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Title: DESTRUCTION OF ASBESTOS USING A PLASMA ARC TORCH

PROJECT ADMINISTRATION DATA

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NONE PROPOSED
Administrative comments -
INITIATION OF D-48-626. FIXED PRICE COOPERATIVE R&D AGMT. (CRDA) WITH 50% COST SHARING FROM TWO SUBCONTRACTORS; ONE AT $25K AND ONE AT $10K.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 11/18/91

Project No. D-48-626 Center No. 10/24-6-R6979-0A0

Project Director CIRCEO L JR School/Lab DEAN ARCH

Sponsor ARMY/CON ENG RES LAB, IL

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Title DESTRUCTION OF ASBESTOS USING A PLASMA ARC TORCH

Effective Completion Date 910228 (Performance) 910228 (Reports)

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NOTE: Final Patent Questionnaire sent to PDPI.

FINAL REPORT

DESTRUCTION AND VITRIFICATION OF ASBESTOS USING PLASMA ARC TECHNOLOGY

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This study was conducted under the U.S. Army
CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

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OCTOBER 1991

EXECUTIVE SUMMARY

In recent years asbestos fibers have been identified as a known carcinogenic agent. Exposure to this hazard creates a serious risk to public safety and health. The U. S. Department of Defense (DoD) is currently faced with multi-million dollar rehabilitation costs relating to asbestos removal and disposal from existing buildings constructed with asbestos-containing building materials. Corrective actions must be taken when contamination levels are too high or when renovating, reconstructing or demolishing these structures. The options range from modified operations and maintenance to complete removal and disposal.

At the present time asbestos and asbestos-containing materials (ACM) can be deposited only at selected Class 1 EPA-approved landfill disposal sites which comply with the National Emissions Standards for Hazardous Air Pollutants (NESHAP). As these disposal sites become filled and are closed, significantly higher disposal costs are anticipated.

Plasma torch destruction of asbestos-containing waste materials could provide an effective, economical and timely solution to this problem. It is anticipated that the very high temperatures (3,000°C - 7,000°C) achievable with plasma arc technology will melt and vitrify asbestos and asbestos-containing materials into a chemically inert glass-like residue which meets all EPA environmental criteria. When pure asbestos is subjected to temperatures above 1,000°C, the asbestos fibers are melted and subsequently vitrified (solidified) into a non-hazardous, chemically inert, solid material. The U.S. Environmental Protection Agency has recognized this concept of thermal destruction of asbestos as a viable technique to render asbestos harmless.

This experiment was conducted at plasma torch power levels of about 170kW and at furnace temperatures above 1,300°C. Twenty-five pounds of pure chrysotile asbestos in metal canisters were fed into the furnace over a 35 minute period. Furnace residence times varied from 6 to 41 minutes. Tests for asbestos fibers were made on the vitrified residue remaining from the melted asbestos, the metal canister residue, samples of residue material found inside the furnace, and air samples inside and outside the process gas stream.

Plasma arc technology has been demonstrated to be an efficient and effective method of destroying and vitrifying pure chrysotile asbestos in an environmentally safe manner.

Trace amounts of asbestos found in the solid residue and gaseous effluent during the analysis consisted of only a few scattered fibers. This amount of asbestos is considered negligible, and far below existing asbestos exposure standards and guidelines; e.g., less than 1% by volume in the solid vitrified material and a maximum airborne concentration of 0.2 fibers per cubic centimeter in the workplace. If necessary, a small increase in furnace temperatures and/or residence time of the asbestos should readily eliminate even these trace amounts.

Asbestos vitrification operating costs for a 7 ton per day mobile Plasma Asbestos Pyrolysis System (PAPS) are estimated at $163 per ton. These costs are about equal to the median level of 1988 ACM landfill disposal costs in the U.S. Thus, a mobile PAPS would be commercially competitive at the present time in many regions of the U.S. Plasma arc vitrification of asbestos would be expected to become increasingly competitive throughout the U.S. as landfill disposal costs increase. In addition, with total relief from the continuing liability of owners, an on-site PAPS facility should present an attractive alternative to landfill disposal.

FOREWORD

This research was performed for the U.S. Army Construction Engineering Research Laboratory (USACERL) under a Cooperative Research and Development Agreement (CRDA) sponsored by the Construction Productivity Advancement Research (CPAR) Program. The work was conducted by the Construction Research Center (CRC), Georgia Institute of Technology; the Materials Science and Technology Laboratory (MSTL), Georgia Tech Research Institute (GTRI); and two industry partners: Plasma Energy Corporation (PEC); and Asbestos Abatement Technology, Inc. (AAT). Mr. Hany H. Zaghloul, Environmental Division, USACERL, was the technical monitor for the program.

The principal investigator for the research program was Dr. Louis J. Circeo, CRC. Appreciation is expressed to the following personnel for the significant roles they played in assisting in the conduct and evaluation of the results of this research program, and for their advice and assistance in the preparation of this document:

Mr. Hany H. Zaghloul, USACERL
Dr. S. L. Camacho, PEC
Mr. S. Brent Reid, AAT
Mr. Guillermo R. Villalobos, MSTL
Mr. James R. Hubbard, MSTL

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1. INTRODUCTION

The U. S. construction industry is currently faced with a multi-billion dollar rehabilitation cost relating to asbestos removal and disposal from existing buildings constructed with asbestos-containing building materials. The EPA estimates that about 750,000 public, commercial and industrial buildings in the U.S. have asbestos-containing materials. Corrective actions must be taken when contamination levels are too high or when renovating, reconstructing or demolishing these structures. The U.S. Government is significantly involved in this costly rehabilitation program.

In recent years asbestos fibers have been identified as a known carcinogenic agent. Exposure to this hazard creates a serious risk to public safety and health. The EPA currently estimates that up to 12,000 deaths each year in the U.S. are caused by asbestos exposure. As a result, Congress passed the Asbestos Emergency Response Act of 1986 (AHERA) which mandates inspection in school grades K through 12. Congress is currently considering extending this legislation to all public and commercial buildings. This legislation specifies what steps are to be taken when asbestos-containing materials are discovered. The options range from modified operations and maintenance to complete removal and disposal.

In the Department of Defense (DoD), asbestos control is one of the top maintenance priorities. At the Pentagon building alone over $5 million has been spent on asbestos control since 1984. The DoD's problems are far ranging because of the amount of property under its control and the remote locations (including foreign countries) of these properties. Because of AHERA only the DoD schools are currently required to be inspected but this could change at any time if Congress decides to act on current proposals. Thus, the asbestos problem is expected to continue for the DoD and the U.S. construction industry for many years in the future.

At the present time asbestos and asbestos-containing materials can be deposited only at selected Class 1 EPA-approved landfill disposal sites which comply with the National Emissions Standards for Hazardous Air Pollutants (NESHAP). As these disposal sites become filled and are closed, transportation distances to remaining sites will increase, with subsequently higher disposal costs. In addition, because of the likelihood of asbestos fibers to cause air and ground water pollution, landfill disposal of asbestos and asbestos-containing materials is very likely to become much more restrictive in the near future. This latter circumstance would create a significant disposal dilemma for both the U.S. construction industry and the U.S. Government.

Plasma torch destruction of asbestos-containing waste materials could provide an effective, economical and timely solution to this problem. It is anticipated that the very high temperatures achievable with plasma arc technology will melt and vitrify asbestos and asbestos-containing materials into a chemically inert glass-like residue which meets all EPA environmental criteria. It is important to determine the applicability of this emerging technology to the destruction of asbestos and asbestos-containing waste materials prior to the declaration of more restrictive asbestos disposal regulations.

This study was conducted to evaluate the potential effectiveness of plasma arc technology to destroy asbestos-containing materials removed from public and commercial buildings. The answers to three questions were sought:

- Can plasma arc technology adequately destroy asbestos?
- Can it be done in an environmentally safe manner?
- Would a commercial process be cost-effective?

If the destruction and vitrification of pure asbestos can be successfully demonstrated, the development of a mobile Plasma Asbestos Pyrolysis System (PAPS) for the on-site destruction of asbestos and asbestos-containing materials (ACM) would have a high probability of success.

2. BACKGROUND

a. The Construction Productivity Advancement Research (CPAR) Program (1)

CPAR is a cost-shared research and development partnership between the U.S. Army Corps of Engineers (USACE) and the U.S. construction industry; e.g., contractors, equipment and material suppliers, architects, engineers, financial organizations, etc. In addition, academic institutions, public and private foundations, non-profit organizations, state and local governments and other entities who are interested in construction productivity and competitiveness are also participants in this program. CPAR was created by the Secretary of the Army to help the domestic construction industry improve productivity and regain its competitive edge nationally and internationally. This will be accomplished by building on the existing USACE construction R&D programs with cost-shared industry partnerships. The objective of CPAR is to facilitate productivity-improving research, development and application of advanced technologies through cooperative R&D programs, field demonstrations, licensing agreements and other means of technology transfer.

The Federal Government is the largest single buyer of construction services. Technology advancements that improve construction productivity will reduce construction program costs. Projects not now economically feasible might become feasible due to lower construction costs. Cost savings would accrue directly to the Federal Government's construction program, as well as benefit the U.S. construction industry and the U.S. economy in general.

CPAR is designed to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity and project costs and on USACE mission accomplishments. R&D and technology transfer under CPAR is based on proposals received from educational institutions, the construction industry and others which will benefit both the construction industry and the Corps of Engineers. The CPAR Program permits USACE to act on ideas received from industry, to cost-share partnership arrangements, and to rapidly implement successful research results through aggressive technology transfer and marketing actions. Section 7 of the Water Resources Development Act of 1988, P.L. 100-676, and the Stevenson-Wydler Technology Innovation Act of 1980, as amended, 15 U.S.C. 3710a et seq., provide the legislative authority for the CPAR Program.

This CPAR program to evaluate the use of plasma arc technology to destroy and vitrify pure chrysotile asbestos was under the overall direction of the Research and Development Office, Headquarters, U.S. Army Corps of Engineers, Washington, DC. Four organizations participated in this government-university-industry joint research program:
(1) U.S. Army Construction Engineering Research Laboratory (USACERL), Champaign, IL. USACERL sponsored this program and was responsible for funding the

Government portion of the project, conducting overall management of the project and providing program guidance to all partners to ensure that CPAR program objectives were fully met.

