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Evaluation of Plasma Arc Technology for the Treatment of Municipal Solid Wastes in Georgia

by

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EXECUTIVE SUMMARY

Waste disposal in the State of Georgia is considered one of the most pressing problems facing the state in the 21st Century. Many millions of tons of municipal solid wastes, hazardous/toxic/industrial wastes, and agricultural wastes are being handled daily in the state. Plasma arc technology produces a form of artificial lightning with temperatures exceeding 7,000°C, which is hotter than the surface of the sun. This technology has been shown to offer great potential to solve or alleviate many of these waste disposal problems. Georgia Tech is a national leader in this area. Its plasma arc technology research program is arguably the largest university-based research program for plasma remediation of waste materials in the United States. In 1991 Georgia Tech established a laboratory-scale "Plasma Applications Research Facility" laboratory on the campus and has successfully conducted a large number of research projects related to the plasma disposal of waste materials.

The principal objective of this research program was to conduct scoping studies relating to the disposal of Municipal Solid Wastes (MSW). In particular, the research project was conducted to determine the existing state-of-the-art and to conduct experiments to evaluate the technical and economic feasibility of using plasma arc technology for the processing of MSW in the State of Georgia.

Plasma arc technology is a relatively new technology which is beginning to emerge as a commercial tool in industries such as steelmaking, metallurgy, and waste disposal. The potential of this technology to treat a wide variety of waste materials in an environmentally safe and cost-effective manner has been fully demonstrated. However, no commercial municipal solid waste plasma processing plants are in operation at the present time because of general availability of less expensive landfill space. In the near future however, as the number of landfills is reduced because of increasingly stringent environmental regulations, plasma processing alternatives are expected to become more economically competitive. The U.S. Navy and the U.S. Air Force are currently designing municipal waste plasma processing plants for shipboard disposal and for remote airbase operations.

The experimental portion of the research program consisted of three experiments using a simulated MSW material. Experiments No. 1 and No. 2 were

identical tests in which canisters of MSW were fed into a furnace preheated to approximately 1,100°C. Experiment No. 3 was an *in situ* test in which a plasma torch was operated in a vertical borehole placed in the middle of a cylindrical container filled with MSW. This experiment was conducted to simulate *in situ* landfill remediation.

The experiments conducted in this research program were successful in demonstrating the viability of the concept of pyrolyzing and melting a simulated MSW material in a furnace (*ex situ*) and in a simulated landfill (*in situ*). In all cases the MSW that was subjected to the intense plasma flame was completely transformed into either a gaseous effluent or a vitrified mass of rock-like material. Similarly, Toxicity Characteristics Leaching Procedure (TCLP) tests have indicated that this residue material has a very high resistance to leaching which meets EPA standards by very wide margins. Although the results are only qualitative, it also appears that significant levels of useful fuel gases can be generated in both *ex situ* and *in situ* geometries.

Sale of the byproducts from a MSW plasma processing system (fuel-laden gases and rock-like slag) could partially or fully offset the process costs of the technology. The use of plasma arc technology for MSW processing in a furnace would eliminate the requirements for a landfill. The *in situ* plasma MSW waste processing geometry would eliminate the landfill itself.

The state-of-the-art of plasma arc technology for *ex situ* and *in situ* MSW processing applications has reached the point where a small, mobile, plasma waste processing prototype system should be designed and built. Along with this effort, fundamental studies should be conducted into the basic phenomenology of these processes. This would culminate in the development of models to better understand the processes and to be in a position to scale up the technology to full industrial processing levels. Additionally, this plasma waste disposal research program should be expanded beyond the range of MSW, to include the plasma processing of a wide variety of hazardous/toxic and pathological/infectious wastes of interest to the State of Georgia.

1.0 INTRODUCTION

Waste disposal is a worldwide problem which is increasing in criticality each year. In the State of Georgia, it is considered one of the most pressing problems facing the state in the 21st Century. Many millions of tons of municipal solid wastes, hazardous/toxic/industrial wastes, and agricultural wastes are being handled daily in the state. Municipalities are facing great challenges in disposing of their wastes in an efficient, cost-effective, and environmentally safe manner. Landfills throughout the state are becoming full, and new ones are difficult to open. Another important concern in the state is the disposal of animal by-products, wastes, and carcasses, both hazardous and infectious. These problems of waste disposal in Georgia must be dealt with effectively in the future. Failure to do so could significantly impact the economy of the state. Existing methods of waste disposal do not offer any significant relief from these scenarios in the foreseeable future.

Plasma arc technology was developed over 30 years ago by the National Aeronautics and Space Administration (NASA) for the United States 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; e.g., steelmaking, metallurgy, precious metal recovery, and waste disposal.

The Georgia Tech plasma arc technology research program is arguably the largest university-based research program for plasma remediation of waste materials in the United States. In March 1991, the President of Georgia Tech authorized and funded the implementation of a three-year "Focused Research Program (FRP) in Plasma Arc Technology" within the university's Construction Research Center to evaluate promising industrial applications. As a result, Georgia Tech established a laboratory-scale "Plasma Applications Research Facility (PARF)" laboratory on the campus and has sucessfully conducted a large number of research projects related to the plasma disposal of waste materials. At the small scale experimental level in the laboratory, plasma arc technology has shown great promise in the pyrolytic destruction and remediation of many waste materials in an efficient, cost-effective, and environmentally safe manner.

Industries and government agencies in the state that could particularly benefit from the development of plasma arc waste disposal applications are as follows:

1. State of Georgia:	• Hazardous/Toxic Wastes • Industrial Sludges • Pathologic Wastes • Animal Carcasses • Radioactive Wastes • Contaminated Soils • Leaching Landfills • Infectious Wastes
2. Cities, Counties and Regions	• Municipal Solid Wastes • Contaminated Groundwater • Underground Storage Tanks • Medical Wastes
3. Pulp & Paper Industry	• Mill Pulping Effluent • Wood Wastes • Paper Recycling Sludges
4. Carpet Industry:	• Carpet Wastes

This research program was established to evaluate the potential application of plasma arc technology to treat municipal solid wastes (MSW). MSW constitutes a great majority of the wastes generated in the State of Georgia. Plasma treatment of both newly created wastes and MSW residing in landfills was studied. The principal objective of the research program was to conduct scoping studies to determine:

1. The existing state-of-the-art capability of plasma arc technology to pyrolyze and vitrify typical municipal solid wastes (MSW) in an environmentally safe and cost-effective manner.
2. The specific energy requirements (SER) to pyrolyze a unit weight of MSW.
3. The weight and volume reduction of the vitrified residue.
4. The general composition of the gaseous effluent emitted during the pyrolysis process.
5. The leachability of heavy metal contaminants from the vitrified residue.
6. The economic potential of using plasma arc technology for disposal of MSW.

2.0 BACKGROUND

2.1 Plasma Arc Technology

A plasma torch is a device that converts electrical energy into thermal energy (Camacho, 1988, 1991). Plasma is an ionized gas that is conditioned to respond to electromagnetic forces. The plasma arc is created when a voltage is established between two points. The plasma acts as a resistive heating element and maintains a temperature around 12,000°C. Plasmas occur naturally in the form of lightning. This resistive heating element presents a distinct advantage over any solid heating element as it is a gas and cannot melt and fail. The plasma arc creates a "flame" that has temperatures ranging from 4,000°C to 7,000°C, which is hotter than the surface of the sun. Thus, plasma torches operate at much higher temperatures, higher enthalpies, and at efficiencies much greater than those of fossil-fuel burners. In addition, plasma torches require only about 5 percent of the gas necessary for fossil fuel burners, therefore, waste effluent gases are greatly reduced. Because of this factor, furnace systems can be built that are much more compact than traditional furnaces, at correspondingly reduced capital costs. Figure 2.1 shows a plasma torch in operation.

On the outside, a plasma torch generally looks like a simple stainless steel cylinder, varying up to several inches in diameter and several feet in length; the specific dimensions being related to the torch power levels. This cylinder contains the electrodes, insulators, gas injectors, and water dividers which are integrated into a functional torch. The two electrodes are separated by an electrical insulator. Cooling

water is circulated within the walls of the tube to prevent the metals (stainless steel and copper) from melting under the high temperatures of the plasma arc. A gas is injected into the tube tangentially to its circumference at the insulator. The gas serves two purposes. First, it replenishes the gas for the plasma (which actually consumes only about 1 percent of the total gas flow). Second, the gas stabilizes the plasma arc column and allows the contact location of the arc to be changed by varying the gas flow rate. In this manner, the copper electrode surfaces can be consumed at a uniform rate. The type of gas used has no great effect on the process; air, argon, nitrogen, oxygen, helium, or other gases can be used. Typically, air is the simplest and least expensive gas source.

The average life of the electrodes in megawatt power level plasma torches is between 200 and 1,000 hours before the surface wears enough to allow the cooling water to leak. A leak does not present an immediate problem to the functioning of the torch; however, the leak indicates extreme wear on the electrode and the need for timely replacement, which is simple. Changing an electrode takes approximately 30 minutes. The plasma torch is powered by DC voltage, obtained through conversion from a standard AC power supply. Plasma torches generally operate in the 100 kW to 10 MW power level range. The electrical to thermal energy conversion is approximately 90 percent efficient (Camacho, 1988).

The plasma torch system consists of the following components; the plasma arc torch assembly, power supply and control panel, closed-loop water-cooling system and heat exchanger, and a gas source. In addition off-gas treatment is also required for many applications. A plasma torch system can be readily transported. A 1 MW, mobile, reverse polarity system (designed for *ex situ* melting), placed on three trailers, has been in operation for several years in Canada.

2.2 Plasma Arc *Ex Situ* Applications

Several plasma arc torch *ex situ* furnace processes for the destruction of a variety of waste materials have been developed and successfully tested. The very high temperatures and energy densities, in conjunction with the ionized and reactive medium, have fully demonstrated the potential of plasma arc technology to eliminate

many waste materials in an environmentally safe and cost-effective manner. Materials vitrified in furnaces with plasma arc torches also readily pass all standard leaching tests. Plasma arc torch technology is currently being used or planned for a variety of industrial and experimental *ex situ* applications. Some of these processes have been commercialized, while others are still in the development stages, including:

- 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 treatment (municipal, medical, asbestos, tires, hazardous/toxic, low-level radioactive materials)
- Biomass energy conversion
- Shale oil recovery
- Platinum recovery
- Zinc recovery
- Chemical synthesis
- MgO refractory production
- Powdered metal production
- Silicon metal production
- Electric arc furnace dust vitrification
- Glass melting

2.3 Plasma Arc *In Situ* Applications

For many years, *in situ* (borehole) thermal vitrification has been recognized as one method to remediate buried wastes. However, the complexity of the process and the uncertainty of the results have limited the use of this remediation technique. Major technological advances in plasma arc technology now permit the *in situ* transformation of all soil, rock, and waste types into a vitrified, rock-like material similar to obsidian, that is durable, strong, and highly resistant to leaching. Conceptually, a plasma arc torch can be lowered into a borehole to any depth, and can be operated to pyrolyze and melt municipal wastes and other contaminated materials into a magma or lava-like material, which cools into a zone of vitrified material. Subsequently, the plasma torch is slowly raised and operated at progressively higher levels to thermally convert a mass of soil into a vertical column of vitrified and remediated material. This process

of plasma remediation of *in situ* materials is rapid, efficient, cost effective, and simple. By applying this technique over a systematic grid pattern, the process becomes a viable means of *in situ* thermal treatment of landfills, contaminated soils, and burial pits (see Figure 2.2).

It is anticipated that the *in situ* plasma vitrification (ISPV) process would be directly applicable to virtually all soil and rock materials containing surface and subterranean deposits of mixed wastes, objects, and contaminants such as sanitary landfills, hazardous/toxic wastes, heavy metals and organics, buried objects, concentrated waste sediments and sludges, radionuclides, and underground storage tanks. Plasma arc torches operated at power levels exceeding 5 MW would be expected to produce vitrified columns greater than 10 feet in diameter. Based on the results of laboratory and field tests ranging from 100 kW to 900 kW, the three DOE sites with the greatest contaminated landfill and soil/buried waste problems have expressed strong interest in ISPV research (Oak Ridge Site, Hanford Site, Savannah River Site). A major portion of the cleanup of these three sites involves contaminated soils and buried debris, all of which would be directly amenable to ISPV treatment.

2.4 Technology Transfer Initiatives

Plasma arc technology for the treatment of domestic and hazardous wastes has been the theme of several major worldwide conferences since 1988. The most recent of these are:

1. Metatechnies, 1994, Proceedings "International Symposium on the Stabilization and Valorization of Ultimate Waste," University of Bordeaux I, Bordeaux, France, 12-14 September, 1994.
2. Georgia Institute of Technology, 1995. Proceedings "International Symposium on Environmental Technologies," Atlanta, Georgia, October 8-11, 1995.
3. National Defense Center for Environmental Excellence (NDCEE), 1996. Proceedings, "Plasma Arc Technology: Current Practices for Waste

Treatment," U.S. Department of Defense, Alexandria, Virginia, October 29-30, 1996.

The Georgia Tech program has been invited as a leading participant and proponent of plasma arc technology at each of these events.

3.0 PLASMA TREATMENT OF MUNICIPAL SOLID WASTE

3.1 Background

3.1.1 *Ex Situ* MSW Disposal

The original concept to treat municipal solid wastes (MSW) using plasma arc technology was put forth by Dr. S. L. Camacho through his December, 1973 patent (Camacho, 1973). In the patent a process was disclosed in which one or more plasma torches would operate in a refractory lined furnace to continuously pyrolyze household and industrial refuse material. The products of this process would be usable materials (e.g., metal ingots and vitrified rock-like gravel residue) and useful forms of energy (e.g., medium BTU gas). Gaseous emissions to the atmosphere would be very limited, and no byproducts would be sent to landfills (see Figures 3.1 and 3.2). Because of the generally unlimited and inexpensive access to large numbers of sanitary landfills at that time, there was no significant interest in pursuing this concept of MSW treatment.

In the late 1980's environmental regulations began to cause significant increases in landfill tipping fees. These regulations also resulted in the closure of large numbers of landfills. At this time interest in the plasma treatment of MSW was renewed. At an international conference in 1988, Resorption Canada Limited (RCL) reported on their MSW plasma gasification process (Carter 1988). Their prototype system used a 150 kW plasma torch in a furnace to pyrolyze approximately 500 pounds of MSW per hour. This research resulted in a U.S. patent, granted in January, 1994 (Carter and Tsangaris, 1994). In this same timeframe, Plasma Energy Corporation (PEC) was also granted a patent for the plasma treatment of MSW materials (Camacho, 1992).

A major conference paper on the plasma treatment of MSW wastes was presented by Dr. Camacho in September, 1990 (Camacho, 1990). In this paper, the results of several experimental programs were presented. Dr. Camacho concluded

that his design of a "Plasma Refuse Converter" offered an efficient, safe, and final disposition of MSW wastes. An RCL paper given at an international conference in Montreal Canada in 1992 (Plasma Technology for a Better Environment) presented similar conclusions (Carter, 1992). In August, 1966 Dr. Camacho was issued his third patent on the plasma pyrolysis and vitrification of MSW (Camacho, 1966).

3.1.2 *In Situ* Landfill Remediation

Most of the MSW material produced in the State of Georgia is deposited into landfills. Within the next several years many of these landfills will reach capacity or will close because of recent highly stringent environmental regulations governing their operation. New landfills are increasingly difficult to create because of strong local opposition, sometimes called NIMBY (not in my backyard). If no new landfills are created, it is estimated that by the year 2000 in the U.S. there will be an annual shortage of landfill space of over 60 million tons of waste material. Thus, both the state and the U.S. will soon enter into a critical period of waste management and disposal in which landfills will become less available with correspondingly significant increases in haul distances, dumping fees, and operational costs. Furthermore, closed and operating MSW landfills throughout the state, the country, and the world pose significant hazardous/toxic environmental leaching problems such as contaminating the groundwater now and for generations into the future.

The original concept for the *in situ* remediation of landfills was espoused in a January, 1993 U.S. Patent, "*In Situ* Landfill Pyrolysis, Remediation and Vitrification." (Circeo et al., 1993). This is a simple and straightforward remediation process which involves drilling and casing a grid of boreholes to the bottom of a landfill mass at an estimated 10-15 feet spacing. A plasma arc torch is operated in each borehole to convert the waste materials into an environmentally safe, glassy residue which is highly resistant to leaching. During the process, the offgas is collected at the top of each borehole in a hood which is attached to a gas treatment system. The resultant cleaned gases have a heating value of approximately 300 BTU per cubic feet, totaling over four times greater than the plasma heat input required to process the landfill wastes. These gases may be commercially useful as fuel gases to cogenerate power

or to produce alternate fuels such as methanol. Thus, landfill wastes could become a major source of renewable energy which could be sold to offset most or all of the landfill remediation processing costs. The volume of the vitrified residue is expected to be ten times less than the original landfill volume, thus recovering over 90 percent of the original landfill capacity. This residue will line the bottom of the landfill with a highly impermeable layer of rock-like material (see Figure 3.3). Therefore, a landfill could be refilled with wastes and remediated through several cycles, substantially extending the useful life of typical landfills to periods well in excess of 100 years. Eventually the rock-like residue material would completely fill up the landfill volume and provide a firm, environmentally safe foundation for construction.

In situ plasma arc technology holds great promise to provide an efficient and cost-effective "ultimate remediation process" for MSW landfills. Furthermore, since the hard residue material is highly resistant to leaching and would stop the transport of heavy metals and other contaminants, this technology would also have direct applicability for the *in situ* remediation of special landfills containing buried hazardous/toxic deposits of waste materials, to include low-level radioactive wastes. The looming landfill crisis in the state and the rest of the U.S. is so great and so widespread that if this technology is successfully developed at a commercial site, it could be expected to result in fundamental improvements in current national concepts of waste management and disposal.

3.2 Recent Activities in *Ex Situ* MSW Disposal

3.2.1 The RCL Process

In June, 1992 the Ontario Ministry of Energy reported on their evaluation of the "plasma gasification" process for MSW disposal (Ministry of Energy, 1992). The report concluded that plasma gasification appears to have tremendous potential as a technology for effectively disposing of MSW, and the technology offers significant energy and environmental benefits over existing MSW disposal processes. An associated Resorption Canada Limited (RCL)1995 research program, processing up to 400 pounds per hour (Carter et al., 1995) indicated that:

1. Plasma gasification is an efficient MSW disposal technology with significant environmental improvements over existing incineration technologies, particularly in the areas of gaseous emissions and leachate toxicity.
2. The monolithic composition and the engineering characteristics of the vitrified slag would make it salable to the construction industry, thereby eliminating the need for landfills.
3. Over four times the thermal energy is produced by the process than the plasma torch energy required to process the MSW (see Figure 3.1).

