2

US Army Corps
of Engineers
Construction Engineering
Research Laboratories

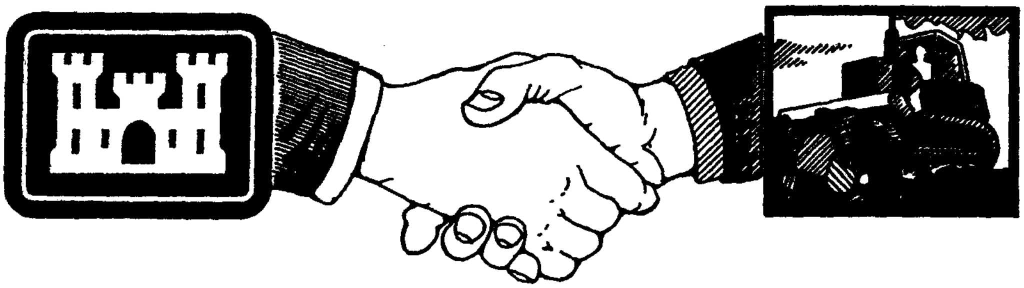
USACERL Technical Report CPAR-TR-EP-93/01
September 1993

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

DESTRUCTION AND VITRIFICATION OF ASBESTOS USING PLASMA ARC TECHNOLOGY

by

Hany H. Zaghloul
Louis J. Circeo



A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
September 1993

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Destruction and Vitrification of Asbestos Using Plasma Arc Technology

5. FUNDING NUMBERS
CPAR
FAD 1-002443,
dated 27 Sep 89

6. AUTHOR(S)
Hany H. Zaghloul and Louis J. Circeo

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR EP-93/01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, U.S. Army Corps of Engineers
ATTN: CERD-C
20 Massachusetts Avenue NW
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Exposure to asbestos fibers creates a serious risk to public safety and health. The Department of Defense (DoD) faces multimillion-dollar rehabilitation costs for asbestos removal and disposal of asbestos-containing materials (ACM) from military facilities. Very few landfills are certified to receive ACM, and as these disposal sites are filled and closed, ACM disposal costs are expected to rise substantially.

Plasma arc destruction of ACM could provide an effective, economical, and timely solution to the asbestos disposal problem. The high temperatures achievable with plasma arc torch technology can melt and vitrify asbestos and ACM into a chemically inert, glasslike residue that may be safely placed in any landfill.

At plasma torch furnace temperatures above 1,300°C, 25 pounds of pure chrysotile asbestos in metal canisters were fed into the furnace over 35 minutes. Furnace residence times varied from 6 to 41 minutes. The vitrified asbestos residue, metal canister residue, residues found inside the furnace, and air samples inside and outside the process gas stream were tested for asbestos fibers. The amounts found were negligible by EPA standards, demonstrating that plasma arc technology can be an environmentally safe, efficient, and effective method of destroying and vitrifying pure chrysotile asbestos.

14. SUBJECT TERMS
asbestos-containing materials (ACM)
asbestos in building
plasma arc technology
environmental compliance
asbestos abatement industry

15. NUMBER OF PAGES
36

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
SAR

EXECUTIVE SUMMARY

In recent years, asbestos fibers have been identified as a carcinogenic agent. Exposure to this hazard creates a serious risk to public safety and health. The Department of Defense (DoD) is currently faced with multimillion-dollar rehabilitation costs for asbestos removal and disposal from existing buildings constructed with asbestos-containing materials (ACM). 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 ACM can be deposited only at selected Class 1 EPA[*]-approved landfills that comply with the National Emissions Standards for Hazardous Air Pollutants (NESHAP). As these disposal sites are filled and closed, significantly higher disposal costs are expected.

Plasma arc destruction of ACM could provide an effective, economical, and timely solution to the asbestos disposal problem. It is anticipated that the very high temperatures (3,000°C - 7,000°C) achievable with plasma arc torch technology will melt and vitrify asbestos and ACM into a chemically inert glasslike residue that meets all EPA environmental criteria. When pure asbestos is subjected to temperatures above 1,000°C, the asbestos fibers melt, then vitrify (solidify) into a nonhazardous solid material. The EPA 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 asbestos residue, the metal canister residue, samples of residue found inside the furnace, and air samples inside and outside the process gas stream.

In this experiment, plasma arc technology was 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 consisted of only a few scattered fibers. This amount of asbestos is considered negligible, and falls far below current asbestos exposure standards and guidelines (i.e., less than 1 percent 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 or residence time of the asbestos should readily eliminate even these trace amounts.

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

---

[*] EPA: Environmental Protection Agency.

FOREWORD

This research was performed for the Directorate of Research and Development, Headquarters, U.S. Army Corps of Engineers under the Construction Productivity Advancement Research (CPAR) Work Unit "Destruction of Asbestos-Containing Waste Materials"; Funding Authorization Document (FAD) 1-002443, dated 27 September 1989. The technical monitor was Mr. Richard G. Donaghy, CERD-C.

The work was conducted through a Cooperative Research and Development Agreement (CRDA) by the Environmental Engineering Division (EP) of the Environmental Sustainment Laboratory (EL), U.S. Army Construction Engineering Research Laboratories (USACERL); the Construction Research Center (CRC) of the Georgia Institute of Technology: the Materials Science and Technology Laboratory (MSTL) of the Georgia Tech Research Institute (GTRI); Plasma Energy Corporation (PEC), Raleigh, NC; and Asbestos Abatement Technology, Inc. (AAT), Atlanta, GA. The USACERL principal investigator was Mr. Hany H. Zaghloul, CECER-EP, and the CRC principal investigator was Dr. Louis J. Circeo. Appreciation is expressed to the following personnel for their significant roles in the experiment, evaluation of the results, and assistance preparing this document: Dr. S. L. Camacho, PEC; Mr. S. Brent Reid, AAT; Mr. Guillermo R. Villalobos, MSTL; and Mr. James R. Hubbard, MSTL. Dr. Edgar D. Smith is Acting Chief, CECER-EP, and Dr. William D. Goran is Chief, CECER-EL. The USACERL technical editor was Gordon L. Cohen, Information Management Office.

LTC David J. Rehbein is Commander of USACERL and Dr. L.R. Shaffer is Director.

CONTENTS

APPENDICES

LIST OF TABLES AND FIGURES

DESTRUCTION AND VITRIFICATION OF ASBESTOS USING PLASMA ARC TECHNOLOGY

1 INTRODUCTION

The U.S. construction industry is currently faced with a multibillion-dollar rehabilitation costs for the removal and disposal of asbestos-containing material (ACM) from existing buildings. The Environmental Protection Agency (EPA) estimates that about 750,000 public, commercial, and industrial buildings in the United States have ACM. Corrective actions must be taken when contamination levels are too high or when renovating, reconstructing, or demolishing these structures. This rehabilitation program creates a significant cost burden for the U.S. Government.

In recent years, asbestos fibers have been identified as a 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 United States are caused by asbestos exposure. As a result, Congress passed the Asbestos Emergency Response Act of 1986 (AHERA), which mandates inspection in school grades Kindergarten through 12. Congress is currently considering extending this legislation to all public and commercial buildings. This legislation specifies the steps to be taken when ACM is discovered. The options range from modified operations and maintenance procedures to complete removal and disposal.

