*, vol. 55, No. 10, October 1965.

E.2.11.2 CORNING 7940

Tolerances and Finishes

Industrial Grade Fused Silica surfaces sawcut +0.250 -0.

Optical, Ultraviolet & Special Grades of Fused Silica	Faces ground (80 grit) +0.020 −0, edges ground + 0.080 −0

Blanchard Ground Ware

Maximum Dimension	Edges	Faces	Parallelism	Flatness
Up to 12"	+0.010"−0	+0.010"−0	within 0.004"	within 0.005"
Over 12" up to 48"	+0.080"−0	+0.010"−0	within 0.004"	within 0.005"
Over 48" up to 80"	+0.080"−0	+0.020"−0	within 0.004"	within 0.005"

Commercial Polished
(Faces Only)

Maximum Dimension	Edges	Faces	Parallelism	Flatness
Up to 12"	+0.010"−0	+0.010"−0	within 0.010"	within 0.005"
Over 12" up to 48"	+0.080"−0	+0.020"−0	within 0.020"	within 0.005"

Optical Properties

Birefringence constant (nm cm ^{1}/kg cm ^{2})		3.45
Refractive index and dispersion		
	n_F (486 mμ)	1.46313
	n_D (589 mμ)	1.45840
	n_C (656 mμ)	1.45637
Abbe Constant	$V = \frac{n_D - 1}{n_F - n_C} =$	67.8

Glass type No 458 678 (MIL-G-174)

Refractive Index (Measured at 20°C)

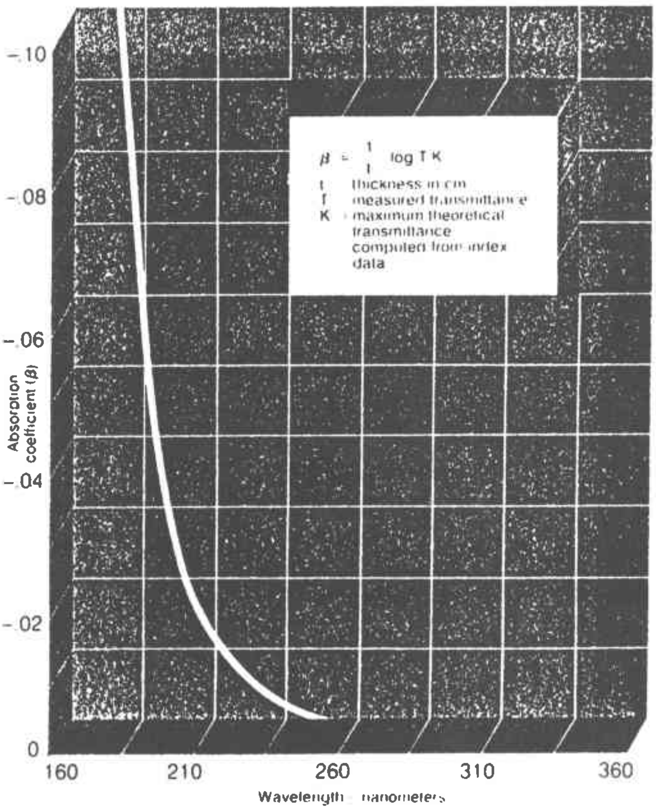
K Maximum possible transmittance(assuming absorption O)
R Single Surface reflectance

WAVELENGTH IN MICRONS	INDEX OF REFRACTION	R	K
155	1 6723	0633	877
1575	1 65945	0615	881
16	1 6179	0599	884
165	1 62798	0571	889
17	1 61138	0548	893
175	1 59734	0529	897
18	1 58529	0512	900
185	1 57485	0498	903
19	1 56572	0486	905
195	1 55766	0475	907
2	1 55051	0466	909
205	1 54411	0457	911
21	1 53836	0449	912
215	1 53316	0443	913
22	1 52845	0437	914
225	1 52416	0431	916
23	1 52024	0426	916
235	1 51664	0421	917
24	1 51333	0417	918
242	1 51208	0416	919
245	1 51027	0413	919
25	1 50745	0409	920
3	1 48779	0384	925
32	1 48274	0378	926
35	1 47689	0371	927
4	1 47012	0362	929
45	1 46557	0356	930
5	1 46233	0352	931
55	1 45991	0349	931
6	1 45804	0347	932
65	1 45664	0345	932
7	1 45529	0344	932
75	1 45424	0342	933
8	1 45332	0341	933
85	1 4525	0340	933
9	1 45175	0339	933
95	1 45107	0339	933
1	1 45042	0334	934
1 3	1 44692	0334	934
1 4	1 44578	0332	935
1 45	1 4452	0332	935
1 5	1 44462	0331	935
1 7	1 44217	0328	936
2	1 43809	0323	936
2 15	1 43581	0320	937
2 25	1 4342	0318	937
2 35	1 4325	0316	938
2 4	1 43163	0315	938
2 6	1 42789	0311	939
2 65	1 4269	0309	939
2 7	1 42588	0308	939
2 75	1 42484	0307	939
2 8	1 42377	0306	940
2 9	1 42156	0303	940
3	1 41925	0300	941

WAVELENGTH IN MICRONS	INDEX OF REFRACTION	R	K
3 1	1 41682	0297	941
3 2	1 41427	0294	942
3 3	1 41161	0291	943
3 4	1 40881	0288	943
3 5	1 40589	0285	944
3 6	1 40282	0281	945
3 7	1 39961	0277	945
3 8	1 39625	0273	946
3 9	1 39272	0269	947
4	1 38903	0265	948
4 15	1 38315	0258	949
4 2	1 3811	0256	949
4 3	1 37684	0251	950
4 4	1 37238	0246	951
4 5	1 3677	0241	952
4 6	1 36278	0236	953

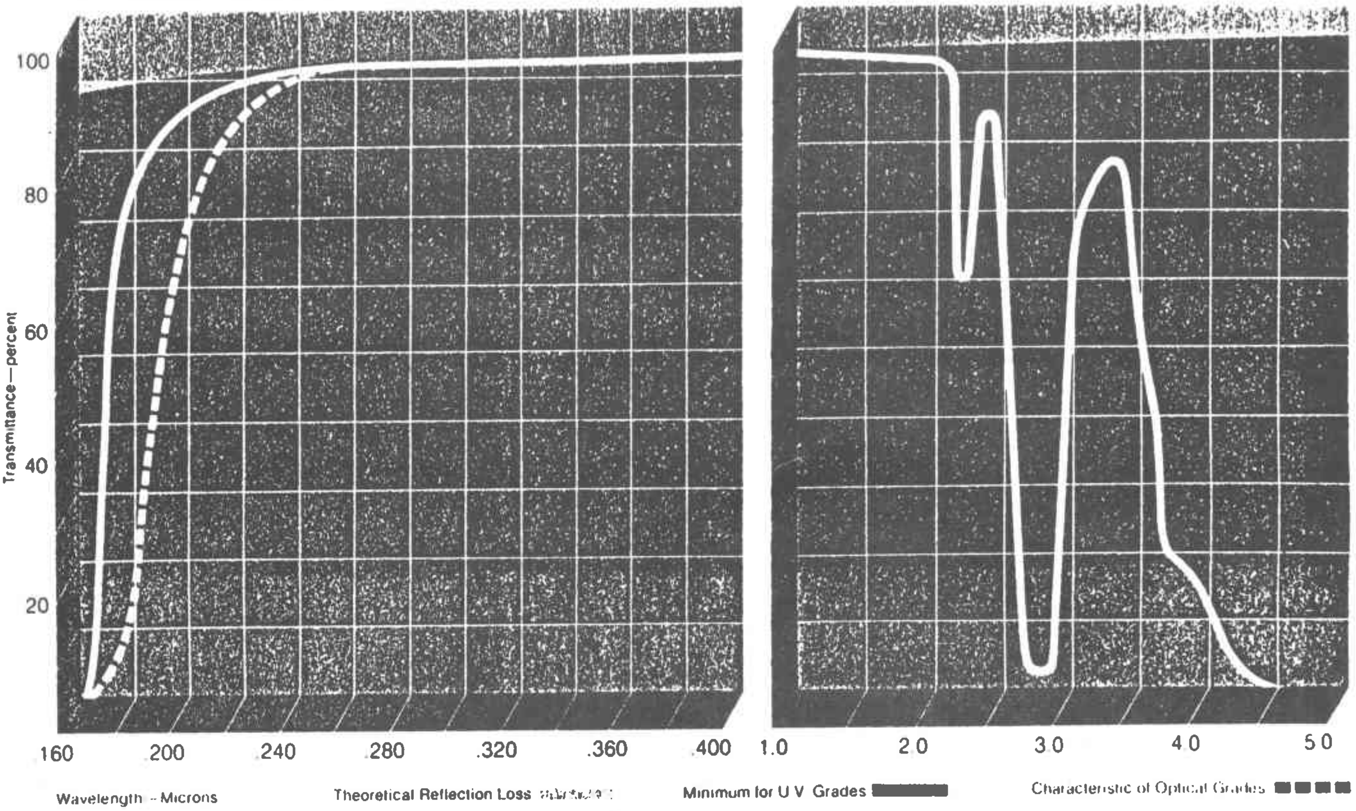
Source Malitson I H Journal of the Optical Society of America 1965

Absorption Coefficient of Fused Silica With Minimum Transmittance of Ultraviolet Grade.