(2) **Construction Research Center (CRC), Georgia Institute of Technology, Atlanta, GA.** The CRC was responsible for the technical portion of the research program; i.e., develop the test plan, conduct the experiment, collect and analyze the data, interpret the results, and prepare the final report. In addition, the CRC coordinated the schedules and the activities of the two industry partners.

(3) **Plasma Energy Corporation (PEC), Raleigh, NC.** As an industry partner, PEC provided their Test and Demonstration Facility (TDF) for the research program. PEC personnel operated the plasma furnace used for the test, assisted in the data collection efforts, and were consultants to Georgia Tech on the interpretation of the test results.

(4) **Asbestos Abatement Technology (AAT), Inc.** AAT was responsible for all aspects of the research program related to the procurement, handling, safety, and disposal of the asbestos materials. They also assisted in the interpretation of the test results and provided important data relating to current asbestos removal and disposal practices. If the research program is successful and proven to be cost-effective, it is anticipated that AAT would commercialize the process.

b. The Asbestos Hazard (2, 3, 4)

Asbestos is a naturally occurring mineral. It is distinct from other minerals by its crystals which form long, thin fibers. Deposits of asbestos are found in the U.S. and throughout the world. The primary sites of commercial production are in Canada, the Soviet Union and South Africa. When extracted from the earth, the asbestos-containing rock is crushed, milled and graded. This produces long, thread-like fibers of material. What appears as a single fiber is actually an agglomeration of hundreds or thousands of fibers, each of which can be divided even further into millions of microscopic fibrils. Chrysotile is the most commonly used type of asbestos and accounts for approximately 95% of the asbestos found in buildings in the United States. Therefore, chrysotile was selected as the type of asbestos to be used in this study. Typical chemical, mineralogical and physical properties of chrysotile asbestos are given in Table 1.

Asbestos achieved widespread use because it was plentiful and inexpensive. Its unique properties (fire resistant, high tensile strength, poor thermal and electrical conductivity) made it a popular product throughout the construction industry. Asbestos is routinely mixed with other materials (binders, cement, asphalt, vinyl, etc.) for these applications; collectively these products are often referred to as asbestos-containing material (ACM). Three categories of ACM are normally used in buildings:

- Surfacing Materials (sprayed or trowelled on surfaces)
- Thermal System Insulation (pipe wrap, blanket insulation, cements and muds).
- Miscellaneous Materials (floor/ceiling tile, roofing felt, concrete pipe, siding, fabrics)

In 1984, over 150,000 metric tons of chrysotile asbestos were consumed in the U.S.

In 1988 the U.S. Environmental Protection Agency (EPA) announced the results of a national asbestos survey of 3.6 million public and commercial buildings in the U.S. About 750,000 of these buildings contained potentially harmful ACM. About 25% of these affected buildings have sprayed- or trowelled-on asbestos surfacing material, such as acoustical plaster on ceilings, while an estimated 80% contained asbestos in thermal system insulation (pipes, boilers, tanks or ducts). The ACM was damaged in approximately 70% of these buildings.

Asbestos is a known human carcinogen which can cause several types of cancer. Asbestos can present a health hazard when it is crushed or pulverized and emits microscopic fibers. These fibers stay suspended in the air for long periods of time; they can become lodged and can accumulate in the lungs. As exposure increases, the risk of disease likewise increases, since the primary health effects from asbestos exposure act on the lungs. No safe threshold has been established for asbestos. The principal diseases which are directly attributable to asbestos inhalation are:

- **Asbestosis:** A disease characterized by fibrotic scarring of the lung.
- **Lung Cancer:** A fivefold increase in risk can result from asbestos exposure.
- **Mesothelioma:** A cancer of the chest cavity lining or in the lining of the abdominal cavity.

- **Other:** Cancer of the esophagus, stomach, colon, and pancreas; pleural plaques, pleural thickening, and pleural effusion.

Under current regulations asbestos waste generators, such as building owners, involved in a project requiring ACM removal must be identified and recorded. Liability is not eliminated by transferring the care, custody or control of the ACM to a landfill owner. Original parties can be held legally accountable even if injury is sustained years after the removal project is completed. Thus, ACM burial in a landfill does not end the liability of the waste generators.

c. **Previous Work** (6, 7)

Disposal of ACM by thermal transformation is based on the fact that asbestos fibers are melted and exhibit a change in molecular structure at elevated temperatures. When chrysotile asbestos is heated to 800-900°C a transformation to a flaky material, called fosterite, occurs. Further heating to temperatures above 1,000°C melts and vitrifies the material into an amorphous, chemically inert solid material. These changes are irreversible; upon cooling, the chrysotile asbestos fiber structure is not restored. The residue material is not considered to be asbestos, and is classified as non-hazardous. The EPA has acknowledged that this thermal vitrification process is sufficient to render asbestos and asbestos-containing materials harmless.

Based on the capability of high temperatures to destroy ACM several competing firms have been developing commercial vitrification processes utilizing conventional heating technologies such as fossil fuels and electric furnaces. An ACM thermal destruction process would be attractive to waste generators since the aforementioned continuing liability of building and landfill owners would be eliminated. However, since temperatures greater than 1,000°C are difficult to achieve and maintain in conventional furnaces, additional measures must be taken in order to assure that the destruction process is complete. These steps can significantly impact the technical and economic viability of an ACM vitrification process.

Existing conventional heating ACM vitrification processes generally require one or more of the following measures:

- Long furnace residence times at elevated temperatures (up to 12 hours).
- Addition of waste glass "cullet" to lower the melting point of the ACM and improve glassification of the residue material and immobilization of any residual asbestos fibers.
- Pre-sorting and separate treatment of ferrous and non-ferrous ACM and "asbestos-contaminated" material.
- Shredding the ACM prior to feeding it into the furnace.

In addition to the above measures, the residue from conventional thermal destruction processes is often not completely melted and vitrified. For example, the vitrified material could contain unmelted metal debris from the original raw material. This could reduce the salability of the residue material (road/concrete aggregate, etc.) and could result in a requirement to landfill the residue.

To our knowledge no commercially successful asbestos vitrification process is currently in operation in the United States.

d. **Plasma Arc Technology** (9, 10, 11, 12)

(1) **General**

A plasma is a gas that has been ionized by the electric arc of a plasma torch and can therefore respond to electrical and magnetic fields. The resistance of the plasma converts electricity into heat energy. This technology was developed over 25 years ago in the U.S. space program to simulate re-entry temperatures on heat shields. Only recently has this technology begun to emerge as a commercial tool in several industries such as steelmaking, precious metal recovery, and waste disposal.

The heart of this technology is the plasma arc torch, essentially a steel cylinder several inches in diameter and several feet in length; the specific dimensions are related to the torch power levels. Plasma torches operate in the 100 kilowatt to 10 megawatt power range and can routinely create controlled furnace temperatures that range from 3,000 to more than 7,000 degrees centigrade. Thus, plasma torches can operate at much higher temperatures and at greatly increased efficiencies than fossil fuel burners. In addition, plasma torches require only about 1% of the air necessary for fossil fuel burners. Therefore, effluent gases are greatly reduced, and furnace systems can be built much more compact than traditional furnaces at correspondingly reduced capitol costs. Additional information on plasma technology extracted from a PEC brochure is given in Appendix A.

(2) Advantages of Plasma Heating

The advantages that accrue from the use of plasma torches include:

- **High Temperatures:** The plasma torch can create temperatures that are not achievable with fossil fuel burners. In the plasma arc torch it is possible to routinely achieve controlled temperatures greater than 7,000°C. This extreme heat is produced instantly, and can be readily automated. Controlled, high temperatures increase feed material throughput, and reduce costs.
- **Controlled Atmosphere:** Because the plasma arc torch is compatible with almost any gas (e.g., reducing, oxidizing, neutral, inert gases, etc.) the furnace atmosphere can be controlled to meet unique requirements.
- **Massless Heat:** Plasma arc torches use 1/100th of the air needed by fossil fuel heaters. Releasing heat energy with almost no mass is a simpler process than conventional heating, and offers greater control and efficiency. It also reduces off gas handling and other capital costs.
- **High Thermal Efficiency:** The efficiency of plasma arc torches consistently reaches between 85% and 93%. Therefore, the faster and more complete reaction kinetics of plasma energy sharply reduces processing time and operating costs.

(3) Plasma Torch Types

There are basically two types of plasma arc torches. On the **Transferred Arc Torch** the positive attachment point is at the rear electrode and the negative attachment point is the work-piece or the melt. For example, if metal scrap is being melted, the negative attachment point is the metallic scrap. On **Non-Transferred Arc Torches** both attachment points are within the torch itself and only the generated plasma flame egresses from the torch.

(4) Plasma Heating System Components

The plasma arc torch is only one component of the plasma heating system. The other components are: **1)** a **power supply** which can be alternating current or direct current; **2)** a **control panel** to control the initiation and sustainment of the plasma arc column; **3)** a **closed-loop water system** to provide cooling to the electrodes and shroud; **4)** a **gas system** to provide the small quantity of gas required for the plasma gas; and **5)** a **starting system** to start the torch.

(5) Plasma Torch Technology Applications (11, 12, 13, 14)

Several plasma torch processes for the destruction of hazardous and toxic wastes have been developed and successfully tested. Research on a variety of waste materials have been conducted using plasma energy. The very high temperatures and energy densities, in conjunction with an ionized and reactive medium, have fully demonstrated the potential of plasma technology to eliminate many waste materials in an environmentally safe and cost-effective manner. Materials vitrified with plasma arc torches readily pass all standard leaching tests.Thus, if pure asbestos can be destroyed in an environmentally safe manner, then asbestos, ACM, and any other materials which are removed from a building should be able to be mixed, vitrified and similarly destroyed in an environmentally safe manner.

At the International Union for Electroheat Conference in October, 1988 several processes for the efficient elimination of wastes were described. Among the promising technologies presented were processes to destroy PCB's, hospital medical wastes and municipal solid wastes. Some of these processes have been commercialized while others are still in the development stage.

