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QUARTERLY TECHNICAL PROGRESS REPORT FOR THE DEVELOPMENT OF "A COAL-FIRED COMBUSTION SYSTEM FOR INDUSTRIAL PROCESS HEATING APPLICATIONS"

CONTRACT DE-AC22-91PC91161

JANUARY 1992 - MARCH 1992

PREPARED FOR

U.S. DEPARTMENT OF ENERGY
PITTSBURGH ENERGY TECHNOLOGY CENTER

PREPARED BY

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PETC has implemented a number of advanced combustion research projects that will lead to the establishment of a broad, commercially acceptable engineering data base for the advancement of coal as the fuel of choice for boilers, furnaces, and process heaters. Vortec Corporation's Coal-Fired Combustion System for Industrial Process Heating Applications has been selected for Phase III development under contract DE-AC22-91PC91161 for such development.

This advanced combustion system research program is for the development of innovative coal-fired process heaters which can be used for high temperature melting, smelting, recycling, and refining processes. The process heater concepts to be developed are based on advanced glass melting and ore smelting furnaces developed and patented by Vortec Corporation. The process heater systems to be developed have multiple use applications; however, the Phase III research effort is being focused on the development of a process heater system to be used for producing glass frits and wool fiber from boiler and incinerator ashes.

The primary objective of the Phase III project is to develop and integrate all the system components, from fuel through total system controls, and then test the complete system in order to evaluate its potential marketability.

During the current reporting period, the primary technical effort has been directed towards the design of modifications to the existing test system configuration. Also bid evaluations for the purchase of a wet ESP and the recuperator were completed and vendors were selected. Testing of available refractories was conducted to evaluate their resistance to corrosion when melting flyash.

The economic evaluation of commercial scale CMS processes has begun. In order to accurately estimate the cost of the primary process vessels, preliminary designs for 25, 50, and 100 ton/day systems have been started under Task 1. This data will serve as input data for life cycle cost analysis performed as part of techno-economic evaluations. The economic evaluations of commercial CMS systems will be an integral part of the commercialization plan.

The program is progressing smoothly except for the preliminary testing task which has been delayed pending final evaluation of the environmental assessment required under the National Environmental Policy Act. It is anticipated that the assessment will be completed during the next reporting period.

SECTION 2 - INTRODUCTION/BACKGROUND

2.1 INTRODUCTION

Effective August 3, 1991, the Pittsburgh Energy Technology Center (PETC) of the U.S. Department of Energy awarded Vortec Corporation contract No. DE-AC22-91PC91161 for the development of "A Coal-Fired Combustion System for Industrial Process Heating Applications. The program established by this contract is described below.

2.2 BACKGROUND

PETC has implemented a number of advanced combustion research projects that will lead to the establishment of a broad, commercially acceptable engineering data base for the advancement of coal as the fuel of choice for boilers, furnaces, and process heaters. This includes new installations and those existing installations that were originally designed for oil or gas firing. The data generated by these projects must be sufficient for private-sector decisions on the feasibility of using coal as the fuel of choice. This work should also provide incentives for the private sector to continue and expand the development, demonstration, and application of these combustion systems.

Vortec Corporation's Coal-Fired Combustion System for Industrial Process Heating Applications has been selected for Phase III development under contract DE-AC22-91PC91161 for such development.

This advanced combustion system research program is for the development of innovative coal-fired process heaters which can be used for high temperature melting, smelting, recycling, and refining processes. The process heater concepts to be developed are based on advanced glass melting and ore smelting furnaces developed and patented by Vortec Corporation. The process heater systems to be developed have multiple use applications; however, the Phase III research effort is being focused on the development of a process heater system to be used for producing glass frits and mineral wool fiber from boiler and incinerator ashes.

This coal-fired process heater system is unique in several important aspects. The important advantages of the technology are as follows:

1. Significantly lower capital cost as compared to conventional gas/oil-fired and electric furnaces.

2. Substantially higher thermal efficiency as compared to conventional gas/oil-fired melting furnaces.

3. Satisfaction of projected future emission requirements for NOx, SOx and particulates.

4. The process heater system has a degree of operational flexibility unmatched by conventional fossil fuel fired mineral melting systems. Several of the unique operational capabilities of this innovative technology include: multi-fuel use capability (including coal, coal slurry, petro-coke, oil and gas), rapid product changeover, and rapid startup/shutdown.

The Vortec CMS represents one of the most significant advancements in vitrification technology in the past 100 years, and significant financial resources have been expended on the development of this suspension melting process for a variety of high temperature process heating applications. The primary components of the CMS are a counter-rotating suspension preheater and a cyclone melter. An artist rendering of the basic CMS concept is shown in Figure 2-1.

Staged combustion and rapid temperature quenching of the combustion products by the inert waste glass particles and staged combustion are the primary means of limiting NO_X emissions. Experimental data obtained during the course of feasibility experiments with the pilot-scale CMS indicate NO_X emissions are lower than the California emission standards (4.5 lbs per ton of glass produced) for glass melting furnaces. In this regard, it should be noted that the California glass melting emission standards for NO_X are currently the most stringent in the United States.

The uncontrolled particulate emission levels of the CMS are about the same as conventional gas-fired glass melting furnaces. Therefore, the use of commercially available particulate control devices will be incorporated into the design as dictated by local flue gas emission regulations.

A block diagram of a Vortec CMS based commercial flyash to mineral wool system is shown in Figure 2-2. The basic elements of a commercial incineration/melting system will include:

1. an advanced CMS consisting of: (a) a precombustor assembly, (b) an in-flight suspension oxidizer/preheater and (c) a cyclone melting chamber;
2. an upstream coal and batch storage and feeding subsystem consisting of storage tanks, blender, and a pneumatic transport assembly;
3. a glass separation and reservoir assembly;
4. a mineral wool fiberizing subsystem;
5. a heat recovery subsystem;
6. a flue gas conditioning/distribution assembly; and
7 a particulate removal/stack assembly.