Transmittance of Fused Silica Code 7940

1 cm Thickness—Surface Reflection Losses Included



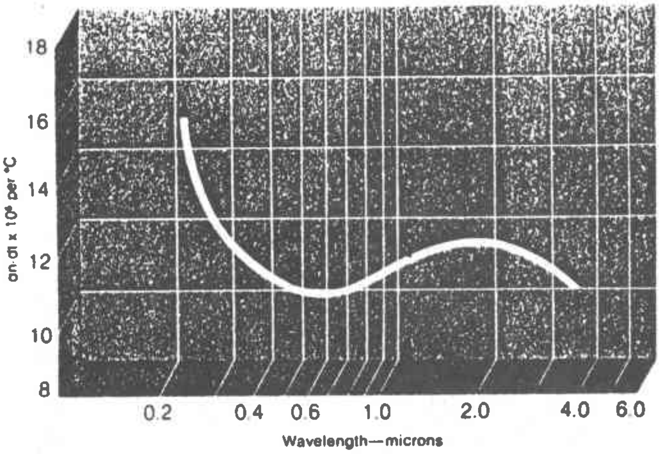
To calculate transmittance (T_2) at a thickness other than 1 cm

$$T_2 = \frac{T_1^{(t_2)}}{K^{(t_2-1)}}$$

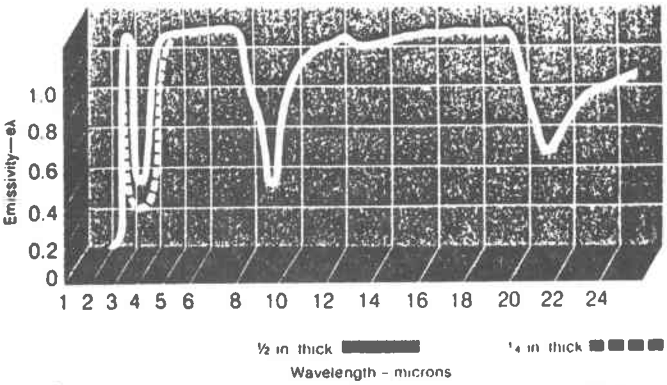
T_1 = Transmittance from plot
K = Max. possible transmittance from refractive index table
t_2 New thickness in centimeters

Optical Properties

Refractive Index Change of Fused Silica



Spectral Normal Emissivity† of Fused Silica



† Computed from room temperature measurements of transmittance and reflectance uniformly heated plates

APPENDIX F

TEST PLAN

APPENDIX F - TABLE OF CONTENTS

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F.0 Test Plan

F.1 Approach to Testing

Two series of tests will be conducted in this overall program.

- Laboratory tests at the University of Dayton Research Institute (UDRI), Dayton, Ohio.
- Receiver/Reactor (R/R) subsystem prototype photolytic detoxifier tests at the White Sands Solar Facility (WSSF), New Mexico.

F.1.1 Laboratory Tests

The laboratory tests to be conducted in Phase II will be used to investigate the photochemical reactions which are basic to the degradation process. UDRI was chosen because of its previous experience investigating thermal destruction of toxic wastes and because much of their equipment is directly usable for the planned tests. Tests are mandatory since data concerning these reactions are nonexistent. A UV radiation source will be used in conjunction with a small electric furnace to simulate the photolytic and thermal degradatory contributions of concentrated solar energy.

Results from these tests will serve three purposes:

- Indicate the extent of photolytic/thermal degradation that can be expected under various conditions of interest.
- Indicate possible areas for improvement of the current prototype design.
- Provide a basis for selecting parameter values for the prototype tests.

F.1.2 Prototype Tests

The prototype tests will be conducted at the WSSF. This facility was selected because of its ability to supply solar UV radiation in sufficient quantity to properly evaluate the prototype R/R. The results of this group of tests will be used to evaluate the R/R design's ability to perform the required toxic waste destruction at a mass flow rate approaching that of a commercial unit.

The prototype R/R's performance will differ from the laboratory reactor primarily due to four reasons:

- The prototype design uses flame mode thermal destruction as opposed to pyrolytic destruction used in the laboratory reactor.
- The percent excess air will probably be much less than in the laboratory reactor and the degree of mixing will differ.
- In the prototype R/R, the toxic substances will be injected as an atomized liquid, as opposed to a vapor. This affects effective residence time at flux/temperature.
- The laboratory tests were conducted on pure undiluted chemicals whereas the majority of the prototype test substances will be target/fuel oil mixtures (the situation that is most frequently encountered commercially).

Although the solar flux intensity and reaction temperature will be lower in the laboratory tests than what will be experienced at the White Sands Solar facility, the reaction kinetics follow well understood physical laws which allow the results to be scaled up to actual solar conditions. In that same vein, the results from the R/R subsystem tests will indicate the feasibility of a commercial unit using this process and provide valuable information for its subsequent design.

F.2 Laboratory Test Plan

F.2.1 Objective

The objective of these tests is to quantify the photochemical effects of ultraviolet radiation on three selected compounds under conditions simulating those expected in the R/R.

F.2.2 Approach

The results of these tests will be embodied in the generation of a number of Destructive Removal Efficiencies (DRE's) and photon absorption figures:

- -- DRE's are a measure of overall destruction effectiveness.
- -- Photon absorption by the waste is required for photolysis (which is basic to this technology). These arrangements will help analyze degradation mechanisms and identify the photolytic improvement over pure thermal degradation.

A sketch of the laboratory setup is given in Figures F-1. A xenon lamp shall be used to generate a simulated solar UV spectrum. Temperature will be controlled by an electric funace. Tests are to be conducted with dilute samples in an atmosphere of flowing air far in excess of that required for stoichiometric oxidation. This approach ensures safe handling of hazardous materials and uniform absorption of simulated solar radiation throughout the reactor.

DRE shall be measured for three different waste streams under various conditions. The DRE of each waste stream shall be determined by the comparison of the Hydrogen Flame Ionization Detector (H2FID) response with the reactor at nondegradative, or transport conditions, to the response at detoxification conditions. Transport conditions are:

-- Xenon lamp off,

-- Temperature = 300 degrees C.

The temperature of 300 degrees C was chosen to ensure that the test substance remains vaporized.

A parametric matrix (see F.2.4) lists the test conditions. Specifically, each waste stream shall be tested at combinations of two mean residence times (t = 0.5 seconds and 2.0 seconds) and two degradation temperatures (T = 700 degrees C and 800 degrees C), in addition to the transport conditions. Furthermore, these conditions shall be tested with UV source on and off to determine the photolytic contribution to degradation at the two elevated gas-phase temperatures. Photon absorbance of the waste and H2FID response for each solar flux level shall be measured.

One photolytic/thermally degraded sample of the reactor effluent shall be collected and subjected to gas chromatographic/mass spectrometric (GC/MS) analysis for identification of possible toxic products of incomplete combustion (PICs). This is another measure of the overall effectiveness of the process.

F.2.3 Major Equipment and Materials

The following is a list of test equipment and materials that require specifications.

UV Source - Xenon lamp and filters to duplicate a given terrestrial solar spectrum.

Lens System - Required for delivering UV radiation to the furnace and to the photo-sensor.

Photo-sensor - For measurement of the UV radiation exiting reactor. Must be calibrated with source to correlate read-out with UV intensity.

Furnace - Capable of supplying the stable temperatures required for reactor simulation and allowing UV radiation for photolysis to enter and leave unobstructed.

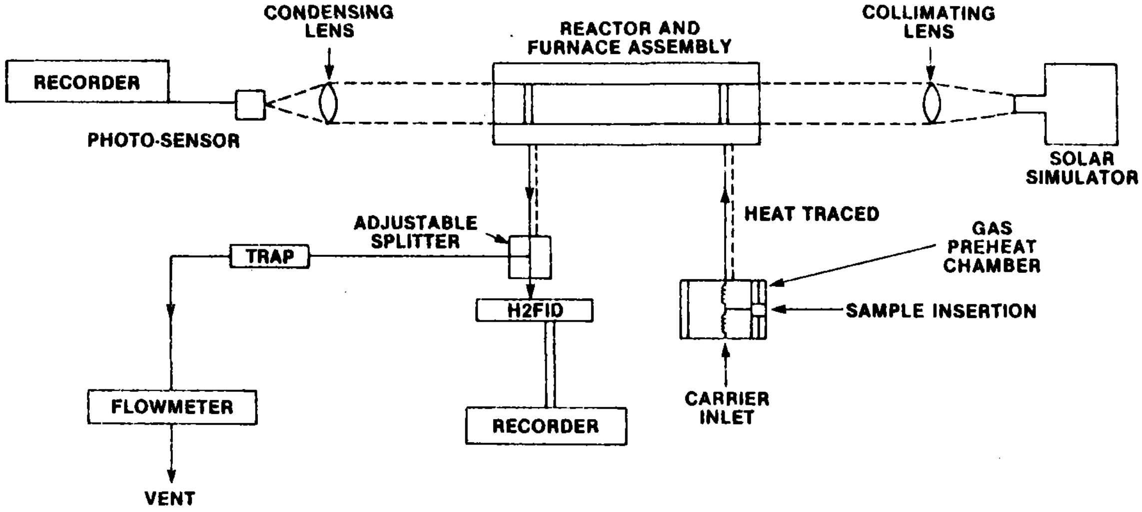

DIAGRAM OF THE LABORATORY TEST SETUP

FIGURE F-1

Quartz Reactor - Reactor must be of high quality to allow maximum transmittance of UV radiation. The material transmittance must be known so as to allow estimation of UV radiation lost to absorption by quartz.

H2FID - This instrument is commonly used to measure mass of toxin remaining after degradation reactions. Its readings shall be used to calculate DRE.

Gas Preheat Chamber - Required for preheating sample/air mixture prior to being admitted to reactor. This facilitates sample transport and ensures temperature homogeneity within reactor.

Flowmeter - To measure exhaust gas mass flow

Trap - To remove any undegraded toxic substances from exhaust gases.

Splitter - Required to remove a percentage of the exhaust gas flow for H2FID measurement.

