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**REVITALIZE THE U.S. SILICON/FERROSILICON INDUSTRY
THROUGH ENERGY-EFFICIENT TECHNOLOGY**

Final Report

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February 1995

Work Performed Under Contract No. DE-FC04-93-AL94598

For
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Office of Industrial Technologies
Washington, D.C.

By
South Carolina Research Authority
N. Charleston, SC

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Final Technical Report

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**Prepared for the
U. S. Department of Energy
Under DOE Albuquerque Operations Office
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Office of Industrial Technologies
Washington, D.C.**

**Prepared by
South Carolina Research Authority
N. Charleston, SC 29418**

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1 Executive Summary

1.1 Program Overview

The production of high quality, cost competitive silicon and ferrosilicon alloys is vital to maintain a strong domestic silicon/ferrosilicon industry. The methods of production currently used in the U.S. are too cost inferior in many cases to compete globally. The primary focus of this program was to prove the hypothesis that there are many advantages in using direct current (DC) power over alternating current (AC). The DC, submerged arc, open top, single electrode design should increase efficiency and result in significant specific energy savings.

SCRA assembled a research consortium, known as the Silicon Technology Competitive Cooperative (STCC), to advance the technology base of the U.S. Silicon and Ferrosilicon industry. A cost shared, cooperative research program was scooped and budgeted with funding via the U.S. Department of Energy (DOE), Industrial Waste Program (IWP). The program goal was to demonstrate energy savings, improve metal recovery, and reduce process emissions.

An existing plasma arc 1.5 MW test facility, located in Charleston, S.C., was extensively modified and used for testing purposes. The program received strong support from the DOE, SKW Alloys, and the research consortium. The program began in March 1993 and concluded with the submission of this final report in February 1995. A draft report was submitted to DOE for review in September 1994, and comments were received back in December. The actual testing period ran from May 2, 1994 through August 6, 1994.

1.2 Test Facility

The test facility was originally constructed in 1990 for smelting studies as a result of the requirement to make the U.S. more competitive in the world ferrochromium market. These studies were conducted under a Department of Defense (DoD) Grant to SCRA and administered by the Defense Logistics Agency (DLA). This furnace was also previously used for taconite tailings testing to support a program with Dow Corning and DOE, with the cooperation of DLA. The furnace was originally constructed as a containment vessel of steel, refractory lined, with a closed roof. The furnace was modified extensively to carry out the objectives of the STCC program, which included removing the closed roof and replacing it with a refractory-lined hood with sliding doors to permit stoking operations. The furnace sides were raised by 18 inches and relined with sidewall refractories. Two insulated ducts were added to the hood to remove the off gases and steel platforms were added to facilitate stoking. The furnace was relined once during the program when making the transition from ferrosilicon to silicon metal operations. A new pulse jet baghouse was installed using teflon coated fiberglass bags provided to the project by BHA Corporation.

1.3 Test Program

The test program began in May 1994. Raw materials utilized for the program consisted of high quality, known raw materials typical of those used by the silicon industry. These raw materials consisted of fine and lump quartz, fine sand, wood chips, coal, coke, iron borings and steel punching. Chemical analysis of each material was conducted and is provided in this report.

The first portion of the test program was dedicated to ferrosilicon operations. Target operating conditions of 100-120V and 6,000-8,000A were never achieved on a steady state basis. When the furnace was charged with mix burden, either the electrode had to be raised to maintain target voltage or if held deep, operating voltage dropped well under 20 volts at times. Extensive charging of mix would drive the electrode up and out of the furnace. The result was a cold furnace bottom that was difficult to tap. A steady, but unacceptable operation was achieved by running the furnace with a small charge pile deep in the furnace. This generated excessive fume and a hot furnace top. Even under these conditions, near-grade alloy was still produced. A later attempt was made in the ferrosilicon testing effort using steel punching, instead of iron borings in the charge mix, in an attempt to decrease the electrical conductivity of the burden pile in the furnace. This worked remarkably better in the furnace and test data was collected at 60 volts and 7000 amps in a submerged arc mode. A better grade alloy was produced under these conditions. Attempts to feed sand and fine quartz down the center of the hollow electrode were unsuccessful. Blockages were repeatedly experienced originating deep in the electrode.

The DC plasma furnace ran well in the submerged arc mode when making silicon metal. The furnace was run for a series of three-day test periods under consistent operating conditions. While significant tap to tap variations were observed, these averaged out over the more extended data periods. The furnace tap hole was usually opened with a shot gun using a zinc projectile. Despite this, the metal contained more iron than commercially acceptable. Electrode consumption was 0.10 lbs per lb of product. Specific energy consumption values ranged from 5.11 to 7.29 kwh/lb silicon while making silicon metal.

Hollow electrode feeding of fine quartz gravel with and without coke was largely unsuccessful due to frequent electrode blockages. While significant progress was made in resolving this problem, sustainable feed through the electrode was not achieved. The full submerged arc operation on silicon metal made the lower end of the electrode column very hot. This in turn promoted melting, fusing, and sticking of silica materials to the inner surface of the electrode. In addition, submerged arc silicon operations tended to run with a higher gas phase pressure at the bottom of the electrode. Electrode feeding was not successful and is not recommended. The hollow electrode system tested was not acceptable, and we know of no way to make it work.

1.4 Conclusions and Recommendations

The report concludes that silicon metal and ferrosilicon can be effectively produced in a DC submerged arc furnace. Specific energy consumption factors measured were favorable to the technology. Considering the small size of the test furnace, this indicates that significant energy

savings over conventional AC practice are likely on a commercial scale. Hollow electrode feeding of the furnace is not feasible as tested. Electrode consumption was low while making metal, indicating that significant electrode cost savings are available by DC technology. Silicon loss to fume averaged less in relation to the silicon charge indicating a high silicon recovery. Silicon reporting to the fume averaged 25.4% of the total silicon output.

In this furnace, 50% FeSi was more difficult to produce than silicon metal. High electrical conductivity in the burden mix severely limited the range of operating voltages available and thus power input to the furnace. The silicon metal portion of the test turned out to be more successful than the ferrosilicon portion. The furnace operated efficiently in this mode and clearly demonstrated that this type furnace was particularly well suited for production of silicon metal at more economical (lower) power consumption.

The industry must seriously consider the identified benefits of DC plasma arc technology for retrofit or new added silicon capacity. A Phase II STCC program to design, build and operate a commercial DC silicon furnace in the United States must be based on the combined findings of this work and Dow-Corning's Manitoba research project. We strongly recommend a merged technical approach and construction of a full sized commercial furnace. The entire domestic silicon industry must have access to the technology, while protecting the vested proprietary interests of the principal participants. A Phase II program is necessary to implement the technology.

The merits of plasma arc technology for the production of both ferrosilicon alloys and silicon metal were clearly demonstrated by this test program. The implementation of this process would result in significant savings to the industry through improved energy efficiency and reduction of wastes. Furthermore, the furnace design also lends itself to economic retrofit of many existing facilities, thus ensuring that the technology can quickly penetrate the industry. As a result, it is highly recommended that a semi-commercial scale program be established to determine operational parameters and address scale up issues. Phase II development at a semi-commercial scale is technically feasible and economically justified. The case is strongest for silicon metal production.

NOTE: An addendum to this report will be published that describes an on-going study of modeling the furnace reactions. Estimated publication date is the fall of 1995.

2 Introduction

The Silicon Technology Competitive Cooperative (STCC) submitted a proposal to DOE dated January 31, 1992 for a cost shared, research program to help revive the domestic silicon/ferrosilicon industry. The STCC was formed as a functional sub-group of The Ferroalloys Association (TFA) and consisted of those TFA member companies that produce silicon and/or ferrosilicon. The primary focus of this project was to explore the many perceived advantages of using DC power over AC, and hollow electrode feeding, such as improved recovery, improved process control, waste reduction and improved specific energy consumption.

The program had particular appeal to the STCC members. First, the test facility had been successfully used in other similar projects. For example, smelting tests to recover ferrosilicon from taconite tailings (an industrial waste product) had been completed in the test facility using a covered furnace configuration. Second, the facility was easily modified to an open configuration. Third, the technology was clearly a departure from the technology being explored by Dow Corning in their pilot facility, which was a closed system. Fourth, the STCC members felt that technology transfer would occur easily to the industry due to the fact that most industry members were participants in the STCC program. Finally, the STCC felt the approach would be more economically feasible to implement at a manageable cost.

2.1 Background

The production of high quality, cost competitive silicon and ferrosilicon alloys is vital to maintain a strong domestic silicon/ferrosilicon industry. In order to meet increasingly stringent customers requirements, the technology for silicon/ferrosilicon production must be efficient and flexible; process control must allow for electrical parameters to be adjusted within minutes. Recovery of silicon/ferrosilicon must be high in relation to raw materials used, and energy consumption must be highly efficient.

The methods of production currently used in the U.S. lag behind these requirements to compete globally. The alternating current (AC) technology employed in furnaces for the production of silicon and ferrosilicon alloys uses a specific energy consumption level that significantly exceeds theoretical requirements. Raw materials must be carefully sized to prevent undesired changes in the furnace environment and minimize silicon losses. Currently, process-control changes can take hours to accomplish. Furthermore, electrode consumption is high and represents a major component of operating costs.

Other research on hollow electrodes indicated that these disadvantages could be greatly reduced by direct current (DC) submerged arc and hollow electrode technologies. Direct current technology, as applied to the steel industry, has already revealed a reduction in graphite electrode consumption, while a hollow electrode enabled the use of fine sized, less expensive ore, and provided flexibility through a greatly improved control response, resulting in higher purity alloys. The use of a submerged arc operation reduces thermal emission losses that accompany open bath operations. The

DC, submerged arc, single electrode design increases energy efficiency and should result in significant specific energy savings.

The utilization of this technology will greatly increase process flexibility and efficiency. Costs will be lowered by the reduction of specific energy consumption and the ability to smelt fine and inexpensive ores. The improved energy efficiency of the DC electrical supply should be greatly enhanced by:

- increased silicon/ferrosilicon recovery rate;
- reduced thermal losses;
- highly responsive process control; and
- elimination of electrical reactance in the furnace.

This was a low-to-medium risk endeavor with a very high probability of significant benefits and measurable gains. The savings to the domestic silicon/ferrosilicon industry were estimated to be as high as \$23 million per year. The lower impurity content of the silicon produced by this technology should result in significantly higher market share gains as the American silicon/ferrosilicon industry regains a larger share of the domestic and global markets. The benefits that could result from this project include increased energy efficiency, higher purity silicon/ferrosilicon, reduced operating costs, and increased production flexibility.

SCRA, the primary contractor, has proven experience in plasma furnace technology and in managing distributed work forces, with an innovative, high-profile management style that has resulted in several successful technology-based projects. The original technical team members (AIMCOR, American Alloys, Elkem, Globe Metallurgical, Macalloy Corporation, SiMETCO, and SKW) were experienced in all phases of silicon production and are well-suited to exploit the proposed technology. Technical support was provided by MIT, Arthur D. Little, and Carnegie Mellon University, all of whom have successful, well-established track records. Carnegie Mellon participation was in the form of consulting input at the beginning of the project.

The technical team members were committed to this project and agreed to contribute one half man-year of effort or other in-kind contributions toward its successful completion. This approach would enable the Team to demonstrate the feasibility of the technologies involved and establish the necessary groundwork for scale-up (Phase II) and implementation (Phase III). During the 15 month period of performance, a silicon/ferrosilicon direct current, submerged arc, hollow electrode system was constructed by modifying and refurbishing an existing plasma arc test facility.

2.2 Description of Equipment

The test facility consists of a 1.5 MW DC plasma arc furnace originally designed and constructed for chromium smelting studies funded by a \$13.5 million grant from the Department of Defense (DoD), administered by the Defense Logistics Agency (DLA). The facility was redesigned and modified and used for this work with the expressed permission of DLA. In this

section, the original furnace design will be discussed followed by the modifications installed for this specific program. Further design and modification discussions are found in section 4 of this report.

The test facility encompassed several sub systems. These include: raw materials preparation; feed system; power supply; electrode mast, arm, and electrode; the plasma furnace; cooling water system; computer/data logging system; and various auxiliary services. Each of these systems will be discussed in detail below. All systems were housed in the eastern end of an existing building at the Macalloy Corporation site. This is an excellent building that has received several upgrades since 1989, including a new roof. The area was serviced by an overhead bridge crane which was vital to the test operations.

2.2.1 Raw Materials Preparation

The facility was designed to process dry materials of multiple sizes. In the materials preparation area, feed materials were selectively screened, stored, weighed, blended, and loaded into transfer hoppers for transport by overhead crane to the appropriate feed bin or boxes (skips). In the ore preparation area, charge mixes were made up to an assigned recipe by weighing individual components on a digital platform scale, and charging them to mix bin. Weighed components were mixed with a front end loader and weighed again to ensure accuracy. They were placed in concrete mixer transfer hoppers and held in the material storage area until needed. The hoppers were then transported to the furnace area via the overhead crane and emptied into the boxes (skips) placed on each side of the furnace opening. When required for feeding down the electrode, sand or fine gravel was charged to one weigh bin and coke breeze to the other.

2.2.2 Feed System

Ore mix consisted of weighed, mixed portions of quartz gravel, sized coal, wood chips, and iron borings/steel punching as required. These materials were pre-mixed and stored in the ore preparation area in marked ore bins. Appendix A (ore mix recipe) Charge mixes of 720 lbs were transferred by crane and dump hoppers to steel boxes, skips, on the charge floor on either side of the furnace. The furnace shift foreman noted in the log each time mix was brought up to the platform. Appendix B (burden sheet) Mix was then manually shoveled from the boxes directly into the east and west sides of the furnace equally.

There was an automated feed system built to deliver solids to the furnace via the hollow electrode at adjustable rates. This system worked well, after calibration, but frequent electrode blockages (discussed elsewhere in this report) precluded its extensive use. The function of the feed system is to deliver ore mix and reductant mix to the furnace at adjustable set rates. The reductant rate could be slaved to the ore rate or set independently. The feed system comprises two live-bottom bins on load cells, two weigh belt feeders, an inclined screw conveyer, and a rotary valve air lock. One bin and weigh feeder is for ore and the other bin and feeder is for reductant. This equipment was manufactured by Vibra Screw Inc. of Totowa, NJ. The weigh bins are both of 40 cubic foot capacity. Because of the difference in density of the materials, the load cell ratings of the bins differ. Similarly, the weigh belt feeders, although they physically look identical, are rated for significantly

different delivery rates. Ore mix and then reductant drop into the inclined screw conveyer, and are transported to a point offset from the center line of the plasma furnace. The feed materials drop into a rotary valve air lock above the furnace. This rotary valve allows materials below the valve to be pressurized with nitrogen for a nitrogen-assisted, gravity drop into the furnace.

Instrumentation for the feed system was mounted on a separate feed system panel in the control room. Digital displays indicated the weight of materials in the ore bin and in the reductant bin. Separate controllers for each weigh feeder indicated feed rate set point, instantaneous feed rate, belt speed, and total weight of material fed since reset. The totalizer reading and the change in bin weight offers a degree of redundancy and a cross-check on the feeder instrumentation. Similarly, a cross-check was available by monitoring the change in bin weight when a known weight of mix is added. These redundancies have proven essential when parts of the feed system instrumentation failed. One hundred pound bags of sand were used to calibrate the weigh bins.

In the design of the test facility, the ability to control the rate that ore mix and reductant were added to the furnace was considered very important. For this reason, the ore was added to the screw conveyer first, with the reductant added to the moving ore stream closer to the furnace. Travel within the screw provided some mixing, and both materials discharged into the rotary valve and the furnace together. This arrangement also made changing the reductant-to-ore ratio easy and rapid. It was not necessary to run a bin empty before a change could be made.

2.2.3 Power System

The power supply was designed and manufactured by Halmar Electronics Inc. of Columbus, Ohio to meet our operating condition specifications. Halmar has since merged with Rubicon, and they were used to perform the necessary service to the equipment. It consisted of two step-down water-cooled transformers (one Delta and one Wye phase), twelve-pulse water-cooled thyristor circuits and water cooled DC reactors on each secondary, and the necessary electronic firing and control circuitry. The transformers, each rated at 350 Volts and 5000 Amps, could be connected in series or parallel mode. In series, the power supply could supply up to 700 V DC with a maximum current load of 5000 A DC. In parallel mode, it could provide up to 350 V DC at 15000 A DC maximum current load. Input voltage was 13,800 V, three-phase, 60 cycle. The actual limit was 5000 A DC on either circuit, so perfect balance of Delta and Wye was required to reach 10,000 A DC.

Internal cooling of the power supply and its major components was by means of closed loop circulating deionized water. Heat was extracted from the deionized water circuits using shell and tube, water-to-water, heat exchanger. Sixty gallons per minute of plant cooling water at less than 85° F provided the heat sink. In practice, the plant water supply exceeded this temperature requiring system shut-down for cooling.

The power supply came with two identical control panels. One was located on the cabinet of the unit and one was in the control room. The controls allowed the power supply to be run in either a constant current or a constant power mode. Arc voltage was controlled independently by adjusting

electrode height. Experience showed the constant current mode to be best. When operating with a stable arc, the power supply provided a very stable set current. Dial gauges displayed DC voltage, DC amperage, DC kilowatts, AC primary amperage for each phase, and delta and Wye transformer currents. The control panels also provided many system status lights and alarms, and a keyed emergency stop/lock out button.

2.2.4 Electrode Mast and Electrode

The electrode clamp, arm, mast and position regulator were purchased from Universal Machinery Company. The clamp was a water-cooled copper clamp as used in conventional three phase AC foundry melting furnaces. The clamp was spring loaded in the clamping position and pneumatically released. The electrode arm was raised and lowered on the mast by a cable/pulley arrangement and a direct current winch. The mast is footed on a massive concrete pedestal, and its top is stiffened with two stay braces. Arm travel was limited by an upper limit switch on the top and a slack cable, stop switch on the bottom. Approximately 6.5 feet of arm motion was available. This travel limitation was consistent with site elevation restrictions imposed by the existing overhead crane and necessary dimensions for the furnace and feed systems. The electrode mast arrangement and crane were well able to manipulate 5 foot electrode sections. The modified furnace with the off-gas hood limited electrode sections to 4 feet.

The arm position regulator was mounted in a control console in the control room. In manual mode, the electrode was raised or lowered with lighted push buttons. Electrode travel speed was set at six feet per minute. Upper and lower limit lights indicated when further travel was not available. Another push button activated the clamp release mechanism used to slip the electrode. The regulator was equipped with an automatic control feature that could move the electrode to hold a desired arc voltage. This capability was never fully commissioned. Manual control was satisfactory. The console included megawatt and MVAR displays, a megawatt hour counter and a trip counter. Several controls not related to the electrode arm were mounted on this console as a point of convenience.

Graphite electrode sections were purchased from Great Lakes Carbon. Other suppliers could supply comparable electrodes. The electrodes used were 10 inches in diameter and 4 feet long, with male and female conical threaded joints on the ends. Both solid and hollow electrodes were used at various times in the test program. The hollow electrodes were drilled with a 2.5-inch bore down the center of the electrode. In the final test segments, a 3-inch bore was substituted for the 2.5-inch bore in an attempt to reduce electrode blockage frequency. In the furnace, electrodes were oriented with the female end down. An electrode lifting cap with a female thread on one end and a steel eye on the other was used to position new sections when adding electrodes. A machined graphite collar screwed onto the top of the electrode column when feeding charge down the electrode. This graphite piece, together with a brass bushing, accommodated a stainless steel feed pipe. The feed pipe remained stationary while the electrode was movable. The stainless feed pipe was electrically insulated from the hood and platforms and operated at the gasses electrode potential.

2.2.5 Furnace

The plasma furnace was basically a containment vessel to hold the reactants and products of reaction (slag and alloy). It consisted of a steel shell, refractory sidewalls, and bottom; each of which is described below in more detail. Some of these furnace components underwent considerable design modification and rebuilding during the test program. Composite design had to provide for insulating properties, thermal expansion, confinement of the liquid phases, and very high temperatures at the working face. In addition, the furnace bottom had to provide current collection, i.e., an electrically conductive path out of the furnace.

The furnace shell was manufactured by Southwire Inc. It is a vertical cylinder of 3/4-inch steel plate. The inside diameter is 8 feet 3.5 inches and the height is 6.5 feet. The bottom plate of the furnace is a circle of 1-inch steel plate. A flange on the bottom of the cylindrical portion allows the sides to be bolted to the bottom plate, with openings for the bottom electrode bus connectors. A flange at the top of the cylinder helps support and align the furnace roof. A stiffening ring near the center of the furnace avoids distortion of the sides. The furnace has one tap hole with a spout welded to the cylindrical furnace shell.

The furnace bottom was one of the original chromium smelting furnace bottoms which was constructed with electrically conductive refractory components. The key components, porous carbon blocks and graphite/magnetite bricks have been in service since first installed in 1989. This bottom has been described previously with drawings. A brief description is repeated here. The bottom most layer was a 50/50 mix of alumina ram refractors and magnetite ram mix to achieve an intermediate thermal conductivity in this layer. A 34"x 34" square copper plate with a 10"x 10" square cutout in the center sat on top of 6.5" of this mixed refractory. Copper bus connectors (1"x 6") exited the bottom of the furnace and connected to the external bus work. A 16-inch thick layer of porous carbon blocks sat on top of the copper plate. These 16 x 16 x 9 inch blocks were purchased from Great Lakes Carbon. They were selected for their combination of high electrical conductivity and moderate thermal conductivity. A graphite paste bedding compound was used between the blocks and the copper plate. A soldier course of conductive carbon-magnetite brick set vertically in a herringbone pattern topped the carbon blocks. The graphite bedding agent was used again between the bricks and the block. Magnesite ram mix (SSK 3000) was rammed between the conductive bottom brick and the sidewall alumina brick. This bottom configuration has proven very effective and durable. The same bottom, with a layer of carbon paste added was used in these silicon tests.

The furnace sidewalls were totally replaced for the ferrosilicon and silicon metal tests. Two furnace configurations were used. The first configuration used in the May/June ferrosilicon tests is shown in figure 1. The working surfaces of the furnace crucible are entirely of carbon made from Solderburg paste. The tap hole was flush with the bottom of the furnace. A 4.5-inch layer of K-28 insulating bricks provided the main thermal insulation. The inside diameter of the furnace was 48". Six thermocouples were mounted in the side wall and protruded to the interface between the insula brick and the 9" alumina backup lining. A strip chart recorder was installed to monitor twelve temperature locations on the furnace shell. During operations, it became apparent that the two most

important temperatures to monitor were the baghouse temperature and the temperature from the thermocouple nearest the tap hole at the furnace bottom.

Figure 1 - Furnace Configuration for Ferrosilicon Test

Because of high electrical conductivity problems experienced during the Ferrosilicon tests, the furnace was frequently operated with a shallow burden and a hot top. When uncovered, the top portion of the sidewalls oxidized and was largely consumed. In view of this occurrence, the top portion of the furnace sidewalls were relined a second time.

For the second silicon operations, the furnace was relined again in the configuration as shown in figure 2. The insula brick and alumina brick were saved intact. A new carbon bottom and sidewall approximately 12" high was rammed into a short steel mandrel. A 48" steel mandrel was tack welded to this and rammed with a 90% alumina plastic refractory. The result was that the upper portion of the second lining was electrically insulating. The upper mandrel was removed by torch after the refractory had been fired in.

Figure 2 - Furnace Configuration for Silicon Test

2.2.6 Cooling Water System

Several critical components of the test facility are water cooled with plant process water. These include the power supply, the cables to the electrode, the electrode clamp and the upper furnace flange. A spare water circuit was used to cool a water cooled section added to the hood around the electrode entry.

With the exception of the electrode clamp and cables which are on a common water circuit, each is piped independently. Each water circuit has a manual valve on its inlet side, that passes through the component it cools and returns to an open drop into a receiving bosh tank. A thermocouple measures the temperature of each return stream just ahead of the bosh. Water is pumped from the bosh tank back to the plant's cooling towers. Figure 3 is a schematic flow diagram of the cooling water circuitry. Approximate flow rates are indicated in the sketch.

The power supply was water cooled. It has internal pumped water circuits in which deionized water is used to cool the thyristors, transformers, chokes, and cabinet air. This internal water passed through shell and tube water-to-water heat exchanger, dumping heat to the plant process water. The power supply specifies an inlet process water temperature below about 85°F at a flow rate of 60 gallons per minute.

Other water circuits for the off-gas pipe, screwback, and gland were eliminated. A portion of the insulated hood near the electrode entry point failed and was replaced with a water cooled steel section. Although unplanned, this reconfiguration worked well during the remaining time of operations. This water requirement utilized one of the excess water circuits eliminated for these tests.

WATER SUPPLY for PLASMA ARC TEST FACILITY

Figure 3 - Water Cooling System

2.2.7 Data Logging and Computer System

The test furnace was highly instrumented. An Allen-Bradley PLC-5 process control computer was the primary input/output data logging device. It was linked to an IBM 386SX (PS/2 55SX-061) personal computer, operator interface. Indelec's "Plant View" software was used to manipulate sensor information from the PLC-5, display operating conditions, and archive the data. This software provided math functions, alarm set points, graphical trending, and functional status flowsheets. The display screens were customized by SCRA to suit the needs of the furnace project. Separate Icon software was used to setup and modify the ladder logic used by the PLC-5 computer. A Best uninterruptible power supply (UPS) conditioner protected the computers from power failures, surges and line distortions. The data logging system malfunctioned during part of the testing period primarily due to the intensity of the magnetic fields and the presence of excessive dust. During the majority of the silicon metal tests, data was printed out on a printer at 10 minute intervals. The UPS failed in service and had to be eliminated. Appendix C (sample of computer data printouts).

2.2.8 Auxiliary Services

Nitrogen gas was supplied by an on-site liquid nitrogen tank and vaporizer. Nitrogen was used at two places in the test facility.

(1) It was used as a plasma support gas, entering the furnace down the hollow graphite electrode along with the solid charge materials.

(2) It was used to purge the seal plates on the rotary valve air lock in the feed system. Nitrogen flow rates were adjusted and controlled manually by means of valves and rotameter in each nitrogen line.

Nitrogen flow down the feed pipe and electrode assisted the charge materials in their descent into the furnace. It worked as a sweep gas and helped prevent charge blockages in the feed pipe. Nitrogen pressure building in the supply line was used as an indicator of electrode blockage.

Three-phase 13,800 volt power was supplied to our test facility from an on-site substation. This substation also serviced the commercial furnaces at Macalloy. The quality of power received was affected by the operating conditions at the commercial furnaces. At times, the three phases were out of balance.

2.3 Program Objectives

The U.S. silicon/Ferrosilicon industry is stagnated in growth and virtually devastated with respect to profitability because of low cost imports. The silicon industry has not been able to justify investment in new construction since the last new plant was built in 1974. The U.S. silicon and Ferrosilicon industries need low cost, energy-saving production technologies that reduce pollution.

The objective of this research is to demonstrate, in a 1.5 MW scale facility, the feasibility and commercial afford ability of an open-furnace operating with a single, hollow electrode, direct current (DC), submerged arc for smelting silicon and silicon alloys. This is expected to save materials and energy, reduce costs to improve U.S. competitiveness, and improve emission control. The technology will then be utilized to retrofit existing furnaces in the U.S. that will displace imports and meet the forecast U.S. demand growth for Ferrosilicon and silicon metal.

2.3.1 Ferrosilicon/Silicon Industry Study

As part of the STCC project, the Department of Energy requested that historical industry statistics be provided which could be used to construct a profile of changes in the industry and a summary of the industry's current status. In response to this request, the industrial partners on the STCC team developed a source blind synopsis of the domestic Ferrosilicon and silicon industry.

Throughout the eight-year period (1985-1992), the furnace capacity of the industry remained fairly constant at about 700,000 - 760,000 tons per year. It depended on which product was more profitable at the time as to which one was produced. Additional furnaces would be activated as necessary to meet the demand at the time. Sales for the silicon metal has been on a continual increase since 1987. Yearly capital expenditures varied from \$6,000,000 - \$14,000,000 with most funds being allocated to furnace and related equipment. The last profitable year for 75% and 50% Ferrosilicon was 1989.