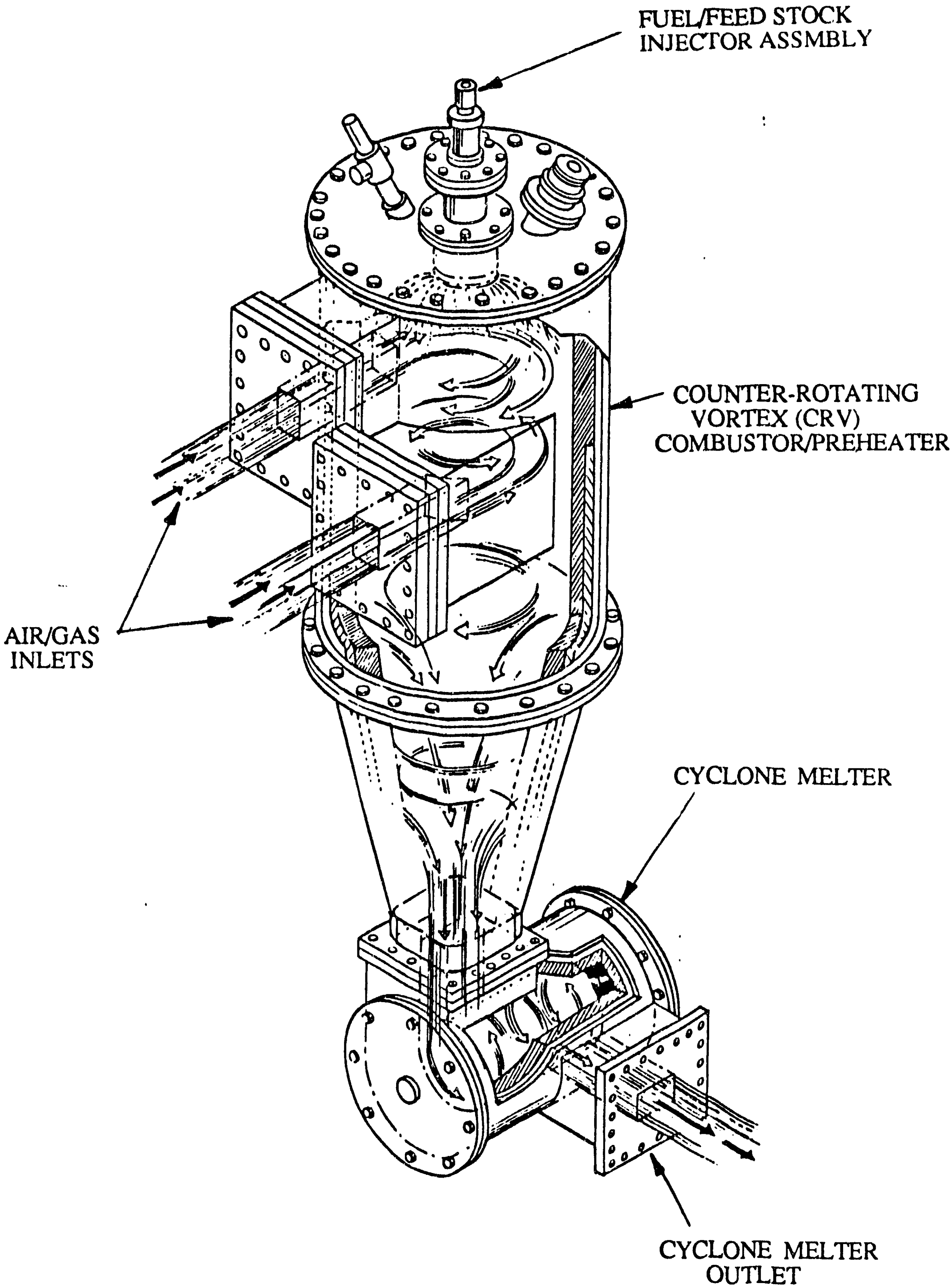

Figure 2-1 Artist Rendering of Vortec CMS

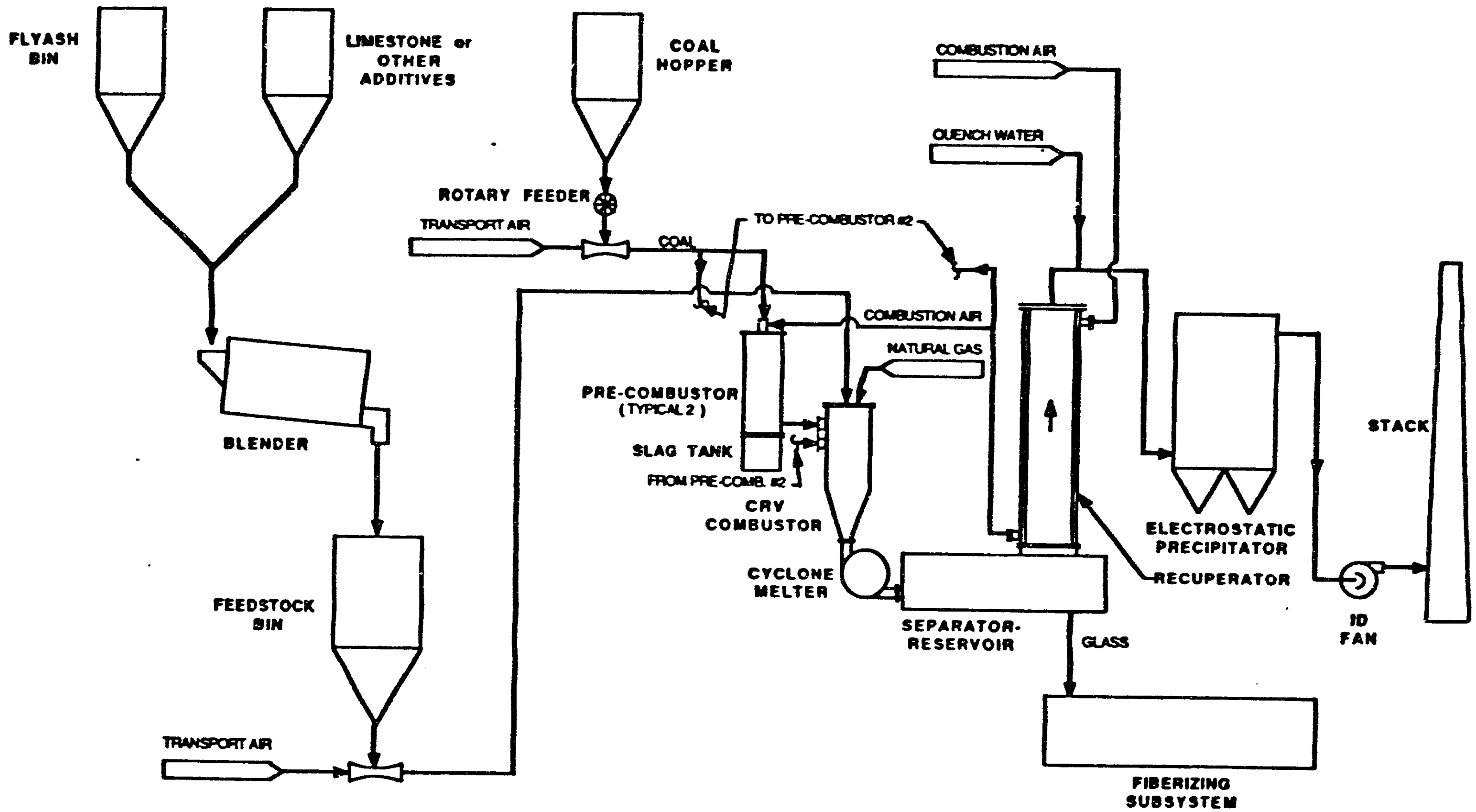

Figure 2-2 Block Diagram of a Vortec Mineral Wool Production System

2.3 OBJECTIVES

This contract is the third phase of a three phase R&D program which was initiated during March 1987. The objective of the program is to develop an advanced industrial process heater capable of using pulverized coal or coal derived fuels as the primary fuel.

The objective of Phase I of the program was to verify the technical feasibility and economic benefits of Vortec's Advanced Combustion and Melting System (CMS) technology using coal as the fuel of choice. Phase I consisted of two segments, Phase I-A and Phase I-B. During Phase I-A, detailed designs of a proof-of-concept scale coal-fired CMS and the supporting test facilities were completed. It also included tradeoff studies and techno-economic studies to cost optimize the advanced process heater and to evaluate the technical and economic feasibility of the process heater system. In Phase I-B of the program, critical components were tested to validate the feasibility of the Vortec process heater for glass melting with coal as the primary fuel. This phase involved the fabrication, installation and operation of a 3 to 5 x 10^6 Btu/hr coal-fired CMS test loop at Vortec's high temperature process test facility in Harmarville, PA. Glass melting with 100% coal firing was effectively demonstrated with minimal contamination effects. Glass cullet was the primary process feedstock during the Phase I test program. A conceptual design of a commercial scale CMS glass melter was also developed and techno-economic studies were continued.

The primary objective of the Phase II effort was to improve the performance of the primary components and demonstrate the effective operation of a subscale process heater system integrated with a glass separator/reservoir. The impact of coal ash on glass production quality was assessed and the melting of more complex glasses was evaluated during this phase. Additionally, due to Vortec's commitment to commercialize the process heater technology it is developing with DOE's support, we have analyzed several different markets, particularly in the areas of waste material recycling, in which the Vortec process heater system will offer unique technical and cost advantages. Some preliminary testing was performed using Vortec's pilot scale test system to demonstrate the feasibility of application of the Vortec process heater to these markets with encouraging results.

The primary objective of the Phase III project is to develop and integrate all the system components, from fuel through total system controls, and then test the complete system in order to evaluate its potential marketability. Vortec's primary target markets for Phase III are ash vitrification for mineral fiber manufacturing and glass frit production for road and building construction applications. Vortec's process heater system is unique in its ability to use boiler and incinerator flyashes as feedstocks for various glass manufacturing processes.

It is further stated, by our industrial partners, that their minimum objective is to run the integrated prototype test facility for 100 hours and to establish that the glass produced is adequate for mineral wool production. Our industrial partner has also made judgements based on their internal technical and marketing studies that the next step beyond the demonstration test should be accomplished at a site and in a specific regional market that meets their corporate needs. These needs are still in the definition stage and will be significantly influenced by the results of the Phase III tests.

Additionally, in keeping with Vortec's above mentioned commitment to commercialization, we propose to also demonstrate the vitrification of some alternative feedstocks in Phase III as a fall-back position. Vortec believes that the coal-fired process heater has other applications beyond the manufacture of mineral fibers from utility flyash. As a result, Vortec believes that the entire test program should have opportunities built into it to demonstrate the systems capability to vitrify alternative feedstocks. In this regard, feedstocks other than flyash are included in the Phase III test plan. It is understood that these additional feedstocks will be introduced and tested only as time and funding permit. The principal focus of the Phase III test program remains to satisfy our industrial partner's requirements for long duration mineral wool glass production.

SECTION 3 - PROJECT DESCRIPTION

3.1 Program Description

To accomplish objectives outlined in Section 2.3, Vortec will supply all the necessary personnel, facilities, materials, and services to execute the tasks in the contract's Statement of Work.

The program is divided into six (6) technical tasks and a program management task distributed over 36 months as shown in Figure 3-1. The work breakdown structure for the program is summarized below.

Task 1 - Design, Fabricate, and Integrate Components

Subtask 1.1 - Component Design

Subtask 1.2 - Component Fabrication

Subtask 1.3 - Component Integration

Task 2 - Perform Preliminary System Tests

Subtask 2.1 - Test Plan

Subtask 2.2 - System Tests

Task 3 - Perform Proof-of-Concept System Tests

Task 4 - Evaluate Economics/Prepare Commercialization Plan

Subtask 4.1 - Economic Evaluation

Subtask 4.2 - Commercialization Plan

Task 5 - Conduct Site Demonstration

Subtask 5.1 - Demonstration Plan

Subtask 5.2 - Site Demonstration

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U.S. DEPARTMENT OF ENERGY
MILESTONE SCHEDULE ☐ PLAN ☒ STATUS REPORT

FORM APPROVED
OMB NO 1901-1400

1. TITLE A Coal-Fired Combustion System For Industrial Heating Application	2. REPORTING PERIOD 9/3/91-12/31/91	3. IDENTIFICATION NUMBER DE-AC22-91PC91161
4. PARTICIPANT NAME AND ADDRESS VORTEC CORPORATION, 3770 RIDGE PIKE, COLLEGEVILLE, PA 19426		5. START DATE 9/3/91
		6. COMPLETION DATE 9/3/94

7. ELEMENT CODE	8. REPORTING ELEMENT	9. DURATION FY 92: O	N	D	J	F	M	A	M	J	J	A	S	FY 91: Q1	Q2	Q3	Q4	FY 92: Q1	Q2	Q3	Q4	FY 93	FY 94	FY 95	FY 96	10. PERCENT COMPLETE plan	actual
1.0	Design, Fab, & Integ. Compon.																										
1.1	Component Design																										
1.2	Compoment Fabrication																										
1.3	Component Integration																										
2.0	Prelim. System Tests																										
2.1	Test Plan																										
2.2	System Tests																										
3.0	Proof-of-Concept T[illegible]																										
4.0	Economic/ Comm. Plan																										
4.1	Economic Evaluation																										
4.2	Commercialization Plan																										
5.0	Conduct Site Demonstration																										
5.1	Demonstration Plan																										
5.2	Site Demonstration																										
6.0	Decommission Facility																										
7.0	Program Manag. & Reporting																										

11. SIGNATURE OF PARTICIPANT'S PROJECT MANAGER AND DATE

Task 6 - Decommission Test Facility

Task 7 - Program Management and Reporting

3.2 Background Patents and Proprietary Data

The basic elements of the proposed coal-fired Vortec Process heater are embodied in U. S. Patent 4,544,394 dated Oct. 1, 1985 and U.S. Patent 4,553,997 dated Nov. 19, 1985. Patent No. 4,957,527, dated September 18, 1990 was filed in accordance with OMB Circ. A-127 Trans. Memo No. 1, patent rights small business firms or non-profit organizations (April 1984). Vortec Corporation has elected to retain title licensing and royalty rights to this patent as per provisions under Contract No. DE-AC22-87PC79651, dated March 11, 1987. Vortec Corporation is in the process of filing additional patents for its process heaters, and will use proprietary information in the execution of this program. Procedures for protecting this proprietary information have been implemented with our subcontractors and consultants via non-disclosure/patent agreements.

SECTION 4 - PROJECT STATUS

During the past quarter (the second quarter of the contract performance period), effort has been concentrated on completing the bid evaluation for the purchase of a wet ESP and radiation recuperator, developing preliminary designs for commercial systems, evaluating available refractory compositions, evaluating refractory installation designs, conducting a fluid dynamic analysis of flue gas sampling probe configurations, and beginning the Commercialization Plan. A task by task summary of the activities performed during this reporting period is presented below.

