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**COLLECTION AND CONVERSION OF SILICON FURNACE WASTE
GAS INTO HIGHER VALUE PRODUCTS**

**Phase III: 6 MW Pilot Plant DC Closed Furnace Technology
Final Report**

**By
Vishu D. Dosaj**

January 1995

Work Performed Under Contract No. AC04-87ID12624

**For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.**

**By
Dow Corning Corporation
Midland, Michigan**

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Prepared for the
U.S. Department of Energy
Under DOE Albuquerque Operations Office
Sponsored by the Office of the Assistant Secretary
for Conservation and Renewable Energy
Office of Industrial Technologies
Washington, D.C.

By
Dow Corning Corporation
Midland, Michigan

PREFACE

This report documents the results of Phase III: Of the U.S. Department of Energy (DOE) supported program "Collection and Conversion of Silicon Furnace Waste Gas into Higher Value Products." This concluding phase of the overall program was conducted from July 1990 to December 1994.

This technology program is jointly sponsored by the US Department of Energy, Canadian Western Diversification, Department of Industry, Trade and Tourism, Manitoba, Canada and Dow Corning Corporation. Bruce Cranford and Doug Gish have been the Program Managers for the DOE Office of Industrial Technologies. Porter Grace is the project Technical Manager for the DOE Albuquerque Operations Office. Frank Childs, the Project Technical Monitor for DOE, is on the staff of Scienteck, Inc., Idaho Falls, Idaho. Vishu Dosaj is the Dow Corning Principal Investigator, Project Manager, and author of this report.

Phase III: Technology Development was conducted in a direct current (dc) closed-furnace silicon pilot plant built in East Selkirk, Manitoba, Canada. The facility was operated by Meadow Materials, a branch of Dow Corning Silicon Energy Systems, Inc. Dow Corning Corporation is the sole owner of the Dow Corning Silicon Energy Systems, Inc.

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EXECUTIVE SUMMARY

Silicon and Ferrosilicon Industries in North America have been on the decline for more than a decade, primarily as a result of the availability of low cost import silicon and ferrosilicon. Although the world demand for silicon is increasing, the high energy and feedstock costs associated with current production methods continue to place North American producers at a disadvantage.

Silicon is conventionally produced by carbothermic reduction of silica in large open submerged arc ac furnaces. The process off-gas, primarily carbon monoxide, is lost by combustion on top of the bed. This loss can be eliminated by enclosing the furnace with a cover and processing the off-gas in a sealed system. Electrode cost, which represents a significant portion of the variable cost for the production of silicon, can be significantly lowered by smelting in a direct current (dc) system; particularly in a closed dc system.

The construction and operation of a 6 MW, closed dc furnace for smelting silicon was the primary focus of Phase III. A 6 MW, dc closed furnace pilot plant was built in East Selkirk, Manitoba, Canada. The furnace is equipped with world's most modern automatic control system used to control and monitor the process variables and operational data. This control system is suitable for commercial applications and could be used with either closed or open dc furnaces for smelting silicon or ferrosilicon. The construction was started in September 1990, and the facility was operational within 18 months. Following successful commissioning of the pilot plant in June 1992, twelve smelting test campaigns were conducted through November 1994.

The first three tests designated as "start-up commissioning runs" were made to demonstrate equipment operation, and resolve any operating problems. The furnace-bottom anode, a critical part of the furnace, was successfully developed and a potentially patentable anode design has emerged through three generations of anode modifications. Anode technology is a key element in successful commercialization of dc silicon smelting technology.

Test runs 004-012 provided the operating experience for managing carbon theory and optimizing feed rate as a function of power input. Managing the flow of raw materials to the smelting zone remains a problem in spite of modifying the mix-movement system. The issue of mix-movement is considered to be a consequence of a closed furnace operation. In a semi-closed

or an open dc furnace, the mix-movement should not be a problem and could be handled as with conventional open, alternating current (ac) furnaces.

The targets for electrode consumption in a dc furnace (expected to be 50% lower than that of an ac furnace) should be met on a commercial furnace operating at a higher voltage even though the targets were not achieved on the pilot plant because it was operated at below design power input.

Economic analysis of converting an existing silicon or ferrosilicon furnace to a semi-closed dc furnace was evaluated since additional effort will be required, beyond the scope of this project, to commercialize closed furnace technology. The base case for a dc semi-closed furnace with an assumed silicon recovery of 82% at a power input of 21 MW provides an attractive IRR (Internal Rate of Return) of 27.7% at a silicon price of \$.70/lb. The technology risk for a retrofit semi-closed dc furnace project is significantly lower compared to commercialization of dc closed furnace technology.

Overall, the results obtained in the Phase III study support continuation of the program to Phase IV: Demonstration of semi-closed dc retrofit technology on a commercial silicon or ferrosilicon furnace.

The commercial experience with a semi-closed dc furnace is expected to develop the mix-movement technology necessary for commercialization of the closed furnace for subsequent commercialization projects.

The dc closed furnace pilot plant received an Award of Excellence by the Canadian Consulting Engineers in 1993 (see Appendix A), and an article on the closed furnace technology advancements was published by the U.S. Department of Energy, Office of Industrial Technologies in 1992. (See Appendix B) The U.S. patent 5,009,703 "Silicon Smelting in a Direct Current Furnace" was also awarded the '1993 Process Patent of the Year' by the Saginaw Valley Patent Law Association.

INTRODUCTION

The Silicon and Ferrosilicon Industries in North America have been on the decline for more than a decade, primarily as a result of low cost imported silicon and ferrosilicon. Although the world demand for Silicon is on the rise, the high energy and feedstock costs associated with the current production methods continue to place North American producers at a disadvantage. Currently, North American manufacturing facilities for these materials operate sporadically and are aging.

Silicon is commercially produced in open alternating current (ac) furnaces. The Open Hearth Furnace is not energy efficient and produces significant quantities of by-product silica fume. In 1988, the North American Silicon and Ferrosilicon Industries emitted nearly a quarter of a million metric tons of silica fume, most of which was land filled, and 1.8 million metric tons of CO₂ into the atmosphere. The North American Silicon and Ferrosilicon Industries desperately need new, low cost production technologies that are less energy intensive and produce less waste than current industrial processes.

The U.S. Department of Energy's Office of Industrial Technologies teamed with Dow Corning Corporation to develop and test a closed furnace direct current technology for producing Silicon and Ferrosilicon in 1987. Dow Corning, a major manufacturer of Silicon based products had previously established the feasibility of this technology in small scale laboratory investigations.

The first stage of this development was conducted on a 0.1 MW closed ac furnace. This effort was focused towards evaluation and optimization of raw materials feed stocks for closed furnace operations. The results of this work are described in DOE Phase II Final Report(1). The next stage of this technology development was conducted on a 2 MW, dc closed furnace pilot plant. An existing dc furnace located in Port Colborne, Canada was modified and operated to produce silicon over a six month period. The technical feasibility of smelting silicon in a dc closed furnace was demonstrated and data necessary for design of a 6 MW dc closed furnace pilot plant was obtained.

Task 1 of Phase III involved smelting taconite tailings in a dc plasma reactor for production of ferrosilicon. This effort was completed in February 1992 and described in Phase III, Task 1, Final Report(2). Task 2 of Phase III involved construction of a closed dc furnace for demonstrating the commercial viability of this technology.

Subtask 2.2, the Engineering Preparation, and Subtask element 2.2.2, the Construction of the Pilot Plant, were not funded by DOE but are briefly summarized in the report. Subtask 2.3, Start-up and Commissioning, was completed in July, 1992. From the groundbreaking for the pilot plant in October 1990, the construction, start-up, and commissioning was completed over an 18 month period. Subtask 2.4, the optimization of operation was completed in October 1994. A total of 12 test campaigns were conducted. The test durations varied from three to six weeks.

In the development and design of the 6 MW pilot facility, the engineering teams addressed a number of very challenging obstacles which included:

- Effective layout of the proposed plant.
- Development and design of a new high temperature electrode seal technology.
- Implementation of a cooling and filtration system to recover high temperature waste gas.
- Development of a feedstock injection system that maintained the internal atmosphere of the closed furnace.
- Implementation of an automatic control system.
- Development of safe operating procedures for operating personnel.
- Development of an environmental monitoring and control system.
- Selection of suitable fabricators to construct the furnace and associated equipment.
- Administration of the project utilizing fast track construction management principals.
- Development of a data acquisition system for the facility.
- Design and development of a new automated molten silicon handling system.

BACKGROUND

Dow Corning Corporation has been involved in silicon research since the 1970s. The Phase I of the program titled "Technical Feasibility Studies" was totally funded by Dow Corning. Phase II, "Collection and Conversion of Silicon Furnace Waste Gas into Higher Value Products" was cost shared by the U.S. Department of Energy (DOE). Experimental studies and verification of the closed furnace concept for smelting silicon and of conversion of the off-gas to methanol were the basic elements of Phase II effort.(1)

A two stage carbon bed reactor was used to simulate the reactions in closed furnace smelting of silicon. The reaction rates and activation energies were experimentally determined for the SiO forming reactions over a range of temperatures and pressures.(1)

A 0.1 MW closed, submerged-arc furnace and off-gas handling facility was built to investigate the operational parameters of closed furnace operation. The optimum raw material mix for the closed furnace operation was defined and the off-gas from the furnace was characterized and the feasibility of its conversion to methanol was demonstrated.(1)

The next phase of the closed furnace development was conducted on a 2 MW dc furnace. An existing dc furnace was modified and operated over a six month period, to demonstrate technical feasibility and obtain necessary data for the design of a 6 MW pilot plant. The size of this pilot facility provides the ability to assess technology issues while obtaining meaningful scale-up information for commercial plants.

SILICON SMELTING PROCESS

Metallurgical silicon is produced by the carbothermic reduction of quartz in an arc furnace according to the overall reaction.

For this reaction, 100% carbon theory is defined as two moles of fixed carbon per mole of silicon dioxide. Fixed carbon is defined as the carbon that remains after volatile organic components are expelled. The silicon is produced via two intermediates, namely silicon monoxide (SiO) and silicon carbide (SiC). The SiO and SiC are produced by the following reactions:

SiO Forming Reactions

SiC Forming Reactions

Silicon is produced by the reaction of the intermediate SiO and SiC

Silicon can also be produced by the reaction of SiO₂ with SiC

For the formation of silicon, the carbon requirements have to be precise. Excess carbon results in SiC formation where as insufficient carbon results in excessive SiO formation which can be lost in the off-gas.

The most commonly used carbon reductants are charcoal, coke, coal, and wood chips. The choice of carbon reductants depends on raw material availability and the desired purity of the final product. Irrespective of the carbon source, there is a loss of volatile material when the carbon is heated. That carbon left after the heating process is referred to as "fixed carbon". The fixed carbon in the feed recipe is typically specified to be 90-98% carbon theory.

Conventional silicon furnaces are run open to the atmosphere. As the raw materials are consumed, a cave is formed around the electrode, and the top of the charge bed becomes a hard crust. This crust must be physically beaten down (stoked) from the top in order for additional raw materials to be fed. Open furnace operation results in loss of feed materials and energy. The energy required for the process is provided by the electric arc between the graphite electrodes.

The silicon is tapped near the bottom of the furnace into ladles where it is refined by blowing oxygen. The purified product is poured into molds where it cools and solidifies. The silicon product is then broken into chunks and placed in a storage bin.

The off-gas primarily containing carbon monoxide (CO) accounts for approximately 52% of the total energy input. In addition to the off-gas, a fume containing about 25% of the in bound silica escapes the process at the top of the bed where silicon monoxide (SiO) is oxidized to silicon dioxide (SiO₂) and the CO is combusted to CO₂. The silica fume is removed by filtration while the off-gas is exhausted to the atmosphere. In addition, a portion of the carbon reductants are also lost in combustion and the electrode is partially consumed at the top of the furnace due to oxidation. The off-gas, SiO₂ fume, and oxidation of carbon materials represent a major loss of energy and raw materials. Also, two waste streams are generated: combustion products and SiO₂ fume. The losses can be reduced or eliminated by enclosing the furnace and processing the off-gas in a sealed system. The energy value of the off-gas could then be recovered and loss of carbon reductants, and electrode loss, due to combustion and oxidation, is eliminated. The invention describing the dc closed furnace for silicon smelting is described in US patent 5,009,703. (3)

STATEMENT OF WORK (PHASE III)

OBJECTIVE

The objective of Phase III is to demonstrate the commercial viability of new closed dc furnace technology for smelting silicon and silicon alloys on a pilot plant scale. The program objective is to save materials and energy, reduce silicon manufacturing costs, improve U.S. competitiveness, and eliminate emissions by recovering fume and process off-gas. Closed furnace technology is expected to recover about 25% of the input silicon and about 50% of the total process energy. The technology will target retrofit of existing furnaces and to build new facilities in the U.S. to displace imports and meet the forecast U.S. demand growth of 3 to 4 percent per year for silicon metal.