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

At the present time, asbestos and ACM can be deposited only at selected Class 1 EPA-approved landfills that comply with the National Emissions Standards for Hazardous Air Pollutants (NESHAP). As these disposal sites are filled and closed, transportation distances to remaining sites will increase, resulting in higher disposal costs. In addition, because asbestos fibers frequently pollute air and groundwater, landfill disposal of ACM is likely to become much more restrictive in the near future. This latter circumstance would intensify the already significant disposal problems faced by both the U.S. construction industry and the U.S. Government.

Plasma arc destruction of ACM could provide an effective, economical, and timely solution to the asbestos disposal problem. It is anticipated that the very high temperatures achievable with plasma arc torch technology will melt asbestos and ACM in such a way that, upon cooling, it will vitrify (solidify) into a chemically inert glasslike residue that meets all EPA environmental criteria. It is important to determine the applicability of this emerging technology to the destruction of ACM before more restrictive disposal regulations are enacted.

This study evaluated the potential effectiveness of plasma arc torch technology in destroying ACM 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 onsite destruction of asbestos and 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 (R&D) 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, nonprofit organizations, state and local governments, and other entities interested in construction productivity and competitiveness also participate 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 enhancing 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 may become feasible due to lower construction costs. Such cost savings would accrue directly to the Federal Government's construction program, and would benefit the U.S. construction industry and the U.S. economy in general.

CPAR is intended to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity, project costs, and USACE mission accomplishments. R&D and technology transfer under CPAR is based on proposals received from educational institutions, the construction industry, and others that 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 sponsorship and overall direction of the Directorate of Research and Development, Headquarters, U.S. Army Corps of Engineers. Four organizations participated jointly in the research:

(1) **U.S. Army Construction Engineering Research Laboratories (USACERL), Champaign, IL.** USACERL monitored the contract for the Corps of Engineers and provided program guidance to all partners to ensure that CPAR program objectives were fully met. Through the Environmental Engineering Division of the Environmental Sustainment Laboratory, USACERL served as overall manager and coordinator of the R&D work.

(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., developing the test plan, conducting the experiment, collecting and analyzing the data, interpreting the results, and preparing the final report. In addition, the CRC coordinated the schedules and activities of the two industry partners.

(3) **Plasma Energy Corporation (PEC), Raleigh,** NC. As an industry partner, PEC provided its Test and Demonstration Facility (TDF) for the research program. PEC personnel operated the plasma furnace used for the test, assisted in data collection, and acted as 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. The company 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 United States and throughout the world. The primary sites of commercial production are in Canada, Russia, and South Africa. When extracted from the earth, the asbestos-containing rock is crushed, milled, and graded. This produces long, threadlike 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 common type of asbestos used in buildings, and accounts for approximately 95 percent of the asbestos found in U.S. buildings. Therefore, chrysotile asbestos was selected for this study. Typical chemical, mineralogical, and physical properties of chrysotile asbestos are given in Table 1.

Asbestos was used widely because it was plentiful and inexpensive. Its unique properties (fire resistance, high tensile strength, low thermal and electrical conductivity) made it a popular material 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 materials, or ACM. Three categories of ACM are normally used in buildings:

- Surfacing materials (sprayed or trowelled onto surfaces).
- Thermal system insulation (pipe wrap, blanket insulation, cements, and muds).
- Miscellaneous materials (floor and ceiling tile, roofing felt, concrete pipe, siding, fabrics).

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

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

Asbestos is a known human carcinogen, and it can cause several types of cancer. Asbestos can present a health hazard by emitting microscopic fibers when crushed or pulverized. 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 also increases because the primary health effects from asbestos exposure act on the lungs. No safe threshold of asbestos exposure has been established. The principal diseases 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

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

Chemical Composition	**$3MgO2SiO_{2}2H_{2}O$**
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

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)

The concept of disposing of ACM by thermal transformation is based on the fact that asbestos fibers melt and change in molecular structure at elevated temperatures. When chrysotile asbestos is heated to 800-900°C, it transforms to a flaky material called fosterite. Heating to temperatures above 1,000°C melts the material into an amorphous, chemically inert material. These changes are irreversible; upon cooling the material solidifies, but the chrysotile asbestos fiber structure is not restored. The residue material is not considered to be asbestos, and is classified as nonhazardous. The EPA has acknowledged that this thermal vitrification process is sufficient to render asbestos and ACM harmless.

Based on the capability of high temperatures to destroy ACM, several competing firms have been developing commercial vitrification processes using conventional heating technologies such as fossil fuels and electric furnaces. A thermal destruction process for ACM would be attractive to waste generators and landfill owners because it would eliminate their continuing liability, as discussed above in Section 2.b. However, because temperatures greater than 1,000°C are difficult to achieve and maintain in conventional furnaces, additional measures must be taken to assure that the destruction process is complete. These additional steps significantly impact the technical and economic viability of ACM vitrification processes based on conventional technologies.

Existing ACM vitrification processes generally require one or more of the following measures to ensure ACM destruction:

- Long furnace residence times at elevated temperatures (up to 12 hours).
- Addition of cullet (crushed waste glass) to lower the melting point of the ACM, improve glassification of the residue, and more effectively immobilize any residual asbestos fibers.
- Presorting and separate treatment of ferrous and nonferrous ACM and asbestos-contaminated material.
- Shredding the ACM before feeding it into the furnace.

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

The authors know of no commercially successful asbestos vitrification process 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 intense heat, such as that created by the electric arc of a plasma torch. Unlike nonionized gases, plasma can respond to electrical and magnetic fields; the resistance of plasma to an electrical field converts the electricity into heat energy. This technology was developed more than 25 years ago in the U.S. space program to simulate re-entry temperatures on heat shields. Only recently has the technology begun to emerge as a commercial tool in several industries, including 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°C to more than 7,000°C. Thus, plasma torches can operate at much higher temperatures and at much greater efficiencies than fossil fuel burners. Furthermore, plasma torches require only about 1 percent of the air necessary for fossil fuel

---

[*] U.S. standard units of measure are used throughout this report. A table of metric conversion factors can be found on page 22.

burners. Therefore, effluent gases are greatly reduced compared to fossil fuel barriers, and furnace systems can be built much more compactly than conventional furnaces, at correspondingly lower capital costs. Additional information on plasma technology, reprinted 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 not achievable with fossil fuel burners. With a 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 potential feed material throughput rates, and reduce costs.
- **Controlled Atmosphere:** Because the plasma arc torch is compatible with almost any type of gas (e.g., reducing, oxidizing, neutral, inert, etc.), the furnace atmosphere can be controlled to meet unique requirements.
- **Massless Heat:** Plasma arc torches use only 1 percent 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 offgas handling and other capital costs.
- **High Thermal Efficiency:** The efficiency of plasma arc torches consistently reaches between 85 percent and 93 percent. Therefore, the faster and more complete reaction kinetics of plasma energy sharply reduces required processing time and operating costs.