It appears that the only way the industry has been able to survive is to have the flexibility to move from one silicon product to another as the market dictates. Certainly, improved furnaces must also have this same flexibility. (see figures 4, 5, 6)

	50% Ferrosilicon							
	1985	1986	1987	1988	1989	1990	1991	1992
Production								
Capacity (Tons)	497,924	491,992	413,513	395,752	394,171	411,385	385,320	377,693
Actual (tons)	254,449	247,211	223,664	247,352	230,075	213,894	145,515	145,552
% On-Line	78	48	79	82	93	81	70	72
Yield	91	84	90	89	86	89	89	88
Electrical Cons (000) KWH	1,171,362	985,962	951,321	1,203,666	1,271,773	1,023,213	649,503	690,905
Electrode Cons (000) lbs.	10,775	10,887	8,655	11,386	12,719	9,691	5,662	6,139
Employment								
Hourly, Full Time	525	395	491	572	574	510	364	380
Manhours	239,576	402,270	379,757	439,214	415,855	334,983	172,841	199,628
Salary, Full Time	253	170	153	164	176	168	125	116
Capital Expenses (\$000)								
Furnace & Related	3,917	9,293	2,926	6,708	8,905	5,718	2,946	3,103
Dust Collection	1,990	4,269	500	4,089	4,674	2,817	893	569
All Other	510	4,179	1,323	22,332	1,201	1,261	1,336	1,954
	1,417	845	1,103	387	3,030	1,640	717	580
Sales (\$000)								
	83,834	70,541	110,464	149,725	136,686	114,069	91,751	91,201
Gross Income (\$000)								
	-2,909	-2,622	1,392	15,241	12,377	-3,975	-12,024	-10,382

Figure 4 - Industry Study 50% Ferrosilicon

75% Ferrosilicon								
	1985	1986	1987	1988	1989	1990	1991	1992
Production								
Capacity (Tons)	148,666	148,876	142,022	155,382	166,448	164,610	161,314	146,581
Actual (tons)	27,637	29,732	33,567	52,515	77,807	65,415	71,131	48,958
% On-Line	43	76	81	84	97	87	61	72
Yield	80	80	87	82	83	87	87	87
Electrical Cons (000) KWH	231,531	244,129	266,457	436,229	645,393	510,565	540,939	377,713
Electrode Cons (000) lbs.	4,096	4,249	3,858	6,389	9,083	7,078	7,526	5,496
Employment								
Hourly, Full Time	49	82	129	175	226	158	156	125
Manhours	101,411	170,336	97,090	195,508	273,295	167,316	167,002	254,283
Salary, Full Time	18	21	44	131	70	51	49	39
Capital Expenses (\$000)								
Furnace & Related	788	3,780	550	748	2,865	2,206	1,987	1,537
Dust Collection	632	946	132	288	1,966	1,619	913	590
All Other	138	2,817	294	360	576	265	721	936
	18	17	124	100	323	322	353	11
Sales (\$000)	11,218	17,175	40,794	60,796	69,950	63,000	50,826	42,110
Gross Income (\$000)	-2,723	-478	1	5,123	6,690	-3,670	-5,607	-3,221

Figure 5 - Industry Study 75% Ferrosilicon

Silicon Metal								
	1985	1986	1987	1988	1989	1990	1991	1992
Production								
Capacity (Tons)	120,335	125,108	148,871	158,712	147,563	157,728	170,620	179,277
Actual (tons)	107,112	109,556	131,681	141,582	129,363	135,503	144,215	153,016
% On-Line	89	88	88	89	88	86	85	85
Yield	74	73	76	76	77	77	78	78
Electrical Cons (000) KWH	1,453,247	1,427,326	1,690,636	1,763,098	1,703,587	1,762,851	1,924,283	1,735,618
Electrode Cons (000) lbs.	29,974	30,433	38,145	43,511	38,174	39,824	40,285	41,379
Employment								
Hourly, Full Time	638	626	642	657	622	645	709	725
Manhours	614,817	588,384	680,281	673,991	610,826	583,502	610,954	646,500
Salary, Full Time	156	160	163	170	173	188	214	208
Capital Expenses (\$000)								
Furnace & Related	5,865	16,331	6,424	7,220	14,503	8,141	12,950	9,401
Dust Collection	5,310	10,612	2,956	5,573	11,943	4,873	8,594	5,441
All Other	350	2,926	3,314	1,185	1,366	2,037	1,899	783
	205	2,793	155	458	1,040	1,231	2,481	3,266
Sales (\$000)	122,239	118,362	158,287	196,111	171,225	160,991	182,346	215,593
Gross Income (\$000)	1,245	-1,419	4,074	17,751	13,412	3,604	2,069	6,504

Figure 6 - Industry Study Silicon Metal

2.3.2 Other Objectives

Additional objectives of the program were in conjunction with the implementation of the program. These included the technical approach and the development of the technical analysis, material requirements, engineering design and the operating plan. (Appendix D is Manual of Operations).

The engineering design and modification objectives included modifying the furnace to comply with the most efficient design by the engineering firm of Hatch and Associates. Detailed cost estimates were to be prepared and competitive construction awards made for the major construction effort.

The objective of the test program was to operate the modified furnace, from training the operators through the start-up process and campaign operations. Four major campaigns were initially planned to cover the 50%, 75% Ferrosilicon, then increase to 90% followed by the production of silicon metal. The 90% alloy was eliminated early on, because of little interest to the manufacturers and a very small market.

Several objectives centered around the areas of evaluation and analysis. The actual data collected was to be analyzed in terms of its quality and acceptability along with the economic analysis. Further, scale-up and commercialization evaluation was to be accomplished at the conclusion of the program.

The management objectives of the program were set up to control the cost and scheduling, reporting, and insure that the technical objectives of the program were met. In addition to the array of DOE reporting required, a management plan was developed for the program. (Appendix E is the Management Plan)

3 Technical Approach

This project was conceived to make use of an existing plasma arc furnace asset to evaluate the merits of DC arc furnace and hollow electrode feed for the production of silicon metal and Ferrosilicon alloys on a large pilot scale. The facility had previously produced Ferrosilicon from taconite tailings in an enclosed furnace mode. A technical team of experts from the producing companies helped focus the effort on technology that could, if successful, be retrofitted into existing production facilities. By consensus, it was agreed that the furnace would be operated with DC power in a submerged arc configuration. Feeding of a partial charge mix to the arc zone of the furnace via a hollow bore in the electrode would be evaluated.

Traditionally silicon and Ferrosilicon alloys are produced in open top, submerged arc, AC furnaces of various configurations. Some have three or even six in line electrodes and others have three electrodes in a delta configuration. Some furnaces are stationary and others have movable, rotating shells to keep the burden pile free from the refractory side walls. All are run submerged arc.

The carbo thermic reduction of silicon dioxide is complex and involves a host of complex reactions and back reactions. A report by MIT (Appendix F - Wooley report) discusses reaction mechanisms and a theoretical rational for hollow electrode feeding. Clearly, silicon monoxide gas is a critical reaction intermediate. It is formed at high temperature deep in the furnace, and reacts with various solids on its ascent to the surface of the burden pile. Silicon monoxide gas condenses according to the following reaction:

This condensation reaction is called disproportionateness. Some silicon monoxide condenses and disproportionate in the bed. Most of this gas which exits the top of the charge pile is oxidized to silica fume in the head space and transported to the gas cleaning system. Silicon carbide solid is both formed and consumed in the bed as a reaction intermediate. High in the furnace, silicon monoxide gas reacts with carbon to form silicon carbide. Lower down, silicon carbide reacts with silicon monoxide gas to form silicon metal. Iron, when present in the system, readily reacts with silicon and effectively reduces the silicon activity.

Carbo thermic reduction of silica (SiO_2) occurs at very high temperatures (in the plasma arc zone) and generates a gaseous suboxide species, silicon monoxide (SiO) and carbon monoxide. Silicon monoxide gas, in turn, is involved in a number of important side reactions some of which yield liquid silicon metal. When metallic iron is present, silicon and iron combine to form the alloy phase, reducing the silicon fugacity. Important reactions include:

These reactions occur predominantly within the burden pile in the furnace at somewhat lower temperatures. Charge porosity on a macroscopic scale is important to enhance gas solid interactions. The major chemical inefficiency in the process relates to silicon monoxide gases exiting the charge pile unreacted and going on to produce silica fume in the gas handling system. Significant energy is consumed in creation of the silicon monoxide which does not result in product yield. Fume production greatly increases specific energy consumption and operating costs.

The formation of silicon carbide (SiC) on the surface of carbon in the charge pile is desirable, as the charge descends into the furnace. Silicon Carbide can result in secondary silicon metal formation. Silicon carbide in the hearth of the furnace is undesirable once it reaches the level where it is no longer exposed to silicon monoxide. It can build up on the hearth, eventually, impeding furnace functioning. This new approach to silicon metallurgy allows a change in ore/reductant stoichiometry between the top and bottom of the furnace. The charge introduced through the hollow electrode can and should be carbon deficient. The conventional submerged arc process does not offer this degree of freedom, because all charge is added to the top of the burden and descends to the hearth over a period of hours.

Almost all submerged arc furnaces are open top, with hood structures to collect furnace off gases and metallurgical fumes. Access doors or chain curtains allow mechanical stoking machinery to push the burden around, charge new mix, and break free crusts and hang ups. Blow holes can form and tend to emit hot gases from deeper zones in the furnace, leading to increased fume formation and loss of efficiency. Stoking practice is aimed at controlling or minimizing blow holes and is accomplished by manually stoking the furnace with wooden poles (2"x 2"x12').

3.1 Technical Basis

A process was developed to produce Ferrosilicon alloys and silicon metal (98+%) in a single electrode DC submerged arc, open top furnace. A hollow electrode feed system was selected to test the viability of injecting a portion of the feed mix as fine sized quartz and reductant directly into the high temperature plasma zone deep in the furnace. Test operations began with a target product composition of 50% silicon alloy, which was considered to be the easiest Ferrosilicon composition to make. The final portion of the work was directed at the production of high quality silicon metal. After these tests were completed, the team agreed that, if budget and schedule constraints permitted, testing would then begin on the 75% alloy.

The approach is a significant advancement from the long-established conventional AC submerged arc practice using three AC electrodes, currently standard in the industry. It adapted several emerging process technologies to the unique difficulties of silicon and Ferrosilicon production. Due to its similarity to existing practice, the research was considered medium risk with a high probability of success and commercial implementation. Due to the current state of the

industry, however, it is largely beyond the capabilities of the individual member companies to undertake the project independently.

3.1.1 Technical Validity

The issue of technical validity rests on the successful implementation of a number of emerging and proven technologies to enhance the manufacture of silicon metal and Ferrosilicon alloys. The component technologies have been proven viable by reduction to practice in related applications:

- submerged arc silicon furnace technology;
- DC single electrode technology;
- hollow electrode feed system technology;
- process control computer technology; and, in the future,
- enclosed top furnace technology for the capture of fuel gas values from the process gas effluent.

Processing is based heavily upon the long-established submerged arc process. This technology is practiced by the member firms of The Ferroalloys Association (TFA), which are participating in this project. The technical resources and submerged arc experience base of these companies are available as important project resources.

In a number of industries, DC single electrode furnaces are replacing three electrode AC smelting furnaces. This is perhaps most notable in electric furnace steel making where the trend is well established. The Japanese are reported to have built a furnace as large as 100 megawatts with potentially major savings in electrode consumption and electrical usage per ton of steel produced. For a comparable energy level, DC furnaces tend to be of somewhat smaller diameter and thus lower capital cost. A research consortium managed by SCRA, with funding through the Defense Logistics Agency, developed and tested a DC plasma arc process for ferrochromium ore fines. A 12 megawatt prototype plant has been built based on the successful Phase I test work. Operational labor and technical supervision from this related venture were used for the silicon/Ferrosilicon project.

Hollow electrodes have been used successfully in submerged arc furnaces for the commercial manufacture of calcium carbide. Several team members developed and have extensive experience in this area. The plasma arc ferrochromium effort, mentioned previously, also generated an experience base working with hollow electrode feed to a plasma arc furnace. This furnace operated in an open bath mode.

This project was directed toward an open top submerged arc furnace to enable mechanical stoking of the charge as is practiced in the conventional process. Combustibles from the burden were burned above the bed and captured with a hood. This avoided a number of operational problems at this stage of the development program. In the future, it will be easier to consider enclosing the top of a single electrode furnace than the three electrode version. Dow-Corning company has built a sealed silicon furnace in Canada, with a closed top. (Dosaj, V. D., Et al.,

"Plasma Smelting of Silicon") This is a higher risk and a more costly venture than the work addressed in this proposal. It supports the technical validity of the project, and the works complement each other.

This technology offers many controllable operating parameters not present in the conventional process. Feed rates of the fine and coarse silica ores and reductant can be independently controlled and adjusted in relation to the power input level. The stoichiometry of reactants in the plasma zone of the furnace becomes controllable within a short time frame. This provides an opportunity for computerized control and optimization of the process not previously possible. This translates to improved product quality, increased product yield, and higher thermal efficiency.

3.1.2 Wide Applicability

Once demonstrated on a reasonable scale, this technology is widely applicable to the domestic production of Ferrosilicon alloys and silicon metal. The technology can be retrofit into existing ferroalloy plants, making good use of major existing investments in infrastructure and capital equipment. Retrofitting will require furnace modifications, electrical rectification of power supplies, and computer control hardware.

Because of the modest capital investment required and significant operating cost savings projected, it is obvious that the domestic producers will be anxious to adapt the technological advances that result from this project. Thus, the effects of this project offer an industry-wide impact.

The ferroalloys companies technical participation in the project enhances the effectiveness of technology transfer to them. Implementation of this technology will improve their competitive position on the global market through superior technology and improved product quality. For these same reasons, it will enable these companies to recapture some of the domestic market which has been lost to low-cost imports. High quality silicon ores are available domestically, and indeed in most parts of the world. Price competition is based on operating costs, transportation costs, tariffs and foreign subsidies. The main operating cost factors are labor, electric energy, electrodes, and reductant. Energy savings will have a major positive impact on operating costs. Electrode savings are also important. Also, significant capital requirements for retrofit are manageable.

3.1.3 Reduced Energy Consumption

The production of all silicon alloys entails high specific energy consumption, mostly in the form of electricity. Carbo thermic reductant and carbon electrodes can be thought of as additional forms of energy consumption. The usage of carbon electrodes is traditionally high. Ferrosilicon uses less specific energy per unit of silicon than does silicon metal in proportion to the alloy grade; however, this usage is still relatively high.

Energy savings to be realized from this technology come from a number of areas. Electrode consumption will be lowered by an anticipated 30%; this is a direct savings in materials and energy

spent for making electrodes. The efficiency of energy transfer to the arc will improve because the DC furnace does not have the reactance of an AC furnace. Operating control parameters will improve product yield by at least 5%. This results in an important energy savings per pound of product. Overall energy savings are conservatively estimated at 5-15% improvement over conventional practice.

Finally, the new technology and single electrode configuration, with its inherent semidry, will make it easier to enclose the furnace to capture off-gases as a usable low-BTU fuel source. This energy saving is not reflected in the 5-15% energy savings estimate for this project. Thus, greater energy savings may ultimately result from the implementation of these technologies.

3.1.4 Manageable Risk

This is a low-to-medium risk project due to several factors. First, the component technologies to be employed are well understood by the participants. It is a combination of the best of traditional and emerging DC plasma technologies. The STCC Team is well-versed in these technologies because its members have extensive experience with silicon processing and metallurgical technology, as well as experience in hollow electrode systems. As a result, they can develop a test system that is responsive to industry needs. The Team includes experts in the management of complex technological projects. Finally, team members are dedicated to the success of this project.

3.1.5 Potential Benefits

The benefits that were anticipated from this project are significant. Savings in specific energy consumption is expected to result from the implementation of this technology. Electrode consumption will be measurably reduced, and will have a significant impact on production costs. Process control is expected to be significantly improved. A higher quality product can be produced at a lower cost if the technology is successfully implemented.

The successful completion of this project opens the way for significant future benefits. Potential savings to the domestic industry may be as high as \$23 million per year. The U.S. silicon/Ferrosilicon industry can expect an increasing share of the domestic and global market as this technology becomes widespread in the domestic silicon/Ferrosilicon industry. Future development of a closed furnace system will facilitate the collection of exit gases as a fuel.

A total reduction in specific energy consumption of 5-15% is possible because of several important factors. One factor is lower thermal losses. Specific energy savings were often not realized in other plasma furnaces because these energy gains were overshadowed by high thermal losses due to an open bath structure, which allows more heat to be lost. The lower thermal losses in a submerged arc operation, on the other hand, allows the realization of these gains. Furthermore, a single electrode operation offers greater electrode depth than is usual with a three electrode operation. The retrofit will be designed with a greater height to diameter ratio. This results in improved product yield, and, therefore, reduced energy consumption to meet desired yield. Finally,

the direct current furnace eliminates reactance, a significant factor in energy loss in alternating current furnaces. As a result, the energy is more efficiently used for smelting.

The elimination of reactance in the DC electric furnace also reduces electrode consumption. High surface currents, referred to as skin heating, and associated with ac electrodes are nearly eliminated. The DC current is more uniformly distributed through the cross-section of the electrode. Electrode consumption is traditionally high in electric furnaces and particularly high in furnaces where intermediate reactants can attack the electrode. Since hot silicon monoxide gas in the furnace can and will react with the carbon electrode, it is important that the deconfiguration exposes much less electrode surface to this gas for reaction than does a comparable AC furnace. On the other hand, DC steel furnace operations have shown reductions of as much as 70% in graphite electrode usage.

Currently, process control is not adequate to the needs of the industry. Hollow electrode technology could help overcome this problem. The use of fine mix feed through the hollow electrode, if perfected, should permit the operator to adjust relative chemical and electrical parameters almost immediately. Such a level of control is not available in a conventional silicon/Ferrosilicon furnace where desired reactant and chemical changes require hours rather than seconds to effect. This added tool has the potential to lead to an even, predictable operation with increased quality control and product flexibility.

~ Three Factors Affecting Energy Efficiency ~	
Reactance	Energy in an AC furnace is wasted as a result of electrical reactance. In a DC furnace, the reactance phenomenon does not exist.
Energy/Yield Ratio	Due to the ability of the single electrode to move deeply into the material, higher yields result from improved silicon recovery in the furnace burden; i.e., holding energy spent as constant, yield increases or holding yield as constant, energy expended is reduced.
Thermal Heat Loss	Using a submerged arc reduces thermal heat loss. Since the arc is submerged in the material, less of the energy is radiated to the roof.

With the opportunity to feed a portion of the raw materials in a fine, granular, naturally occurring state, (sand), high quality Ferrosilicon products for electrical steels and foundry alloys and silicon metal for chemical and aluminum applications will be feasible at reasonable production costs. Stringent customer demands for high quality, purer alloys will be met. Thus, responsiveness to market will be improved.

A single electrode furnace suggests a design which can be used for further research. Unlike a three-electrode furnace, a single electrode design more readily enables the construction of a closed furnace for silicon metal; this allows increased energy savings because the product off gases can be captured and used as a secondary fuel source. This type of research is beyond the scope of the current project, which will focus on the implementation of direct current, hollow electrode technology; however, this project will pave the way for further enhancements.

The total projected savings resulting from these cost reductions, based on 1990 domestic production, would range from about \$10-23 million over the course of a year. The estimate does not take into account any improved market share by domestic competitors which will result from a higher purity, more competitive product. This factor will further enhance system cost competitiveness.

The reduction in production costs, coupled with the increased quality of the product will make the U.S. silicon/Ferrosilicon industry more competitive on the global market, resulting in an increase in the domestic and world market share. This will provide significant benefits to the industry.

This process is environmentally clean. Hazardous waste is not generated. Process fumes will continue to be used for concrete manufacture where they add product strength. The implementation of this technology will have no adverse affect on the environment.

The benefits of this technology are summarized in the following table.

~ Technology Benefits ~
<i>Reduced Specific Energy Consumption</i> -- 5-15% total reduction in energy consumption is possible.
<i>Reduced Electrode Consumption</i> -- a 15-30 % reduction in electrode consumption.
<i>Improved Process Control</i> -- Desired changes in process control will take seconds instead of hours.
<i>Product Quality Improvement</i> -- Higher purity alloys, product flexibility.
<i>Ability to use Fine Ores</i> -- Fine ores in higher parities are less expensive than coarse ores, and do not require crushing prior to use. These ores produce a higher quality product.
<i>Environmental Safety</i> -- This process is environmentally clean. Hazardous waste is not generated. Process fumes will continue to be used for concrete manufacture where they add product strength.
<i>Potential Savings to the Industry</i> -- The total projected savings resulting from these cost reductions based on 1990 domestic production can be as high as \$23 million.
<i>Increased Market Share</i> -- The reduction in production costs, coupled with the increased quality of the product will make the U.S. silicon/Ferrosilicon industry more competitive on the global market, resulting in an increase in the domestic and world market share.
<i>Potential of a Closed Silicon Furnace</i> -- Future development of a closed unit will facilitate the collection of exit gases for use as fuel sources. This will result in further energy improvements.

3.2 Test Plan

The technical committee of the STCC constructed, critically evaluated, and agreed upon a test plan to maximize the use of available experience and the technical resources of the member companies. This plan was summarized in a Test Sequence Matrix assuming three months of testing. Companies committed to supporting various segments of the testing with manpower and technical supervision. At this stage of planning, it was assumed that testing would involve roughly equal time periods on FeSi50, FeSi75, and Silicon metal. Three day data collection periods at constant operating parameters were established as the optimum for this scale of operation. Tests with and without feed down the electrode were anticipated. The master test plan appears as Appendix G.

In mid-June, half way through the program, a revised test plan focusing on the remaining Silicon metal portion of the program was prepared and reviewed with the remaining active testing participants. Lessons learned in the FeSi50 experiments were reflected in this updated plan. The test furnace was cleaned and relined. The plan consisted of a start up regiment and seven three day test sequences. The plan called for extensive use of feed down the electrode. Indeed even the start up involved hollow electrode feeding.

Start-up

As planned, the furnace heat up was conducted with all the quartz and coke as reductant added to the furnace through the electrode. Wood chips as needed were added by shovel to the top of the furnace. The initial arc was struck against a small pile of coke under the electrode. Power was increased to 300 KVA over a period of four hours. Some wood chips were added to cover the electrode. Quartz and coke were fed down the electrode commencing at a low rate (2lbs./min. and 0.9lbs./min) and power was steadily increased to 80V and 5000A. To the extent feasible, these conditions were held for the next 12-16 hours. Over the next two days as the furnace approached a steady state temperature profile power was ramped up to 1000KVA and feed rate increased to 7.9lbs./minute quartz and 3.1lbs./min. coke breeze. Beginning on day two, it was planned to tap the furnace once per shift.

Test Period Si 1

The initial test period (Si 1) was set to last for seven days. This sequence would try to establish acceptable operating parameters with all quartz and coke added to the furnace via the electrode. The goal was to achieve three contiguous days of steady operations at one set of conditions. Field trials would determine (burden depth), and how much of a submerged arc operation was feasible.

Test Period Si 2

This was planned as a base case test period. The furnace would be run in a full submerged arc mode with no feed through the electrode. Feed materials consisted of fine quartz, coal and wood

chips mixed to a carbon theory of 90%. The furnace would be tapped once per shift. The goal was three days of steady state submerged arc operations.

Test Period Si 3

In this period only quartz would be added to the furnace through the electrode. The feed rate would be adjusted to give about 25% of the total quartz input. Normal charge mix was added to the furnace by shovel from the top. Extra coal was added to the top mix formula to balance the silica added through the electrode. The furnace would be tapped once per shift. There may be a scheduled eight hour power shut down during this period.

Test Period Si 4

This period differed from Si3 in that the feed rate through the electrode was increased to 50% of the total charge silica and 25% of the calculated fixed carbon would be added as coke breeze through the electrode. The deficiency in fixed carbon was made up by extra coal in the top mix charge burden.

Test Period Si 5

It was intended to use this test period to obtain more experience and a second data set operating the furnace under conditions found to be favorable in the earlier tests. This would involve some level of feed through the electrode and may or may not have included reductant through the electrode. Maximum sustainable power levels would be attempted which may exceed previous test conditions.

Test Period Si 6

This test sequence was reserved for a repeat of the base case, submerged arc operating conditions. It was aimed at reinforcing test data. Test period Si6 could be abandoned or modified if necessary to accommodate other test conditions identified as of particular interest during earlier testing.

Test Period Si 7

This block of test time may be used to apply knowledge gained in the silicon metal testing to the 50% FeSi alloy work. If done, this extension must be done at the end of the silicon metal series to avoid premature contamination of the system with iron. Alternatively, this period could be used to run a single set of parameters on 75% FeSi.

3.2.1 Silicon DC Submerged Arc Smelting

When it became clear that feed down the hollow electrode was not technically feasible, the test plan was revised again to maximize the useful data obtained on DC submerged arc smelting of

silicon metal. Three, three-day test sequences were scheduled at 60V and 8000A, 4000A, and 6000A power settings. These were to be run with the furnace full to the top with burden and a unified stoking practice.

3.3 Raw Materials

Efforts were made to use high quality, raw materials as typical as possible of those used by the silicon industries. Raw materials consisted of fine and lump quartz, sand, wood chips, coal, coke, iron borings, and steel punching. Analytical tests were run to insure that the composition of the materials were known.

The lump and fine quartz came from North Carolina and is the same quartz used by several producers. The lump quartz was approximately 2" x ½" nominally, however, there was a considerable amount of fine quartz included which dictated that the material be screened prior to introduction into the furnace. This material was screened on site to ½" which resulted in only 2" x ½" lump quartz being introduced into the furnace. The fine quartz, or white gravel, was 1/4" x 1/8" and of uniform good quality requiring no additional preparation after receipt. The sand used during the test was an industrial grade dry sand, JC-20 purchased in 100# bags pelletized and stretch wrapped. This sand was of high quality and free of moisture. Coarse and fine quartz gravel were unloaded and outside. When rained upon they drained freely and did not hold significant water content. The coal consisted of two grades from the same seam, but of differing ash content. The grades of coal used were S-2 low ash blue gem and S-3 medium ash blue gem from Gatliff coal provided by Scancarbon, Inc. Coke was obtained in dry supersacs in 3/8" x 10" mesh size. Supersacs were used to insure a low moisture content. Wood chips were obtained locally, as required on short notice, and were a 3/4" hardwood paper chip. These chips were of high quality as the team sampled the product prior to purchase.

The other main raw materials used during the test consisted of low lead scrap iron, or iron borings, and 3/8" steel punching. These materials produced significantly different results when introduced into the testing process. A chemical analysis of each mater is included in figures 7, 8, and 9.

Iron and Steel											
	Fe	S	Cr	Ni	Mn	C	P	Ti	Ca	Pb	Cd
Iron Turnings	72.3	0.16	0.32	0.78	0.6	4.31	0.008	0.018	0.41	0.001	0.002
Iron Turnings	80	0.16	0.38	0.08	0.6	4.31	0.008	0.02	0.41	0.0031	0.0002
Steel Punchings	98	0.04	0.2	0.26	0.48	1	0.015			0.0058	<.001

Figure 7 - Iron and Steel Analysis

	Al ₂ O ₃	Fe ₂ O ₃	CaO	TiO ₂
Coal - Low	25.11	18.34	10.06	1.01
Coal - Med	22.06	28.82	2.37	1.03

Figure 8 - Ash Content

Raw Materials													
	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	CaO	Moist	FC	TiO ₂	P ₂ O ₅	Ash	VM	S	
Lump Quartz	98.97	0.04	0.223	0.102	0.012	0.00		0.004	0.003				
Fine Quartz	98.69	0.08	0.280	0.400	0.050	0.60		0.004	0.002				
Sand	99.30		0.116	0.062	0.008	0.00		0.004	0.003				
Coal - Low							58.50			1.06	40.44	0.76	
Coal - Med							57.93			3.61	38.46	1.04	
Coke						<1.00	88.88			8.36	2.76	0.90	
Wood Chips						42.00	7.50				50.50		

Figure 9 - Raw Materials Analysis

Furnace feed mix make-up (carbon theory) for FeSi50, FeSi75, and Silicon metal can be seen in Table I.

Table I - Furnace Feed Mix Makeup

50% FeSi	Quartz	Iron Borings	Coal	WoodChips
110% Fixed Carbon	900lbs	350	610	300
119% Fixed Carbon	900lbs	350	660	300
109% Fixed Carbon	1000lbs	440	634	500
Silicon Metal	Quartz	Iron Borings	Coal	Wood Chips
105% Fixed Carbon	1000lbs	0	585	1000
110% Fixed Carbon	1000lbs	0	620	1000
113% Fixed Carbon	1000lbs	0	640	1000
75% FeSi	Quartz	Iron Borings	Coal	Wood Chips
110% Fixed Carbon	1000lbs	200	585	1000

4 Engineering Design and Modifications

Furnace modifications involved changing the furnace from an enclosed configuration with a refractory roof to an open top configuration. The existing furnace placement was left as is, as was the furnace shell and conductive furnace bottom. The side wall refractories were replaced. The height of the furnace was extended and a new hood arrangement was installed to capture off-gases.

4.1 Design Modifications

Hatch Associates was retained to provide detailed engineering design drawings for required equipment modifications. They were contracted on an established hourly rate basis with a not-to-exceed contract limitation. The inside working diameter of the furnace was fixed by the existing steel shell dimension of the furnace and the refractories necessary to build up the side walls. The furnace had previously been operated in an open bath mode for which a side wall height of about 40" was suitable. For submerged arc testing, greater bed height was needed. This was achieved by adding a flanged steel spool piece extension on the top of the furnace shell which added 18" to the height of the furnace.

Because the furnace was to be fed and stoked manually from the top, new working platforms were required. To reduce worker exposure to electrical hazards, the decks of these platforms had to be electrically insulated. Platform height was set at the level of the new top of the furnace. On the west side, the platform extended to the existing mezzanine floor structure. This was smaller than optimum, but acceptable. It was one step down from the mezzanine elevators. A new platform to the east of the furnace was of optimum dimensions and provided a second access ladder to the floor level. These two platform sections were joined by a removable walkway to the south over the casting mold. The platforms and walkway were constructed of a steel frame and steel floor grating. Plywood decking was anchored to the steel grating and ½" rubber matting was installed on top of the wood. Hand rails around the furnace, the furnace shell and the furnace hood were all grounded electrically. The central graphite electrode, clamp, and part of the arm mechanism were electrically "hot" relative to these grounded structures. Drawings M-003 and S-001 in Appendix H show the structural details of the new work platforms.

The furnace hood was a complicated structure subject to several physical constraints and requirements. It was fabricated of mild steel and refractory lined. Because of limited available electrode arm travel, the center of the hood had to be as low as practically allowable. The hood was suspended over the furnace on brackets and allowed a 3" air gap all around for cooling air. It had two off-gas duct connectors on either side of the electrode. The central electrode entry port had to be electrically insulated, yet fit snugly around the electrode. The hood was slightly larger than the inside diameter of the furnace. Initially, sliding doors on either side of the hood permitted adjustable opening to work the burden pile in the furnace. These doors could be closed off entirely, if desired, or opened to a wide rectangular slot opening. With the doors open, the furnace could be stoked from several positions and there was good access to all portions of the top of the furnace. With the doors mostly closed, laborers were well protected from bed eruptions.