TASK DESCRIPTION

The task description is summarized in Appendix C.

TASK 2.2 PILOT PLANT DESIGN AND CONSTRUCTION

2.2.1 Pilot Plant Design. A brief technical description of the pilot plant for the major components is provided. The heart of the pilot plant is a dc closed furnace including the power supply, the electrode and electrode assembly, the bottom electrode (anode), raw material feed system, off gas handling and cleaning system, product tapping, and casting and storage. The key concepts and pilot plant features were designed by Dow Corning. As part of the detailed engineering contract services, UMA engineering prepared detailed engineering drawings based on input from design teams. The pilot plant design basis is a 6 MW closed furnace with direct current, submerged, transferred-arc system.

2.2.1.1 Transformer/Rectifier. The furnace power supply system consists of four 1.5 MW Robicon furnace power supply units operated from a common Furnace Power Supply Control Panel (FPSCP). The FPSCP is capable of operation from 0 to 200 volts DC and 0 to 50,000 amps. The system is limited to a maximum of 6 MW. The power supply is capable of delivering 50 KA at 120 volts or 30 KA at 200 volts and 12,500 amperes. The lower level ac-current is then converted to dc-current (rectified) by Silicon Controlled Rectifier (SCR's). The normal mode of operation is for all four power supply units to be in operation. Four units produce the lowest level of harmonics on the electrical system.

2.2.1.2 Rail Siding. The rail access to the site was upgraded with new ballast and ties.

2.2.1.3 Infrastructure. Certain site drainage, fire water lines, utilities, general grading, access streets, and parking facilities were installed.

2.2.1.4 Process Building. The process building is comprised of three sections. The first section is a two story area that houses mechanical equipment, computer termination cabinets, a control room, and lunch room. The wall between the process area and the control room is of reinforced concrete construction; for safety in the event of an explosion in the furnace area. The metal handling area is 50 feet tall and 4800 square feet. This area is used for breaking silicon, moving

it to the product storage bin and for ladle preparation. The furnace tower is 4800 square feet by 125 feet tall, with numerous floor levels. This structure was designed to support the weight of process equipment and raw materials that are distributed through the facility. It also contains the raw material storage bins and associated materials handling equipment.

2.2.1.5 Furnace. The furnace is one of the most complex and sophisticated systems existing in the industry. Key features include the location of off-gas ports that exit below the operating feed level, a hydraulically controlled stoking system to move the mix within the closed furnace, level probes to measure the bed height, a sophisticated furnace-bottom anode, multilayered refractory and carbon lining, an electrode assembly, and numerous thermocouples located over the entire furnace to monitor critical temperatures. The sealed furnace is designed to operate in a fix mode and does not rotate. A simplified cutaway view of the furnace is shown in Figure 1.

The bottom anode is the most critical item for the operation of a dc furnace. The anode was a proprietary Dow Corning design based on a conductive hearth concept. The commercial anode designs used for dc steel furnaces are shown in Figure 2. None of the anodes as described in Figure 2 could be used due to the molten silicon in contact with the hearth.

The anode connection proved to be a challenge in its design and operation. The initial design failed during the initial furnace bake out process. Eventually a potentially patentable anode design emerged through three generations of anode modification.

2.2.1.6 Off-Gas System. The off-gas system is comprised of a refractory lined chrome-moly pipe system that fed process gas to a cooler where water is injected to reduce the gas temperature to 350°C. The off-gases from the furnace, consisting of by-product SiO, CO, H₂, and volatiles from the carbon reductants, exit the furnace through off-gas ports. The off-gas is carried via the off-gas pipes to a bag-house filter where the particulates are separated. The bag-house system has three bag-houses, each with a dedicated pulse jet cleaning system, and fume collector hopper. The clean gases from the bag-house go to a blower which provides the necessary force to pull the off-gases through the entire off-gas handling system and transport it to an incinerator. The incinerator is equipped with a natural gas burner to effectively burn the off-gas. Since this is a

FIGURE 1. A VIEW OF THE DC CLOSED FURNACE.

CONDUCTIVE BOTTOM
ABB

UNARC PIN TYPE ANODE
MAN GHH/NKK

BILLETT TYPE ANODE
DAVY CLECIM

FIN TYPE ANODE
DVAI

FIGURE 2. COMMERCIAL ANODE DESIGN CONCEPTS FOR DC STEEL FURNACES.

pilot scale operation, no effort was made to utilize the off-gas and it is cleanly burned.

The off-gas is continuously sampled and analyzed for CO, CO₂, H₂, and O₂. the CO data coupled with the off-gas flow rate provides a useful input for monitoring carbon balance. The oxygen level in the off-gas is important for safety of the operation. The results from the off-gas analysis are continuously displayed on the process computer screen and various trend plots are available to display not only off-gas composition but the silicon production efficiency based on this measurement.

Carbon monoxide, the major component of the furnace off-gas, is a toxic, odorless, and colorless gas. The plant CO leak-detection system consists of 20 CO sensors placed at strategic locations in the process building. The CO alarm panel in the control room displays all the sensor locations, and if a sensor detects a high level of CO, the indicating light on the panel of the respective sensor lights up along with the sounding of the audible alarm. A strobe light at the sensor location also lights up warning high CO level. In addition, personal CO monitors are mandatory for operating personnel in the process building.

2.2.1.7 Process Equipment. The process equipment includes feed storage equipment, weighing and mixing facilities, feed purge hoppers, a ladle heater, casting molds, and silicon breaking equipment. The system utilizes a bucket elevator to place feeds into "day hoppers". The feeds are then vibrated to smaller bins that include weigh cells to achieve the desired batch weight. The weighed feed is vibrated in layers onto a conveyer belt and mixed before entering one of the six purge hoppers. In the purge cycle, air is displaced by a nitrogen flow. Then on command, the feeds are dropped to the furnace.

Silicon is removed from the furnace periodically in the tapping process. The tapped silicon flows into a ladle where oxygen is blown to remove aluminum and calcium. After purification, the silicon is poured onto chill tables to solidify. The solid silicon cast is broken into smaller pieces. The lumps are transported by conveyer to a rail car when desired.

2.2.1.8 Mechanical Services. This area includes the air compressors and dryers, service water cooler, nitrogen system, vacuum system, and other miscellaneous services.

2.2.1.9 Electrical Services. The furnace is equipped with world's most modern automatic control system which could be used with closed or open dc furnaces for smelting silicon or ferrosilicon. Electrical services include all power and control wiring. This bus is designed for the 50,000 ampere capacity. The area under the furnace is air cooled. The top system includes a flexible section to permit the vertical movement of the electrode column.

A Fischer and Porter Distributed Control System (DCS) is used to control and monitor the process, as well as store and analyze process variables and operational data. Four Distributed Control Units (DCUs) and three control room monitors are used to operate and monitor all aspects of operation that included raw material receiving equipment, automated batch weighing, feeding to the furnace, automated voltage control, automated stoking, and furnace pressure control.

The DCS also performs safety interlocking and monitoring functions to display operational or safety alarms on the control screens or shut off any process equipment if hazards exist.

The operation of the furnace is automatically controlled by a Fischer and Porter distributed control system. The furnace power supply control panel interfaces with the plant Distribution Control System. The Distributed Control Units (DCU's) interface with the field instrument reading inputs and setting outputs. The DCU's do the actual sequence and loop control. They also perform calculations for use in control or for operator information. The four DCU's have the following operating tasks:

DCU1

- Batch Feed System Control
- Emergency Shutdown Control

DCU2

- Furnace Power Control
- Electrode Position Control
- Electrode Slipping Control
- Emergency Shutdown Control

DCU3

- Off-gas Temp. Checks
- Incinerator Shutdown Control
- Bag-house Dump Cycle Control

- Furnace Off-gas Nitrogen Flow Control
- Furnace Low Pressure Nitrogen Flow Control
- Furnace Pressure Control
- Utilities Control
- Furnace Power Supply Interlock Checks
- Off-gas System Controls
- Emergency Shutdown Control

DCU4

- Mix Movement Control
- Furnace Hydraulics Power Pack Control
- Emergency Shutdown Control

The Operator Command Stations are a collection of computers and Graphical Display Units that serve as the interface between the operator and the distributed control units. The pilot plant is equipped with two Operator Command Stations, one in the control room with two Graphical Display Units, and one in the Nest room with one Graphical Display Unit and an Engineering Terminal. The Operator Command Station in the control room serves as the primary control station for the operators while the Nest room station serves as an engineering work station and as a backup for the control room station.

Each station is currently configured with 77 graphic screens, 140 historical trends, and 32 current trends. The operator uses these graphic screens and trends to monitor and control the process. Basic parameters monitored by an operator are temperatures, pressures, flows, and electrical outputs. For example, by going to a historical trend, the operator can observe what the temperatures in the furnace roof have been for the past hour, day, or days (up to five days of data can be displayed on the screen at one time). The historical trend data is also automatically archived to disk for later viewing. The operator can also observe a bar graph of the current, voltage, and power. He can input set points for the electrical control of the voltage and current. The operator can change the recipes for the batch feed system and, by clicking on a control point with the (computer) mouse, can request a batch feed to the furnace. By clicking on another control point, a level probe sequence is initiated. Control loops can be put in manually and adjustments can be made to the output signal of a control valve in the off-gas system.

The Nest room station is also configured to perform the data collection using the Process Data System (PDS) and print reports hourly using MATRIX spreadsheets. The PDS currently

collects 245 different data points every 15 minutes. In addition, 15 data points are collected at one hour sampling rate.

The control room station has two "C" language programs that perform advanced calculations. One of these programs executes every 30 seconds and the other every 2.5 minutes. These calculations are used to perform sophisticated analyses of the process which the operators and engineers rely upon to monitor and control the pilot plant.

2.2.2 Pilot Plant Construction. The construction phase of the pilot plant was started immediately following the approval of the environmental license in September 1990. Leading the construction phase was detailed design, engineering, and plant layout. Comstock Canada. Winnipeg. Manitoba was awarded the general sub-contract and was responsible for the installation of the equipment. Construction phase of the project was accomplished over an 18 month period. Construction activity schedule is shown in Table 1. In spite of some delay caused by the environmental license issuance date and some delays in delivery of the furnace, off-gas system, and electrical services, the overall time for pilot plant construction was a significant accomplishment; particularly in view of the Manitoba winter.

TABLE 1. CONSTRUCTION SCHEDULE

SCHEDULE OF ACTIVITIES	START	FINISH
Transformer/Rectifier	January 1990	April 1991
Admin. Building	September 1990	December 1990
Rail Siding	September 1990	October 1990
Infrastructure	September 1990	August 1991
Process Building	October 1990	May 1991
Furnace	February 1991	February 1992
Trans/Rect. Installation	January 1991	October 1991
Off-Gas System	March 1991	January 1992
Process Equipment	January 1991	November 1991
Mechanical Services	December 1990	November 1991
Electrical Services	February 1991	February 1992

2.2.3 Process Description. The process flow diagram for the closed furnace operation is shown in Figure 3. All the raw materials are brought into the site by rail, except charcoal is delivered via truck. The raw materials are discharged on to a receiving conveyor, elevated to the top of the process building via a bucket elevator, and stored in any one of the five day bins. From the day bins that store quartz, coal, and charcoal, the raw material mix is gravity fed to the furnace via the weigh-hoppers and air locks. The energy required to reduce quartz to silicon metal in the furnace is provided by an electric arc between the graphite electrode (cathode) and the bottom anode. Fresh mix is added to the furnace as old mix is consumed. Due to low bulk density of the mix, the downward movement of the mix is aided by top and side stokers. Three top stokers are used to break any raw material bridges. Four off-gas parts are located below the typical level of the mix. Four side stokers are used to keep these parts clear to maintain an unobstructed flow of gases to the parts. By-product reaction gases from the smelting reactions exit the closed furnace via off-gas ports. The off-gas lines carry the by-product gases to a bag-house filter where the particulates are removed. The off-gas is pulled through the bag-house and into an incinerator via a blower. The molten silicon is tapped into a ladle, refined, poured into molds, cooled, and broken to a convenient handling size and stored for shipment.

2.2.4 Closed Furnace Operation. The raw materials stored in the day bins are gravity fed to the furnace through weigh-hoppers. In order to prepare a batch of mix, the quartz, charcoal, and coal is separately weighed in weigh-hoppers and dropped on to the reversing belt mixing conveyor which is transported to swing distributors, and then the mix is added to the furnace. The sequence of feeding, batch preparation, and the batch weight is set by the operator and controlled by the computer to minimize human error.