In October, 1996 Plasma Technology Corporation reported on their Plasma Pyrolysis/Vitrification (PPV) process for MSW disposal (Camacho, 1996). In addition to MSW disposal, the PPV process also emphasizes the ability to mix MSW with selected "hazardous" waste materials (e.g., used tires, medical wastes, sludges) to significantly increase the waste stream tipping fees. This capability, along with the elimination of a requirement for landfills, and the potential sale of process byproducts (fuel-laden gases and vitrified slag), could make the PPV process highly cost-effective. A schematic diagram of the PPV process is shown in Figure 3.4.

3.2.2 MSW Incinerator Ash Vitrification

Incinerator ash from MSW incinerators is being considered a hazardous waste in many countries, to include the United States (Engineering News Record, 1994). The ash, which cannot readily pass standard leachability tests, generally contains a significant amount of heavy metals. Two countries, Japan and France, have implemented regulations to preclude the disposal of MSW incinerator ash in sanitary landfills. In Japan plasma vitrification of incinerator ash has already been implemented as a commercial technology (Inaba, 1995). In France an incinerator ash plasma vitrification plant is under construction near the city of Bordeaux, a project to which Georgia Tech made significant research contributions. Completion is anticipated in early 1997 (Pineau, 1995).

Incinerator ash vitrification is being commercialized before the MSW pyrolysis and vitrification process for the following economically driven reasons:

1. The MSW incinerators are already in place and operational in many countries. In France and Japan about 70 percent of MSW is burned in conventional incinerators; in the U.S., the percentage is only about 16 percent.
2. The recent regulations reclassifying MSW incinerator ash as a hazardous waste in many countries has threatened to increase by up to ten times the current cost of landfilling the incinerator ash.
3. Vitrification of the MSW incinerator ash eliminates the need and cost to landfill the residue, and creates a salable byproduct.

3.3 Current Practices in *Ex Situ* Plasma Treatment of MSW

At the present time, no commercial MSW plasma processing plants are operational. It is considered technically feasible to destroy MSW with plasma arc technology and recover useful gases and salable slag residue. However, the process has not been demonstrated outside the laboratory, at the industrial level, and the economic feasibility has not been proven. It is anticipated that, in the United States, as the number of landfills continue to decrease, and as environmental regulations concerning the toxicity of incinerator ash become more stringent, the cost of MSW disposal will rise dramatically; then alternate solutions to current MSW disposal practices will become more economically competitive. At the present time, MSW disposal costs are already quite high in some areas of the U.S. Department of Defense. In two organizations, MSW plasma processing plants are already being designed.

3.3.1 The U.S. Navy Plasma Arc Waste Destruction System (PAWDS)

The U.S. Navy has been tasked by Congress to comply with the MARPOL Treaty for the disposal of solid wastes at sea by the year 2000. The Navy has determined that only plasma arc processing of shipboard wastes can meet this requirement. The Plasma Arc Waste Destruction System (PAWDS) is currently under design for use in U.S. Navy Carrier Battle Groups (CBG) (Leatherman, 1996). A daily

processing throughput of eight tons of MSW is planned. It is anticipated that three PAWDS systems will be made operational in each CBG. Each PAWDS will be capable of processing approximately 500 pounds per hour of Navy municipal-type wastes. Following treatment the vitrified rock-like slag will be considered sufficiently stable and inert for disposal overboard.

3.3.2 The U.S. Air Force Bare Base Waste Processing System

The U.S. Air Force has an important mission for rapid deployment of forces capable of setting up and operating airfield operations in remote areas in a short period of time. This "bare base" contingency plan, as it is known, consists of specific numbers of airmen and equipment. However, within this bare base "package," waste processing remains the least developed. In order to correct this deficiency the Air Force Wright Laboratory is developing a mobile, air-transportable bare base plasma arc waste processing system (Construction Research Center, 1996). This system is being designed to process approximately four tons per day of municipal-type waste. In addition, it will be evaluated for its capability to process other wastes which would be considered hazardous, e.g., paints, solvents, oil. medical wastes, etc. The system will be designed to operate from 750 kW generators already provided in the bare base deployment package.

3.4 Current Practices in *In Situ* Landfill Remediation

To date, no *in situ* experiments have been conducted, in the laboratory or elsewhere, to examine the feasibility of *in situ* landfill remediation. The concepts, discussed earlier, were based on existing data relating to *ex situ* plasma processing of waste materials in furnaces and to the *in situ* plasma vitrification of inorganic soils and buried contaminants.

The *in situ* landfill experiment planned in this series of laboratory scoping tests is the first one to be conducted. This is an important experiment, since it will verify or refute many of the ideas developed about *in situ* landfill remediation. Previously, these ideas have been extrapolated from a combination of *ex situ* organic waste processing studies and *in situ* inorganic soil plasma vitrification experiments. It is

anticipated that the results of this experiment will form the basis for development of a comprehensive research program to explore the technical and economic feasibility of *in situ* landfill remediation in the State of Georgia.

4.0 RESEARCH PLAN

The experimental portion of this research program consisted of scoping trials of *ex situ* and *in situ* plasma treatment of simulated municipal solid wastes. Two *ex situ* (furnace) experiments were conducted; one *in situ* (landfill remediation) experiment was conducted. All experiments were performed using the 100 kW plasma heating system at the Georgia Tech Plasma Applications Research Facility (PARF). Table 4.1 lists basic information on the three experiments.

Table 4.1 Municipal Solid Waste 100 kW Plasma Experimental Program

Experiment Number	Date	Test Geometry	No. of Canisters	Total Sample Weight (pounds)	Remarks
1	6/28/96 (Furnace)	*Ex Situ*	27	36.11	6 pounds molten metal bath
2	11/14/96 (Furnace)	*Ex Situ*	30	28.48	6 pounds molten metal bath
3	11/15/96 (Landfill)	*In Situ*	N/A	211.30	Soil weight @ 20% (26.92 pounds)

4.1 Plasma Applications Research Facility (PARF)

The Georgia Tech plasma arc technology research program is arguably the largest university-based research program for plasma remediation of waste materials in the United States. In 1991 Georgia Tech established a laboratory-scale Plasma Applications Research Facility (PARF) laboratory on the campus and has successfully

conducted a large number of research projects related to the plasma disposal of waste materials.

4.1.1 Test Facilities

The primary experimental testing was conducted at the Georgia Tech PARF in Atlanta, Georgia (see Figure 4.1). The PARF contains two plasma heating systems: a 100 kW and a 240 kW plasma heating system (PHS) both built by Plasma Energy Corporation (PEC). A insertion-plunger furnace, with a semi-batch feeding system, was designed for the 100 kW PHS and fabricated by Plasma Technology Corporation (see Figure 4.2). The GTRI staff modified the unit to accommodate easier extraction and removal of the processed product. The original design for the graphite crucible was also modified to insert thermocouples and to allow larger quantities of waste materials to be fed into the furnace during each test (see Figure 4.3).

4.1.2 The PT50 Plasma Heating System

The PEC PT50 plasma heating system was used in the experimental portion of this research project. It is on loan to Georgia Tech from the Georgia Power Company, Technology Applications Division. It operates in the non-transferred mode only. It is rated at 100 kW and has been operated primarily using air as the plasma gas. Argon and hydrogen have also been used as plasma gases in this system. The plasma torch which was used for the MSW experiments is 6.0 feet long and 2.5 inches in diameter. At operating conditions the PT50 plasma torch has a water flow of 30 GPM (gallons per minute) and a plasma gas flow of five SCFM (standard cubic feet per minute). The PT50 plasma heating system is ideal for use in a laboratory setting to conduct bench-scale experiments of plasma arc technology applications. These tests can be conducted very rapidly and at a relatively low cost.

4.2 Simulated Municipal Solid Waste Constituents

In order to obtain comparative results in each experiment, it was decided to develop an artificial MSW material to use in all tests. The constituents of the MSW samples were based on average U.S. values as determined by the U.S.

Environmental Protection Agency (EPA) (Corbitt, 1990). Table 4.2 lists these average constituents along with the corresponding planned weight of simulated MSW for the three experiments. Water was added to each sample to simulate average moisture contents; and soil was added to the *in situ* material to simulate typical landfill mixtures.

Table 4.2 Average Municipal Solid Waste Constituents in the United States*

MSW Constituents	Average U.S. Weight (%)	*Ex Situ* Experiment Planned MSW Composition (lbs)	*In Situ* Experiment Planned MSW Composition (lbs)
Paper	42.00	10.50	56.54
Fabric	5.20	1.30	7.00
Plastic	4.50	1.13	6.06
Food	17.90	4.48	24.10
Wood	4.50	1.13	6.06
Sweepings	1.90	0.48	2.56
Ferrous Metals	9.80	2.45	13.19
Aluminum	1.10	0.28	1.48
Non-Ferrous	0.40	0.10	0.54
Other Burnables	12.70	3.18	17.10
Rubber		1.00	10.00
Glass		1.20	5.00
Grass/Leaves		1.00	2.00
Total	100.00	25.00	134.62
Moisture Content	27.00	9.25	49.79
Total		34.25	184.40
Soil (Landfill)			26.92**
Total			211.33

*(Corbitt, 1990) Standard Handbook of Environmental Engineering, McGraw-Hill

** Calculated at 20 percent of dry weight

4.3 Test Plan

4.3.1 *Ex Situ* Experiments

Two identical *ex situ* experiments were planned using the 100 kW graphite crucible furnace (see Figures 4.2 and 4.3). In these tests approximately 30 pounds of simulated household MSW waste was scheduled to be pyrolyzed. The MSW was placed in about 30 canisters, each 8.5 inches long and 3 inches in diameter, weighting approximately 1.0 pound each. Both ends of each canister were sealed with duct tape. The canisters were fed into the furnace at approximately three minute intervals, at crucible temperatures exceeding 1,100°C. A small molten metal bath, composed of six pounds of scrap iron, was developed at the bottom of the graphite crucible prior to feeding the canisters into the furnace. This weight was not included in the MSW constituent weight.

4.3.2 *In Situ* Experiment

One *in situ* plasma experiment was planned to simulate MSW landfill remediation using the 100 kW torch (See Figure 4.4). Approximately 211 pounds of simulated MSW of the type found in sanitary landfills was placed in an upright, two-foot diameter and three-foot high steel cylinder. A 100 kW plasma torch was initiated near the bottom of a small borehole placed in the center of the cylinder. As the MSW was pyrolyzed, the torch was slowly raised. A hood placed over the top of the cylinder collected the gases for measurement of key constituents and treatment.

4.4 Data Collection and Analysis

The following data were collected and analyzed during the experimental phase of the program:

1. Pretest
   a. General characterization of the MSW.
   b. Weight and volume of the MSW.
2. During Test
   a. Plasma torch power levels

b. Crucible temperatures
c. Gaseous effluent

3. Post Test
   a. Vitrified residue weight and volume
   b. Leachability tests
   c. X-ray diffraction tests on the vitrified residue
   d. Scanning Electron Microscope (SEM) micrographs
   e. Analysis of the gaseous effluent (SO_2, NO_x, CO, CO_2, HCl, H_2, Total hydrocarbons)

5.0 EXPERIMENTAL PROGRAM

5.1 Experiment No. 1

Experiment No. 1 was principally a calibration experiment. Since no previous MSW tests had been conducted at the PARF, it was necessary to run this test in order to determine what reactions and byproducts could affect data collection and safety conditions in future tests; e.g., canister loading interval, negative pressure in furnace, gaseous emissions, particulate emissions, scrubber efficiency, etc. No gaseous effluent analyses or toxicity leaching test analyses were conducted due to the costly nature of such tests. These studies were performed during Experiment No. 2 which was identical to this experiment.

This *ex situ* MSW experiment was conducted in the 100 kW graphite crucible furnace (see Figure 4.2). Twenty seven (27) canisters of simulated MSW were loaded into the furnace at an average of three-minute intervals. This time interval was determined to be more than adequate to get complete pyrolysis and melting of each canister. The pyrolysis and melting process for this experiment was captured on a video recording. The tapes, made a permanent part of the record of this experiment, are on file at the Construction Research Center, Georgia Tech.

One thermocouple was used in this experiment. It was placed in the center of the graphite crucible, one inch below the bottom of the crucible (see Figure 4.3). Feeding of the MSW canisters into the furnace began when the thermocouple temperature reached 800°C. At this thermocouple temperature, one inch below the

crucible bottom, it was assumed that the temperature at the bottom of the crucible would be approximately 1,100°C. The MSW canisters were fed into the furnace over a 92 minute period. The operating conditions and the data collected during the experiment are described in Appendix A.

The initial MSW weight of 36.1 pounds was reduced to 5.9 pounds, a weight reduction of 84 percent. This was accompanied by a volume reduction of about 96 percent. X-ray diffraction and SEM micrograph data on the experiment are contained in Appendix D. These data indicate that the vitrified residue is an amorphous material containing a preponderance of iron, which likely represents the material that was in the molten metal bath.

Experiment No. 1 indicated that there were no unforeseen problems relating to data collection or safety that would be caused when organic matter, placed in canisters, is subjected to plasma pyrolysis in the 100 kW graphite crucible furnace.

5.2 Experiment No. 2

Experiment No. 2 was identical to Experiment No 1; however, it included a much larger data collection effort than the first test, which was mainly to calibrate the furnace and the process for follow-on tests. The purpose of Experiment No. 2 was a scoping test to examine the technical and economic potential of plasma processing of MSW waste materials in the State of Georgia.

The experiment was conducted in the 100 kW graphite crucible furnace, as shown in Figure 4.2. Thirty (30) cardboard canisters of simulated MSW, weighing slightly less than one pound each, were loaded into the furnace. The feeding interval of the canisters averaged about three minutes. As in Experiment No. 1 the pyrolysis and melting process of the canisters was recorded on video tape, and made a permanent part of the project record at the Georgia Tech Construction Research Center. Canister feeding began when the thermocouple, one inch under the bottom of the graphite crucible, reached a temperature of 969°C.

The experiment was conducted over a period of 164 minutes, with the canisters fed to the furnace over a period of 111 minutes. Following a period of cooling, the

furnace was disassembled. Byproducts of the melting process totaled 11.5 pounds, and were found in three locations:

1. Crucible: 2 pounds of vitrified material
2. Furnace Walls: 8.5 pounds of vitrified material
3. Furnace Top (inside lid): 1 pound of flyash

It was assumed that the six pounds of iron for the molten metal bath placed in the crucible at the beginning of the experiment were still present in the byproducts. Therefore, the residue from the experiment itself totaled 5.5 pounds.

The operating conditions of the experiment and the data collected during the experiment are described in Appendix B. The initial MSW weight of 28.5 pounds was reduced to 5.5 pounds, a weight reduction of 81 percent. This was accompanied by a volume reduction of 96.5 percent. Toxicity leaching test (TCLP) results were below EPA permissible levels by a wide margin. Offgas analysis indicated that over 95 percent of the gaseous emissions were hydrogen (H_2), carbon monoxide (CO) and carbon dioxide (CO_2). X-ray diffraction and SEM micrograph data are contained in Appendix D. These data indicate that the vitrified residue is an amorphous material containing a preponderance of iron, which likely represents the material that was in the molten metal bath.,

5.3 Experiment No. 3

This experiment was conducted to simulate the *in situ* plasma remediation of MSW in a landfill. The test was conducted in a steel cylindrical container 24 inches in diameter and 36 inches high. In addition, a 12-inch high gas collection cover with an exhaust port was mounted on top of the container. A cross section of the test geometry is shown in Figure 4.4. The container was prepared with a one-inch insulating ceramic blanket and three inches of soil at the bottom of the container. The waste constituents were then placed on top of that bottom four-inch layer and around the stovepipe in a random fashion, compressing the layers as much as possible along the sides. Once all the constituents were in place, a 9-inch layer of soil was added to fill

the entire volume of the test container. Figure 4.5 is a photograph of the test chamber for this experiment.

The plasma torch was positioned nine inches above the bottom of the borehole at the beginning of the experiment. The operating conditions of the experiment and the data collected during the experiment are described in Appendix C. The torch was withdrawn up the borehole at a rate of three inches every ten minutes. The experiment lasted 90 minutes and was uneventful, except for an unexplained five-inch diameter hot spot on the side of the container, about 15 inches up from the bottom of the container.

Disassembly of the container revealed that, before slumping, the original four-inch stove pipe was gone, and that an empty vertical shaft, about 14 inches in diameter was now running through the entire height of the cylinder (see Figure 4.6). The remaining MSW and the top layer of soil had subsequently slumped several inches from their original locations (see Figure 4.7). A relatively flat plate-like melt varying from 14 to 16 inches in diameter, averaging two to four inches thick and weighting 33.1 pounds, was at the bottom of the container (Figure 4.8). In addition, nine pounds of flyash from the experiment was found inside the lid at the top of the furnace. Therefore, the total weight of the residue was 42.1 pounds. The MSW remaining in the container weighed 108 pounds. The inside edges of this mass (next to the empty vertical shaft) were slightly baked, but for the most part this remaining MSW was unaltered, as can be seen in Figure 4.7.

As calculated in Appendix C, the initial MSW weight plus the weight of the topsoil that was pyrolyzed and vitrified was estimated to be 103.75 pounds. This was reduced to 42.1 pounds, a weight reduction of 59 percent. This was accompanied by a volume reduction of 88.6 percent. Toxicity leaching test (TCLP) results indicated that all tests were below detectable limits, and therefore far below EPA permissible levels. Offgas analysis indicated that over 95 percent of the gaseous emissions were hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2). X-ray diffraction and SEM micrograph data are contained in Appendix D. These data indicate that the vitrified residue is an amorphous material containing a preponderance of silicon,

which likely represents the large amount of soil that was vitrified during the plasma treatment of the MSW.

6.0 DATA ANALYSIS

6.1 Weight Loss

All experiments resulted in significant weight loss from the initial MSW weight to the final vitrified product. The loss in weight of the MSW in the three experiments is shown in Table 6.1. In the two furnace tests (*ex situ*), the weight loss exceeded 80 percent. In these tests most of the simulated MSW material was organic. This material is pyrolyzed and gasified. Thus, large weight losses are to be expected.