Data Recorder - Sufficient equipment of suitable accuracy to record the data.

Test Waste Compounds - Either a source of certifiably pure compounds or a procedure for producing them is required.

Reaction Air - A system is required to supply air far in excess of that required for stoichiometric oxidation of test materials. It must be supplied at constant flow and must be devoid of dust, water vapor and other contaminants.

Gas Chromatograph/Mass Spectrometer - This system is required for the detailed analysis of the reactor effluent.

F.2.4 Test Procedures

The DRE's shall be completed as a function of:

-- Waste material composition,

-- Reaction temperature,

-- Residence time,

-- Ultraviolet radiation.

The DRE for each toxic waste stream shall be determined by the comparison of the H2FID response to detoxification conditions and to transport conditions.

Laboratory
Test Matrix

		Tt	T1		T2	
		UV_{off}	UV_{on}	UV_{off}	UV_{on}	UV_{off}
Target 1	t1					
	t2					
Target 2	t1					
	t2					
Target 3	t1					
	t2					

Tt = Transport Temperature
T = Reaction Temperature
t = Mean Residence time

The following toxic wastes and parameter values have been tentatively chosen:

Wastes: Hexachlorobenzene
2, 2', 4', 5, 5' - pentachlorobiphenyl
Aroclor 1260

Transport Temperatures: Tt = 300 degrees C

Reactor Temperature: T1 = 700 degrees C
T2 = 800 degrees C

Mean Residence Time: t1 = 0.5 seconds
t2 = 2.0 seconds

For each set of conditions the following primary data shall be recorded:

-- H2FID reading,

-- Photo-sensor reading

Based on the results of these tests, one photolytic/thermally degraded sample shall be collected and subjected to GC/MS analysis for identification of possible toxic PICs.

Photolytic degradation is directly dependent on the amount of ultraviolet solar radiation supplied. A commercial unit's geographic location, the time of day, the time of year and atmospheric conditions will affect the amount of ultraviolet radiation available for detoxification.

At this time it is assumed that the laboratory results can be extrapolated for these differing conditions by comparing the laboratory UV spectral profile and intensity to those encountered at any particular site. Should validation of this approach be required, an additional group of tests could be conducted. This would require the testing of a single target chemical, as before, except that a different spectral profile would be used.

F.2.5 Data Reduction

Photon absorptions can be calculated taking every "UV on" photosensor reading and subtracting from it a baseline sensor reading which is made in the absence of test material in the reactor. A baseline sensor reading shall be made for every "Reactor temperature" (T).

DRE's can be calculated using the following equation:

$$\text{DRE} = \frac{W_{in} - W_{out}}{W_{out}} \times 100$$

To calculate the DRE results from both thermal and photolytic effects at each given condition, the following substitutions are made:

W_{in} = H2FID reading at Tt, UV off

W_{out} = H2FID reading at T, UV off

For a given feed, reactor temperature (T) and residence time (t), the increase in DRE due to photolysis can be seen by comparing these two results.

With the exception of the incidental presence of UV radiation which does not invalidate the application, this technique has been used by UDRI in the evaluation of DRE for pure thermal degradation.

F.3 Prototype Subsystem Tests

F.3.1 Objective

The objectives of the Prototype Subsystem Tests using the photolytic detoxifier are as follows:

- -- Measure the extent to which the R/R detoxifying subsystem design can achieve the DREs that are indicated by the laboratory results.
- -- Gather data on DRE as a function of new control variables.
- -- Measure the maximum sustained mass flow rate of target chemical, per energy input, that can be processed while maintaining a DRE of 99.99%.

F.3.2 Approach

A sketch and description of the WSSF is given in Appendix I. The concentrated beam at the WSSF will supply the solar flux to the R/R subsystem as described in Appendix I. The R/R will be mounted on a table at the focal zone and the beam will be projected through the R/R's quartz window. The test substance will be injected as an atomized liquid into an air stream moving from the quartz window rearward through the R/R vessel. The feed substance will undergo the following sequence of events:

- -- Vaporize due to the high temperature environment and mix with the air stream.
- -- Absorb a portion of the UV energy which will cause partial degradation due to photolysis.

- -- Be incinerated at high temperature at some point toward the rear of the R/R completing the detoxification process.
- -- Combustion products and remaining air will be exhausted out of the rear of the R/R.
- -- A portion of the effluent will be analyzed.

This process shall be performed under various sets of conditions as defined by the main test matrix. Data for each condition shall be generated by slowly increasing the mass flow to the point where the 99.99% DRE requirement is no longer maintained.

The solar beam supplies both the photolytic and thermal energy to the R/R. This causes some difficulty in that the two parameters (UV flux and reaction temperature) can not be varied independently.

Another difficulty results from the fact that residence time is essentially governed by the air velocity through the reactor. For a given mass flow, increasing the air flow in order to decrease residence time also changes the amount of air available for the oxidation reaction. The magnitude of that effect (change of air flow vs. DRE) must be investigated prior to the main body of tests.

Two other variables should be investigated prior to the main tests. The first is degree of atomization. It is believed that atomization itself is not a prime variable. However, droplet size does influence the effective residence time at temperature. It also affects the photon absorption, which differs for liquids and vapors.

The second variable is the effect of preheating the feed prior to injection. Elevated temperature affects photon absorption beneficially, which in turn affects photolytic degradation. The magnitude of this influence requires investigation.

Unlike the laboratory tests, these experiments will allow the reactor effluent to enter the environment. As such, the tests must be conducted under strict adherence to EPA regulations concerning toxic waste disposal. The ramifications of these regulations are currently under investigation and may significantly alter the manner in which these tests are performed.

F.3.3 Major Equipment and Materials

A preliminary equipment and test instrumentation list with specifications has been generated and is provided in Table F.1.

The following specialized instrumentation will also be required for the tests:

> Pyrheliometer - This instrument is required for measurement of the direct solar energy available to the facility during the performance of tests.
>
> Spectroradiometer - This instrument will measure the net UV radiation reaching the R/R. Readings shall be made frequently during tests. The measurements will also be required for comparing test results at this site to other geographic locations.

A list of the WSSF standard equipment is provided in Table F.2. Their pyrheliometer is adequate for solar constant measurement. However, their spectroradiometer is not adequate for the UV measurements required.

Other equipment and materials which need specification are:

> Transmittance Measurement - Equipment and procedures are required for quartz window UV transmittance measurement. Measurements must be made before and after the test program. It should also be measured periodically during testing because window deterioration could adversely affect UV transmission.
>
> Test Waste Compounds - A source of certifiably pure compounds is required.
>
> Gas Chromatographic/Mass Spectrometric Analysis - This system is required for the detailed analysis of the reactor effluent.
>
> H2FID - Required for the continuous monitoring of undegraded target chemical mass flow exiting the reactor. This instrument was selected because its readings are linear over 6 to 7 orders of magnitude, its read-out is available in "real time" and it can measure amounts as small as 10^{-13} grams/second.

F.3.4 Test Procedures

Values for the parameters to be investigated in the following tests cannot be chosen until after the laboratory tests have been completed and the results evaluated.

F.3.4.1 Baseline Tests

As with the laboratory tests, a "transport condition" baseline must be generated prior to performing any tests. The procedure in this case, however, is necessarily more complicated. The DRE for the laboratory tests can be calculated by directly using the H2FID read-outs. This is possible due to the fact that the same mass flow rate will be used for both transport and degradation measurements.

The feed mass flow rates required for the prototype baseline tests are much too large to be captured or to be allowed to enter the environment. As a result, the following procedure shall be used.

- A very small flow rate shall be chosen which is either acceptable for release to the environment or which can be captured.
- Transport condition tests shall be performed using this flow rate.
- A calibration curve shall be generated for each target chemical, plotting toxin flow vs. H2FID read-out.
- As the main body of tests are performed, DRE can be monitored by comparing target chemical feed rate as measured by a flowmeter and effluent target chemical flow rate indiated by H2FID readings.

The H2FID is extremely sensitive. Prior to making a measurement, all flows through the R/R must be established and stable.

For valid readings under conditions of these tests, the following should be measured for each H2FID reading:

- -- feed flow rate,
- -- total air mass flow through reactor,
- -- percent of total exhaust flow delivered to H2FID.

F.3.4.2 Preliminary Tests

Prior to the main body of tests, three parameters shall be investigated for one pure target chemical. The effects of these three variables are believed to be general enough in nature that only one compound need be tested and the results can be extrapolated to the other compounds. Furthermore, the effects of the three variables are assumed to be independent in the ranges considered. Their effects on DRE shall be reviewed and subsequently values shall be chosen which shall remain constant during the main test matrix. These parameters are:

- -- percent excess air over stoichiometric,
- -- atomization (droplet size),
- -- feed preheating

For the following three groups of tests, a value shall be chosen for solar flux level and residence time and these values shall be held constant. These same values shall be used for all three groups of tests.

Group One - Percent Excess Air:

- -- The DREs shall be measured for three different percentages of excess air.
- -- Atomization for this group shall be the "less than 100 micron" droplet size. (When an atomization specification is given in

terms of a droplet dimension, that size refers to the upper limit for all the droplets in that group.)

- Feed preheat shall be zero.

Group Two - Feed Atomization:

- The DREs shall be measured for three different categories of atomization. Information exists which suggests that 100 microns is the droplet size limit above which atomization is insufficient for the attainment of 99.99% DREs. This then shall form the group of the largest sized droplets (least atomized).
- Excess air shall be based on Group One test results.
- Feed preheat is zero.

Group Three - Feed Preheat:

- The DREs shall be measured for three different preheat temperatures.
- Excess air shall be based on Group One tests results.
- Atomization shall be based on Group Two test results.