(3) Plasma Torch Types

There are two basic 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 workpiece 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 either 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 to create the plasma; 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 has been conducted using plasma energy. The very high temperatures and energy densities, in conjunction with the 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 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 PCBs, hospital medical wastes, and municipal solid wastes. Some of these processes have been commercialized while others are still in development.

Plasma torch technology is currently being used 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 nonhazardous material that 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 thermal destruction of asbestos and ACM.

(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 on 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 ACM in an environmentally safe manner.

c. The PEC Test and Demonstration Facility

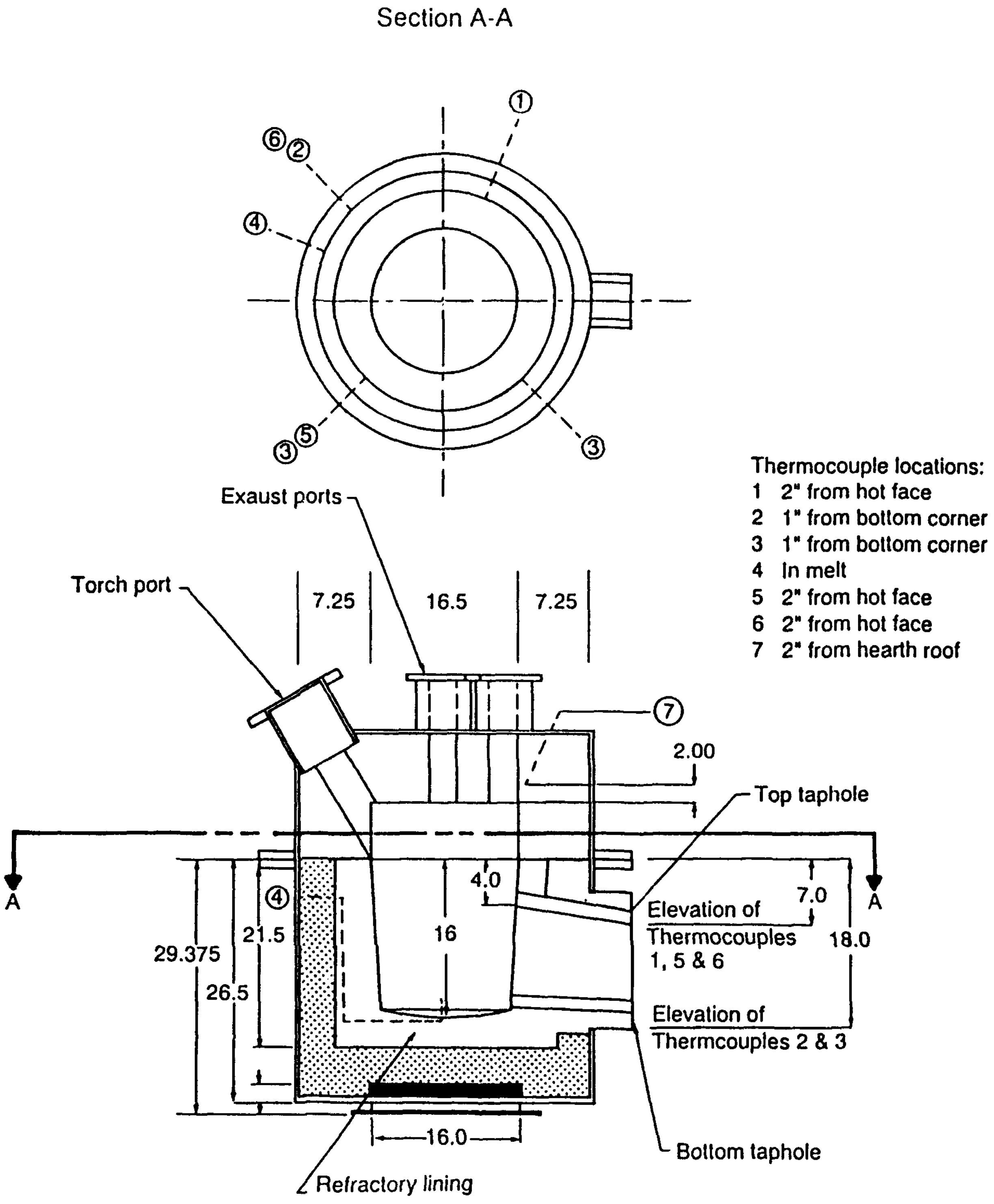
The asbestos vitrification test was conducted at the Test and Demonstration Facility (TDF), Plasma Energy Corporation. The TDF was built specifically to test plasma torch processes for a variety of applications. The TDF power supplies, coupled with different PEC plasma torches, can produce plasma arc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

The furnace system used for this experiment was a small smelting/melting furnace (2 cubic feet) capable of being tilted on an axis and continuous pouring while being heated with a 300 kilowatt plasma arc torch 4 inches in diameter. This furnace is capable of accepting materials measuring up to 3 inches. 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 ensure 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 commercial quality specifications. The four grades of chrysotile asbestos used in this experiment (3, 4, 6, 7) comprise about 90 percent of annual U.S. consumption of chrysotile asbestos.

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



Thermocouple locations:
1 2" from hot face
2 1" from bottom corner
3 1" from bottom corner
4 In melt
5 2" from hot face
6 2" from hot face
7 2" from hearth roof

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

length, capped at each end (Figure 2). Up to 2 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, were loaded into the furnace.

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

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 lb	75 oz

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

4 EXPERIMENTAL PROCEDURE

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

Table 3. Asbestos Vitrification Test Data

Time (Min)	Canister Feed Schedule	Plasma Arc Power Volts	Plasma Arc Power Amperes	Plasma Arc Power kW (Avg)	Furnace* Temp (°C)	Melt Temp (°C)**
0	Startup					
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	Shutdown				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.