Table 6.1 MSW Weight Loss from Plasma Processing

Experiment No.	Initial Weight (lb)	Final Weight (lb)	Weight Loss (%)
1	36.1	5.9	84
2	28.5	5.5	81
3	103.8	42.1	59

In the *in situ* experiment, a significant amount of soil was mixed with the MSW. In addition, about half of the nine inch covering soil layer over the 14 inch vitrified MSW column was vitrified and contributed to the final weight. Soil is inorganic and would not be gasified or otherwise reduced in weight. Therefore, the 59 percent weight reduction experienced in the *in situ* (landfill remediation) experiment would be consistent with the data collected in Experiments No. 1 and No. 2.

6.2 Volume Reduction

All experiments showed significant volume reductions from their initial MSW volume to the final vitrified product. This volume reduction in the three experiments is indicated in Table 6.2. Experiments No. 1 and No. 2 have almost identical volume reductions (96 percent), and they are consistent with past studies. The slightly lower volume reduction in Experiment No. 3 (89 percent) is undoubtedly due to the

presence of the large amount of inorganic soil in the MSW landfill mixture that was vitrified (melted), but not pyrolyzed (gasified) during the experiment.

Table 6.2 MSW Volume Reduction from Plasma Processing

Experiment No.	Initial Volume	Final Volume	Volume Reduction (%)
1	1,621 in^3	67.9 in^3	95.8
2	1,801 in^3	63.3 in^3	96.5
3	2.45 ft^3	0.28 ft^3	88.6

In the *in situ* (landfill remediation) test (Experiment No. 3), the vitrified central core of MSW was reduced to a plate-like layer of vitrified material at the bottom of the cylindrical container. This plate measured from 14 to 16 inches in diameter and 2 to 4 inches thick. This vitrified residue configuration was consistent with anticipated results of landfill plasma remediation concepts (see Figure 3.3). Considering the entire height of the MSW, plus the soil covering layer, the plate-like vitrified residue represented an 88.6 percent reduction in the "landfill" volume inside the cylinder. This volume reduction is also what would be expected in a landfill remediation program, and verifies the concept that a large percentage of the original landfill volume can be reclaimed.

6.3 Toxicity Leaching Tests

Standard Toxicity Characteristics Leaching Procedure (TCLP) tests were conducted on vitrified sample materials from Experiments No. 2 and No. 3. In *the ex situ* (furnace) experiment all heavy metals were below detectable levels except for Barium (0.47 mg/l). With a permissible concentration of 100 mg/l, even the detected Barium level was over 100 times below EPA permissible levels (100 mg/l). In the *in situ* test, all heavy metals are below detectable levels. Tables 6.3 and 6.4 are extracts of these data from Appendices B and C.

Table 6.3 TCLP Test Results for Experiment No. 2 (*Ex Situ* test)

Heavy Metal	Permissible Concentration (mg/l)	Measured Concentration (mg/l)
Arsenic	5.0	BDL (0.1)
Barium	100.0	0.47
Cadmium	1.0	BDL (0.1)
Chromium	5.0	BDL (0.1)
Lead	5.0	BDL (0.1)
Mercury	0.2	BDL (0.01)
Selenium	1.0	BDL (0.2)
Silver	5.0	BDL (0.1)

BDL - Below Detectable Limit

Table 6.4 TCLP Tests Results for Experiment No. 3 (*in situ* test)

Heavy Metal	Permissible Concentration (mg/1)	Measured Concentration (mg/l)
Arsenic	5.0	BDL (0.1)
Barium	100.0	BDL (0.1)
Cadmium	1.0	BDL (0.1)
Chromium	5.0	BDL (0.1)
Lead	5.0	BDL (0.1)
Mercury	0.2	BDL (0.01)
Selenium	1.0	BDL (0.2)
Silver	5.0	BDL (0.1)

BDL - Below Detectable Limit

6.4 Offgas Analysis

Appendices B and C contain the offgas analysis data taken during Experiments No. 2 and No. 3. Offgas sampling and analysis was conducted using Sensidyne

detector tubes in order to achieve cost-effective operations. This technique is useful to obtain a qualitative measurement of the type of offgas emissions from each experiment. Quantitatively, however, the technique is not as accurate as standard residual gas analyzers. However, for the purpose of this scoping study, the Sensidyne measurements were considered sufficient. Table 6.5 summarizes typical offgas emission data from Experiments No. 2 and No. 3. As shown in the Table 6.5 in both experiments the most prevalent offgasses (over 95 percent) were Hydrogen (H_2), Carbon Monoxide (CO) and Carbon Dioxide (CO_2). The first two gases (H_2 and CO_2) are fuel gases and constitute over 50 percent of the offgases in both experiments. This result is consistent with past studies (Camacho, 1990; Carter et al., 1995).

Table 6.5 Typical Offgas Emission Data for Experiments No. 2 and No. 3

	Concentration (parts per million)	
Offgas Type	Experiment No. 2 (*Ex Situ*: Furnace)	Experiment No. 3 (*In Situ*: Landfill)
Hydrogen (H_2)	> 20,000	> 20,000
Carbon Monoxide (CO)	100,000	> 100,000
Carbon Dioxide (CO_2)	100,000	90,000
Nitrogen Oxides (NO_x)	< 50	100
Hydrogen Sulfide (H_2S)	100	80
Hydrogen Chloride (HCl)	<20	225
Hydrocarbons	>5,000	>4,500

The Experiment No. 3 data is the first time that *in situ* landfill plasma pyrolysis offgas data has been analyzed. The results reveal some interesting observations:

1. The composition and quantity of *in situ* offgas emissions from MSW landfill pyrolysis are essentially the same as the offgas emissions from *ex situ* furnace-fed MSW.
2. The potential for recovery of salable fuel gases from *in situ* landfill pyrolysis and remediation appears to be very promising.
3. Acid gas formation is relatively low. Therefore, it appears that a relatively unsophisticated gas treatment system would be sufficient to treat the offgas emissions.

6.5 Specific Energy Requirement (SER)

The Specific Energy Requirement (SER) of a material refers to the amount of plasma torch energy, normally expressed in kilowatt-hours (kWh), required to pyrolyze and vitrify a specific mass of material, normally expressed in pounds or tons. Specific energy requirements generally range from 0.25 kWh/lb for steel scrap melting to over 6 kWh/lb for production of ceramic materials. The SER for municipal solid wastes generally range between 0.3 kWh/lb and 0.7 kWh/lb.

Determination of the SER for this series of experiments is meaningful only for the *in situ* test (Experiment No. 3). Experiments No. 1 and No. 2 were directed toward complete pyrolysis and vitrification of each canister prior to feeding another canister. Thus the time interval, between capsule feed during these *ex situ* furnace experiments, would be considered excessive. For example, even though most canisters were pyrolyzed within one minute, the average time interval to feed canisters was three minutes. From an SER standpoint, this was a very inefficient procedure, and SER's would be very large. Thus, the SER's for Experiments No. 1 and No. 2 were 4.24 kWh/lb and 6.49 kWh/lb respectively. These SER's are much higher than what has been observed in past studies.

Experiment No. 3 was conducted in a geometry approximating an *in situ* landfill pyrolysis project. Therefore, SER results are more meaningful than the *ex situ*

experiments. The Appendix C data indicate that Experiment No. 3 was conducted for a period of 90 minutes (1.50 hours) at a plasma torch power level of 96 kW. A 14 inch diameter column of MSW plus about half of a similar column of the topsoil material was pyrolyzed and vitrified (see Figure 4.6). As indicated in Appendix C the weight of this column of the transformed material was estimated to be 103.75 pounds. Therefore the 144 kWh of energy required to pyrolyze this mass of material resulted in an SER of 1.39 kWh/lb. This is about twice the SER range of past MSW furnace experiments. However, future research into the area of *in situ* pyrolysis phenomenology would be expected to result in energy efficiencies which would, at the least, meet the SER's established for *ex situ* processes.

6.6 X-Ray Diffraction and Scanning Electron Microscope Data

X-ray diffraction and Scanning Electron Microscope (SEM) data are presented in Appendix D. Analysis of the vitrified residue indicated similar results in all experiments. The vitrified residue was amorphous and monolithic in nature. Elemental composition was also similar; however, the *ex situ* experiments indicated a preponderance of iron from the molten metal baths, and the *in situ* sample exhibited the presence of much larger amounts of silicon, due to the large amount of soil mixed in with the simulated MSW material.

7.0 SUMMARY

Waste disposal in the State of Georgia is considered one of the most pressing problems facing the state in the 21st Century. Many millions of tons of municipal solid wastes, hazardous/toxic/industrial wastes, and agricultural wastes are being handled daily in the state. Plasma arc technology has been shown to offer great potential to solve or alleviate many of these waste disposal problems. The principal objectives of this research program were to conduct scoping studies relating to the disposal of Municipal Solid Wastes (MSW). In particular, the research project was conducted to determine the existing state-of-the-art and to conduct experiments into the technical and economic feasibility of using plasma arc technology for the processing of MSW in the State of Georgia.

The experimental portion of the research program consisted of three experiments using a simulated MSW material. Experiments No. 1 and No. 2 were identical tests in which canisters of MSW were fed into a furnace preheated to approximately 1,100°C. Experiment No. 3 was an *in situ* test in which a plasma torch was operated in a vertical borehole placed in the middle of a cylindrical container filled with MSW. This experiment was conducted to simulate *in situ* landfill remediation.

The three experiments in this research effort were successful in demonstrating the viability of the concept of pyrolyzing and melting a simulated MSW material in a furnace (*ex situ*) and in a simulated landfill (*in situ*). In all cases the MSW that was subjected to the intense plasma flame was completely transformed into either a gaseous effluent or a vitrified mass of rock-like material. Similarly, Toxicity Characteristics Leaching Procedure (TCLP) tests have indicated that this residue material has a very high resistance to leaching which meets EPA standards by very wide margins. Although the results are qualitative, it also appears that significant levels of useful fuel gases can be generated in both *ex situ* and *in situ* geometries.

There is a potential market for the byproducts of the MSW plasma pyrolysis process. The rock-like vitrified slag could be sold as road gravel or as aggregate for concrete or asphalt pavements. In addition to offsetting process costs, this technology would eliminate the necessity to landfill any residue material, thus saving tipping fees and eliminating the need for landfills. The fuel gases emitted by the plasma pyrolysis and vitrification process could be sold directly for its heating value or converted to electricity or other useful products such as methanol. In any case the sale of the byproducts from the process could provide significant offsets in the processing costs, even to the break-even point, where income from the byproducts could equal the processing cost.

8.0 CONCLUSIONS

The following conclusions are drawn as a result of this research program:

1. Plasma arc technology is a relatively new technology which is beginning to emerge as a commercial tool in industries such as steelmaking, metallurgy, and waste disposal. The potential of this technology to eliminate many

municipal, hazardous/ toxic, and radioactive waste materials in an environmentally safe and cost-effective manner has been demonstrated.

2. The three experiments conducted in this research effort were successful in demonstrating the technical feasibility of pyrolyzing and melting a simulated municipal solid waste material. The first two experiments demonstrated the viability of *ex situ* processing of MSW in a furnace environment. The third experiment demonstrated the feasibility of *in situ* processing of MSW in a landfill configuration; i.e., operating plasma torches in a grid of boreholes for the *in situ* remediation of a sanitary landfill.
3. Since most of the organic material in MSW becomes gasified, significant reductions in weight and volume were observed. In the *ex situ* tests (Experiments No. 1 and No. 2) weight losses of over 80 percent were noted. Because of the presence of a significant amount of inorganic soil in the *in situ* landfill remediation experiment a lower weight loss of 59 percent was noted. Similarly, all experiments showed significant volume reductions with the two *ex situ* experiments having greater volume reductions (about 96 percent) than the *in situ* experiment (89 percent).
4. The results of the TCLP toxicity leaching tests indicated that the rock-like vitrified slag met EPA leaching criteria by a wide margin, 10 to 100 times less in most cases. This very high resistance to leaching has resulted in a residue material that is almost inert in nature, and which could have commercial value as a gravel or aggregate.
5. The offgas emissions in both the *ex situ* and *in situ* experiments were very similar. Acid gases which constituted only a small portion of the offgas stream, can be readily treated with a relatively unsophisticated gas treatment system. Most of the offgas was composed of hydrogen gas and carbon monoxide gas, which could be sold commercially as useful fuel gases.
6. Analysis of the x-ray diffraction and Scanning Electron Microscope (SEM) data indicated similar results in all experiments. The vitrified residue was amorphous and monolithic in nature. Elemental composition was also similar, although the *in situ* sample exhibited the presence of much larger

amounts of silicon. This was due to the large amount of soil mixed in with the simulated MSW material.

7. Sale of the byproducts from a MSW plasma processing system could partially or fully offset the process costs of the technology. The *ex situ* (furnace) application of plasma arc technology for MSW processing in a furnace would eliminate the requirements for a landfill. The *in situ* applicaiton of plasma technology to MSW would eliminate landfill itself.

9.0 RECOMMENDATIONS FOR FUTURE RESEARCH

Recommendations for future research are as follows:

1. The state-of-the-art of plasma arc technology for *ex situ* MSW processing applications has reached the point where a small waste processing prototype system (e.g., one ton per eight hour day) should be designed and built. This system could serve as the basis for a long term study of the MSW process and its associated economics. Along with this effort, basic studies should be conducted into the basic phenomenology of the *ex situ* plasma pyrolysis and vitrification process. This would culminate in the development of models to better understand the processes and to be in a position to scale up the process to industrial processing levels.
2. The promising capability of plasma arc technology for the *in situ* remediation of MSW landfills should be developed, tested and evaluated as soon as practical. The successful implementation of this technology could result in fundamental improvements in environmental cleanup technologies and in future MSW disposal practices. Central to this requirement would be the design and procurement of a 500 kW mobile plasma heating system that could conduct landfill remediation studies and pursue other waste treatment opportunities throughout the state Basic studies of the fundamental physics involved in the *in situ* process also need to be conducted. Virtually no research or modeling has been conducted in this area. It is anticipated that significant technical and economic efficiencies would result from these efforts.

3. This research program should be expanded beyond the range of MSW, to include the plasma processing of a wide variety of hazardous/toxic and pathologic/infectious wastes of interest to the State of Georgia.

FIGURES

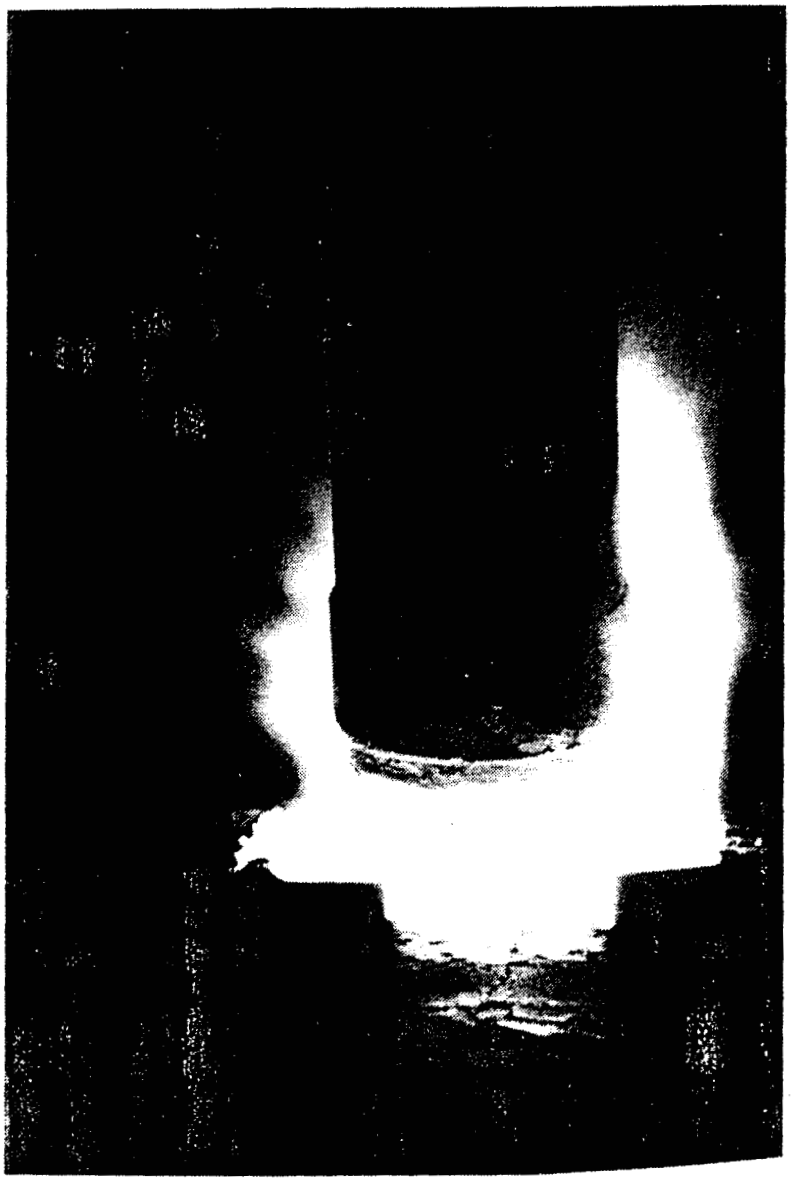
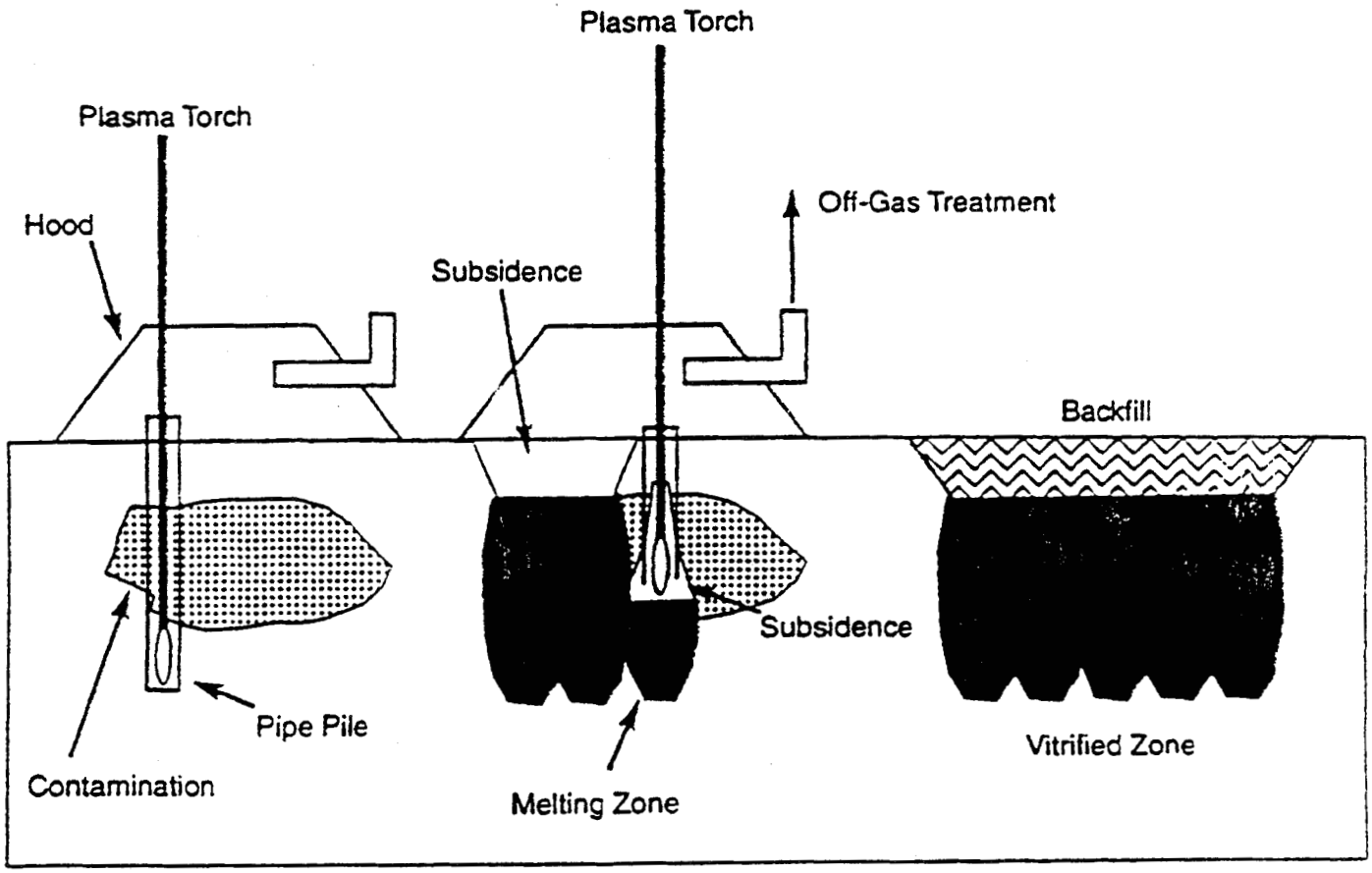