F.3.4.3 Main Test Matrix

Maximum destruction rates (MDR) for the following matrix shall be generated by setting the indicated conditions and then increasing the mass flow rate to the point at which a 99.99% DRE can no longer be maintained.

MDR shall be measured as a function of:

- waste material composition,
- mean residence time,
- solar flux/reactor temperature,
- waste concentration in No. 2 fuel oil

The three target chemicals wastes tested are those investigated in the laboratory experiments:

-- Hexachlorobenzene,

-- 2, 2', 4', 5, 5' - pentachlorobiphenyl

-- Aroclor 1260

Additional test materials as identified in Appendix B could also be included in the test program.

Test Matrix

		Max F			F2			F3		
		t1	t2	t3	t1	t2	t3	t1	t2	t3
Target 1	x%									
	y%									
	100%									
Target 2	x%									
	y%									
	100%									
Target 3	x%									
	y%									
	100%									

F = solar radiation flux
t = residence time
% = percent pure target chemical in No. 2 fuel oil

For each of the set conditions, the following primary data shall be recorded:

-- H2FID response,

-- feed rate,

-- exhaust gas mass flow,

-- percent of exhaust gas flow delivered to H2FID.

After this series of tests, one detailed analysis shall be made for each of the three test compounds resulting in the highest MDR for that compound.

The following supplementary information shall be recorded for every data point:

Solar Constant

R/R Internal Pressure

Temperature:

  R/R Internal

  Window Curtain Air In

  Exhaust Gas

  Cooling Air In

  Cooling Air Out

  Feed Inlet

Mass Flow:

  Window Curtain Air

  Combustion Air

  Atomization Air

  Exhaust Gas

  Cooling Air

Internal Reactor Temperature is difficult to measure and may not be extremely accurate. During testing, alternative indicators of R/R condition and integrity are Window Temperature and Exhaust Temperature. These should be continually monitored during R/R operation.

F.3.5 Data Reduction

Destruction rates for the various conditions defined by the main test matrix are observed while increasing the flow rate in a stepwise manner and simultaneously calculating the DRE for each step. Maximum Destruction Rate (MDR) is that flow rate at which the DRE has fallen to 99.99%.

Monitoring the DRE while making these flow rate readings requires that the following calculation procedure be repeated for each flow rate increase.

$$DRE = \frac{W_{in} - W_{out}}{W_{out}} x\ 100$$

For these tests the following substitutions are made:

W_{in} = target chemical mass flow from flowmeter

W_{out} = A/B

A = target chemical flow indicated from H2FID using the calibration curve generated in Baseline tests.

B = percent of total reactor exhaust flow delivered to H2FID

F.3.6 Receiver/Reactor Inspection

After completion of the test program the following shall be accomplished:

-- The R/R shall be completely disassembled and inspected for cracks, local melting, distortion, and other degenerative effects.

-- The transmittance of the quartz window shall be measured and compared with a similar measurement made prior to testing.

-- The feed atomization system shall be carefully inspected for build-up of resin deposits and material damage due to its proximity to the high temperature zone.

F.4 Expected Results

A proof of principle for the photolytic detoxification concept will be demonstrated.

An increase of photolytic effect due to elevated temperature will be demonstrated.

An improvement of DRE over that attainable by commercial incineration will be indicated.

TABLE F-1

R/R SUBSYSTEM EQUIPMENT LIST

	Part	Manufacturer	Price ($)
PCB/Fuel Supply System			
Metering pump w/motor	Microflo 680	Pulsafeeder	1240
Metering valve	1315 M4Y	HOKE	60
Atomizer Assembly (Pair)	1/4 JBC-FF Setup 22B-18096-6	Spraying Systems 3376-FF	3570
Combustion Air Supply			
2 Air flowmeters	NAHL 10	HASTINGS	2 x 750
W/Digital readout		"	2 x 550
W/Totalizer		"	2 x 315
W/8-ft Cable		"	2 x 45
2 Air Pressure Regulators	PR-2	GO	2 x 60
2 Check Valves	6113 M4B	HOKE	2 x 12
2 Metering Valves	1315 M4Y	HOKE	2 x 60
Air Compressor w/tank	3HP-20	AJAX	488
Cooling System			
Window cooling fan W/Variable speed motor	4E Blower	Buffalo Forge	1125
Air compressor	4E Blower	Buffalo Forge	1125
Air pressure regulator	PR-2	GO	60
Incinerator Cavity			
Ceramic cylinder	Silicon Carbide	Norton Company (approximate estimate)	5000
Exhaust			
Exhaust fan W/Damper	(Approximate estimate)		1000
Pressure			
Pressure transducer	1151 DP	Bailey	1200
Vacuum gauge (analog or digital)	NV 800 or DNNV 800	HASTINGS	500 or 700
Temperature			
Pyrometer	F188-B-12	Marlin	118
W/Connector	1010-B	"	9
W/10-ft X-wire		"	4
W/Display	400A-B	"	380
Thermocouple (window) W/Display	618-K-20	"	1280

TABLE F-2

WSSF INSTRUMENTATION

Instrument	Quantity	Purpose
1. T.C. Recorder DORIC MDL 415	1	Temp Measurement
2. Stripchart Recorder HP MDL 7402A	2	Signal Recording
3. XY Recorder Esterline Angus MDL 540T	1	Signal Recorder
4. Digital Storage Oscilloscope Nicolette MDL 206-1	1	Signal Record and Digitizer
5. Spectroradiometer United Detector 11A	1	Spectrum Measurement
6. Optical Pyrometer (Solar Blind) Barnes MDL 128.60	1	Surface Temp Measurement
7. Optical Pyrometer Barnes MDL IT-7	1	Surface Temp Measurement
8. Calorimeters Hycal MDL 1300 MDL 1312	12	Heat Flux
9. Pyrheliometer Eppley MDL NIP	2	Direct Solar Insolation
10. Pyrheliometer Total Hycal P8405	2	Total Solar Insolation

APPENDIX G

DETOXIFIER EXPERIMENTAL COSTS

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G.0 Detoxifier Experimental Costs

During Phase I, the current costs associated with the actual Phase III prototype detoxifier test at a solar facility were estimated. These costs include hardware costs for the detoxifier and instrumentation, detoxifier fabrication, and the test facility procurement. Costs have not been included for test burn material procurement, off gas monitoring requirements and costs associated with team member test follow time.

G.1 Prototype Detoxifier System Costs

G.1.1 Detoxifier Costs

Material Cost (Plate, head, cyclinder, flanges, misc.)	$ 7.3 K
Ceramic Liner (estimated)	$ 5.0 K
Window (estimated)	$ 1.0 K
Insulation, seals, etc. (estimated)	$ 1.5 K
Welding and Assembly	$ 6.7 K
Subtotal	$21.5 K

G.1.2 System Costs

Subsystem Equipment Costs	$16.0 K
Detoxifier System Pre-assembly Check-out	$14.0 K
Instrument Test Panel Design/Material/Assembly	$17.0 K
Subtotal	$47.0 K

G.1.3 Shipping Costs

Packaging and Truck Shipment (Ohio to New Mexico)	$ 1.5 K
Subtotal	$ 1.5 K

G.1.4 Solar Test Facility Costs

The costs identified in Section C.4.2 have been used as the basis for the facility procurement costs. These costs are based on a three (3) day set-up and a one (1) day removal span. The actual testing has been based on ten (10) days. As noted previously, this test span is for comparison purposes and may vary depending on the final test plan. These costs are based on the White Sand Solar Facility.

Test Costs	$47.6 K
Subtotal	$47.6 K

G.1.5 Experimental System Costs

Based on the costs identified in Sections G.1.1 through G.1.4, the total hardware and testing costs are estimated to be $117,600 or approximately $120,000.

APPENDIX H

PHOTOCHEMICAL EFFECTS LITERATURE SEARCH

APPENDIX H - TABLE OF CONTENTS

H.0 Photochemical Effects Literature Search

During Phase I, a literature search was initiated to identify the effect of solar radiation on the destruction of hazardous wastes. This appendix presents the results of this work and identifies the basis for the major sources of information.

H.1 Evaluation of Photolytic Effects

Photolysis involves the breaking of molecular chemical bonds by the addition of a specific amount of solar energy. This electromagnetic energy is embodied in "photons" or "quanta", each of which has a particular wavelength which varies with the magnitude of energy it possesses. Different chemical bonds require excitation by photons of different levels for dissociation to result. Simply passing solar radiation through a chemical solution or vapor does not cause photolysis to occur. The energy must first be absorbed. Each photon can excite only one molecule. Thus photochemical processes are not proportional to gross energy available but rather to the number of suitable individual photons absorbed.

The majority of available literature on photolytic reduction of toxic organic chemicals is aimed at natural sunlight as the ultraviolet (UV) source. Inspection of the sunlight spectrum at the earth's surface shows that the short wavelength spectra cut-off is at approximately 280 nm. Most PCB's absorb in the 240 to 310 nm region with the higher chlorinated biphenyls absorbing between 280 and 310 nm. Since the absorption band of PCB's and available wavelengths of natural sunlight overlap, sunlight has the potential to reduce PCB's. Previous experimenters used mercury lamps or direct sunlight as the irradiation source, which irradiated dilute solutions of PCB's in alkaline polar solvents exposed in quartz tubes [8, 27, 30] (See Table H-1). The polar solvents used provided hydrogen ions to the photolytic reactions.

The exact reaction path for decomposition by photolytic reactions is not known, although the literature showed reductive dehalogenation as the main photoreaction. The photolytic reaction products were mostly lower chlorinated biphenyls and chlorinated solvent radicals with dehalogenation yields of 90%. These results were obtained after hours of exposure [31].