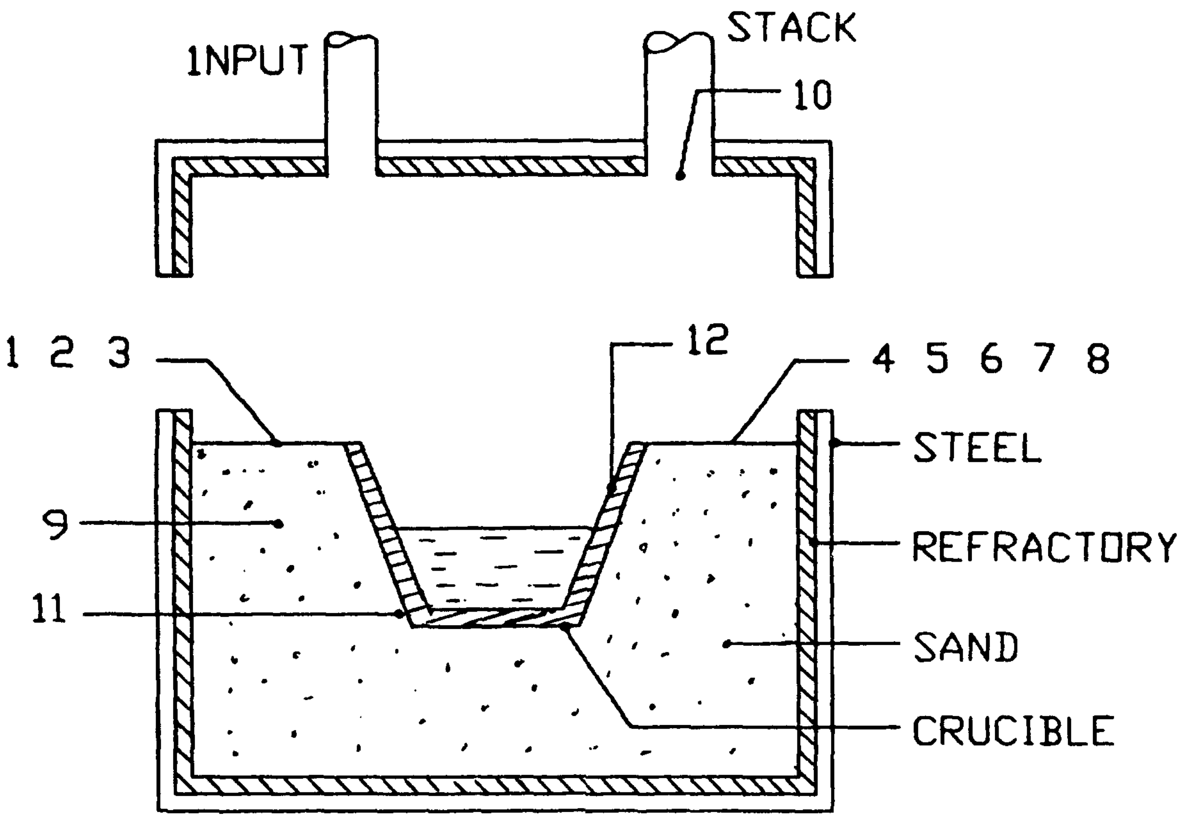


Figure 3. **Cross-section diagram of experiment geometry and material sampling locations.**

Because the temperature dropped briefly following the insertion of each canister, a short delay time was required between the insertion of each canister in order to raise the furnace temperature back above 1,200°C. A total of about 35 minutes were required to insert all 16 canisters. This was completed at 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 minutes 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 shutdown.

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, and sections of the baghouse filter were tested for asbestos after the experiment.

The furnace was allowed to cool for a period of about 2 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).

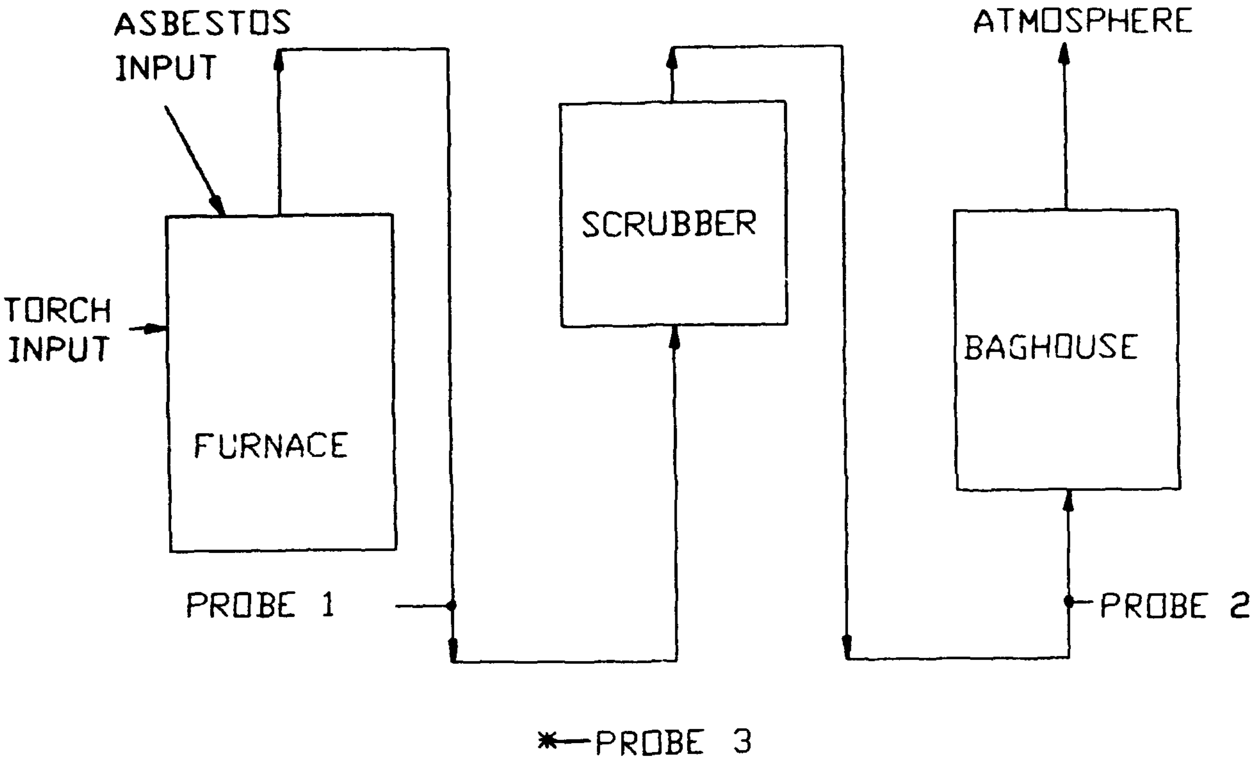


Figure 4. Schematic layout of asbestos vitrification process with gas filter sampling locations.

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 rocklike material was the amorphous vitrified residue from the melted asbestos. Figure 5 compares the pretest pure chrysotile asbestos with the vitrified solid residue from the experiment. The metal plate comprised 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 melted was 25 pounds, 10 ounces.

The samples of vitrified asbestos were prepared for transmission electron microscopy (TEM) analysis for asbestos fibers. First, small pieces of the samples were created using a hammer and coal chisel. Next, the pieces were 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