Plasma torch technology is currently being utilized or planned for a variety of industrial and experimental applications. These include:

- Titanium scrap melting
- Coal gasification
- Ferro-alloy production
- Molten steel ladle heater
- Aluminum recovery from dross
- Volume reduction of equipment
- Tundish heating for steel casting
- Incinerator ash vitrification
- Iron ore reduction
- Waste pyrolysis (municipal, medical, asbestos, tires, hazardous/toxic, low level radioactive)
- Biomass energy conversion
- Shale oil recovery
- Platinum recovery
- Zinc recovery
- Chemical synthesis
- MgO refractory production
- Powder metal production
- Silicon metal production
- Electric arc furnace dust vitrification
- Glass melting

3. RESEARCH PLAN

a. General

The principal goal of this research effort was to determine if plasma arc technology can effectively destroy pure chrysotile asbestos in an environmentally safe manner. Specific research objectives were as follows:

(1) Subject pure chrysotile asbestos to melting and vitrification in a plasma arc pyrolysis furnace.

(2) Evaluate the extent to which the chrysotile asbestos has been adequately destroyed and transformed into a non-hazardous material which meets EPA requirements.

(3) Analyze the gaseous effluent to verify that it complies with EPA effluent standards.

(4) Evaluate the anticipated economic feasibility of the process.

b. Research Tasks

(1) Conduct a review of literature on the destruction of asbestos and asbestos-containing materials by thermal means.

(2) Conduct a feasibility study on the potential application of plasma arc technology to destroy asbestos in a cost-effective manner.

(3) Develop an experimental procedure to subject pure asbestos to melting and vitrification by a plasma torch.

(4) Conduct a plasma arc melting and vitrification test of pure chrysotile asbestos. Analyze the solid residues and the gaseous effluents to verify compliance with EPA standards.

(5) Evaluate the anticipated economics and cost-effectiveness of plasma arc technology to destroy asbestos and asbestos-containing materials in an environmentally safe manner.

c. The PEC Test and Demonstration Facility

The asbestos vitrification test was conducted at the Test and Demonstration Facility (TDF), Plasma Energy Corporation. The TDF was built specifically to test plasma processes for a variety of applications. The TDF power supplies, coupled with different PEC plasma torches, can produce plasma arc power levels up to 6MW. Gases for the plasma torch and process gases for testing are supplied by on-site storage facilities. Cooling water for the torches is provided by a 200 psi, 200-GPM water system.

The furnace system used for this experiment was a small smelting/melting 2 cubic foot furnace capable of being tilted on an axis and continuous pouring while being heated with a 300kW plasma arc torch of 4-inch diameter. This furnace is capable of accepting materials up to 3-inch size. The gaseous effluent from this furnace is channeled into a packed bed scrubber, the lower portion of which contains several layers of spray nozzles. Water is used to quench the effluent gas to insure that it is cooled before it contacts the bed. Water from the scrubber is recirculated through a closed-loop system into a settling tank, where it is subjected to a bypass filter. Gases passing through the scrubber are sent through a baghouse filter before being released to the atmosphere. Figure 1 is a cross section diagram of the plasma arc furnace system used in this experiment.

d. Asbestos Samples

The chrysotile asbestos samples used in this experiment were obtained from J. M. Asbestos, Inc., Asbestos, Quebec Province, Canada. The Quebec standard has eight grades of pure asbestos fibers classified by length and by commercial quality specifications. The four grades (3, 4, 6, 7) of chrysotile asbestos which were used in this experiment comprised about 90% of the annual U.S. consumption of chrysotile asbestos.

In order to meet safety requirements for handling and loading the asbestos into the furnace, AAT packed the pure asbestos fibers into galvanized steel canisters, three inches in diameter and one foot in length, capped at each end (Figure 2). Approximately two pounds of asbestos could be loaded into each canister (see Table 2). A total of 16 canisters with a total asbestos weight of about 25 pounds was loaded into the furnace.

4. EXPERIMENTAL PROCEDURE

The experiment was carried out on December 12, 1990. Table 3 contains the pertinent data points which were taken during the experiment. The furnace was sealed and heated with a 300kW torch for a period of approximately one hour. The asbestos canister melting took place in a crucible which was surrounded by sand and placed in the furnace (see Figure 3). A power level of about 170kW was required throughout the experiment in order to maintain desired furnace temperature sensor levels greater than 1,200°C. The actual temperatures inside the crucible were higher (greater than 1,300°C) since the furnace temperature sensor was located outside the crucible at the bottom of the furnace, and out of the direct thermal influence of the plasma torch.

Because of a temperature drop following the insertion of each canister, a short delay time was required between the insertion of each canister in order to raise the furnace temperatures back to above 1,200°C. A total time period of 35 minutes was required to insert the 16 canisters, occurring 94 minutes into the experiment. The torch was shut down at 100 minutes. Therefore, the residence time for the asbestos canisters under plasma arc heating ranged from 6 to 41 minutes.

As indicated in Table 3, the furnace temperature sensor during insertion ranged from 1,243°C to 1,319°C. An optical pyrometer recorded a maximum melt temperature inside the crucible of 1,616°C at the time of plasma torch power shut down.

Throughout the testing period, asbestos collection filters sampled the exhaust gases at two locations in the gas stream; asbestos samples were also taken in air filters at an ambient air location (see Figure 4). Samples of scrubber water were taken before and after the experiment. In addition, sections of the baghouse filter were tested for asbestos after the experiment.

The furnace was allowed to cool for a period of about two hours before the furnace top was removed. Samples of material were taken from 12 locations in the furnace to look for asbestos fibers (see Figure 3).

5. TEST RESULTS

a. Solid Residue Tests

When extracted from the crucible, the solid residue consisted of a dense, gray, rocklike material above a flat plate of metal. The dense rock material was the amorphous vitrified residue from the melted asbestos. Figure 5 is a photo which compares the pretest pure chrysotile asbestos with the post test solid residue. The metal plate was comprised of the melted galvanized steel canisters into which the asbestos was packed for insertion into the furnace. As shown in Table 2, the weight of the metal plate was 8 pounds, 1 ounce; therefore, the amount of pure chrysotile asbestos which was melted was 25 pounds, 10 ounces.

The samples of vitrified asbestos were prepared for transmission electron microscopy (TEM) analysis for asbestos by first creating small pieces of the samples using a hammer and coal chisel. The pieces were then pulverized with a three piece anvil set made for that purpose. The resulting powder was placed in a 35mm film container along with 3 or 4 steel shot and the container lid tightly taped. The container was shaken in a vibrating mill to produce a very fine powder. A weighed portion of powder was placed in a beaker with 2ml distilled water which contained a very small amount of dispersing agent. This suspension was diluted as necessary to produce a sample with a proper concentration for TEM analysis. A 5 microliter drop of the suspension was placed on a carbon film coated TEM grid and allowed to dry. The prepared grids were examined in the TEM and any suspect asbestos fibers were identified by electron diffraction. Ten grid openings were analyzed on each grid.

The TEM analysis was able to identify only trace amounts of a few scattered asbestos fibers within the vitrified mass. Figure 6 illustrates these results with pretest and post test photographs of the pure asbestos fibers and the subsequent vitrified residue taken through the Transmission Electron Microscope. The trace amounts of fibers found in the analysis are considered negligible, far below existing asbestos exposure standards; i.e., less than 1% by volume for the solid vitrified material. Even these trace amounts of asbestos were encapsulated and immobilized within the vitrified mass of residue material. If necessary, a small increase in furnace residence time should readily eliminate any trace amounts of asbestos fibers.

A similar TEM analysis was conducted on a sample taken from the flat metal plate formed at the bottom of the crucible. No asbestos was detected in this material.

It was not considered necessary to conduct an EPA toxicity leaching test on the vitrified residue material to test for heavy metals (arsenic, selenium, chromium, cadmium, barium, lead, mercury, silver). As shown in Table 1, pure chrysotile asbestos is a compound consisting of magnesium and silicon oxides, and may contain some trace amounts of other elements. It does not contain any of the heavy metals of concern to the EPA, and therefore does not require testing for these elements.

b. **Furnace Residue Material Tests**

Following completion of the experiment, 12 samples of residue material were taken inside the furnace to look for asbestos fibers, (see Figure 3). Table 4 indicates the results of this study. Trace amounts of scattered asbestos fibers were found at two of the 12 sampled locations. One location was directly below the canister insertion tube of the furnace. Unmelted pieces of a canister at this location indicated that this canister impinged on the top of the crucible and probably was not fully exposed to the required furnace temperatures. The other location was in the "splash zone" inside the crucible, and likely contained fibers not fully melted which were splashed and deposited onto the side of the crucible.

c. **Exhaust Gas Filter Tests**

Figure 4 shows a schematic layout of the plasma furnace, scrubber, and baghouse filter. The points marked Probe 1 and Probe 2 are the locations of asbestos collection filters which sampled the exhaust gases for unmelted asbestos fibers. Probe 1 was placed to sample the exhaust gas stream immediately after it exited the furnace and before it passed through filtration devices. Probe 2 was positioned the monitor the effectiveness of the scrubber should asbestos be detected at Probe 1.

It was necessary to continually change the filter at the Probe 1 location. The exhaust gas stream contained a large amount of ash which tended to clog the fine filter. A total of five filters were used at the Probe 1 location during the test. The filter at Probe 2 was only changed one time, 2 minutes into the experiment. The second filter at Probe 2 continued to operate during the remainder of the test. An additional filter (Probe 3) was used to test the ambient air in the vicinity of the furnace during the test.

The membrane filters were removed from the air filter cassettes and placed in beakers. A measured amount of distilled water with dispersant was used to wash out the cassette body and the water poured into the beaker. The water was stirred using ultrasonics to release particles from the filter membrane and disperse them throughout the water. The suspension was diluted to a usable concentration and a 5 microliter drop was allowed to dry on a carbon-film-coated TEM grid. These samples were then analyzed in the TEM as previously described.

Results of the TEM analysis for asbestos fibers were as followed:

(1) **Probe 1 (Exhaust gas from furnace):** Five filters were tested. Trace amounts of scattered asbestos fibers were detected on the second and fourth filters. No asbestos was found on the first, third, and fifth filters.

(2) **Probe 2 (Exhaust gas from scrubber):** Two filters were tested. No asbestos fibers were detected.

(3) **Probe 3 (Ambient Air Filter, in vicinity of furnace):** One filter was tested. No asbestos fibers were detected.

U.S. standards permit airborne asbestos fiber concentrations up to 0.2 fibers per cubic centimeter in the workplace (2). The exhaust gas filter tests indicated that a negligible amount of asbestos fibers escaped from the furnace environment; these were readily scavenged by the scrubber. Thus, the gaseous effluent from the plasma arc destruction and vitrification of asbestos can be considered to be environmentally safe by a large margin.

d. **Other Exhaust Gas Tests**

The scrubber water was analyzed for asbestos fibers which may have been scrubbed from the exhaust gas stream. It was necessary to analyze the water both before and after the experiment since some municipal water systems contain trace amounts of asbestos fibers. No asbestos fibers were detected in any of these tests.