A new pulse jet baghouse from BHA was installed, replacing and upgrading an inadequate unit. Special, high-temperature fiberglass bags were donated to the project by BHA Corporation, who also donated a CPM 3000 opacity meter. The bags were manufactured from a newly developed teflon-coated fiberglass material.

New duct work was required between the hood off-takes and the baghouse. The initial sections of duct were refractory insulated to protect the steel from high operating temperatures at the hood. Dilution air from the tapping hood joined the duct work to the east of the furnace, and a common uninsulated duct ran to the baghouse. Manual dampers allowed modulation of the flow from the various source points. These were adjusted infrequently on an as needed basis. Some silica fume accumulated in the hood off-takes and required periodic cleaning. The duct design is shown on several drawings in Appendix H.

A used 6'x 6' cast iron mold was obtained from SKW's Niagara Falls plant as a program donation. This mold fit snugly under the tap hole between structural steel platform supports. The mold was lined with a shallow layer of dry sand. Alloy or metal was removed from the mold after each tap. Very little slag was tapped from the furnace during test operations, and usually was associated with an upset condition.

Charge skips (steel boxes) were lifted to the charging platform by overhead crane. These contained about 500 to 600 lbs of charge mix. Mix was shoveled manually from the skips into each side of the furnace. The skips were refilled by using a concrete dump hopper and the overhead crane. Each filling of the skips was logged in the record sheet. See Appendix B. The transfer hopper would hold 720 lbs of mix and in later tests this quantity was charged to each box.

Fume, collected and discharged from the baghouse, was accumulated in super sac shipping bags. In the later tests, a platform scale was obtained and the super-sac sat on a wood pallet directly on this scale. Thus fume weight collected corresponding to each tap was logged as part of the operating data on the tap sheet summary. A sample of this sheet is in Appendix I. Baghouse fume tended to hang up on the sloped surfaces of the discharge bin at the bottom of the baghouse. This was manually broken free by periodically rapping on the sides of this bin with a 12-pound hammer. Some tap-to-tap variation in fume rate data is due to variability in this procedure. Overall fume production data is meaningful because no permanent build up of fume was experienced. Ease of fume discharge was greatly influenced by the baghouse operating temperature and ambient air humidity. On very humid days, the fume product became sticky and frequent blockages of the discharge screw conveyer were experienced. The problem was less common at night and on less humid days. Fume analysis was performed periodically and is shown in figure 10.

Fume Analysis																			
	Date	SiO2	Al2O3	Fe2O3	C O	NgO	Cd	PbO	Moist	LOI	C	MnO	TiO2	P2O5	Cr2O3	Na2O	K2O	ZnC	So3
	1994																		
FeSi	5/17	60.2	1.90	18.80	0.34	3.7	<.001	0.0220	0	4.22	4.5	0.98	0.042	0.037	6.80	0.380	0.23		
FeSi	6/9	80.4	2.00	7.50	1.20	2.6	<.001	0.0030	0	4.55					0.40				
FeSi	8/5	74.7	2.00	16.90	2.10	2.1	<.001	0.0037	0					0.047	0.50	0.200	0.23	<.001	
Si	7/27	93.9	0.75	0.51	0.46	2.6	<.001	0.0037	0	8.90				0.037	0.47	0.058	0.17	0.58	0.22

Figure 10 - Fume Analysis

The PLC-5 process control computers, alarm and data logging system was customized, revised, simplified, and upgraded in an effort to improve data logging capabilities. Troublesome thermocouple multiplexing boards were eliminated and new thermocouples from the furnace shell were direct wired to new TC cards installed in the PLC-5. An expert was hired locally to set up and properly calibrate and scale the computer data collection. Midway through the test program this was partially reprogrammed by an engineer on loan from SKW Corporation. The data logging computer was neither magnetically shielded nor enclosed, which resulted in some hardware and software difficulties. As a consequence, the functionality of automatic data capture was deficient and incomplete. Manual data recording was also utilized to supplement automated data recording. Appendix J (samples of manual forms used).

In the process of facility design modifications several technical committee meetings were convened to seek consensus, obtain expert guidance, and resolve open technical issues. In all cases the technical team worked together effectively. Each company had full opportunity for input into the program and most responded. A final pretest meeting of the technical team was convened on April 12, 1994. The purpose of the meeting was to plan the test phase of the program as well as building team relationships. This was accomplished in a superb manner. The STCC member companies were well represented from the upper technical management level. The participation and contributions by the attendees was positive and enthusiastic and aided tremendously when test operations began. Appendix K (April 12, 1994 Technical Meeting conference minutes)

4.2 Construction

Furnace modifications consisting primarily of ducting, hood, spool piece, and platforms were competitively bid. Huber Construction Company won the bid and performed the modifications as enumerated in paragraph 4.1. Field supervision was provided by SCRA and weekly scheduling, progress, and safety review meetings were held at the site. Construction work was completed on schedule.

5 Test Program

The test program involved operation of the test facility specifically to produce 50% FeSi, 75% FeSi and Si metal under controlled and monitored conditions. Available funding indicated that two to three months of around the clock testing would be possible. Based on this limitation a detailed test plan was prepared and reviewed with the technical team, DOE, and other interested parties. An overview of the test plan is provided in paragraph 3.1. It was agreed that testing would begin with 50% FeSi alloy because operating experience showed this to be the easiest alloy to produce. Silicon metal was acknowledged as far more difficult to work with. Parties agreed that 75% FeSi testing should be placed at the end of the schedule with relatively low priority status because commercially, this is a minor product and not of great interest to the producing companies. The consensus was that should any experimental difficulties arise, the 75% FeSi testing could to be sacrificed or curtailed. By plan, the schedule called for the furnace to be shut down, cooled off, dug out, and relined before the silicon metal tests were run. This was necessary to eliminate as much iron as possible from the system.

The test plan called for the furnace to be operated at a specified set of conditions for three days with constant monitoring to establish each operational data set. Tap-to-tap variation was anticipated. Material balance closure on silicon for each data set was considered very important but acknowledged as difficult to obtain in field tests.

Campaigns on FeSi50 alloy and on silicon metal are discussed separately in the following sections.

5.1 50% FeSi Alloy

The furnace, newly lined with a carbon paste sidewall and bottom, was first energized on 11 May to begin baking in the lining. The final stages of construction were still ongoing. The furnace was charged with coke, the electrode was lowered into the coke and current was passed through the bed of coke. Power was applied intermittently, based on the amount of fume, smoke, and flame coming from the carbon paste as organic binders were distilled and driven off. The hood was not in place during this operation in order to protect the baghouse. The furnace was cooled on 13 May to allow final installation of the hood and duct work. The first mix was charged to the furnace on May 17.

On FeSi, initial target operating power conditions were 130V and 6000 Amps. Trying to hold these conditions resulted in the electrode being raised to the top of the charge bed. With the furnace full of mix, this is an inoperable condition because little or no energy is released low in the furnace and the bottom remains or becomes cold. The furnace cannot be tapped and drained with a cold bottom. The electrode must be lowered and positioned such that the bottom of the electrode is 6 to 12 inches from the bottom of the furnace. It was quickly determined that the high electrical conductivity of the charge pile was conducting electricity to the carbon side walls of the furnace crucible, resulting in side arcing. Extra wood chips did not adequately control side discharging of the arc via the burden pile. A secondary problem with this mode of operation was that the top of

the furnace ran very hot, as did the baghouse. Maximum draft was needed to control baghouse temperatures.

The high draft and hot top operations resulted in sparks traveling in the off-gas stream being transported through the flue system to the baghouse and perforating some bags. The baghouse stack which had been visibly perfectly clear, then showed a smoke discharge. Because continued operations with a visible stack emission would be in violation of the Department of Health and Environmental Control (DHEC) operating permit, the furnace was shut down for repairs on 18 May.

A smoke test of the baghouse indicated approximately 20 damaged bags in the inlet end of the baghouse. Spot inspections indicated the damaged bags had finger size holes burned in them from sparks and hot embers held against the bags. Failure was at the point of impingement. The bags had not been overheated in other respects. These bags were special order items and not stocked, and therefore, had to be ordered and manufactured before they could be shipped. All the bags in the baghouse were inspected and ultimately 28 were replaced. The baghouse was leak tested before being placed back in service. A new spark box was installed in the duct system down stream of the insulated duct work. This was a large vertical, baffled drop-out chamber. It provided for some additional heat loss, a lower gas velocity, particulate impingement, change of direction, and a dead zone for particulate and sparks to accumulate. An inspection door was provided to clean the chamber when the system was down. No further difficulties from sparks at the baghouse were experienced after the spark box was installed.

Ferrosilicon testing resumed after reheating on May 27th. For several days, the operators and supervisors gained experience as to the operating characteristics of the furnace. Charges of quartz and wood chips around the electrode helped keep the electrode low in the furnace. Some limestone on charge helped to thin a thick slag. The tap hole was opened by use of an oxygen lance. A liquid oxygen storage system with vaporizer improved oxygen availability over the previously used cylinder manifold system. We also learned to burn down the burden in the furnace by withholding mix additions to clean up the furnace crucible and general conditions of the furnace. It was apparent that the furnace could not be run at high voltages ($> 120V$) and full of mix. It would run satisfactorily with a low burden (blowing open). Acceptable quality Ferrosilicon metal was produced and tapped from the furnace on a regular basis. Daily hand-written log sheets are enclosed as Appendix L.

The main power supply transformer has two three-phase outputs; one referred to as the Delta circuit and one as the Wye circuit. These are supposed to be in balance with half of the DC power coming from each. This balancing circuitry became progressively less reliable. A manufacturers service representative was called in to repair the power supply and in particular the Delta/Wye balance bridge. In working on the unit, he caused several (8) of the high amperage fuses to blow and these had to be flown in for replacement. Several days were lost in trouble shooting the power supply. Ultimately, a poor solder connection to an inexpensive resistor was found to be the source of the problem.

The furnace was not successfully operated in the full submerged arc mode during these shake down tests, because of the inability to maintain target operating voltage. The furnace was, however, run with shallow charge bed. Good quality Ferrosilicon was produced.

Attempts to feed quartz sand, fine quartz gravel, or gravel and coke directly into the arc zone of the furnace were largely unsuccessful due to frequent charge blockages in the electrode. Sustained feed down the electrode for more than about one hour was not achieved. No useful operating data was obtained with feed down the electrode.

At the conclusion of the July 94 Silicon metal tests, one additional test period of three days was tried on 50% FeSi with 3/8" steel punching substituted for the iron borings previously used. This test period also took advantage of the non-conductive sidewalls of the second furnace configuration and procedural gains from the silicon metal test work. By this time we had experienced more acceptable operations at lower voltage (60V) and lower furnace power levels. This test period was successfully completed at 60V and 7,000 Amps from August 3-6.

5.2 Silicon Metal

For this portion of the test program, the furnace was relined with plastic 90% alumina ramming refractory. Preheating of the new lining began on 22 June. The initial silicon test involved feeding sand and coke down the electrode into a furnace containing a large pile of wood chips which covered the electrode. Repeated electrode blockages were experienced. The feed rate control system tended to deliver too much quartz because we were at the lower design limit of the equipment. This required close adjustment to the bin discharge gate at the weigh feeder.

Furnace operations were again interrupted when lightning destroyed the main off-gas blower motor on June 30. When a new motor was purchased and installed, excessive blower vibrations indicated that the blower bearings were also destroyed by the lightning strike. These had to be obtained out of state and flown in. After resuming operations, further exploratory testing demonstrated that the furnace could be run in the submerged arc DC mode when making silicon metal. Operating voltages of 100 to 120V were sustainable, but the furnace ran well at lower voltage. Furthermore, was easier to keep the electrode low in the furnace. Feeding sand down the electrode while the electrode was submerged in a charge pile of quartz, coal and wood chips was not sustainable. Blockages low in the electrode required excessive down time to clean out the electrode.

Because the computer data logging system was not completely reliable by this time, an extensive system to manually record all necessary data was initiated. The operator in the control room was required to fill in several standardized data sheets as well as control the power supply and periodically shovel charge mix to the top of the furnace. The shift foreman logged other data, periodically checked the functioning of all equipment, made up mix batches, and oversaw the tapping of the furnace. Technical supervisors maintained a research log book, checked that all data was properly recorded and worked up a daily shift summary sheet. Sample data sheets are attached to this report as Appendix N.

Between 1 July and 30 July, the furnace was operated on silicon metal in a fully submerged mode for three 3-day test periods at specified power input levels. Data summary sheets for these days are shown in Appendix O. A graphite spoon sample was taken from the tap stream for each tap. The furnace was tapped on a four hour cycle. The tap hole was opened primarily with an 8 gauge industrial shotgun. On occasion, oxygen lances were used with or without the assistance of the shotgun. Each lance pipe weighed 13 pounds. When lance pipes were used, they were counted and the weight of lance pipes was subtracted from the product weight. High iron levels in some samples is directly attributable to the use of oxygen lance pipes. Use of a graphite oxygen lance pipe was proposed, and tried, but never successfully implemented. The team member who had proposed using graphite lance pipes was unavailable to the program when needed.

An additional one-day test on silicon metal at even lower input voltage was run on July 30. Furnace operating parameters were 40V and 8,000A. Data for each of these test periods is summarized and included in Appendix O. From this data a smelting rate for each nominal power setting was derived and is plotted in Figure 11. This data fits a straight line. The line drawn on the figure is a least squares fit of the four data points. This line extrapolated to zero appears to very nearly pass through the origin. This tends to suggest that heat loss from the furnace is not a significant energy factor and heat loss through the charge bed is directly proportional to smelting rate. In this regard, DC submerged arc smelting differs considerably from the open bath smelting work which was previously conducted in the same furnace.

Figure 11 - Smelting Rate

If this line is taken as representative of the experimental findings, specific energy consumption can be plotted as a function of furnace power over the experimental range. This plot is shown in figure 12, and is obviously non-linear.

**Figure 12 - Specific Energy vs Power For Experimental Furnace
Runs: T1, T2, T3, and T6**

Commercial furnaces are normally operated at near design-capacity to maximize throughput. The curve shown in Figure 12 should not be taken to give any indication that operation of a larger furnace, at higher power levels, will result in high specific-energy consumption. This curve is for the small test-furnace configuration only and represents a limited amount of test data. It is accepted that a properly designed commercial scale furnace can be expected to operate at significantly lower specific energy than any comparably-configured test scale furnace. Indeed, a plot of Specific Energy Consumption vs Scale of Operation (for commercial furnaces designs operating at full power) will slope downward to the right (larger scale operation, higher power).

6 Evaluation

This section of the report presents the operating data obtained and the interpretation of the results. Typical data sheets as well as selected data sets and composite data averaged over multiple tap cycles are presented here in the body of the report. More complete daily summary sheets and individual tap metal and alloy composition data is assembled in Appendices M and N.

6.1 Data Acquisition

The collection of test data evolved and improved significantly over the course of the experimental program. The test program began with 50% Ferrosilicon and the initial emphasis was on start-up of equipment and learning how to run all subsystems while making 50% alloy. Data was collected on a PLC-5 process control computer and logged on a PC computer using Plant View software. In addition, a daily operating log was manually recorded and an experimental chronological running commentary was maintained. Appendix P is a typical daily log sheet dated 5/26/94. This log sheet tallies the furnace power consumption by shift, the time and weight of metal tapped from the furnace, outages and their cause, and other similar information. A complete assemblage of daily log sheets through June 17, 1994 is available in Appendix L. Most of the data logged by the computer during this period was lost due to computer malfunctions. Some was transferred to floppy disc, but is of little value. Spoon samples from almost all metal taps were taken using graphite spoon sample holders donated by one of the member companies. Each sample was analyzed by X-ray Florescence (XRF) Spectrometer by the Macalloy Corporation Lab.

For most, but not all of the silicon metal series, the computer data logging system functioned better. Data was printed out on a 10 minute cycle. Appendix C shows a typical print cycle. Again, difficulty was encountered in down loading data from the hard drive to disc. Hardware problems (computer) are due to the harsh working environment (dirt and strong magnetic fields) to which the equipment was exposed. The print record is complete except for short periods when the printer ran out of paper or ink. This record is available, but not appended due to its bulk. Recognizing the deficiencies in automated data logging, the manual data collection was markedly increased. The furnace operator, foreman, and shift supervisor were required to maintain several operating log sheets. The shift supervisor was responsible for auditing these records during the shift to ensure they were being maintained properly and accurately. Examples of these are attached at Appendix J. They are mostly self explanatory and simplified the data collection process. KWH meter readings were recorded hourly as was electrode arm position which gives a measure of electrode consumption. Mix charge to the furnace was recorded when it was delivered to the mix boxes on the furnace charge floor. The baghouse discharge was collected in supersacs which were weighed on a platform scale. Scale readings were recorded corresponding to each tap. The shift supervisor on duty collects the data sheets, audits them, and compiles a daily log of the operations. Appendix L contains all available daily log sheets.

6.2 Analytical Data

As described earlier in this report, a spoon sample was obtained from the tap stream each time the furnace was tapped. This sample was delivered to the Macalloy Lab for analysis. The sample was coarse crushed and an aliquot was further ground in a dedicated shatter box grinding device which was cleaned after each use. The sample was mixed with a weighed amount of binder, pulverized again for a set time in the shatter box, and pressed into a flat disc for insertion into the XRF analysis machine. Samples were compared against known standards prepared in a similar manner and x-ray counts at preset wavelengths were radioed by computer elemental interfaces were compensated for computer. Duplicate samples were submitted to a lab at one of the member companies. Analytical results for each tap analyzed are presented in Appendix M.

6.3 Data Interpretation

6.3.1 Silicon Metal

During the silicon metal testing period the furnace was successfully operated under stable conditions for several days. Three three-day tests were run at 60 volts and at several power levels. In addition, a one day (24 hour) test period was run at 40 volts and 8000 amps. These operating parameters are summarized in Table II. Table III summarizes the chemical composition of the metal produced in each of these periods. In Table IV, the quantity of silicon in the product metal is calculated for each of these periods and a smelting rate is derived. In figure 11 this smelting rate is plotted against the nominal operating power. As can be seen, these four data points fall on a straight line and the line, if extrapolated, appears to pass through the origin. The smelting rate was directly proportioned to power level over the range tested. For this to be true, heat loss from the furnace, bottom and sidewalls had to be inconsequential, and heat loss to the furnace off-gas was directly proportioned to smelting rate. This is reasonable for submerged arc operations. Figure 12 presents a plot of specific energy consumption as a function of furnace operating power. This plot was derived from the experimental line in Figure 11. It is interesting that the most favorable specific energy consumption occurs at the lowest furnace throughput rate.

Table II - Furnace Operating Parameters

Sequence Code	Target Alloy	V DC	A DC	Tap Cycle	# of Taps	C Theory	Bed Depth
T1	100%Si	60	6000	4hr	18	105-110	Full
T2	100%Si	60	4000	4hr	18	110-113	Full
T3	100%Si	60	8000	4hr	18	113	Full
T6	100%Si	40	8000	4hr	6	113	Full

Table III - Average Metal Composition

Sequence Code	Si %	Fe %	Ca %	Al %	Ti %	Mn %
T1D1	90.16	7.05	1.10	1.29	0.135	0.045
T1D2	95.32	2.32	0.89	1.04	0.073	0.021
T1D3	95.08	3.90	0.23	0.60	0.082	0.024
Avg T1	93.52	4.42	0.74	0.98	0.097	0.030
T2D1	96.97	2.40	0.059	0.30	0.052	0.014
T2D2	96.88	2.12	0.207	0.51	0.064	0.014
T2D3	92.26	2.93	3.13	1.41	0.077	0.017
Avg T2	95.37	2.48	1.93	0.74	0.064	0.015
T3D1	90.44	3.29	3.03	2.90	0.080	0.021
T3D2	95.62	2.54	0.55	0.98	0.077	0.020
T3D3	94.20	2.10	1.37	2.02	0.073	0.022
Avg T3	93.42	2.64	1.65	1.97	0.077	0.021
T6D1	89.20	4.44	2.73	3.27	0.086	0.024

Table IV - Smelting Rate

Sequence Code	Corrected Tap Weight (lbs)	Si (%)	Si in Metal (lbs)	Time (hrs)	Smelting Rate (lbs÷hour)
T1	3594	93.52	3361	70.34	47.8
T2	2567	95.37	2448	69.7	35.1
T3	3847	93.42	3594	61.1	58.8
T6	1050	89.20	936.6	22.9	40.9

In table V the quantity of fume collected for each period is included and the weight of silicon in the fume is calculated. A calculated silicon recovery is derived by dividing the weight of silicon in product metal by the total silicon weight in metal and fume products. For the ten days of silicon testing with the best data collection in effect, 74.6% of the total silicon collected was in the metal product. Electrode consumption was measured during each test segment. Table VI includes a value for pounds of electrode consumed per pound of silicon in product metal. The average for the ten days was 0.144 lbs of electrode per pound of silicon in product.

Table V - Silicon Metal as % of Total Silicon Output

Sequence Code	Si in Metal	Fume Weight	% Si	Si in Fume	Total Out	Si÷ Si Out %
T1	3361	2726	43.82	1194.5	4555.5	73.8
T2	2448	1532	43.82	671.3	3119.3	78.5
T3	3594	2567	43.82	1124.9	4718.9	76.1
T6	936.6	1205	43.82	528.0	1464.6	64.0
TOTALS	10,339.6			3518.7	13858.3	Average 74.6%

Table VI - Electrode Consumption Data

Sequence Code	Si in Metal (lbs)	Electrode Consumed (lbs)	Electrode Consumptions (lbs Elect÷lbs Si)
T1	3361.0	297.6	0.089
T2	2448.0	334.6	0.137
T3	3594.0	563.7	0.157
T6	936.6	293.3	0.313
TOTAL	10,339.6	1,489.2	Average 0.144

6.3.2 Ferrosilicon (Three Day Period)

Although the test facility was operated for several weeks on FeSi 50% in May and June, the best test data was collected during a three day period in early August when steel punching were substituted for iron borings used earlier. The use of steel punching enabled the furnace to be run in a submerged arc mode approximately 3/4 full of burden. The results of these tests are summarized in Tables II through VIII which present the following information:

Table VII:	Furnace Operating Parameters
Table VIII:	Average Alloy Composition
Table IX:	Smelting Rate
Table X:	Si in Alloy as % of total Si out

Table XI: Electrode Consumption Data
Table XII: Specific Energy Consumption
Table XIII: Online Time

Table VII - Furnace Operating Parameters

Sequence Code	Target Alloy	V DC	A DC	Tap Cycle	# of Taps	C Theory	Bed Depths
T8D1	50%	60	7000	4hrs	6	110%	3/4 full
T8D2	50%	60	7000	4hrs	6	110%	3/4 full
T8D3	50%	60	7000	4hrs	6	110%	3/4 full
T8	50%	60	7000	4hrs	18	110%	3/4 full

Table VIII - Average Alloy Compositions

Sequence Code	Si %	Fe %	Cr %	Ca %	Al %	Ti %	P %	Mn %
T8D1	45.0	53.2	0.42	0.16	0.37	0.10	0.017	0.07
T8D2	43.3	55.7	0.28	0.02	0.15	0.06	0.018	0.07
T8D3	45.3	54.0	0.36	0.02	0.12	0.04	0.017	0.07
T8	44.5	54.3	0.35	0.07	0.21	0.07	0.017	0.07

Table IX - Smelting Rate

Sequence Code	Tap Weight	Si %	Si in Alloy (lbs)	Time (hours)	Smelting Rate #Si 1hr
T8D1	2536	45.0	1141	23.5	48.55
T8D2	2874	43.3	1244	24	51.83
T8D3	4028	45.3	1825	23.9	76.36
T8			4210	71.4	58.96

Table X - Silicon in Alloy as % of Total Silicon Output

Sequence Code	Si in Alloy	Fume Wt	% Si	Si in Fume	Total Out (lbs)	Si Alloy÷ Si Out (%)
T8D1	1141	1175	74.7	875	2016	56.6
T8D2	1244	663	74.7	493	1737	71.6
T8D3	1825	698	74.7	520	2345	77.8
T8	4210			1888	6098	69.0

Table XI - Electrode Consumption Data

Sequence Code	Si in Alloy (lbs)	Electrode Consumed (lbs)	Electrode Consumption (lbs÷lb Si)
T8D1	1141	128.3	0.112
T8D2	1244	146.7	0.118
T8D3	1825	91.7	0.050
T8	4210	366.7	0.087

Table XII - Specific Energy Consumption

Sequence Code	Power Consumption	Alloy Weight	Si in Alloy	SEC
T8D1	9220	2536	1141	8.08
T8D2	9530	2874	1244	7.66
T8D3	9100	4028	1825	4.99
T8	27850	9438	4210	6.62

Table XIII - Online Time

Test Sequence	Online Time	Total Time (hours)	Minutes Lost (minutes)
T8D1	97.9	24	30
T8D2	100	24	0
T8D3	99.5	24	7
T8	99.1	72	37

6.4 Scale Up and Commercialization

Hollow electrode feed to a submerged arc furnace is not ready for commercialization. It has been shown that the temperature inside the electrode far exceeds the temperature at which silicon becomes sticky and this promotes electrode blockage. Scale up to a larger bore electrode is not likely to resolve the problem.

Scale up and commercialization of the DC furnace concept with a single central electrode is feasible, especially for silicon metal production. This work has demonstrated the technical feasibility of the approach. Results were sufficiently positive to justify scale up of testing to a semi-commercial size of 4-7 megawatts. The hardware items required to do so are commercially available. Indeed the 12 MW DC power supply at Macalloy is suitable. It has a capacity of 40,000 amps, which is just about right for a silicon demonstration unit. The 24" diameter electrode clamp and electrode winch are also probably usable. For a number of reasons, the Macalloy site and furnace is not suitable for a test site for a larger furnace.

Electrode consumption averaged 0.144 lbs per pound of silicon during these tests. Electrode is consumed by surface oxidation and clearly higher with small diameter electrodes than larger electrodes. A DC single electrode furnace will use significantly less electrode than a comparable three phase AC furnace. Specific energy consumption results derived in this project are encouraging. There is strong indication that a commercially sized DC furnace would use less electricity than its AC counterpart. Test results are not sufficient to quantify the magnitude of the potential savings. The projected 5 to 15 percent savings are still reasonable to anticipate. Sustained operation at a larger semi-commercial scale will be necessary to quantify potential savings. Operations at or above 4 megawatts is a necessary and logical step in the commercialization of the technology. Preliminary discussions indicate the silicon industry is interested in pursuing DC furnace technology.

7 Results

During the overall test program, about 58,000 lbs of 50% FeSi alloy and 29,000 lbs of silicon metal were produced in the test facility. Operating problems were largely overcome, and steady state operation was achieved on silicon metal production in a DC submerged arc mode. Hollow electrode feed was not achieved on a sustainable basis. The following specific subsections focus on results obtained during the silicon testing.

7.1 Yield

Yield can be defined in a number of ways. The most generally accepted would be:

$$\text{Silicon Yield} = \text{Si in product} \div \text{Si in Furnace Feed}$$

Table XIV presents yield data calculated in this manner. Yield values for individual periods vary considerably, from 70.8 to 119.4%. The overall yield is 83.7%. The data on weight of quartz charged to the furnace is somewhat suspect and is reflected in the yield data calculated in this manner. These are high values for silicon.

Table XIV - Yield

Test Sequence	Si in Metal	Si in Feed	Yield
T1	3361	4056	82.9%
T2	2448	2050	119.4%
T3	3594	5073	70.8%
T6	936.6	1173	79.8%
Total	10,339.6	12,352	83.7%

Yield can also be calculated as a percentage of total silicon output. This was done in table XII. The difference in the two yield values is due to non-closure of the material balance on silicon. Silicon material balance data is summarized below in table XV.

Table XV - Alternate Yield Calculation

Test Sequence	Quartz In	Silicon In	Metal Weight	Silicon In Metal	Fume Weight	Silicon In Fume	Silicon Out
T1	8781	4056	3594	3361.0	2726	1089	4450
T2	4439	2050	2567	2448.0	1533	612	3060
T3	10984	5073	3847	3594.0	2567	1025	4619
T6	2541	1173	1050	936.6	940	375	1312
Total		12352		10339.0		3101	13441

7.2 Power Consumption

Power consumption is usually reported as specific energy consumption (SEC) in terms of KWH per pound of silicon produced. During the silicon metal test periods, kwh meter readings were recorded hourly and at the conclusion of each tap. Power consumption for each test sequence is summarized in Table XVI. The overall average SEC value was 7.74.

Table XVI - Specific Energy Consumption

Test Sequence	Power Consumption	Metal Production	Silicon In Metal	SEC
T1	24610	3594	3361	7.32
T2	14801	2567	2448	6.05
T3	32200	3847	3594	8.96
T6	8430	1050	936.6	9.00
Total	80041		10339.6	7.74

Figure 11 earlier in the report plotted SEC versus Power derived from the experimental Smelting rate vs power line. The most favorable specific energy values occur at low power levels in the furnace.

7.3 Electrode Consumption

In other industries, it is well established that DC furnaces consume less electrodes than comparably sized AC furnaces. The major mechanism of electrode consumption is surface oxidation. Part of this occurs above the burden pile in the furnace. There is also some reaction between the carbon electrode and reactants and intermediates in the burden. We have observed a coherent layer of silicon carbide build up on the electrode surface when an electrode column is removed from the furnace. This was probably formed by reaction with hot silicon monoxide gas, below the burden surface. This provides a secondary reaction mechanism for electrode consumption. Charge mix composition will have a significant effect on electrode consumption. A mix deficient in fixed carbon promotes rapid electrode wear, as the electrode is used as a reductant. In a general sense, geometric factors are very important. One electrode presents only one third the surface area for reaction as three electrodes of comparable size. Similarly, larger diameter electrodes will have a lower surface to mass ratio and accordingly will wear more slowly. Electrode surface temperature is also an important factor in electrode consumption. Electrodes submerged in the burden pile become incandescent (very high temperature) below the bed surface. Table XVII summarizes electrode consumption in terms of silicon production.