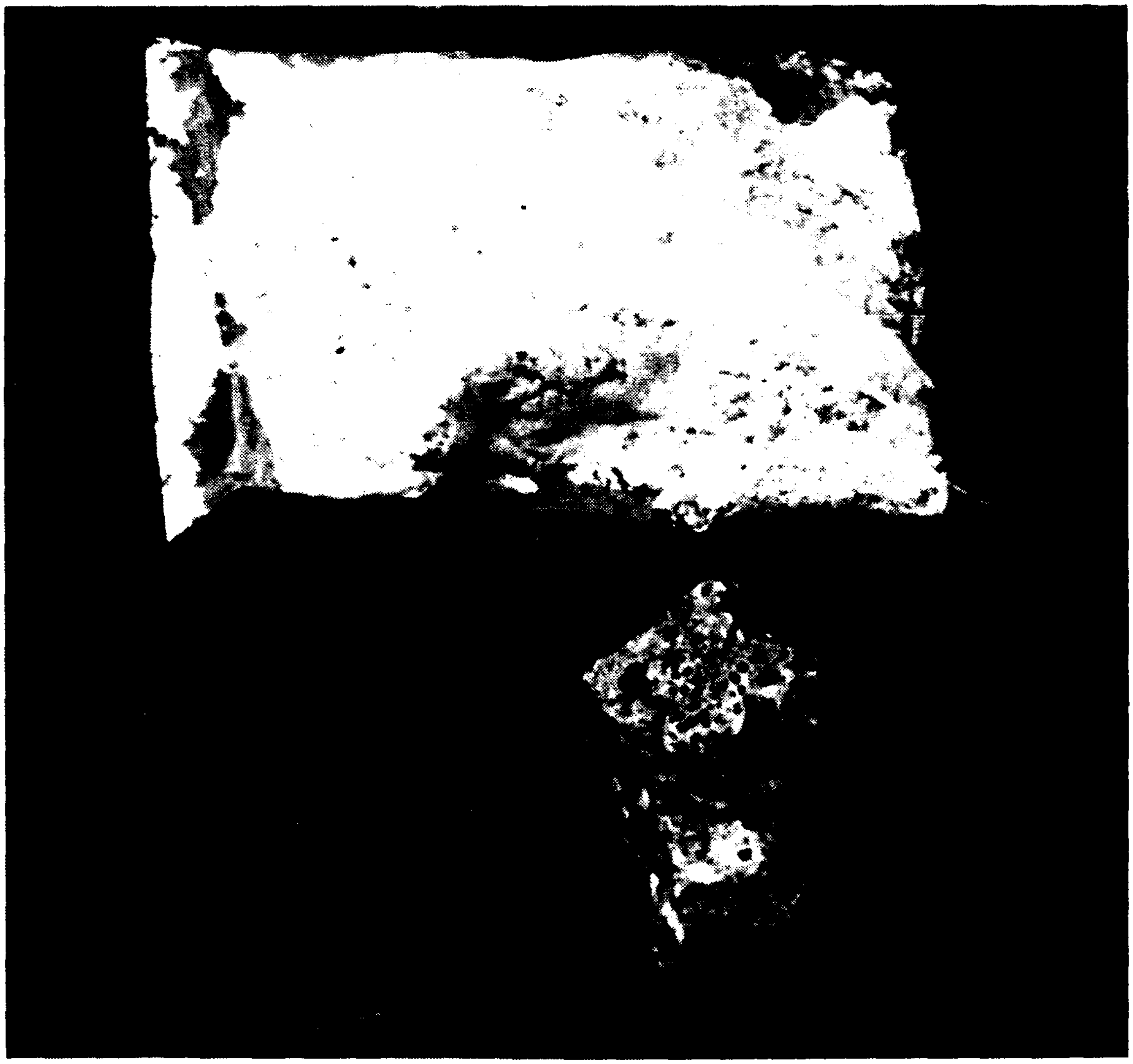


Figure 5. Samples of pretest raw chrysotile asbestos and post-test vitrified solid residue (approximately 2 pounds each).

powder. A weighed portion of powder was placed in a beaker with 2 milliliters of distilled water that contained a very small amount of dispersing agent. This suspension was diluted as necessary to produce a sample with the 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 on each grid were analyzed.

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 compared with the vitrified residue imaged through the TEM. The trace amounts of fibers found in the analysis are considered negligible, far below existing asbestos exposure standards—i.e., less than 1 percent 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 for heavy metals (arsenic, selenium, chromium, cadmium, barium, lead, mercury, silver) on the vitrified residue material. 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 from 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

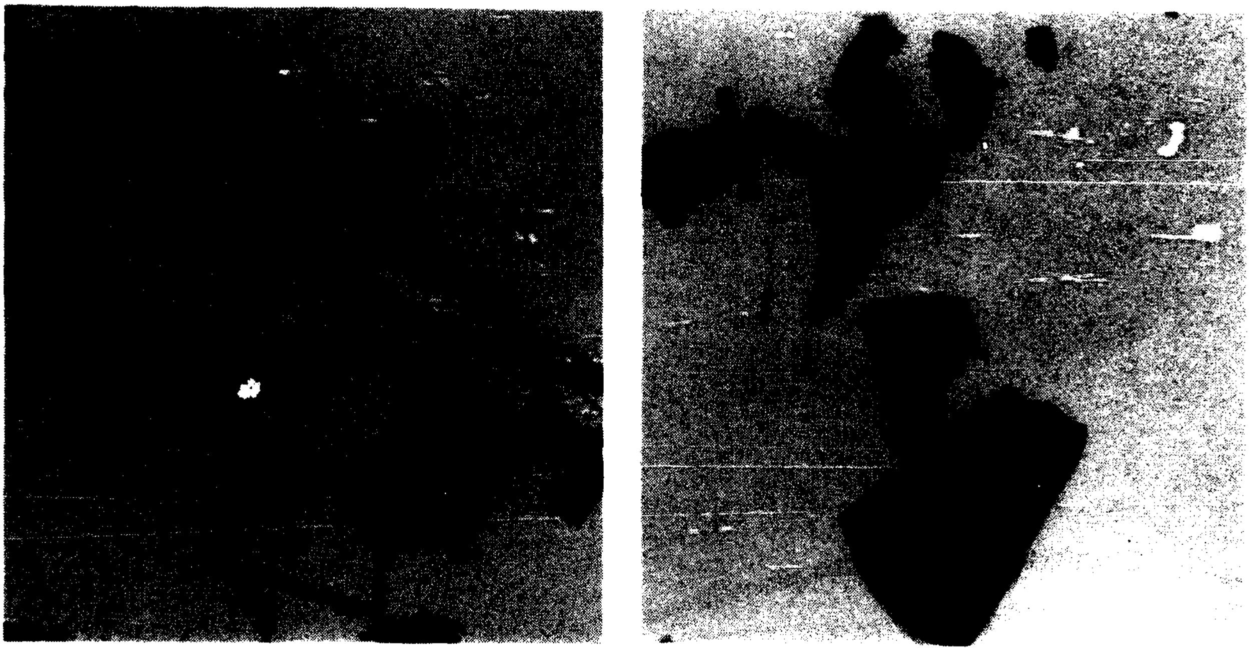

(a) (b)

Figure 6. TEM photographs of (a) pretest asbestos fibers and (b) post-test vitrified residue.

was directly below the furnace's canister insertion tube. Unmelted pieces of a canister at this location indicated that one 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 probably contained fibers, not fully melted, that 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 the asbestos collection filters that 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 the furnace's filtration devices. Probe 2 was positioned to monitor the effectiveness of the scrubber should asbestos be detected at Probe 1.

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.

It was necessary to continually change the collection 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 collection filters were used at the Probe 1 location during the test. The filter at Probe 2 was clogged by ash and changed only 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 filter membranes 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, then poured into the beaker. The water was stirred using an ultrasonic device 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 by the method previously described.

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

(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, or 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.