The baghouse filters were removed following the experiment. A section of one of the filters was removed and analyzed. A trace amount of asbestos in the form of a few scattered fibers was detected on this filter.

6. ECONOMIC ANALYSIS

a. General

In addition to proving the technical feasibility of destroying asbestos using plasma arc technology, the economic viability of the process must be proven in order to become a commercially successful enterprise. Three areas must be addressed in order to determine if this concept is economically feasible:

- What is the anticipated cost of the plasma arc asbestos destruction process?
- What is the current cost of asbestos disposal in landfills?
- In the future, as landfills are closed, what increased disposal costs can be expected?

At this early stage of research it would be very difficult to develop firm disposal cost comparisons. Even if this was possible, current disposal costs vary so widely around the U.S. that only a range of costs would be possible. However, it should be possible to arrive at general destruction and disposal costs in order to evaluate the economic viability of this plasma arc destruction and vitrification process.

b. Projected Cost of Plasma Destruction of ACM

The anticipated capital and operating costs of a mobile Plasma Asbestos Pyrolysis System (PAPS) were based on a PEC financial analysis for a similar system for medical waste disposal (17). The system was designed for a 300kW plasma heating system and furnace mounted on a 45-foot van.

The cost analysis assumed a Specific Energy Requirement (SER) of approximately 0.35KWH of plasma torch power to melt and vitrify one pound of ACM (18, 19). The precise SER rate can only be determined through challenge tests for ACM optimum feed rate, scheduled for a follow-on phase of this research program. This system would be capable of processing an estimated 6.86 tons of ACM per 16 hour processing day. The projected financial analysis of the PAPS facility is explained in Appendix B. If the facility is operated at full capacity, the projected operating cost breakdown is as follows:

Power Costs	1.75 cents/pound	
Labor Costs	2.86 cents/pound	
Maintenance Costs	1.75 cents/pound	
Equipment Amortization Costs	1.78 cents/pound	
Total Projected Operating Cost	**8.14 cents/pound**	**= $163/ton**

Appendix B also contains an analysis of the economic sensitivity of increased power costs and interest rates. These two operating cost factors are based on economic conditions that cannot be closely controlled in developing a PAPS facility. The analysis indicates that a 2¢/KWH higher power cost (to 7¢/KWH) increased operating costs to $177/ton. When a 2% higher interest rate is added (to 10%), operating costs increased to $180/ton. The sensitivity analysis indicates that even with higher power costs and interest rates, the operating costs of a PAPS facility are not significantly increased. Thus, the general operating costs of ACM destruction with plasma arc technology can be determined with relative confidence.

The projected costs of ACM destruction and vitrification could be offset to some extent by the sale of the vitrified residue material. Its very dense jagged and rocklike structure would make it useful as a road aggregate, concrete mix, etc. It may also be economically feasible to pour the molten ACM from the furnace directly into molds in order to produce bricks and other construction materials.

c. Current Cost of Asbestos Disposal

In 1988 Plasma Energy Corporation participated in several discussions with asbestos abatement contractors in the Cleveland, Ohio area. These contractors were required to transport asbestos waste materials to authorized landfills, often at considerable distances from the Cleveland area. Tipping (dumping) fees at the landfills ranged from $100 to $240 per ton (19). This wide range of disposal costs is due to the fact that landfill disposal fees are generally based on volume of waste rather than weight. Therefore, lightweight ACM, such as insulation, would be proportionately more expensive to dispose of than heavy ACM such as tile. The above range of disposal fees are considered to be representative of costs throughout the U.S. In the northeast U.S., tipping fees are expected to be higher; in the southeast U.S. tipping fees are lower. These costs do not include the cost of transporting the asbestos waste from the Cleveland area to the landfills.

d. Future Landfill Costs

There are an estimated 9,000 landfills currently in operation in the U.S. By the year 2000 approximately half of these will reach their capacity and will be subject to closure. Proportionately, about half the Class 1 EPA-approved landfills authorized to accept ACM could also be expected to close. The existing trends toward public environmental awareness and stronger environmental regulations are severely restricting the number of new landfills being created. Therefore, it can be expected that the costs to dispose of asbestos waste materials will significantly increase due to two factors: increased tipping fees at the landfills and the increased distances to authorized landfills. Current projections predict landfill tipping fee increases of at least 10% a year. Based on these increases, by the year 2000 the current costs of ACM disposal at the landfill would increase over 300%. These significant cost increases would be further exacerbated by the increased travel distances to the landfills and by the growing resistance to new landfills in local communities; i.e., their developing "Not in My Back Yard (NIMBY)" attitude toward landfills. Thus, it is anticipated that over time, a mobile PAPS facility will become increasingly more cost-effective compared to traditional landfill disposal practices.

7. SUMMARY AND CONCLUSIONS

When pure asbestos is subjected to temperatures above 1,000°C, the asbestos fibers are melted and subsequently solidified (vitrified) into a non-hazardous chemically inert solid material. The U.S. Environmental Protection Agency has recognized this concept of thermal destruction of asbestos as a viable technique to render asbestos harmless.

Several commercial processes have been developed to vitrify asbestos based on conventional heating technologies such as fossil fuel burners and electric furnaces. Because of difficulties in achieving and maintaining furnace temperatures in excess of 1,000°C, these conventional processes have not yet been proven to be technically viable or economically feasible. To our knowledge, no commercially successful asbestos vitrification process is currently in operation in the U.S.

Plasma arc technology has a capability to produce controlled temperatures many times higher than any conventional heating source. This unique characteristic promises to overcome many of the disadvantages of conventional heating processes:

- No ACM pre-sorting, preprocessing or shredding.
- No additive required to lower ACM melting point or to glassify residue material.
- Furnace residence time measured in minutes rather than hours.
- Complete melting and vitrification of ACM and all other associated materials placed in the furnace.

The experiment in this study was conducted at plasma torch power levels of about 170kW and at furnace temperatures above 1,300°C Twenty-five pounds of raw chrysotile asbestos were fed into the furnace over a 35 minute period. Furnace residence times at the designated torch power level varied from 6 to 41 minutes. Tests for asbestos fibers were made on the vitrified residue remaining from the melted asbestos, the metal canister residue, samples of material found inside the furnace, and air samples inside and outside the process gas stream.

The analyses of the test samples were as follows:

- Vitrified asbestos residue: Trace amounts of asbestos fibers were detected.
- Melted metal canisters: No asbestos detected.
- Furnace residue material: Trace amounts of asbestos were detected at 2 of the 12 sample locations.
- Exhaust gas stream:
  - Before scrubber: Trace amounts of asbestos were detected in 2 out of 5 filters
  - After scrubber: No asbestos detected.
- Ambient air outside furnace: No asbestos detected.
- Baghouse filter: Trace amounts of asbestos were detected.
- Scrubber water: No asbestos detected.

Asbestos vitrification operating costs for a 7 ton per day mobile Plasma Asbestos Pyrolysis System (PAPS) are estimated at $163 per ton. These costs are about equal to the median level of 1988 ACM landfill disposal costs in the U.S. A portion of the cost of vitrification could be offset by the sale of the vitrified residue as road aggregate, concrete mix, construction bricks, etc. In addition, with total relief from the continuing liability of owners, an on-site PAPS facility should present an attractive alternative to landfill disposal at the present time.

Landfill disposal costs are expected to increase significantly during the 1990's due to increased environmental regulations, a decreasing number of landfills which will accept ACM and increased transportation costs. This trend should result in asbestos vitrification becoming increasingly commercially competitive with ACM landfill costs throughout the U.S. Furthermore, since ACM landfill costs are expected to increase at a much faster rate than the operating costs of a PAPS facility, ACM vitrification should become the most cost-effective method of asbestos disposal in the near future.

As a result of this research program the following conclusions can be made:

- Plasma arc technology has been demonstrated to be an efficient and effective method of destroying and vitrifying pure chrysotile asbestos in an environmentally safe manner.
- Trace amounts of asbestos found in the solid residue and gaseous effluent during the analysis consisted of only a few scattered fibers. This amount of asbestos is considered

negligible, and far below existing asbestos exposure standards and guidelines; e.g., less than 1% by volume in the solid vitrified material and a maximum airborne concentration of 0.2 fibers per cubic centimeter in the workplace. If necessary, a small increase in furnace temperatures and/or residence time of the asbestos should readily eliminate even these trace amounts.

- The capability of plasma arc technology to safely destroy asbestos, ACM, and any other contaminated materials removed from a building has a high probability of success.
- A mobile 7 ton per day Plasma Asbestos Pyrolysis System (PAPS) would be anticipated to be commercially competitive at the present time in many regions of the U.S. where costs of ACM landfill disposal are above average. In the future, plasma arc vitrification of asbestos would be expected to become increasingly competitive throughout the U.S. as landfill disposal costs increase.