4.1 Task 1 - Design, Fabricate, and Integrate Components

4.1.1 Task 1.1 - Component Design

During this quarter, preliminary designs for commercial systems were developed, and commercial refractory installation designs were completed and reviewed by refractory installers. In addition to this design work, a bid evaluation and vendor selection for the purchase of a wet ESP and recuperator was completed, testing was conducted on various refractory compositions, and computational fluid dynamic (CFD) modeling of the flue gas sampling probe was completed. The following is a summary of the work performed in each of these areas.

4.1.1.1 Commercial System Design

Designs of the primary process vessels for a commercial scale system were initiated. Initially systems with capacities of 25 to 100 ton/day will be examined. The designs will provide needed information for developing cost estimates for the commercial systems. The commercial cost estimates will be input to the commercialization plan being developed under Task 4.

4.1.1.2 Refractory Installation Design

During December, a refractory design review was conducted with a refractory vendor and a refractory installer. As a result of this review, several changes were made to the design of the refractory shapes. These changes were made to meet the manufacturer's requirements for weight, size, shape, and the installers requirements for lifting and installing the shapes.

The revised drawings were sent to the refractory vendor and price quotations for refractory for a 25 ton/day commercial system were obtained.

4.1.1.3 APC Subsystem

The existing test facility is currently being modified with the addition of an improved air pollution control (APC) system to improve the collection efficiency for very fine particulates, i.e. submicron particulate. It is also important from a commercialization standpoint to demonstrate the CMS integrated with a state-of-the-art APC system.

Several classes of devices were evaluated for this application including:

- Wet Scrubbers,
- Fabric Filters,
- Granular Beds Filters,
- Dry Electrostatic Precipitators, and
- Wet Electrostatic Precipitators.

A brief description of each of these technologies and their advantages and disadvantages is provided below.

Wet Scrubbers

The type of wet scrubber most suitable for this application can be classified as a gas-atomized high energy scrubber. These are relatively simple devices which rely on the energy in the flue gas stream to atomize a liquid (usually water) and create liquid droplets which collect the solid particulates by inertial deposition. Inertial or impingement separation of the liquid phase follows. The simplicity lends itself to low cost, relatively compact units. This type also has the advantage that it can collect either dry, wet, or sticky particulate.

The existing test loop has a Fisher Klosterman wet venturi scrubber; however, this unit, as well as other wet scrubbers of this type, has several major disadvantages. First, a high pressure drop across the scrubber is necessary to achieve the desired efficiency on the submicron particulate encountered in our testing. We have been advised that a pressure drop of 60 in. wg. would be necessary for a 99% collection efficiency on particulate less than 1 micron in diameter. This high pressure drop requires a fan with a high HP motor which results in high installation and operating costs. Our current ID fan develops a maximum 28 in.wg. static pressure and has a 40 HP motor.

Secondly, at reduced flow conditions the efficiency drops off rapidly. The existing test loop was designed to operate a 5 x 10^6 Btu/hr, but test operations vary from 2 to 4.5 x 10^6 Btu/hr. Assuming a new fan were purchased to obtain 60 in. wg. pressure drop at design conditions, when operating at 3 x 10^6 Btu/hr the maximum pressure drop across the scrubber would be 21 in. wg. Although the scrubber has a variable venturi, we have not been able to develop high differential pressures at reduced loads with the existing system.

Overall, a wet scrubber would have the lowest cost of all the systems considered, but our experience to date indicates that a better technology would be required to handle the size particulate we have encountered in the past.

Fabric Filters

Dry collecting of particulate is desirable in that it would allow direct recycle of carryover back to the CMS if desired, and it would not create a waste water problem. Discussions with a baghouse manufacturer concerning our application indicate that HEPA filters would be required downstream of the fabric filter to achieve our required collection efficiency. HEPA filters would be necessary to collect the small micron particles not captured by the primary filter. This second filter enclosure complicates the installation in our limited area.

The maximum operating temperature of a fabric filter is 400°F to 550°F and is filter media dependent. Given the limited space available in our facility, the use of dilution air to cool the flue gas is not practical. Dilution air cooling would triple the volume flow through the baghouse, resulting in an increase in the unit size of the baghouse and a greater capital cost Evaporative cooling of the flue gas could be effective, but precise control of the water sprays would be necessary to prevent water carryover or condensation on the filter bags. Wet or moist filter bags would cause caking of the particulate to occur and the baghouse "would bind up" rapidly.

Good filter cake release is required to maintain operation within an acceptable pressure drop range; therefore, adhesive particles, the possibility of moisture in the filter cake, or cementatious filter cakes cannot be tolerated.

Granular Bed Filters

These devices operate in principle much like fabric filters; however, they utilize a bed of moving granular material as the filter media, allowing them to operate at high temperatures if required. Recent augmentation with electrostatic precipitation has resulted in excellent efficiencies in the sub-micron range. However, the release problem cited in the fabric filter discussion also apply to this device. Adhesive or cementatious cakes would be difficult to clean off the granules.

Our application was discussed with EGB Filters, a granular bed manufacturer, and they agreed that their unit was not suitable for our test loop application. Also, the high moisture content in the flue gas would not be compatible with their ionizing section.

Dry ESP

The principle factors affecting the design of a electrostatic precipitator are the gas flow rate, particle size distribution, dust loading, particle resistivity, temperature, and flue gas composition. ESP's are routinely selected for the collection of flyash. They achieve high efficiencies, especially above one micron; and they are reliable, low maintenance, low pressure drop devices.

Past testing at U-PARC has demonstrated that high particulate loadings are possible. At a high loading, the electric field in an ESP can collapse; therefore, a prefilter, or other suitable clean-up device, would be necessary prior to the ESP. The ESP would then function as a "polishing" unit to collect submicron particles only. Other disadvantages with respect to our test lop design include: sensitivity to particle resistivity and high flue gas humidity, the dependence of resistivity on temperature, and potential fouling problems with adhesive particulate. For these reasons, an ESP was deemed unsatisfactory for our application.

Wet ESP

The WESP is a variation of the standard ESP design which lends itself to the collection of particulate which are adhesive or moist. The WESP can handle high concentrations of submicron particles and is not highly sensitive to particle composition. The style of WESP considered for this application is the tubular type, consisting of square or hexagonal tubes with rigid electrode masts in the center of each tube. The WESP requires a saturated gas and, therefore, is typically located downstream of a wet scrubber. Removal of large particulate in this way is more economical than providing for additional WESP capacity. Additionally, the existing test loop has a Fisher Klosterman wet venturi scrubber which would be suitable for integration with a WESP. The charged particles are collected on the walls of the tubes and are cleaned via irrigation with water which is collected with the particulate, and through periodic flushing of the collecting walls by auxiliary cleaning sprays.

The main disadvantage to a WESP is that some means of water clean-up may be necessary. Since we are not expecting the particulate to contain heavy metals or be acidic, most of the particulate could pass on to our facilities chemical waste disposal system. However, since a recirculation tank is required, we will be able to test the water in the tank prior to draining the system. If the water is acidic, it will be neutralized prior to disposal. If the particulate contains heavy metals, the water will be decanted from the solids and then particulate disposed of in accordance with regulations. The water will also be tested and disposed of properly.

Even with this one disadvantage, for the CMS pilot system the WESP will handle the widest variation of possible particulate and will provide the best range of clean-up for the test loop.

During the first quarter, a specification was generated for the wet electrostatic precipitator (WESP). Also during this quarter, three competitive bids were received from qualified vendors, and a bid evaluation was conducted. All three bids were technically acceptable, therefore, the low bidder was selected. The selected unit is an upflow design utilizing 116 - 6 inch hexagonal x 60 inch long collecting tubes providing a total collection area of 100 sq. ft. A rod deck venturi scrubber will be provided at the inlet even though the WESP has been sized to accommodate the full design dust loading.

4.1.1.4 Heat Recovery Subsystem

The only heat recovery devices suitable for Vortec's CMS technology are double shell or cage type recuperators. Typically, the double shell recuperator is the most economical recuperator for smaller capacity furnaces such as the pilot-scale test unit. For a system with higher combustion air pressure, a cage type recuperator would be used to prevent buckling of the inner shell.

In order to prepare the recuperator specification, performance requirements had to be prepared. Initially it was desired to obtained a 1550°F air preheat (the upper limit attainable with a metallic recuperator), however, cost considerations led us to establish performance data for an optional unit which would supply a 1200°F air preheat.

Prior to preparing the specification, recuperator manufacturers were contacted to determine the data needed to properly specify the performance requirements. As the test unit will operate a various heat inputs and preheat values, the manufacturers wanted to see the maximum flue gas temperature at the maximum flow, along with the highest preheat temperature required. If the flue gas temperature remains constant while the mass flow decreases, the air preheat temperature will rise. As a consequence, it will be necessary to supply more combustion air than is required in order to maintain metal temperatures at a safe level. Excess combustion air will have to be released from the system by means of a bleed valve, this arrangement is common in processes with varying load conditions. It is with these requirements in mind that a performance specification was developed which provided operating ranges as well as typical operating points. The specified maximum flow operating condition was based on a coal heat input of 5×10^6 Btu/hr and a gas heat input to the separator/reservoir of 800,000 Btu/hr. A typical operating point of 4×10^6 Btu/hr of coal thermal input and 800,000 Btu/hr for the separator/reservoir was also supplied. As discussed above, the vendors were requested to provide quotations for air preheat temperatures of 1200°F and 1550°F.

Three vendors responded to the inquiry, and a review of the proposals indicated that the recuperator specified with the 1550°F air preheat temperature was within the budget for the program. Based on the bids received, a vendor was selected to provide the recuperator. The selected unit is a parallel flow design with a heat transfer surface of approximately 116 sq ft. The inner shell is constructed with Incoloy 800H material with the outer shell constructed of 304 SS. The cold air plenum is also constructed of 304 SS with the hot air plenum constructed of 309 SS. The unit will be externally insulated with 4-1/2 inch thick block insulation.

The unit is fixed at the bottom, and is free to expand upward to allow for thermal expansion of the inner shell. Differential thermal expansion between the inner and outer shell is taken up by a 321

SS expansion joint located in the outer shell of the recuperator. Constant load hangers at the top of the unit will be attached to structural steel, provided by Vortec, to carry the dead weight of the recuperator. The refractory base ring for the bottom seal will be provided by the vendor.