Current Federal standards permit airborne asbestos fiber concentrations of 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, but these were readily scavenged by the scrubber. Thus, the gaseous effluent from the plasma arc destruction and vitrification of asbestos in this experiment can be considered environmentally safe by a large margin.

d. Other Exhaust Gas Tests

The scrubber water was analyzed for asbestos fibers that may have been scrubbed from the exhaust gas stream. It was necessary to analyze the water both before and after the experiment because 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 if the process is to be commercialized. Three areas must be addressed 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 increase in 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 nation that only a range of costs would be identifiable. However, it should be possible to estimate general destruction and disposal costs for the purpose of evaluating the economic viability of this plasma arc destruction and vitrification process.

b. Projected Cost of Plasma Arc Destruction of ACM

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

The cost analysis assumed a Specific Energy Requirement (SER) of approximately 0.35 kilowatthours 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 the optimum ACM feed rate, which are scheduled for a follow-on phase of this research program. This system would be capable of processing an estimated 6.86 tons of ACM in one 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 system's economic sensitivity to higher 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 power cost increase of $0.02 per kilowatthour (to $0.07 per kilowatthour) would increase operating costs to $177/ton. If the interest rate were to rise 2 percent (to 10 percent), operating costs would increase to $180/ton. The sensitivity analysis indicates that these higher power costs and interest rates would not significantly affect the operating costs of a PAPS facility. Thus, the general operating costs of ACM destruction with plasma arc technology can be estimated with a good degree of confidence.

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

c. Current Cost of Asbestos Disposal

In 1988, PEC participated in several discussions about disposal costs with asbestos abatement contractors in the Cleveland, Ohio, area. These contractors were required to transport waste ACM 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). (These figures do not include the cost of transporting the asbestos waste from the Cleveland area to the landfills.) This wide range of disposal costs was 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. This range of disposal fees is considered representative of costs throughout the nation. In the northeast United States, tipping fees are expected to be higher; in the southeast United States, tipping fees are lower.

d. Future Landfill Costs

There are an estimated 9,000 landfills currently operating in the United States. By the year 2000 approximately half of these will reach their capacity and be subject to closure. Proportionately, about half the Class 1 EPA-approved landfills authorized to accept ACM could also be expected to close. Trends toward greater 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: higher tipping fees as landfills become scarcer, and the greater distances to authorized landfills. Current projections predict landfill tipping fee increases of at least 10 percent a year. At that rate, by the year 2000, current ACM disposal costs at landfills would increase over 300 percent. These large cost increases would be aggravated by the increased travel distances (and resulting transportation costs) to the landfills, and by the growing resistance to new or expanded landfills in local communities. Thus, it is anticipated that over time, a mobile PAPS facility will become increasingly cost-effective compared to conventional landfill disposal practices.

7 SUMMARY AND CONCLUSIONS

When pure asbestos is subjected to temperatures above 1,000°C, the asbestos fibers melt and subsequently solidify (vitrify) into a nonhazardous, 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 using conventional heating technologies such as fossil fuel burners and electric furnaces. Because of difficulties in achieving and maintaining furnace temperatures over 1,000°C, these conventional processes have not yet proven to be technically viable or economically feasible. The authors know of no commercially successful asbestos vitrification process currently in operation in the United States.

Plasma arc technology can 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 presorting, preprocessing, or shredding is required.
- No additives to lower ACM melting point or to glassify residue material are required.
- Long furnace residence times could be reduced dramatically.
- Instead of leaving residues contaminated with undestroyed asbestos, ACM and all other associated materials placed in a plasma arc furnace would completely melt and vitrify.

The experiment in this study was conducted at plasma torch power levels of about 170 kilowatts and furnace temperatures above 1,300°C. Twenty-five pounds of raw chrysotile asbestos encased in metal canisters 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 two of five 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 PAPS are estimated at $163 per ton. These costs are about equal to median U.S. ACM landfill disposal costs for 1988. A portion of the processing cost could be offset by selling the vitrified residue as road aggregate, concrete mix, construction bricks, etc. In addition, by offering total relief from the continuing liability of owners, an onsite PAPS facility presents an attractive asbestos disposal alternative.

Landfill disposal costs are expected to increase significantly during the 1990s due to more stringent environmental regulations, a decreasing number of landfills that will accept ACM, and rising transportation costs. This trend should help to make the cost of asbestos vitrification increasingly competitive with ACM landfill costs throughout the United States. Furthermore, because ACM landfill costs are expected to increase at a much faster rate than the operating costs of a PAPS facility, ACM vitrification could be the most cost-effective method of asbestos disposal in the near future.

As a result of this research, 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 (i.e., less than 1 percent 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 or residence time should readily eliminate even these trace amounts.
- The capability of plasma arc technology to safely destroy asbestos, ACM, and any other contaminated building materials has a high probability of success.
- A mobile 7 ton-per-day PAPS could be expected to be commercially competitive right now in many regions of the nation where ACM landfill disposal costs are above average. In the future, plasma arc vitrification of asbestos is likely to become increasingly competitive throughout the nation as landfill disposal costs increase.

METRIC CONVERSION FACTORS

1 cu ft = 0.028 m^3
1 ft = 0.305 m
1 gal = 3.78 L
1 in. = 2.54 cm
1 lb = 0.453 kg
1 oz = 28.35 g
1 sq in = 6.452 cm^2
1 ton = 1,016 kg

REFERENCES

1. "Guidelines for Participation, Construction Productivity Advancement Research (CPAR) Program"; U.S. Army Corps of Engineers, January 1989.

2. Ouellette, Robert P. et al., "Asbestos Hazard Management," Technomic Publishing Co., Inc., Lancaster, PA, 1987.

3. "Supervision of Asbestos Abatement Projects: Course and Workshops," Environmental Sciences and Technology Division, GTRI, Washington, DC, 9-13 April 1990.

4. "Asbestos Reference Guide," Environmental Health and Safety Division, Economic Development Laboratory, Georgia Tech Research Institute, Atlanta, GA, 1989.

5. EPA560/5-85-024, "Guidance for Controlling Asbestos-Containing Materials in Buildings," U.S. Environmental Protection Agency, Washington, DC, June 1985.

6. Gillis, Christopher S., "The Vitrification Alternative," Outlook Magazine, April 1990, pp. 16-20.

7. Penberthy, L., "Glassification of Asbestos-Containing Material for Destruction of the Asbestos," National Asbestos Council Journal, Summer 1987.

8. Oliver, S. L. and Spencer, L., "Who will the Monster Devour Next?," Forbes Magazine, 18 February 1991, pp 75-79.

9. Camacho, S. L., "Industrial-Worthy Plasma Torches: State-of-the-Art," Pure and Applied Chemistry, Vol. 60, No. 5, 1988.

10. Camacho, S. L., "Plasma Technology," High Temperature Process-High Tech Show of 1986, Osaka, Japan, May 1986.

11. Camacho, S. L., "Plasma Pyrolysis of Hydrocarbon Wastes," BNCE Technical Conference, Wadham College, Oxford, England, 25-27 September 1990.

12. Camacho, S. L., "Municipal Solid Waste Plasma Pyrolysis System," Plasma Energy Corporation, February 1989.

13. "Plasma Destruction of Wastes," International Union for Electroheat, UIE Arc Plasma Review 1988, Paris, France, 1988.