The operation of a closed furnace is different from a conventional open furnace. The operator does not have the ability to view the top of the furnace bed and must rely on instrumentation and operating data to make decisions. This feature eliminates much estimating and adjusting based on subjective observations.

After going through the pre start-up checklist, the furnace is energized. The current is gradually raised, from 10 kA to 30 kA over a 24 hour period. The voltage, a function of

FIGURE 3. PROCESS FLOW DIAGRAM FOR THE CLOSED FURNACE PILOT PLANT.

electrode position, is varied from 40 to 100 volts. Coal is added to the furnace upon reaching stable operation. A normal cycle involves tapping every two hours. The common procedure for adding mix to a closed furnace is not quite as simple in case of an open furnace. The bed level is measured, and this measurement suggests the location and the amount of feed mix to be charged to the furnace. False readings cause the furnace to be over fed or under fed. The furnace roof is equipped with thermocouples that can pin point the need for localized mix addition. The cross check for over feeding or under feeding is tracked by the energy input to the furnace. This indicator is quite reliable during stable continuous operation. In case of a furnace which has been shut down for a short period of time, the energy required to reheat the furnace to operating temperatures should be considered.

The furnace is operated at a slightly positive pressure. The furnace pressure is controlled by maintaining a constant flow of gas through the off-gas system. This is accomplished by controlling the coarse and the fine valves located on the discharge side of the blower. The off-gas pipes were sized to handle the off-gases up to a load of 6 MW.

Critical operating data is analyzed on an on-line basis with the aid of the computer process screens. The operator on the computer terminal has access to key screens in order to monitor and change any operating parameters that may be necessary. An example of the furnace control process screen is shown in Figure 4. The electrode moves up or down to maintain the voltage set point in the auto "on" position. This screen also allows the operator to measure the bed depth. The upper left hand corner on the screen lists the critical parameters namely – SiC build up which is a calculated value, energy in MWh, on-line time, MWh between taps, electrode consumption, and furnace pressure.

The key variables are also plotted as historical trends and stored for the five previous days of operation. The operator command station displays 140 historical trends. Four such trends are shown in Figures 5 through 8. Each Figure shows four plots. Figure 5 shows the historical trends for current, electrode voltage, furnace power, and furnace resistance. The x-axis shows the time and the window can be compressed or expanded to see the data. Figure 6 shows the furnace differential pressure (dp), power, off-gas flow, and the maximum roof temperature point. Figure 7 shows the CO flow rate and energy consumption calculated from this data. Figure 8 shows the calculated SiC build-up and carbon theory.

FURNACE CONTROL GRAPHIC

15.43 PEDESTAL ELEV.
25.12 1800C ELEV.
194.037 Adj. MWH
139.12 On-line Hours
0.5 CALC TAP CYCLE MWHr
237.431 MWHr CALC'D
306.2 ELEC. CONS. (IN)
1.546 EL. BURNOFF IN/HR
0.39 1.32 1.2PT300

POSITIONING CYLINDERS
ELECTRODE POSITION
30.2 INCHES (48" MAX)
STOPPED

TAP CYCLE RESET

MANTLE
BLOWER
CONTROL

ELECTRODE

SLIPPING BAND

JACKING CYLINDERS
MAX ON POS 'N

HOLDING BAND

ELECTRODE
CONTACT
SHOE

DO NOT OPERATE MOVEMENT EQUIPMENT
IF IN AUTOMATIC CONTROL

TAPPING CONTROL

AUTOMATIC VOLTAGE CONTROL

AUTO VOLTAGE CONTROL IS OFF

MANUAL ELECTRODE MOVEMENT MOVE DOWN

SPEED AND DIRECTION 36.0 (SEE BELOW)
MOVE ELECTRODE - MOVE AND STOP MANUALLY

AUTOMATIC ELECTRODE POSITION CONTROL

DISTANCE TO MOVE (3.0 IN MAX) 0.0 INCHES
SPEED AND DIRECTION 36.0
0-50 - DOWN 0 = MAX SPEED DOWN
50-100 - UP 100 = MAX SPEED UP
STOPPED UP SPEED LIMIT = 69.0
STOPPED DOWN SPEED LIMIT = 35.0

ELECTRODE SLIPPING CONTROL

CONTROL: SLIP AUTO-OK?

266.3
TOTAL SLIP

ALLOW SLIP WAIT TIMER

LEVEL MONITOR TIMERS

370 TIME OFF: 3331 MINUTES IN MIX 0 SECONDS
370 DUTY CYCLE: 10 MINUTES SP 40 SECONDS
371 TIME OFF: 3331 MINUTES IN MIX 0 SECONDS
371 DUTY CYCLE: 10 MINUTES SP 40 SECONDS
372 TIME OFF: 3331 MINUTES IN MIX 0 SECONDS
372 DUTY CYCLE: 10 MINUTES SP 55 SECONDS

FURNACE POWER
CONTROL ALARMS

FPS1 ON
FPS2 ON
FPS3 ON
FPS4 ON

FIGURE 4. FURNACE CONTROL PROCESS SCREEN.

1 ET300.OUT
2 IE 330.OUT
3 RES300.OUT
4 JE 330B.OUT

ELECTRODE VOLTAGE AT FCE
FPS AMPERAGE
FURNACE RESISTANCE
DC FURNACE POWER

0.0 TO
0.0 TO
0.0 TO
0.00 TO

200.0 VOLTS
50.0 KAMPS
40.0 MOHM
6.00 MWATTS

REFRESH RATE

1 M

CURRENT VALUE

1 - 36.0
2 - 10.2
3 - 3.4
4 - 0.31

VALUE AT ARROWS

1 - 94.4
2 - 26.0
3 - 3.5
4 - 2.50

TIME AT ARROWS

12-APR-94 18:21

COLLECTION START

02-APR-94 11:33

DISPLAY START

12-APR-94 17:26

COMPRESS RATIO

6:1

DISPLAY WINDOW

125 OF 143

FIGURE 5. HISTORICAL TREND CURVES FOR VOLTAGE, AMPERAGE, RESISTANCE, AND POWER.

1 FDP300.OUT
2 PPV001.OUT
3 AFT300.OUT
4 RT300.OUT

FILE DP (1P1000-5F1300)
FURN POWER ACTUAL
ADJUSTED OFFGAS FLOW
MAX ROOF TEMP

-10.0 TO
0.00 TO
-100 TO
0 TO

90.0 IN WG
6.00 MWATTS
900 SCFM
700 DEG C

REFRESH RATE

30 S

CURRENT VALUE

1 - -0.4
2 - 1.13
3 - 136
4 - 336

VALUE AT ARROWS

1 - 0.4
2 - 1.82
3 - 224
4 - 333

TIME AT ARROWS

18:42:30

COLLECTION START

02-APR-94 11:03

DISPLAY START

12-APR-94 17:56

COMPRESS RATIO

1:1

DISPLAY WINDOW

249 OF 281

FIGURE 6. HISTORICAL TREND CURVES FOR FURNACE DIFFERENTIAL PRESSURE, POWER, OFF-GAS FLOW, AND ROOF TEMPERATURE.

1 1JF 3308 OUT
 2 2AI 300C.OUT
 3 2AI 300B.OUT
 4 EF 300.OUT

DC POWER (ROBICON)
 CO FLOW RATE
 CO SCFM/KW GEN RATE
 CALCULATED KWH/KG SI

0 TO
 0 TO
 0.000 TO
 0.0 TO

5000 KW
 500 SCFM
 0.200 CFM KW
 20.0 KWH KG

REFRESH RATE

10 S

CURRENT VALUE

1 - 1000
 2 - 82
 3 - 0.081
 4 - 11.6

VALUE AT ARROWS

1 - 1380
 2 - 104
 3 - 0.078
 4 - 12.0

TIME AT ARROWS

17:55:40

COLLECTION START

02-APR-94 11:44

DISPLAY START

12-APR-94 17:42

COMPRESS RATIO

1:1

DISPLAY WINDOW

740 OF 854

FIGURE 7. HISTORICAL TREND CURVES FOR CO FLOW RATE AND ENERGY CONSUMPTION.

1 PET300C.VS
2 IE 330.OUT
3 PPV001.OUT
4 ICT300.OUT

FEDESTAL (TEU=100+E*VX)
FPS AMPERAGE
FURN POWER ACTUAL
INSTANT CT W/ ELECT

-10.0 TO
0.0 TO
0.00 TO
85.0 TO

40.0
50.0 KAMPS
6.00 MWATTS
105.0 PERCNT

REFRESH RATE

1 M

CURRENT VALUE

1 - 8.0
2 - 21.0
3 - 1.06
4 - 102.8

VALUE AT ARROWS

1 - 2.2
2 - 21.0
3 - 1.18
4 - 101.2

TIME AT ARROWS

12-APR-94 17:15

COLLECTION START

01-APR-94 21:54

DISPLAY START

12-APR-94 15:32

COMPRESS RATIO

1:1

DISPLAY MINDON

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FIGURE 8. HISTORICAL TREND CURVES FOR SIC BUILDUP, AMPERAGE, POWER, AND CARBON THEORY.

TASK 2.3 START-UP AND COMMISSIONING

2.3 Start-Up and Commissioning. Commissioning and start-up was initiated upon completion of the construction by Comstock, the general subcontractor, and UMA, the engineering contractor. The commissioning plan, followed by the visual inspection of the installed equipment, consisted of:

- Staffing and Operator Training
- Safety Programs
- Subsystem Checks
- Dry Run Testing
- Furnace Bake-Out
- Start-up Runs

2.3.1 Staffing and Operator Training. Establishing the appropriate operating personnel team was an important activity. The staff to operate the pilot plant was selected such that most individuals had skills and flexibility to perform more than one job. Once the appropriate operating staff was assembled, significant effort was devoted to conducting training courses for the personnel. Training was carried out in all the areas that cover corporate standards, provincial regulations, equipment, and safe operating procedures. A list of the topics for training include:

- Manitoba Workplace Safety and Health Rules
- Site Safety Committee
- Eye, foot, and head protection
- Hand safety
- Back care, proper lifting, and generally good ergonomic practices
- Respiratory protection
- Hearing protection
- Fork truck training
- Principles of electricity and its hazards
- Electrical lockout procedures
- Carbon Monoxide hazards and protection
- Molten metal hazards
- High temperature protective equipment
- Eye protection for high intensity light
- First aid training
- General use of fire protection equipment
- Use of eye wash and safety showers
- Hoisting & rigging
- Safety orientation

- Safe work permits
- Process change requests
- Confined space entry
- Standard operating procedures

2.3.2 Safety Programs. Establishing new technology on a site with new people, while minimizing potential for safety problems, is a significant challenge. Dow Corning Corporation and all of its affiliates must follow rigid safety guidelines that include Safe Operating Procedures (SOPs), Safety Audits, Operating Change Requests (OCRs) and Safe Work Permits.

Fourteen SOPs were prepared to describe the process procedures of the plant. Those written include:

SOP 01	General Safety
SOP 02	System
SOP 03	Distributed Control System
SOP 04	Raw materials - delivery to day bins
SOP 05	Furnace - air locks to tapping
SOP 06	DC Electrical - electrode clamps through system to anode plate
SOP 07	Metal handling - ladle to rail car
SOP 08	Off gas - furnace through incinerator
SOP 09	Dust collector
SOP 10	Services - water, air, nitrogen, oxygen, vacuum, electrical
SOP 11	Hydraulics
SOP 12	Analyzer equipment and summary
SOP 13	Lab equipment
SOP 14	Maintenance

The Safety Audit program utilized three experienced personnel to review designs, layouts, physical facilities, SOPs, and general operating plans to perform a comprehensive assessment of the program. These Safety Audits found no significant issues.

The Operating Change Request Program is established so that any changes to the system or components, software or operating set points are scrutinized to assure the plant maintains a high level of operating safety. Software changes require review to assure the safety logic is not compromised. Changes to operating set points must be reviewed to assure equipment operates within designed safety and operation limits.

All work done in the plant that breaches equipment, involves flame or spark producing equipment, or requires vessel entry or involves electrically or mechanically energized equipment

must be done under supervision. Safe Work Permits, Vessel Entry Permits and formal lockout procedures are used as required. These programs were all in place and utilized fully.

2.3.3 Subsystem Checks. The pilot plant was divided up into subsystems and checklists were prepared. Each subsystem was broken down into major items. Each item was inspected for mechanical integrity, electrical connections, controls function, etc. Stress analysis was conducted where appropriate. As the equipment was checked, any correction or improvements were made as necessary and documented. Those subsystems that could be run independently were tested as a unit once the component parts were all checked out.