Figure 2.1 A 100 kW Plasma Torch in Operation



Schematic illustration of in situ melting of contaminated materials using a plasma arc torch. The torch is raised during melting to create cylindrical volumes. New material falls into the melt from the upper subsidence zone and is incorporated into the melt. After each melt, the torch is moved to the next pipe pile and melting is repeated. Offgas are processed with standard technology. The final subsidence zone is backfilled.

Figure 2.2 *In Situ* Plasma Vitrification (ISPV)

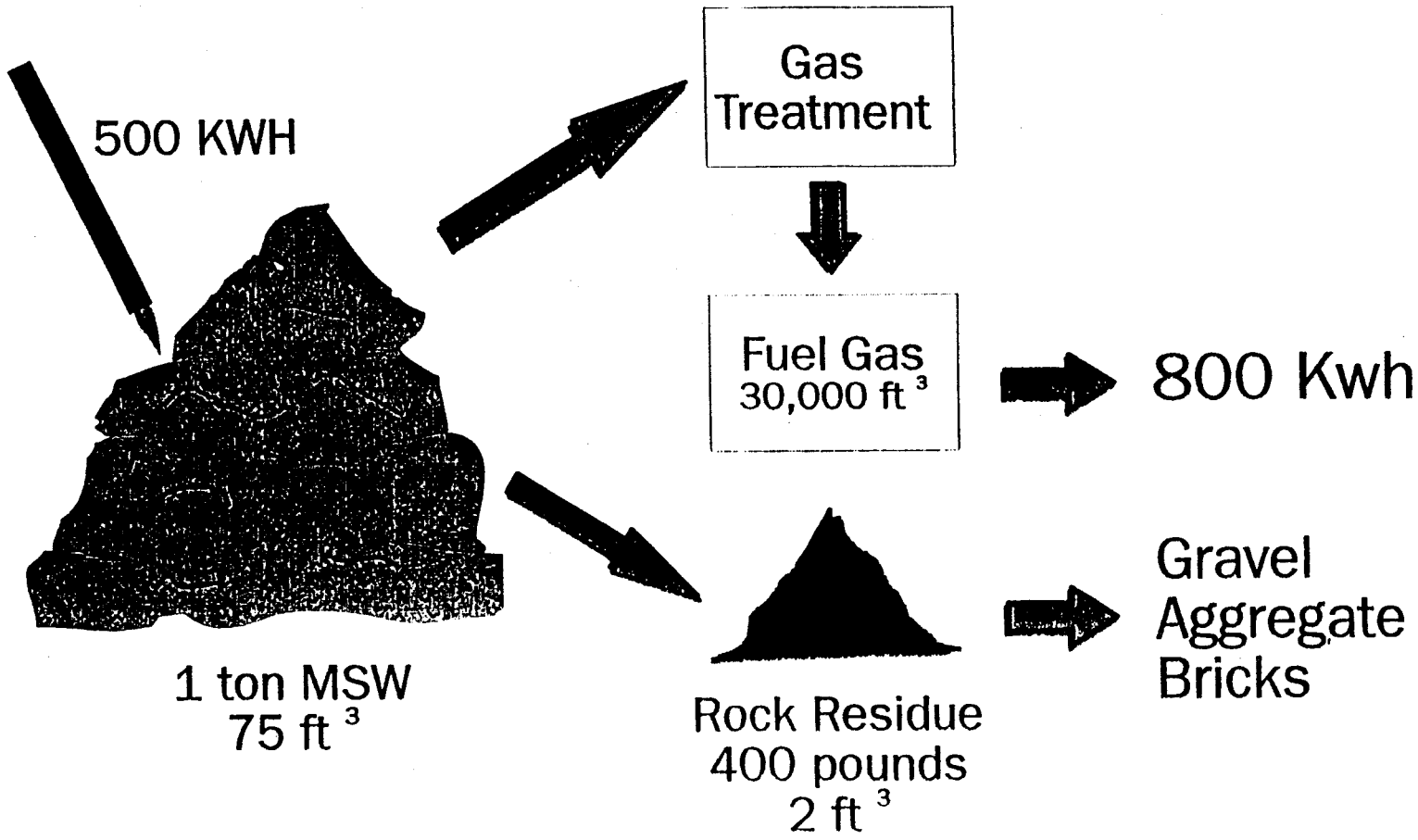


Figure 3.1 Plasma Municipal Solid Waste Processing Cycle

Figure 3.2 Typical MSW Vitrified Residue Material

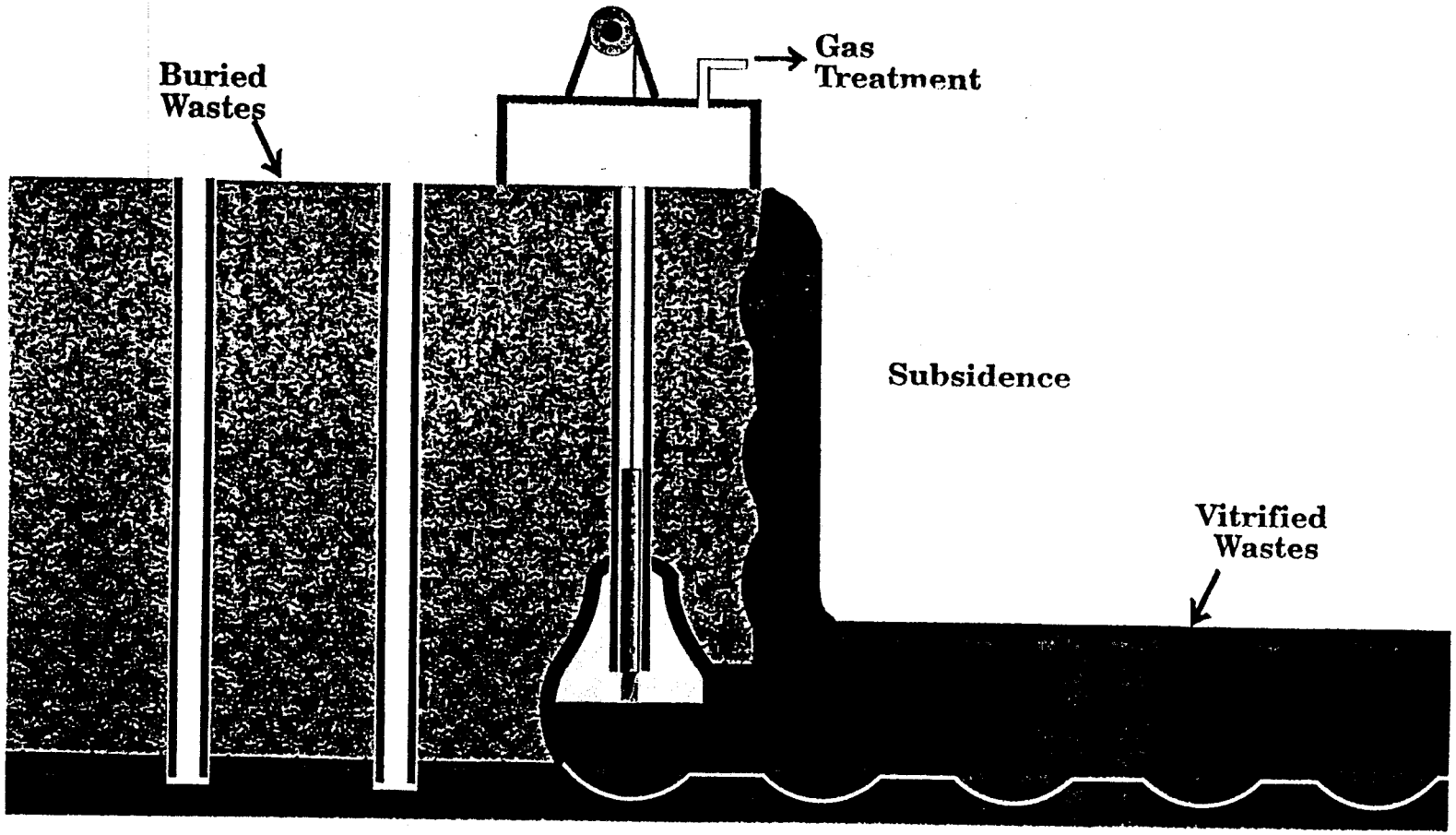


Figure 3.3 *In Situ* Plasma Remediation of Landfills

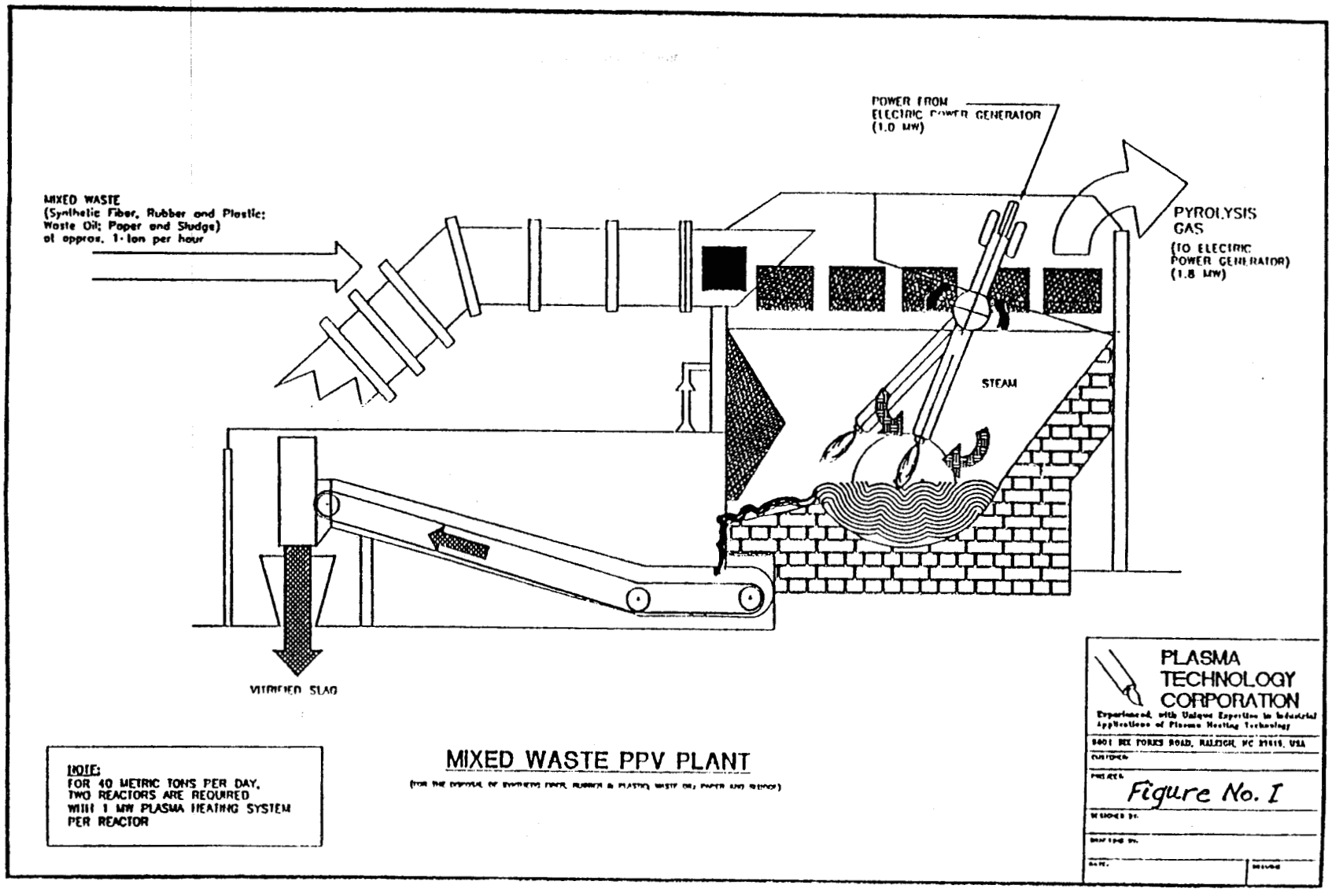


Figure 3.4 Schematic Diagram of the PPV Process (Camacho, 1996)

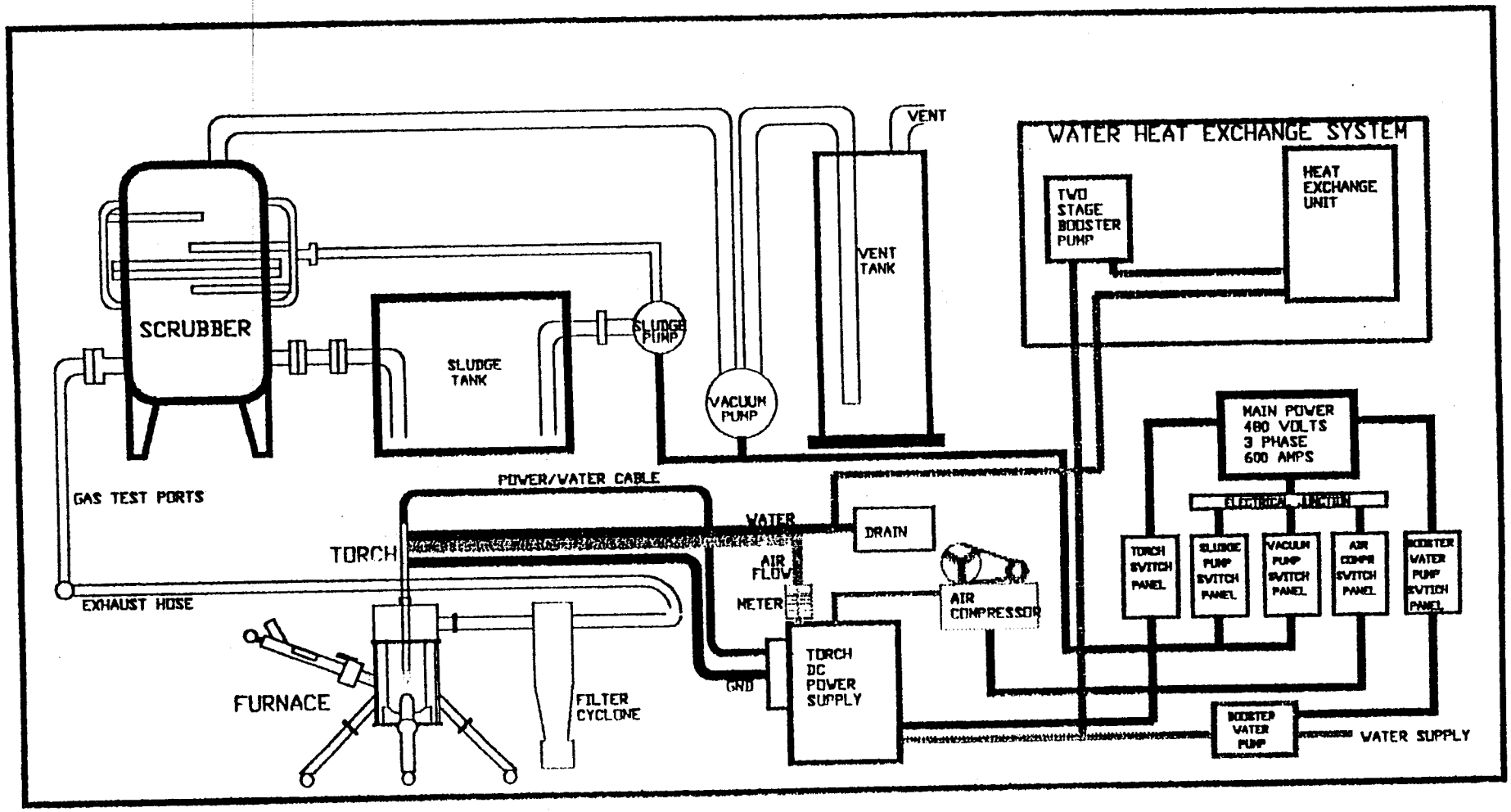


Figure 4.1 The Georgia Tech Plasma Applications Research Facility (PARF)