14. Camacho, S. L. and Circeo, L. J., U.S. Patent No. 4,067,390, "Apparatus and Method for the Recovery of Fuel Products from Subterranean Deposits of Carbonaceous Matter Using a Plasma Arc," 10 January 1978.

15. U.S. Environmental Protection Agency, "National Emission Standards for Hazardous Air Pollutants; Amendments to Asbestos Standard; Final Rule," 49 CFR 13661, 5 April 1984.

16. U.S. Department of Labor, Occupational Safety and Health Administration, 29 CFR 1910.1001 Amended, "Occupational Exposure to Asbestos, Tremolite, Anthophyllite, and Actinolite; Final Rule," FR 51 (119), 20 June 1986.

17. "Program for the Development and Marketing of the Plasma Hospital Waste Pyrolysis System," Plasma Energy Corporation, July 1988.

18. Camacho, S. L., "F-1 Manual, Application of Plasma Technology" (draft), Plasma Energy Corporation, 1988.

19. Private Communication, S. L. Camacho, Plasma Energy Corporation, August 1991.

20. Plasma Energy Corporation brochure, First Mississippi Corporation, 1988.

APPENDIX A. Overview of Plasma Arc Technology.

(Source: Plasma Energy Corporation [PEC] brochure [First Mississippi Corporation, 1988]. Used with permission.)

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.

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.

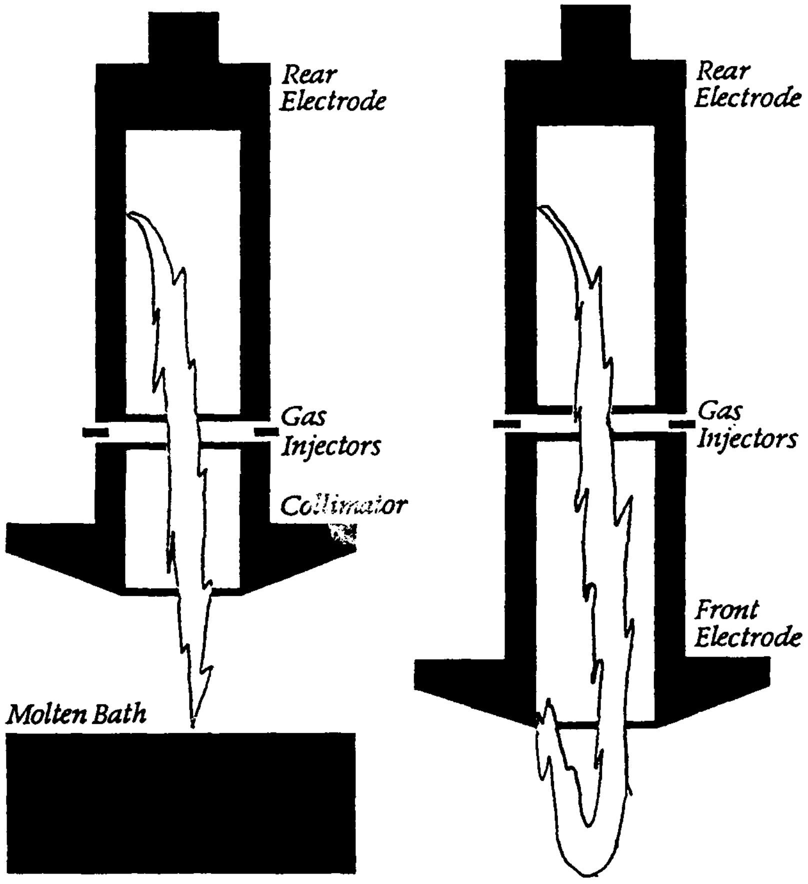
Plasma heating systems ionize gases to convert electricity into heat. They operate with almost any gas including air, argon, helium, hydrogen, CO_2, or CH_4. For added flexibility, they can also operate with many gas mixtures. Many torch configurations are available from low power convertible torches,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



Transferred Arc *Non-Transferred Arc*

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-transferred 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

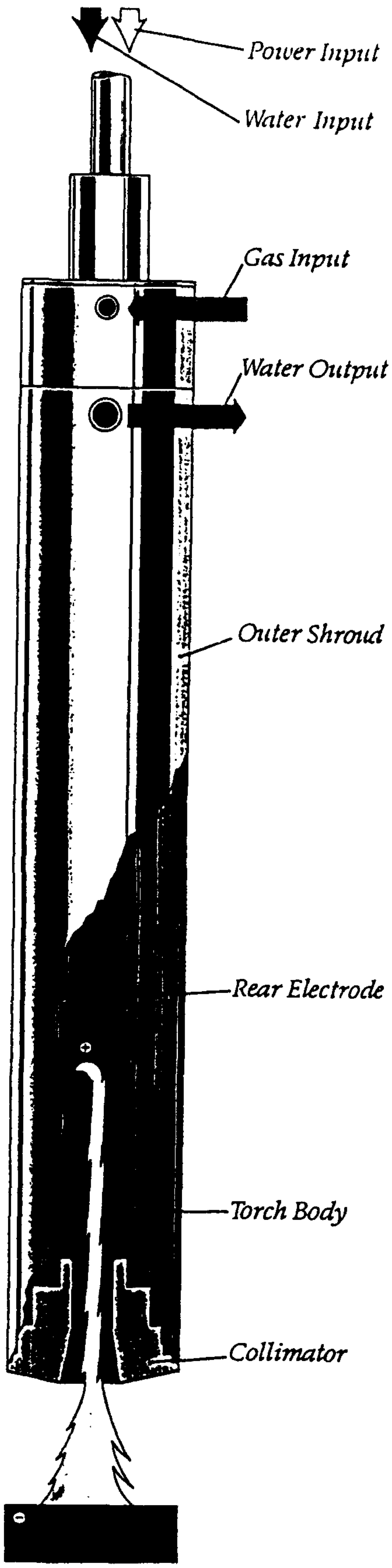
Plasma arc torches operate efficiently at temperatures well beyond those possible with fossil fuel burners. They can routinely create temperatures that range from 4,000 - 7,000 degrees centigrade or higher. This extreme heat is produced instantly, and can be easily automated. Controlled, high temperatures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