2.3.4 Dry Run Testing. Dry run testing plans for the pilot plant operation were defined. Trials related to electrical system, hydraulically operated components, feed delivery system, off-gas cleaning and product handling system were conducted.

2.3.5 Furnace Bake Out. In order to bake out the furnace to drive off the moisture from the refractory and volatiles from the carbonaceous ramming materials, a resistive column was added between the electrode and the hearth. The furnace was electrically heated by bringing the electrode in contact with the column. The bake out procedure was conducted over a five day period. This activity proceeded as expected except that the bottom connection to the anode overheated. Inspection of the anode connection, upon cool down, revealed that severe heating or arcing occurred on the connection. The problem originated from swelling of a cast refractory on the furnace-bottom. The expansion raised the hearth causing a gap which resulted in arcing upon passing the current. Corrective actions were taken to repair the anode, and the anode was checked out for the start-up runs.

2.3.6 Start-Up Runs. The first three tests were characterized as start-up and commissioning tests. The purpose of these tests were to operate the pilot plant, demonstrate the operation of various process trains such as feed delivery system, furnace operation, off-gas recovery system, silicon tapping and casting bay, and make improvements to the process and the equipment as necessary. These tests were up to 100 hours in duration. The power input during these tests was

limited to 1 MW at a current setting not to exceed 21 kA. During all three runs, feed to the furnace consisted entirely of quartz and charcoal. All of the process trains functioned quite well during the start-up runs. Minor items such as seal leaks on the off-gas blower and operating problems in the airlocks were identified and corrected.

2.3.6.1 Start-Up Run-001. Run 001 was started at 22:30 hours on July 20, 1992. The purpose of this run was to verify functioning of the system components. The furnace was run for 93 hours during which period, 43 MWh of energy was consumed. A total of 21,686 kg quartz and 11,183 kg charcoal was fed to the furnace. Six taps were made and approximately 2128 kg silicon was produced.

The modified anode design worked satisfactorily at 21 kA over a short test period. All systems such as power delivery, raw material feed, furnace operation, silicon tapping, and casting all functioned well. The electrode position control was not used due to lack of confidence in the position measuring device. The run was terminated voluntarily after four days of operation.

2.3.6.2 Start-Up Run 002. Run 002 was started at 03:30 hours on September 16, 1992. The mix remaining in the furnace from Run 001 was raked and 10 batches of mix were added to the furnace during the start-up period. A typical batch weight consisted of 130 kg quartz and 71 kg charcoal. The energy input to the furnace was 19.1 MWh over a 55 hour period. The run was prematurely terminated after 55 hours primarily due to negative pressure between the vent lines and the furnace as well as high levels of oxygen in the off-gas. The furnace was also over fed plugging four feed lines thus malfunctioning the feed-mix system. Three taps were made and approximately 800 kg of silicon are tapped. During the third tap, molten silicon leaked through a hole in the tapping spout adjacent to the furnace shell. The hole in the tapping spout resulted from the oxygen lance which is used to open the tap hole. Excavation of the furnace revealed the furnace to be choked with feed mix.

Over feeding of the furnace with the raw material mix was the primary reason for terminating run 002. Four out of the six feed chutes were backed up from the furnace to the airlocks and two feed lines, past the airlocks.

2.3.6.3 Start-Up Run 003. Run 003 was started at 11:50 hours on October 1, 1992. One purpose of this run was to lower the mix level in the furnace. The furnace was run for 43 hours during which period 14.5 MWh of energy was consumed. As the furnace was operated, it was observed that the mix was consumed at a significantly higher rate at specific locations around the electrode. This uneven mix consumption caused an open cavity around the area of rapid mix consumption. In order to cover up the cavity, nine batches of mix were added to the furnace during the 42 hour period. Three taps produced a total of 672 kg of silicon. The furnace was stoked and raked approximately every two hours after the initial 24 hour operating period. The power input rate varied from 0.3 - 1 MW. The current varied from 7 - 15 kA at a voltage of 50 - 100 volts. Excavation of the furnace revealed that the mix level in the furnace was appropriately lowered. However, a 12 to 18 inch hole around the 18 inch electrode was observed. This cavity is not desired because it allows the SiO fume to escape from the furnace without reacting with the charcoal in the burden.

The negative pressure across the off-gas lines and the furnace and high levels of oxygen in the off-gas stream were the primary reasons for shutting down runs 002 and 003. The oxygen levels in the off-gas, which is related to the negative pressure, was observed to be in the range of 3-4% towards the end of run 003. Upon cool down, the furnace was excavated and the smelted materials were removed from the furnace. With completion of run 003, the commissioning of the pilot plant was successfully completed.

TASK 2.4 OPTIMIZATION OF OPERATION

2.4.1 Operating Strategy. The key variables influencing the furnace operation are carbon theory and power input. Excess carbon in the furnace results in silicon carbide formation. Excess carbon in the furnace can result from higher carbon input or excessive SiO losses. If SiO losses were eliminated and the silicon yield was 100%, the furnace would require two moles of fixed carbon for each mole of silica. Carbon contributors to furnace are reductants (coal, charcoal) and electrode. Carbon theory is effected by variations in fixed carbon, moisture, weighing error, loss of fines, etc. Electrode consumption also effects carbon theory. During a typical start-up, the carbon contribution by electrode can be significant resulting in silicon carbide build-up in the furnace.

Other critical variables effecting furnace operation are current and voltage. In a dc furnace, the power control scheme can be rather simple. At a preset current, the voltage is regulated by moving the electrode position. As current is raised, it is typical that the voltage is adjusted to get an optimum distribution of energy in the furnace.

The furnace operating strategy was based on evaluation and analysis of critical data on a real time basis. The data was gathered using three methods. On-line historical trends were plotted by the Distributed Control System (DCS). Data was also transferred from the DCS to the PC spreadsheet, where it was processed to produce graphs and trends on the data. From the critical data, the feed rates and quartz-to-carbon ratios were specified corresponding to energy input in order to maximize silicon yield.

The furnace operation was controlled by monitoring fixed carbon, carbon theory, and power input as a function of electrode voltage at a constant current. The other variables monitored were temperatures, furnace pressure, off-gas composition and flow rate, bed height, etc. The calculated responses were electrode consumption, silicon carbide build-up, etc. The following parameters were closely monitored during the operation:

- Four-hour moving average carbon theory with and without electrodes
- Carbon theory actual vs. target
- Silicon recovery by tap and average power input

- Energy consumption by tap and average power
- SiO_2 inventory in the furnace as Si (Si Deficit), Ca and Al inventory in the furnace and Ca and Al in the tap stream
- Fume and silicon recovery
- Four-hour moving average for Si fed as SiO_2 /MWh and total SiO_2 fed as Si

2.4.2 Optimization Tests. The first three runs beginning in July, 1992, were characterized as start-up and commissioning tests. Runs four through 12 were designated as optimization tests. The purpose of these tests was to first demonstrate sustained operation, and at the same time, optimize the raw materials mix suitable for a closed furnace operation. Targets were set for key performance variables such as silicon recovery, energy consumption, electrode consumption, fume weight, and on-line time. One of the key objectives was to meet or exceed the targets.

2.4.3 Optimization Run-004. Run 004, first in a series of runs for optimization of the operation, was started on December 1, 1992, at 00:20 hours using quartz and charcoal. The test was ended on December 13, 1992, at 12:22 hours.

The furnace was started at 92% carbon theory. The furnace was initially loaded with 5,971 kg of quartz, 3,293 kg charcoal and 586 kg wood chips. The wood was added to increase the bed porosity. In addition to the above mix, 736 kg silicon and 475 kg petroleum coke was added at the top of the hearth to form a protective layer of silicon carbide upon heating the furnace. During the 300 hour operation, 41,295 kg of quartz and 22,796 kg charcoal was added to the furnace plus an energy input of 176.8 MWh. The net operating time was 242 hours and the remaining 58 hours were required for maintenance. Towards the end of the run, the carbon theory was changed to 90% based on an indication of silicon carbide build-up in the furnace. A total of 28 taps were made and 11,820 kg silicon was tapped. The overall silicon yield was 61%. However, during stable operation, the steady state silicon yield was 85%. The average power consumption for the run was 14.8 kWh/kg and 12 kWh/kg for the stable operating period. The fume loss from the furnace was estimated at 400 kg, approximately 1% of the operating quartz feed. Upon heating the furnace to operating temperature, the voltage was maintained around 100 volts and the current was gradually raised to 22 kA. Run 004 summary was as follows:

Gross Operating Hours	300
Net Operating Hours	242
Energy Input (MWh)	176.8
Maximum Power (MW)	2.2
Maximum Current (kA)	22
Charcoal Input (kg)	22,796
Coal Input (kg)	0
Quartz Input (kg)	41,295
Estimated Fume Weight (kg)	400
Silicon Tapped (kg)	11,820

Silicon samples from run 004 were analyzed for iron, aluminum and calcium levels. The iron content averaged around 0.2% during the steady state operation. This value is typical based on the mass balance calculations. The aluminum level varied from .02 to .12%. The aluminum levels were quite similar to the ones calculated from raw material mass balance. The calcium level varied from 0.1 to 1.1%. The calcium values were much lower than the calculated data suggesting calcium tie up within the furnace as an oxide slag.

2.4.4 Optimization Run 005. Run 005 aimed at optimization of the closed furnace operation was started on February 23, 1993, at 08:15 hours and completed on March 6, 1993, at 23:00 hours. The run was started with the furnace full of mix from run 004. Three and a half batches of mix with 131 kg quartz per batch and stoichiometric amounts of charcoal at 90% carbon theory were added to the furnace prior to turning the power on.

The starting carbon feed to the furnace was based on 100% charcoal. The carbon theory for run 005 was started at 90%. After tap 10, the carbon theory was lowered to 88% and raised back to 90% after tap 16. After tap 20, with a change in the charcoal bin, the carbon theory was raised to 92.5%. This increase in carbon theory was made to compensate for the loss in carbon by the water gas reaction from the high level of moisture measured in the charcoal. The moisture level in the charcoal increased from 3% to 14% during the run. After tap 23, the carbon theory was lowered to 91.5% and finally to 91% after tap 25 for the remainder of the run. Run 005 summary was as follows:

Gross Operating hours	234
Net Operating hours	223
Energy Input (MWh)	209.1
Maximum Power (MW)	2.28
Maximum Current (kA)	23
Charcoal Input (kg)	23,445
Coal Input (kg)	0
Quartz Input (kg)	42,920
Estimated Fume Weight (kg)	1730
Silicon Tapped (kg)	15,834

Upon cooling of the furnace, the mix was systematically removed and various reaction zones in the process were evaluated.

2.4.5 Optimization Run 006. Run 006, aimed at further optimization of the closed furnace operation, was started on April 13, 1993, at 16:52 hours and completed on April 18, 1993, at 1:12 hours. The furnace was loaded with 50 batches of mix with 131 kg quartz per batch and stoichiometric amounts of charcoal. The starting carbon feed to the furnace was based on 100% charcoal. From batch 131 onwards, 25% of the fixed carbon was added as coal. From Batch 196 onwards, the coal content of the mix was raised to 38%. The carbon theory for run 006 was started at 91%, from batches 51 to 81 the carbon theory was lowered to 90%, and then raised back to 91% for batches 82 to 87. The carbon theory was further raised to 93% for batches 88 to 200. The carbon theory was then lowered back to 91% from batch 201 and was maintained between 90 and 91% for the remainder of the run. The changes in theory were made to compensate for the loss in carbon by the water gas reaction from the varying levels of moisture in the charcoal. Run 006 summary was as follows:

Gross Operating Hours	104
Net Operating Hours	103
Energy Input (MWh)	142.6
Maximum Power (MW)	2.95
Maximum Current (kA)	20.1
Charcoal Input (kg)	19,807
Coal Input (kg)	4761
Quartz Input (kg)	43,739
Estimated Fume Weight (kg)	1340
Silicon Tapped (kg)	7882

The furnace operation was quite good with minimal down time. No significant problems were noticed with the off-gas system after introducing coal to the mix. The fume color with coal in the mix was darker and the fume was relatively stickier. The run was concluded due to failure of the electrical isolation between the electrode assembly and the furnace shell.

2.4.6 Optimization Run 007. Run 007 was aimed at further optimization of the closed furnace smelting operation with coal in the mix. This run was started on May 28, 1993, at 03:00 hours and completed on June 11, 1993.