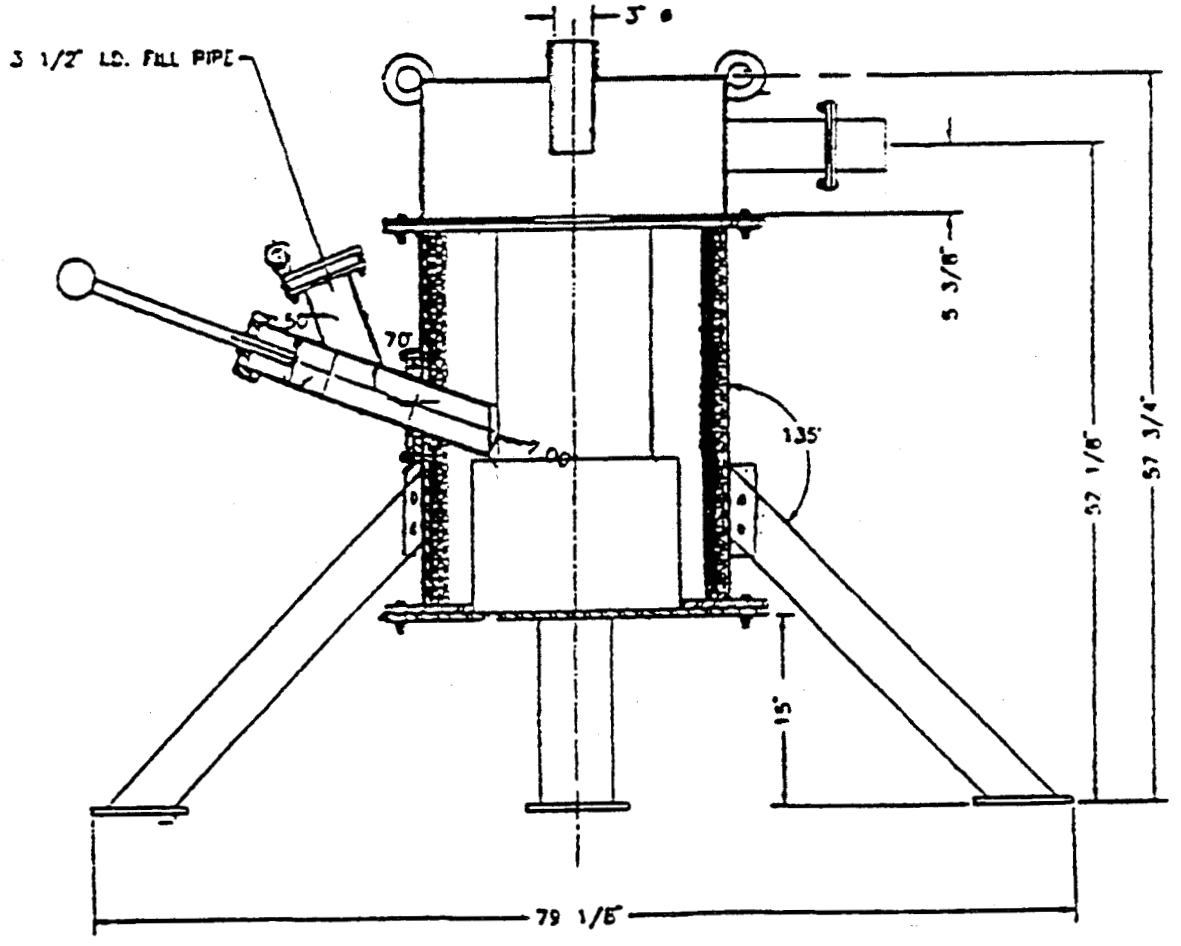


Figure 4.2 The 100 kW Graphite Crucible Furnace

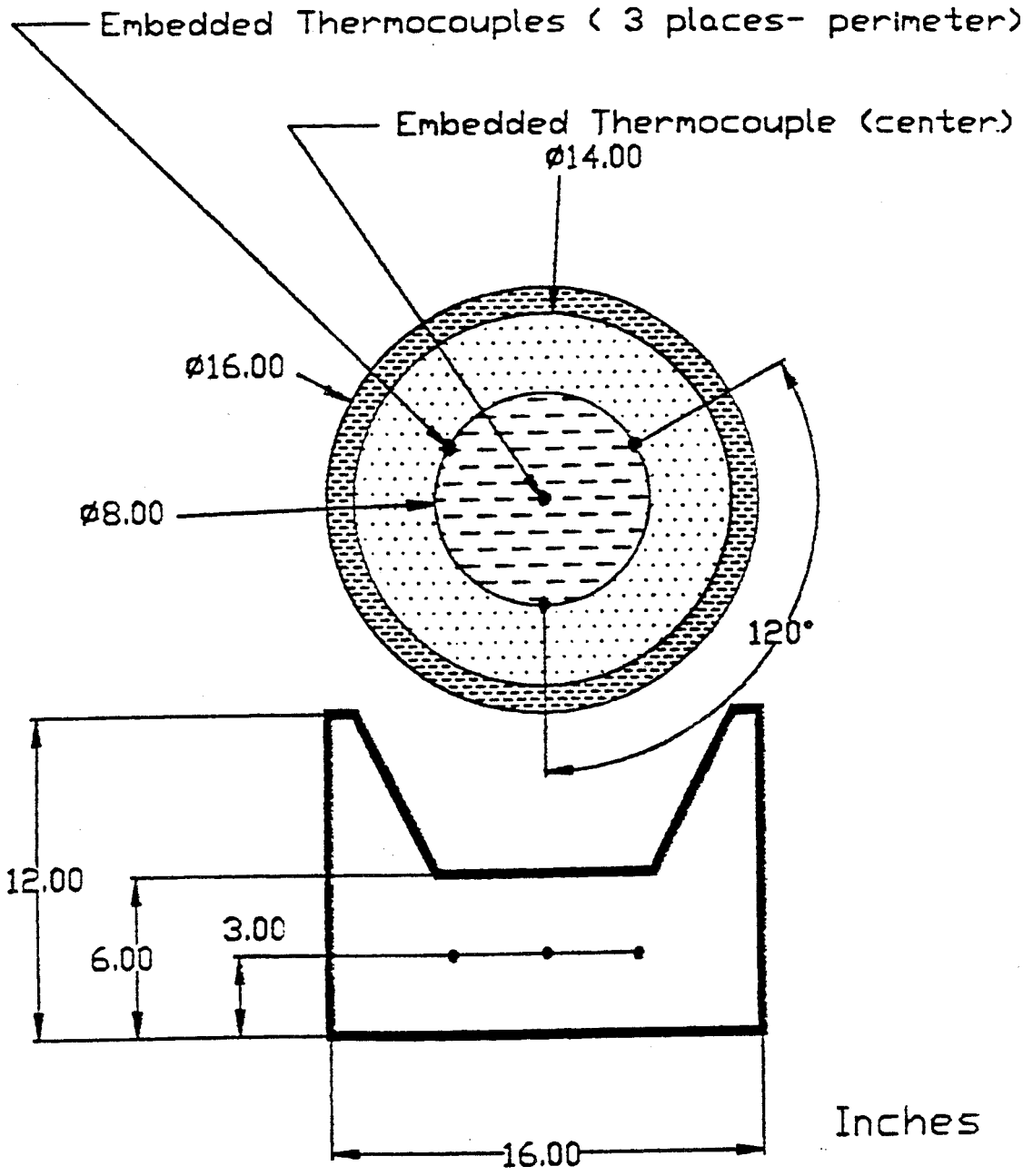


Figure 4.3 Furnace Crucible with Thermocouple Locations

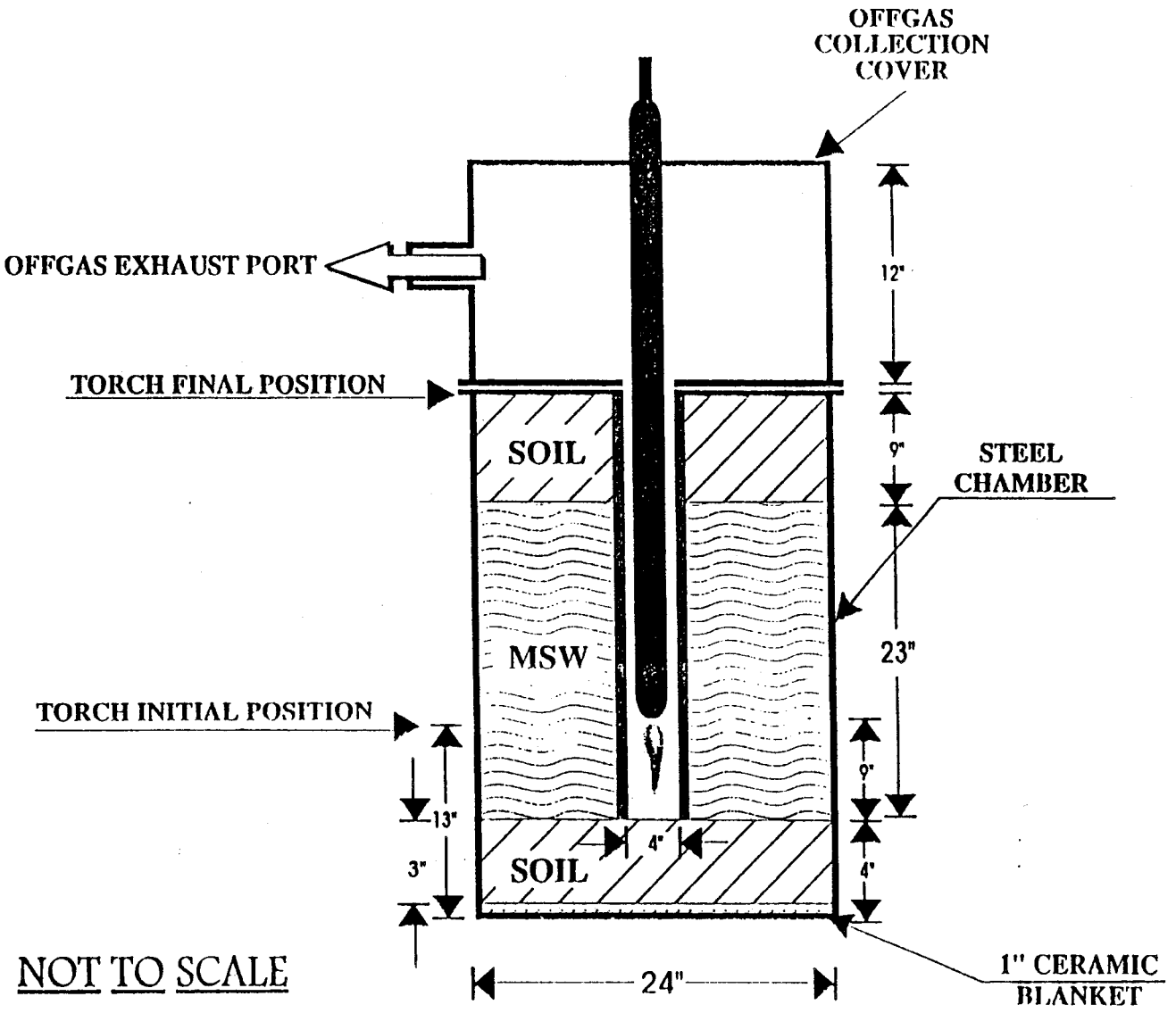


Figure 4.4 *In Situ* MSW Test Geometry for Experiment No. 3

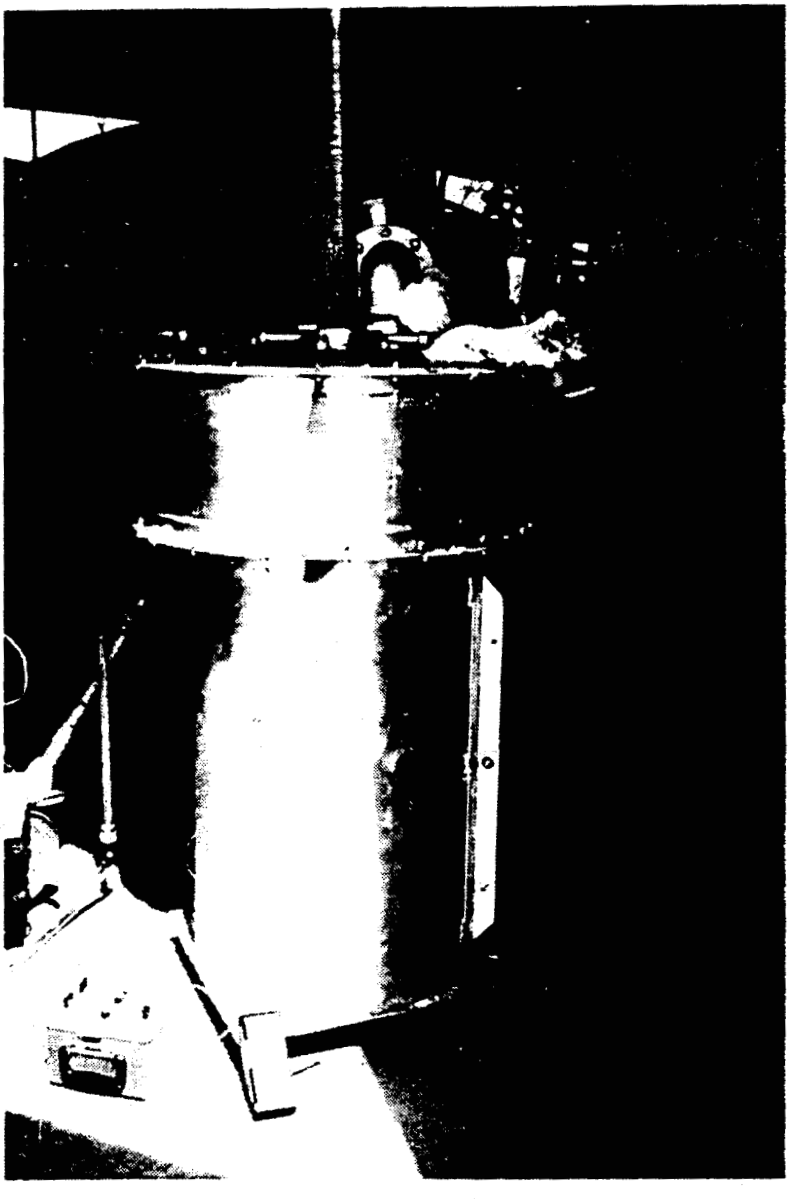


Figure 4.5 Photograph of Test Chamber for Experiment No. 3

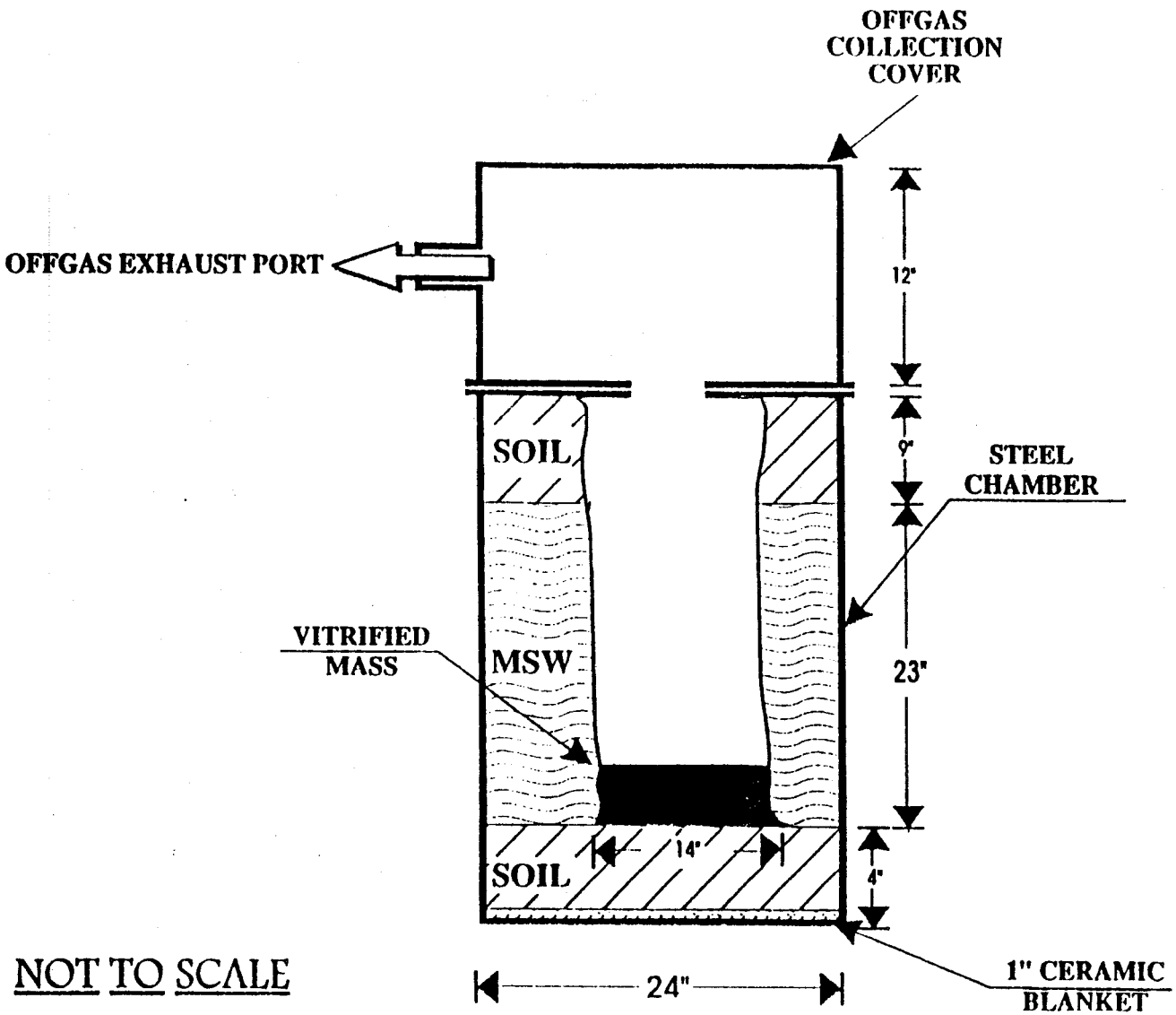


Figure 4.6 Post Test Cross Section Diagram of Experiment No. 3 before Slumping.