Table 1. Typical Chemical, Mineralogical and Physical Properties of Chrysotile Asbestos (2)

Chemical Composition	**$3MgO2SiO_22H_2O$**
Essential Composition	**Hydrous silicate of magnesium**
Percentage Chemical Composition (%)	
SiO_2	37 - 44
MgO	39 - 44
FeO	0.0 - 6.0
Fe_2O_3	0.1 - 5.0
Al_2O_3	0.2 - 1.5
H_2O	12.0 - 15.0
CaO	Tr. - 5.0
Color	White
Flexibility	Good
Specific gravity	2.55
Hardness (Mhos)	2.5 - 4.0
Fiber length (mm)	1-80
Fiber diameter (μm)	0.03 - 100
Tensile strength (MN/m^2)	3100
Fusion point (°F)	2770
Acid resistance	Fair to poor
Specific heat (BTU/lb/°F)	0.266
Electric charge	Positive
Filtration properties	Slow

Table 2. Asbestos Canister Weight Data

Canister No.	Weight (Canister plus Asbestos) Pounds	Ounces
1	2	0
2	2	2
3	2	0
4	2	4
5	1	10
6	1	10
7	1	10
8	2	0
9	2	4
10	2	5
11	2	4
12	2	7
13	2	4
14	2	4
15	2	6
16	2	5
TOTAL	**29 pounds**	**75 ounces**

Total Weight Canisters plus Asbestos:	**33 lb.**	**11 oz.**
Tare Weight Canisters:	**8 lb.**	**1 oz.**
Total Weight Chrysotile Asbestos:	**25 lb.**	**10 oz.**

Table 3. Asbestos Vitrification Test Data

Time (Min)	Canister Feed Schedule	Plasma Arc Power Volts	Plasma Arc Power Amperes	Plasma Arc Power kW (Ave)	Furnace* Temp (°C)	Melt Temp (°C)**
0	Start Up					
15	-	530/585	300	167	751	-
41	-	530/585	300	167	966	-
54	-	550/590	300	171	1,207	-
59	1	555/600	300	173	1,272	1,377
66	2	570/590	300	174	1,301	-
67	3, 4	565/590	300	173	1,319	-
71	5, 6	560/580	300	171	1,275	-
79	7, 8	550/560	300	166	-	-
80	9	560/575	300	170	1,273	-
84	10, 11	590/600	300	178	1,263	-
86	12	560/580	300	171	1,257	-
88	13	560/580	300	171	1,248	-
90	14	570/585	300	173	1,243	-
92	15	550/565	300	167	1,244	-
94	16	565/580	300	172	-	-
97	-	550/590	300	171	1,233	-
100	Shut Down				1,230	1,616
109	-	-	-	-	-	1,323

* Temperature sensor was located below the crucible at the bottom of the furnace.

** Temperature taken inside the crucible with an optical pyrometer.

Table 4: Furnace Residue Material Test Data

Sample* Number	Location	TEM Asbestos Analysis
1.	Outside Crucible Circumference	None
2.	Outside Crucible Circumference (Directly under canister insertion tube)	Trace amount of scattered fibers
3.	Outside Crucible Circumference	None
4.	Outside Crucible Circumference	None
5.	Outside Crucible Circumference	None
6.	Outside Crucible Circumference	None
7.	Outside Crucible Circumference	None
8.	Outside Crucible Circumference	None
9.	1 inch below sand surface (Directly under location #2)	None
10.	Solid residue in entrance of the exhaust gas stack	None
11.	Underneath crucible at sand interface	None
12.	Splash zone inside crucible	Trace amount of scattered fibers

*See Figure 3 for diagram of material sampling locations.

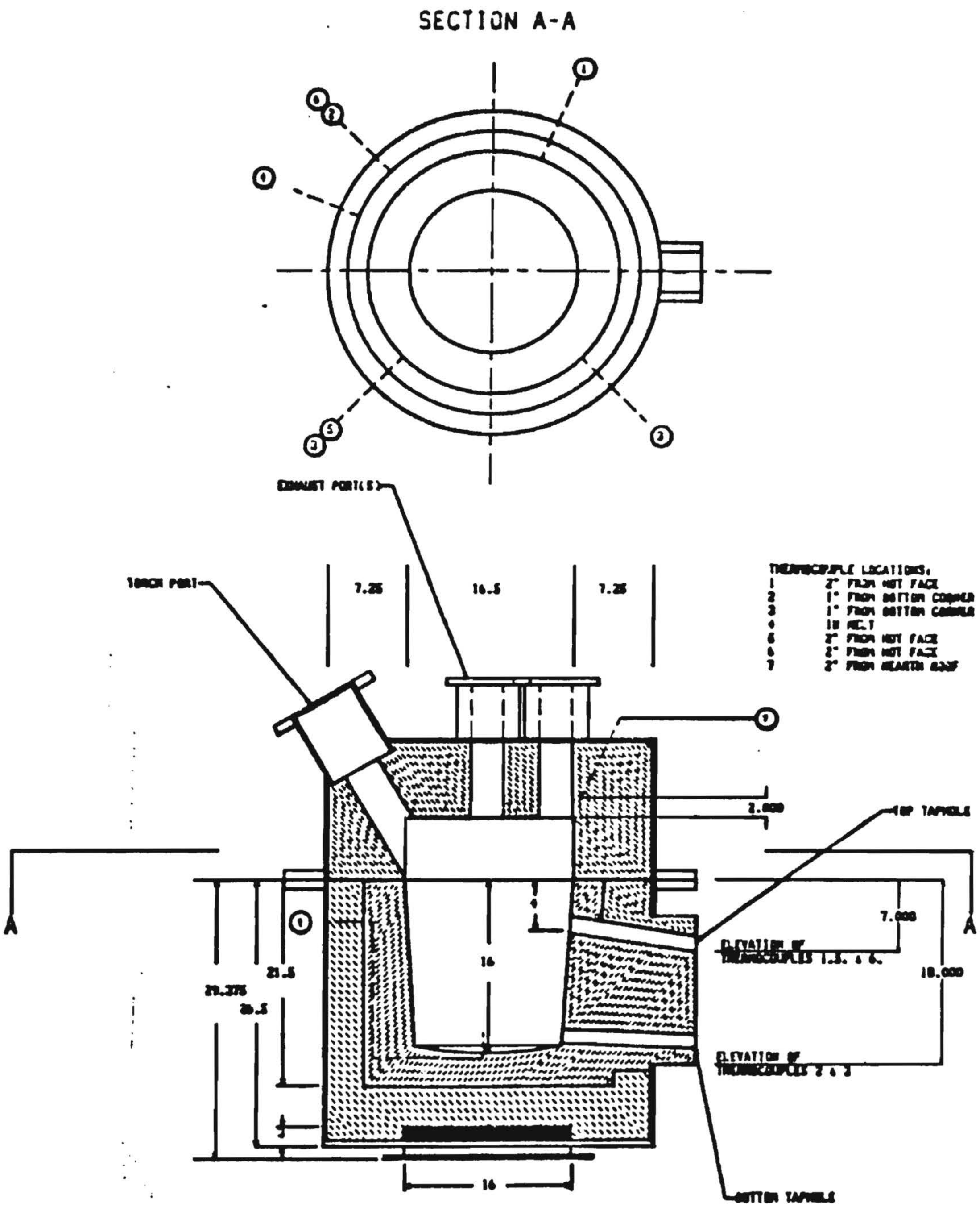

Figure 1. **Diagram of the PT-150 plasma arc tilt-furnace used for the asbestos destruction tests.**

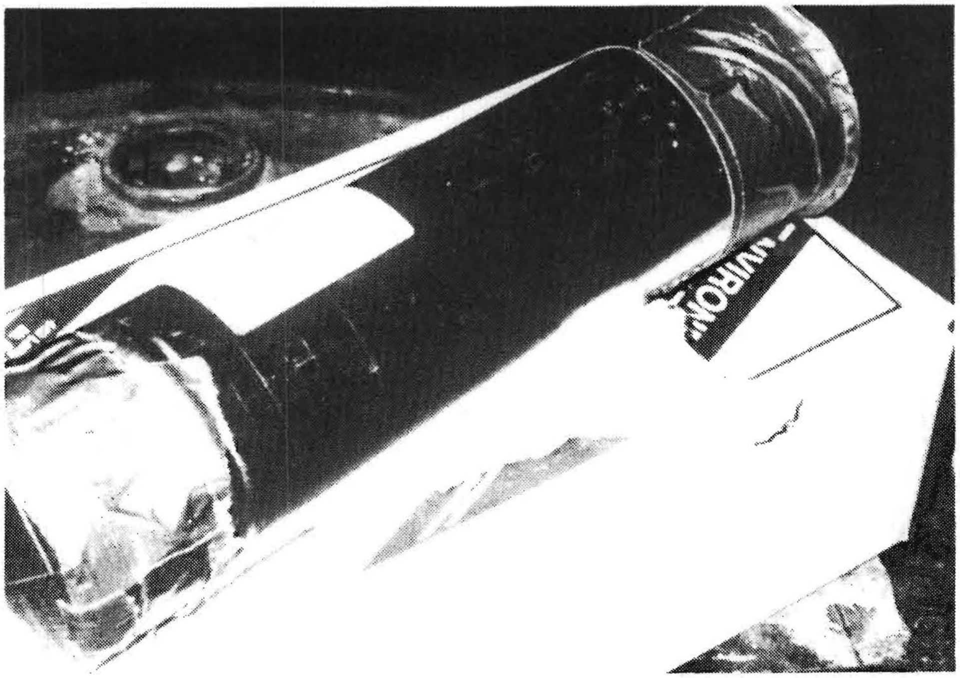

Figure 2. Photograph of one of the metal canisters containing pure chrysotile asbestos which were used in the experiment.