The run was started with a cleaned out furnace. The furnace was loaded with 40 batches of mix with 131 kg quartz per batch and stoichiometric amounts of charcoal at 96% carbon theory. The starting carbon feed to the furnace was based on 100% charcoal. Upon reaching stable operation, 25% of the fixed carbon was added as coal. This change was made after approximately 60 hours of operation. The coal content of the mix was raised to 50% after 90 hours of operation starting from batch 204.

The carbon theory for run 007 was started at 91%. From batches 51 to 100, the carbon theory was lowered to 90% and then further lowered to 89% for batches 101 to 129. The carbon theory was then raised to 90% from batch 160 and was maintained at this level.

No significant problems were noticed with the off-gas system after introducing coal to the mix. The fume color with coal in the mix was darker and the fume was relatively stickier. The furnace was down on two occasions and both times the outage was due to hydraulic related issues.

The run was aborted due to severe bridging of the feed mix below the feed chutes. A summary of the run data is as follows:

Gross Operating Hours	312
Net Operating Hours	264
Energy Input (MWh)	290
Maximum Power (MW)	2.3
Maximum Current (kA)	28
Charcoal Input (kg)	21,554
Coal Input (kg)	10,016
Quartz Input (kg)	58,000
Estimated Fume Weight (kg)	5454
Silicon Tapped (kg)	17,381

Excavation and dig out of the furnace revealed build up of silicon carbide in the furnace in spite of carefully controlling the carbon theory. The silicon carbide build up was most likely due to too-high an operating resistance and to a lesser extent due to the carbon balance.

2.4.7 Optimization Run-008. Run 008 was started on September 2, 1993, at 06:43 hours. The furnace was started with 100% charcoal in the feed. At an energy input of 53 MWh, 25% coal was introduced to the feed. At 108 MWh, the coal content of the feed was raised to 38%. At 149 MWh, the coal content was raised to 50% and maintained at this level for nine days. The overall carbon theory for the run was 88.9%. From tap 25 on, the cumulative silicon recovery was around 89%. The fume accounted for 4.5% of the quartz input.

The run was temporarily shut down on September 18, 1993, due to a plugged off-gas line. After cleaning the vent lines, the furnace was started back on September 27, 1993. The mix was switched to 100% charcoal. The furnace was run for six days and finally shutdown on October 3, 1993, at 14:00 hours due to high differential pressure between the furnace and the off-gas lines. The power on-line time was 437 hours and the total energy input was 562 MWh. During this campaign, a total of record 120,970 kg quartz was fed to the furnace and 41,982 kg silicon was produced. The overall carbon theory for the run was 88.1%. The overall carbon theory including the electrode was 99.4%. A summary of the run data is as follows:

Gross Operating Hours	751
Net Operating Hours	437
Energy Input (MWh)	562
Maximum Power (MW)	2.6
Maximum Current (kA)	28
Charcoal Input (kg)	42,354
Coal Input (kg)	20,591
Quartz Input (kg)	120,970
Estimated Fume Weight (kg)	4525
Silicon Tapped (kg)	41,982

2.4.8 Optimization Run-009. Run 009 was started on November 14, 1993, at 20:00 hours. The furnace was started with 100% charcoal mix. After three days of operation, the mix was changed to contain 50% coal. On November 22, 1993, the furnace power was turned off due to high differential pressure between the furnace and the off-gas line. The furnace was allowed to cool

down and the mix around the off-gas line was moved to open the blockage. The furnace was restarted on November 25 at 03:00 hours. After operating the furnace for five days, the test was concluded on December 1, 1993, at 12:25 hours due to too-high a differential pressure between the off-gas line and the inside of the furnace. The overall carbon theory for the run was 88.3%. The overall carbon theory including the electrode was 97.3%. The operating results for the run 009 were as follows:

Gross Operating Hours	400
Net Operating Hours	229
Energy Input (MWh)	344
Maximum Power (MW)	2.25
Maximum Current (kA)	30.2
Charcoal Input (kg)	27,329
Coal Input (kg)	13,697
Quartz Input (kg)	78,367
Estimated Fume Weight (kg)	2,810
Silicon Tapped (kg)	23,785

2.4.9 Optimization Run 010. The furnace was retrofitted with side pushers in an effort to enhance the mix-movement, cover the cave, and solve the vent line blockage problem. Four side pushers, one directly under each off-gas port, were installed with the purpose of pushing the mix up and in towards the electrode. The side pushers are expected to push "old" mix out of the way of the off-gas ports allowing furnace gases to exit the furnace. The side pushers were mounted at an angle of 30 degrees below the horizon so that they would push up and in towards the electrode.

Run 010 was started on April 4, 1994, at 12:20 hours and completed on April 22, 1994, at 03:00 hours. The furnace was loaded with feed mix at a level of approximately 12 inches above the off-gas port. The carbon theory for run was started at 91% and necessary carbon theory changes were made as required during the operation. Run 010 was terminated due to bridging of the mix at the top of the bed, causing the feed to back up in the feed pipes. Overall carbon theory for the run was 89.1%. Overall carbon theory including the electrode was 98%. The operating results for the run were as follows:

Gross Operating Hours	351
Net Operating Hours	239
Energy Input (MWh)	237

Maximum Power (MW)	2.5
Maximum Current (kA)	25
Charcoal Input (kg)	28,600
Coal Input (kg)	0
Quartz Input (kg)	53,000
Estimated Fume Weight (kg) *	
Silicon Tapped (kg)	13,935

* not available

2.4.10 Optimization Run 011. Run 011 was started on May 15, 1994, at 06:00 hours and completed on June 26, 1994, at 18:00 hours. The furnace was loaded with feed mix to a level approximately six inches above the off-gas port. Upon reaching steady state, on May 18, 50% coal was introduced to the mix. With the aid of the side pushers and lower bed height, the issue of mix bridging was resolved. A total of 192,936 kg of quartz was fed to the furnace. The carbon theory for run was started at 91% and maintained around 88% during the operation. Higher levels of fume collection resulted from operating the furnace with a lower bed height. The higher fume levels resulted in plugging the off-gas line which had to be cleaned out to maintain operation. This was a record run with six weeks of operation and 839 MWh of energy input. The overall carbon theory for the run was 88.4%. The overall carbon theory including electrode consumption was 97.3%. The run summary was as follows:

Gross Operating Hours	1008
Net Operating Hours	563
Energy Input (MWh)	839
Maximum Power (MW)	2.17
Maximum Current (kA)	30
Charcoal Input (kg)	56,804
Coal Input (kg)	36,844
Quartz Input (kg)	192,936
Estimated Fume Weight (kg)	13,972
Silicon Produced (kg)	59,880

2.4.11 Optimization Run 012. Run 012 was started on September 25, 1994, and completed on October 27, 1994. The operating results were as follows:

Gross Operating Hours	768
Net Operating Hours	265
Energy Input (MWh)	488

Maximum Power (MW)	2.6
Maximum Current (kA)	31
Charcoal Input (kg)	33,819
Coal Input (kg)	17,489
Quartz Input (kg)	109,152
Estimate Fume Weight (kg)	11,506
Silicon Tapped (kg)	34,609

The furnace was loaded with feed mix consisting of quartz and 100% charcoal. The bed height for this run was started at a lower level, so as not to cover the off-gas ports. Upon reaching stable operation, 50% coal was introduced to the mix. Higher fume levels resulted in plugging the off-gas lines and the furnace was down for maintenance from October 6 to October 18, 1994. The overall carbon theory for the run was 87%. The overall carbon theory including electrode consumption was 97%.

TASK 2.5 DISCUSSION OF RESULTS

2.5 Discussion of Results. Key results from the smelting campaigns are discussed in terms of measurable parameters such as silicon yield, energy consumption, electrode consumption, on-line time, silicon quality, as well as operational issues effecting sustained operation. The operating results, along with the targets are presented in Table 2.

Silicon yield is presented as both overall yield and stable operating yield. Overall yield is calculated based on the silicon produced as a percentage of total quartz fed. Since the overall yield does not discount the quartz remaining in the furnace upon termination of the run, the overall silicon yield is always lower than would be expected on a commercial operation, where the furnace inventory of quartz is insignificant compared to the tonnes of quartz processed. Due to the short duration of the runs ranging from two to six weeks, steady state operating yield data are much more representative of typical operation. The steady state operating yield was in the low to high eighties for most of the runs.

Carbon theory is an important factor that effects the silicon recovery and furnace operation. A closed furnace allows better control of carbon theory, by eliminating carbon oxidation losses. Any build-up of silicon carbide accumulated in the furnace was evaluated using the following schemes:

- Temperature extrapolation - This procedure measures the temperature of the bottom anode at various elevations. By knowing the thermal conductivity of the anode materials and by assuming a temperature at the pedestal, the hearth build up can be calculated. This approach is not conclusive and provides the trend for any build up. The plot of temperature vs. elevation is shown in Figure 9, which predicts the build up at the time of the plot. This approach is not valid during the heat-up or cool down period.
- The electrode consumption in a closed dc furnace can be monitored closely by the current-erosion rate relationship. The absence of oxidation makes this calculation more reliable.
- Overall carbon balance, based on silicon recovery and fume production, is also used for determining the extent of silicon carbide build up.

In spite of detailed attention paid to carbon theory, Silicon Carbide accumulation at the bottom of the furnace under the electrode, was a significant issue. The build-up is related largely to the effective control of carbon-to-silicon ratio in the system. This is impacted by erroneous

GRAPHIC 98 - BOTTOM CENTER TEMP PROFILE

CURRENT 20.99 DC KAMPS
VOLTAGE 57.6 DC VOLTS
CALC POWER 1.208 DC MWATTS

ELECT CONSUM 306.54"
CALC MWHR 237.653

FIGURE 9. FURNACE BOTTOM TEMPERATURE PROFILE.

and variable carbon contents in the feed, varying electrode consumption rates, and varying rates of fume loss. Significant progress was made at identifying and monitoring key issues to maintain control of the SiC pedestal. This aspect of the process requires significant attention during operation and is certainly more sensitive than in the conventional process.

Typical bag-house fume yield was around 5% relative to the quartz input. The fume level was lower for runs where the bed height was maintained at an operating level above the off-gas ports. The fume levels for the various runs varied from 2-10%.

TABLE 2. OPERATING RESULTS COMPARED TO GOAL

Run #	Silicon Produced kg	Overall Yield %	Steady State Yield %	Overall Power Consumption kwh/kg	Steady State Power Consumption kwh/kg	Electrode Consumption kg/Mt	On-line Time %
4	11,820	61	85	14.8	12	67	*
5	15,833	78	83	13.2	12	105	95
6	7029	42	74	19	14	109	99
7	17,381	49	60	18	15	136	72
8	41,982	77	89	12.9	11.9	98	79
9	23,785	65	80	14.5	12.9	126	58
10	13,935	56	87.9	17.2	13.7	151	68
11	59,880	72	85	14	12	127	66
12	34,609	70	79	14	13.8	120	65
Target	Produce Silicon	N/A	90	N/A	12	60	95

* data not available

The energy consumption data are presented as overall power consumption and steady state power consumption. Overall power consumption values include the energy needed to heat the system where as steady-state power consumption data are more representative of the energy required for smelting silicon in a commercial operation. These values correlate well with the values calculated by accounting for the energy losses through electrode heating, bus losses, and

thermal losses. With the exception of runs 7, 9 and 10, the stable energy consumption was below the target of 12 kWh/kgSi. This result is quite encouraging for a furnace operating at 2.5 to 3 MW. A furnace operating at a higher load is expected to give even lower energy consumption figures.

The electrode consumption was targeted at 60 kg/Mt Si at 6 MW based on expected results with dc current. The electrode consumption has ranged from 100-150% of target value for most of the runs. The electrode consumption is also impacted by system heat-up, excessive down time, short run times, and silicon retained in the furnace as SiC pedestal. Electrode breakage problem was not encountered during the program. This result is attributed to uniform dc current flow through the electrode resulting in lower temperature gradient through the electrode cross section, elimination of electrode oxidation, and no rotation of the furnace.

On-line time is one of the most important factors effecting process efficiency. Runs 001-004 on-line time was impacted by start-up, commissioning, and system debugging issues and are not considered representative. Run 005 has good on-line time. Run 006 also had an impressive 99% on-line time, but the run was terminated because of a maintenance problem that required significant down time to rectify. The remaining runs had low on-line times to allow maintenance of the furnace and off-gas pipes, roof temperature issues, anode maintenance, and mix-movement problem. The mix-movement problem required intervention that would be unacceptable for commercial operation.

Most of the silicon taps from the test campaigns were analyzed for iron, aluminum, and calcium. The quality of silicon with respect to these impurities have been typical of expected values based on mass balance calculations. When comparing these results to open furnace product, the impurity levels have been lower due to about 10% lower carbon consumption in a closed furnace and the corresponding ash from the carbon being eliminated.