Table XVII - Electrode Consumption

Test Sequence	Electrode Consumption	Metal Produced	Silicon In Metal	Electrode Consumption
T1	297.6	3594	3361	0.089
T2	334.6	2567	2448	0.137
T3	563.7	3847	3594	0.157
T6	293.3*	1050	936.6	0.313*
Total	1489.2	11058	10339.6	0.144

* A piece of electrode was broken off the column during this period.

The average electrode consumption rate over the silicon test periods was 0.144 pounds of electrode per pound of silicon produced. This included some loss of electrode due to breakage.

7.4 Online Time

Testing operations were curtailed a number of times due to equipment and other problems which were corrected. These shut downs ranged from several hours to several days, and were particularly disruptive because the furnace cooled off to the point that it required reheating time before data collection could be resumed. The major shut downs were due to the following:

- A Scheduled Macalloy Power Outage.
- A Substation Fire
- Lightning Strike--200 HP Motor Loss
- Replace Blower Bearings
- Loss of Baghouse Bags by Sparks
- Power Supply Delta/Wye Balancing, Fuses

Normal furnace operations did not involve down time. That is to say, that the furnace was charged with mix, stoked, and tapped under power. Many tap to tap cycles ran with power on 100% of the time. Electrode consumption required that a new electrode section (4 ft) be added about once every 1.5 to 2 days. This procedure was done with power off and required 20 minutes or less to complete, when done well. After adding an electrode section the furnace was re-energized and normal operations resumed promptly.

On several occasions the furnace power supply overheated and tripped out. This was due primarily to high cooling water temperature and weather conditions. These outages lasted 10 to 20 minutes, until the power supply cooled down. Sometimes the heat exchanger in the cooling circuit was blown out with compressed air to remove scale build up from the cooling water and improve heat transfer. Process water quality at Macalloy is very poor. These problems were intermittent, and more of an annoyance than a real impediment to the program.

Fume accretions tended to form in the duct work right at the hood connection. These had to be removed manually by poking at them with a bent pipe. For safety reasons furnace power was shut off whenever the ducts required cleaning. Downtime for duct cleaning averaged 15 minutes.

Finally, when running at high amperage, the power supply would occasionally trip off due to an over current excursion. It could usually be brought back online almost immediately. Lost time was one to two minutes.

Percentage of time online was recorded for each tap cycle and totaled on the daily log sheets. Table XVIII presents the online time information for the data collection periods of the silicon testing campaign.

Hollow electrode tests experienced frequent blockages of the feed system. When blockages were detected, the feed was stopped and furnace power was shut down. Usually the feed pipe was removed from the electrode by overhead crane. The pipe itself was generally easy to clean out. Feed in the pipe was not fused. Blockages in the lower end of the electrode were usually cleared with an air lance down the electrode from the top, which blew charge mix, sparks, and embers out the top of the electrode. When this procedure failed to clear the electrode, the entire electrode column was lifted from the furnace by crane, and cleaned from the bottom at floor level or substituted for with a new column. Depending on the severity of the blockage, the cleaning operation took from 30 to 120 minutes. With frequent blockages, no useful data was collected.

Table XVIII - Online Time

Test Sequence	Online Time (%)	Total Time (Hrs.)	Minutes Lost
T1D1	99.70	24	5
T1D2	100.00	24	0
T1D3	99.70	24	5
T1		72	10
T2D1	99.70	24	5
T2D2	97.70	24	48
T2D3	100.00	24	0
T2		72	53
T3D1	93.95	16	58
T3D2	94.16	24	84
T3D3	97.50	24	36
T3		64	178
T6	95.10	24	86

7.5 Off-Gas Recovery

The off-gas handling system consisted of: a hood over the furnace, insulated duct work, a spark box, control dampers, uninsulated ducting to the baghouse, a pulse jet baghouse, a control damper, the off-gas fan, and a short stack. An opacity meter monitored the stack after the baghouse, and exhaust fan. The stack was maintained visually clear by inspection. Smoke tests with florescent dye run on the baghouse established that it was operating leak free.

While the baghouse captured particulate matter in the off-gas efficiently, the fume collected did not discharge freely from the baghouse. The baghouse had a discharge hopper on the bottom with steep sidewalls that sloped into a screw conveyer at the bottom. Fume released from the bags tended to hang up on the sidewalls of this hopper until released by striking the sidewalls of the hopper with a hammer. This release and hold up was variable. It depended partly on the ambient humidity, being worst on days with high humidity or right after a rain shower. The screw conveyer discharge through a rotary valve air lock to a super-sac container. The super-sac was supported on a platform scale to monitor the rate of dust collection. Scale readings were recorded at the completion of each tap. Because the hold up of material in the baghouse hopper was variable, individual weights are

not reliable. However over multiple cycles the values become significant, in that the baghouse hopper never filled up and residual hang up was not as significant.

Note also that the production of fume was highly variable. It depended primarily on the presence or absence of blow holes in the burden pile. Very little fume was released when the furnace had a uniform cold top free of blow holes. Silicon recovery and thus efficiency is directly related to fume production. Fume production is heavily influenced by operating procedures, particularly stoking and charging practices. These practices varied with the operating crew, foreman, and supervision. The presence or absence of observers influenced stoking procedures and thus furnace efficiency. A standardized operating procedure was written up, posted, and discussed, but some level of variation persisted. Some shifts did consistently poorer than others. This observation would be true of any commercial submerged arc operation as well. It is feasible to improve recovery significantly by optimum operating practice. This is not easy to achieve.

7.6 Silicon Quality

The quality of silicon metal is measured by its chemical composition and the amounts of various impurity elements present. Different users (customers) will have different requirements. In general to be sold as silicon metal, the silicon content should be over 98%. In commercial operations some metal is refined by ladle oxygen injection. Impurities originate predominantly with feed materials charged to the furnace and from tapping procedures.

The best single tap of the silicon campaigns was tap # 31. It analyzed: 98.11% Si; 1.38% Fe; 0.026% Ca; 0.22% Al; 0.05% Ti; and 0.01% Mn. Taps with good metal quality tended to cluster together. When something disrupted metal quality, it took time and several taps for the perturbation to subside.

The quartz ore procured for these tests was of high quality, and as received did not contribute significantly to impurities in the product metal. The coal used was donated by Scan Carbon, and was a grade of coal specifically used by Silicon producers. Two grades were used: a mid ash grade and a low ash grade. For the silicon tests the low ash grade was required. Coal ash constituents are a major source of impurity elements in the product metal. Significant amounts of iron, aluminum and calcium can come from coal ash. See the section on raw materials for analytical information on the feed materials used.

More importantly, these materials were dumped on the ground at Macalloy and extensively handled by heavy equipment in making up charge mixes. The mix area was swept clean before testing commenced, but wind, rain, and traffic continually introduced dirt to the mix preparation area. Even the wood chips which were stored outside were visibly contaminated with plant soil. Some contamination was inevitable. The Macalloy soil consists mostly of crushed chromium smelter slag. It is high in iron, calcium aluminum, and of coarse chromium.

Two other controllable sources of contamination should be discussed here. They are limestone purposefully added to the furnace and iron lance pipes used to open the tap hole. Limestone was

added to the furnace on a few occasions when a sticky viscose slag was detected at the tap hole. This was suggested by an on site SKW expert, and seemed to help the problem. However, calcium levels in the product spiked up in direct response to these additions. It took more than one tap for the calcium level to return to normal after a limestone addition. Finally, when necessary, the tap hole was opened with an iron oxygen lance pipe. This was only done when the hole could not be opened by shot gun. The weight of iron pipe introduced was subtracted from the product metal weight, and the tap stream was sampled well after lancing the hole. Iron was none the less elevated in the sample button. Once introduced, iron persisted in the metal.

7.7 Projected Energy Savings

During ten days of sustained silicon metal production in the DC submerged arc mode, the specific energy consumption was 7.74 KWH/lb of Si in the product metal. When operated at 60V and 4000A the specific energy consumption was measured at 6.05 KWH/Lb of Si. These values are specific to this furnace. A larger commercial furnace should achieve lower yet SEC values.

As discussed earlier, smelting rate data suggest that heat loss from the furnace was not a dominant energy factor during these tests. Heat to furnace off-gases was proportional to smelting rate and was the main non-productive energy path. A larger furnace will have a higher ratio of burden volume to megawatt input, which will improve the specific energy consumption. It is projected that a commercially sized 10 to 15 MW DC furnace could produce Silicon metal at a SEC of <5.8 KWH/Lb S%.

The industry survey indicates the SEC for AC submerged arc furnaces averaged 6.39 KWH/lb Si while producing Silicon from 1985 to 1992. The DC technology offers a possible energy savings of 9.2% or better from this value. This projection is based on very limited data. It begs confirmation at an intermediate scale. Indeed more testing in the plasma arc test facility to confirm the findings would be worth while, but not as useful as larger scale testing.

7.8 Emission Reduction

From a fugitive emission stand point, a single electrode furnace will be easier to hood than a three electrode furnace. However, fugitive emissions are well controlled at present, and any improvement would be marginal.

Silica fume from silicon manufacture is a commercial product that is sold. While improved metal recovery, (corresponding to decreased fume production) is economically desirable, it does not have a strong environmental implication in terms of particulates and solid wastes. The process does not produce any significant amount of slag. Usually no slag is made.

The most important emission reduction attributable to improved technology is the reduction in carbon dioxide release to the atmosphere. Improved energy efficiency and metal recovery both contribute to the carbon dioxide emission reduction.

7.9 Economic Benefits through 2010.

Economic savings through the year 2010 were projected during the proposal phase of this project based on a 5-15% energy savings. The experimental data for DC submerged arc operation without feed down the electrode supports a 9.2% energy savings over conventional AC practice. This is a significant savings, and if sustained over an extended period, could serve as the basis of industry to strongly compete on conversion to DC power. Thus the earlier projections remain valid. More work is required to convince the industry that retrofitting existing furnaces is worth the expense.

8 Technology Transfer

Technology transfer can be enabled by taking advantage of all opportunities, including presentation of papers at technical meetings and publication of journal articles. Prior government (DOE) coordination was obtained on all information prepared for public release. The Ferroalloys Association (TFA) will have access to the information gained from the project. A conference will be conducted at the earliest possible time to present and evaluate the application of the results into the industrial community, and to determine, in conjunction with DOE, should any patents be appropriate.

A key activity in the STCC program is the transfer and implementation of technology and the use of the integrated structure to accomplish the transfer. When the investigative work makes major breakthroughs it will count for little if these results are not implemented on a widespread basis. Implementation of project results is extremely important and includes the training of users and other personnel within the ferroalloy companies.

Current technology transfer activities are isolated in "levels" of industry and normally applied to larger companies. The unique feature of the technology transfer proposed is its "multilevel" and smaller business approach. The technology transfer will use existing industry (associations) and government structures to aid the task of effective technology transfer. The approach supports the needs of smaller producers by providing them with an opportunity to become involved in the activity. The multilevel strategy provides a secondary benefit of "cross-transfer". This is where several industries benefit from communicating between one another.

Technology transfer, as it applies to the technical program of work, will be achieved by scheduled meetings between the team of researchers and program participants. This technology transfer operates most effectively when there is an open dialogue between the team members.

Member companies have not promoted an awareness of the industry or its importance, but it is a vital and cost effective manufacturing segment. Silicon/ferrosilicon producers are seldom overtly aware of the capabilities of the other producers in the industry. There is a need to educate individual companies on the capabilities of the silicon/ferrosilicon industry and particularly the design flexibility and inherent strength of new processes.

The critical step in any technology transfer is the successful scale up to commercial size. This can be accomplished by merging the results of this STCC research program with those from the Dow-Corning research project in Manitoba, Canada, to design, build, and operate a commercial DC furnace. This needs to be done in an operating plant at a U.S. silicon producing company. It will require Federal cost share support, with the input of major industrial cost share. Without this cooperative technology transfer, the technology advanced will languish and not be implemented by the domestic industry. A proposal for a commercial scale DC furnace conversion at a U.S. facility merging the Dow/STCC technologies is in process. Industry interest is very supportive for continued work in this area.

9 Conclusions and Recommendations

The report concludes that silicon metal and ferrosilicon can be very effectively produced in a DC submerged arc furnace. Specific energy consumption factors measured were favorable to the technology. Considering the small size of the test furnace, this indicates that significant energy savings over conventional AC practice are likely on a commercial scale. Hollow electrode feeding of the furnace does not appear feasible. Electrode consumption was 0.144 lbs/lb of silicon while making metal, much of which occurred above the burden pile. This indicates that significant electrode cost savings are available by DC technology. Silicon loss to fume averaged 19.5% of the silicon charge indicating a high silicon recovery.

In this furnace, 50% FeSi was more difficult to produce than silicon metal. High electrical conductivity in the burden mix severely limited the range of operating voltages available and thus power input to the furnace. The substitution of steel punching for iron borings in the charge mix helped mitigate the effect, but even with punchings, the furnace could not be run with full burden. It was operated successfully about 3/4 full. The condition of high conductivity may be less of a problem in a larger furnace.

The silicon metal portion of the test was far more successful than the ferrosilicon portion. The furnace was operated in a fully submerged mode for several three day test campaigns at specific power input levels. The furnace was tapped on a four hour cycle with the tap hole being opened with an industrial 8-gauge shot gun. The furnace operated very efficiently in this mode and clearly demonstrated that this type furnace in this mode was particularly well suited for production of silicon metal at more economical power rates.

The industry should seriously consider the merits of DC plasma arc technology for retrofit upgrade, or new capacity, particularly for silicon metal. Hollow electrode feeding, however, does not appear ready for these applications without more extensive use and design modifications.

The industry must seriously consider the identified benefits of DC plasma arc technology for retrofit or new added silicon capacity. A Phase II STCC program to design, build and operate a commercial DC silicon furnace in the United States must be based on the combined findings of this work and Dow-Corning's Manitoba research project. We strongly recommend a merged technical approach and construction of a full sized commercial furnace. The entire domestic silicon industry must have access to the technology, while protecting the vested proprietary interests of the principal participants. A Phase II program is necessary to implement the technology.

Phase II development at a semi-commercial scale is technically feasible and economically justified. This technology may well be the basis for international competitiveness. A recommendation to support such an effort is certainly in order.

STCC TECHNICAL REPORT

APPENDICES

Appendix A	Ore Mix Recipe
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Appendix A

STCC PROGRAMMIX MAKING

BELOW IS A TYPICAL MIX ORDER. THE HEQ/UTILITY MAN MUST FILL OUT AND RECORD EACH MIX MADE ON HIS TURN. CHANGE IN THE MIX ORDER WILL HAVE A NEW NUMBER. THIS WILL BE AUTHORIZED BY THE SUPERVISOR ON DUTY. THE MIXES MADE WILL BE RECORDED ON THE FURNACE SHEET AT THE END OF EACH SHIFT.

STCC PROGRAM MIX ORDER

DATE: _____ SHIFT _____ MIX NUMBER _____

PRODUCT: _____ FEED RATE _____

WOODCHIPS: _____ #

GATLIFF COAL: _____ #

STEEL PUNCHINGS: _____ #

NC GRAVEL: _____ #

DRYED SAND (ELECT) _____ .# PER MINUTE.

NUMBER MIXES MADE THIS SHIFT _____

HEQ OPERATOR _____

Appendix B

BURDEN FEED

Date:

Shift:

[illegible]

Appendix C

134.000 xF t2 : 12.0000 xF t3 : 1111.00 xF t4 : 1743.00 xF
 1315.00 xF t5 : 12.0000 xF t7 : 12.0000 xF t8 : 12.0000 xF
 12.0000 xF

Ambient Air : 12.0000 xF

Bottom Steel
 t20: 12.0000 xF t21: 12.0000 xF t22: 12.0000 xF
 t23: 12.0000 xF t24: 12.0000 xF

t25: 12.0000 xF Feed Pipe Voltage: 0 V
 t26: 12.0000 xF Mast Position: 10.0567 '

Shell
 t27: 12.0000 xF t28: 99.0000 xF t29: 99.0000 xF t30: 99.0000 xF
 t31: 104.000 xF t32: 12.0000 xF

> Air Temps 08-04-1994 @ 00:08:31

1: INCP /* Bottom Air Temp */
 2: 0 xF /* Dilution Air Temp */
 3: INCP /* Combustion Air Temp */

> Water Temps

08: 12.0000 xF /* Main Header Inlet Water Temp */
 09: 99.0000 xF /* Bosh Tank Outlet Water Temp */
 010: 99.0000 xF /* Halmar Outlet Water Temp */
 02: 1192.00 xF /* Electrode Gland Outlet Water Temp */
 03: 12.0000 xF /* Furnace Shell Outlet Water Temp */
 04: 12.0000 xF /* Furnace Roof Skewback Outlet Water Temp */
 05: 12.0000 xF /* Off Gas Outlet Water Temp */
 06: 12.0000 xF /* Electrode Cables Outlet Water Temp */
 07: 97.0000 xF /* Electrode Arm Outlet Water Temp */

> Non-Multiplexed Temps

82: INCP /* Off Gas Temp at Furnace Roof */
 86: 1145.00 xF /* Combustion Chamber Temp */
 83: 109.000 xF /* Off Gas Temp at Bag House Inlet */

> ----- Voltage/Current Data --- 08-04-1994 @ 00:08:31

V Ph. Phase AB: 3959.00 KV DCV Electrode : 53.0526 VDC
 V Ph. Phase AC: 4092.00 KV DCI Electrode : 5920.00 A
 Feed Pipe DCI : 0 V

> ----- Ore/Reductant Data -----

s Feed Rate : 0 #/m Red Feed Rate : 0 #/m
 s Bin Wt. : -5.50000 lb Red Bin Weight : 0 lb

> ----- Offgas Chemical Comp -----

s Gas CO2 Level: 0 % Offgas CO Level : 0 ppm

> ----- Damper Positions -----

100 Air Damper : 0 % Comb Air Damper : 0 %
 s Gas Fan Inlet: 10.8491 % Environmental CO: 0 ppm

> ----- Pressures -----

s Bag Pressure at Furnace Roof : -1.500000 "

> ----- Gas Flows -----

nitrogen Flow : 0 cfm Comb Air Flow : 2076.47 cfm
 dilution Air Flow: 0 cfm Bottom Air Flow : 0 cfm
 s- Gas Flow : 24892.2 cfm Electrode Arm Pos: 10.0567 '

Mass Body Temperatures: 08-04-1994 @ 00:18:30

> Anode (hearth):

: 134.000 xF t2 : 11.0000 xF t3 : 1111.00 xF t4 : 1743.00 xF
 : 1315.00 xF t5 : 12.0000 xF t7 : 12.0000 xF t8 : 12.0000 xF
 : 12.0000 xF

Ambient Air : 12.0000

```

-----
Furnace
Off Gas Pressure at Furnace Roof: 10.510000
-----
Gas Flows
Nitrogen Flow : 0.000000 Comb Air Flow : 2078.47 cfm
Dilution Air Flow: 0 cfm Bottom Air Flow : 0 cfm
Off-Gas Flow : 24872.2 cfm Electrode Arm Pos: 10.0567
-----

```

```

Furnace Body Temperatures: 08-04-1994 1 00:18:30
>>> Anode (hearth)
t1 : 454.000 xF t2 : 11.0000 xF t3 : 1111.00 xF t4 : 1727.00 xF
t5 : 2516.00 xF t6 : 32.0000 xF t7 : 32.0000 xF t8 : 32.0000 xF
t9 : 32.0000 xF

```

```

Ambient Air : 32.0000 xF
>>> Bottom Steel
t20: 32.0000 xF t21: 32.0000 xF t22: 32.0000 xF
t23: 32.0000 xF t24: 32.0000 xF

```

```

Roof T1: 32.0000 xF Feed Pipe Voltage: .183150 V
Roof T2: 32.0000 xF Mast Position: 10.0567
>>> Shell
t37: 32.0000 xF t38: 97.0000 xF t39: 98.0000 xF t40: 96.0000 xF
t44: 99.0000 xF t45: 32.0000 xF
-----

```

```

>>> Air Temps 08-04-1994 2 00:18:30
t31: INOP /* Bottom Air Temp */
t36: 0 xF /* Dilution Air Temp */
t46: INOP /* Combustion Air Temp */

```

```

>>> Water Temps
t108: 32.0000 xF /* Main Header Inlet Water Temp */
t109: 88.0000 F /* Bosh Tank Outlet Water Temp */
t101: 96.0000 xF /* Halmar Outlet Water Temp */
t102: 2192.00 xF /* Electrode Gland Outlet Water Temp */
t103: 32.0000 xF /* Furnace Shell Outlet Water Temp */
t104: 32.0000 xF /* Furnace Roof Skewback Outlet Water Temp */
t105: 32.0000 xF /* Off Gas Outlet Water Temp */
t106: 32.0000 xF /* Electrode Cables Outlet Water Temp */
t107: 97.0000 xF /* Electrode Arm Outlet Water Temp */

```

```

>>> Non-Multiplexed Temps
t182: INOP /* Off Gas Temp at Furnace Roof */
t186: 2145.00 xF /* Combustion Chamber Temp */
t183: 171.000 xF /* Off Gas Temp at Bag House Inlet */
-----

```

```

>>> ----- Voltage/Current Data --- 08-04-1994 3 00:18:30
ADV Pri, Phase AB: 3910.00 KV DCV Electrode : 65.6842 VDC
ADV Pri, Phase AC: 4095.00 KV DCI Electrode : 6040.00 A
Feed Pipe DCI : .183150 V

```

```

>>> ----- Ore/Reductant Data -----
Ore Feed Rate : 0 #/m Red Feed Rate : 0 #/m
Ore Bin Wgt : -5.80000 lb Red Bin Weight : 0 lb

```

```

>>> ----- Offgas Chemical Comp -----
Off Gas CO2 Level: 0 % Offgas CO Level : 0 ppm

```

```

>>> ----- Damper Positions -----
Dilut Air Damper : 0 % Comb Air Damper : 0 %
Off Gas Fan Inlet: 10.8491 % Environmental CO: 0 ppm

```

```

>>> ----- Pressures -----
Off Gas Pressure at Furnace Roof : -1.500000 "

```

```

>>> ----- Gas Flows -----
Nitrogen Flow : 0.000000 Comb Air Flow : 2078.47 cfm
Dilution Air Flow: 0 cfm Bottom Air Flow : 0 cfm
Off-Gas Flow : 25671.5 cfm Electrode Arm Pos: 10.0567
-----

```

Furnace Body Temperatures:

Anode (hearth):

t1 : 454.000 xF t2 : 32.0000 xF t3 : 1111.00 xF t4 : 1742.00 xF
t5 : 2516.00 xF t6 : 32.0000 xF t7 : 32.0000 xF t8 : 32.0000 xF
t9 : 32.0000 xF

Ambient Air : 32.0000 xF

Bottom Steel

t20 : 32.0000 xF t21 : 32.0000 xF t22 : 32.0000 xF
t23 : 32.0000 xF t24 : 32.0000 xF

Roof T1: 32.0000 xF

Feed Pipe Voltage: 0 V

Roof T2: 32.0000 xF

East Position: 10.0567

>>> Shell

t37 : 32.0000 xF t38 : 95.0000 xF t39 : 95.0000 xF t40 : 95.0000 xF
t44 : 100.000 xF t45 : 32.0000 xF

>>> Air Temps

09-04-1994 @ 00:28:30

t31: INDP /* Bottom Air Temp */
t36: 0 xF /* Dilution Air Temp */
t46: INDP /* Combustion Air Temp */

>>> Water Temps

t108: 32.0000 xF /* Main Header Inlet Water Temp */
t109: 88.0000 F /* Bosh Tank Outlet Water Temp */
t101: 95.0000 xF /* Halmar Outlet Water Temp */
t102: 2192.00 xF /* Electrode Gland Outlet Water Temp */
t103: 32.0000 xF /* Furnace Shell Outlet Water Temp */
t104: 32.0000 xF /* Furnace Roof Skewback Outlet Water Temp */
t105: 32.0000 xF /* Off Gas Outlet Water Temp */
t106: 32.0000 xF /* Electrode Cables Outlet Water Temp */
t107: 87.0000 xF /* Electrode Arm Outlet Water Temp */

>>> Non-Multiplexed Temps

ti92: INDP /* Off Gas Temp at Furnace Roof */
ti96: 2145.00 xF /* Combustion Chamber Temp */
ti93: 196.000 xF /* Off Gas Temp at Bag House Inlet */

>>> ----- Voltage/Current Data ----- 09-04-1994 @ 00:28:30

ACV Pri, Phase AB: 4054.00 KV DCV Electrode : 44.0000 VDC
ACV Pri, Phase AC: 3852.00 KV DCI Electrode : 5040.00 A
Feed Pipe DCI : 0 V

>>> ----- Ore/Reductant Data -----

Ore Feed Rate : 0 #/m Red Feed Rate : 0 #/m
Ore Bin Wgt : -5.90000 lb Red Bin Weight : 0 lb

>>> ----- Offgas Chemical Comp -----

Off Gas CO2 Level: 0 % Offgas CO Level : 0 ppm

>>> ----- Damper Positions -----

Dilut Air Damper : 0 % Comb Air Damper : 0 %
Off Gas Fan Inlet: 10.7548 % Environmental CO: 0 ppm

>>> ----- Pressures -----

Off Gas Pressure at Furnace Roof : -1.500000 "

>>> ----- Gas Flows -----

Nitrogen Flow : 0 cfm Comb Air Flow : 2075.47 cfm
Dilution Air Flow: 0 cfm Bottom Air Flow : 0 cfm
Off-Gas Flow : 25351.5 cfm Electrode Arm Pos: 10.0567

Furnace Body Temperatures:

09-04-1994 @ 00:28:29

>>> Anode (hearth):

t1 : 454.000 xF t2 : 32.0000 xF t3 : 1111.00 xF t4 : 1742.00 xF
t5 : 2516.00 xF t6 : 32.0000 xF t7 : 32.0000 xF t8 : 32.0000 xF
t9 : 32.0000 xF

Ambient Air : 32.0000 xF 63


```

Air Temps
t31: INDF /* Bottom Air Temp */
t32: 0 xF /* Dilution Air Temp */
t44: INDF /* Combustion Air Temp */

Water Temps
t108: 32.0000 xF /* Main Header Inlet Water Temp */
t109: 33.0000 xF /* Bush Tank Outlet Water Temp */
t101: 96.0000 xF /* Halmar Outlet Water Temp */
t102: 2192.00 xF /* Electrode Bland Outlet Water Temp */
t103: 32.0000 xF /* Furnace Shell Outlet Water Temp */
t104: 32.0000 xF /* Furnace Roof Shearwater Outlet Water Temp */
t105: 32.0000 xF /* Off Gas Outlet Water Temp */
t106: 32.0000 xF /* Electrode Cables Outlet Water Temp */
t107: 37.0000 xF /* Electrode Arm Outlet Water Temp */

>>> Non-Multiplexed Temps
t182: INDF /* Off Gas Temp at Furnace Roof */
t186: 2145.00 xF /* Combustion Chamber Temp */
t187: 171.000 xF /* Off Gas Temp at Bag House Inlet */

```

```

>>> ----- Voltage/Current Data ----- 05-04-1994 @ 00:45:25
ACV Pri, Phase AB: 3922.00 KV DCV Electrode : 50.5715 VDC
ACV Pri, Phase AC: 4095.00 KV DCI Electrode : 5760.00 A
Feed Pipe DCI : 1.06880 V

>>> ----- Ore/Reductant Data -----
Ore Feed Rate : 0 #/m Red Feed Rate : 0 #/m
Ore Bin Wgt : -5.30000 lb Red Bin Weight : 0 lb

>>> ----- Offgas Chemical Comp -----
Off Gas CO2 Level: 0 % Offgas O2 Level : 0 ppm

>>> ----- Damper Positions -----
Dilut Air Damper : 0 % Comb Air Damper : 0 %
Off Gas Fan Inlet: 10.8491 % Environmental CO: 0 ppm

>>> ----- Pressures -----
Off Gas Pressure at Furnace Roof : -1.500000 "

>>> ----- Gas Flows -----
Nitrogen Flow : 0 cfm Comb Air Flow : 2076.47 cfm
Dilution Air Flow: 0 cfm Bottom Air Flow : 0 cfm
Off-Gas Flow : 25631.5 cfm Electrode Arm Pos: 10.0567 '

```

```

Furnace Body Temperatures: 05-04-1994 @ 00:55:28
>>> Anode (hearth)
t1 : 454.000 xF t2 : 32.0000 xF t3 : 1111.00 xF t4 : 1741.00 xF
t5 : 2516.00 xF t6 : 32.0000 xF t7 : 32.0000 xF t8 : 32.0000 xF
t9 : 32.0000 xF

Ambient Air : 32.0000 xF

>>> Bottom Steel
t20: 32.0000 xF t21: 32.0000 xF t22: 32.0000 xF
t23: 32.0000 xF t24: 32.0000 xF

Roof T1: 32.0000 xF Feed Pipe Voltage: 1.744700 V
Roof T2: 32.0000 xF Mast Position: 10.0567 '

>>> Shell
t37: 32.0000 xF t38: 100.000 xF t39: 98.0000 xF t43: 96.0000 xF
t44: 103.000 xF t45: 32.0000 xF

```

```

>>> Air Temps 05-04-1994 @ 00:58:28
t31: INDF /* Bottom Air Temp */
t32: 0 xF /* Dilution Air Temp */
t44: INDF /* Combustion Air Temp */

Water Temps

```


Appendix D

steel program

MANUAL OF OPERATIONS

OPERATIONS MANUAL
STCC SILICON TESTS

MAY 1994

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STCC PROGRAM

SCHEDULE OF OPERATIONS

THE BRICK LINING OF THE FURNACE WILL TAKE PLACE MAY 2, 1994 THROUGH MAY 6, 1994. THE CARBON PASTE BOTTOM AND SIDE WALLS WILL BE RAMMED IN PLACE MAY 9th AND 10th. ON MAY 11th AND 12th, FOR 24 HOURS, WE WILL ARC THE UNIT ON COKE TO BAKE IN THE CARBON LINING. THE HOOD WILL NOT BE IN PLACE AT THAT TIME TO AVOID PASTE FUMES BLINDING THE BAGS IN THE BAGHOUSE. ON MAY 12th AND 13th, THE REFRACTORY CAST HOOD WILL BE INSTALLED AND THE FURNACE WILL BE READY FOR OPERATIONS.