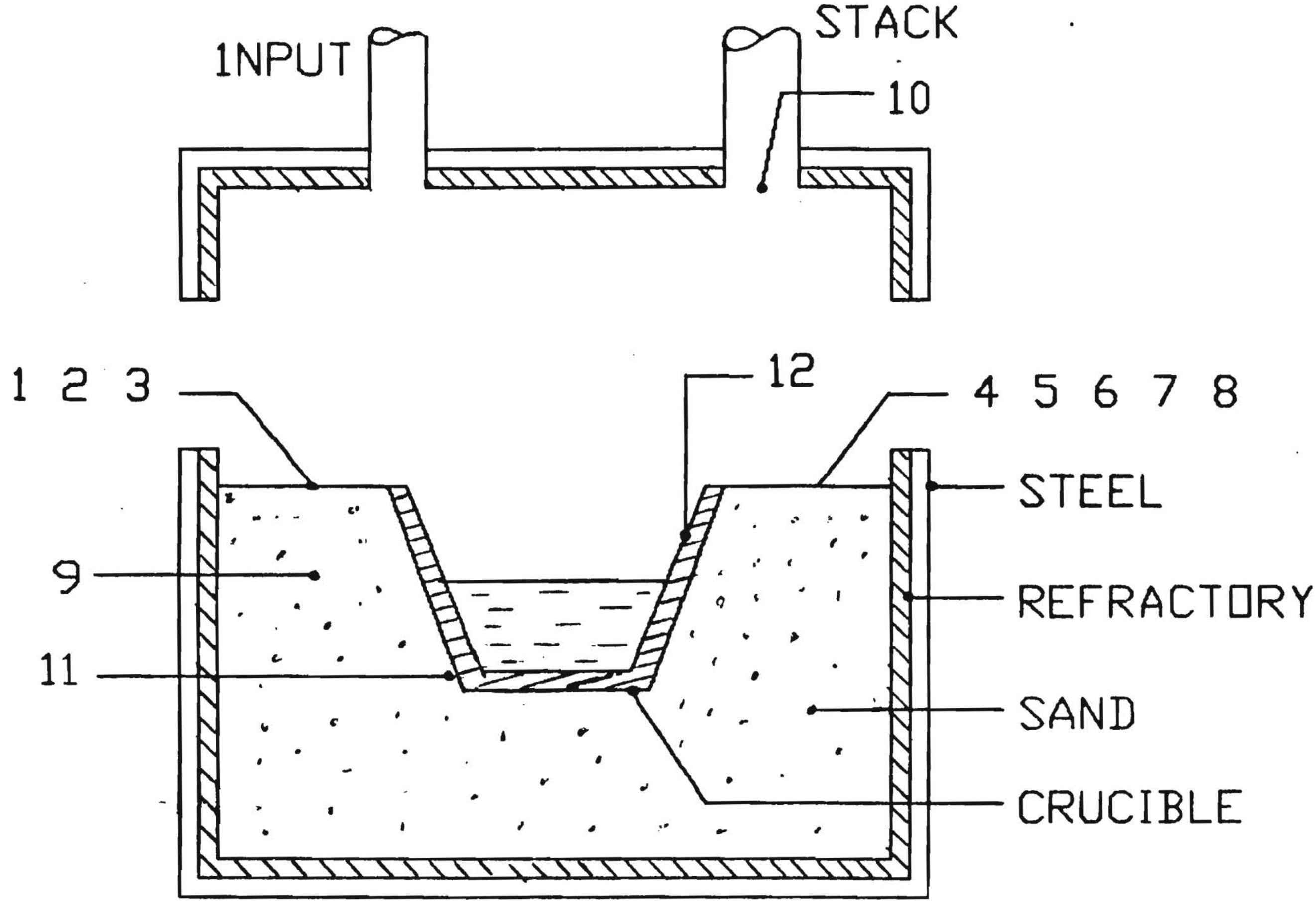

Figure 3. Cross section diagram of experiment geometry and material sampling locations.

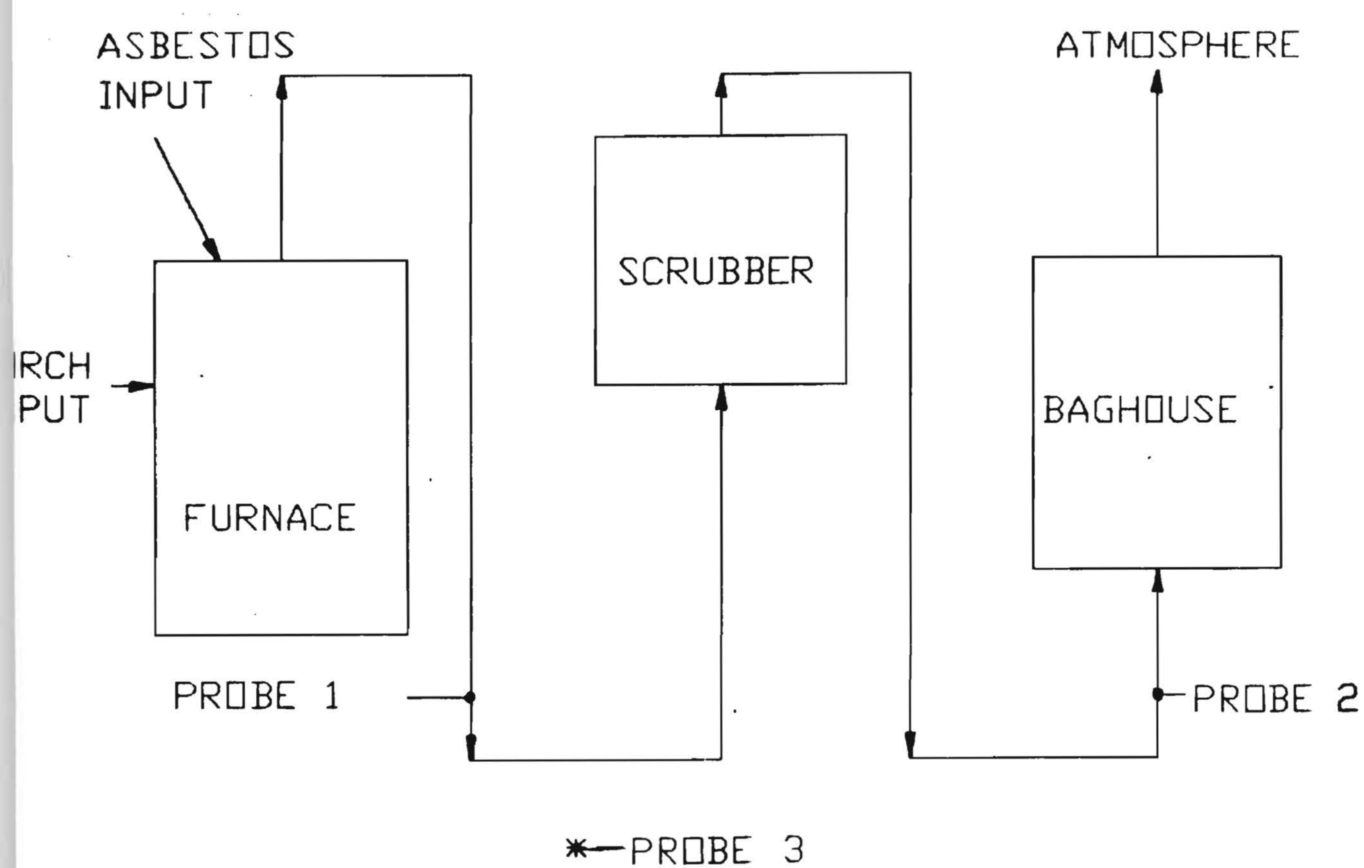

Figure 4. Schematic layout of asbestos vitrification process with gas filter sampling locations.

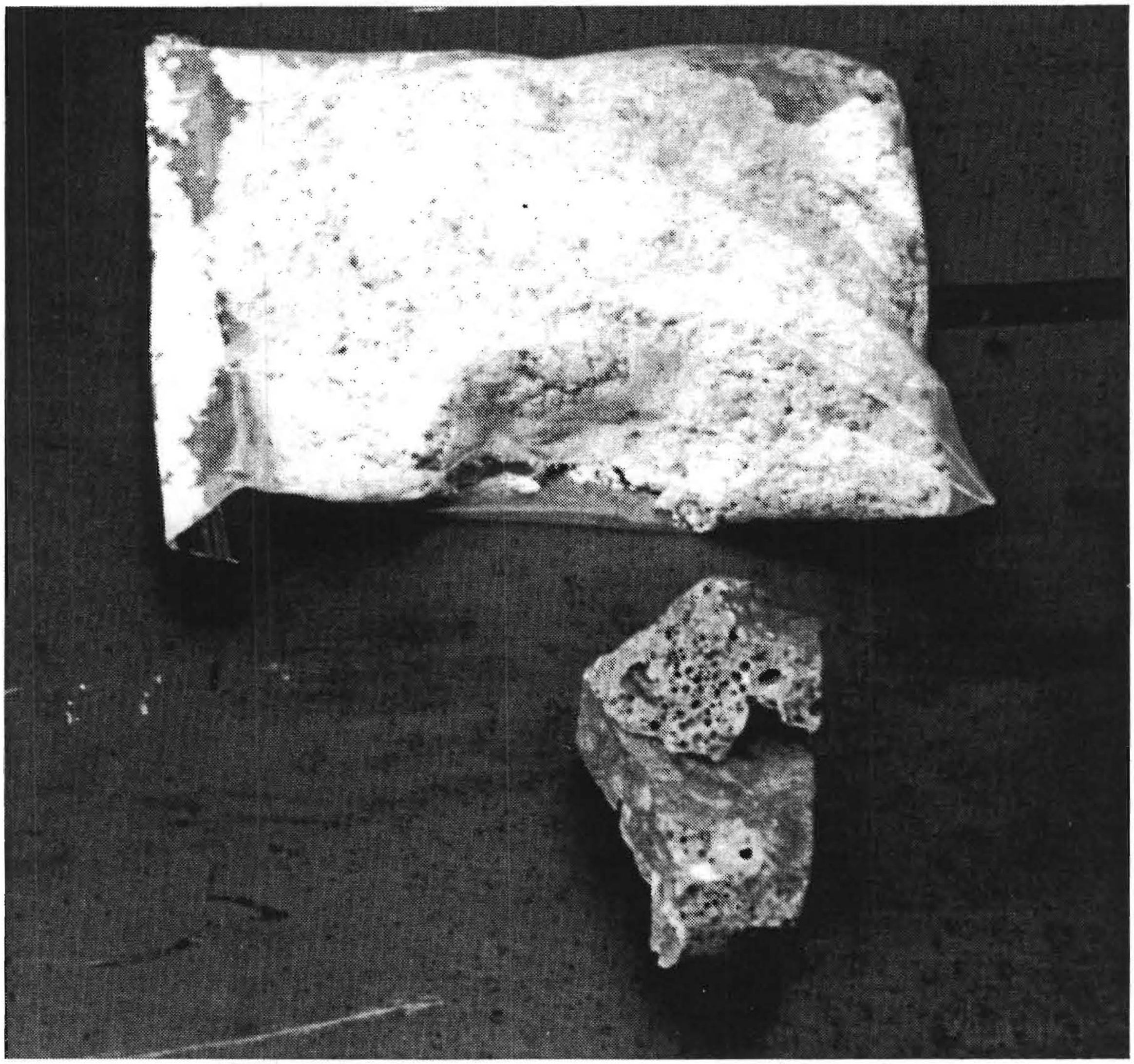

Figure 5. Samples (approximately 2 pounds each) of the pretest raw chrysotile asbestos and the post test vitrified solid residue