Many theories have been proposed for the mechanism of photolytic reactions, but the generally accepted mechanism is as follows. The route for excitation occurs by a transition of electrons in the Pi ground state system to an excited Pi* state. The carbon-halogen bond undergoes fission from the excited state (which can be of single or triplet multiplicity) giving rise to phenyl and halogen radicals. The radicals then combine with hydrogen from the media, combine back with each other, or combine with like radicals to form diatomic halogens or polymeric phenyl [10]. On a macroscopic level these phenomena manifest themselves as a "rate' of photochemical reaction. The reaction rate is dependent on both steric considerations and on the bond energy of the carbon-halogen bond involved (the carbon/chlorine bond requires about 97 Kcal/mole of photons for disassociation to occur, which corresponds to approximately 294 nanometer wavelength light). Of primary importance is the light intensity. The higher the flux of suitable photons supplied per unit volume of toxin, the higher the reaction rate.

Several experiments [6, 27, 28, 30] were conducted with in-situ irradiation of PCB's on the ground. Samples were put in quartz tubes and put in fields to expose the samples to sunlight. Very long irradiation times were required (days) with low conversion (less than 10%). Other studies conducted in hexane solvent with dilute Aroclor 1254 showed 100% decomposition (as observed from PCB gas chromatograph peaks) after 30 minutes [30]. The same authors experimented with hexane solutions of PCB's in quartz tubes exposed to direct sunlight. They concluded the sunlight test results and laboratory test results agreed fairly well except that the overall rate of degradation in sunlight was much slower due to the lower intensity and absence of shorter wavelengths in sunlight compared to the laboratory lamp. They further concluded that the close correlation in the degradation patterns at different concentrations suggest the process is not concentration dependent. These two factors will be enhanced in the B&W Phase III design, as the proposed flux is concentrated to an intensity 1000 times greater than natural sunlight, and emphasis has been placed on maximizing the UV content. The shorter wavelengths will provide the energy needed to excite the lower chlorinated biphenyls into photolytic dehalogenation. The higher intensity should also speed the photolytic reaction considerably as shown by the previous experimenters work.

The discussion above has concerned itself with what is called direct photolysis, light energy being absorbed directly by the reacting molecule. The major drawback of this process is that only the high energy photons (which contribute a relatively small portion of the solar spectrum) are capable of causing disassociation. There are a few methods which get around this problem, the most promising being "sensitization". This is a process of indirect photolysis which uses an intermediate molecule to capture longer wavelength light. Molecular collisions then result in energy transfer to the reactant, which in turn provides the impetus for degradation of the PCB's. In certain situations this results in a significant contribution of the overall reaction rate. This type of process could easily be adapted to the B&W Phase III design.

H.2 Results of Investigations

The results of these investigations are summarized below.

1. Chlorararomatics as a group absorb solar energy round a wavelength of 290-300 nanometers.
2. Rates of reaction are directly proportional to the light intensity.
3. Stepwise dechlorination seems to be the main route of degradation though the actual mechanisms are still subject to debate.
4. The dechlorination and resulting rate of destruction is compound specific and varies significantly. Some species rates of photolysis are surprisingly rapid while others are slow. Mechanistic reasons for this are not well understood.
5. Photolysis rates are affected by a compound's physical state; vapor, solution, absorbed in other materials, etc.
6. Elevated temperature will probably have a beneficial effect on photolysis rate due to the absorption curve shift, but to what extent is unknown.
7. In most cases organic solvents tend to increase reductive dechlorination.

Table H-1
Summary of Major Documents Reviewed for UV Effects on Destruction of Hazardous Wastes

1. "Sensitized Photodegradation of Adsorbed Polychlorobiphenyls (PCB's)", G. Occhiucci and A. Patacchiola, Istituto di Chimica Nucleare del C.N.R., C.P. 10 - 00016 Monterotondo Stazione, Rome, Italy.
2. "PCB Detection in the Field", EPRI Journal, March 1984, Page 29.
3. "Local Involvement in Air Quality Planning", N. T. Stephens and L. K. Luedtke, Virginia Polytechnic Institute and State University, Blackburg, Virginia, 24061.
4. "Air Pollution Sampling and Monitoring at Hazardous Waste Management Facilities", D. A. Oberacker, U.S. Environmental Protection Agency, Cincinnati, OH 45268, and P. K. Ase, IIT Research Institute, Chicago, IL 60616.
5. "Hazardous Waste Incineration and Gaseous Waste Pollution Control", Richard A. Carnes, U.S. Environmental Protection Agency, and Frank C. Whitmore, Versar, Inc.
6. "A Review of Spectroscopic Techniques Applied to the Study of Interactions Between Minerals and Reagents In Flotation Systems", E. W. Giesekke, Internation Journal of Mineral Processing, 11(1983)19-56, Elsevier Science Publishers, B.V., Amsterdam.
7. "Environ. Sci. Technol." 76/10/00 P971.
8. "Photochemical Degradation of Chlorobiphenyls (PCBs)", by O. Hutzinger, S. Safe, and V. Zitko., Environmental Health Perspectives.
9. "Photolysis of 3,4-Dichloroaniline in Natural Waters", by Glenn C. Miller, Richard Zisook, and Richard Zepp.
10. "Transformation Pathways of Hexachlorocyclopentadiene in the Aquatic Environment", by N. L. Wolfe, R. G. Zepp, P. Schlotzhauer, and M. Sink, Environmental Research Laboratory, U.S. Environmental Protection Agency, College Station Road, Athens, Georgia 30613.
11. "Photodecomposition of Unsymmetrical Polychlorobiphenyls", L. Ruzo, S. Safe, M. Zabik, University of Guelph, Ontario, Canada, 1975.
12. "Photolysis Rates of (2,4,5-Trichlorophenoxy) acetic Acid and 4-Amino-3,5,6-Trichloropicolinic Acid in Natural Waters" by Yuri I. Skurlatov, Richard G. Zepp and George L. Baughman.
13. "Methoxychlor and DDT Degradation in Water: Rates and Products" by N. Lee Wolfe, Richard G. Zepp, Doris F. Paris, George L. Baughman, and Reginald C. Hollis, Environmental Research Laboratory, U.S. Environmental Protection Agency, Athens, Georgia 30601.

Table H-1 (Cont'd)

14. "Retention Times and Electron-Capture Detector Responses of Some Individual Chlorobiphenyls" by V. Zitko, O. Hutzinger and S. Safe, Fisheries Research Board of Canada, Biological Station, St. Andrews, N.B. and National Research Council of Canada, Atlantic Regional Laboratory Halifax, N.S.

15. "Projected Temperature Dependence of Quantum Yields for Photoreactions Involving Energy or Electron Transfer", by Guilford Jones, II and Richard J. Butler, Department of Chemistry, Boston University, Boston, MA 02215

16. "Waste Management Options for PCBs," F. L. Harison, Argonne National Lab., Argonne, IL

17. "Interim Guidelines for the Disposal/Destruction of PCBs and PCB Items by Non-Thermal Methods," Report for Sep. 80-Jul. 81, E. W. Sworzyn, et al, TRW, Redondo Beach, CA.

18. Emerging Technologies for the Control of Hazardous Wastes (Final Report), Barbara H. Edwards, et al, Ebon Research Systems, Washington, DC, March 82.

19. Toxic Organic Chemical's - Destruction and Waste Treatment, pages 40-53, 68-79

20. "Chapter 12 - Detailed Waste Treatment Designs and Costs - The PCB's Example" Toxic Organic Chemical's - Destruction and Waste Treatment, pages 285-317.

21. "Loss of Polychlorinated Biphenyl Homologues during Chromium Trioxide Extraction of Fish Tissue," Michael J. Szeiewski, David R. Hill, Stuart J. Spiegel, and Edwin C. Tim, Jr., O'Brien & Gere Engineers, Inc., 1304 Buckley Road, Syracuse, New York 13221.

22. "Experience in Operation of Ultraviolet-Ozone (Ultrox) Pilot Plant for Destroying Polychlorinated Biphenyls In Industrial Waste Influent", Ruth K. Arisman, Manager, Environmental Planning and Safety, Richard C. Musick, Manager, Analytical Chemistry, General Electric Company, Hudson Falls, New York 12839, Jack D. Zeff, President, Thomas C. Crase, Chemist, Westgate Research Corporation, West Los Angeles, CA 90025.

23. "Conquering the Monster - The Photochemical Destruction of Chlorodioxins", D.G. Crosby, Department of Environmental Toxicology, University of California, Davis, CA 95616.

24. "Polychlorinated Biphenyls: Photolysis of 3,4,3',4'-tetrachlorobiphenyl and 4,4'-dichlorobiphenyl in Solution," by Luis Octavio Ruzo, Matthew J. Zabik and Robert D. Scheutz, Department of Chemistry-Department of Entomology, Pesticide Research Center, Michigan State University, East Lansing, Michigan 48823.

25. Deleted.

Table H-1 (Cont'd)

26. "Approaches to Decontamination or Disposal of Pesticides Photodecomposition", Jack R. Plimmer, Organic Chemical Synthesis Laboratory, Federal Research, Science, and Education Administration, USDA, Beltsville, MD 20705.

27. Safe, S. and Hutzinger, O., Nature, 232, 642 (1971) "Polychlorinated Biphenyls - Photolysis of 2, 4, 6, 2', 4', 6' Hexachlorobiphenyl."

28. Quistad, G. B., Mullholland, K. M., J-Arric, Food Chem 1983, 31, 621-624, "Photodegradation of Dienchlor by Sunlight."

29. Frakin, L., Barisas, S., Argonne National Laboratory Report Conf 8206182-1, "Waste Management Options for PCBs".

30. Herring, J. L. Hannan, E. J. Bills, D. D., Technical Paper 3279 OSU, "UV Irradiation of Aroclor 1254."

31. "Hutzinger, O. Safe, O., Zilko, F., CRC Press, Boco Ratan 1974, The Chemistry of PCBs.