Figure 4.7 Photograph of the Post Test Chamber of Experiment No. 3 Showing Slumped Material

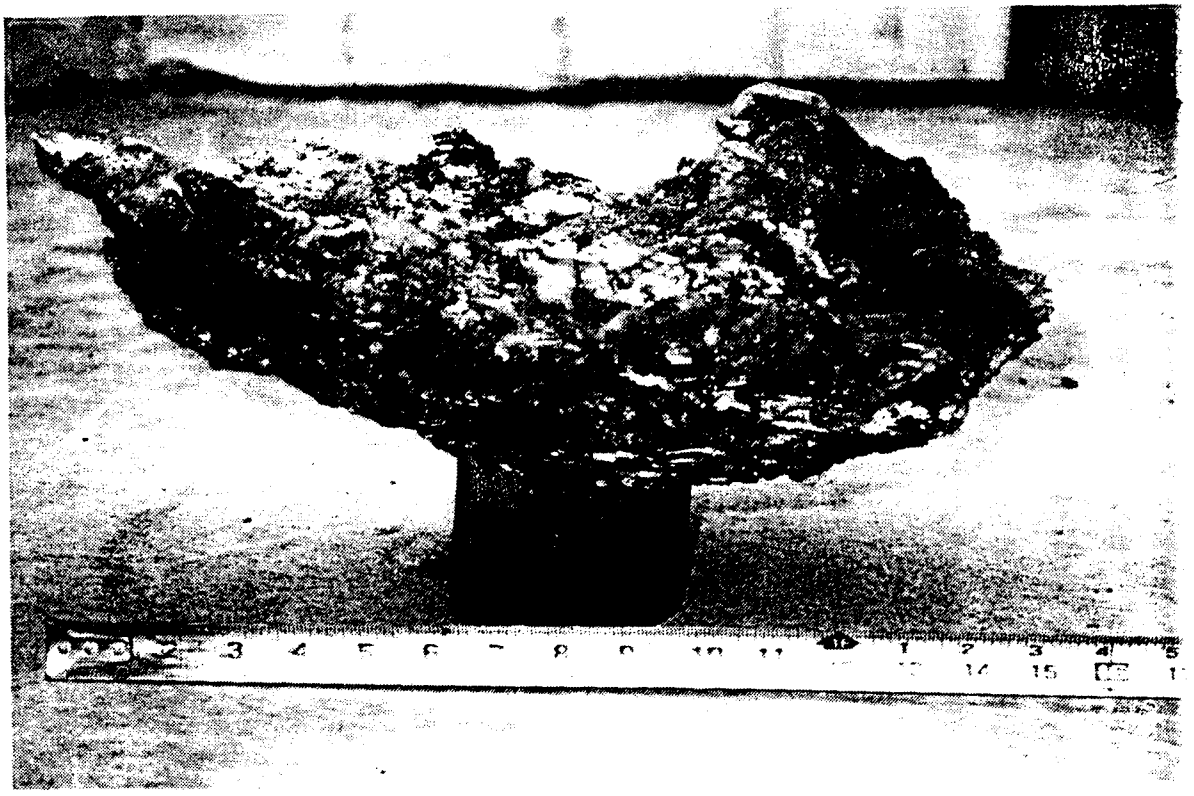


Figure 4.8 Photograph of Post Test Vitrified Melt at the Bottom of the Test Chamber (Experiment No. 3)

10.0 REFERENCES

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APPENDIX A

Experiment No. 1 Supplemental Data

1. Experiment No. 1 Operating Sequence: See Attached Data Sheet
2. Pretest Weight of MSW: 36.1 pounds (16,393.6 grams: See Attached Data Sheet)
3. Post Test Weight of Vitrified Residue
   a. Crucible: 10.5 pounds of vitrified material
   b. Furnace top (inside lid): 1.4 pounds of flyash
   c. Less weight of molten metal bath: 6 pounds
   d. Net weight of residue: 5.9 pounds
4. Pretest Volume of MSW
   a Volume of canisters (3 inch diameter x 8.5 inches long)
      1. Each canister: $V = pR^2H = p\ (1.5)^2 \times 8.5 = 60.05\ in^3$
      2. 27 canisters: $V = 27 \times 60.05 = 1{,}621.35\ in^3$
5. Post Test Volume of MSW
   a. Assume vitrified material and flyash have a density of 150 pounds per cubic foot. This is equal to 0.087 pounds per cubic inch or 11.5 cubic inches per pound.
   b. Post Test Volume = $11.5 \times 5.9 = 67.85\ in^3$
6. Post Test Volume Reduction = 1 — 67.9 / 1,621.4 = 0.958 = 95.8%
7. Specific Energy Requirement (SER)
   a. Canister feeding time: 92 minutes = 1.53 hours
   b. Plasma torch power level: 100 kW
   c. Weight of MSW processed: 36.1 pounds
   d. SER = 100 x 1.53 / 36.1 = 4.24 kWh/lb

Ga Waste Ex Situ #1
Date: June 28, 1996
Preload/metal = 6 pounds
Vacuum = 2.5" H_2O

Time Minutes	TC(center) °C	Pyrometer °C	Comments	Sample #	Weight Grams
0	23		Torch on @ 6"		
8	291	1468			
14			Torch @ 9"		
20		1374	Torch @ 8"		
28	584		Torch @ 7"		
30	628				
32	648	1321			
34			Torch @ 6"		
39	736				
41	750		pH = 7.4		
45	800				
46				1	333.8
48			Torch @ 9"		
50	765			2	449.4
53	791			3	638.3
58	760			4	711.5
59	762			5	808.0
62	776			6	739.6
65	816			7	328.8
67		1340	pH = 7.4		
68	875			8	387.0
72	010			9	444.2
75	925			10	766.1
78	935			11	798.7
81	940			12	1,041.2
84	938			13	799.7
87	950			14	988.5
90	948			15	874.0
94	975			18	929.0
97	976	1336		17	497.6
100	1036			18	436.0
103	1038			19	499.1
106	1100			20	432.4
109	1138			21	554.4
112	1175			22	446.6
115	1136			23	388.5
118	1121			24	494.4

Time Minutes	TC(center) °C	Pyrometer °C	Comments	Sample #	Weight Grams
121	1200		pH = 7.7	25	568.6
124	1290			26	557.1
127	1302			27	834.00
137	1312				
138	1200	1070	Torch Off		
				Total	16,393.6

APPENDIX B

Experiment No. 2 Supplemental Data

1. Experiment No. 2 Operating Sequence: See Attached Data Sheet
2. Pretest Weight of MSW: 28.48 pounds (12,930 grams: See Attached Data Sheet)
3. Post Test Weight of Vitrified Residue
   a. Crucible: 2 pounds of vitrified material
   b. Furnace walls: 8.5 pounds of vitrified material
   c. Furnace top: (inside lid): 1 pound of flyash
   c. Less weight of molten metal bath: 6 pounds
   d. Net weight of residue: 5.5 pounds
4. Pretest Volume of MSW
   a. Volume of each canister = 60.05 in^3
   b. Volume of 30 canisters = 1.801.5 in^3
5. Post Test Volume of MSW
   a. Assume density of residue = 150 lb/ft^3
      = $\underline{0.087\ lb/in^3}$
      = 11.5 in^3/lb
   b. Post Test Volume = 11.5 in^3/lb x 5.5 lb = 63.25 in^3
6. Post Test Volume Reduction = 1 — 63.25 / 1,801.5 = 0.965 = 96.5%
7. Specific Energy Requirement (SER)
   a. Canister feeding time: 111 minutes = 1.85 hours
   b. Plasma torch power level: 100 kW
   c. Weight of MSW processed: 28.5 pounds
   d. SER = 1.85 hrs x 100 kW / 28.5 pounds = 6.49 kWh/lb
8. TCLP Analysis: See Attached Data Sheet
9. Sensidyne Offgas Analysis: See Attached Data Sheet
10. X-Ray Diffraction and SEM Data: See Appendix D

	Temperature C								Torch Parameters			Comments	#	Wt.(g)
Time	TC1	TC2	TC3	TC4	TC5	TC6	TC7	Exh	KW	Volts	Amps	Torch @6"		
0												Start Torch		
2								120	70.2	540	130			
5	119	269	231	226	65	50	16	150	88.4	520	170			
8	238	385	336	392	84	82	25	180	93.6	520	180			
10	330	460	437	517	131	121	41	254	98.8	520	190	pH=9.7		
14	397	533	516	600	188	165	64	238	100	500	200	pH=8.6		
30	634	778	814	1108	418	360	310	264	99	495	200			
37	890	847	872	1184	490	432	430	306	100	500	200			
42	914	890	897	1217	537	475	498	331	100	500	200			
45	948	925	935	1275	574	513	541	328	98	490	200			
53	969	958	992	1289	668	598	636	348	100	500	200	Torch @9"	1	456
56	983	933	1011	1276	740	663	663	355	100	500	200	Torch @12"	2	392
65									100	500	200		3	462
6[illegible]									95	475	200		4	436
6[illegible]									98.8	520	190		5	345
72	870	917	1020	1208	825	761	662	420	100	500	200		6	420
75									100	500	200		7	396
79									100	500	200		8	440
82	826	969	1100	1530	876	818	679	438	99	495	200		9	413
84									100	500	200		10	414
86									100	500	200		11	394
95									100	500	200		12	432
96									96	480	200		13	475
98	840	1106	1240	1380	950	902	785	460	100	500	200		14	381
113									100	500	200		15	459
114	756	1188	1321	off	1009	973	864	470	100	500	200		16	378
121									100	500	200		17	449
122									100	500	200		18	404
128									100	500	200		19	408
131									100	500	200		20	509
134	682	1246	1322	off	1050	1012	910	590	100	500	200		21	511
136									100	500	200		22	450
140	672	1265	1344	off	1060	1020	930	588	100	500	200		23	427
142									100	500	200		24	459
146									100	500	200		25	440
148									100	500	200		26	492
151									100	500	200		27	431
152									100	500	200		28	448
156									100	500	200		29	440
161									100	500	200		30	369
164	616	1349	1350	off	1103	1058	1021	557				Torch OFF	g	12930

Client #: ATL-95-100906
Address: GA Tech

042 O'Keefe
Atlanta, GA 30332
Bob Newsom

Date: 12/11/96
Log #: L13296-2

Sample Description:

TCLP Analysis
Ga Waste

Label: Ex Situ
Date Sampled: 11/15/96
Time Sampled: 00:00
Date Received: 12/03/96
Collected By: Client

Parameter	Results	Units	Method	Reportable Detect Limit	Extr. Date	Analysis Date	Analyst
[illegible]							
Arsenic	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Barium	0.47	mg/l	1311/6010	0.10	12/04	12/05	PVP
Cadmium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Chromium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Lead	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Mercury	BDL	mg/l	1311/7470	0.010	12/04	12/10	PVP
Selenium	BDL	mg/l	1311/6010	0.20	12/04	12/05	PVP
Silver	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP

Selected Air Contaminant Concentrations Collected from Plasma Torch Exhaust Stream during Ex-situ Test on Municipal Waste (November 14, 1996)

Air Contaminant	Concentration (ppm) (time sample collected)						
Carbon Dioxide (CO_2)	*3100 (10:50)*	> 100,000 (12:04)	110,000 (12:23)	100,000 • (12:28)	90,000 (12:57)	100,00 (1:10)	
Nitrogen Oxides (NOx)	*< 50 (10:58)*	350 • (11:52)	< 50 (12:10)	< 50 (12:34)	< 50 • (12:47)	< 50 • (12:50)	< 50 • (12:50)
Carbon Monoxide (CO)	*< 12.5 (10:55)*	80,000 (12:16)	100,000 (12:37)	> 100,000 (1:06)	100,000 (1:08)		
Hydrogen (H_2)	*< 5000 (11:01)*	> 20,000 • (11:55)	> 20,000 (12:25)	> 20,000 (1:01)	> 20,000 (1:18)		
Hydrogen Sulfide (H_2S)	*< 10 (11:03)*	100 • (11:58)	< 10 (12:18)	110 • (12:41)	< 10 (12:42)	115 • (12:43)	< 10 (12:45)
Hydrogen Chloride (HCl)	*< 10 (11:06)*	< 20 • (11:54)	< 20 •• (12:09)	< 10 •• (1:04)			
Higher Class Hydrocarbons[1]	*550 (11:14)*	> 3000 • (11:40)	> 3000 (12:20)	> 3000 (12:38)	> 3000 (1:00)	> 3000 (1:17)	
Lower Class Hydrocarbons[2]	*1000 (11:10)*	1500 • (11:50)	3000 •• (12:09)	2000 • (12:54)	1000 (1:14)		

The first column (italics) indicates air contaminant concentrations prior to municipal waste sample injections.

(1) - Higher class hydrocarbons include n-hexane, n-heptane, n-octane, n-nonane, n-decane, n-pentane. Carbon monoxide concentrations greater than 1000 ppm, acetylene, and ethylene give a plus error on the tube reading

(2) - Lower class hydrocarbons include acetylene, butane, ethylene, heptane, hexane, isobutane, isopentane, and propane. Higher boiling point hydrocarbons will give a plus error on the tube reading.

• - indicates that the sample was collected immediately after a municipal waste tube was injected into the plasma torch chamber.

•• - sample was collected after 2 municipal waste tubes were injected into the plasma torch chamber.

Note: Air samples were collected using a Sensidyne, Model 800, piston pump (100 milliliter capacity) and Sensidyne short term detector tubes. Detector tube readings have an error of ± 25%.

APPENDIX C

Experiment No. 3 Supplemental Data

1. Experiment No. 3 Operating Sequence: See Attached Data Sheet
2. Pretest Weight of MSW: 211.33 pounds (See Table 4.2)
3. Pretest Total Volume of MSW: $V = \pi \times (1)^2 \times 1.92 = 6.03\ ft^3$
4. Pretest Density of MSW: 211.33 pounds / 6.03 = 35 lb/ft^3
5. Petest Weight of MSW Subjected to Pyrolysis and Vitrification (See Figures 4.4 and 4.6)
   a. Volume of empty MSW shaft (1.17 ft diameter x 1.92 ft high)

      volume = $\pi \times (0.58)^2 \times 1.92 = 2.05\ ft^3$

   b. Pretest weight of pyrolyzed MSW = 35 x 2.05 = 71.75 lb.
6. Pretest Weight of Topsoil Subjected to Vitrification
   a. Assumptions
      1. One-half the soil in the 1.17 ft. diameter shaft (Figure 4.6) is vitrified
      2. Soil density is 80 pounds per cubic foot
   b. Pretest volume of topsoil subjected to vitrification
      1. Volume of empty topsoil shaft = $\pi\ (0.58)^2 \times 0.75 = 0.80\ ft^3$
      2. One-half volume = $0.40\ ft^3$
      3. Pretest weight of vitrified topsoil = 80 x 0.40 = 32 pounds
7. Total Pretest Weight of MSW and Topsoil Subjected to Pyrolysis and Vitrification

   71.75 + 32 = 103.75 pounds
8. Post Test Weight of Residue
   a. Melt at bottom of container (Figure 4.8): 33.1 pounds
   b. Flyash inside the top lid of furnace: 9 pounds
   c. Total weight of residue: 42.1 pounds
9. Post Test Weight Reduction: 1 — 42.1 / 103.75 = 0.59 = 59%
10. Pretest Total Volume of Material Subjected to Pyrolysis and Vitrification

    $V = 2.05 + 0.40 = 2.45\ ft^3$

11. Post Test Volume of Residue Material
    a. Assume residue density = 150 lb/ft^3
    b. Volume = 42.1 lb / 150 lb/ft^3 = 0.28 ft^3
12. Post Test Volume Reduction = 1 — 0.28 / 2.45 = 0.886 = 88.6%
13. Specific Energy Requirement (SER)
    a. Duration of experiment: 90 minutes = 1.50 hours
    b. Power level: 96 kW
    c. Weight of material processed: 103.75 pounds
    d. SER = 1.5 h x 96 kW / 103.75 lb = 1.39 kWh/lb
14. TCLP Analysis: See Attacned Data Sheet
15. Offgas Analysis: See Attached Data Sheet
16. X-ray Diffraction and SEM Data: See Appendix D

DATA SHEET

Experiment No. 3 Operating Sequence
Date: November 15, 1996
Vacuum = 6.0 " H^2O

Time	Torch Parameters		
(Minutes)	kW	Volts	Amps
0			
2	76.8	480	160
3	94	470	200
30	96	480	200

Time Minutes	Torch Position
0	Start Torch 9" from bottom of hole
10	Torch up 3" (12" from bottom of hole)
20	Torch up 3" (15" from bottom of hole)
30	Torch up 3" (18" from bottom of hole)
45	Torch up 3" (21" from bottom of hole)
55	Torch up 3" (24" from bottom of hole)
60	Torch up 3" (27" from bottom of hole)
70	Torch up 3" (30" from bottom of hole)
80	Torch up 3" (33" from bottom of hole)
90	Torch Off

Our Quality Control Is Your Quality Assurance

Client #: ATL-95-100906
Address: GA Tech

042 O'Keefe
Atlanta, GA 30332
Bob Newsom

Page: Page 1 of 2
Date: 12/11/96
Log #: L13296-1

Sample Description:

TCLP Analysis
Ga Waste

Label: In Situ
Date Sampled: 11/15/96
Time Sampled: 00:00
Date Received: 12/03/96
Collected By: Client

Parameter	Results	Units	Method	Reportable Detect Limit	Extr. Date	Analysis Date	Analyst
[redacted]							
Arsenic	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Barium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Cadmium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Chromium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Lead	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Mercury	BDL	mg/l	1311/7470	0.010	12/04	12/10	PVP
Selenium	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP
Silver	BDL	mg/l	1311/6010	0.10	12/04	12/05	PVP

Selected Air Contaminant Concentrations Collected from Plasma Torch Exhaust Stream during In-situ Test on Municipal Waste (November 15, 1996)					
Air Contaminant	**Concentration (ppm) (time sample collected)**				
Carbon Dioxide (CO_2)	90,000 (10:59)	70,000 (11:19)	90,000 (11:37)		
Nitrogen Oxides (NOx)	300 (11:13)	100 (11:24)	< 50 (11:30)	<50 (11:32)	150 (11:44)
Carbon Monoxide (CO)	> 100,000 (11:06)	> 100,000 (11:17)	> 100,000 (11:18)	> 100,000 (11:38)	
Hydrogen (H_2)	> 20,000 (11:15)	> 20,000 (11:39)			
Hydrogen Sulfide (H_2S)	< 10 (11:14)	80 (11:26)	80 (11:31)	65 (11:40)	
Hydrogen Chloride (HCl)	100 (11:16)	225 (11:26)	210 (11:32)	250 (11:42)	
Higher Class Hydrocarbons[1]	> 3000 (11:12)	> 3000 (11:19)			
Lower Class Hydrocarbons[2]	700 (11:11)	1500 (11:23)	3000 (11:36)	2000 (11:46)	

[1] - Higher class hydrocarbons include n-hexane, n-heptane, n-octane, n-nonane, n-decane, n-pentane. Carbon monoxide concentrations greater than 1000 ppm, acetylene, and ethylene give a plus error on the tube reading

[2] - Lower class hydrocarbons include acetylene, butane, ethylene, heptane, hexane, isobutane, isopentane, and propane. Higher boiling point hydrocarbons will give a plus error on the tube reading.