4.1.1.5 Alternate Refractory Compositions

A key design consideration for the successful commercialization of the CMS system is refractory selection. Discussions with refractory suppliers were initiated to explore potential refractory compositions which will enhance wall life. Currently two different bonded refractories are installed in the CMS. Alumina-Zirconia-Silica (AZS) refractory is installed in the CRV and Chrome-Alumina refractory is installed in the melter. Because both refractories exhibit approximately the same wear rate, the refractory suppliers indicate that the primary wear mechanism is probably corrosion of the bonding material. Zedmark, a bonded refractory supplier, has agreed to conduct "Basin Studies" where test coupons of different refractory compounds are exposed to molten flyash under controlled laboratory conditions to evaluate corrosion. Examination of the grain micro structure will then indicate the best refractory for this application.

The Zedmark tests were conducted using glass produced from a previous pilot-scale test. The glass composition used for the tests was 80% utility flyash and 20% limestone. The basin test was conducted at 2650°F for 72 hours. Table 4-1 presents the different Zedmark refractories tested, the product class, and chemical composition. Also listed in Table 4-1 are the Figure numbers corresponding to the photomicrographs of each sample after testing.

The bonded AZS refractories (photomicrographs shown in Figures 4-1 through 4-4) exhibited the highest corrosion rates. As can be seen in the photomicrographs, the bonding material holding the alumina has been corroded away exposing individual alumina "chunks". This exposes a much higher surface area for continued corrosion as well as allowing the alumina to separate from the brick and dissolve in the molten glass. Of the AZS refractories tested, the material with the highest zirconia content, Zedmul 40-C, performed the best.

The Zedcor 98-C dense alumina refractory shown in Figure 4-5 exhibited corrosion rates similar to those of the AZS materials.

The dense zirconia refractories, Zed Zircon and Zed Zircon C, exhibited better corrosion resistance than the AZS and alumina products. As can be seen in Figures 4-6 and 4-7, distinct corrosion of the bonding material is not as evident as was observed in the AZS products. Also the depth of the "cut" was not as deep as with the AZS materials.

The bonded refractories that performed the best were the chrome based compositions, Zedcor CR-10 and Zedcor CR-30. As can be seen in Figures 4-8 and 4-9, the corrosion of these materials was

Table 4-1 Zedmark Refractories Tested

Product Name	Product Class	Chemical Composition		Figure Number
Zedmul 20-C	Bonded AZS	Al_2O_3	66%	Figure 4-1
		ZrO_2	21%	
		SiO_2	12%	
Zedmul 20 SC	Bonded AZS w/ Enhanced Matrix	Al_2O_3	69%	Figure 4-2
		ZrO_2	19%	
		SiO_2	12%	
Zedmul 30-C	Bonded AZS	Al_2O_3	56%	Figure 4-3
		ZrO_2	28%	
		SiO_2	16%	
Zedmul 40-C	Bonded AZS	Al_2O_3	32%	Figure 4-4
		ZrO_2	44%	
		SiO_2	23%	
Zedcor 98-C	Bonded Alumina Corundum	Al_2O_3	98%	Figure 4-5
		SiO_2	2%	
Zed Zircon	Dense Zircon Brick	Al_2O_3	2%	Figure 4-6
		ZrO_2	65%	
		SiO_2	33%	
Zed Zircon C	Dense Zircon Cast Composition	Al_2O_3	1%	Figure 4-7
		ZrO_2	64%	
		SiO_2	34%	
Zedcor CR-10	Pressed, Alumina Bonded Alumina Chrome	Al_2O_3	86%	Figure 4-8
		Cr_2O_3	10%	
		SiO_2	2%	
		TiO_2	2%	
Zedcor CR-30	Pressed, Alumina Bonded Alumina Chrome	Al_2O_3	68%	Figure 4-9
		Cr_2O_3	30%	
		SiO_2	1%	