32. "Research Advances in Chemical 'Disposal' of PCB's", Electric Light and Power, November, 1980.

33. "The Dechlorination of Polychlorinated Biphenyls of UV-Irradiation. IX. Reactions of Monochlorobiphenyls in a 2-Propanol Solution", Tohru Nishiwaki, Tsutomu Shinoda, Kinji Anda, and Mitsuhiko Hida, Organic Division, Tokyo Metropolitan Industrial Technology Center, Nishigoaka, Kita-ku, Tokyo 115, Department of Industrial Chemistry, Faculty of Technology, Tokyo Metropolitan University , Fukazawa, Setagaya-ku, Tokyo 158

34. "The Dechlorination of Polychlorinated Biphenyls of UV-Irradiation. VIII. Reactions of 2,3- and 3,4-Dichlorobiphenyl in a 2-Propanol Solution," Tohru Nishiwaki, Tsutomu Shinoda, Kinji Anda, and Mitsuhiko Hida, Organic Division, Tokyo Metropolitan Industrial Technology Center, Nishigoaka, Kita-ku, Tokyo 115, Department of Industrial Chemistry, Faculty of Technology, Tokyo Metropolitan University, Fukazawa, Setagaya-ku, Tokyo 158

35. "Polychlorinated Biphenyls: Photolysis of 3,4,3',4'-tetrachlorobiphenyl and 4,4'-dichlorobiphenyl in Solution," by Luis Octavio Ruzo, Matthew J. Zabik and Robert D. Scheutz, Department of Chemistry-Department of Entomology, Pesticide Research Center, Michigan State University, East Lansing, Michigan 48823

36. "Project Summary, Interim Guidelines for the Disposal/Destruction of PCBs and PCB Items by Non-Thermal Methods," E. M. Sworzyn and D. G. Ackerman. EPA-600/52-82-069 July 1982, US EPA, Industrial Environmental Research Laboratory, Research Triangle Park, NC 27711.

37. "Mobile Reactor Destroys Toxic Wastes in "Space", Kenneth W. Lee and William R. Schofield, J. M. Huber Corp., and D. Scott Lewis, Radian Corp., Chemical Engineering, April 2, 1984.

38. Zepp, R. G., Cline, D. M. "Rates of Direct Photolysis in Aquatic Environment", 1977.

APPENDIX I

SOLAR TEST SITE FACILITY DESCRIPTIONS

APPENDIX I - TABLE OF CONTENTS

I.0 Solar Test Site Facility Descriptions

Section I.1 and I.2 present a general description of the solar furnace test facilities located at WSSF and CRTF. The remaining sections of this appendix provide technical information applicable to the facilities.

I.1 Central Receiver Test Facility (CRTF)

The horizontal axis solar furnace consists of a sun tracking heliostat, an adjustable light attenuator, a mirrored stationary paraboloid that provides the concentrated solar beam, a remotely controlled platform for positioning test items in the beam, and a minicomputer for data acquisition and furnace control (see Figure I-1).

The heliostat has 12 flat mirror facets, giving it a total size of 7.3 m by 7.3 m. It tracks the sun in an open-loop, computer controlled mode or by using a set of photocells that detect the direction of its reflection and provide a closed-loop, or analog control. The controlled heliostat reflection gives total illumination of the concentrator throughout the day.

The attenuator, located between the heliostat and concentrator, is an array of horizontal metal slats that are remotely controlled to provide zero to full power on a test item in 90 discrete increments. Its time for full travel is about two seconds. It is used to start an experiment and to automatically terminate furnace operation for safety reasons. A failure of electric power of the attenuator control system causes it to close by gravity.

The stationary paraboloid uses 228 second surface, silvered glass mirrors, contoured by the slump-glass process, to provide the concentrated beam. Each mirror was adjusted on its independent mount to reflect the incoming solar beam to the focus of the paraboloid. The concentrator diameter is 6.7 m, with the central one meter diameter not covered by mirrors. The focal length is 4.5 m, and the half angle of the incident beam is about 4.5 degrees.

A remotely controlled platform positions experiments weighing up to 450 kg (1000 lb) in the beam with an accuracy of better than 0.2 mm in all three directions. Thirteen bit encoders indicate the position of each independent axis to test site operator and for the control computer.

I.2 White Sands Solar Facility (WSSF)

The WSSF is a focusing-type thermal facility. It consists of four main components: (1) heliostat, (2) attenuator, (3) concentrator, and (4) a test and control chamber (see Figure I-2).

The heliostat consists of 356 flat plate mirrors, each 2 ft x 2 ft, mounted on a steel frame 40 feet wide and 36 feet high. Each mirror is front surfaced with an aluminized acrylic material (3M product No. ECP-91A, see Section I.4.2) in order to provide as much ultraviolet radiation as possible in the concentrated solar beam. In operation, the heliostat reflects the solar radiation received from the sun along the optical axis of the WSSF to the concentrator. The heliostat automatically (closed loop) tracks the sun during the day, or moon at night, thus keeping the concentrated solar energy located at the focal plane in a fixed position during the course of an experiment.

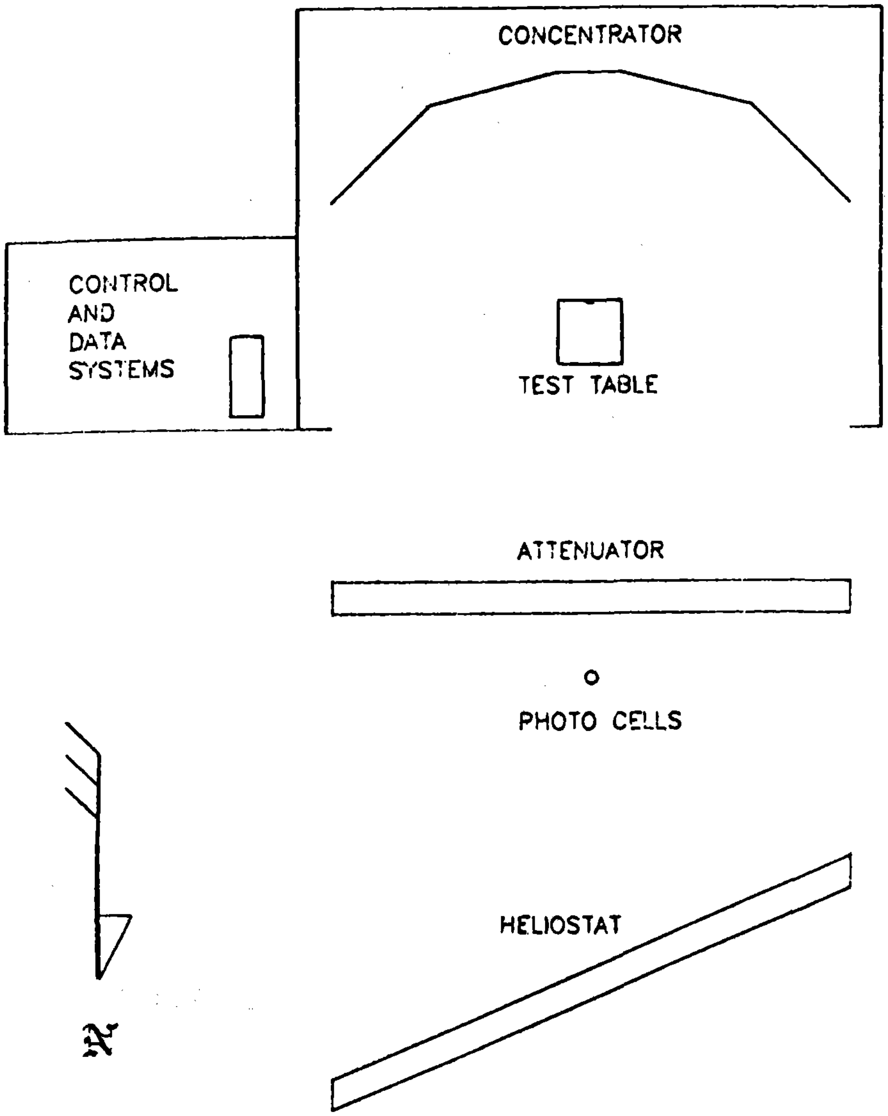
The concentrator consists of 180 spherical section mirrors, each approximately 2 ft x 2 ft and mounted on a steel frame 30 ft x 30 ft located 96 feet south of the heliostat. Each mirror comprising the concentrator is individually pre-positioned to concentrate the solar energy at the focal plane, 36 feet to the north, located inside the test and control chamber.