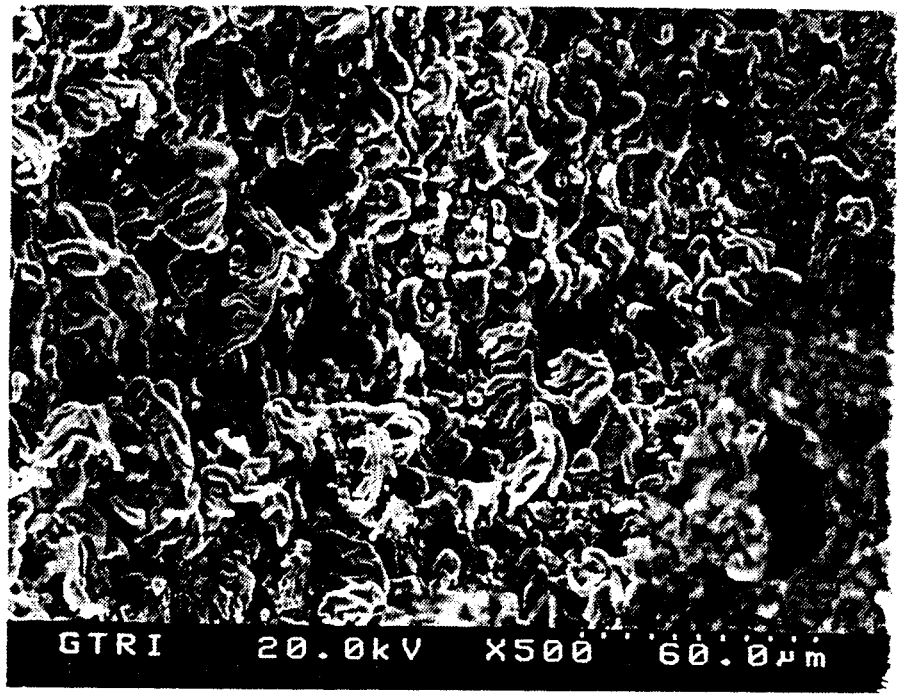
Note: Air samples were collected using a Sensidyne, Model 800, piston pump (100 milliliter capacity) and Sensidyne short term detector tubes. Detector tube readings have an error of ± 25%.

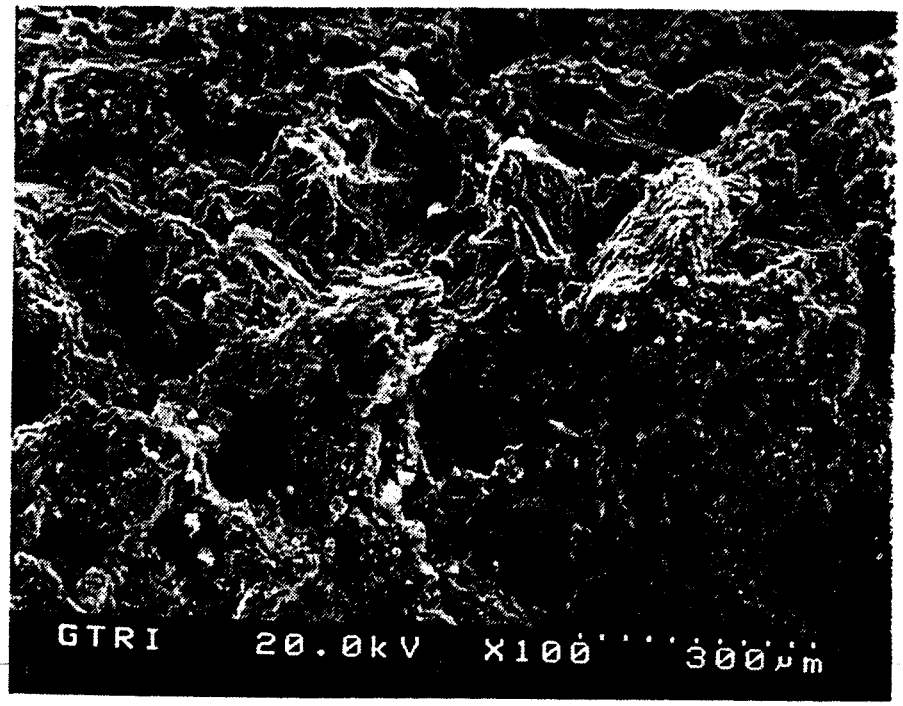
APPENDIX D

X-Ray Diffraction, Elemental Analysis and Scanning Electron Microscope (SEM) Data

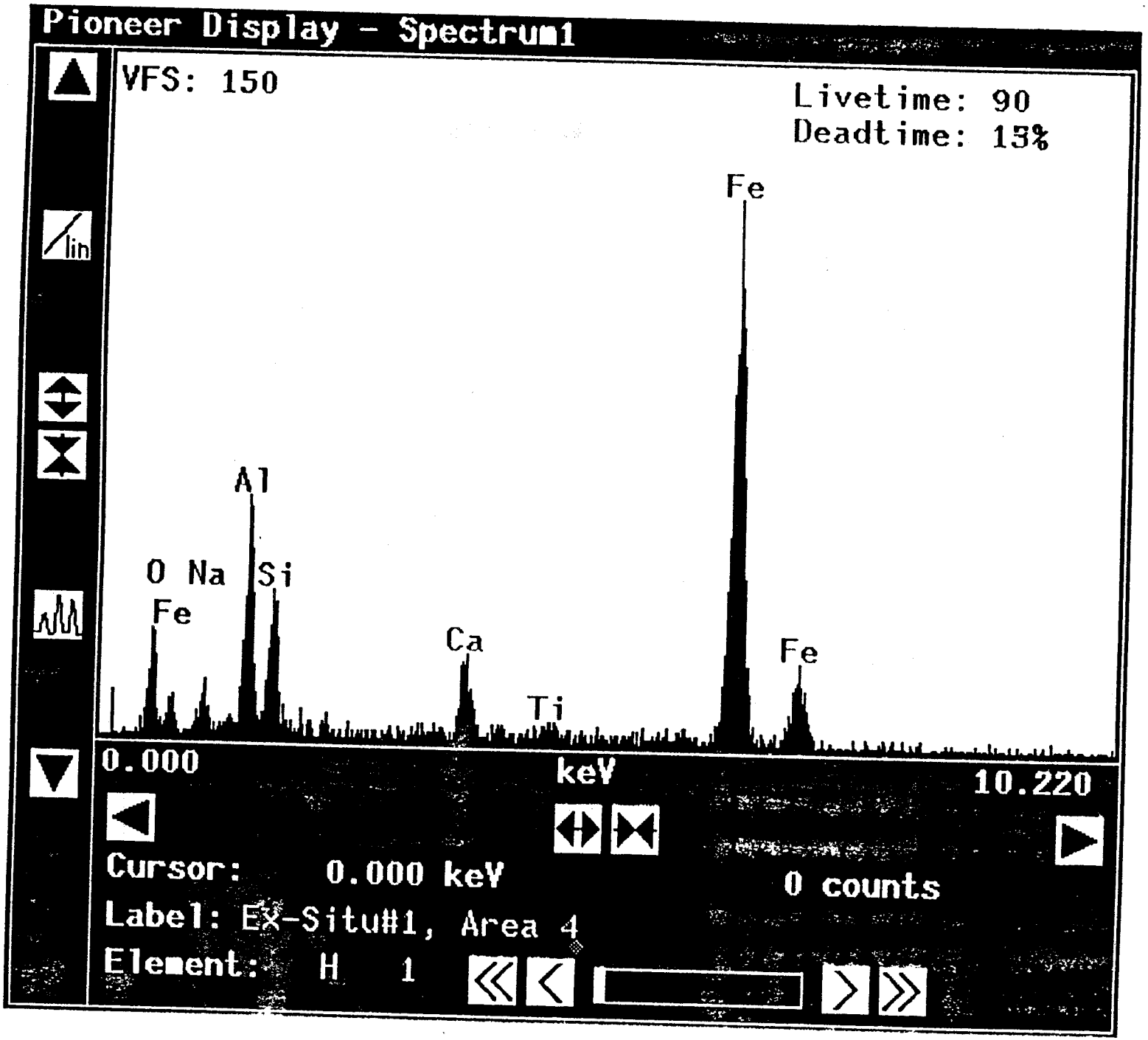
X-Ray Diffraction

Experiment No. 1	SiO_2 Quartz
	Fe_3O_4
	Fe_2O_3
	Ca_2SiO_4
	Amorphous Material
Experiment No. 2	SiO_2 Quartz
	Fe_3O_4
	Fe_2O_3
	Ca_2SiO_4
	Amorphous Material
Experiment No. 3	SiO_2 cristobalite
	SiO_2 avirtz
	Al_2O_3
	$CaSiO_3$
	$CaFe_4O_3$
	Fe_3O_4
	Amorphous Material





Typical Micrographs, Experiment No. 1


Pioneer Display - Spectrum1
VFS: 150
Livetime: 90
Deadtime: 15%
lin
Fe
Al
O Na Si
Fe
Ca
Ti
Fe
0.000
keV
10.220
Cursor: 0.000 keV
0 counts
Label: EX-Situ#1, Area 4
Element: H 1

Refit _C -K' _C -K* _F -K' _F -K* _Fe-L' _Fe-L* _Mg-K' _Mg-K* _P -K' _P -K* _Ti-L' _Ti-L* _Mn-K' _Mn-K*
Refit _C -K _Si-K' _Si-K* _Al-K' _F -K _Ca-K* _Fe-K* _Na-K' _Na-K* _Ti-K* _Ti-L

Mon Jan 6 14:19:43 1997

Ex-Situ#1, Area 4

Chi-sqd = 1.42 Livetime = 90.0 Sec.
Standardless Analysis

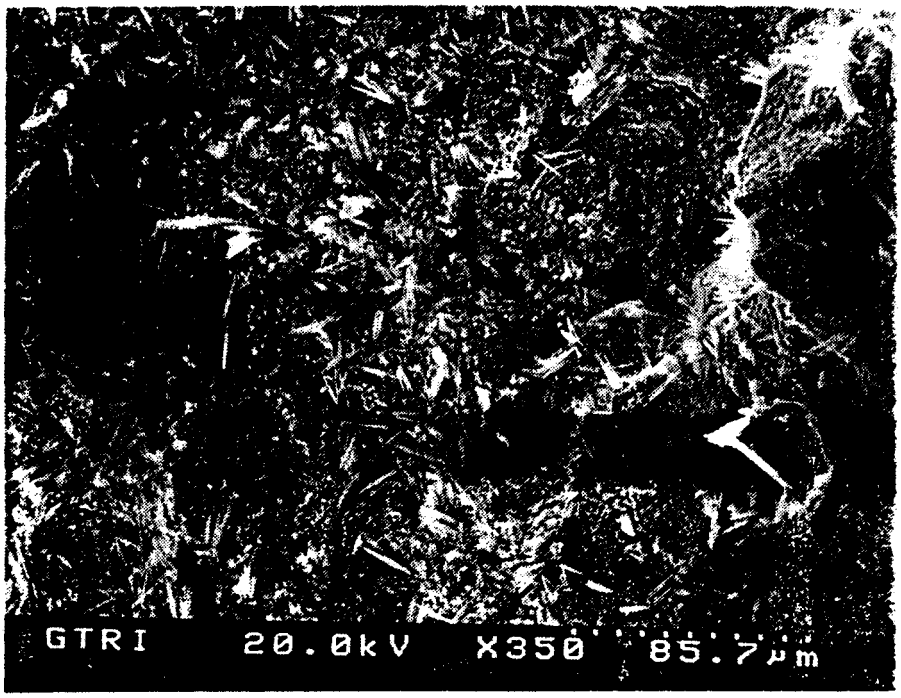
Element	Relative k-ratio	Error (1-Sigma)	Net Counts	Error (1-Sigma)
C -K	0.00000	+/- 0.00001	0	+/- 0
O -K	0.10316	+/- 0.01504	247	+/- 36
Si-K	0.04442	+/- 0.00282	425	+/- 27
Al-K	0.06136	+/- 0.00570	571	+/- 53
F -K	0.00000	+/- 0.00001	0	+/- 0
Ca-K	0.05174	+/- 0.00394	302	+/- 23
Fe-K	0.69881	+/- 0.01964	2170	+/- 61
Fe-L	---	---	129	+/- 26
Na-K	0.01592	+/- 0.00184	104	+/- 12
Mg-K	0.00220	+/- 0.00198	20	+/- 18
P -K	0.00329	+/- 0.00203	27	+/- 17
Ti-K	0.00833	+/- 0.00346	41	+/- 17
Ti-L	---	---	0	+/- 0
Mn-K	0.01077	+/- 0.00466	37	+/- 16

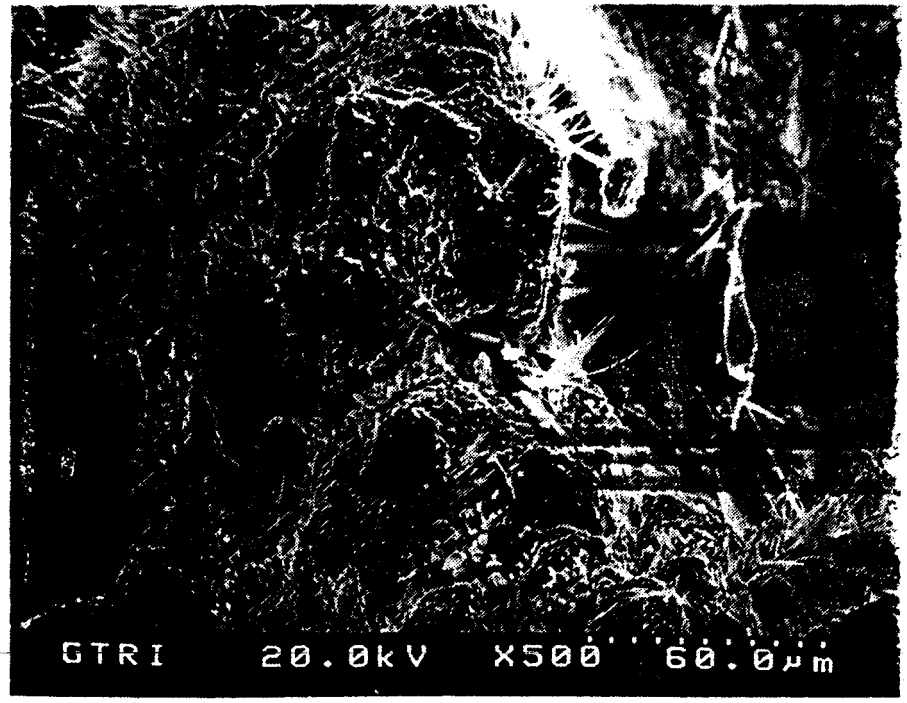
Adjustment Factors	K	L	M
Z-Balance:	0.0000	0.0000	0.0000
Shell:	1.0000	1.0000	1.0000

PROZA Correction Acc.Volt.= 20 kV Take-off Angle=43.20 deg Tilt = 20 deg
Number of Iterations = 5