Runs 001 through 005 were conducted with 100% charcoal in the feed mix and remaining runs were conducted with 50% coal and 50% charcoal. Operation at 70% coal was achieved for a short period during Run 11. Coal in the feed mix did not cause plugging problems in the bag-houses because of tars, with the exception of Run 009, where long downtimes and low power rates caused excess cooling and condensation of tars on the filters. Several minor modifications to the instruments and gas analysis systems were required to eliminated plugging.

The off-gas contains approximately 70% CO, 20% hydrogen and other volatiles, discounting N₂ and H₂O. Use of the off-gas as a fuel or chemical feed stock would depend on the specific location and the specifications of dirt, moisture, and inerts permitted. A careful review of plant siting issues and capital costs that affect off-gas use would be required to assure cost of recovery does not exceed value.

The fume from a closed furnace was characterized and the results are listed in Table 3. The fume collected from a 100% charcoal mix appeared green in color and turned to dark gray as coal was introduced to the mix. The bulk density of the fume was measured around 3.6 lbs/cu. ft. and the particle size of the fume was <20 microns.

TABLE 3: TYPICAL FUME CHARACTERIZATION RESULTS

Feed Mix	Color	Elemental Analysis			X-Ray Diffraction
100% Charcoal	Green	Fe	Ca	Al	90% Amorphous SiO ₂ 3% Cristobalite 2% β SiC 1% Graphite 4% SiO
		.01	.05	0.8	
Coal/Charcoal	Dark Gray	.04	.11	.08	71% Amorphous SiO ₂ trace cristobalite 14% SiC 13% Si

2.5.1 Benefits of Closed Furnace. A closed furnace operation for smelting silicon offers several advantages over an open furnace. The most significant of these are:

A. Energy Savings

The energy savings in the closed furnace silicon process was verified at 1.47×10^{12} BTU/yr for a 20 MW furnace, producing 13.6×10^3 metric tons or 30×10^6 lbs of silicon/year and operating 330 days/year (95% on-line time). The energy is saved in four ways:

1. Raw Materials
2. Process Energy Efficiency

3. Process Off-gas
4. Closed Furnace Bag-house vs. Open

Raw materials account for the largest portion of the energy savings. Major contributions to raw material savings come from improved silicon yield and carbon oxidation losses. In a closed furnace, the electrode consumption is reduced by 33% compared to open furnace operation. The carbon requirements at higher silicon yields are 3-5% less than carbon requirements in an open furnace, due to loss of carbon via oxidation. The total raw material energy savings resulting from the increase in silicon yield from 78 to 94% is 5.3 kWh/lb Si or 18,200 Btu/lb Si as shown in Table 4.

TABLE 4. (*) ENERGY SAVINGS FROM RAW MATERIALS

Material	kg/kg Si Existing 78% yield	kg/kg Si Closed Furnace 94% yield	kg/kg Si Savings	Energy Embodied 10 ³ Btu/kg	Energy Savings Btu/lb Si
Quartz	2.747	2.28	0.467	0.143	30
Coke	0.240	0	0.24	34.8	3790
Coal	1.057	0.799	.258	28.7	3360
Wood	1.533	----	1.533	18.7	13030
Charcoal	---	0.366	(0.366)	30.9	(5130)
Electrode	0.115	.076	.039	176.4	<u>3120</u>
				TOTAL	18200

(*) This table was obtained from report titled "Collection and Conversion of Silicon Furnace Waste Gas into Higher Value Products, Phase III: Experimentation Final Report authored by Vishu D. Dosaj, Issued February 1992 by DOE.

DOE/ID/12624-1 (DE93000906)

The process off-gas, in an open furnace, is a waste stream and it accounts for 52% of the total energy input to the furnace. The off-gas from the closed furnace was shown to have an energy value of 350-396 Btu/ft³. The average fuel value of off-gas was 375 Btu/ft³. For an estimated rate of off-gas evolution of 2093 SCFM the energy savings are 0.78×10^{12} Btu/Minute.

A 20 MW furnace (producing 13.6 thousand metric tons or 30×10^6 lbs of silicon operating 330 days/year at an on-line time of 95%) will save 0.352×10^{12} Btu/yr. The energy savings is 11,800 Btu/lb Si.

The bag-house in a closed furnace is expected to process approximately 50-fold less process off-gas compared to an open furnace. Such reduction in process gas is expected to save 3800 Btu/lb silicon.

The process energy required decreases with the improvement in silicon recovery from 78 to 94 % with the closed furnace process. The electric energy for a 20 MW furnace is expected to decrease from 14.55 kWh/kg Si to 11.35 kWh/kg resulting in net electrical energy savings of 1.45 kWh/lb Si, or 15,200 Btu/lb silicon when the inefficiency of generating electricity is considered (10,500 Btu/lb per kWh_e).

The projected energy savings by using a 20 MW closed furnace is 49,000 Btu/lb Si (1). For a 30×10^6 lb/yr plant (20 MW), the projected annual energy saving is 1.47×10^{12} Btu/furnace per year. About 61% of this saving is in the energy content of the raw materials and of the recovered off-gas.

B. Recovery of Off-Gas

In an open furnace, the off-gas is a waste stream and 52% of the energy input to the furnace is contained in the off-gas. The off-gas from the Closed Furnace Mini-Plant had an energy content of 375 Btu/ft³. A closed furnace makes recovery of this energy possible.

C. Reduced Electrode Consumption

In an open furnace, the portion of the electrode just above the raw materials is oxidized resulting in a loss of electrode. In a closed furnace, oxygen is not present, therefore, the

electrode consumption is reduced. Additional reduction in electrode usage is expected with a dc closed furnace.

D. Reduced Carbon Oxidation Losses

In an open furnace, a portion of the carbon is lost at the furnace top due to burning. The absence of oxygen in the closed furnace eliminates this loss of carbon. This benefit was proven in the closed dc furnace where the typical carbon theory in the mix was 88-89%. Previous experience with an open furnace of similar size required a carbon theory of 91-93%. Thus, a closed furnace reduces the carbon oxidation losses and requires 3-5% less carbon for smelting.

E. Improved Safety

A closed furnace results in improved safety through reduced exposure of operating personnel to heat and fume during stoking and other operations close to the furnace.

F. Improved Pollution Control

A closed furnace results in better pollution control. In an open furnace, it is not uncommon for large amounts of fume to escape the top of the furnace and create a pollution concern. The closed furnace almost completely eliminates this potential for pollution since the fume and off-gas are all contained and processed.

2.5.2 Environmental Standards Test. In order to assure compliance with environmental standards, CanadEER Ltd., from Markham, Ontario, was retained to determine the concentration and emission rate of total suspended particulates and to perform continuous emissions monitoring (CEM) at the incinerator outlet stack. Target gases included oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), oxygen (O_2) and carbon dioxide (CO_2).

All testing was conducted, in May, 1994, using approved methodologies including Environment Canada Reference Method EPS 1/RM/8: Measurement of Releases of Particulate From Stationary Sources, for total suspended particulate matter and National Standard of Canada CAN/CSA-Z223.2-M86: Method for the Continuous Measurement of Oxygen, Carbon Dioxide,

Carbon Monoxide, Sulphur Dioxide, and Oxides of Nitrogen in Enclosed Combustion Flue Gas Streams for CEM measurement.

The average particulate emission rate for the incinerator outlet stack was determined to be 0.085 g/s with an average particulate concentration of 16.3 mg/DSm³. The stack gas characteristics analysis yielded an average volumetric flow rate of 18900 DSm³/hr¹ and concentrations of 14.2% and 7.7% for O₂ and CO₂ respectively.

NOTE: (DSm³/hr = Dry Standard cubic meters per hour. Standard conditions = 77°F and 29.92" Hg).

CEM stack gas analysis performed on the incinerator outlet stack yielded average bias corrected concentrations of 14.1% O₂, 7.7% CO₂, 14.7 ppmv CO, 97.7 ppmv NO_x, and 72.9 ppmv SO₂.

A comparison of the incinerator discharge data presented in the environmental impact assessment is given in Table 5.

TABLE 5. A COMPARISON OF THE INCINERATOR DISCHARGE DATA

Component	EIA	Expected	Operating	Results
	lb/hr	Concentration	lb/hr	Concentration
Carbon Dioxide	5400	16.1%	6300	7.7%
Sulfur Dioxide	30	700 ppm	8.7	72.9 ppmv
Carbon Monoxide	-	-	0.8	14.7 ppmv
Nitrogen Oxides	4	120 ppm	5.5	97.7 ppmv
Oxygen				14.2%
Nitrogen	11000	77.4%		
Particulates	<50		0.7	

There is slightly more carbon dioxide and nitrogen oxides present in the stack than predicted. Both can be attributed to the burning of supplemental fuel (natural gas) to maintain high incinerator temperatures that assure complete combustion of the carbon monoxide.

The air quality results are presented in Table 6. Air quality is based on ground level concentrations. Dispersed concentrations meet air quality guidelines.

TABLE 6. AIR QUALITY RESULTS

Component	Rate lb/hr.	EIA Basis lb/hr.	Dispersion Prediction 24 Hr. Basis	Guidelines
Sulfur Dioxide	8.7	30	18	150 mcg/m ³
Nitrogen Oxides	5.5	4	2	60 mcg/m ³
Carbon Monoxide*	0.8		4ppm	5ppm (8 hr avg.)
Particulates	0.7	<50	30 mcg/m ³	60 mcg/m ³

*EIA basis for CO was via all unburned CO to the emergency vent.

The process performs to meet environmental requirements based on the assessment in Table 6.

2.5.3 Predictions for Year 2010

Silicon/Ferrosilicon Markets. Silicon and ferrosilicon consumption for the USA in the year 2010 is projected from 1994 data with a compounded growth rate of 3.5% per year for silicon and 1.2% for ferrosilicon. For silicon, the projection is from 259 kton (short)/yr or 0.518×10^9 lb/yr to 0.90×10^9 lb/yr for year 2010. For ferrosilicon, the projection is from 478 kton (short)/yr or 0.95×10^9 lb/yr to 1.16×10^9 lb/yr for year 2010.

For silicon market penetration, assuming that silicon furnace built in 1974 and before would be phased out by the year 2010 and environmental constraints would only allow the construction of closed-furnace technology furnaces, the total silicon production by the year 2010 in U.S. and Canada using closed furnace technology is estimated at 1.03×10^9 lbs/yr.

For ferrosilicon market penetration, assuming that 62% of the production is converted to closed furnace technology, a total of 0.72×10^9 lb/yr of contained silicon would be produced.

A total for silicon and for contained-silicon in ferrosilicon of 1.75×10^9 lb (year 2010) was used for subsequent energy savings, and other benefits calculated for the market penetration of closed furnace technology.

Energy Savings. Based on the above assumptions, and an energy savings of 49,000 Btu/lb of silicon (1) and contained-silicon (assumed similar on a per-pound-of-silicon basis), the energy savings predicted for year 2010 is 86×10^{12} Btu/yr. This assumes a total of 57 furnaces; 33 silicon furnaces (20 MW each) and 24 ferrosilicon furnaces yielding equivalent quantities of contained-silicon (greater than 20 MW each).

Emissions Reductions. Emissions reductions for year 2010 are based on the elimination of the discharge of the off-gas which would have resulted from the continued use of current open-furnace technology, and by the reduced emissions resulting from not having to generate as much electricity to produce the silicon and ferrosilicon with the closed-furnace technology. The off-gas emission reduction assumed that all carbon in the off-gas (CO and CH_4) was oxidized to CO_2 which is of interest because of its contribution to global warming. The total gaseous emissions reduction is expressed in pounds of carbon dioxide because it is the only global-warming significant gas in the off-gas.

For the year 2010, the open-furnace off-gas composition which is being eliminated is: 61 vol% CO ; 22 vol% H_2 ; 10 vol% CH_4 ; and 7 vol% other, with a total off-gas emission of 31.5 SCF/lb-silicon. It was assumed that all the carbon in the off-gas was oxidized to CO_2 when mixed with the excess cooling air. The total volume of CO was calculated, converted to weight using the perfect gas law, and then increased by molecular weight ratio to the weight of CO_2 . Similarly, the weight of CH_4 was calculated, and then increased by molecular weight ratio to the weight of CO_2 . For the 1.75×10^9 lb/yr (year 2010) of silicon and contained-silicon in ferrosilicon, this resulted in 3.8×10^9 lb- CO_2 /yr.

Similarly, the weight of CH_4 was calculated, increased by molecular weight ratio to the weight of CO_2 , and resulted in 0.6×10^9 lb- CO_2 /yr.