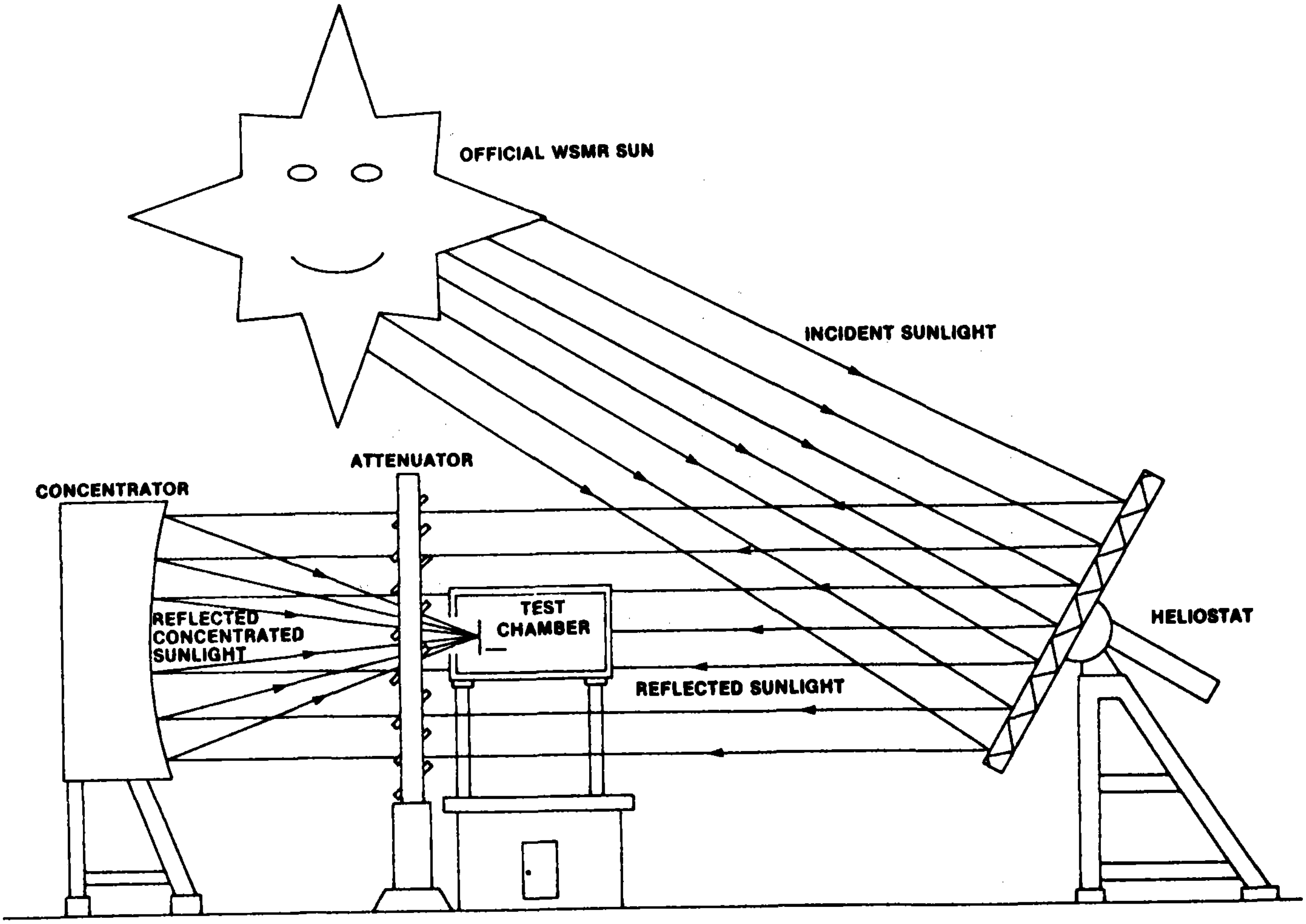
The attenuator, which is located between the test and control chamber and the concentrator, consists of a louvered structure whose blades can be positioned in such a manner as to regulate the amount of solar energy reaching the concentrator. The attenuator can continuously vary the power level of the WSSF to suit the test requirement and for safety reasons.

FIGURE I-1

CRTF

SOLAR FURNACE LAYOUT





WHITE SANDS SOLAR FACILITY

FIGURE I-2

The test and control chamber is 8 ft x 8 ft in cross section presented to the reflected thermal energy from the heliostat and is 16 feet in length. It contains the experimental test area, the controls for operation of the facility, and the shutter systems for modulating the solar energy.

I.3 Test Site Instrumentation

Table I-1 and I-2 provide the test site instrumentation available at WSSF and CRTF, respectively.

I.4 Reflectance Properties

I.4.1 Transmittance Calculation for CRTF Concentrator Mirrors

$$B = (1/t) \ln(T/K)$$

where: t = Optical Path Length (cm)

T = Transmittance

K = Maximum Theoretical Transmittance

B = Absorption coefficient = -2.41 cm^{-1} (from the attached excerpts of the "Solar Collector Design and Fabrication Program Final Report", by Raytheon Company)

Glass thickness: double strength = 3.25 mm.

Therefore, Optical path Length (t) = 2 x 3.25 = 6.5 mm

K = unknown: assume 100T

Then,

$$-2.41 = (1/.65 \text{ cm}) \ln(T)$$

Thus: $T = 0.209$

We assumed 100% Theoretical Maximum Transmittance (which does not include reflection losses) so 0.209 is an upper limit.

Figure I-3 identifies reflectance properties of silver and aluminum surfaces.

SOLAR COLLECTOR DESIGN AND FABRICATION PROGRAM

FINAL REPORT

BR-10394

MAY 1978

Prepared for
SANDIA LABORATORIES
SANDIA CORPORATION
Albuquerque, New Mexico 87115

Under
Purchase Order 05-4571

Prepared by
RAYTHEON COMPANY
MISSILE SYSTEMS DIVISION
Bedford, Massachusetts 01730

Prepared by
SANDIA LABORATORIES
Albuquerque, New Mexico 87115 and Livermore, California 94550
For the
UNITED STATES DEPARTMENT OF ENERGY
Under
Contract AT(29-1)-789
Sandia Report No. SAND78-7035

UNCLASSIFIED

6.3 Glass physical properties. The nominal physical properties of the water-white crown glass for the solar concentrator mirrors covered by this specification are summarized as follows:

Chemical properties

% $Fe_2O_3 \le 0.01$

Mechanical properties

Young's modulus (0°C):	$10.5\text{x}10^6$PSI
Rigidity modulus (0°C):	$4.3\text{x}10^6$PSI
Poisson's ratio:	0.21
Hardness:	490 Knopp
Density	2.46 gm/cc
Expansion Coefficient (0°-300°C):	$8.7\text{x}10^{-6}$/°C

Optical properties

Index of refraction (nd):	1.510
V-value:	63.5
Homogeneity:	$\pm$ $2\text{x}10^{-5}$ maximum variation of nd.

Absorption coefficients:

λ(nm)	$B(cm^{-1})$
300	2.41
350	0.032

Absorption coefficients: (continued)

400	0.0077
500	0.0060
600	0.0046
800	0.0040
1000	0.0040
1500	0.0040
2000	0.0050

Viscosity data

Strain Point	505°C
Anneal Point	548°C
Softening Point	730°C
Flow Point	920°C

TABLE I-1

WSSF INSTRUMENTATION

Instrument	Quantity	Purpose
1. T.C. Recorder DORIC MDL 415	1	Temp Measurement
2. Stripchart Recorder HP MDL 7402A	2	Signal Recording
3. XY Recorder Esterline Angus MDL 540T	1	Signal Recorder
4. Digital Storage Oscilloscope Nicolette MDL 206-1	1	Signal Record and Digitizer
5. Spectroradiometer United Detector 11A	1	Spectrum Measurement
6. Optical Pyrometer (Solar Blind) Barnes MDL 128.60	1	Surface Temp Measurement
7. Optical Pyrometer Barnes MDL IT-7	1	Surface Temp Measurement
8. Calorimeters Hycal MDL 1300 MDL 1312	12	Heat Flux
9. Pyrheliometer Eppley MDL NIP	2	Direct Solar Insolation
10. Pyrheliometer Total Hycal P8405	2	Total Solar Insolation

TABLE I-2

CRTF

SOLAR FURNACE ACCESSORIES

THERMOCOUPLES, RTD'S, AND THERMISTORS

THERMOCOUPLE REFERENCE JUNCTION, 150 DEGREES F

TYPE	NUMBER
K	20
T	20
S	20

SOFTWARE REDUCTION FOR THERMOCOUPLE TYPES

J,K,T,E,R,S,B, NICROSIL--NISIL(14 avg), NICROSIL-NISIL(28 avg)

SOFTWARE REDUCTION FOR PLATINUM RTD

PLATINUM, = 0.00385 OHMS/OHM/DEG C, 100 OHMS AT 0 DEG C

SOFTWARE REDUCTION FOR THERMISTORS

YSI 44004	YSI 44033
OMEGA 44004	OMEGA 44033
FENWALL UUA32J3	FENWALL UUA32J4

RADIOMETERS

KENDALL SELF CALIBRATING:

.1 W/CM^2
150 W/CM^2
1000 W/CM^2

CIRCULAR FOIL FLUX GAGES

A VARIETY OF STYLES AND RANGES FROM 12 W/CM^2 TO 400 W/CM^2

INSOLATION

EPPLEY RADIOMETER

WEATHER

WIND SPEED, DIRECTION, AND TEMPERATURE

CLOSED CIRCUIT B&W TV

25-350mm ZOOM LENS WITH TWO 2X CONVERTERS
PLACED 15 FEET FROM TARGET ON AXIS

SOLAR BLIND OPTICAL PYROMETER

TEMPERATURE RANGE: 400 TO 4500 DEG. F

TABLE I-2 - CONT.

SOLAR FURNACE DATA ACQUISITION SYSTEMS

I) HP 3497A DATA ACQUISITION SYSTEM

100 CHANNELS, RELAY

MAX SCAN RATE	RESOLUTION
34 CHANNELS/SEC	6 1/2 DIGIT
88 CHANNELS/SEC	4 1/2 DIGIT

VOLTAGE RANGES	4 1/2 DIGIT	6 1/2 DIGIT
0.1	10uV	100nV
1.0	100uV	1uV
10.0	1mV	10uV
100.0	10mV	100uV
170.0	100mV	1mV

MIXING VOLTAGE RANGES DURING SCAN IS PERMITTED.