#1: 50% FERROSILICON:

MAY 16, 1994: 12:01AMSTART OF OPERATIONS. START WARM-UP ON COKE AT 100 VOLTS, 2500 AMPS FOR FOUR (4) HOURS. PLUG THE TAPHOLE (AT LEAST 12" DEEP) AND START MIX ADDITONS (LOW IN COKE). BRINGING THE MIX UP TO 2/3rds OF THE FURNACE DEPTH. CARRY 130 VOLTS, 6000 AMPS, 800 KW LOAD. WE WILL MAKE THE FIRST TAP AT 3000 KWH AFTER MIX CHARGING BEGINS.

MAY 17th - 18th: PRODUCING 50%. WARMING UP THE FURNACE TO "STEADY STATE" OPERATIONS. TRAINING PERSONNEL. DEBUGGING EQUIPMENT.

MAY 19TH >>>>>>>> SEE NEXT PAGE FOR "MASTER TEST PLAN"

MASTER TEST PLAN

HRL 4/20/94

Date	Data	Target	Power	Hollow Electrode		Top Charge	Notes
	Set	Alloy	(mw)	% of SiO ₂	% of F.C.		
May 17-18		Heat Furnace and train staff, Debug Equipment					
May 19-21	1	50%	0.8	10%	0%	balance	1st test
May 22-24	2	50%	1.0	0%	0%	100%	base case
May 25-27	3	50%	1.0	25%	0%	balance	no carbon
May 28-30	4	50%	1.0	25%	12.50%	balance	carbon
May 31-J2	5	50%	0.8	25%	?	balance	low power
Jun 3-5	6	50%	1.0	50%	0-25%	balance	high sand
Jun 6-8	7	50%	1.0	0%	0%	100%	base case
Jun 9-15		Furnace Digout, Repairs, Supervision Change					
Jun 16-18		Heat Furnace, Train Staff, Establish Tap Procedure					
Jun 19-21	8	100%	1.0	10%	0%	balance	1st silicon
Jun 22-24	9	100%	1.0	25%	0%	balance	more sanc
Jun 25-27	10	100%	1.0	10%	5%	balance	carbon
Jun 28-30	11	100%	1.0	25%	12.50%	balance	higher
Jul 1-3	12	100%	1.0	50%	0-25%	balance	most sand
Jul 5-7	13	100%	1.0	0%	0%	100%	base case
July 8th		Change Over, Repairs? Heat up, New Supervision					
Jul 9-11	14	75%	0.8	10%	0%	balance	1st 75%
Jul 12-14	15	75%	1.0	0%	0%	100%	base case
Jul 15-17	16	75%	1.0	25%	0-12.5%	balance	more sand
Jul 18-20	17	75%	1.0	35%	0-15%	balance	higher
Jul 21-23	18	75%	0.8	50%	0-25%	balance	highest
Jul 24-26	19	75%	1.0	50%	0-25%	balance	more C?
Jul 27-29	20	75%	1.0	0%	0%	100%	base case
July 30th		Shut Down, Inspect					

STCC PROGRAM

FURNACE POWER SUPPLY

SANTEE-COOPER POWER COMPANY OWNS THE HIGH VOLTAGE SUBSTATION IN THE YARD. AT THAT POINT, POWER AT 13,800 VOLTS IS SENT TO THE BREAKER UNDER THE MEZZANINE FLOOR. AFTER THE ISOLATION SWITCH, IT COMES TO THE HALMAR TRANSFORMER ROOM LOCATED OUTSIDE THE MAIN BUILDING, BY THE BAGHOUSE. THE VOLTAGE IS THERE STEPPED DOWN TO 350 OR 700 VOLTS. WE WORK WITH THE 350 VOLT SETTING. IT THEN GOES THROUGH THE SCR'S (RECTIFIERS) WHICH THEN SEND OUT DC POWER.

THE INCOMING BUSS AND WATER COOLED POWER CABLES FEED THE MAST AND ELECTRODE CLAMP. BOTH ARE WATER COOLED. THE 10" ELECTRODE IS HELD WITH A SPRING LOADED ACTION, OPENED BY AIR PRESSURE. THE ELECTRODE CONDUCTS POWER THROUGH THE CHARGE, EXITING THROUGH THE CONDUCTIVE CARBON BOTTOM, COPPER PLATE, AND RETURN BUSS.

THE MAIN TRANSFORMER IS COOLED BY WATER FROM MACALLOY'S COLD WELL. ALL THE WATER COOLING FOR THIS UNIT COMES THROUGH THE SUPPLY HEADER BELOW THE TRANSFORMER ROOM AND IS PUMPED BACK TO THE MACALLOY HOT WELL.

IF YOU LOSE ALL POWER IN THE BUILDING, THE WATER LINES WILL HAVE TO BE MANUALLY TURNED OFF, OR YOU WILL HAVE THE BIGGEST FLOOD YOU'VE SEEN FOR A WHILE! (NO POWER FOR THE RETURN PUMP.)

INTERNAL COOLING OF THE SCR UNITS IS ACCOMPLISHED WITH DEIONIZED WATER AND COOLING PUMPS LOCATED INSIDE THE CUBICLE. THE FLOW RATE HAS BEEN SET AND SHOULD NOT BE A PROBLEM. SENSORS IN THE CUBICLE WILL WARN OF HOT WATER AND WE MAY SEE SOME OF THIS DURING HOT WEATHER.

THE TRANSFORMER HAS A CONTROL CABINET DUPLICATING THE ONE IN THE CONTROL ROOM.. INCLUDING METERING. YOU CAN ACTUALLY START THE UNIT FROM THE TRANSFORMER ROOM, BUT IT IS NOT RECOMMENDED. THERE ARE "LOCAL AND REMOTE" SWITCHES THAT ENABLE YOU TO WORK IN EITHER AREA. THE "EMERGENCY STOP" BUTTON IN EITHER AREA IF DISENGAGED WILL NOT LET THE UNIT COME ON.

STCC PROGRAM

FURNACE OPERATION

THE FURNACE OPERATOR WILL BE RESPONSIBLE FOR ALL OPERATIONS IN THE CONTROL ROOM:

1. MAINTAINING SPECIFIED VOLTAGE AND AMPERAGE.
2. WHEN FEEDING MATERIAL DOWN THE ELECTRODE, HE WILL OPERATE THE MIX CONTROLS SO THAT THE CORRECT MATERIAL AND FLOW RATE IS FED THROUGH THE SYSTEM AND INTO THE FURNACE WITHOUT PLUGGING THE FEED PIPE OR ELECTRODE. THIS IS NOT AS EASY AS IT SOUNDS, BUT THE OPERATOR IS THE ONLY ONE THAT CAN CONTROL AND AVOID THIS PROBLEM.
3. SINCE THERE WILL BE MUCH AND AT TIMES ALL OF THE MIX MANUALLY FED INTO THE OPEN TOP OF THE UNIT, THERE WILL BE TWO (2) OPERATOR/UTILITY PEOPLE IN THIS AREA. ONE WILL BE IN THE CONTROL ROOM AT ALL TIMES, THE SECOND ON THE PLATFORMS ON EITHER SIDE OF THE UNIT. THE PREPARED MIX WILL BE SENT TO THE FURNACE FOR HAND SHOVELING INTO THE CRUCIBLE IN SKIPS. THE CRANE/UTILITYMAN WILL BRING FULL SKIPS TO THE AREA AND RETURN EMPTY SKIPS TO THE MIX AREA. WE MAY BE ABLE TO UTILIZE THE "AUXILIARY BIN" ABOVE THE CONTROL ROOM FOR CHUTE CHARGING SOME MIX TO THE WEST SIDE OF THE FURNACE. A STOKING BAR SET UP WILL BE IN PLACE EAST AND WEST ON THE UNIT. THE MIX WILL BE PUSHED INTO THE ACTIVE AREA NEAR THE ELECTRODE. ON 50% FERROSILICON, NOT MUCH "STOKING" SHOULD BE NECESSARY. ON SILICON METAL AND 75% FERROSILICON, CONSIDERABLE STOKING WILL BE REQUIRED.
4. THE TWO OPERATORS WILL ADD ELECTRODES AS NEEDED.
5. THE CONTROL FOR THE BAGHOUSE DAMPER, WHICH DETERMINES THE TEMPERATURE GOING INTO THE BAGHOUSE IS IN THE CONTROL ROOM. THE COMPUTER WILL MONITOR TEMPERATURES IN THE SHELL, COOLING WATER TEMPERATURES AND BAGHOUSE TEMPERATURES. THE BAGS ARE GOOD FOR 500 DEGREES, BUT WE ARE LOOKING FOR 300 GOING INTO THE UNIT.
6. THE FURNACE SHEET WILL BE FILLED IN BY THE OPERATOR. DATA WILL BE RECORDED BY THE OPERATOR, SHOWING AMPS, VOLTS, KW LOAD EACH HOUR, MIX ADDED, KWH CONSUMED, ETC. THIS DATA IS VERY IMPORTANT. SINCE THE PURPOSE OF THESE TESTS IS TO DETERMINE WHAT RESULTS THIS TECHNOLOGY WILL YIELD. POOR DATA MEANS WASTED MONEY.

STCC PROGRAM

MIX SYSTEM OPERATION

THERE ARE TWO (2) MIX HOPPERS ABOVE THE CONTROL ROOM. EACH HAS A LIVE BOTTOM, WHICH VIBRATES TO KEEP MATERIAL FLOWING. THEY ARE ON LOAD CELLS WHICH TELL YOU HOW MUCH IS LEFT IN THE HOPPER. THE HOPPERS ARE FILLED BY THE CRANE TRANSPORTING BLUE CONCRETE BUCKETS OF MATERIAL.

THE HOPPERS DISCHARGE TO A SMALL CHAIN DRIVEN, VARIABLE SPEED BELT. VARYING THIS SPEED GIVES YOU POUNDS PER MINUTE GOING INTO A SCREW CONVEYOR. THE SCREW CONVEYOR DICHARGES INTO A ROTARY VALVE, FROM THERE IT FLOWS DOWN THE PIPE INTO THE ELECTRODE. HELPED BY NITROGEN GAS TO KEEP IT MOVING.

THE PROPER SEQUENCE FOR FEEDING MIX DOWN THE ELECTRODE IS:

1. MAKE SURE THE NITROGEN IS FLOWING. RECORD N₂ FLOW.
 2. START THE ROTARY VALVE..CHECK.
 3. START THE SCREW CONVEYOR. (COLLECTING CONVEYOR).CHECK
 - ** 4. START THE ORE (SAND) FEEDER (BELT)
 5. START THE ORE BIN ACTIVATOR.
 6. CHECK FEED RATE AND REPROGRAM IF NEEDED.
 - ** 7. START THE COAL FEEDER (BELT) IF BOTH ARE REQUIRED!
 8. START THE COAL BIN ACTIVATOR
 9. CHECK FEED RATE AND REPROGRAM IF NEEDED.
- ** THE FURNACE **MUST** BE RUNNING AND ARCING. THE VOLTAGE **MUST** BE 120 OR BETTER. IF THE FURNACE GOES DOWN, SHUT OFF THE FEED SYSTEM **IMMEDIATELY!** FAILURE TO DO THIS WILL RESULT IN A PLUGGED ELECTRODE. (NO FUN).

FOR THE FIRST FEW DAYS ON 50% FERROSILICON, ALL THE MIX WILL BE MANUALLY FED INTO THE CRUCIBLE. WE WILL THEN FEED A PORTION OF THE QUARTZITE (SAND) DOWN THE ELECTRODE. THE MIX TO BE MANUALLY FED DURING THE COMBINED FEED WILL BE ADJUSTED FOR LESS LUMP GRAVEL. IT IS IMPORTANT TO KEEP THE MIX STRAIGHT. YOU CAN NOT TELL BY LOOKING AT IT, HOW MUCH GRAVEL IS IN THE MIX. AT SOME POINT IN TIME, WE WILL INTRODUCE BOTH SAND AND COAL DOWN THE ELECTRODE. THE SAND WILL ALWAYS GO IN THE WEST BIN. THE COAL WILL ALWAYS BE IN THE EAST (RIVER) BIN.

STCC PROGRAM

MIX MAKING

MIX MAKING IS THE RESPONSIBILITY OF THE HEO/UTILITY MAN. SUPERVISION WILL MONITOR EACH MIX MADE.

WE WILL UTILIZE THE IC 28 PAYLOADER WHICH HAS A SIDE DUMP CAPABILITY AND THE PLATFORM SCALE IN THE MIX BIN AREA. EACH RAW MATERIAL WILL BE IN A DESIGNATED, WELL MARKED BIN.

THE RAW MATERIALS WE WILL USE ARE:

1. 2" x 7/8" QUARTZITE (GRAVEL) HAND CHARGE BINS ONLY.
2. GATLIFF COAL
3. DRYED SAND OVERHEAD BIN FOR ELECTRODE ONLY.
4. WOODCHIPS... HAND CHARGE BINS.
5. STEEL PUNCHINGS...HAND CHARGE BINS.

No. 1: WHEN ALL FEED GOES TO SKIPS FOR HAND CHARGING. THE HEO OPR. WILL BE GIVEN A "MIX ORDER". IT WILL BE SOMETHING LIKE:

50% FESI..#1 MIX ORDER:

WOODCHIPS.....	25 #
COAL.....	160 #
STEEL PUNCHINGS.....	120 #
NC GRAVEL.....	250 #

THIS MIX WILL BE MADE IN THE 4' x 4" STEEL BINS ON THE PLATFORM SCALE. THE EMPTY SKIP WEIGHT WILL BE ON THE SIDE OF THE SKIP. CHECK WEIGH BEFORE EACH MIX IS MADE.

No. 2: WHEN FEEDING SOME OF THE MATERIAL DOWN THE ELECTRODE, THE MIX ORDER WILL LOOK SOMETHING LIKE THIS:

* 50% FESI..#2 MIX ORDER:

WOODCHIPS.....	25 #	
COAL.....	160 #	
STEEL PUNCHINGS.....	120 #	
NC GRAVEL.....	125 #	
DRYED SAND (BIN).....	125 #	50% DOWN ELECT.

- * ONE (1) MIX FROM THE BIN MUST GO IN THE FURNACE EACH 36 MINUTES. THE SAND FROM THE "ORE" BIN WILL BE FED AT A RATE OF 3.5 #/MIN. (PROGRAMMED ON MIX SYSTEM.)

.....

----- HED OPERATOR

----- NUMBER MIXES MADE THIS SHIFT

----- DRYED SAND (ELECT) # PER MINUTE.

----- # NC GRAVEL:

----- # STEEL PUNCHINGS:

----- # GATLIFF COAL:

----- # WOODCHIPS:

----- PRODUCT: ----- FEED RATE

----- DATE: ----- SHIFT ----- MIX NUMBER

STCC PROGRAM MIX ORDER

.....

BELOW IS A TYPICAL MIX ORDER. THE HED/UTILITY MAN MUST
FILL OUT AND RECORD EACH MIX MADE ON HIS TURN. CHANGE IN
THE MIX ORDER WILL HAVE A NEW NUMBER. THIS WILL BE
AUTHORIZED BY THE SUPERVISOR ON DUTY. THE MIXES MADE WILL
BE RECORDED ON THE FURNACE SHEET AT THE END OF EACH SHIFT.

MIX MAKING

STCC PROGRAM

Estimate of Raw Material Requirements for Phase I

10

INPUT Values in Boxes

Product	Si Metal	75% FeSi	50% FeSi
% Si	99.1	75.0	49.0
% Fe	0.3	24.0	50.0

Relative Mix Order

Basis:

lb Quartz fed	1000	1000	1000
% Recovery of Si in Alloy	70	80	90
% Recovery of Fe in alloy	100	96	98

Raw Materials:

Quartz

Name	N.C. Gravel	N.C. Gravel	N.C. Gravel
% SiO2	99.5	99.5	99.5
lb	1000	1000	1000
(Total FC required, lb)	377.9	385.8	393.8

Coal

Name	Gatliff	Gatliff	Gatliff
% moisture	1.5	1.5	1.5
% Fixed Carbon (dry)	62	62	62
lb FC required	326.9	351.8	385.3
lb (natural)	535.3	576.1	630.9

Woodchips

Name	?	?	?
% of Quartz	60	40	10
% moisture	15	15	15
% Fixed Carbon (wet)	10	10	10
lb (natural)	600.0	400.0	100.0
lb FC provided	51.0	34.0	8.5

Steel Scrap

Name	?	?	?
% Fe		92	92
lb		135.5	476.1

Production:

lb Si	327.2	374.0	420.7
lb Fe	1.0	119.7	429.3
lb Alloy	330.2	498.6	858.6

Operating Parameters

Furnace Power, kW	1000	1000	1000
Operating Time, %	85	90	93
SEC, kWh/lb Si	7.00	6.00	5.40
Theoretical FC, %	95	97	99

Production Rate

lb Si/h	121.4	150.0	172.2
NT Si/day	1.5	1.8	2.1
lb Alloy/h	122.5	200.0	351.5
NT Alloy/day	1.5	2.4	4.2

Raw Material Feed Rate

Quartz			
lb/h	371.1	401.1	409.4
NT/day	4.5	4.8	4.9
Coal			
lb/h	198.6	231.1	258.3
NT/day	2.4	2.8	3.1
Woodchips			
lb/h	222.7	160.4	40.9
NT/day	2.7	1.9	0.5
Steel Scrap			
lb/h		54.3	194.9
NT/day		0.7	2.3

STSCC PROGRAM

TAPPING AND CASTING

1. 50% FERROSILICON: PRODUCTION RATE SHOULD BE ABOUT 350 LBS/HR. AT FULL LOAD. WE WILL TAP EACH FOUR (4) HOURS AND GET ABOUT 1400 # OF ALLOY.

PRESENTLY, WE HAVE ONE (1) CAST IRON MOLD DONATED TO THE PROGRAM BY SKW. AT TWO TAPS PER SHIFT, WE WILL PROBABLY LEAVE IT UNDER THE SPOUT AND PULL THE CASTS FROM THE MOLD.

WE WILL HAVE OXYGEN, LANCE PIPE AND TAPPING BARS ON SITE. WE SHOULD BE ABLE, AFTER A FEW TAPS, TO OPEN THE TAPHOLE WITH A SHARP BAR. WE WILL PLUG WITH A CARBONACEOUS PLUGGING COMPOUND (AIMCOR). SPOON SAMPLES WILL BE TAKEN ON EACH TAP AND THE ALLOY PLACED IN SKIPS. IT WILL THEN BE STORED OUTSIDE IN PILES, FOR FINAL DISPOSAL AFTER THE RUN IS COMPLETE.

ACCURATE CAST WEIGHTS AND IDENTIFICATION IS IMPORTANT TO THE DATA NECESSARY TO JUDGE THE EFFICIENCY OF EACH PHASE OF THE TESTS!

2. SILICON METAL: ON THIS ALLOY, WE SHOULD MAKE ABOUT 1000# PER SHIFT. WE WILL TAP IT ONCE/SHIFT. IT IS NOW PLANNED TO USE THE SAME SKW CAST IRON MOLD, LEAVING IT IN PLACE AND PULLING THE CAST FROM THE MOLD. SHOULD IT BE NECESSARY, WE MAY MAKE A SAND BED MOLD OUT OF TWO 4' x 4' METAL SKIPS.

SINCE WE SHOULD NOT USE LANCE PIPE OR BARS ON SILICON, WE MAY OPEN THE TAPHOLE WITH AN OXYGEN - GRAPHITE LANCE. WE WILL PROBABLY PLUG THE HOLE WITH A CLAY-COKE PLUGBALL. WE HAVE CONTACTED WINCHESTER ABOUT A SMALLER GAUGE SHOTGUN WITH LESS MUZZLE ENERGY TO TRY A TEST ON SHOOTING OPEN THE HOLE WITH A ZINC SLUG. THEY ARE HAND LOADING SOME TEST SLUGS AND WILL BE AVAILABLE TO TEST THIS PROCEDURE, DURING THE 50% RUN, AT NO CHARGE TO US!

AS ABOVE, WE WILL NEED TO HAVE ACCURATE WEIGHTS AND ANALYSIS OF THE PRODUCTION. ON THIS ALLOY, CAST SAMPLES, WITH TOP AND BOTTOM OF THE CASTS ARE PREFERRED. MACALLOY LAB WILL BE USED TO ANALYZE PRODUCTION SAMPLES, WITH OTHER LABS PROVIDING REPORT TYPE ANALYSES.

ALLOY WILL BE STORED OUTSIDE, BY GRADE, UNTIL IT IS REMOVED AT THE CONCLUSION OF THE CAMPAIGN.

STCC PROGRAM

MANUAL DATA LOGGING

A COPY OF THE "DAILY FURNACE RECORD" IS ATTACHED ON THE FOLLOWING PAGE. THE OPERATOR/UTILITY PERSON IN THE CONTROL ROOM IS RESPONSIBLE FOR FILLING IN ALL INFORMATION NEEDED ON THAT SHIFT. IT IS TO BE SIGNED AT THE END OF THE SHIFT. THE SUPERVISOR OF THE SHIFT WILL ALSO INSPECT THE SHEET FOR THAT SHIFT AND SIGN IT.

PRODUCT:

DATE:

STCC PROGRAM - DAILY FURNACE RECORD

TIME	AMPS	VOLTS	KW	FED TO FURNACE TOP				DELAYS				TAP TIME	TAP WEIGHT	% Si	% Fe	% C	
				R/M NE QTZ	COAL	STEEL	WCHIPS	OFF	ON	MIN	REASON						
12 ⁰⁰																	
1 ⁰⁰																	
2 ⁰⁰																	
3 ⁰⁰																	
4 ⁰⁰																	
5 ⁰⁰																	
6 ⁰⁰																	
7 ⁰⁰																	
8 ⁰⁰																	
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7 ⁰⁰																	
8 ⁰⁰																	
9 ⁰⁰																	
10 ⁰⁰																	
11 ⁰⁰																	

SUPERVISOR	OPERATOR	NITROGEN FLOW RATE	ELECTRODE ADDED	B.H. DUST WEIGHED	R/M FED DOWN ELECTRODE		KWH METER	OP HRS
					SAND	COAL		
							12 ⁰⁰ M	KWH/HR
							8 AM	% OT
								LBS
							4 PM	KWH/LB
								AVE
							12M	KW

STCC PROGRAM

BAGHOUSE OPERATION & DUST HANDLING

AS NOTED UNDER THE OPERATORS DUTIES, THE BAGHOUSE FAN DAMPER CONTROLLER IS LOCATED IN THE CONTROL ROOM (LEFT HAND CONTROL). IT SHOWS A PERCENTAGE OPEN, FROM ZERO TO 100%. IT IS WISE TO PERIODICALLY INSPECT THE POSITION OF THE DAMPER ON THE FAN ITSELF. IF IT IS NOT FUNCTIONING AUTOMATICALLY, IT CAN BE PUT IN THE MANUAL MODE.

THE UNIT IS A "MICROPULSE" BAGHOUSE, WITH COMPRESSED AIR CLEANING OF THE BAGS ON A PROGRAMMABLE CYCLE. THE CONTROLS FOR THE TIMING OF THE PULSES IS ON AN INSTRUMENT LOCATED ON THE EAST SIDE OF THE BAGHOUSE ITSELF. NATURALLY THE AIR COMPRESSOR MUST BE RUNNING. IT SHOULD HAVE THE MOISTURE DRAINED FROM THE TANK EACH SHIFT.

THERE ARE 255 "BHA TEX" BAGS WHICH WERE INSTALLED NEW IN MARCH OF THIS YEAR. THEY ARE RATED AT 500 DEGREES F, BUT WE SHOULD LOOK AT AVERAGING 300, TO LEAVE ROOM FOR SWINGS IN TEMPERATURE.

THE SCREW CONVEYOR AND ROTARY VALVE SHOULD BE LEFT RUNNING AT ALL TIMES. WE PLAN TO DEPOSIT THE DUST INTO "SUPER-SACKS". WE WILL SAMPLE THE DUST DAILY. THE FULL DUST SACKS WILL BE LABELED AND TAGGED. THE WEIGHT WILL BE RECORDED ON THE FURNACE SHEET AND THE SACK ON A PALLET WILL BE STORED IN THE RAW MATERIAL AREA.

Appendix E

STCC

Management Plan

May 17, 1993

SILICON TECHNOLOGY COMPETITIVE COOPERATIVE

INTRODUCTION

The U.S. silicon/ferrosilicon industry is stagnated in growth and virtually devastated with respect to profitability because of low-cost imports. The silicon industry has not been able to justify investment in new construction since the last new plant was built in 1974. At this time, the present technology which incorporates alternating current (a.c.), three electrode, submerged arc, open furnace operation is energy inefficient and produces undesirable quantities of fume and CO₂. The U.S. silicon and ferrosilicon industries need low-cost, affordable energy-saving production technologies that address these needs.

OBJECTIVE

The objective of this research is to demonstrate, at about a 1.5 MW scale, the feasibility and commercial viability of an open furnace operating with a single, hollow electrode, direct current (d.c.), submerged plasma arc for smelting silicon and silicon alloys. This is expected to provide an affordable capitalization in order to save materials and energy, reduce costs to improve U.S. competitiveness, and address emissions. The technology will then be available to retrofit existing furnaces in the U.S. that can compete to displace imports and meet the forecasted U.S. demand growth for silicon metals.

Statement of Work

TASK DESCRIPTION

The Contractor shall provide the necessary personnel, facilities, services and materials required to perform the following tasks:

1. Task 1 - Technical Approach

The objective of Task 1 is to develop the technical analysis, the operating plan, the engineering design, the material requirements, performance projections, maintenance procedures, and test plan. The task will address modification of an existing 1.5 MW furnace in Charleston, SC for smelting silicon/ferrosilicon with a single, hollow electrode, direct current (d.c.), submerged arc in an open-furnace configuration.

The approach proposed is a significant advancement from the long-established conventional a.c. submerged arc practice using three a.c. electrodes, currently standard in the industry. It will adapt several emerging process technologies to the unique difficulties

of silicon and ferrosilicon production. Due to its similarity to existing practice, the research is considered low-to-medium risk with a high probability of success. This in no way suggests that the tasks to be undertaken are easy or that the initiative is not essential to the survival of the domestic silicon/ferrosilicon industry. It is largely beyond the capabilities of the individual member companies to undertake the project independently.

Carbothermic reduction of silica (SiO_2) occurs at very high temperatures (in the plasma arc zone) and generates a gaseous suboxide species, silicon monoxide (SiO) and carbon monoxide. Silicon monoxide gas, in turn, is involved in a number of important side reactions some of which yield liquid silicon metal. When metallic iron is present, silicon and iron combine to form the alloy phase, reducing the silicon fugacity. Important reactions include:

These reactions occur predominantly within the burden pile in the furnace at somewhat lower temperatures. Charge porosity on a macroscopic scale is important to enhance gas solid interactions. The major chemical inefficiency in the process relates to silicon monoxide gases exiting the charge pile unreacted and going on to produce silica fume in the gas handling system. Significant energy is consumed in creation of the silicon monoxide which does not result in product yield. Fume production greatly increases specific energy consumption and operating costs.

The formation of silicon carbide (SiC) on the surface of carbon in the charge pile is desirable, as the charge descends into the furnace. Silicon Carbide can result in secondary silicon metal formation. Silicon carbide in the hearth of the furnace is undesirable once it reaches the level where it is no longer exposed to silicon monoxide. It can build up on the hearth, eventually, impeding furnace functioning. This new approach to silicon metallurgy allows a change in ore/reductant stoichiometry between the top and bottom of the furnace. The charge introduced through the hollow electrode can and should be carbon deficient. The conventional submerged arc process does not offer this degree of freedom, because all charge is added to the top of the burden and descends to the hearth over a period of hours.

- 1.1 **Technical Analysis** - The technical analysis for the engineering design of the modified furnace shall reflect the best available technology based on the full-use of the silicon/ferrosilicon furnace experience from each project participant.

These technologies are:

- submerged arc silicon furnace technology;
- d.c. single electrode technology;
- hollow electrode feed system technology;
- process control computer technology; and, in the future,
- enclosed top furnace technology for the capture of fuel gas values from the process gas effluent.

In a number of industries, d.c. single electrode furnaces are replacing three electrode a.c. smelting furnaces. This is perhaps most notable in electric furnace steel making where the trend is well established. The Japanese are reported to have built a furnace as large as 100 megawatts with potentially major savings in electrode consumption and electrical usage per ton of steel produced. For a comparable energy level, the furnaces tend to be of somewhat smaller diameter and thus lower capital cost. In South Africa, Mintek piloted a d.c. open bath plasma process for high carbon ferrochromium, and Middleburg Steel and Alloy is operating a 40 megawatt ferrochromium furnace based on this technology. A research consortium managed by SCRA, with funding through the Defense Logistics Agency, has developed and tested a d.c. plasma arc process for ferrochromium ore fines. A 12 megawatt semicommercial plant is now being built based on the successful Phase I test work. Key personnel from this related venture are proposed for the silicon/ferrosilicon project.