The reduction of electrical energy used in the closed-furnace for the bag-house and for the process energy (Table 19) totaled 4.01 kWh_(e)/kg-Si (6200 Btu_(e)/lb-Si). Multiplied by the $1.75 \times$

10^9 lb/yr (year 2010), the total electric savings is 10.9×10^{12} Btu_(e)/yr. Reference 3, indicates that the CO_x emissions from the generation of electricity are: 113, 161, and 208 lb of CO_x per 10^6 Btu_(e) for respective fuel sources natural gas, petroleum, and coal. This results in a range of CO_x emissions of 1.23 to 2.26×10^9 lb-CO_x/yr (2010). Biasing somewhat toward coal for electricity generation, a value of 2×10^9 lb-CO_x/yr (2010) was selected as representative.

Total emissions reductions were summed for the: off-gas burned for its fuel value and off-gas consumed as a feedstock for a higher valued product (e.g. methanol) rather than just being released to the atmosphere after oxidation with excess air as is done now with the current open-furnace technology.

<u>Emission Constituent</u>	<u>Emissions Reductions Year 2010</u>	
	<u>Burned</u> (10^9 lb/yr)	<u>To Feedstock</u> (10^9 lb/yr)
Off-gas		
CO ₂ from CO	0	3.8
CO ₂ from CH ₄	0	0.6
Non-Generated Elect	<u>2.0</u>	<u>2.0</u>
	2.0	6.4

Total carbon dioxide equivalent emission reduction for year 2010 is predicted to be 2 or 6.4×10^9 lb-CO₂/yr (1 or 3.2 million tons-CO₂/year) for burning the off-gas for heating value or using it for feedstock for another product.

In addition to the gaseous emissions that open-furnace smelting releases, initially gaseous SiO reacts and condenses to very fine particles of SiO₂ in the excess cooling air after it leaves the furnace. The EPA has been tightening fine particle emission limits, because of concerns of respiratory illnesses, and there is industry concern that particle containment costs may become excessive. By increasing the Si yield (ratio of product-output-Si to feedstock-input-Si) from 78% to 94%, the closed furnace technology will reduce the emission of fine silicon dioxide particles by 0.8×10^9 lb/yr (0.4 million tons/yr) by the year 2010.

2.5.4 Economic Analysis. The next logical advancement of this technology is commercialization of semi-closed or open dc furnace due to too-high a risk involved with commercializing closed furnace technology. It is expected that commercialization experience gained with the semi-closed or open dc furnace would allow us to proceed with commercialization of closed furnace technology with minimal risk.

The economics of converting an existing silicon or ferrosilicon ac furnace, at an operating plant to an open dc furnace was evaluated. The results measured in terms of capital afforded to give the Internal Rate of Return (IRR) and the Net Present Value (NPV) at 15% IRR are presented in Table 7.

The raw materials and electricity costs used for the economic evaluation are for a furnace located in Ohio Valley, representative of a typical ferroalloy site.

In order to take technology advantages offered by a dc furnace while maintaining low commercialization risks, commercialization of semi-closed or open dc furnaces is recommended.

TABLE 7. RESULTS OF ECONOMIC ANALYSIS

	Case I Worst	Case II Best	Case III Base
Power Input (MW)	18	24	21
Net Silicon Recovery	82	85	82
Conversion Capital (Million Dollars)	22	39.9	29.6
Raw Material Costs			
Quartz (\$/MT)	40	40	40
Coal #1 (\$/MT)	70	70	70
Charcoal (\$/MT)	300	300	300
Wood Dry (\$/MT)	30	30	30
Electrode (\$/MT)	1850	1850	1850
Electricity (Mils)	28	28	28
Fume (Mils)	100	100	100
Fines (Mils)	565	565	565
Silicon Price (Mils)	1540	1540	1540

Feed Mix as Fixed	Case I Worst	Case II Best	Case III Base
Carbon			
Coal #1	70	70	70
Charcoal	10	10	10
Wood	20	20	20
Carbon Theory	87.5	91.0	88.5
Employee Labor (#)	44	51	48
Labor wage (\$900 \$)	34	34	34
Employee Salary (#)	6	6	6
Salary wage (1000 \$)	45	45	45
% Capital Spending			
Year (0)	20	20	20
Year (1)	60	60	60
Year (2)	20	20	20
Cash Flow			
Silicon Price for 15% IRR	.62	.53	.58
IRR @ (.70/lb Si)	15	15	15
NPV at 15% IRR	0	0	0

The worst case (Case I) assumes 82% silicon recovery at 18 MW power input. The best case (Case II) assumes 85% silicon recovery at 24 MW input and for the base case (Case III), the silicon recovery of 82% at 21 MW power input.

To meet the 15% IRR internal rate of return at a silicon price of \$0.70/lb. the project can afford up to \$29.6 M in capital cost. This economic analysis suggests that a retrofit to dc technology is a low technical risk with acceptable rewards.

For the commercialization of a closed furnace, which will require additional development effort beyond the scope of this project, two economic options were evaluated. In case of a conversion of an existing silicon or ferrosilicon furnace, an internal rate of return of 18% was calculated based on silicon recovery of 90%, power input of 21 MW, silicon price of \$0.70/lb. For a green site project with similar assumptions, the internal rate of return was calculated to be 15%. The results for the above cases are summarized in Table 8.

TABLE 8. INTERNAL RATE OF RETURN FOR COMMERCIALIZATION OPTIONS

COMMERCIALIZATION OPTIONS	INTERNAL RATE OF RETURN
Open furnace dc - conversion of an existing furnace	15
Closed furnace dc - conversion of an existing furnace	18
Closed furnace dc - green site	15

In spite of the highest IRR of 18% offered by the closed furnace dc-conversion option, the high risks involved in commercialization of this technology due to mix-movement issues, favours a semi-closed or open dc conversion project at a lower IRR. It is expected that the commercialization experience gained with the mix-movement issues in a semi-closed or open dc furnace would allow us to proceed with commercialization of closed furnace technology.

PHASE III - CONCLUSIONS AND RECOMMENDATIONS

The Phase III of the "Collection and Conversion of Silicon Furnace Waste Gas into Higher Value Products" program consisted of design, construction, start-up, and operation of the 6 MW dc closed furnace pilot plant. Twelve smelting campaigns were conducted to demonstrate the closed furnace silicon smelting technology.

A 6 MW closed dc furnace pilot plant and off-gas recovery system was built to demonstrate silicon smelting technology and obtain data for evaluating the commercial viability of this project. This furnace is considered to be the world's most modern, state of the art, automated control system suitable for commercial applications and could be used for closed or open dc furnaces for smelting silicon or ferrosilicon.

The scale up of dc closed furnace technology to a commercial size furnace is achievable, however, the issues of mix management, energy distribution, silicon carbide build-up, and on-line time present unacceptable risk factors in the first commercial furnace design until after further research and development.

An economic analysis evaluated converting an existing silicon or ferrosilicon furnace to a semi-closed or an open dc furnace. A semi-closed dc furnace eliminates any mix-movement risks and at the same time allows one to realize the benefits of a dc furnace. The base case for a dc semi-closed furnace with an assumed silicon recovery of 82% at a power input of 21 MW and an IRR of 15% at a silicon price of \$0.70/lb would allow the project capital cost to be around \$30 million. The technology risk for a retrofit project is significantly lower compared to commercialization of dc closed furnace technology.

For the commercialization of closed furnace technology, which will require additional development effort beyond the scope of this project, two economic options were evaluated. In case of conversion of an existing silicon furnace an internal rate of return of 18% was calculated. For a green site project the internal rate of return was calculated to be 15%.

In spite of the highest IRR of 18% offered by the closed furnace de-conversion option, the high risks involved in commercialization of this technology due to mix-movement issues, favours a semi-closed or open dc furnace conversion project at lower IRR. It is expected that the commercialization experience gained with the mix-movement issues would allow us to proceed with the commercialization of the closed furnace technology.

Overall, the results obtained in the Phase III study support continuation of the program to Phase IV: Demonstration of semi-closed or open dc retrofit technology on a commercial silicon or ferrosilicon furnace.

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APPENDIX A

AWARD OF EXCELLENCE

Meadow Materials silicon pilot plant

UMA Engineering Ltd. — Winnipeg

Silicon tapping from the furnace (above), and the final silicon product (r).

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Consulting Engineer*, a Southam Inc.
publication.

Despite growing world demand for silicon, the silicon and ferrosilicon industries in North America have been declining for more than a decade, primarily as a result of the availability of less expensive imported product. North American manufacturing facilities operate sporadically and are aging, and producers are further disadvantaged by the high energy and feedstock costs associated with current production methods.

This situation could soon change, because an innovative new production technology has been developed and implemented for the first time in the world in a pilot plant, through a successful collaboration between Meadow Materials, a division of Dow Corning Silicon Energy Systems, and UMA Engineering Ltd. of Winnipeg.

To become viable, the North American silicon and ferrosilicon industries desperately need new, low-cost production technologies that are less energy intensive and less polluting than current methods involving open-hearth furnace, alternating current technology.

The open-hearth furnace is very energy inefficient, produces significant quantities of harmful emissions and exposes operating personnel to the hazards associated with open flames. The process also emits very fine particles of silicon dioxide (fume) and off-gas (mainly carbon monoxide), which contribute to air pollution. In 1988, the North American silicon and ferrosilicon industries emitted nearly 250,000 tonnes of fume and 1.8 million tonnes of carbon dioxide into the atmosphere.

In 1987, the U.S. Department of Energy's office of industrial technologies teamed up with Dow Corning Corporation, a major manufacturer of silicon-based products, to develop and test a closed-furnace direct-current technology. Dow had previously established the feasibility of this technology in bench-scale laboratory investigations. Along with the Energy Department, Dow studied the reactions taking place in the proposed closed silicon furnace, and then built a 0.1 MW closed furnace

for laboratory evaluation of feed stocks and operating processes.

The Canadian government and the Manitoba Energy Authority, encouraged by the U.S. government's participation, joined the team in 1990 and made a significant financial commitment to the development of a large-scale testing program.

Engineers from UMA and Meadow Materials designed a 6 MW closed-furnace pilot plant to be used for further tests. Begun in November 1989, the development, implementation and construction of the entire facility in East Selkirk, Man. was accomplished over an extremely short period of time: the plant went into operation in June of 1992, and the first silicon 'tapping' was carried out the following month.

The project presented engineering teams with a number of challenges, including optimizing the proposed plant on a small footprint site; developing the furnace technology and a feedstock injection system; designing and developing high-temperature seal technology and a new automated molten-silicon handling system; implementing a filtration and cooling system for the waste-gas system (involving extremely high temperatures), an overall automation and control system and an operating and evaluation program to examine the facility and the technology.

The closed-furnace process, which requires only about 60 per cent of the energy used by conventional open-furnace technology, may lead to savings of almost 116 MJ per kg (50,000 BTU/lb) of silicon produced. Most of these savings will come from recovery and use of furnace off-gas, which contains more than half of the energy originally required by the furnace. Burning the off-gas for its fuel value will generate some savings, and recovery and re-use of silicon particles in the fume will lead to 20-per-cent higher yield from the silicon input. Significant savings in electricity use will result from reduced need for gas clean-up and the lower energy requirements of the direct current process.

Industry experts estimate that by

2010 all open-hearth silicon furnaces will have been retired, and 100 per cent of North American silicon production will come from closed-furnace technology. Also, half of today's ferrosilicon furnaces will have been retired by 2010, and all new construction will be of closed furnaces.

In this 2010 scenario, total energy savings in silicon and ferrosilicon production will be 91 petajoules (86 trillion BTU), assuming continued growth in demand for the two materials, and carbon dioxide emissions will be reduced by one to three million tons annually, depending on whether the off-gas is burned as fuel or converted to methanol or some other higher-value product. Silicon dioxide emissions will be reduced by 0.4 million metric tons.

Production cost savings associated with closed-furnace technology are also very attractive. Dow Corning estimates that the direct-current closed furnace will produce silicon for about 30-per-cent less than today's open-hearth furnaces. In the longer term, these costs might be reduced even more. In addition, the capital cost of the new furnace should be significantly less than the conventional furnace. Successful implementation of closed-furnace technology, with its advantages over open-furnace production of silicon and ferrosilicon, may pave the way to revitalizing a strategic North American industry.

APPENDIX B

Industrial Innovations

FOR TOMORROW

**Advances in Industrial
Energy-Efficiency Technologies**

Innovative Closed-Furnace Technology Generates New Hope for Ailing U.S. Silicon Industry

Current processes waste energy, produce harmful emissions, and diminish U.S. industry's ability to compete with foreign producers.