Controlled Furnace Atmosphere

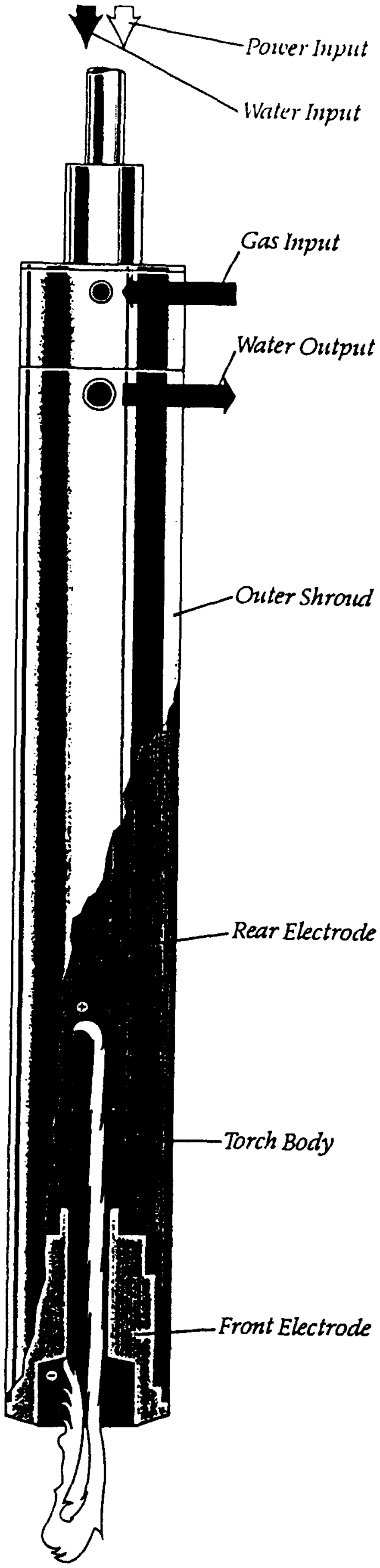
PEC plasma arc torches operate with almost any gas or gas mixtures (oxidizing, reducing, inert, etc.). This flexibility means the furnace atmosphere is completely variable, and can be tailored to satisfy the individual processing environment.

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.



Transferred Arc Torch



Non-Transferred Arc Torch

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.

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**

USACERL DISTRIBUTION

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: CEHEC-IM-LP (2)
ATTN: CECG
ATTN: CERD-M
ATTN: CECC-P
ATTN: CERD-L
ATTN: CECW-P
ATTN: CECW-PR
ATTN: CEMP-E
ATTN: CEMP-C
ATTN: CECW-O
ATTN: CECW
ATTN: CERM
ATTN: CEMP
ATTN: CERD-C
ATTN: CEMP-M
ATTN: CEMP-R
ATTN: CERD-ZA
ATTN: DAEN-ZCM
ATTN: DAEN-ZCE
ATTN: DAEN-ZCI

CECPW
ATTN: CECPW-F 22060
ATTN: CECPW-TT 22060
ATTN: CECPW-ZC 22060
ATTN: DET III 79906

US Army Engr District
ATTN: Library (40)

US Army Engr Division
ATTN: Library (13)

US Army Europe
ATTN: AEAEN-EH 09014
ATTN: AEAEN-ODCS 09014

29th Area Support Group
ATTN: AERAS-FA 09054
100th Support Group
ATTN: AETT-EN-DEH 09114
222d Base Battalion
ATTN: AETV-BHR-E 09034
235th Base Support Battalion
ATTN: Unit 28614 Ansbach 09177
293d Base Support Battalion
ATTN: AEUSG-MA-AST-WO-E 09086
409th Support Battalion (Base)
ATTN: AETTG-DEH 09114
412th Base Support Battalion 09630
ATTN: Unit 31401
Frankfurt Base Support Battalion
ATTN: Unit 25727 09242
CMTC Hohenfels 09173
ATTN: AETTH-DEH
Mainz Germany 09185
ATTN: BSB-MZ-E
21st Support Command
ATTN: DEH (10)
US Army Berlin
ATTN: AEBA-EH 09235
ATTN: AEBA-EN 09235
SETAF
ATTN: AESE-EN-D 09613
ATTN: AESE-EN 09630
Supreme Allied Command
ATTN: ACSGEB 09703
ATTN: SHIHB/ENGR 09705

INSCOM
ATTN: IALOG-I 22060
ATTN: IAV-DEH 22186

HQ XVIII Airborne Corps 28307
ATTN: AFZA-DEH-EE

US Army Materiel Command (AMC)
Alexandria, VA 22333-0001
ATTN: AMCEN-F
Installations:
ATTN: DEH (19)

FORSCOM
Forts Gillem & McPherson 30330
ATTN: FCEN
Installations:
ATTN: DEH (23)

National Guard Bureau 20310
ATTN: Installations Div

Fort Belvoir 22060
ATTN: CETEC-IM-T
ATTN: CECC-R 22060
ATTN: Engr Strategic Studies Ctr
ATTN: Australian Liaison Office

USA Natick RD&E Center 01760
ATTN: STRNC-DT
ATTN: DRDNA-F

TRADOC
Fort Monroe 23651
ATTN: ATEO-G
Installations:
ATTN: DEH (20)

USARPAC 96858
ATTN: DEH
ATTN: APEN-A

SHAPE 09705
ATTN: *Infrastructure Branch LANDA*

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

HQ USEUCOM 09128
ATTN: ECJ4-LIE

AMMRC 02172
ATTN: DRXMR-AF
ATTN: DRXMR-WE

CEWES 39180
ATTN: Library

CECRL 03755
ATTN: Library

USA AMCOM
ATTN: Facilities Engr 21719
ATTN: AMSMC-IR 61299
ATTN: Facilities Engr (3) 85613

Military Traffic Mgmt Command
ATTN: MTEA-GB-EHP 07002
ATTN: MT-LOF 20315
ATTN: MTE-SU-FE 28461
ATTN: MTW-IE 94626

Fort Leonard Wood 65473
ATTN: ATSE-DAC-LB (3)
ATTN: ATZA-TE-SW
ATTN: ATSE-CFLO
ATTN: ATSE-DAC-FL

Military Dist of WASH
Fort McNair
ATTN: ANEN 20319

USA Engr Activity, Capital Area
ATTN: Library 22211

Norton AFB 92409
ATTN: Library

US Army ARDEC 07806
ATTN: SMCAR-ISE

Engr Societies Library
ATTN: Acquisitions 10017

Defense Nuclear Agency
ATTN: NADS 20305

Defense Logistics Agency
ATTN: DLA-WI 22304

US Military Academy 10996
ATTN: MAEN-A
ATTN: Facilities Engineer
ATTN: Geography & Envr Engrg

416th Engineer Command 60623
ATTN: Gibson USAR Ctr

USA Japan (USARJ)
ATTN: APAJ-EN-ES 96343
ATTN: HONSHU 96343
ATTN: DEH-Okinawa 96376

Naval Facilities Engr Command
ATTN: Facilities Engr Command (8)
ATTN: Division Offices (11)
ATTN: Public Works Center (8)
ATTN: Naval Constr Battalion Ctr 93043
ATTN: Naval Civil Engr Service Center (3) 93043

8th US Army Korea
ATTN: DEH (12)

US Army HSC
Fort Sam Houston 78234
ATTN: HSLO-F
Fitzsimons Army Medical Ctr
ATTN: HSHG-DEH 80045
Walter Reed Army Medical Ctr 20307

Tyndall AFB 32403
ATTN: HQAFCESA Program Ofc
ATTN: Engrg & Srvc Lab

USA TSARCOM 63120
ATTN: STSAS-F

American Public Works Assoc. 60637

US Army Envr Hygiene Agency
ATTN: HSHB-ME 21010

US Gov't Printing Office 20401
ATTN: Rec Sec/Deposit Sec (2)

Nat'l Institute of Standards & Tech
ATTN: Library 20899

Defense Tech Info Center 22304
ATTN: DTIC-FAB (2)

275
9/93

This publication was reproduced on recycled paper.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1993—3510-S/80074