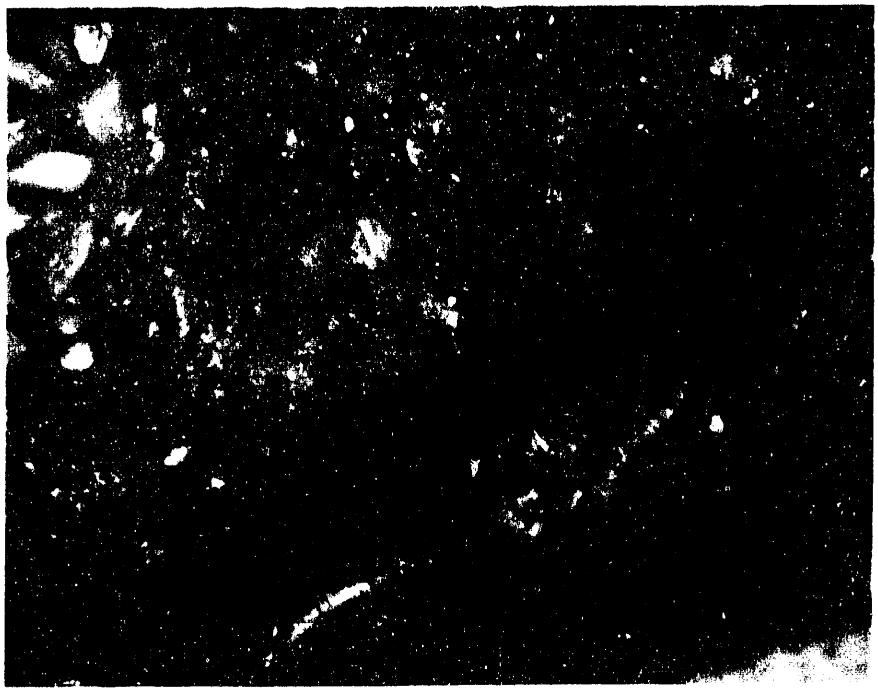


Figure 4-1 Photomicrograph of bonded AZS - Zedmul 20-C

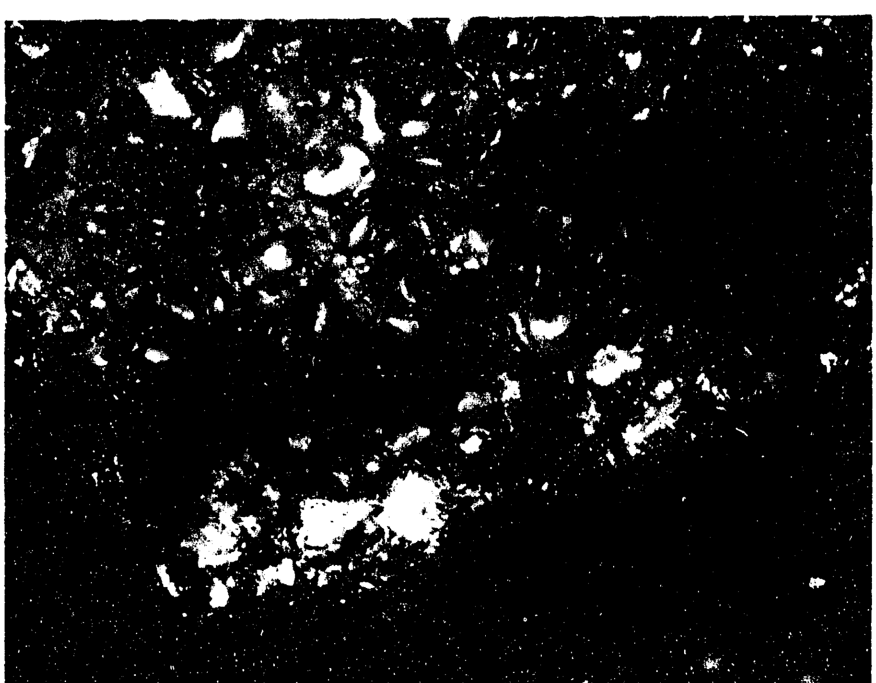


Figure 4-2 Photomicrograph of bonded AZS - Zedmul 20-SC

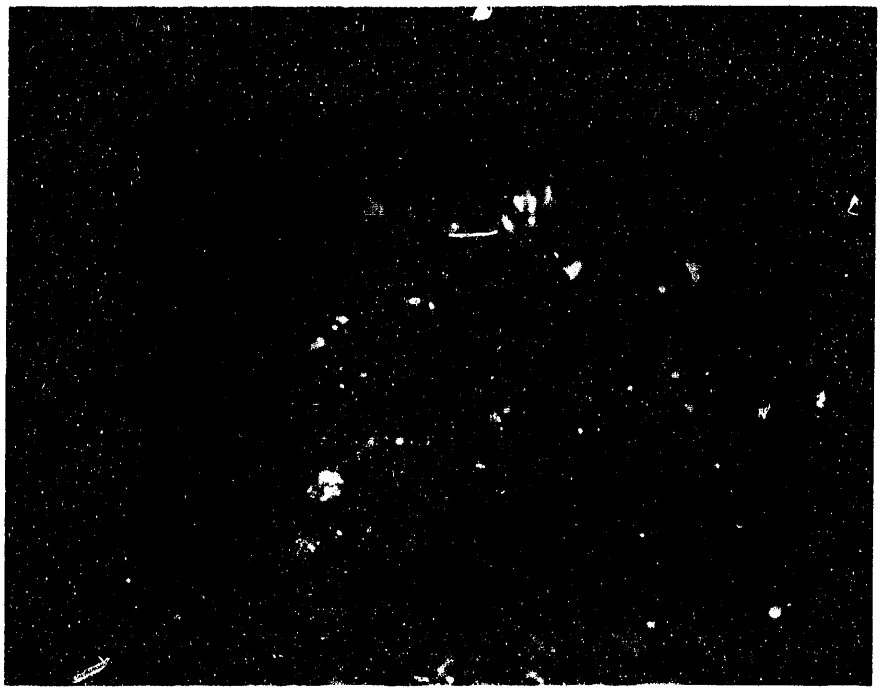


Figure 4-3 Photomicrograph of bonded AZS - Zedmul 30-C

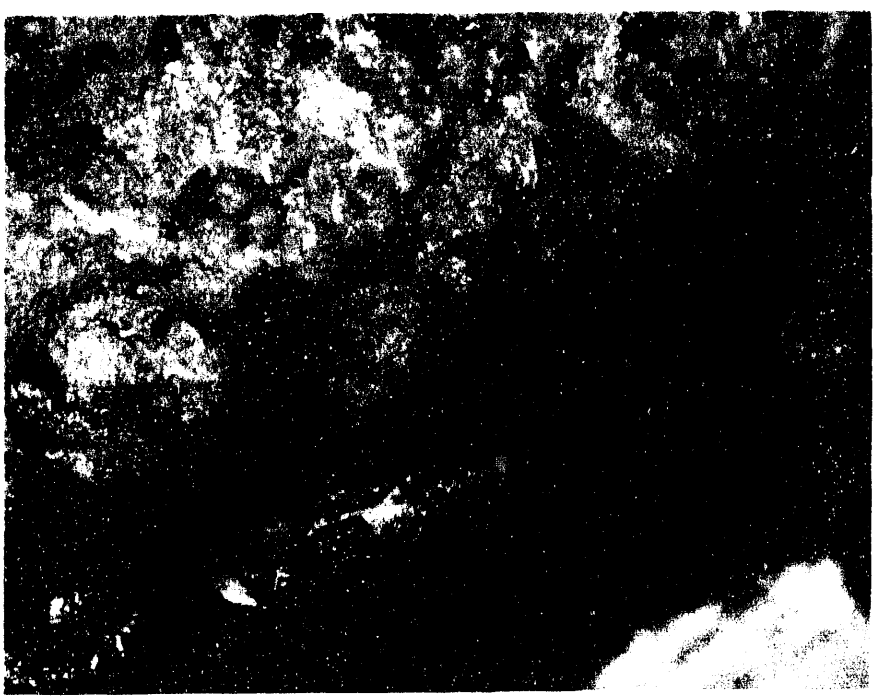


Figure 4-4 Photomicrograph of bonded AZS - Zedmul 40-C

Figure 4-5 Photomicrograph of bonded Alumina - Zedcor 98-C

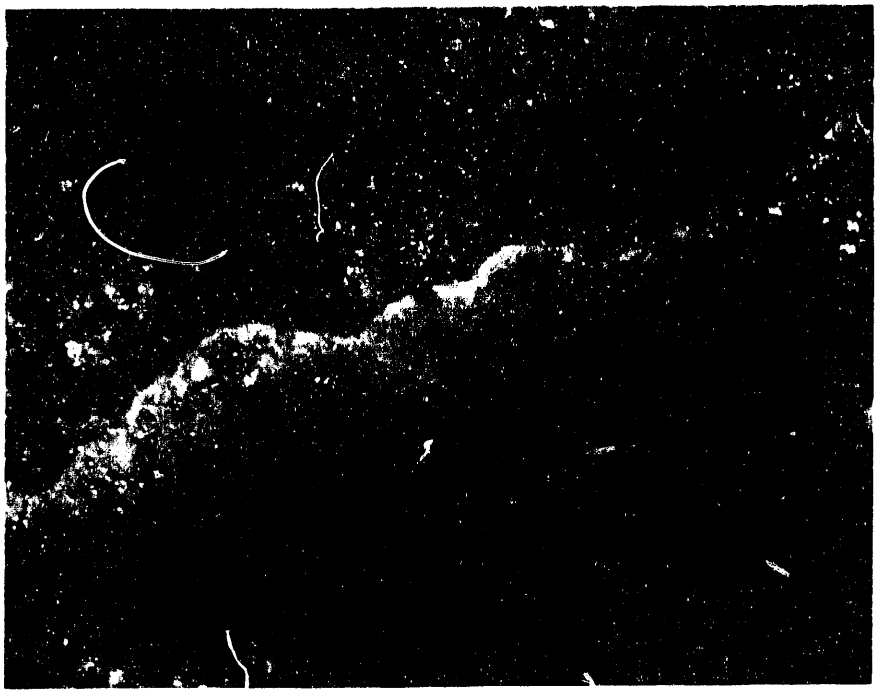


Figure 4-6 Photomicrograph of bonded dense Zircon brick - Zed Zircon

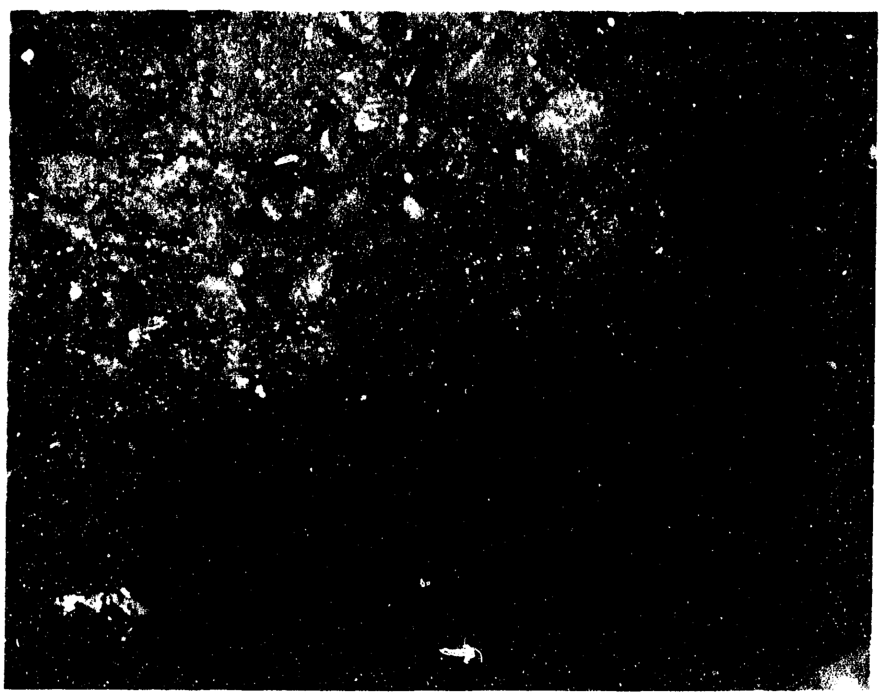


Figure 4-7 Photomicrograph of bonded dense Zircon castable - Zed Zircon - C

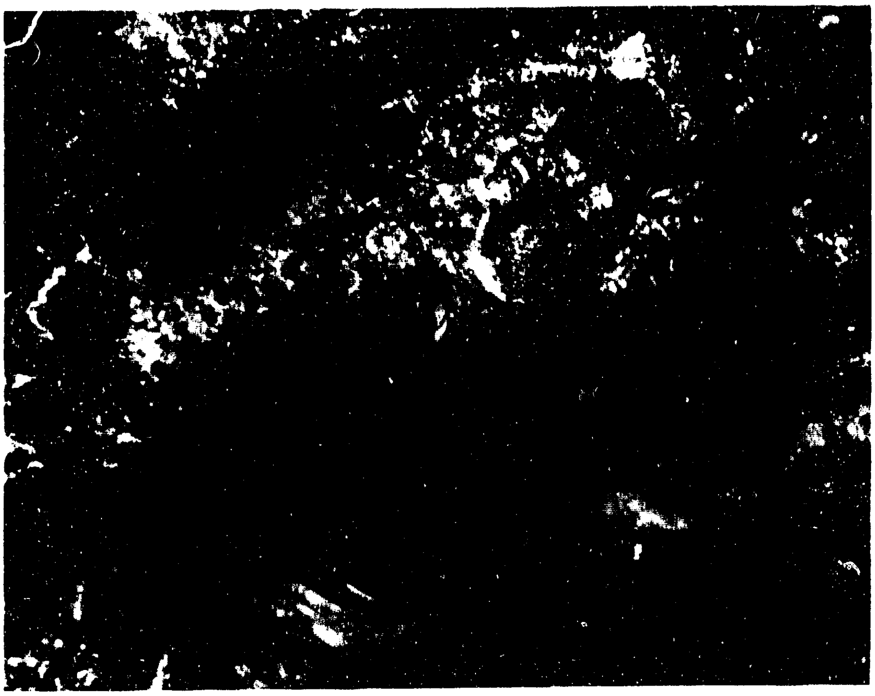


Figure 4-8 Photomicrograph of bonded Chrome-Alumina - Zedcor CR-10

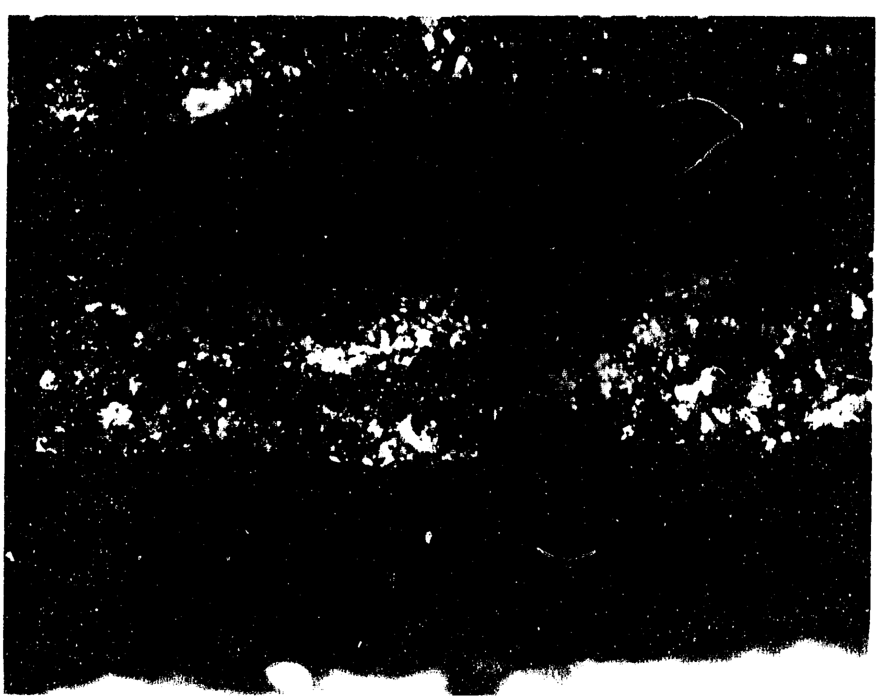


Figure 4-9 Photomicrograph of bonded Chrome-Alumina - Zedcor CR-30

markedly less than that found with either the AZS or dense zirconia products. The high chrome, Zedcor CR-30, refractory was the best bonded refractory tested showing very little wear relative the the other refractory compositions.

Because of the relatively high corrosion rates experienced with bonded refractory, fused cast refractory was also tested. The fused cast refractory is manufactured by melting the refractory mixture and pouring the molten refractory into molds to produce a monolithic shape. This refractory exhibits a much greater resistance to corrosion; however, it is also much more expensive.