Hollow electrodes have been used successfully in submerged arc furnaces for the commercial manufacture of calcium carbide. Several team members developed and have extensive experience in this area. The plasma arc ferrochromium effort, mentioned previously, also generated an experience base working with hollow electrode feed to a plasma furnace.

This project is directed toward an open submerged arc furnace to enable mechanical stoking of the charge as is practiced in the conventional process. Combustibles from the burden will be burned above the bed and captured with a side hood. This avoids a number of operational problems at this stage in the development program. In the future, it will be easier to consider enclosing the top of a single electrode furnace than its three electrode relative. Dow-Corning company is reported to be building a sealed silicon furnace in Canada. (Dosaj, V. D., Et al., "Plasma Smelting of Silicon") This is a higher risk, more costly venture than the work addressed in this proposal. It supports the technical validity of the project, and ultimately the works should complement each other.

This technology offers many controllable operating parameters not present in the conventional process. Feed rates of the fine and coarse silica ores and reductants can be independently controlled and adjusted in relation to the power input level. The stoichiometry of reactants in the plasma zone of the furnace becomes controllable within a short time frame. This provides an opportunity for computerized control and optimization of the process not previously possible. This will translate to improved product quality, increased product yield, and higher thermal efficiency.

Schematic of Furnace

- 1.2 Engineering Design - The modified-furnace engineering design shall be developed with layout engineering drawings plus draft specifications for critical components. It will reflect full-use of project participants experience. Auxiliary systems shall be included as appropriate.

- 1.3 Materials Requirements - The necessary materials and equipment for the modified furnace design shall be specified. This shall include replacement of furnace sidewall refractories and increased furnace working depth. An open furnace fume-hood system with provisions for stoking the charge pile shall be incorporated. High quality, sized raw materials (lump quartz, fine quartz, charcoal, wood chips, etc.) shall be located and procured in

sufficient quantity to complete the entire test program without a change in raw materials.

- 1.4 Performance Projections - The Contractor shall predict smelting system performance, plant and national energy savings, plant and national emissions reductions, and economic viability through the year 2010. This will require comparing baseline state-of-the-art performance with the performance of the improved process along with the market penetration of the improved process in the U.S. silicon/ferrosilicon industry. Differences from economic, energy, and environmental benefits previously predicted in the proposal shall be noted. Assumptions and the calculation method for the analysis shall be discussed with DOE before proceeding, and will be presented in the Final Report. These open-furnace results shall be compared with the closed-furnace configuration from DOE Contract No. DE-AC04-87ID12624. The projection results shall be reviewed with DOE as soon as they are available.
- 1.5 Maintenance Procedures - Suitable maintenance procedures shall be developed for the safe, reliable operation of the furnace in conformance with appropriate environmental permits.
- 1.6 Test Plan - An initial Test Plan shall be developed and submitted to DOE for review at least two weeks prior to starting testing. The plan shall include but not be limited to estimated dates and duration, objective, criteria for a successful test, feedstock description, samples to be taken for analysis, significant operating parameters including stepwise changes, and significant measurements required to obtain the operating parameters.

II. Task 2 - Engineering/Modification

The design for the modification of the furnace shall be completed, procured, and constructed.

- 2.1 Modification Design - Engineering drawings and specifications shall be prepared for all equipment necessary for furnace operation including required auxiliary systems. The design will reflect full-use of project participants experience. Auxiliary systems shall include electrical, raw material handling, hydraulic, environmental control, safety, water cooling, and process gases. Each system shall be sized and the process flows determined. Piping and instrument diagrams shall be drawn based on these specifications. The performance projections shall be updated if significant changes are produced by this design effort. DOE and its representatives

shall be invited to participate in the design review for the modification. Two sets of design information shall be transmitted to DOE at least two weeks prior to the review meeting.

- 2.2 Site Coordination - The Contractor shall coordinate with the site operator the layout and preparation of the site for the modified furnace, including all required auxiliary systems.
- 2.3 Procurement - A detailed cost estimate shall be prepared based on vendor quotations and engineering cost estimates for the subject design. Bids shall be obtained in accordance with Federal Acquisition Regulations (FAR), and shall be available for review by DOE. A mutually positive go/no decision will be made by DOE and the Contractor before proceeding with construction. In the event of a negative decision by DOE, the Contractor may proceed with the project without DOE participation.
- 2.4 Construction - All aspects of furnace modification and auxiliary system construction shall be performed and funded by the contractor and non-DOE participants including material and equipment procurement, site preparation, equipment installation, establishment of procedures, safety reviews, etc. Likewise, major plant modifications and repairs shall be the responsibility of the contractor.

A detailed schedule shall be prepared showing key equipment delivery and all construction work. This schedule shall provide a basis for coordinating all phases of the construction and shall be updated as needed.

III. Task 3 - Testing

The operation of the modified furnace, from training of operators through start-up and operating campaigns with the equipment, shall be performed in accordance with established plans and procedures. The test site is located in Charleston, S.C., and consists of approximately 125 acres, including rail, ship and truck access. Facilities exist to handle and dispose of slag and wastes generated by furnace operations. Preparation facilities for samples of raw materials, ferrosilicon, slag, etc., are grouped in a building in close proximity to a chemical laboratory. The chemical laboratory is equipped to obtain the complete analyses of all types of raw material, alloys and slag quickly and accurately.

The plasma furnace consists of a steel shell, refractory sidewalls, a 12 inch alumina cast roof, and a bottom with electrically conductive refractory components. The test facility is a 1.5 megawatt plasma arc furnace designed to process dry materials and fine ore less

than 1/4 inch in size. The weigh belt feed system delivers ore mix and reductant mix to the furnace at adjustable rates. The power supply consists of two step-down water-cooled transformers, a water-cooled twelve-pulse thyrister circuit, water-cooled d.c. reactors, and the necessary electronic firing and control computer serviced by an IBM 386X (PS/2 55SX-061) PC operator interface. The furnace has the capability to operate at temperatures in excess of 1650C, with an energy input of up to 1.5 megawatts with a working volume of about 170 cubic feet. It is normally operated in a continuous feed batch tap mode and can be fed either through a hollow electrode or through drop points in the roof. The plasma arc process can effectively run high temperature reactions such as carbothermic reductions. Because the plasma can pump energy into the reaction zone, largely independent of other factors, endothermic reactions can be run very effectively. The test facility works best for systems which require or can tolerate the presence of carbon due to the consumable graphite electrode and carbon containing heat refractories. Fine particle reactants can be charged directly into the reaction zone through the hollow electrode.

- 3.1 Test Start-Up - All personnel who shall be operating the pilot plant will participate in an extensive training program to assure that they are familiar with all safety procedures, environmental procedures, and equipment functions. Emergency response procedures and potential safety hazards shall be thoroughly reviewed. A dry run of all systems shall be performed to best simulate operating conditions at minimum exposure. Any equipment problems discovered shall be corrected, and those systems subjected to additional dry run testing.
- 3.2 Campaign Operations - Following successful start-up of the modified furnace, longer-term experimental tests shall be made with the objective of providing the necessary engineering inputs for predicting commercial performance characteristics for the process. For each test, a brief update of the plan (from Task 1.4) for the next test, with schedule, shall be submitted to DOE with as close to two weeks lead-time prior the test as practical. It is recognized that actual test conditions often require deviations from the plan.
 - 3.2.1 Campaign 1 - Campaign 1 shall verify and establish operating procedures and charge mix recipes for the production of 50% ferrosilicon alloy (FeSi50) in the modified test furnace. The furnace shall be operated over a range of power input rates and specific energy consumption shall be determined.
 - 3.2.2 Campaign 2 - Campaign 2 shall focus on the production of silicon metal. Operating parameters shall be changed to achieve stable

furnace conditions while producing high quality silicon metal. Fume generation, silicon recovery, and specific energy consumption shall be quantified.

3.2.3 Campaign 3 - In Campaign 3, the charge mix shall be adjusted to product 75% ferrosilicon alloy (FeSi75). The effect of the higher silicon grade on SiO fume generation and silicon metal recovery shall be quantified. Specific energy consumption shall be determined. Operation procedures shall be optimized for this alloy.

3.2.4 Campaign 4 - In Campaign 4, the charge mix shall be adjusted to produce 90% ferrosilicon alloy (FeSi90). The effect of the higher silicon grade on SiO fume generation and silicon metal recovery shall be quantified. Specific energy consumption shall be determined. Any modifications required in operating procedures and furnace performance shall be noted.

IV. Task 4 - Evaluation

Data from furnace operation shall be acquired, analyzed, and used to predict full-scale commercial furnace operation and economics.

- 4.1 Data Acquisition and Qualification - All furnace test data shall be collected and analyzed by the operating personnel and engineering team. As appropriate, the data shall be used for real time control followed by off-line evaluation of the test results. Long term trend estimates and process capability studies shall be made using this data.
- 4.2 Sample Collection and Analysis - All pertinent samples shall be collected on a systematic basis for the above described tests. Samples shall include the raw materials input, silicon alloys produced, and system by-products such as off-gas and particulates. These samples shall be analyzed either in the participants laboratories or at certified outside laboratories. Complete mass balances, silicon chemistry and off-gas compositions shall be prepared from the analysis and used in the evaluation of system performance.
- 4.3 Projection Updates - The results of furnace operation and of system and process data analysis shall be used to confirm or modify estimates of smelting system performance, plant and national energy savings, plant and national emissions reductions, and economic viability. The evaluation of

long-term industry trends and the extent of market penetration shall be updated if needed. Differences from economic, energy, and environmental benefits previously predicted shall be noted. DOE shall be notified promptly if test results indicate a significant change in performance projections.

- 4.4 Scale-Up and Commercialization Report - The Contractor shall prepare a detailed plan for scaling up and commercializing this technology. Assumptions shall be stated and specific roles and commitments from the project industrial participants shall be identified.

V. Task 5 - Project Management and Reporting

The purpose of this task is to provide the management necessary to meet technical objectives within planned schedule and cost, and to fulfill reporting requirements to DOE.

5.1 Project Management

A project manager shall be responsible for all project coordination, and information transfer and dissemination. The project shall be managed to assure successful completion of all tasks in the Statement of Work within the developed schedule and cost budget. Management controls shall include technical assessment, schedule assessment, and products quality assessment.

The technical progress shall be reviewed on a regular informal basis with DOE and/or designated representatives. Project review meetings shall be held with DOE personnel and DOE's representatives as necessary during the project. Advance notification shall be provided to DOE for possible attendance at the following events: design reviews, and furnace tests. The Contractor shall plan to participate in two program reviews for DOE management in Washington, DC.

5.2 Technology Transfer

The contractor shall take advantage of opportunities for technology transfer, including presentation of papers at technical meetings and publications of journal articles. Prior DOE concurrence shall be obtained on all information prepared for public release. Three weeks lead-time is normally required to obtain DOE patent clearance of material for public release. No foreign technology transfer will be permitted for a period of 36 months following issuance of the Final Report.

Reports

Reports shall be prepared as detailed in the Reporting Requirements Checklist and the Report Distribution List.

- 5.3.1 Management Plan - A detailed Management Plan with a Milestone Schedule, Cost Plan, and Contract Management Summary Report shall be submitted to DOE for concurrence within 30 days of award. Similarly, updates shall be required after significant changes in approved funding and scope.
- 5.3.2 Periodic Reports - Project status, cost, and schedule shall be prepared and provided as detailed in the Reporting Requirements Checklist and the Report Distribution List. Monthly reports are due within 20-days after the end of the calendar month.
- 5.3.3 Topical Reports - If a Topical Report is required, an outline for the report shall be submitted and approved by DOE prior to commencing work on the report. Draft and final versions of the report shall be submitted to DOE in a procedure similar to that described for the Final Report in the following section.

To the extent consistent with progress in the report period and appropriate to the topic, the Topical Report shall contain a discussion of 1) concept/project background and description; 2) system description; 3) discussion of the design, construction, and installation of the system; 4) the test program conducted and test results; and analysis of data and evaluation of technical results. These analyses shall include updates of the quantitative economic analysis, the market analysis, the energy savings analysis, and the environmental effects. The DOE threshold analysis inputs shall also be updated. In coordination with DOE, the Contractor shall generate a project description to DOE format and a summary table of the performance projections in a format suitable for input into the DOE Industrial Programs Threshold Model.

- 5.3.4 Final Report - A Final Report for the project shall be a stand-alone document summarizing all work accomplished. It shall put the project background, performance, and results and accomplishments into perspective by highlighting planned commercialization of the furnace technology. An outline for the Final Report shall be submitted and approved by DOE prior to commencing work on the

furnace technology. An outline for the Final Report shall be submitted and approved by DOE prior to commencing work on the report. A Final Report draft shall be submitted to DOE within 30-days after completion of the technical effort. Comments resulting from the DOE review shall be resolved and the report revised accordingly prior to final submission for publication. The final submission shall be within 90-days of the end of the technical effort unless the DOE review period takes more than 30-days after which a day-for-day extension shall be applied. No foreign technology transfer will be permitted for 36 months following issuance of the report.

STCC MANAGEMENT AND CONTROL

WBS Element	SCRA	MIT	CMU	ADL	HATCH	AAC	AlmCor	Elkem	Globe	SIMECo	SKW	SMT	Macalloy
1.0 TECHNICAL APPROACH	P												
1.1 Technical Analysis	C	S	S		S	S	S	S	S	S	S	S	
1.2 Engineering Design	S	S	S	C		S	S	S	S	S	S	S	
1.3 Material Requirements	S	S				S	S	S	S	S	S	S	
1.4 Performance Projections	C	S			S	S	S	S	S	S	S	S	
1.5 Maintenance Procedures	S	S				S	S	S	S	S	S	S	
1.6 Test Plan	C	S				S	S	S	S	S	S	S	
2.0 ENGINEERING MODIFICATIONS	P												
2.1 Modification Design		S			S								
2.2 Site Coordination		S			S								
2.3 Procurement		S		C									
2.4 Construction		S			S								
3.0 TESTING	P	C											
3.1 Startup	C	S				S	S	S	S	S	S	S	
3.2 Campaign Operations	C	S				S	S	S	S	S	S	S	
4.0 EVALUATION	P	C				S	S	S	S	S	S	S	
4.1 Data Acquisition and Qualification		C	S										
4.2 Sample Collection and Analysis		C	S										
4.3 Projection Updates		C	S										
4.4 Scale Up & Commercialization Report		C	S			S	S	S	S	S	S	S	
5.0 PROJECT MGMT & REPORTING	P												
5.1 Project Management	P	C											
5.2 Technology Transfer	P	C	S			S	S	S	S	S	S	S	
5.3 Reports	P	C				S	S	S	S	S	S	S	
5.3.1 Management Plan	P												
5.3.2 Periodic Reports	S				S	S	S	S	S	S	S	S	
5.3.3 Topical Reports	C	S			S								
5.3.4 Final Report	C	S				S	S	S	S	S	S	S	
6.0 TRAVEL	P	I	I	I	I	I	I	I	I	I	I	I	
7.0 OTHER INDIRECT CHARGES	P	I	I	I	I	I	I	I	I	I	I	I	
8.0 INDIRECT CHARGES	P	I	I	I	I	I	I	I	I	I	I	I	

P=Primary Responsibility C=Coordination Responsibility from Other Members to Prime S=Supporting Responsibility to Prime I=Individual Responsibilities

STCC Schedule

Project STCC
Date: 5/14/93

Intermediate Event [Bar with triangle] Activity Summary [Bar with triangle]
Milestone [Triangle] Progress [Bar with triangle] Milestone Complete [Triangle]

Appendix F

HOLLOW GRAPHITE CATHODE DIRECT CURRENT PLASMA ARC
FURNACE FOR CARBOTHERMIC REDUCTION OF SILICA:

A Literature Review and Preliminary Thermodynamic Study

Julian Szekely and David Woolley

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Cambridge, MA 02139

November 18, 1993

INTRODUCTION

We submit a report to outline our current modelling abilities, and to discuss the direction of further modelling.

Most of the available literature on the subject of carbothermic reduction of silica with plasma discusses the conventional submerged arc technology [3,5,9,11]. Modelling of the Si-O-C system has been pursued in order to improve silicon yield and increase energy efficiency. Modelling of this system and of the closely associated Fe-Si-O-C system began with thermodynamic models. Since then attempts have been made to model the kinetics of the system, and there have been recent efforts at modelling the submerged arc technology beginning with fundamental concepts of heat and mass transport [5-7,13].

It seems likely that the behavior of the system using hollow graphite cathode, direct-current transferred arc technology will differ fundamentally from that of the conventional submerged arc furnace. The literature cites recent work using the hollow graphite cathode DC arc technology which indicates that this technology may yield fundamental improvements in silicon recovery and energy efficiency due to changes in the reaction scheme [4].

THERMODYNAMIC MODELLING

An idealized description of the carbothermic reduction of silica in a submerged arc furnace follows [5,9]. The description is based on the Si-O-C system, although the discussion applies well to the Fe-Si-O-C system; the presence of the iron generally decreases the silicon activity, and consequently increases silicon recovery and energy efficiency. Any model of the system must have at least two zones, an inner (hot) zone containing the arc, and an outer (cooler) zone. In the conventional process, a charge of carbon and silica is added to the outer zone. The charge descends in an atmosphere of SiO and CO; these are the only gas species that are present in significant quantities.

The reactions in any part of the outer zone are a linear combination of the following two reactions [5]:

In the inner zone the reactions are a linear combination of the following three reactions [5]:

Thermodynamic considerations show that the inner zone temperature must be above about 1800 °C [2,5,8,9]. The descending carbon reacts with SiO in the outer zone to produce SiC. The silicon carbide, silica, and unreacted carbon continue into the inner zone, where the very high temperatures allow the (net) reaction between silica and silicon carbide.

We can now perform routine heat and mass balances and determine the equilibrium composition of the zones of the furnace. There are two differing approaches to this preliminary thermodynamic modelling. One uses the mass-balance equations to establish furnace stoichiometry in terms of a few process parameters. This approach yields algebraic relations between, for example, silicon recovery and the ratio of carbon to silica in the feed stream. The second approach assumes that the furnace can be divided in to several zones, each in thermodynamic equilibrium. Material is passed between the zones, and the equilibrium composition of each zone is determined by minimizing the free energy of the zone, given initial amounts of the various species.

The first approach we have pursued is based on the work at Elkem Research in Norway [5,9]. For each of the five reaction equations mentioned above, we define a variable for the extent of the reaction (a, b, c, d, e). We then define variables for the amount of silica added, amount of carbon added, SiC buildup on the hearth, silicon recovered, SiO lost in the top gas, and CO lost in the top gas. These are used in setting up mass balance equations for each of the six components (SiO₂, C, SiC, Si, SiO, CO). These six relations are reduced to four using identities between the process variables mentioned above (amount of silica added, etc.) and four more variables---namely, the silicon recovery, the C/SiO₂ ratio in the feed, the fraction of carbon that does not react in the outer zone, and the proportion of SiO in the gas leaving the inner zone. Now we have four equations and four unknowns---namely, the extent-of-reaction variables a, c, d, e. We can solve for these four variables in terms of b, which is the extent of the condensation reaction in the outer zone, and the variables: silicon recovery, C/SiO₂ ratio, fraction C unreacted in outer zone, fraction SiO in gas from inner zone.

This approach yields interesting information about the process. The silicon

recovery increases linearly with the C/SiO₂ ratio in the charge up to some limit, beyond which the recovery decreases (Fig. 1) [5]. This limit depends on the fraction of C that does not react in the outer zone and the SiO fraction in the gas leaving the inner zone, but it is in the range of 1.8 to 2. If we assume no SiC buildup on the hearth the silicon recovery reduces to the C/SiO₂ ratio minus one; this is a handy rule-of-thumb.

Figure 1. Silicon recovery vs. the C/SiO₂ ratio in the feed material [5].

The results in Fig. 1 implicitly vary with temperature since both the fraction of C that does not react in the outer zone and the fraction of SiO in the gas leaving the inner zone are temperature-dependent. The reaction in the outer zone between carbon and SiO:

is highly exothermic, so an increase in temperature will increase the fraction of C that does not react. In the inner zone, the equilibrium temperature for the presence of silica, silicon, and silicon carbide is in the range 1807-1830 °C.

Above this temperature, two reactions are important:

The literature indicates that the first reaction, between silica and silicon carbide is quite slow, so second reaction will dominate [9]. This reaction, between silicon carbide and silicon monoxide gas is highly endothermic, so an increase in temperature will decrease the fraction of SiO in the gas leaving the inner zone. If the temperature is 2000 °C, the equilibrium constant, K, is about 1 so the fraction of SiO in the gas leaving the inner zone would be 0.5 [9].

The heat balance becomes important when we consider the extent of the

condensation reaction in the outer zone. The descending charge can only accept a limited amount of the heat from the (exothermic) condensation reaction for SiO:

This limits the silicon recovery unless some other heat sink is available in the outer zone (Fig. 2) [9].

Figure 2. SiO condensate in the outer zone vs. the proportion of SiO gas leaving the inner zone. The vertical line at 0.58 on the horizontal axis indicates the maximum condensate such that the descending charge can accept all the heat of condensation. This plot assumes 100% silicon recovery [9].

Another approach we have pursued is based on the energy-minimization software SOLGASMIX, originally developed by G. Eriksson (1975). We divide the reactor into layers and equilibrium is determined for each layer individually. This approach either requires the assumption of energy-control or temperature-control; we must either assume that the energy consumption per unit charge is constant, or that the temperatures of the layers are fixed [3]. This approach may be fundamentally flawed for this system, however, due to kinetic considerations. In the outer zone, we mentioned that the condensation reaction proceeds:

This reaction proceeds more rapidly than other condensation reactions that are more thermodynamically favored [5]. SOLGASMIX ignores this detail and simply finds what the equilibrium composition will be. In this system, however, this may not be very informative, since it seems that the system does not run in thermodynamic equilibrium. This issue has not been resolved satisfactorily. The SOLGASMIX software can be used, however, for certain calculations, where the assumption that the system moves directly toward lowest free energy is valid.

We have done overall heat and mass balance calculations using SOLGASMIX by assuming a temperature profile (Table 1) in a furnace modelled as three intercommunicating layers; adding more "cool zone" layers, in which the descending charge reacts in an atmosphere of SiO and CO does not introduce any fundamentally new behavior.

ZONE	TEMPERATURE (°C)
Top gas	600
Charging zone (C added)	1000
C-SiO reaction	1600
Inner zone (SiO ₂ added)	2000

Table 1. Typical temperature profile in SOLGASMIX calculation.

For a given zone, if we prescribe the temperature, the pressure, and the initial amounts of various species, we can determine the equilibrium composition. We can also perform a heat balance on each zone by prescribing the material flows (amount and temperature), and the external heat. For the heat balance calculation in a given zone we can leave one variable unspecified and solve for the value that will close the heat balance in that zone. It may be possible to use an iterative process to close the overall heat balance, but this is not feasible with this software [3]. We are investigating other software that may permit this type of calculation.

FURNACE OPTIMIZATION

We can answer certain questions based on thermodynamic considerations. We can determine the effect of adding raw materials in different proportions. We can determine the effect of diluting the SiO (g) in the reactor. We can determine the effects of changes in temperatures of the zones, or changes in external heat. We can determine the effect of adding iron to the system.

There are other questions we cannot answer using thermodynamic modelling---namely those concerning kinetics and practical operating conditions. Ultimately, our thermodynamic calculations can only describe the average behavior of the furnace; we average over time and space when we ignore kinetics and discretize the furnace. For the hollow graphite cathode direct current plasma arc technology it seems certain that the reaction scheme will change. In fact, this is what we are hoping for; it is fairly certain that the conventional technology is not the most efficient when we take into account energy costs, and costs of sized raw

materials.

In order to predict the effect of adding part of the charge directly into the arc, we need to determine what reactions will dominate. We must determine what happens when a mixture of nitrogen gas carrying solid silica particles enters the plasma zone; this question has not been covered in the literature. Possibilities exist for gas phase reactions, and gas-solid reactions. Initial calculations may determine the residence time of the silica particles in the arc, and therefore the heating available. We are interested in whether reactions occur in the arc, or whether they occur only in the melt and the arc simply propels the solid particles into the melt zone.

Kinetic considerations and a thorough understanding of the arc is necessary to answer these questions. The spatial averaging we used in the thermodynamic calculations most affected results in the hearth region (i.e. the inner zone). This is precisely where the most dramatic changes would occur as a result of feeding through the hollow electrode. We must model this region in more than one dimension especially.

To optimize practical operating conditions, we need to pursue a dual approach. First, we continue to use our abilities to make thermodynamic calculations to set upper and lower bounds on our calculations. These calculations can help determine what reactions are may occur, and to tell us what things are theoretically possible. One basic technique is to minimize free energy given a mass balance to determine equilibrium compositions.

The second part of our approach will yield the understanding we need to optimize furnace performance. We concentrate on the kinetics of the reactions and the phenomena associated with the heat and mass flow in the arc zone. Modelling of heat and mass flow in the upper parts of the reactor will help us understand condensation mechanisms, and may provide ideas on reducing coking costs.

SUMMARY AND CONCLUSIONS

In this report we have provided an outline of our thermodynamic modelling capabilities to date. These calculations can provide bounds, but in general the results we can expect are semi-quantitative, and the understanding we can extract regarding the effect of changes in operating parameters is qualitative. A more complete understanding of the furnace must follow mathematical modelling of the kinetic processes in the furnace. This comment is more or less true in general but is particularly important in our case where, although we may have something approximating steady-state, very little in the furnace is in thermodynamic

equilibrium.

We especially have difficulties using thermodynamic modelling in the arc region where temperature gradients are so large. This problem has been largely ignored in the literature in modelling of the submerged arc technology. In a submerged arc furnace, the the maximum temperature is determined by the melting point of the alloy we are producing. In the hollow graphite cathode, DC plasma arc furnace, however, the maximum arc temperature will be much higher, perhaps on the order of 20,000 K, and consequently the temperature gradients in the inner zone will be much larger than in a conventional submerged arc furnace. It is likely that the assumption of zones each in thermodynamic equilibrium will not apply to the inner zone in the hollow cathode technology. This is the region we need to investigate to understand what new reactions will occur when the charge is added down the cathode.

We are very interested in your reaction to this report. Your input regarding practical operating characteristics is crucial. If the modelling is proceeding is the right direction perhaps Prof. Szekely could meet with some of your team in South Carolina in December or January.

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Appendix G

MASTER TEST PLAN

HRL 4/20/94

Date	Data	Target	Power	Hollow Electrode		Top Charge	Notes
	Set	Alloy	(mw)	% of SiO2	% of F.C.		
May 17-18		Heat Furnace and train staff, Debug Equipment					
May 19-21	1	50%	0.8	10%	0%	balance	1st test
May 22-24	2	50%	1.0	0%	0%	100%	base case
May 25-27	3	50%	1.0	25%	0%	balance	no carbon
May 28-30	4	50%	1.0	25%	12.50%	balance	carbon
May 31-J2	5	50%	0.8	25%	?	balance	low power
Jun 3-5	6	50%	1.0	50%	0-25%	balance	high sand
Jun 6-8	7	50%	1.0	0%	0%	100%	base case
Jun 9-15		Furnace Digout, Repairs, Supervision Change					
Jun 16-18		Heat Furnace, Train Staff, Establish Tap Procedure					
Jun 19-21	8	100%	1.0	10%	0%	balance	1st silicon
Jun 22-24	9	100%	1.0	25%	0%	balance	more sanc
Jun 25-27	10	100%	1.0	10%	5%	balance	carbon
Jun 28-30	11	100%	1.0	25%	12.50%	balance	higher
Jul 1-3	12	100%	1.0	50%	0-25%	balance	most sand
Jul 5-7	13	100%	1.0	0%	0%	100%	base case
July 8th		Change Over, Repairs? Heat up, New Supervision					
Jul 9-11	14	75%	0.8	10%	0%	balance	1st 75%
Jul 12-14	15	75%	1.0	0%	0%	100%	base case
Jul 15-17	16	75%	1.0	25%	0-12.5%	balance	more sanc
Jul 18-20	17	75%	1.0	35%	0-15%	balance	higher
Jul 21-23	18	75%	0.8	50%	0-25%	balance	highest
Jul 24-26	19	75%	1.0	50%	0-25%	balance	more C?
Jul 27-29	20	75%	1.0	0%	0%	100%	base case
July 30th		Shut Down, Inspect					

Appendix H

REV	DATE	DESCRIPTION	BY	CHKD	APP'D
1	10/1/83	REVISED FOR	WEL	WEL	WEL
2	10/1/83	REVISED FOR	WEL	WEL	WEL
3	10/1/83	REVISED FOR	WEL	WEL	WEL
4	10/1/83	REVISED FOR	WEL	WEL	WEL
5	10/1/83	REVISED FOR	WEL	WEL	WEL
6	10/1/83	REVISED FOR	WEL	WEL	WEL
7	10/1/83	REVISED FOR	WEL	WEL	WEL
8	10/1/83	REVISED FOR	WEL	WEL	WEL
9	10/1/83	REVISED FOR	WEL	WEL	WEL
10	10/1/83	REVISED FOR	WEL	WEL	WEL

SOUTH CAROLINA RESEARCH AU
 NORTH CHARLESTON, S CAROLINA
 6/28/83
 SCALE: 1/4" = 1'-0"
 M 001

PLAN

SCALE: 1/2" = 1'-0"

SECTION A-A

SCALE: 1/2" = 1'-0"

FRONT ELEVATION

SCALE: 1/2" = 1'-0"

DETAIL "A"

SCALE: 1/2" = 1'-0"

NOTE:
CONTRACTOR TO VERIFY ELEVATION
TO THE TOP OF FURNACE PRIOR TO
ANY CONSTRUCTION. ADJUST HEIGHT
OF SPOOL PIECE TO SUIT 8'-2" ELEV.