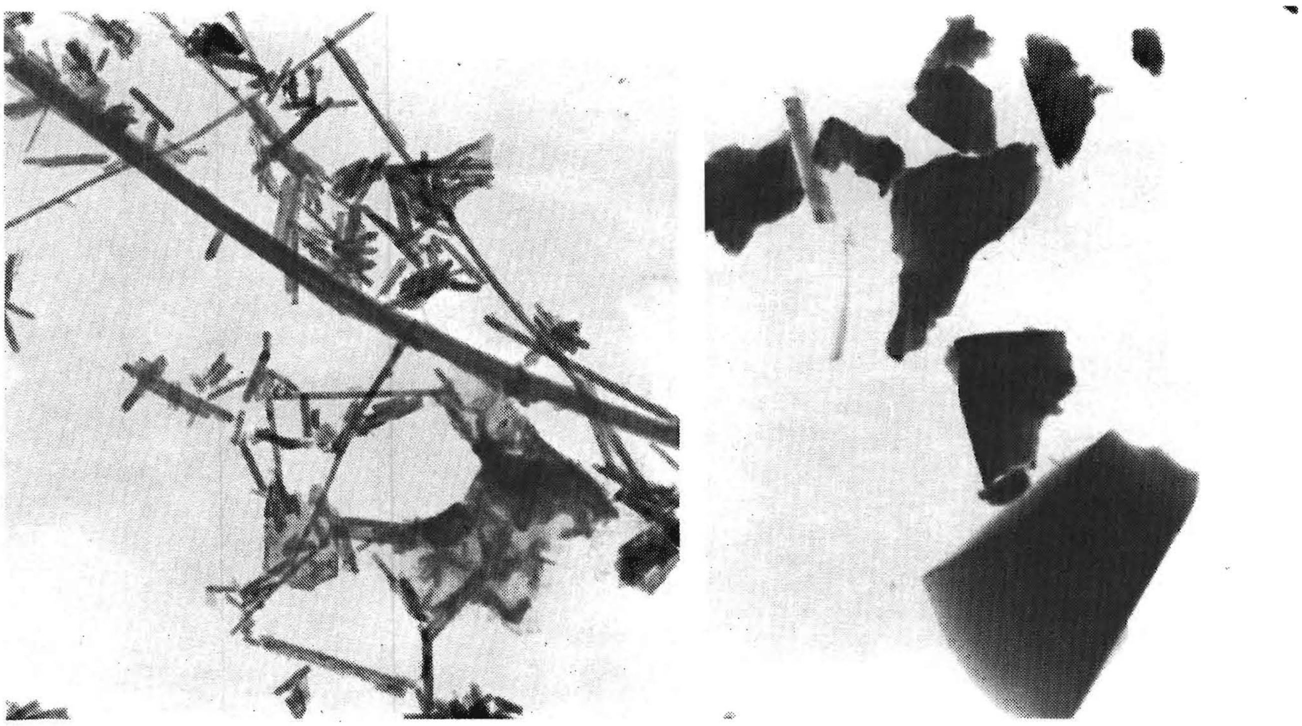

Figure 6. Transmission Electron Microscope (TEM) photographs of the pretest asbestos fibers and the post test vitrified solid residue.

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In today's competitive industrial and commercial environments, new processing methods are essential for growth and productivity. Until recently, heat processing was typically limited to conventional fuel combustion, but advancements in heating technology now offer more efficient options. One of the proven alternatives for generating heat is the Plasma Arc Heating System, a high technology product of intensive research, practical experience, industrial demands, and aerospace technology.

Plasma heating systems are among the most effective means for efficiently generating heat. They far surpass conventional methods because they offer greater temperature control, faster reaction time, better processing control, lower capital costs, greater throughput, and more efficient use of energy.

The applications for plasma heating systems are widespread, ranging from industrial and research environments to municipal waste management. They include ladle and tundish heating, melting (ferrous and non-ferrous metals), vacuum melting, recovery processes, municipal and hazardous waste treatments, and chemical synthesis.

Plasma energy is a common, naturally-occurring resource. It is the most prevalent state in the universe. Simply stated, plasma energy is any gas that conducts or can be made to conduct electricity. The discharged static electricity in thunderstorms (lightning) is an example of plasma energy, and so is the aurora borealis or Northern Lights.

Plasma heating technology has a proven record of success in certain industrial applications. Over 20 years ago in the space program, plasma heating technology was used to simulate the torrid temperatures of re-entry into the earth's atmosphere, and today, plasma heating systems continue to demonstrate their strength in a wide variety of industrial and commercial environments.

Plasma Energy Corporation (PEC), a subsidiary of First Mississippi Corporation, is a major international manufacturer and supplier of plasma heating systems for industrial, commercial, and research applications. We offer the experience and technology that can make plasma energy a real asset in your facility.

APPLYING PLASMA ENERGY

Plasma energy technology is a valuable resource for many commercial environments, including steel mills, reactive metal industries, municipal and hazardous waste disposal sites, research laboratories, and more.

As a controlled, high-intensity, and reliable heat source, plasma heating systems can be used in vacuum furnaces for titanium processing, as gas heaters for drying, heat treatment, or preheating, in glass/ceramic processing, and for gasification of coal. They can also be used for bulk melting, smelting, pyrolysis, precious metal recovery, or other extractive metallurgical processes.

Plasma heating systems offer exciting options for refining refractory metals and super alloys. In collaboration with Leybold AG., an international producer of vacuum process engineering, PEC has developed torches for processing metals in high purity environments. During processes like cold-crucible and cold-hearth melting, plasma heating systems deliver the controlled, concentrated energy that insures purity, homogeneity, and controlled solidification. This technology can also be applied to scrap recycling and ceramic synthesis.

In the steel industry, Plasma Tundish Heating helps reduce melting and casting costs, and improves product quality. Plasma heating systems control the temperature of the steel directly in the tundish and/or the ladle. Such precise temperature control results in more uniform cast structures, improves the continuous casting process, reduces downtime, lowers temperature requirements for casters, allows casting in narrower temperature zones, and increases productivity.

Plasma heating systems ionize gases to convert electricity into heat. They operate with almost any gas including air, argon, helium, hydrogen, CO_2, or CH_4. For added flexibility, they can also operate with many gas mixtures. Many torch configurations are available from low power convertible torches, which are perfect for research laboratories, to the high power systems suitable for vacuum processing.

PLASMA ARC TORCHES

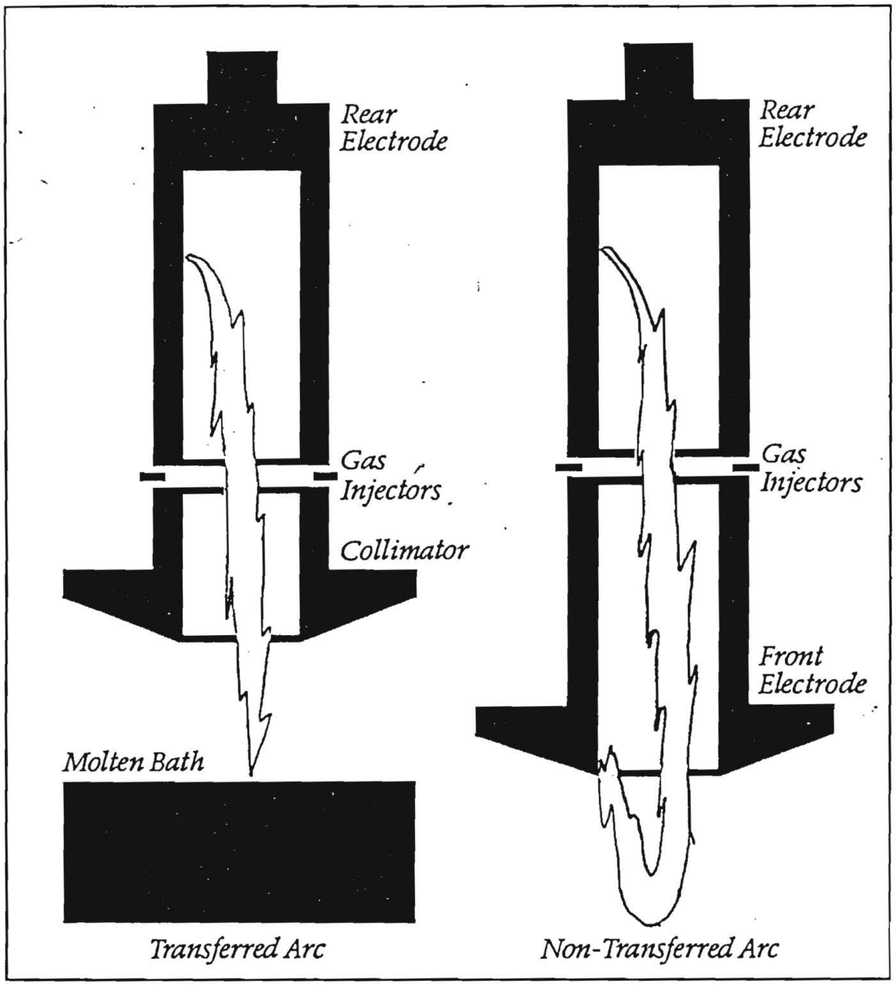
PEC offers a selection of plasma arc torches which can be adapted for almost any operating requirements. All of these torches benefit from the same positive features of plasma energy, and are available in many sizes, ranging from 50 kW to 6,000 kW.

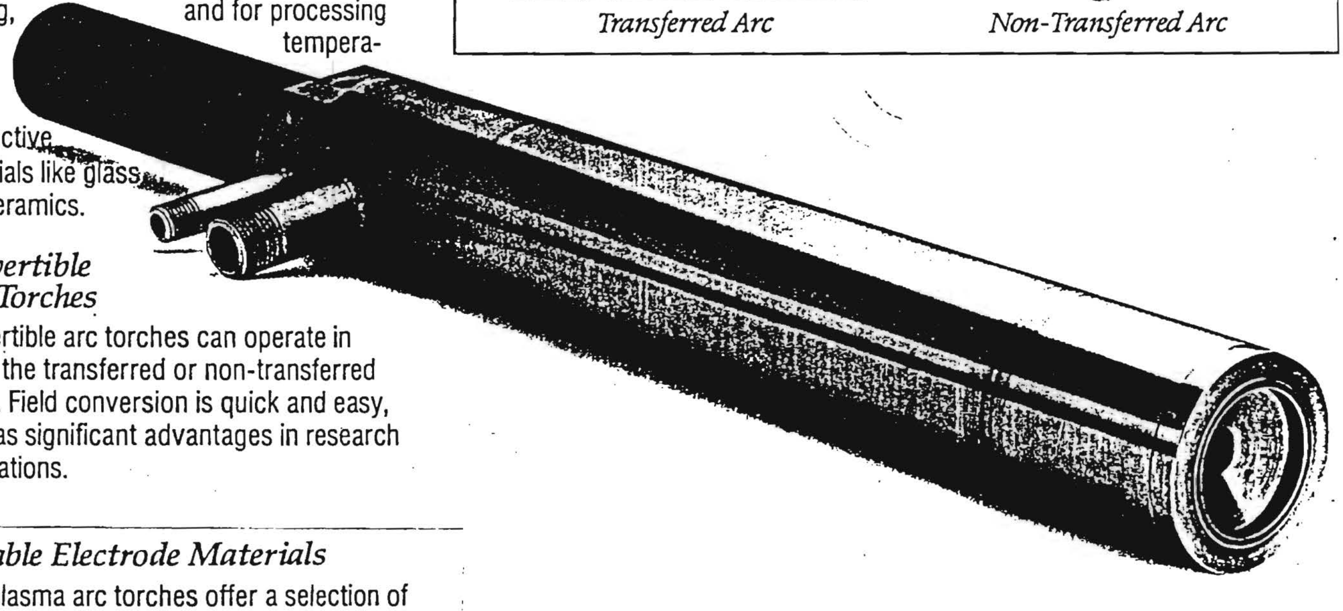
Transferred Arc Torches

A transferred arc torch uses the working material to conduct electricity. Its positive polarity is in the rear electrode, and its negative polarity is in the work piece. The result is an intense, direct heat that is ideal for melting, smelting, gasification, annihilation, recovery and reclamation, plus much more.