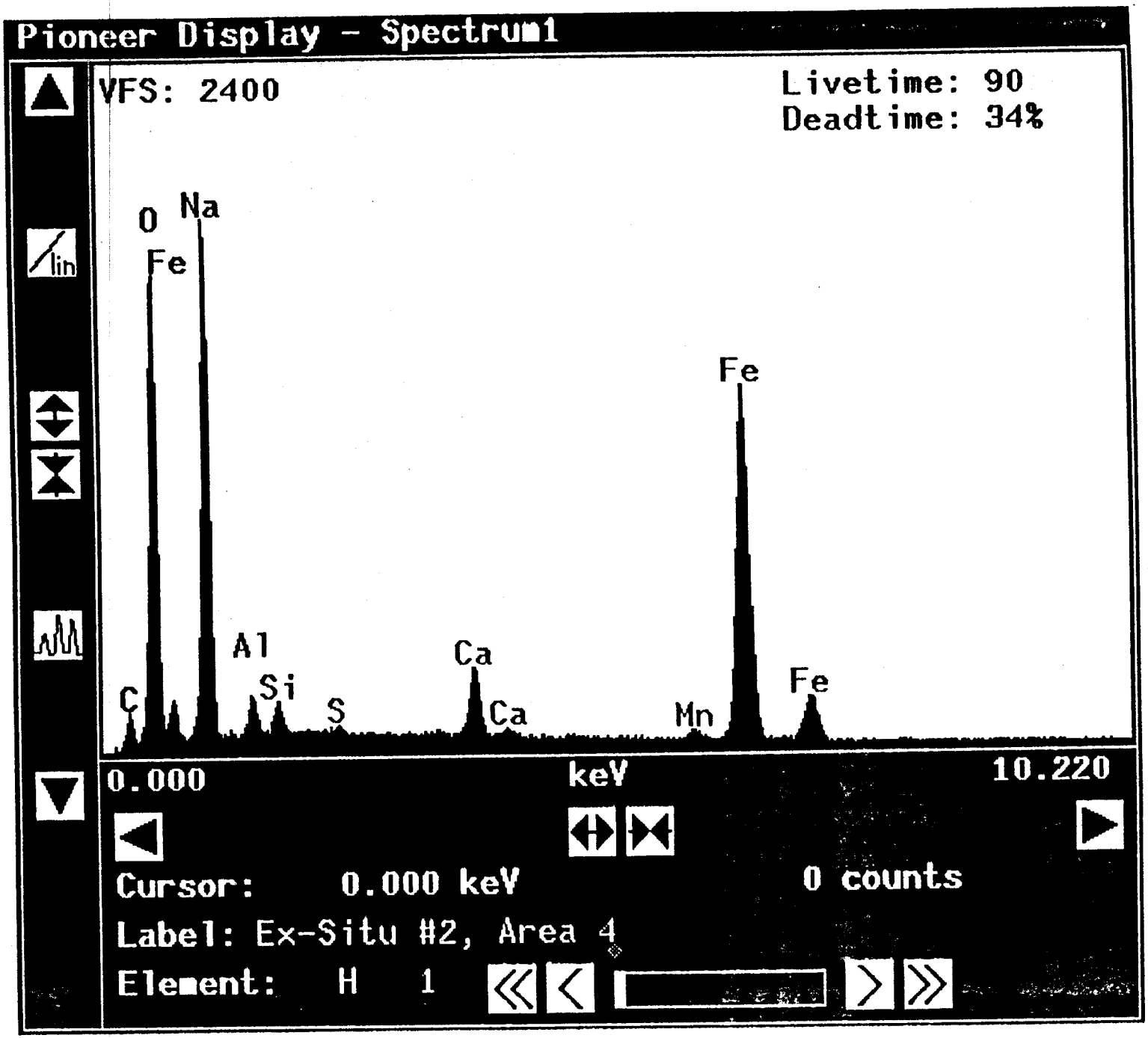
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Stoich-iometry
C -K	0.00000	4.667	0.00	0.00	+/- 0.00	0.001
O -K	0.07560	2.314	36.16	17.50	+/- 2.55	24.000
Si-K	0.03256	1.779	6.82	5.79	+/- 0.37	4.526
Al-K	0.04497	2.122	11.69	9.54	+/- 0.89	7.760
F -K	0.00000	2.320	0.00	0.00	+/- 0.00	0.000
Ca-K	0.03792	1.028	3.22	3.90	+/- 0.30	2.134
Fe-K	0.51213	1.096	33.23	56.13	+/- 1.58	22.056
Na-K	0.01167	4.093	6.87	4.77	+/- 0.55	4.558
Mg-K	0.00161	2.821	0.62	0.45	+/- 0.41	0.411
P -K	0.00241	1.596	0.41	0.38	+/- 0.24	0.273
Ti-K	0.00611	1.051	0.44	0.64	+/- 0.27	0.294
Mn-K	0.00789	1.121	0.53	0.88	+/- 0.38	0.353
Total			100.00	100.00		

Stoichiometry results are based upon 24 Oxygen atoms





Typical Micrographs, Experiment No. 2


Pioneer Display - Spectrum1
VFS: 2400
Livetime: 90
Deadtime: 34%
lin
O
Na
Fe
Fe
Al
Si
C
S
Ca
Ca
Mn
Fe
0.000
keV
10.220
Cursor: 0.000 keV
0 counts
Label: Ex-Situ #2, Area 4
Element: H 1

Refit _F -K' _F -K" _Mg-K' _Mg-K" _P -K' _P -K" _Ti-K' _Ti-K" _Ti-L' _Ti-L" _Cu-L' _Cu-L"
Refit _C -K' _Si-K" _F -K _Fe-L" _Mg-K _Ti-K _Ti-L _Mn-K"

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Ex-Situ #2, Area 4

Chi-sqd = 3.21 Livetime = 90.0 Sec.
Standardless Analysis

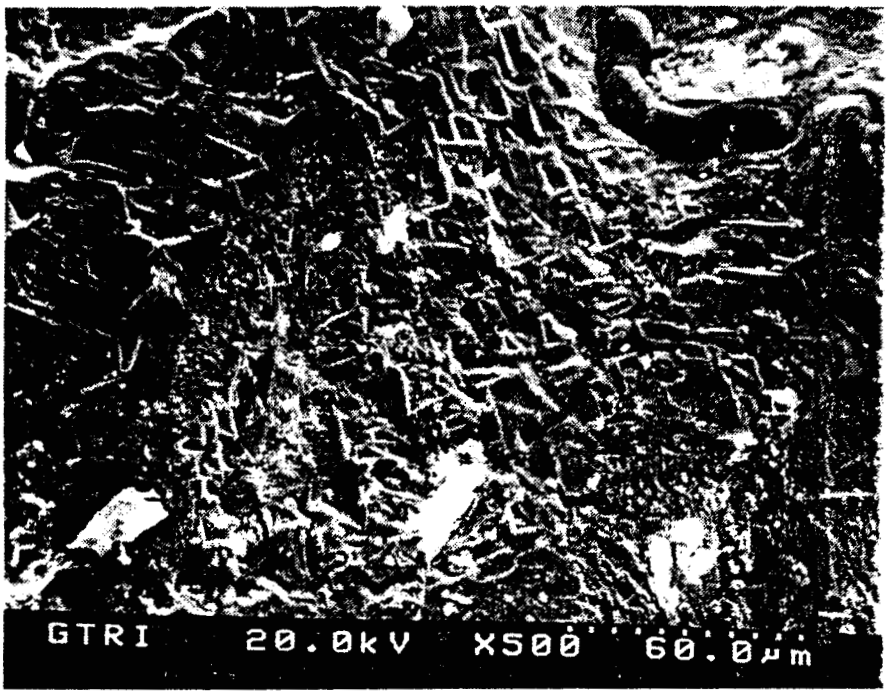
Element	Relative k-ratio	Error (1-Sigma)	Net Counts	Error (1-Sigma)
C -K	0.09132	+/- 0.00443	1258	+/- 61
O -K	0.35569	+/- 0.00509	19723	+/- 282
Si-K	0.00748	+/- 0.00036	1659	+/- 80
Al-K	0.00792	+/- 0.00070	1707	+/- 150
F -K	0.00000	+/- 0.00001	0	+/- 0
Ca-K	0.03320	+/- 0.00072	4488	+/- 98
Fe-K	0.36262	+/- 0.00401	26076	+/- 288
Fe-L	---	---	2810	+/- 181
Na-K	0.12871	+/- 0.00134	19475	+/- 203
Mg-K	0.00000	+/- 0.00001	0	+/- 0
P -K	0.00059	+/- 0.00040	108	+/- 74
Ti-K	0.00000	+/- 0.00001	0	+/- 0
Ti-L	---	---	0	+/- 0
Mn-K	0.00766	+/- 0.00087	609	+/- 69
Cu-K	0.00246	+/- 0.00230	109	+/- 102
Cu-L	---	---	57	+/- 243
S -K	0.00236	+/- 0.00076	461	+/- 149

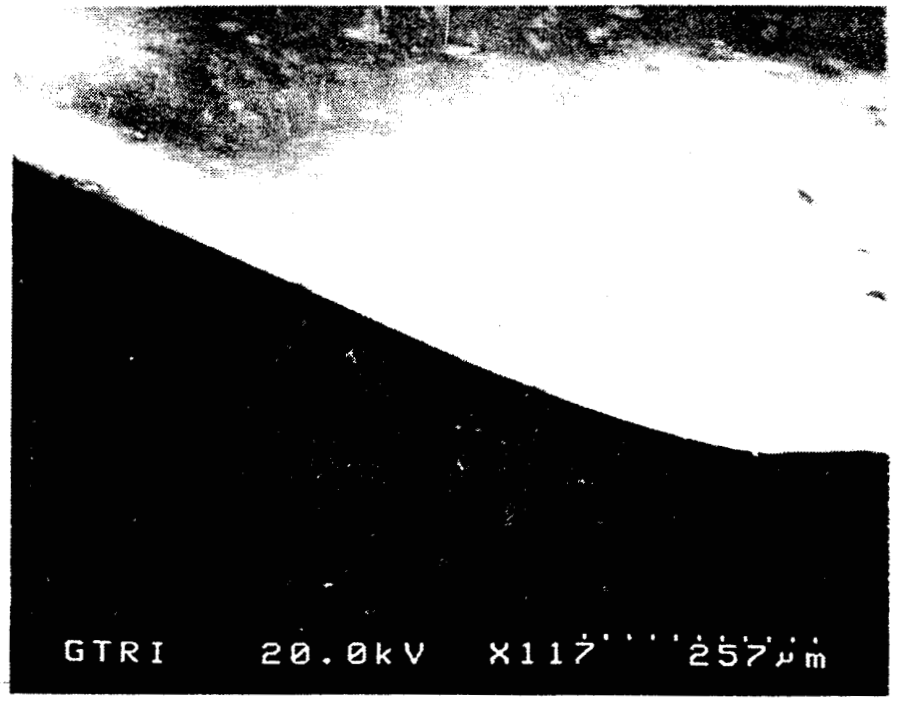
Adjustment Factors	K	L	M
Z-Balance:	0.0000	0.0000	0.0000
Shell:	1.0000	1.0000	1.0000

PROZA Correction Acc.Volt.= 20 kV Take-off Angle=43.20 deg Tilt = 20 deg
Number of Iterations = 7

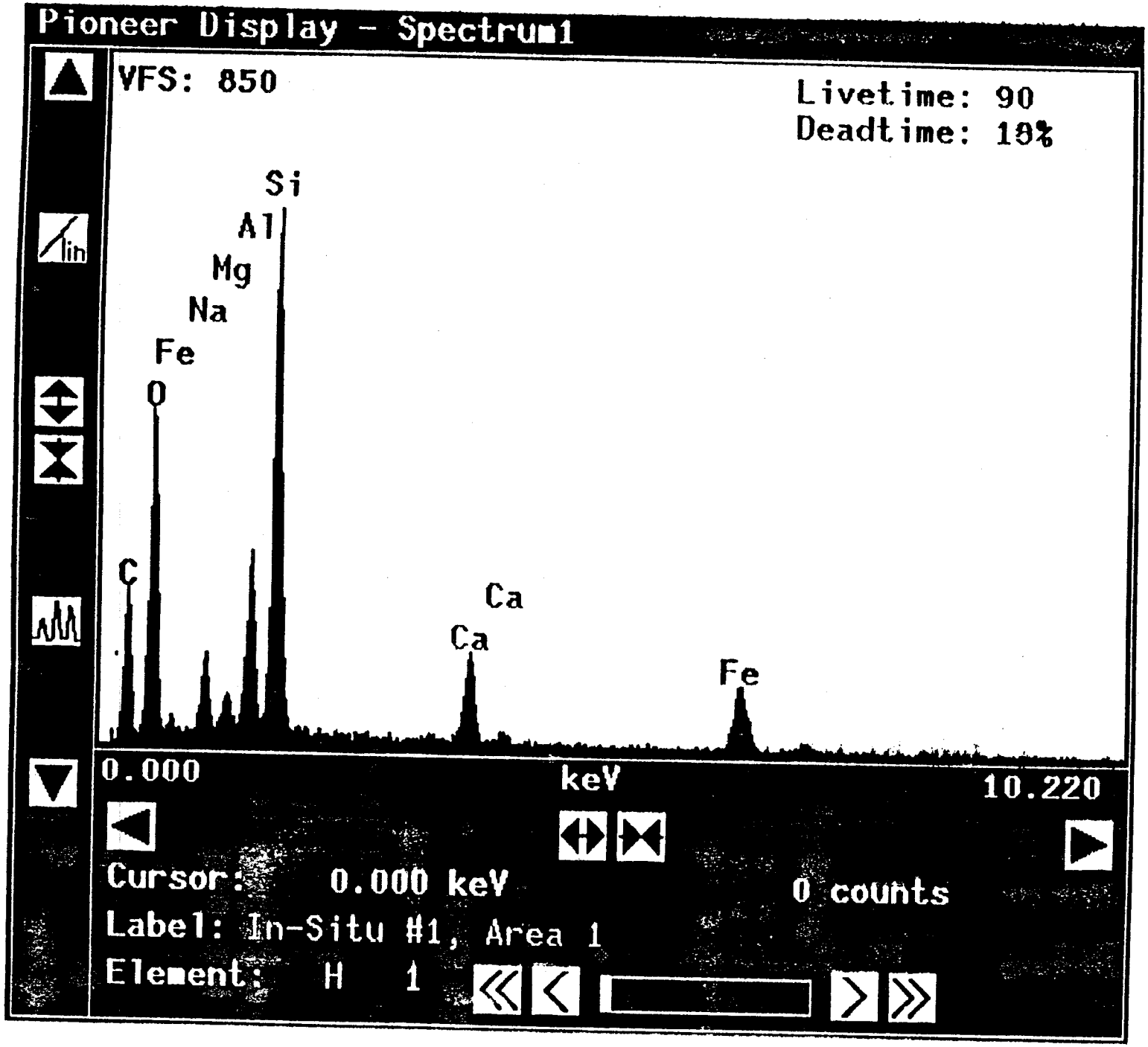
Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Stoich-iometry
C -K	0.04277	3.656	25.15	15.64	+/- 0.76	12.128
O -K	0.16660	2.474	49.77	41.22	+/- 0.59	24.000
Si-K	0.00351	1.649	0.40	0.58	+/- 0.03	0.192
Al-K	0.00371	2.102	0.56	0.78	+/- 0.07	0.269
F -K	0.00000	4.245	0.00	0.00	+/- 0.00	0.000
Ca-K	0.01555	1.092	0.82	1.70	+/- 0.04	0.395
Fe-K	0.16985	1.197	7.03	20.32	+/- 0.22	3.390
Na-K	0.06029	3.151	15.96	18.99	+/- 0.20	7.696
Mg-K	0.00000	2.920	0.00	0.00	+/- 0.00	0.000
P -K	0.00028	1.480	0.03	0.04	+/- 0.03	0.012
Ti-K	0.00000	1.100	0.00	0.00	+/- 0.00	0.000
Mn-K	0.00359	1.219	0.15	0.44	+/- 0.05	0.074
Cu-K	0.00115	1.274	0.04	0.15	+/- 0.14	0.022
S -K	0.00111	1.285	0.09	0.14	+/- 0.05	0.041
Total			100.00	100.00		

Stoichiometry results are based upon 24 Oxygen atoms





Typical Micrographs, Experiment No. 3


Pioneer Display - Spectrum1
VFS: 850
Livetime: 90
Deadtime: 10%
Si
Al
Mg
Na
Fe
O
C
Ca
Ca
Fe
0.000
keV
10.220
Cursor: 0.000 keV
0 counts
Label: In-Situ #1, Area 1
Element: H 1

Refit _F -K' _F -K* _Ti-K' _Ti-K* _Ti-L' _Ti-L* _Mn-K' _Mn-K* _Cu-K' _Cu-K*
Refit _C -K* _Si-K' _Al-K' _F -K _Ca-K* _Fe-L' _Fe-L* _Na-K' _Mg-K' _Mg-K* _P -
K* _Ti-L _Mn-K _Cu-K _Cu-L' _Cu-L* _S -K'
Refit _P -K' _Cu-L

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In-Situ #1, Area 1

Chi-sqd = 2.01 Livetime = 90.0 Sec.
Standardless Analysis

Element	Relative k-ratio	Error (1-Sigma)	Net Counts	Error (1-Sigma)
C -K	0.46820	+/- 0.01045	2376	+/- 53
O -K	0.25014	+/- 0.00891	5112	+/- 182
Si-K	0.10897	+/- 0.00197	8897	+/- 161
Al-K	0.03406	+/- 0.00214	2706	+/- 170
F -K	0.00000	+/- 0.00001	0	+/- 0
Ca-K	0.04132	+/- 0.00114	2058	+/- 57
Fe-K	0.06797	+/- 0.00343	1801	+/- 91
Fe-L	---	---	366	+/- 90
Na-K	0.01817	+/- 0.00170	1013	+/- 95
Mg-K	0.00717	+/- 0.00095	557	+/- 74
P -K	0.00180	+/- 0.00064	122	+/- 43
Ti-K	0.00031	+/- 0.00064	13	+/- 28
Ti-L	---	---	0	+/- 0
Mn-K	0.00000	+/- 0.00001	0	+/- 0
Cu-K	0.00000	+/- 0.00001	0	+/- 0
Cu-L	---	---	0	+/- 0
S -K	0.00190	+/- 0.00099	137	+/- 71

Adjustment Factors	K	L	M
Z-Balance:	0.0000	0.0000	0.0000
Shell:	1.0000	1.0000	1.0000

PROZA Correction Acc.Volt.= 20 kV Take-off Angle=43.20 deg Tilt = 20 deg
Number of Iterations = 11

Element	k-ratio (calc.)	ZAF	Atom %	Element Wt %	Wt % Err. (1-Sigma)	Stoich-iometry
C -K	0.16496	2.721	55.43	44.89	+/- 1.00	35.207
O -K	0.08813	4.625	37.79	40.76	+/- 1.45	24.000
Si-K	0.03839	1.390	2.82	5.34	+/- 0.10	1.790
Al-K	0.01200	1.606	1.06	1.93	+/- 0.12	0.673
F -K	0.00000	5.445	0.00	0.00	+/- 0.00	0.000
Ca-K	0.01456	1.152	0.62	1.68	+/- 0.05	0.394
Fe-K	0.02395	1.276	0.81	3.05	+/- 0.15	0.515
Na-K	0.00640	2.637	1.09	1.69	+/- 0.16	0.692
Mg-K	0.00253	1.925	0.30	0.49	+/- 0.06	0.188
P -K	0.00063	1.388	0.04	0.09	+/- 0.03	0.027
Ti-K	0.00011	1.253	0.00	0.01	+/- 0.03	0.003
Mn-K	0.00000	1.280	0.00	0.00	+/- 0.00	0.000
Cu-K	0.00000	1.323	0.00	0.00	+/- 0.00	0.000
S -K	0.00067	1.257	0.04	0.08	+/- 0.04	0.025
Total			100.00	100.00		

Stoichiometry results are based upon 24 Oxygen atoms