BILL OF MATERIALS

REV	ITEM	QTY	DESCRIPTION
C.S.	1	1	HOOD - DWG. 79640-M-008
	2	2	DOOR TRACK TO FIT - BEND TO 3/4" RAD McMASTER-CARR #1867A899 OR EQUAL
	3	6	CENTER BRACKET McMASTER-CARR #1867A22 OR EQUAL
	4	4	END BRACKET McMASTER-CARR #1867A23 OR EQUAL
	5	12	DOOR TRACK McMASTER-CARR #1321A23 OR EQUAL
C.S.	6	6	HOOD DOOR - DWG. 79640-M-008
H.S. Revised	7	1	KADWOL. ELECTRODE SEA - DWG. 79640-M-1 set
C.S.	8	1	SEAL RETAINING RING - DWG. 79640-M-008
H.S. Revised	9	1	KADWOL. CERAMIC FIBER INSULATION - DWG. 79640-M-008

M-007

REV	DESCRIPTION	DATE	BY	APP'D FOR	DATE	BY	APP'D	REVISIONS	DATE	BY	APP'D
0	CONSTRUCTION

HATCH ASSOCIATES CONSULTANTS, INC.

8/25/93
AS NOTED
BY T. CHORN

SOUTH CAROLINA RESEARCH AU
NORTH CHARLESTON, S. CAROLINA
PILOT FURNACE - FERRO SILICON MODIFY

PLAN
SCALE: 1/4\"/>

DETAIL "A" SUPPORT LUG
SCALE: 1/2\"/>

DETAIL "B" SUPPORT LUG
SCALE: 1/2\"/>

NOTES:
1. FIELD WELD ELECTRODE MUST CLAMP DIMENSIONS BEFORE FABRICATION.
2. ALL WELDS SHALL BE 1/4\"/>

SECTION B-B - ELECTRODE SEAL SUPPORT
SCALE: 1/2\"/>

DETAIL "C" TRACK SUPPORT
SCALE: 3/4\"/>

DETAIL "D" INSULATION DETAIL
SCALE: 1/2\"/>

DETAIL "E" INSULATION DETAIL
SCALE: 1/2\"/>

DETAIL "F" INSULATION DETAIL
SCALE: 1/2\"/>

ELEVATION
SCALE: 1/2\"/>

DETAIL - FUME HOOD
SCALE: 1/2\"/>

INSULATION DETAIL
SCALE: 1/2\"/>

INSULATION DETAIL
SCALE: 1/2\"/>

HATCH ASSOCIATES CONSULTANTS INC.

8/15/83
SOUTH CAROLINA RESEARCH AUT
NORTH CHARLESTON, S. CAROLINA
PILOT FURNACE - FERRO SILICON MOODY

27

FURNACE

12'-2" NTS
REF.

51'-0"

EXISTING
BAGHOUSE INLET

A

PLAN OF HOOD DUCT

SCALE: 1/4" = 1'-0"

PLAN OF TAPPING HOOD DUCT

SCALE: 1/4" = 1'-0"

SECTION A-A

SCALE: 1/4" = 1'-0"

SECTION B-B

SCALE: 1/4" = 1'-0"

SECTION C-C

SCALE: 1/4" = 1'-0"

GENERAL NOTES:

1. DUCTWORK - ALL DUCTWORK TO BE FABRICATED FROM 10 GA. C.S.
2. REFRACTORY LINING - PLURICO LHM-28 OR 2" THICK
3. FLANGES L2 x 2 x 1/4" UNLESS NOTED OTHERWISE
4. DUCT FLANGE LOCATIONS ARE SHOWN FOR FABRICATOR ONLY. CONTRACTOR SHALL LOCATE FLANGES TO ACCOMMODATE FABRICATION, INSTALLATION AND REFRACTORY LINING.
5. FOR GENERAL ARRANGEMENT SEE DWG 7064C

SOUTH CAROLINA RESEARCH AUT
NORTH CHARLESTON, S. CAROLINA
PILOT FURNACE - FERRO SILICON MODIFIC

NO.	REVISIONS	DATE	ISSUED FOR	BY	DATE
0	CONSTRUCTION

HATCH ASSOCIATES CONSULTANTS, INC.

M-009

11/5/83
1/4" = 1'-0"
BY: [signature]
CHECKED: [signature]

DATE	BY	CHKD	APP'D	REVISION	DESCRIPTION
7/23/83				1	FOR CONSTRUCTION

SECTION A-A DWS. S-001, S-002

GENERAL NOTES:

I. GENERAL

1. ALL WORK SHALL COMPLY WITH THE APPLICABLE PORTIONS OF LOCAL BUILDING CODES AND OSHA REGULATIONS.
2. ALL DIMENSIONS ON OR TO EXISTING CONSTRUCTION SHALL BE VERIFIED BY CONTRACTOR BEFORE CONSTRUCTION BEGINS.
3. THIS STRUCTURE HAS BEEN DESIGNED FOR THE FOLLOWING LOADS:
STAIRS AND PLATFORMS 150 PSF

II. FOUNDATIONS

1. FOUNDATIONS SHALL BEAR ON SOIL CAPABLE OF SUSTAINING AN AVERAGE BEARING PRESSURE OF 1500 PSF. NOTIFY OWNER IF SUITABLE BEARING CANNOT BE OBTAINED AT ELEVATIONS SHOWN ON DRAWINGS.

2. ANY OVER-EXCAVATED FOUNDATION AREAS SHALL BE RAISED WITH WELL COMPACTED GRANULAR FILL OR CONCRETE.

III. CONCRETE

1. ALL CONCRETE WORK SHALL CONFORM TO ALL REQUIREMENTS OF ACI 308 "SPECIFICATIONS FOR STRUCTURAL CONCRETE FOR BUILDINGS", EXCEPT AS MODIFIED BELOW.
2. ALL CONCRETE SHALL BE 4000 PSI/28 DAYS WITH A MAXIMUM W/C RATIO OF .44.

GENERAL NOTES CONT.:

IV. REINFORCING

1. REINFORCING STEEL SHALL BE GRADE 60 STEEL PER ASTM A615-63 OR A706 GRADE 60.

V. STRUCTURAL STEEL

1. FABRICATION AND ERECTION OF STRUCTURAL STEEL SHALL BE IN CONFORMANCE WITH THE AISC CODE OF STANDARD PRACTICE, EXCEPT AS MODIFIED BELOW.

2. ALL STRUCTURAL STEEL AND PLATE SHALL MEET ASTM A-36
3. ALL BOLTS, NUTS, AND WASHERS SHALL MEET ASTM A325 (SL)

4. WELDING ELECTRODES SHALL BE E70XX. WHEN WELDING TO EXISTING STEEL, SELECT ELECTRODES THAT WILL DEVELOP WITH THE STEELS TO BE WELDED.

5. WHEN REACTIONS ARE NOT SHOWN, BEAM CONNECTIONS SHALL DEVELOP $\frac{1}{2}$ OF THE TOTAL ALLOWABLE UNIFORM LOAD FOR THE LATERALLY SUPPORTED MEMBER. BRACING CONNECTIONS SHALL DEVELOP THE FULL TENSILE STRENGTH.

6. MINIMUM CONNECTIONS TO BE 2- $\frac{1}{2}$ INCH DIAMETER BOLTS/1 INCH CONTINUOUS FLAT WELD. MINOR CONNECTIONS SUCH AS HANDRAILS OR GRIPS MAY USE $\frac{1}{2}$ INCH A307.

7. CEMENT GROUT TO BE EMBOCO 636 BY MASTER BUILDERS.

SECTION B-B DWS. S-001, S-002

S-003

REV. NO.	DESCRIPTION	DATE	BY	CHKD.	APP. DATE	APP. DATE
0	CONSTRUCTION	JUL 11, 1993				

10/23/93
SOUTH CAROLINA RESEARCH AUT
NORTH CHARLESTON, S. CAROLINA

Appendix I

Supervisor

TAP SHEET

Date:

Shift:

Time: (Close) -	KWH B - A = C -	A B Start KWH - End KWH -
Volts	Amps	Tap Wt (lbs)
	Burden Wt (lbs)	Electrode Wt (lbs)
Quartz		
Coal		
Chips		
Total Feed Weight (lbs)		
No. of Tap Bars		
# Shells		
★Fume weight (after tap)		

★Rap on baghouse each hour.

Appendix J

Product:

DATE:

STCC PROGRAM - DAILY FURNACE RECORD

TIME	AMPS	VOLTS	KW	R/M FED TO FURNACE TOP		OFF	DELAYS		REASON	TAP TIME	TAP WEIGHT	% Si	% Fe
				NC QTZ	COAL		ON	MIN					
12:00													
1:00													
2:00													
3:00													
4:00													
5:00													
6:00													
7:00													
8:00													
9:00													
10:00													
11:00													
12:00 N													
1:00													
2:00													
3:00													
4:00													
5:00													
6:00													
7:00													
8:00													
9:00													
10:00													
11:00													
SUPERVISOR	OPERATOR			NITROGEN FLOW RATE	ELECTRODE ADDED	B.H. DUST WEIGHED	R/M FED SAND	R/M FED DOWN	ELECTRODE COAL	KWH METER	OP HRS		
										12:00	KWH/DRE	% OT	
										8:45	LBS	KWH/LB	
										9:00	AVE KW		
										12:00			

STOKING TIME

[illegible]

Foreman

ELECTRODE FEED

Date:

Shift:

Time start - finish	Quartz lbs/min	Quartz Total lbs	Coal lbs/min	Coal Total lbs	Total lbs	Tap #
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						
-						

Daily data sheets

Date:

tap#/time	Op. time (%)	SI weight		start (KWh)	Electricity		Length (in)	Electrode		Quartz (lbs)	SI Recovery (%)	Fume weight (lbs)	Comments.
		Gross (lbs)	Net (lbs)		end (KWh)	Total (KWh)		Weight (lbs)	Consumption (lbs/lbs)				

ELECTRICAL INFORMATION

Date:

Shift:

Time	Volts	Amps	KW	KWH	Explanation

STCC PROGRAMMIX MAKING

BELOW IS A TYPICAL MIX ORDER. THE HEO/UTILITY MAN MUST FILL OUT AND RECORD EACH MIX MADE ON HIS TURN. CHANGE IN THE MIX ORDER WILL HAVE A NEW NUMBER. THIS WILL BE AUTHORIZED BY THE SUPERVISOR ON DUTY. THE MIXES MADE WILL BE RECORDED ON THE FURNACE SHEET AT THE END OF EACH SHIFT.

STCC PROGRAM MIX ORDER

DATE: _____ SHIFT _____ MIX NUMBER _____

PRODUCT: _____ FEED RATE _____

WOODCHIPS: _____ #

GATLIFF COAL: _____ #

STEEL PUNCHINGS: _____ #

NC GRAVEL: _____ #

DRYED SAND (ELECT) _____ # PER MINUTE.

NUMBER MIXES MADE THIS SHIFT _____

HEO OPERATOR _____

BURDEN FEED

Date:

Shift:

[illegible]

TAP SHEET

Date:

Shift:

Time: (Close)	KWH B - A = C	A B Start KWH - End KWH
Volts	Amps	Tap Wt (lbs)
	Burden Wt (lbs)	Electrode Wt (lbs)
Quartz		
Coal		
Chips		
Total Feed Weight (lbs)		
No. of Tap Bars		
# Shells		
★Fume weight (after tap)		

★Rap on baghouse each hour.

Appendix K

Minutes

of the

STCC Meeting

at

SCRA

North Charleston, S.C.

April 12, 1994

Attendees:

Ben Perkins, SCRA
Harold Larson, MIT
Bob Kaiser, Elkem
Ed Bredniak, SKW
Dieter Ksinsik, SKW
Skip Davis, Globe
Doug Katt, Aimcor
Jerry Rich, Aimcor
John Wolfe, Macalloy
Tim Nelson, Macalloy
Bill Schneider, Macalloy
Jim Welborn, ADL
Darla Nettles, ADL

Overview

Ben opened the meeting by presenting the agenda. He then went on to discuss the cost share situation and presented a slide of the total cost share picture. A significant amount of cost share will be generated during the testing period. Ben stated that he expected EPRI to provide \$100,000. Ben then went on to give an overview of the technical approach, which was to produce 50%, 75% ferrosilicon and silicon metal.

Proprietary Considerations

Ben stated that our teaming agreements dealt with the issue of proprietary information. He stated that the technology developed in the program is not proprietary, but would be shared with all the participants, for them to take back to their companies and adapt for their own domestic needs. Matters such as pricing would not be discussed, nor the particular processes currently used by the companies. The experimental data gathered would be available for all. Ben also pointed out that if any company had any concerns about proprietary data, that company should discuss the matter with SCRA.

Modelling

Harold then discussed the MIT modelling effort. He pointed out that the student who was doing the work was funded for a year, and that we hoped to fund him an additional year. The idea would be that he could then funnel actual data from the furnace through the model. Harold then distributed a report from the student.

Major Goals

Ben went over the major goals of the test program which are to produce an acceptable product with a savings of 5% to 15% in energy and 5% to 10% in materials. Dieter asked if those savings were regardless of volume. Harold responded in the affirmative. Dieter asked if any detailed information regarding the design of the furnace was available. Copies of the design drawings were given to the team members. Harold pointed out that over half of the construction was completed and that they would view the furnace after lunch. He pointed out that several things needed to be done in terms of instrumentation.

Current Status

John took a few minutes to give an overview of the current state of the furnace. He pointed out that the small furnace has only been run a few months on three tests. He also pointed out that there were several equipment problems that arose and that we could anticipate some in this test. He discussed some of the problems that had arisen and were corrected, so that we would probably experience different problems. He also pointed out that because they had recently done some testing with the furnace, it would be much easier for the STCC to bring it up to speed. He also pointed out that the problems were no reflection on the technology. He discussed some of the advantages of the technology, such as how easy it is to control voltage.

Harold pointed out that the problems that were encountered in the Taconite program would not be encountered with the STCC program. The first problem was blockage in the off gas system. The second was a problem with blockages in the electrode. However, the design for the STCC test is entirely different from the design used in Taconite testing. Therefore, these problems should not occur.

Schedule

Harold then went on to discuss the schedule. His goal was to determine dates for the test runs and to get commitments from the companies as to when they would be present at the test. The campaigns were planned to produce 3 tests: 1. 50% ferrosilicon, 2. silicon metal and 3. 75% ferrosilicon. The first test would be 50% because that is easier to produce than silicon metal. The second test would be silicon metal. If time permits, then 75% ferrosilicon would be produced. These tests were planned to cover a 3 month period, i.e., approximately 1 month per test cycle.

Harold then went on to discuss the restraints on the program. One constraint is time. We are not at liberty to extend the program. A second restraint is resources. He pointed out that we have 3 shifts available from Macalloy. With this amount of labor, you would run 10 days then have 4 days off, which could be used to dig out the furnace if need be, and 10 days on for the completion of the test. Dieter asked how long it would take to reach a steady state, and Harold replied that it would take 3 days. This would mean that 30% of the testing time would be spent

reaching steady state before dependable results could be obtained.

Ed asked if it would be possible to hire enough people to have 4 shifts and run continuously. Harold stated that if we could get additional labor, we could run continuously for the 20 days, but that we might have a problem finding labor. He did add, however, that we might be able to use some temporary labor as a source, as we did in Plasma Arc. John stated that he would look into the possibility of getting enough Macalloy labor to run continuously and get back with costs and the availability of experienced laborers.

The following dates were agreed upon for the testing, provided sufficient labor is available for 4 shifts:

Dates	Product	Company Participants
May 16 - June 8	50% Ferrosilicon	Aimcor, Elkem, Globe
June 16 - July 2	Silicon Metal	SKW, Globe
July 6 - July 27	75% ferrosilicon	SKW, Aimcor

The companies were reminded that they could have as many observers from their company on site as they wished. Arrangements have been made with Resident's Inn to provide housing for the company participants and observers during testing. It was also pointed out to those present that SCRA would be glad to assist in making travel arrangements.

Furnace Lining

Harold described the lining of the furnace. Currently, the plan is to use a thicker lining than has been used in the past. The sides of the furnace will be extended upward by 18 additional inches. A layer of insulating brick will be placed on the sides, and a nine inch layer of 70% alumina brick will be placed inside the insulating brick. A layer of carbon paste will be rammed into the sides to an inside diameter of 50 inches. Skip asked if there had been any problems with side arcing. Harold responded that there have never been any problems with side arcing.

Tapping

The matter of where to place the tap hole block was discussed, along with the problem of how to tap the furnace. The tap hole should be as low as possible to avoid leaving a metal heel in the furnace. It was decided that Macalloy's shotgun was too large to tap the small furnace. Jerry asked about the possibility of using an iron bar or a wooden pole to tap it. Skip suggested a graphite lance. Dieter asked if we could rent tapping equipment instead of buying it.

The question was raised of what to do with the molten material when it was tapped. John estimated that it would produce about a ton per 4 hours. He added that there were no casting

molds available. It was suggested that a 6 X 6, max, mold was needed, preferably two such molds. Ed said that they might have an old mold that could be used. Jerry stated that Aimcor might have 1 or 2 cast iron molds that could be donated. Both Ed and Jerry agreed to check.

Analysis

The question of how to handle the analysis came up. Basically, Jim Trunzo has volunteered the use of his laboratory in Washington. However, it would take several days get results. Bob pointed out that Jim Trunzo's offer would be useful for the test report results, but that we still need control sampling while the tests were being conducted to tell you what is going on and what you need to do. Jim asked if Macalloy had any lab equipment that would do. John pointed out that their equipment was geared toward Ferrochromium and not silicon analysis. Bob stated that there were some quick and dirty analysis that could be done to provide needed control analysis. He asked if a wet chemist were available. John stated that their wet chemist had just retired 2 years ago, but he might be available to come back for the project. The question of whether or not the wet chemist would be available and what type of additional equipment might be needed was left open.

Harold briefly discussed the current data gathering mechanisms. He stated that we have the capacity to measure the weight of the materials going into the furnace and that we have thermocouples located in the furnace that can capture temperature information which can be logged on a computer. We can also weigh and sample the tap. He pointed out that it would be a simple matter to collect the fume for analysis. Harold pointed out, however, that we do not have any super sacks to collect it at the moment. Jerry stated that he could obtain some super sacks to collect it.

Harold again raised the issue of what types of data we could gather. This included weighing of inputs, cast weights, fume weights, temperature on the shell, cooling air temperature and baghouse gas temperature. He added, however, that there was not a volume flow meter to the baghouse.

Safety

The question of safety came up for the stoker. John stated that Macalloy could provide the tapper's clothing, but that he felt some sort of screen was needed between the stoker and the furnace. Tim pointed out that there was also very little room on the platform. John added that we might need to provided rubber decking for electrical insulation.

Ed asked if there were a matrix set up to identify the parameters we would be controlling. Harold stated that a matrix of operating parameters with power levels was in the works. The question of determining the quality of the tap was brought up. Rich stated that it would be easy to identify 50% ferrosilicon optically, but that you would want a dipstick to test the stream for silicon and 75%.

Power

Bob asked about the power situation. Tim and John pointed out that the small furnace would be billed at an average rate by Macalloy. Ed asked if we could be taken off line if we were to shut down, so that we would not be paying for power in the event that we had to shut the furnace off for a period of time. Bill stated that you would have to call the Macalloy control room to notify them when you wanted to be off power. Dieter asked if the price of power would result in a financial overrun. Harold pointed out that the power arrangements were planned for, and in fact, the indications were that we were actually going to get a better rate than we had budgeted.

Raw Materials

The discussion then centered on materials. Harold stated that Gatliff coal has been donated to the project by Scan Carbon, but that we would have to pay for transportation. This would not be a problem however, since the coal was already in Charleston and on Shipyard Creek. The coal is all from the same seam, but is of three different grades. Bob stated that we could get a raw material analysis via Jim Trunzo's lab.

Harold stated that the quartz was from North Carolina. Bob said that the size was between 2" and 7/8 and that we also had sand. These materials were donated.

The question arose as to how to get these materials dry. It was decided to try and buy dry bagged sand. Since only open storage is available, you would have to dry the coal immediately before putting it in the furnace, because with the humidity and rain in Charleston during July it would be impossible to keep it completely dry.

Harold stated that we have found wood chips 100 miles from Charleston, and that we would have to buy those materials. The chips are approximately 3/4". Jim stated that we only have half of the scrap iron that we need. We need 30 additional tons.

Ed asked if we needed to gather any special information on the environmental side. Harold said that the main thing was to have a clean stack test, and that we would have the dust generated analyzed.

Tim pointed out that if any materials were left on-site after the test, Macalloy would want them to be removed. They do not want to have to deal with the leftovers, because they would have no use for them. Surplus materials should be returned to the source.

Issues and Action Items

1. Tapping the furnace - A method for tapping the furnace must be found and equipment located.
2. Casts - Jerry and Ed will look to see if they have suitable molds to donate
3. Lab Support - Jim Trunzo can do raw materials analysis and analysis for final report. Macalloy has an available chemist, but we may want to augment their support with one person from the member companies. We may rent or borrow equipment from one of the companies. A tungsten crusher will be needed.
4. Manpower - Macalloy will check to see if 4 shifts will be available.
5. Shipping/disposing of fume - Bob will check on this.
6. Super sacks for fume - Jerry will donate some super sacks.
7. An effort will be made to determine if a screen needs to be added to allow the safe charging of the furnace.
8. Harold will work on a matrix for the testing parameters.
9. Drying the materials will be a problem - The possibility of buying bagged dry sand will be looked into.
10. 30 tons of scrap iron is needed.

Appendix L

The handwritten originals for this appendix were not sufficiently legible for publication and were omitted.

Appendix M

PLASMA

PRODUCT 50% Fe S_i

2 copies
WOLF

DATE	SHIFT	TAP	Si	Fe	Cr	Ca	Al	Ti	P	Mn
5/17/94	10PM		41.86	56.72	0.640	0.01	0.12	0.045	0.029	0.38
5/18/94	2	1	34.18	64.22	0.796	0.01	0.07	0.034	0.030	0.46
5/17/94	2	1	37.62	61.06	1.33	0.01	0.11	0.044	0.025	0.36
5/27/94	3	1	34.30	63.02	1.87	0.01	0.05	0.039	0.029	0.48
5/31/94	9PM		42.51	55.47	1.23	0.01	0.14	0.038	0.027	0.33
5/31/94	1PM		44.95	53.23	1.08	0.01	0.14	0.143	0.024	0.25
6/1/94	12-8		40.54	56.61	1.13	0.01	0.13	0.080	0.025	0.32
6/02/94	1	1	34.39	58.97	1.81	0.32	3.76	0.20	0.023	0.32
6/02/94	1	2	37.10	60.75	1.24	0.019	0.45	0.09	0.019	0.18
6/02/94	9PM		33.62	64.42	1.45	0.01	0.15	0.070	0.021	0.25
6/02/94	12N		36.55	61.84	1.11	0.01	0.06	0.055	0.020	0.26
6/02/94	639		39.17	59.39	0.823	0.003	0.16	0.104	0.025	0.23
6/05/94	1	1	42.18	55.86	1.05	0.01	0.43	0.099	0.021	0.23
6/05/94	2	1	41.12	57.10	0.78	0.01	0.24	0.084	0.020	0.22
6/05/94	8-45		38.93	59.69	0.66	0.01	0.16	0.134	0.022	0.21
6/06/94	3PM		40.80	56.33	0.98	0.01	0.10	0.107	0.023	0.19
6/06/94	1	1	41.67	58.01	0.55	0.01	0.22	0.092	0.022	0.33
6/09/94	1	2	42.11	56.71	0.65	0.01	0.22	0.084	0.020	0.31
6-09-94	1	2	36.01	59.50	3.84	0.01	0.10	0.069	0.020	0.27

6-09-94
EUNE

140

140

PLASMA

PRODUCT Si METAL

DATE	SHIFT	TAP	Si	Fe	Cr	Ca	Al	Ti	P	Mn
6/30/94	1	1	48.11	50.53	—	0.054	0.470	0.066	—	0.440
7/1/94	CAST		50.84	48.31	—	0.011	0.122	0.406	—	0.104
"		1	84.80	14.31	—	0.009	0.287	0.345	—	0.046
"		2	63.75	35.26	—	0.013	0.285	0.441	—	0.081
7/1/94	8 pm		85.82	11.40	—	0.280	1.906	0.325	—	0.066
7/2/94	12 NOON		90.08	8.90	—	0.024	0.421	0.301	—	0.074
7/2/94	#2 8 pm		89.69	9.26	—	0.032	0.427	0.312	—	0.074
7/2/94	8 pm		93.08	6.08	—	0.033	0.375	0.173	—	0.059
7/2/94	8 pm #2		94.15	5.00	—	0.038	0.414	0.148	—	0.059
7/2/94	12 pm		90.64	8.40	—	0.030	0.382	0.271	—	0.070
7/3/94	4 pm		91.33	7.68	—	0.074	0.476	0.170	—	0.068
7/3/94	2	1	92.37	6.18	—	0.189	0.828	0.168	—	0.059
7/3/94	9:45 pm spoon		88.63	8.67	—	0.590	1.546	0.221	—	0.089
7/3/94	9:45 pm #2		92.72	6.09	—	0.138	0.605	0.190	—	0.064
7/3/94	9:45 pm #3		93.32	5.44	—	0.115	0.667	0.195	—	0.061
7/5/94	Top 2		92.45	5.76	—	0.423	1.000	0.152	—	0.039
7/6/94	3 AM		81.98	15.95	—	0.695	0.933	0.178	—	0.062
7/6/94	8-11		67.75	31.09	—	0.238	0.490	0.150	—	0.081
7/5/94		1	91.78	7.03	—	0.155	0.578	0.203	—	0.055
7/6/94	#1		94.67	4.09	—	0.209	0.667	0.132	—	0.039
7/6/94	#2		90.91	7.78	—	0.235	0.655	0.162	—	0.058
7/7/94	12-8	8	87.76	10.98	—	0.154	0.664	0.162	—	0.067
7/7/94	#1		88.73	8.98	—	0.583	1.345	0.175	—	0.065
7/7/94	#2		74.01	24.90	—	0.175	0.441	0.163	—	0.106
7/7/94	9:30 pm		88.45	9.78	—	0.311	0.967	0.198	—	0.086
7/8/94	8-11		88.57	6.00	—	1.674	3.352	0.139	—	0.054
7/8/94	4-12 #1		88.89	8.41	—	0.394	0.902	0.123	—	0.051
7/8/94	4-12 #2		90.19	6.43	—	0.936	2.067	0.128	—	0.045
7/9/94	12-8 #1		90.98	5.32	—	1.479	1.837	0.130	—	0.042
7/9/94	2-12 pm		88.48	9.47	—	0.683	0.973	0.137	—	0.050
7/9/94	6:55 pm #2		89.55	6.20	—	1.879	2.007	0.046	—	0.046
7/11/94	12-1 pm		63.99	35.33	—	0.064	0.202	0.173	—	0.132
7/11/94	2-3 pm		56.21	42.87	—	0.101	0.302	0.173	—	0.139
7/11/94	4-12 11 pm		91.20	6.43	—	0.839	1.184	0.096	—	0.054
7/11/94	4-12 9 pm		87.95	6.16	—	2.632	2.896	0.101	—	0.052
7/11/94	4-12 6 pm		89.25	5.93	—	2.198	2.248	0.114	—	0.050
7/11/94	4-12 4:30		84.38	11.89	—	2.275	1.756	0.132	—	0.063

PLASMA
PRODUCT SIMETAL

	DATE	SHIFT	TAP	Si	Fe	Cr	Ca	Al	Ti	P	Mn
	7/12/94	12-8 ¹	1 AM	92.60	3.008	—	2.741	1.440	0.027	—	0.017
	7/15/94	4-12 ²	9 PM	85.29	9.83	—	2.548	1.835	0.203	—	0.086
	7/16/94	12-8 ³	1.2 AM	88.36	6.599	—	2.34	2.268	0.185	—	0.046
	7/16/94	12-8 ⁴	5 AM	84.63	11.49	—	1.77	1.699	0.147	—	0.053
	7/16/94	12-8 ⁵	9 AM	91.96	6.63	—	0.403	0.662	0.096	—	0.044
	7/16/94	4-12 ⁶	5 PM	89.43	6.603	—	1.68	1.911	0.128	—	0.046
	7/16/94	4-12 ⁷	9 PM	84.39	12.05	—	1.581	1.533	0.186	—	0.064
	7/17/94	12-8 ⁸	1 AM	89.34	6.91	—	1.598	1.732	0.164	—	0.047
	7/17/94	12-8 ⁹	5 AM	95.68	3.068	—	0.272	0.652	0.101	—	0.026
✓	7/17/94	8-4 ¹⁰	9 AM	95.67	2.645	—	0.560	0.816	0.074	—	0.026
✓	7/17/94	4-12 ¹¹	1 PM	96.32	2.516	—	0.336	0.539	0.067	—	0.020
✓	7/17/94	4-12 ¹²	5 PM	91.15	3.256	—	2.799	2.459	0.103	—	0.034
✓	7/17/94	4-12 ¹³	9 AM	97.02	1.97	—	0.184	0.540	0.072	—	0.016
✓	7/18/94	12-8 ¹⁴	1 AM	96.67	1.99	—	0.302	0.754	0.068	—	0.016
✓	7/18/94	12-8 ¹⁵	5 AM	95.09	1.567	—	1.172	1.898	0.057	—	0.017
✓	7/19/94	8-4 ¹⁶	9 AM	94.48	3.324	—	0.803	1.094	0.079	—	0.021
✓	7/19/94	8-4 ¹⁷	#23	94.77	4.869	—	0.143	0.584	0.097	—	0.029
✓	7/19/94	4-12 ¹⁸	#24	95.759	3.480	—	0.066	0.397	0.075	—	0.023
✓	7/19/94	4-12 ¹⁹	#25	94.588	4.437	—	0.091	0.535	0.099	—	0.029
✓	7/20/94	12-8 ²⁰	26	94.645	4.448	—	0.130	0.473	0.079	—	0.024
✓	7/20/94	12-8 ²¹	27	96.226	2.844	—	0.153	0.492	0.067	—	0.019
✓	7/20/94	8-4 ²²	28	95.554	3.596	—	0.152	0.419	0.059	—	0.020
✓	7/20/94	8-4 ²³	29	96.886	2.522	—	0.072	0.258	0.047	—	0.015
✓	7/20/94	8-4 ²⁴	30	96.769	2.563	—	0.043	0.349	0.060	—	0.017
✓	7/20/94	8-4 ²⁵	31	98.112	1.379	—	0.026	0.223	0.050	—	0.010
✓	7/21/94	4-12 ²⁶	32	97.761	1.66	—	0.043	0.337	0.040	—	0.016
✓	7/21/94	4-12 ²⁷	33	96.759	2.729	—	0.023	0.221	0.055	—	0.013
✓	7/21/94	4-12 ²⁸	34	97.249	2.057	—	0.047	0.358	0.075	—	0.015
✓	7/21/94	4-12 ²⁹	35	95.06	4.264	—	0.037	0.335	0.077	—	0.022
✓	7/21/94	4-12 ³⁰	36	96.69	1.521	—	0.086	0.838	0.052	—	0.012
✓	7/21/94	4-12 ³¹	37	97.46	1.438	—	0.193	0.655	0.052	—	0.011
✓	7/22/94	4-12 ³²	38	97.38	1.718	—	0.146	0.480	0.065	—	0.012
✓	7/22/94	4-12 ³³	39	97.46	1.76	—	0.139	0.369	0.061	—	0.011
✓	7/22/94	4-12 ³⁴	40	95.94	2.40	—	0.579	0.786	0.077	—	0.013
✓	7/22/94	4-12 ³⁵	41	96.22	3.07	—	0.067	0.341	0.077	—	0.016
✓	7/22/94	4-12 ³⁶	42	86.73	4.901	—	6.05	1.964	0.122	—	0.028
✓	7/22/94	4-12 ³⁷	43	92.38	2.98	—	3.386	1.127	0.069	—	0.015