Non-Transferred Arc Torches

A non-transferred arc torch uses two internal electrodes. A small column of injected gas creates the plasma flame that extends beyond the tip. A non-tranferred torch produces the more dispersed heat that is needed for air and gas heating, drying, annealing, solid particle ignition, cutting, and for processing high temperature, non-conductive materials like glass and ceramics.





Convertible Arc Torches

Convertible arc torches can operate in either the transferred or non-transferred mode. Field conversion is quick and easy, and has significant advantages in research applications.

Variable Electrode Materials

PEC plasma arc torches offer a selection of electrode materials for complete process compatibility: copper, tungsten, molybdenum, certain alloys, and others. With this selection of electrode materials, greater strength is available, process contamination is controlled, and cost is minimized. Once expended, PEC electrodes are easily replaced.

FEATURES AND BENEFITS OF PLASMA HEATING SYSTEMS

Massless Heat

PEC plasma arc torches use 1/100th (or less) of the air needed by fossil fuel heaters. Releasing heat energy with almost no mass is a simpler process than conventional heating, and offers greater control and efficiency. It also reduces fabrication expansion, offgas-handling, and other capital costs, because plasma arc torches operate in smaller furnaces than fossil fuel heaters.

Higher Temperatures

Plasma arc torches operate efficiently at temperatures well beyond those possible with fossil fuel burners. They can routinely create temperatures that range from 4,000 - 7,000 degrees centigrade or higher. This extreme heat is produced instantly, and can be easily automated. Controlled, high temperatures increase throughput, and reduce costs.

Controlled Furnace Atmosphere

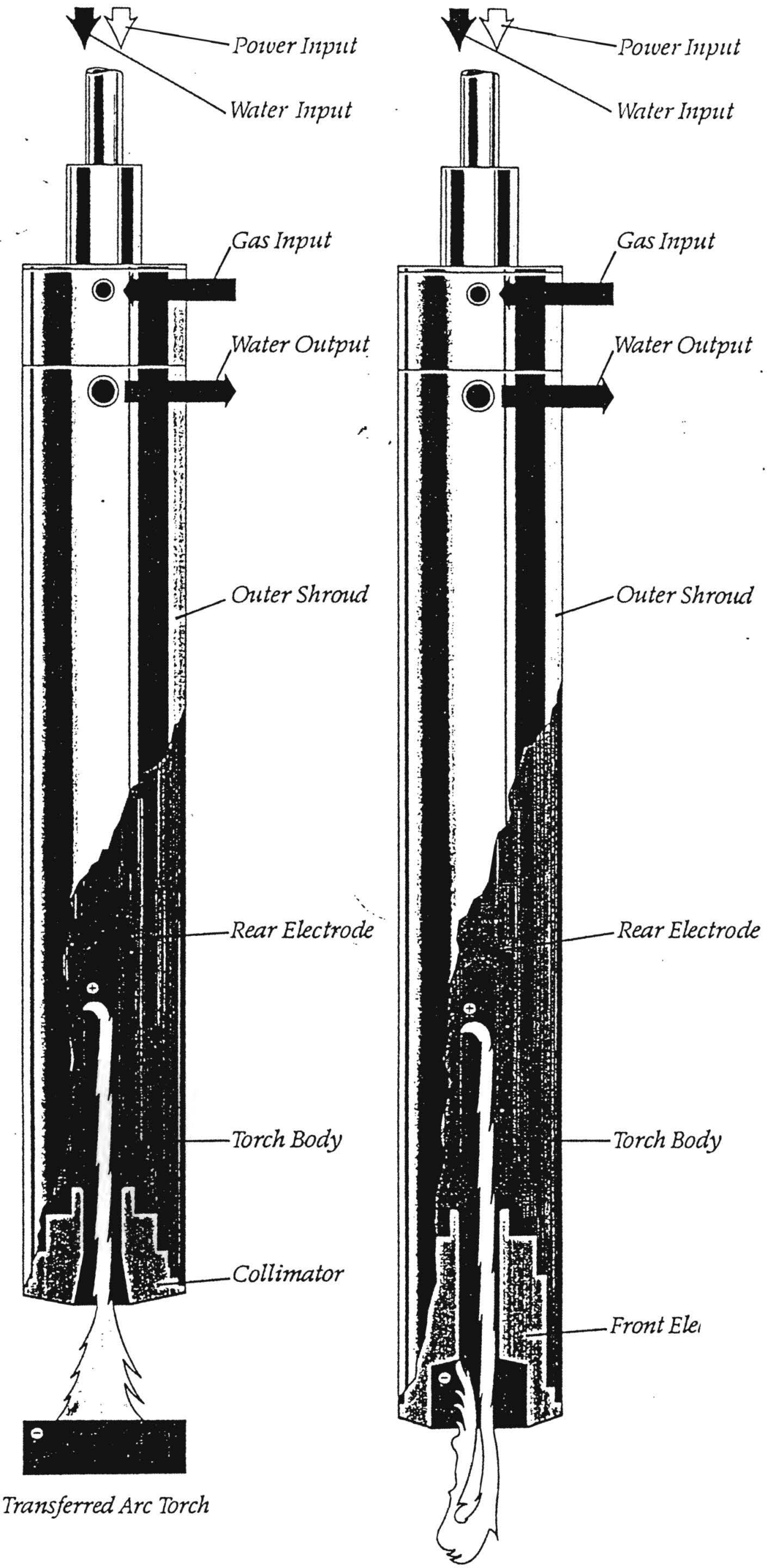
PEC plasma arc torches operate with almost any gas or gas mixtures (oxidizing, reducing, inert, etc.). This flexibility means the furnace atmosphere is completely variable, and can be tailored to satisfy the individual processing environment.

High Thermal Efficiency

The efficiency of the PEC plasma arc torch alone consistently reaches between 85% and 93% (depending on the torch used). Therefore, the faster and more complete reaction kinetics of plasma energy sharply reduces turnaround time and operating costs.

Efficiency and Safety

Because the plasma column is rigidly controlled, plasma arc torches can direct heat at specific surfaces. Intense heat is available instantly, and temperature control is easily automated. Torch configurations vary to suit the exact processing needs. The plasma arc flame can be extinguished quickly. Numerous safety and monitoring features are designed into the PEC control panel to insure maximum efficiency and control.



Transferred Arc Torch

Non-Transferred Arc Torch

APPENDIX B. ECONOMIC ANALYSIS (17)

1. **List of Assumptions:**

   a. Plasma heating system (PHS) cost: $1,000/kW
   b. PHS Size: 300kW (857 pounds/hour)
   c. PHS installation in 45-ft van: $50,000
   d. Operations: 2 shifts per day
      21.25 days per month
      255 days per year

   e. Average Processing Time: 16 hours per day
   f. Labor Costs: $50,000 per year each shift
   g. Maintenance Costs: $15/hr. (torch @ $10; other at $5)
   h. Specific Energy Requirement (SER): 0.35 KWH per pound of ACM
   i. Power Cost: 5 cents per kilowatt hour (7¢/KWH for sensitivity analysis)
   j. Capital Investment Amortization: 10 years @ 8% interest (10% interest for sensitivity analysis)
   k. Salvage Value of Capital Equipment in 10 years: $80,000

2. **Capital Investment Costs**

   a. **Plasma Heating System**

300kW x $1,000:	$300,000	
Installation in Van:	50,000	
Start-up Tests:	10,000	
Contingency @ 15%:	54,000	
Total		**$414,000**

   b. **Furnace and Scrubber System**
   (based on Hearth Incinerator formula)

System Cost:	$85,243	
Contingency @35%:	29,835	
Total		**$115,078**

   c. **Capital Investment**

(1) Total Capital Investment	$529,078
(2) Present Value of Salvage Equipment	- 37,055
(3) Present Value of Capital Investment	**$492,023**

3. System Throughput — 291,428 #/mo.
300kW/0.35KWH/# x 16 hrs./day x 21.25 days/mo.

4. **Power Costs** — 1.75 ¢/# (2.45¢/#)
0.35kWH/# x 5¢/KWH (7¢/KWH)

5. **Labor Costs** — 2.86 ¢/#
$100,000/yr./12 mo./yr./291,428 #/mo.

6. **Maintenance Costs** — 1.75 ¢/#
$15/hr./857#/hr.

7. **Capital Amortization Costs (CAC)** — 1.78 ¢/# (1.95¢/#)
(Salvage Value taken into account)

   a. Monthly P&I payments:
      (1) $5,205 for 8% interest
      (2) $5,669 for 10% interest

   b. CAC = monthly payment/291,428#/mo.

8. **Summary of Operating Costs:**

		Base	7¢/KWH	7¢/KWH Plus 10% Interest
a.	Power Costs	1.75 ¢/#	2.45 ¢/#	2.45 ¢/#
b.	Labor Costs	2.86	2.86	2.86
c.	Maintenance Costs	1.75	1.75	1.75
d.	Equipment Amortization Cost	1.78	1.78	1.95
		8.14 ¢/#	8.84 ¢/#	9.01 ¢/#
	Total Operating Costs	**$163 /ton**	**$177 /ton**	**$180 /ton**