II) HP 6942A MULTIPROGRAMMER

64 CHANNEL FET CARD AND A/D CARD

MAXIMUM INPUT = +-10.24V
A/D CONVERSION TIME = 30uS

RANGE	RESOLUTION	SETTLING TIME TO .01%
+-100mV	50uV	40uS
+- 1V	500uV	16uS
+- 10V	5mV	15uS

MINIMUM SCAN TIME/CHANNEL IS CONVERSION TIME PLUS SETTLING TIME.
VOLTAGE RANGES MAY NOT BE MIXED DURING SCAN.

III) HONEYWELL 1858 VISICORDER

18 CHANNELS

BANDPASS: 5MHZ

SPEED, In/sec	MULTIPLIER
1, 2, 4, 8, 16	0.1, 1, 10

1881 HIGH GAIN DIFF. AMP 2 CHANNEL OCCUPANCY
mV LEVELS 1, 2, 5, 10, 20, 50, 100, 200, 500

1883 MEDIUM GAIN DIFF. AMP 1 CHANNEL OCCUPANCY
V LEVELS .05, .1, .2, .5

NOTE: THE AVAILABLE CHANNELS ARE REDUCED BY THE CHANNEL OCCUPANCY OF THE PLUGIN. THUS, 18 1883'S CAN FIT INTO THE 1858 BUT ONLY 9 1881'S CAN FIT. THE AMPLIFIERS CAN BE MIXED.

TABLE I-2 - CONT.

DATA CAPABILITIES

DATA CHANNELS

100 CHANNELS WHICH CAN BE SPLIT BETWEEN THREE SYSTEMS.

DATA STORAGE

TAPE CASSETTE, HP9845 (TAPE CASSETTE # HP 98200A). HP 9845B COMPATIBLE
HARD DISC, HP7906 (DISC CARTRIDGE # HP 12940A). HP 9845B COMPATIBLE
9 TRACK TAPE, 800 BPI, HP 1000 COMPATIBLE

PLOTTING

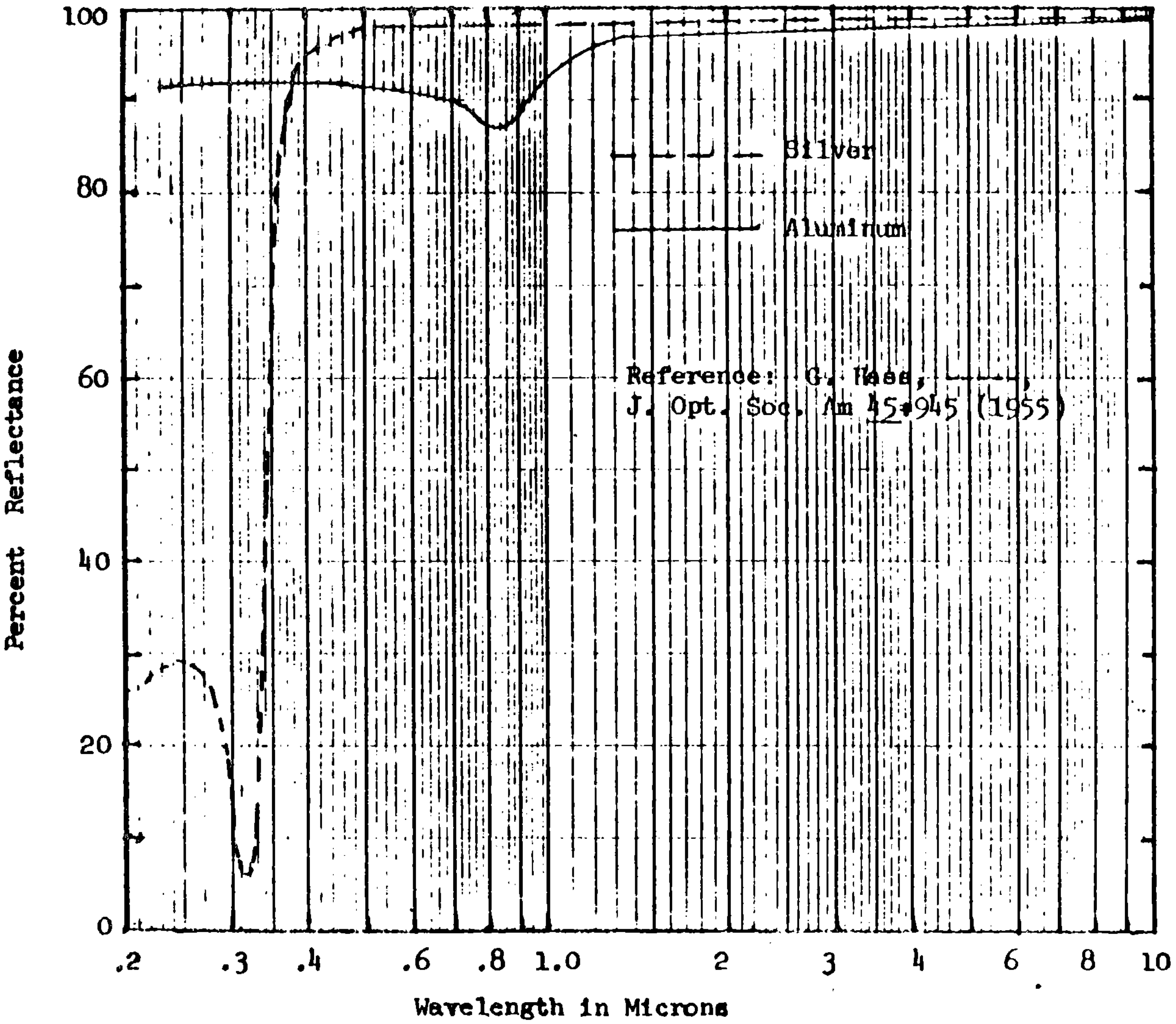
PLOT ON CRT AND DUMP TO THERMAL PRINTER.
HP 9872B 4 PEN X-Y PLOTTER (11" X 16 1/2" MAX).

PRINTING

THERMAL 80 COL PRINTER.
HP 2631G 132 COL LINE PRINTER.

SOFTWARE

REGRESSION ANALYSIS.
CUSTOM SOFTARE.



REFLECTANCE OF METAL SURFACES

FIGURE I-3

I.4.2 Ultraviolet Reflectance Property for 3M Product ECP-91A

The following are total reflectances (reflectance plus absorptance) figures obtained from 3M Corporation. Tests were performed on a specimen with 4 times the normal thickness of acrylic coating.

Wavelength (Microns)	Reflectance
0.400	85%
0.350	86%
0.300	78%
0.290	70%

This information is obtained from the 3M Corportation "Design Guide" provided in Figure I-4.

FIGURE I-4

Energy Control Products

3M

Design Guide

ECP-91A Solar Energy Collection Film With Adhesive Backing

Description

ECP-91A is an energy collecting film being offered as a cost effective, highly reflective, high strength film with superior outdoor weathering properties. With its adhesive backing it can be easily and permanently applied to most smooth, non porous substrates whether flat or planar curved.

Construction

Opaque, highly reflective metallized layer on a special smooth surface, high strength, 3M Polyester. A protective overcoating on the metallized surface provides low loss specular optics with durable, long lived outdoor weathering properties. It has an adhesive backing and liner. The adhesive is water activatable, pressure-sensitive and outdoor weatherable.

Physical Properties

Tensile Strength	45 lbs/in. of width
Nominal Thickness:	.0025"
Stretch at Break:	100%

Optical Properties

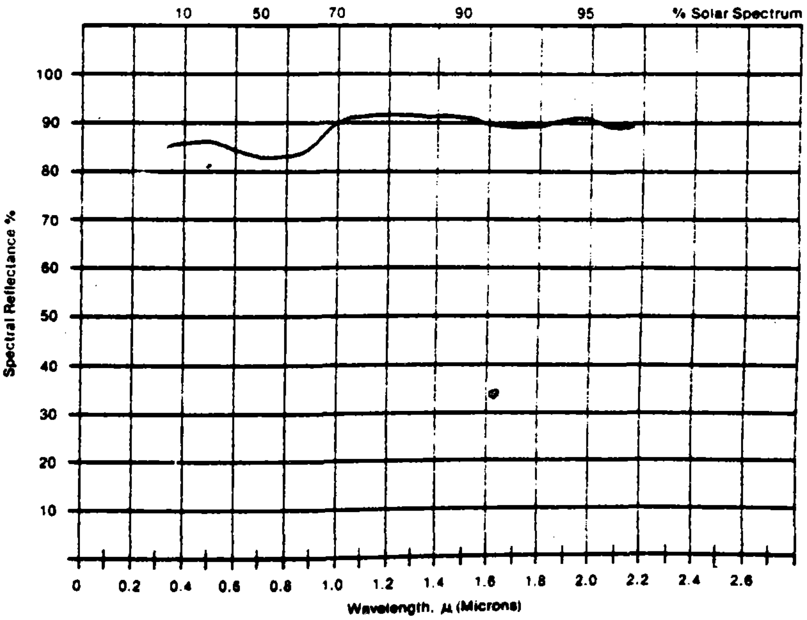
Solar Reflectance.	Minimum of 85% total reflectance integrated over air mass-2 solar spectrum.

Terms and Conditions of Sale

The following is made in lieu of all warranties, express or implied. Seller's and manufacturer's only obligation shall be to replace such quantity of the product proved to be defective. Neither seller nor manufacturer shall be liable for any injury, loss or damage, direct or consequential, arising out of the use of or the inability to use the product. Before using, user shall determine the suitability of the product for his intended use, and user assumes all risk and liability whatsoever in connection therewith.

Statements or recommendations not contained herein shall have no force of effect unless in an agreement signed by officers of seller and manufacturer.

Spectral Reflectance of ECP-91A Solar Energy Collection Film with Adhesive Backing
(Measured using a Beckman DK2A Ratio Recording Spectrophotometer and an Edwards-Type Integrating Sphere Reflectometer)



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