Carborundum Company, a leading producer of fused cast refractory, agreed to conduct corrosion testing of their refractory using the same glass composition used for the bonded refractory testing, i.e., 80% utility flyash and 20% limestone. These test were conducted using cylindrical "fingers" approximately 5 in. long and 1/2 in in diameter half immersed in the glass at 2700°F (1482°C) for 132 hours.

The four types of fused cast refractory tested are presented in Table 4-2.

Table 4-2 Carborundum Refractories Tested

Product Name	Product Class	Chemical Composition		Figure Number
Monofrax S-5	Fused Cast AZS	Al_2O_3	46%	Figure 4-10
		ZrO_2	40%	
		SiO_2	13%	
Monofrax Z	Fused Cast Zirconia	Al_2O_3	1%	Figure 4-11
		ZrO_2	94%	
		SiO_2	3%	
Monofrax K-3	Fused Cast Chrome-Alumina	Al_2O_3	59%	Figure 4-12
		Cr_2O_3	27%	
		MgO	6%	
		SiO_2	2%	
Monofrax E	Fused Cast Chrome-Spinel	Al_2O_3	7%	Figure 4-13
		Cr_2O_3	78%	
		MgO	7%	
		SiO_2	2%	

Figure 4-10 is a photomicrograph of the fused cast AZS material showing that the the sample failed at the metal line and was completely dissolved.

Figure 4-11 is a photomicrograph of the fused cast Zirconia sample showing the metal line corrosion. Corrosion at the metal line was 14.61% of the cross sectional area. The sample exhibited substantial corrosion and would be unacceptable.

Figure 4-12 is a photomicrograph of the metal line of the Monofrax K-3 fused cast Chrome-Alumina sample. This sample exhibited good corrosion resistance with little metal line refractory loss (8.69%).

Figure 4-13 is a photomicrograph of the metal line of the Monofrax E fused cast Chrome-Alumina sample. This sample performed the best of any refractory tested. This sample showed very little (3.25%) refractory loss at the metal line. However, this refractory is the second most expensive refractory tested (after the Monofrax Z).

Overall, both the Zedmark and Carborundum test indicate that for a glass composition primarily of utility flyash, a Chrome based refractory exhibits the best corrosion resistance. For a commercial application, the fused cast Monofrax K-3 Chrome-Alumina appears to be the best choice for the high wear areas from a cost and corrosion resistance stand point. For the lower wear areas, a high Chrome based bonded refractory such as Zedcor CR-30 would be used.

4.1.1.6 Computational Fluid Dynamic Modeling

The objective of this modeling effort was to perform an analytical investigation of the aerodynamics and particulate behavior in the vicinity of a suction-type gas sample probe in a high temperature multiphase flow. The model was developed to study the flow pattern, particle trajectory, the cause of probe clogging, and improvement of probe arrangement.

One of the difficulties in modeling this problem is that the geometric dimensions of the sample probe and the flow channel are different by several orders of magnitude. In order to obtain detailed information in the vicinity of the sample probe with a reasonable computation effort, non-uniform grid arrangement is employed in the entire computation domain.

The geometric configuration of the flow passage is shown in Figure 4-14. Heat flux boundary condition of 1000 Btu/hr.sq.ft. (experimental input) has been used. The thermal boundary conditions for the probe tip is derived from the equation of heat transfer incorporating both convection and radiation.

Figure 4-10 Photomicrograph of Fused Cast AZS - Monofrax S-5

Figure 4-11 Photomicrograph of Fused Cast Zirconia - Monofrax Z

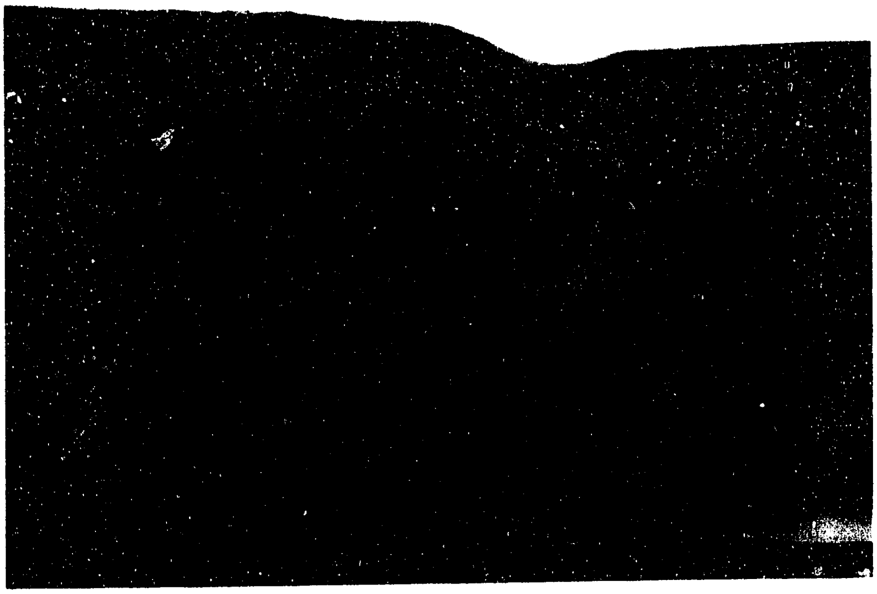


Figure 4-12 Photomicrograph of Fused Cast Chrome-Alumina - Monofrax K-3

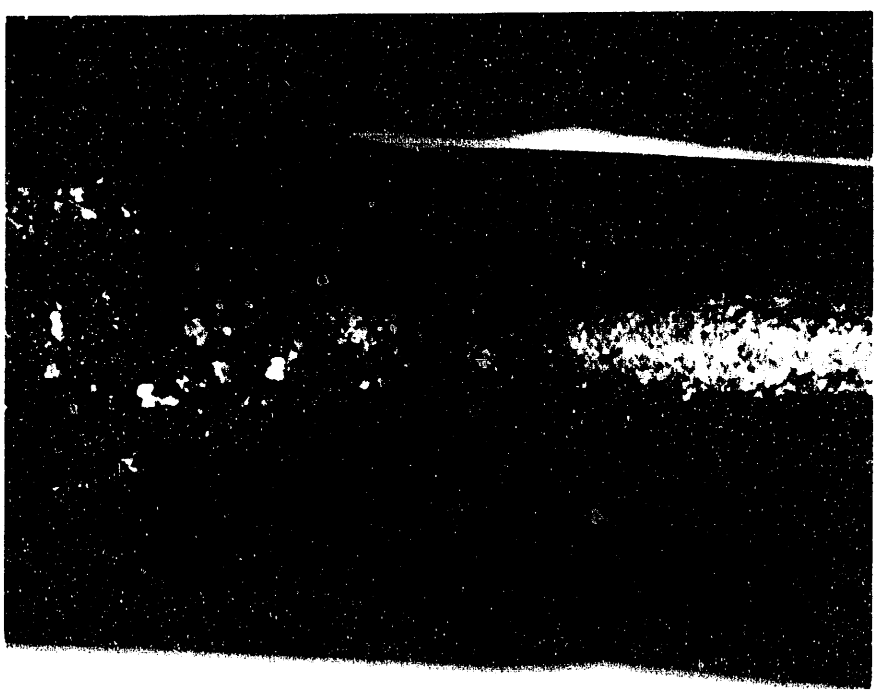


Figure 4-13 Photomicrograph of Fused Cast Chrome-Alumina - Monofrax E

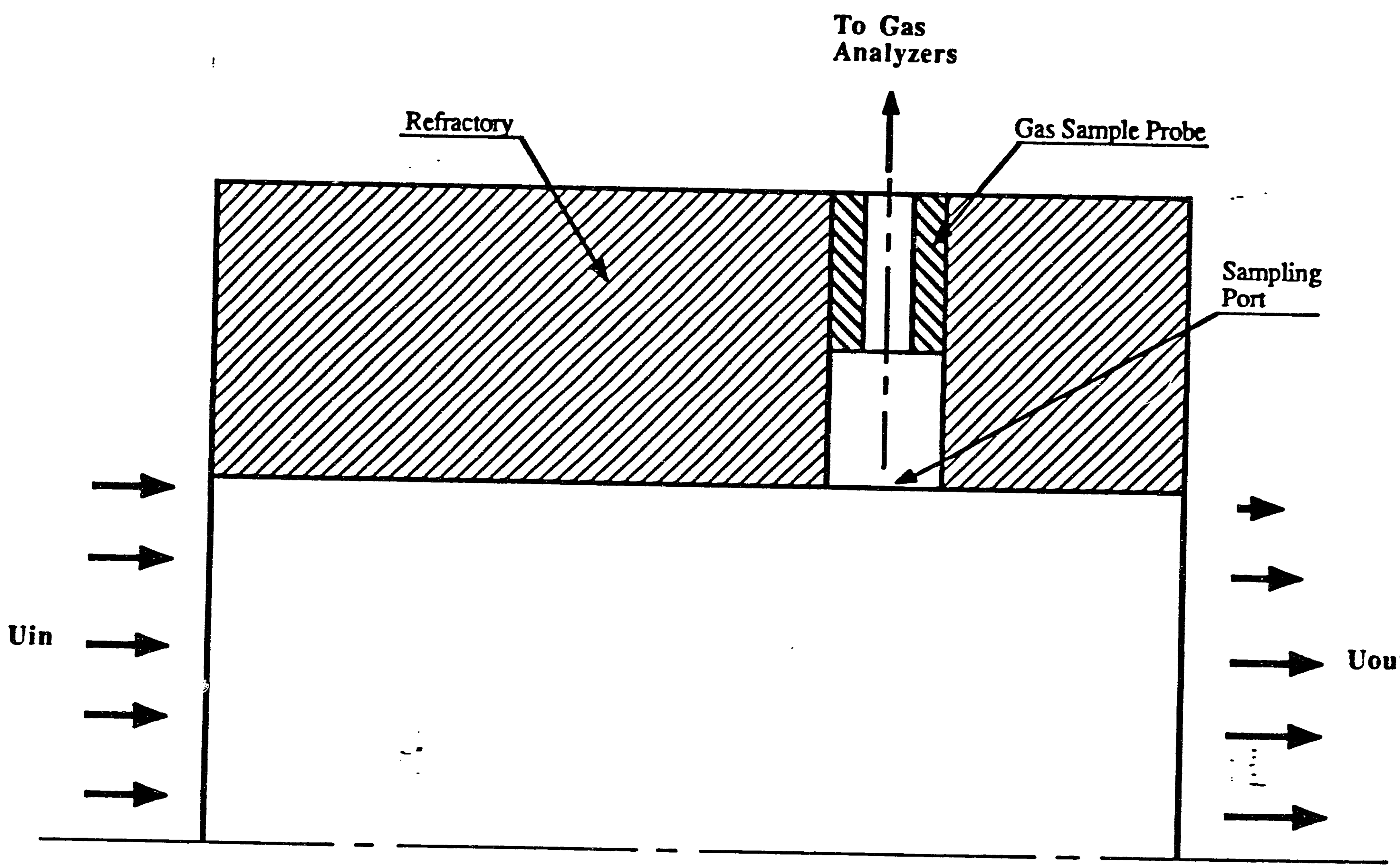


Figure 4-14 Configuration of the Modeling Domain

The following conservation equations were considered and solved in the present simulation:

Continuous Phase:

(1) Continuity equation for total mass (in the form of pressure correction).
(2) Conservation equations for momentum.
(3) Conservation equation for turbulent kinetic energy (k).
(4) Conservation equation for the rate of dissipation of turbulent kinetic energy (e).
(5) Conservation equation for energy.
(6) Radiation heat transfer between the flow and bounding walls.