PLASMA

PRODUCT Si Mict

DATE	SHIFT	TAP	Si	Fe	Cr	Ca	Al	Ti	P	Mn	
7/23/94		44	96.95	1.766	—	0.531	0.489	0.056	—	0.012	
7/23/94	2	45	85.36	2.451	—	0.144	3.755	0.065	—	0.016	
7/23/94	3	46	92.84	2.362	—	1.954	2.356	0.063	—	0.017	
7/23/94	4	47	92.12	2.868	—	2.09	2.629	0.061	—	0.019	
7/23/94	5	48	83.36	2.659	—	7.931	5.753	0.075	—	0.014	
7/23/94	6	49	86.30	4.376	—	4.63	4.38	0.084	—	0.022	
7/24/94	7	50	92.77	4.232	—	1.177	1.486	0.102	—	0.029	
7/24/94	8	51	95.27	3.20	—	0.409	0.814	0.096	—	0.023	
7/24/94	9	52	94.168	3.904	—	0.615	0.992	0.091	—	0.031	
7/24/94	10	53	95.16	2.543	—	0.701	1.286	0.084	—	0.024	
7/24/94	11	54	95.93	2.263	—	0.385	1.119	0.076	—	0.020	
7/24/94	12	55	83.59	1.425	—	0.710	1.09	0.084	—	0.069	
7/25/94	13	56	96.03	2.122	—	0.663	0.893	0.070	—	0.015	
7/25/94	14	57	96.81	1.884	—	0.401	0.614	0.068	—	0.015	
7/25/94	15	58	95.63	1.967	—	0.911	1.198	0.069	—	0.021	
7/25/94	16	59	95.25	2.424	—	0.782	1.246	0.072	—	0.025	
7/25/94	17	60	94.97	2.579	—	0.766	1.373	0.080	—	0.028	
7/25/94	18	61	92.16	1.833	—	2.374	3.341	0.080	—	0.019	
7/26/94	19										
7/26/94	20	63	93.00	1.723	—	2.047	2.940	0.064	—	0.018	
7/26/94	21	64	96.45	1.566	—	0.513	1.189	0.063	—	0.018	
7/26/94	22	65	95.45	3.247	—	0.292	0.718	0.064	—	0.019	
7/26/94	23	66	95.86	2.965	—	0.277	0.618	0.062	—	0.017	
7/27/94	24	67	96.14	2.578	—	0.346	0.642	0.069	—	0.020	
7/27/94	25	68	95.18	3.391	—	0.307	0.812	0.079	—	0.031	
7/27/94	26	69	94.67	3.875	—	0.293	0.840	0.084	—	0.035	
7/27/94	27	70	95.02	2.846	—	0.531	1.307	0.072	—	0.025	
7/27/94	28	71	91.73	5.225	—	0.799	1.891	0.111	—	0.044	
7/27/94	29	72	95.32	2.544	—	0.504	1.322	0.081	—	0.024	
7/28/94	30	73	95.26	2.187	—	0.688	1.572	0.071	—	0.021	
7/28/94	31	74	95.18	2.630	—	0.514	1.365	0.083	—	0.023	
	32										
	33										
	34										
	35										
DUST SAMPLER Rcd	36	7/27/94	93.9	2.60	0.76	0.51	1.0097	<0.0001	0.46	0.47	0.5
	37		K ₂ O	Na ₂ O	P ₂ O ₅	SO ₃					
			0.17	0.058	0.037	0.22					

product

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PLASMA

PRODUCT

50%

Fe Si

7590

DATE	SHIFT	TAP	Si	Fe	Cr	Ca	Al	Ti	P	Mn
7/31/94		90	78.86	18.90	0.367	0.093	0.69	0.042	0.019	0.11
7/31/94		91	47.70	50.10	0.378	0.179	1.08	0.111	0.020	0.23
7/31/94		92	56.80	40.28	0.459	0.265	1.38	0.060	0.020	0.20
?		93	-	-	-	-	-	-	-	-
?		94	-	-	-	-	-	-	-	-
8/1/94		95	33.14	65.41	0.479	0.031	0.21	0.065	0.024	0.44
8/1/94		96	36.69	61.85	0.470	0.061	0.40	0.057	0.020	0.26
8/1/94		97	34.55	63.96	0.418	0.050	0.42	0.057	0.022	0.32
8/1/94		98	31.36	67.43	0.532	0.027	0.14	0.068	0.024	0.27
?		99	-	-	-	-	-	-	-	-
8/2/94		100	34.24	63.88	1.272	0.039	0.10	0.065	0.024	0.18
8/2/94		101	37.88	59.39	0.461	0.071	1.66	0.103	0.039	0.20
8/2/94		102	36.32	62.31	0.477	0.112	0.32	0.060	0.020	0.19
8/2/94		103	37.86	61.20	0.336	0.052	0.16	0.066	0.017	0.11
8/3/94		104	39.69	58.08	0.521	0.128	1.16	0.111	0.021	0.09
8/3/94		105	35.71	62.71	0.775	0.044	0.36	0.066	0.022	0.12
8/3/94		106	46.13	50.83	0.698	0.557	1.29	0.146	0.026	0.12
8/3/94		107	46.99	52.73	0.522	0.075	0.31	0.069	0.021	0.08
8/3/94		108	40.18	58.77	0.485	0.030	0.25	0.052	0.023	0.09
8/3/94		109	46.46	52.50	0.351	0.070	0.31	0.040	0.016	0.06
8/3/94		110	42.00	56.98	0.390	0.035	0.27	0.042	0.017	0.07
8/3/94		111	46.68	51.94	0.342	0.125	0.71	0.047	0.015	0.06
8/4/94		112	48.57	46.06	0.445	0.632	3.85	0.254	0.015	0.08
8/4/94		113	45.22	53.46	0.325	0.020	0.15	0.043	0.018	0.06
8/4/94		114	39.62	59.52	0.384	0.023	0.12	0.046	0.018	0.07
		115	-	-	-	-	-	-	-	-
8/4/94		116	43.94	54.57	0.111	0.020	0.07	0.028	0.016	0.06
8/4/94		117	41.83	57.46	0.225	0.023	0.14	0.031	0.020	0.07
8/5/94		118	46.18	52.81	0.364	0.036	0.28	0.052	0.017	0.07
8/5/94		119	46.10	52.90	0.364	0.027	0.32	0.071	0.016	0.08
8/5/94	No Sample	120	45.89	53.08	.46	.012	.04	.042	.017	.07
8/5/94	No Sample	121	47.26	51.93	.41	.015	.06	.035	.015	.07
8/5/94	3PM	122	40.17	59.03	.42	.014	.07	.033	.018	.08
8/5/94	No Sample	123	45.26	53.55	.43	.012	.02	.035	.018	.07
8/5/94	11PM	124	57.89	47.72	.08	.017	.19	.034	.015	.05
8/6/94	3PM	125	48.69	52.25	.37	.036	.34	.036	.014	.06
		126	-	-	-	-	-	-	-	-

DATE	TIME	Fe	Ca	Al	Ti	Si
07/01/94	TAP1	14.83	0.03	0.25	0.38	84.49
07/01/94	Plasma S/M	37.40	0.06	0.31	0.50	61.83
07/02/94	SPL2	9.63	0.04	0.30	0.33	89.63
07/03/94	SPL2	6.30	0.13	0.40	0.19	92.77
07/05/94	TAP2	5.63	0.38	0.87	0.19	92.72
7-8-94	3:00 AM	19.08	0.78	1.25	0.23	78.49
7-6-94	4-12 #1	4.94	0.19	0.82	0.17	93.65
7-6-94	4-12 #2	9.95	0.32	0.92	0.21	88.41
7-7-94	8-4#1	10.35	0.63	1.59	0.22	87.03
7-7-94	8-4#2	24.46	0.99	2.88	0.35	71.27
7-7-94	9:30 PM	11.75	0.27	1.05	0.26	86.53
7-7-94	12-8S/M	12.13	0.12	0.58	0.19	86.77
7-8-94	8-4 S/M	5.65	3.26	5.32	0.16	85.37
7-9-94	2:15 PM	10.86	1.19	1.51	0.16	86.04
7-8-94	4-12 #1	10.17	0.40	1.06	0.16	87.97
7-8-94	4-12 #2	7.27	1.01	2.54	0.16	88.78
7-9-94	655 #2 S/M	6.70	1.87	2.30	0.13	88.73
07/09/94	TAP1	5.51	1.25	1.37	0.13	91.47
7-11-94	12:30 PM	39.15	0.15	0.27	0.20	60.03
7-11-94	2:30PM S/M	47.07	0.30	0.49	0.19	51.74
7-11-94	4:30PM S/M	13.39	2.25	1.93	0.17	82.03
7-11-94	6:30PM S/M	8.85	2.02	2.57	0.13	86.16
7-11-94	9:00PM S/M	7.37	2.91	3.82	0.12	85.50
7-11-94	11:00 PM	7.74	1.23	1.78	0.12	88.85
07/12/94	TAP1 AM	13.02	11.63	6.53	0.07	68.42
7-15-94	9:00PM #1	12.20	2.38	1.92	0.28	83.10
07/16/94	TAP1	7.31	1.42	1.47	0.14	89.40
7-16-94	9:00PM #2	14.42	1.69	1.78	0.24	81.71
7-17-94	1:00AM S/M	7.51	1.51	2.07	0.20	88.51
7-17-94	9:00AM S/M	3.07	0.64	1.07	0.09	94.82
7-17-94	5:00PM S/M	2.25	0.12	0.45	0.08	96.78
07/17/94	????????????	2.25	0.14	0.34	0.08	96.87
07/17/94	TAP11	2.86	0.13	0.27	0.08	96.34
7-18-94	05:00 AM	1.97	1.00	1.81	0.07	94.82
07/18/94	TAP16	6.71	0.15	0.30	0.08	92.44
07/18/94	TAP17	15.46	3.55	3.58	0.10	77.03
07/18/94	TAP18	16.53	2.17	2.05	0.11	78.85
07/18/94	TAP19	3.63	0.30	0.77	0.12	94.90
07/19/94	TAP21	3.89	1.30	1.85	0.10	92.56
07/19/94	TAP22	4.18	0.94	1.09	0.10	93.39
07/19/94	TAP23	5.32	0.12	0.41	0.10	93.75
07/19/94	TAP24	4.48	0.09	0.36	0.09	94.67
07/20/94	TAP26	5.06	0.06	0.26	0.08	94.22
07/20/94	TAP27	3.12	0.10	0.31	0.07	96.07
07/20/94	TAP28	3.92	0.15	0.35	0.06	95.18
07/20/94	TAP29	3.60	0.06	0.24	0.06	95.70
07/20/94	TAP30	2.71	0.04	0.29	0.06	96.56
07/21/94	TAP31	1.78	0.02	0.18	0.06	97.62
07/21/94	TAP32	2.61	0.08	0.34	0.06	96.57
07/21/94	TAP33	3.01	0.02	0.14	0.06	96.43
07/21/94	TAP34	1.82	0.08	0.34	0.07	97.36
07/21/94	TAP35	3.66	0.03	0.23	0.06	95.88
07/21/94	TAP36	1.67	0.45	0.88	0.06	96.60
07/21/94	TAP37	1.64	0.23	0.83	0.06	96.90

07/22/94	TAP38	1.81	0.09	0.45	0.06	97.25
07/22/94	TAP39	2.23	0.07	0.33	0.07	96.97
07/22/94	TAP40	2.99	0.06	0.33	0.11	96.22
07/23/94	TAP46	2.73	1.88	2.59	0.07	92.40
07/23/94	TAP47	3.33	2.02	2.76	0.07	91.49
07/23/94	TAP48	2.79	7.55	5.99	0.08	83.27
07/23/94	TAP49	4.51	3.72	4.06	0.09	87.31
07/24/94	TAP50	5.23	1.19	1.63	0.12	91.55
07/24/94	TAP51	3.30	0.42	0.82	0.10	95.06
07/24/94	TAP52	3.96	1.54	3.29	0.23	90.81
07/24/94	TAP53	2.94	0.68	1.43	0.10	94.55
07/24/94	TAP55	15.18	0.46	1.20	0.10	82.76
07/25/94	TAP56	3.17	1.02	1.88	0.12	93.53
07/25/94	TAP57	2.31	0.38	0.65	0.08	96.26
07/25/94	TAP61	2.16	2.39	3.39	0.08	91.66
07/26/94	TAP63	1.98	0.84	2.79	0.07	93.99
07/26/94	TAP64	2.11	0.55	1.16	0.08	95.78
07/26/94	TAP65	4.07	0.30	0.72	0.08	94.51
07/26/94	TAP66	3.34	0.31	0.67	0.07	95.28
07/27/94	TAP67	2.99	0.40	0.83	0.08	95.38
07/27/94	TAP68	3.35	0.27	0.80	0.07	95.18
07/27/94	TAP69	4.26	0.41	1.25	0.10	93.68
07/28/94	TAP72	2.80	0.46	1.34	0.09	94.90
07/28/94	TAP73	2.53	0.63	1.51	0.08	94.83
07/28/94	TAP74	2.33	0.38	1.07	0.07	95.82
07/28/94	TAP77	3.21	0.35	0.83	0.08	95.21
07/31/94	TAP90	20.92	0.09	0.44	0.07	78.15
	TAP200	7.34	0.24	0.36	0.10	91.66
	TAP201	58.21	0.05	0.06	0.11	41.28
	TAP202	55.61	0.02	<0.01	0.16	43.97
	TAP203	57.25	0.02	<0.01	0.11	42.33
	TAP204	19.97	1.52	0.96	0.19	77.15
	TAP205	58.09	0.08	0.11	0.11	41.32
	TAP206	30.89	1.03	0.76	0.15	66.92
	TAP207	7.79	1.88	1.41	0.21	88.52
	TAP208	55.28	0.23	0.15	0.14	43.84
	TAP209	61.78	0.07	<0.01	0.09	37.75
	TAP210	10.95	0.04	0.20	0.29	88.41
6/2/94	TAP211	58.09	0.31	1.75	0.23	39.45
6/16/94	TAP212	61.82	0.03	0.11	0.15	37.84
	TAP213	58.36	0.03	0.04	0.08	41.17
	TAP214	4.92	2.60	1.80	0.12	90.28
	TAP215	1.15	0.02	0.12	0.08	98.31
	TAP216	54.77	0.03	0.14	0.12	44.86
5/29/94	TAP217	55.77	0.02	0.01	0.10	43.80
	TAP218	61.85	0.02	<0.01	0.10	37.73
4-12 7/2/94	TAP219	7.57	0.03	0.24	0.16	91.76
6/18/94	TAP220	58.79	0.03	0.02	0.10	40.76
	TAP221	63.87	0.02	<0.01	0.11	35.71
	TAP222	56.89	0.02	<0.01	0.10	42.69
	TAP223	63.15	0.02	<0.01	0.09	36.43
	TAP224	7.54	0.02	0.17	0.17	91.87
	TAP225	59.96	0.02	<0.01	0.11	39.62
	TAP226	63.51	0.02	<0.01	0.15	36.07
	TAP227	13.35	0.22	1.25	0.35	84.78
	TAP228	5.84	0.15	0.45	0.19	93.16
	TAP229	57.17	0.02	<0.01	0.12	42.41

	TAP231	7.99	0.21	0.51	0.19	90.89
6/4/94	TAP232	57.10	0.03	0.06	0.24	42.41
6/6/94	TAP233	61.32	0.02	<.01	0.10	38.26
	TAP234	8.35	0.14	0.40	0.23	90.71
	TAP235	7.01	0.13	0.49	0.19	91.97
7/5/94	TAP236	9.94	0.02	0.25	0.31	89.39
4AM 7/7/94	TAP237	8.65	0.06	0.33	0.18	90.56
7/18/94	TAP238	4.43	0.15	0.37	0.08	94.65
	TAP239	62.34	0.02	0.01	0.15	37.23
	TAP240	58.28	0.02	0.05	0.16	41.25

Appendix N

Daily data sheets

Date:

tap#/time	Op. time (%)	Si weight		start (KWh)	Electricity		Length (in)	Electrode		Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)		end (KWh)	Total (KWh)		Weight (lbs)	Consumption (lbs/lbs)				

Appendix O

Daily data sheets

Date: 17-18 July 1994

60 V - 6000 A

105% fixed carbon

tap#/time	Op. time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
10 / 9h00	100	240	240	42870	41620	1250	14	64.2	0.267	847	60.9	161	
11 / 13h00	97.9	230	217	44310	42870	1440	10	45.8	0.211	462	101.0	120	42" slip
12 / 17h00	100	217	217	45750	44310	1440	2	9.2	0.042	696	67.0	139	
13 / 21h00	100	208	208	47070	45750	1320	-8	-36.7	-0.176	557	80.3	58	
14 / 1h00	100	201	201	48530	47070	1460	-1	-4.6	-0.023	348	124.2	200	
15 / 5h00	100	341	341	49930	48530	1400	23	105.4	0.309	348	210.7	388	Burn-down
Total		1437	1424			8310	40	183.3		3258		1066	
Sp. consump						5.84			0.129		94.0		

Daily data sheets

Date: 18-19 July 1994 60 V -6000 A 105% fixed carbon 110% FC after 1h00 am tap

tap#/time	Op. time (%)	Si weight		Electricity		Total (KWh)	Length (in)	Electrode		Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)			Weight (lbs)	Consumption (lbs/lbs)				
16 / 9h00	100	143	91	51120	49930	1190	-8	-36.7	-0.403	557	35.1	85	
17 / 13h00	100	270	244	52420	51120	1300	16	73.3	0.301	279	188.0	115	
18 / 17h00	100	203	164	53900	52420	1480	2	9.2	0.056	557	63.3	65	
19 / 21h00	100	158	112	55290	53900	1390	-12	-55.0	-0.491	557	43.2	174	
20 / 1h00	100	109	83	56800	55290	1510	0	0.0	0.000	417	42.8	221	
21 / 5h00	100	266	266	58170	56800	1370	16	73.3	0.276	209	273.7	184	
Total		1149	960			8240	14	64.2		2576		844	
Sp consump						8.58			0.067		80.1		

Daily data sheets

Date: 19 20 July 1994

60 V -6000 A

110 % fixed carbon

tap#/time	Op. time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
22 / 9h00	97.9	209	196	59580	58170	1410	-6	-27.5	-0.140	526	80.1		Problem with scale
23 / 13h00	100	197	184	60730	59570	1160	-6	-27.5	-0.149	421	94.0		Problem with scale
24 / 17h00	100	262	236	62180	60730	1450	4	18.3	0.078	495	102.5	80	
25 / 21h00	100	161	135	63550	62180	1370	-2	-9.2	-0.068	550	52.8	85	
26 / 1h00	100	130	130	64800	63550	1250	8	36.7	0.282	550	50.8	157	
27 / 5h00	100	328	328	66220	64800	1420	13	59.6	0.182	405	174.1	208	
Total		1287	1209			8060	11	50.4		2947		530	Problem with scale
Sp. consump						6.67			0.042		88.2		

STCC Program

Daily data sheets

Date: 20-21 July 1994

60 V - 4000 A

110 % FC

tap#/time	Op. time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
28 / 9h00	100	246	194	67150	66220	930	0	0.0	0.000	313	133.3	146	
29 / 13h00	97.5	288	256	68050	67150	900	5	22.9	0.090	275	200.2	112	22" slip
30 / 17h00	100	214	214	68980	68050	930	10	45.8	0.214	412	111.7	143	
31 / 21h00	100	167	128	69840	68980	860	6	27.5	0.215	165	166.8	91	
32 / 1h00	100	144	144	70780	69840	940	-16	-73.3	-0.509	275	112.6	71	
33 / 5h00	100	70	43	71700	70780	920	-12	-55.0	-1.279	248	37.3	133	
Total		1129	979			5480	-7	-32.1		1688		696	
Sp. consump						5.60			-0.033		124.7		

Daily data sheets

Date: 21-22 July 1994

60 V - 4000 A

110% fixed carbon

tap#/time	Op time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
34 / 9h00	100	168	128	72510	71700	810	2	9.2	0.072	275	100.1	133	
35 / 13h00	93.5	205	205	73340	72510	830	24	110.0	0.537	275	160.3	36	
36 / 17h00	92.5	134	134	74150	73340	810	8	36.7	0.274	275	104.8	149	
37 / 21h00	100	130	130	74950	74150	800	5	22.9	0.176	275	101.6	74	
38 / 1h00	100	107	100	75880	74950	930	-9	-41.2	-0.412	275	78.2	68	
39 / 5h00	100	93	80	76410	75880	530	-10	-45.8	-0.573	344	50.0	97	
Total		837	777			4710	20	91.7		1719		557	
Sp. consump						6.06			0.118		97.2		

Daily data sheets

Date: 22-23 July 1994 60 V 4000 A 110% fixed carbon 113% fc after 13h00 tap

tap#time	Op. time (%)	Si weight		Electricity		Total	Length (in)	Electrode		Quantity (lbs)	Si (%)	Fume (lbs)
		Gross (lbs)	Net (lbs)	end (KWh)	Start (KWh)			Weight (lbs)	Consumption (lbs/lbs)			
40 / 9h00	100	140	140	77190	73410	780	0	0 0	0 000	275	109.5	40
41 / 13h00	100	219	149	77820	77190	630	0	0 0	0 000	69	454.3	62
42 / 17h00	100	103	103	78460	77820	640	16	73 3	0.712	275	80.5	44
43 / 21h00	100	110	110	79180	78460	720	8	36 7	0.333	138	171.4	57
44 / 1h00	100	187	167	80040	79180	860	0	0 0	0 000	137	262.1	49
45 / 5h00	100	168	142	80800	80040	760	8	36 7	0.258	133	221.2	27
Total		927	811			4390	32	146.7		1032		279
Sp. consump						5.41			0.181		169.0	

Run above

Daily data sheets

Date: 25-26 July 1994

60 V -8000 A

105% fixed carbon

tap#/time	Op. time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
58/0900 hrs	100	352	312	2800	960	1840	6	27.5	0.088	443	151.4	401	
59/1300 hrs	89.2	256	229	4300	2800	1500	12	55.0	0.240	526	93.6	189	
60/1705 hrs	96	194	187	5840	4300	1540	8	36.7	0.196	443	90.8	69	
61/2105	100	200	200	7530	5840	1690	8	36.7	0.183	460	93.5	178	
62/0100 hrs	100	293	293	9290	7530	1760	10	45.8	0.156	507	124.3	126	
63/0500 hrs	100	339	339	11370	9290	2080	13	59.6	0.176	693	105.2	157	
Total		1634	1560			10410	57	261.2		3072		1120	
Sp. consump.						6.67			0.167		109.2		

Daily data sheets

Electrode feeding (Injection of small particles)

Date: 26-27 July 1994

tap#/time	Op. time (%)	SI weight		Electricity			Electrode			Quartz (lbs)	SI Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
64/1300 hrs		314	314	13450	11370	2080	15	0.0	0.000	693	97.4	163	
65/1500 hrs		212	212	15300	13450	1850	-7	0.0	0.000	737	61.8	84	
66/2030 hrs	93.2	268	268	17330	15300	2030	2	0.0	0.000	737	78.2	118	
67/0100 hrs		268	268	18980	17330	1650	(4)	0.0	0.000	554	104.0	107	pushed electrode
68/0500 hrs		209	209	20810	18980	1830	6	0.0	0.000	554	81.1	83	
69/1215 hrs		298	285	23050	20810	2240	4	18.3	0.064	1108	55.3	210	
Total		1569	1556			11680	4	18.3		4383		765	
Sp. consump.						7.51			0.012		76.3		

Daily data sheets

Electrode feeding (Injection of small particles)

60 V -8000 A

Date: 27-28 July 1994

tap#/time	Op. time (%)	SI weight		Electricity			Electrode			Quartz (lbs)	SI Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
70/1700 hrs		190	173	24490	23050	1440	-5	-22.9	-0.132	460	80.9	187	
71/2100 hrs	100	243	203	26280	24490	1790	9	41.2	0.203	368	118.6	233	
72/ 0100 hrs		205	179	27590	26280	1310	10	45.8	0.256	554	69.5	105	
73/0500 hrs	100	277	274	29530	27590	1940	6	27.5	0.100	554	106.3	145	
74/0900 hrs	100	296	290	31450	29530	1920	4	18.3	0.063	762	81.8	260	
75/1300 hrs	100	178	138	33160	31450	1710	-6	-27.5	-0.199	831	35.7	190	
			1257			10110	18	82.5		3529		1120	
Sp. consump.						8.04			0.066		76.6		

Daily data sheets

Date: 28-29 July 1994

60 V -8000 A

tap#/time	Op. time (%)	SI weight		Electricity			Electrode			Quartz (lbs)	SI Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
76/1700 hrs	56.25	209	155	34530	33160	1370	14	64.2	0.414	485	68.7	197	
77/2100 hrs	88.4	305	240	36010	34530	1480	0	0.0	0.000	481	107.3	204	
78/0100 hrs	75	215	150	37300	36010	1290	6	27.5	0.183	556	58.0	162	
79/0500 hrs	75	110	110	38670	37300	1370	4	18.3	0.167	861	27.5	231	
80/0900 hrs	75	110	80	40520	38670	1850	-5	-22.9	-0.286		#DIV/0!	60	
81/1300 hrs	91.25	104	77	42660	40520	2140	-3	-13.7	-0.179		#DIV/0!	566	
Total		1053	812			9500	16	73.3		2383		1420	
Sp. consump.						11.70			0.090		73.3		

Daily data sheets

Date: 29-30 July 1994

40 V -8000 A

13% fixed carbon

tap#/time	Op. time (%)	SI weight		Electricity			Electrode			Quartz (lbs)	SI Recovery (%)	Fume weight (lbs)	Comments
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
82/2100 hrs	89.2	350	282	43460	42660	800	1	4.6	0.016	338	179.4	289	
83/0100 hrs		167	133	44700	43460	1240	11	50.4	0.379	412	69.4	80	
84/0500 hrs		109	82	46100	44700	1400	0	0.0	0.000	365	48.3	265	
85/0900 hrs		135	122	47440	46100	1340	10	45.8	0.376	0	#DIV/0!	215	
86/1300 hrs	91	310	283	48680	47440	1240	3	13.7	0.049	619	98.3	194	
87/1700 hrs	100	284	244	50400	48680	1720	19	87.1	0.357	344	152.5	201	
Total		1355	1146			7740	44	201.7		2078		1244	
Sp. consump.						6.75			0.176		118.6		

Daily data sheets

Date: 30-Jul-94

50% Ferro-Silicon

60 V -8000 A

100% fixed Carbon

tap#/time	Op. time (%)	Si weight		Electricity			Electrode			Quartz (lbs)	Si Recovery (%)	Fume weight (lbs)	Comments.
		Gross (lbs)	Net (lbs)	end (KWh)	start (KWh)	Total (KWh)	Length (in)	Weight (lbs)	Consumption (lbs/lbs)				
90/0400 hrs		113	113	53940	53290	650	-18	-82.5	-0.730	140	173.5	50	
91/0700 hrs	100	150	150	55200	53940	1260	22	100.8	0.672	138	233.7	65	
92/1100 hrs	100	184	184	56260	55200	1060	-9	-41.2	-0.224	550	71.9	60	
93/1400 hrs	100				56260	-56260	-9	0.0	#DIV/0!		#DIV/0!		
94/						0	12	0.0	#DIV/0!		#DIV/0!		
95/						0	-1	0.0	#DIV/0!		#DIV/0!		
Total		447	447			-53290	26	-22.9		828		175	
Sp. consump.						-119.22			-0.051		116.1		

Appendix P

The handwritten originals for this appendix were not sufficiently legible for publication and were omitted.

Appendix Q