Silicon and ferrosilicon industries in the United States have been sluggish for more than a decade because of the availability of low-cost imports. The current sales prices of silicon and ferrosilicon fluctuate around their production costs; consequently, manufacturing facilities for these materials operate sporadically. Although U.S. demand for both materials is on the rise, the high energy and feedstock costs associated with current production methods will continue to place domestic producers at a disadvantage.

Both silicon and ferrosilicon are produced using open-hearth-furnace, alternating-current technology. The open-hearth furnace is very energy inefficient, produces significant quantities of harmful emissions, and forces operating personnel to be exposed to open flames. In addition, the process emits very fine particles of silicon dioxide ("fume") and off-gas (mainly carbon monoxide), which contribute to poor urban air quality. In 1988, the U.S. silicon and ferrosilicon industries emitted nearly a quarter of a million metric tons of fume and 1.8 million metric tons of carbon dioxide (which results from oxidation in the atmosphere of carbon monoxide in the off-gas). To become viable, the U.S. silicon and ferrosilicon industries desperately need new, low-cost production technologies that are less energy-intensive and less polluting than current technologies.

Closed-furnace, direct-current technology will produce silicon for 30% less than open-hearth furnaces.

New closed-furnace technology offers a cost-effective, energy-efficient solution.

In 1987, the U.S. Department of Energy's (DOE's) Office of Industrial Technologies teamed with the Dow Corning Corporation to develop and test closed-furnace, direct-current technologies for producing silicon and ferrosilicon. Dow Corning, a major manufacturer of silicon-based products, had previously established the feasibility of this technology. Together, Dow Corning and DOE studied the reactions taking place

in a silicon furnace. They then built a 0.1-megawatt (MW) closed furnace for evaluating feedstocks and operating processes.

The tests showed that the off-gas emitted from the process could be successfully converted to methanol, a useful fuel. In addition, they demonstrated that ferrosilicon can be made from low-cost feedstocks such as waste taconite tailings and waste coke fines. Silicon can also be made from lower cost waste feedstocks.

New Technology for Silicon Production

In 1990, the Canadian government and the Manitoba Energy Authority, encouraged by DOE's participation, joined the team and have made significant financial commitments to large-scale testing. Engineers designed a pilot-scale (6-MW) closed furnace to be used for further demonstration tests. The pilot plant construction was completed in Manitoba, Canada, in 1992, and initial trials are now under way.

Application will save energy, reduce emissions, and promote competitiveness.

The new closed-furnace technology will require only about 60% of the energy used by conventional open-hearth technology. This will lead to a savings of almost 116 MJ/kg (50,000 Btu/lb) of silicon produced. The majority of these savings will come from the recovery and use of the furnace off-gas, which contains more than half of the energy originally input to the furnace. Burning the off-gas for its fuel value will generate some of these savings. In addition, recovery and reuse of the silicon particles in the fume will lead to 20% more yield from the silicon input. Finally, significant savings in electricity use will result from reduced requirements for gas cleanup and the lower energy requirements of the direct-current process.

Industry experts estimate that, by 2010, all open-hearth silicon furnaces in the United States will have been retired and 100% of our silicon production will come from closed-furnace technology. Also by 2010, half of the current ferrosilicon furnaces will have been retired, with closed furnaces representing all new construction. Under this scenario, total energy savings in silicon and ferrosilicon production in 2010 will be 91 petajoules (86 trillion Btu), assuming continued growth in demand for the two materials. Correspondingly, annual emissions of carbon dioxide will be reduced by 1 million to 3 million metric tons depending on whether the off-gas is burned as a fuel or converted to methanol or some other higher value product. Silicon dioxide emissions will be reduced by 0.4 million metric tons.

The production cost savings associated with closed-furnace technology are also very attractive. Dow Corning estimates that the direct-current closed furnace will produce silicon for about 30% less than today's open-hearth furnaces. In the longer term, these costs might be reduced even more. In addition, the capital cost of the new furnace should be significantly less than for the conventional furnace.

Successful operation of the pilot facility should promote commercial use and licensing opportunities.

Commissioning of the Manitoba pilot facility was completed in 1992. Operation optimization tests will follow and will run through 1993.

If tests at the pilot facility are successful, commercialization of full-scale (20-MW) facilities for silicon and ferrosilicon production will not be far behind. Dow Corning, a major user of silicon, has already discussed technology licensing possibilities with its suppliers, who have responded enthusiastically.

A 6-MW pilot plant for closed-furnace production of silicon began operating in 1992 in Manitoba, Canada.

For More Information

Industrial Waste Reduction
Program
CE-222
Office of Industrial Technologies
U.S. Department of Energy
1000 Independence Ave., SW
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APPENDIX C

TASK DESCRIPTION

Task 1- 1 MW Transferred Arc Plasma Pilot Plant: This work was completed and a final report titled "Taconite Smelting to Produce Ferrosilicon" has been published. (2)

Task 2 - 6 MW DC Submerged Arc Plasma Pilot Plant: The objective of Task 2 is the design, construction, and operation of a 6 MW pilot plant for DC submerged arc plasma smelting of silicon alloys. Task 2.1 and the physical construction of the pilot plant at the participant's site in Manitoba, Canada are not funded as part of this contract, but are included for reference in this Statement of Work.

2.1 Engineering Preparation

2.1.1 Detailed Cost Estimate. A detailed engineering cost estimate, accurate, to about 10%, shall be prepared for the capital cost of designing, constructing, and commissioning the 6 MW pilot plant. The operating expense shall also be estimated to about 10% accuracy.

2.1.2 DC Submerged Arc Testing. Two tests, of approximately five days duration each, shall be made at the INCO Pilot Plant in Port Colborne, Ontario using Manitoba sand and other selected raw materials to produce silicon. These tests shall provide important design information to support Task 2.1.1.

2.1.3 Data Analysis

2.1.3.1 Data Acquisition and Analysis. All data from the DC submerged arc plasma tests shall be collected and analyzed by the operating personnel and engineering team as it is generated. The data shall be used for real time control and for off-line evaluation of the test results. Long term trend estimates and process capability studies shall be made using this data.

2.1.3.2 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 Dow Corning Analytical Services 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. The silicon alloys produced shall be tested for performance. The silicon alloys produced shall be tested for performance in the consuming process and results of these tests used for quality optimization.

2.1.4 Site Preparation. All issues related to the use of the selected site shall be resolved including obtaining of an environmental license from the Manitoba Ministry of Environment and the Workplace Safety and Health Department. A go/no go construction decision will be made before proceeding with physical site preparation, equipment orders, or construction. Site preparation work such as fencing and grading shall be completed to prepare for construction. Long delivery equipment shall be ordered.

2.2 Detailed Design and Construction. The objective of this task is to perform the engineering design (concept development through detailed drawings), to procure equipment, to generate the plant layout, to perform facilities engineering, and to construct a 6 MW DC Closed Submerged Arc Plasma Pilot Plant.

2.2.1 Engineering Design

2.2.1.1 Reactor Design. The 6 MW pilot plant reactor shall be designed. The results from the INCO and Closed Furnace Mini-Plant smelting tests shall be used to provide a basis for the development of the design. Data from these and other tests shall be used to establish the optimum crucible size, thermodynamic profiles, and kinetics for the 6 MW reactor.

2.2.1.2 Auxiliary Systems Design. The necessary auxiliary systems for the reactor concept design, such as electrical, raw material, hydraulic, environmental control, safety, water cooling, and process gas treatment, shall be sized and process flows determined.

2.2.1.3 Plant Layout. A fully detailed plant layout shall be developed. It shall include all mechanical, electrical, civil and architectural information, to insure proper installation of the reactor at the Manitoba plant.

2.2.1.4 Equipment Specifications. Engineering specifications shall be prepared for all equipment necessary for pilot plant construction. Piping and instrument diagrams shall be drawn based on these specifications.

2.2.1.5 Subcontracting. After approval of the capital authorization request by Dow Corning management, request for bids shall be sent out for supply of all equipment and outside contracting work. Pre-award conferences shall be held with the selected bidders to set delivery and contract terms and then purchase orders shall be issued to successful bidders.

2.2.1.6 Schedule. 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.

2.2.2 Construction. All aspects of pilot plant 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.

2.3 Start-Up and Commissioning. The initial operation of the 6 MW pilot plant, from training of operators through dry run and full commissioning of the equipment, shall be performed in accordance with established plans and procedures.

2.3.1 Operator Training. 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 and equipment functions. Emergency response procedures and potential safety hazards shall be thoroughly reviewed. This training is expected to take about one hundred hours to accomplish

and shall be conducted by the engineering team who installed the equipment and experts from the vendor companies.

2.3.2 Dry Run Tests. Dry run test 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.

2.3.3 Start-Up Operation

2.3.3.1 Test Plan. A test plan, with a test schedule, shall be prepared and received by DOE for review at least two weeks prior to the start of the commissioning tests. Revisions to the plan may be made as the tests progress, but the revisions shall be coordinated with DOE with as much lead-time as practical. The plan shall include test objectives and operating criteria for judging the success of the start-up and commissioning tests.

2.3.3.2 Start-up Test. An estimated 16-hour initial start-up test shall be made after all systems have completed a successful dry run test. This test shall provide information on raw material flow, reactor temperature profiles, and environmental systems capabilities. All safety and data collection systems shall be checked out. Problems discovered during this test shall be corrected and, if necessary, this test shall be repeated until problems are resolved.

2.3.3.3 Commissioning Tests. An estimated four commissioning tests, about 60 hours duration each, shall be conducted to completely verify all system operating capabilities. The predetermined operating criteria shall be used to judge when the commissioning is successfully completed. Repeat tests may be required. As appropriate, equipment supplier representatives shall be present to observe the results and resolve problems.

2.4 Optimization of Operation. Following successful commissioning of the pilot plant, longer-term experimental tests shall be made with the objective of providing the necessary engineering inputs for optimization of the process.

2.4.1 Test Plan. A test plan, with a test schedule, shall be prepared and received by DOE for review at least two weeks prior to the start of the 6 MW optimization tests. Revisions to the plan may be made as the tests progress, but the revisions shall be coordinated with DOE as much lead-time as practical. The plan shall include test objectives and operating criteria for judging the success of the operation tests.

2.4.2 Operation Tests. Continuous tests of up to six months duration shall be made to allow optimization of all process parameters and to provide the performance data and operating information necessary to evaluate technical, economic, and environmental characteristics of the process.

2.5 Data Analysis

2.5.1 Data Acquisition and Analysis. All data from the dry run, commissioning, and operation tests shall be collected and analyzed by the operating personnel and engineering team as they are generated. The data shall be used for real time control and for off-line evaluation of the test results. Long term trend estimates and process capability studies shall be made using this data.

2.5.2 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 Dow Corning Analytical Services 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. This silicon alloys produced shall be tested for performance in the consuming process and results of these tests used for quality optimization.

2.6 Update of Projections. The results of pilot plant testing and operation and of system and process data analysis shall be used to confirm or modify estimates of economic viability and concept applicability, and to produce new estimates of the extent to which the process will be

implemented or substituted in the U.S. silicon manufacturing. Evaluation of process capabilities and long-term industry trends shall be updated. From this revised market evaluation, an updated prediction of national energy savings potential shall be provided. An updated evaluation of environmental effects associated with concept utilization shall also be made. Differences from previously predicted economic, energy, and environmental benefits shall be noted.

Task 3 - 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.

3.1 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. Management controls shall include technical assessment, budget 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, commissioning tests, and significant optimization and sustained-operation tests.

3.2 Technology Transfer. The contractor shall take advantage of opportunities for technology transfer, including presentation of papers at technical meetings and publication 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 presentation material.

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

3.3.1 Management Plan. A detailed Management Plan with a Milestone Schedule, Cost Plan, and Contract Management Summary Report shall be submitted to the DOE Project Manager for DOE concurrence within 15-days of contract modification for funding and adding the Statement of Work for Phase III.

3.3.2 Periodic Reports. Project status, cost, and schedule shall be prepared and provided as detailed in the Reporting Requirements Checklist and the Report Distribution List.

3.3.3 Technical Progress Reports. An outline for each Technical Progress Report shall be submitted and approved by DOE prior to commencing work on the report. A draft report shall be submitted to DOE within thirty days after the end of each calendar year.

To the extent consistent with progress in the report period, each technical progress report shall contain a full 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.

3.3.4 Phase III - Final Report. A Final Report for Phase III of the project shall be prepared summarizing all work accomplished during Task 2. Because this document shall also serve as the final report for the entire contract, it must put the project background, performance, and results and accomplishments into perspective by highlighting planned commercialization of the closed furnace technology with lighting planned commercialization of the closed furnace technology fume and off-gas recovery and utilization. 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 work. Comments resulting from the DOE review shall be resolved and the report revised accordingly prior to final submission for publication.