Dispersed Phase:

(1) Conservation of mass.
(2) Conservation of momentum.

The flow field was solved first and assumed to have no chemical reactions. However, heat transfer through the walls was taken into account which was expected to affect the behavior of particles due to temperature gradients adjacent to the walls. Particles were injected at the section inlet to produce a uniform solid loading profile. The particle trajectories were tracked using a Lagrangian approach based on the solved flow field.

Computations were performed in the domain shown in Figure 4-14 with the following boundary conditions:

Flue Thermal Input	3.5 MMBtu/hr
Flue Gas Flow Rate	3098 lb/hr
Flue Gas Temperature	2700 °F
Flue Gas Density	0.0119 Lb/cu.ft
Inlet Velocity	145 ft/s
Sample Flow Velocity	12.1 ft/s
Temperature of Sample Probe Tip	297 °F
Wall Heat Flux	1000 Btu/hr.sq.ft.

In order to study the impact of probe arrangement on the flow field and hence the particle behavior, two different probe arrangements were studied, that is, (1) with the probe tip aligned with the wall of the channel and (2) with the probe pulled half way back into the refractory-lined wall. The results of the two arrangements are discussed as follows, respectively.

1. Probe Tip Aligned with the Wall

The objective is to study particle trajectories and to identify if the particles would get into the sample probe. Because of the relatively simple geometry, the problem is modeled in 3 dimensional space.

The results are summarized as follows:

(1) The velocity field indicates that the main stream would simply branch into two, however, the domain is dominated by the main stream with no secondary circular movement.

(2) When operated with a multiphase flow, particulate tracking demonstrates (as indicated in Figure 4-15) that particles do get into the passage of the sample probe.

(3) The findings in (1) and (2) lead to the belief that particulates are at least partially responsible for the clogging of the probe.

2. Probe Pulled Half Way Back into the Refractory-Lined Wall

In order to reveal the detailed flow structure in the sampling port and its coupling with the main stream, the following simplifications are made: (1) The sampling port is in the center of the top wall of the channel which suggests that the problem can be regarded as symmetric with respect to z-direction (spanwise); (2) Assume that the flow (except for the region adjacent to the wall) is not affected if the same sampling port is used on the bottom wall opposite to the one on the top. This leads to a flow which is symmetric with respect to y-direction; (3) Further, assume that the side wall has no significant effect on the flow around the sampling port due to the large dimensional aspect ratio. Thus, based on the three assumptions, the problem was modeled in a two dimensional configuration. This simplification drastically reduces the computational effort compared to that of a three dimensional model, and enables a detailed two dimensional analysis on the flow structure in the computation domain. The model was converged and the results are presented below.

The velocity profile at the channel exit indicates that the flow remains in the developing region, which confirms the estimation that no fully developed velocity profile exits in this flow section. The flow pattern near the inlet of the sampling port is show in Figure 4-16. A recirculation flow pattern is generated in the sampling port by the viscous shear force at the flow interface of the sampling port and the main stream. This recirculation flow pattern is believed to have certain impact on the particle carry-over and will be elaborated in the recommendation section.

A raster plot of the temperature distribution is illustrated in Figure 4-17. Slightly lower temperature is expected near the walls due to heat loss to the surroundings. Relatively low temperature in the sampling port is the result of the heat loss through the refractory-lined walls and the water-cooled jacket of the probe, while limited energy is convected into the region due to the small mass flow. The relatively high temperature zone near the wall on the right hand side is due to the convection of flue gas from the main stream.

Trackings of submicron particles injected at the channel inlet indicate that particles will not easily get into the sampling probe unless injected just up stream of the sampling probe.

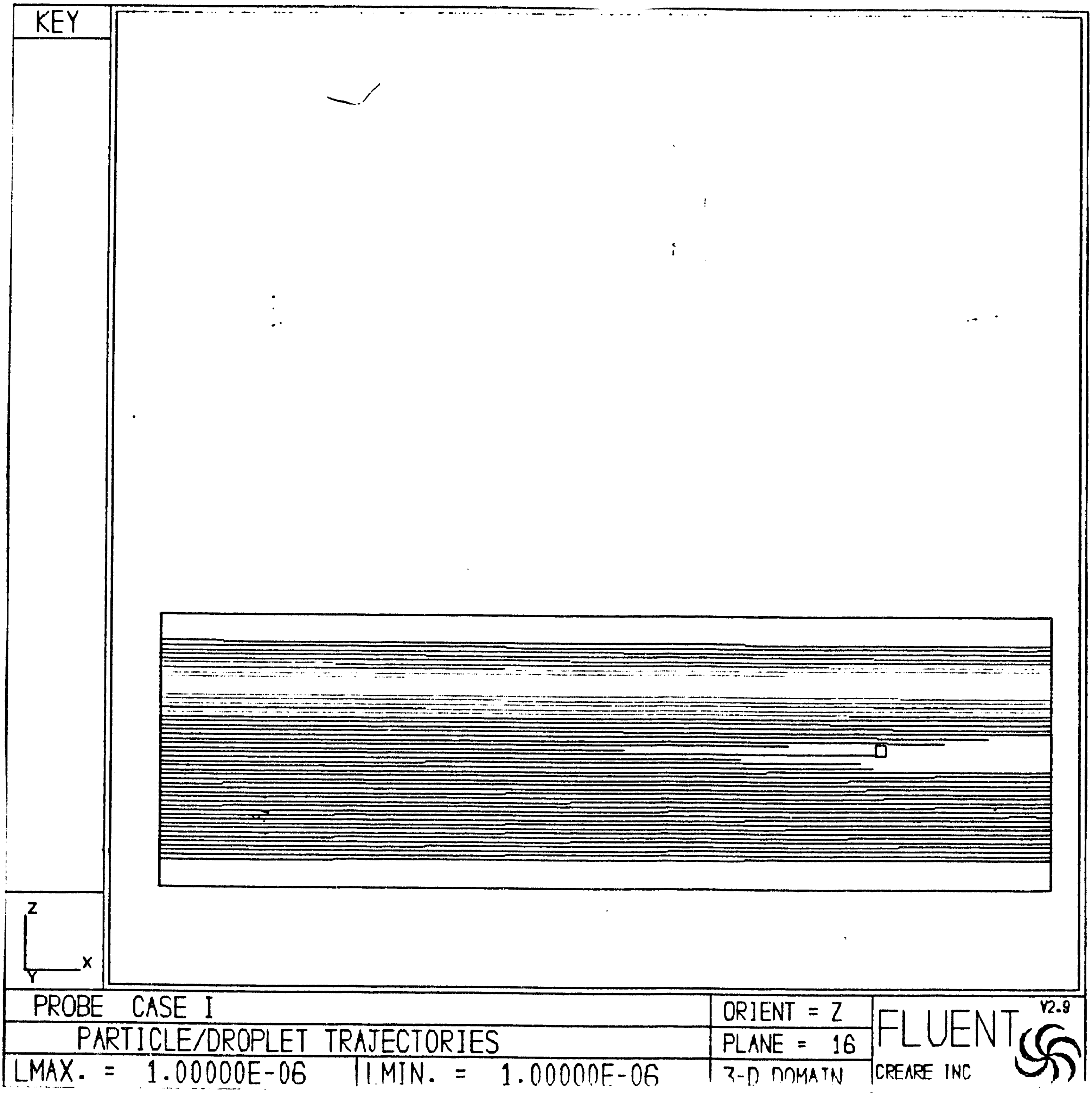


Figure 4-15 Particle Trajectories in the Channel (3D modeling)

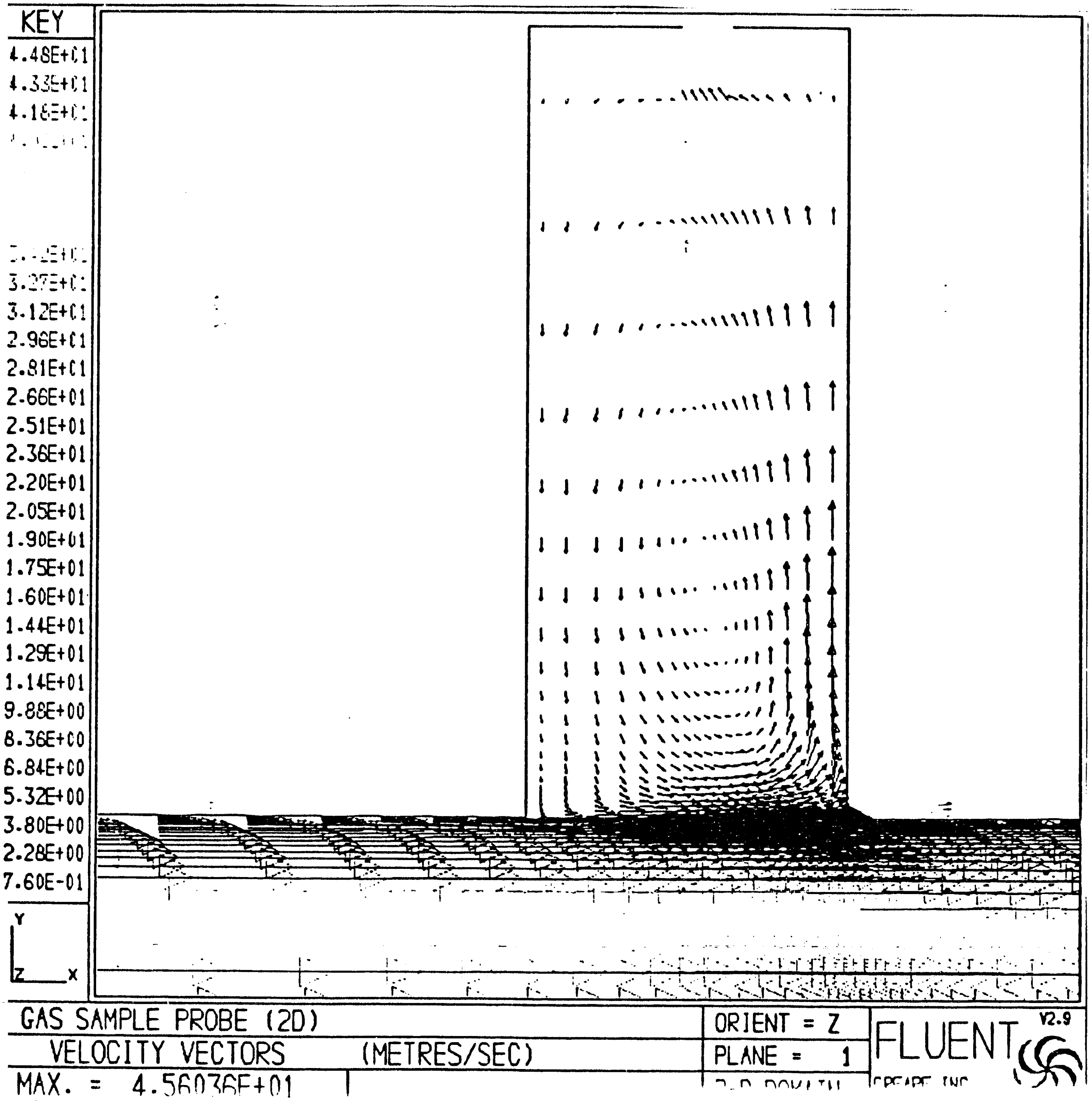


Figure 4-16 Flow Pattern in the Sampling Port

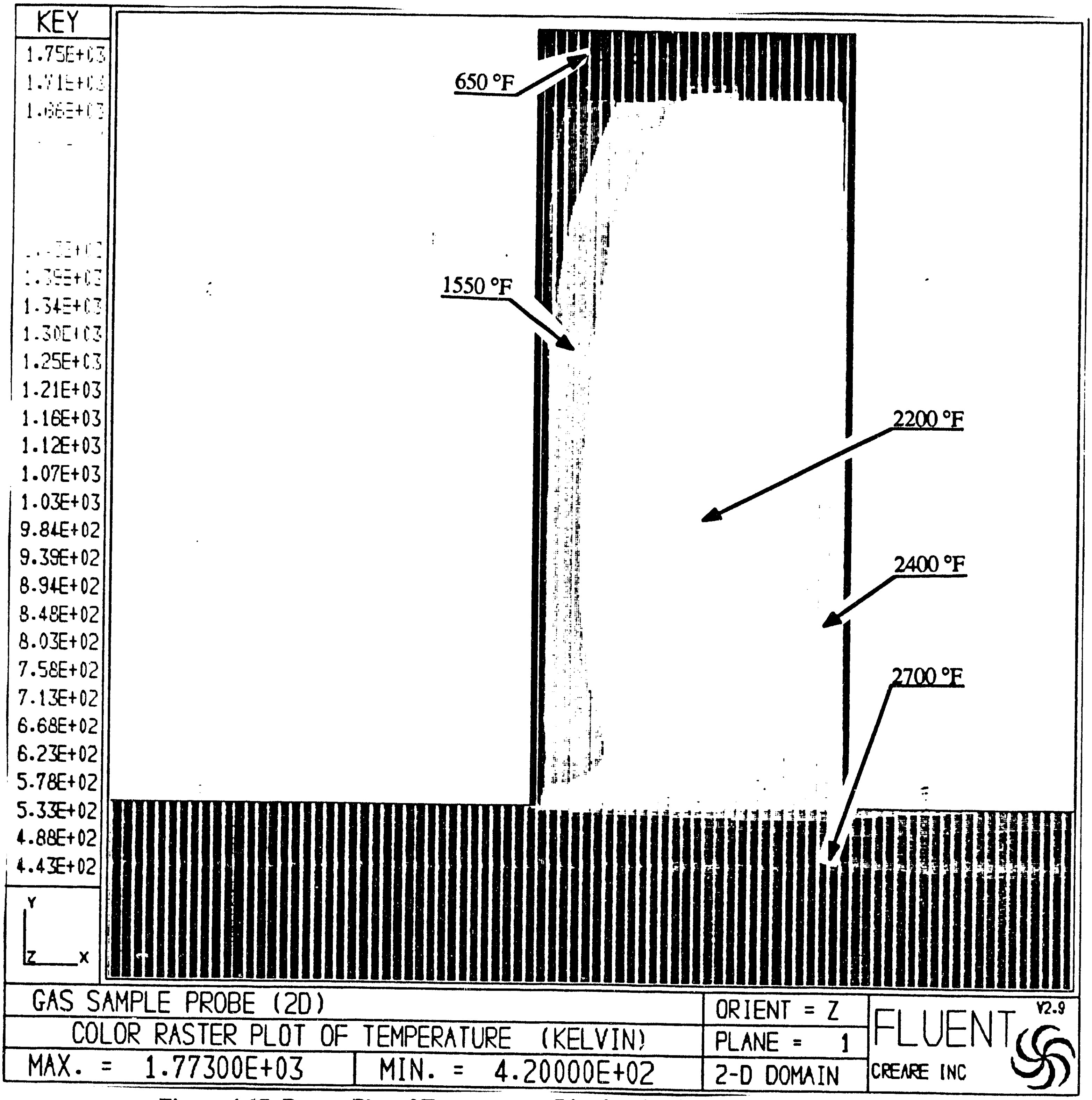


Figure 4-17 Raster Plot of Temperature Distribution in the Sampling Port

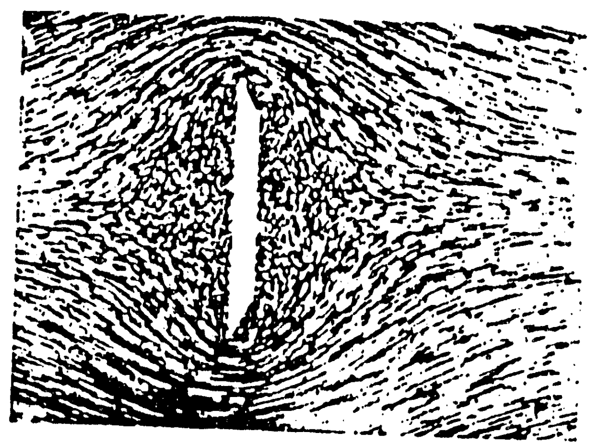
Several potential methods for eliminating particulate clogging of the sample probe are summarized below.

Baffle Design
The main idea of this design is to remove the linear momentum of the particles to avoid direct impingement of particles on the sample probe. However, this baffle will either generate two "dead" zones filled with particles (at low Reynolds numbers, Figure 4-18 (a)) or a wake with strong flow recirculation (at high Reynolds numbers, Figure 4-18 (b)). In both cases, particles will be carried by the gas sample into the probe.

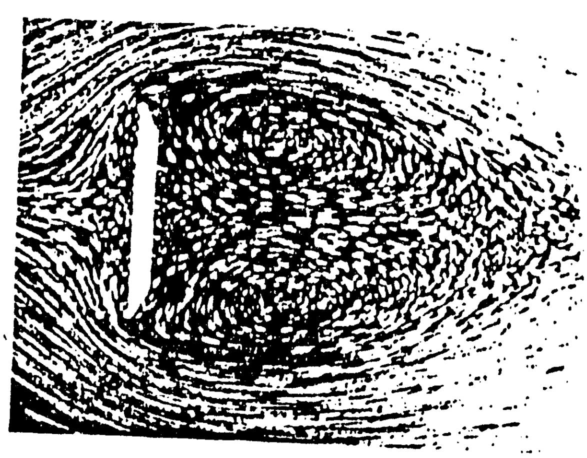
Cylindrical Design
Figure 4-19 shows a particle-seeded fluid moving past a circular cylinder at different values of Reynolds numbers. The flow relative to the cylinder is steady, so that these particle paths are portions of streamlines. The purpose of this design is to use the curvature of the cylinder surface to balance the loss of the static pressure, therefore to avoid boundary layer separation. This arrangement, as shown in Figure 4-19 (Re=0.65, 3.64), may work for flows of very low Reynolds numbers, but does not work for flows of high Reynolds numbers where boundary layer separation is inevitable, as indicated in Figure 4-19 (Re=13.05, 39, 57.7). The Reynolds number of the flow currently being investigated could be well above 3×10^4 in which boundary layer separation on the probe surface is almost guaranteed.

Spherical Design
Spherical design may help postponing boundary layer separation (with maximum Reynolds number doubled from that of the cylindrical case), but it faces the same problem as what the cylindrical design does. The upper limit of Reynolds number for a sphere with no wake lies approximately around Re = 100 which is still orders of magnitude lower than that of the flow presently being analyzed.

Aerofoil Design
Figure 4-20 illustrates the flow past an aerofoil with the boundary layer being just discernible as a collection of very short streaks on the trailing edge of the slender body. A steady boundary layer subjected to a decelerating external stream like that on the upper surface of the aerofoil in Figure 4-20 is usually unstable and a turbulent boundary layer takes its place; turbulent boundary layers are less prone to separation, since the fluctuating cross-currents are able to transfer forward momentum from the outer layers to the slow-moving layers of fluid near the wall. However, the character of the flow is quite different when separation of boundary layer occurs, as it does when the body is not sufficiently slender (Cylinders, spheres, etc.) or when the body is slender but not aligned with the stream (Figure 4-20 (b)). In the case of the inclined aerofoil, the maximum velocity just outside the boundary layer occurs on the upper surface quite close to the leading edge and boundary



(a) Re = 0.25



(b) Re = 10

Figure 4-18 Streamlines of Steady Flow Past a Baffle

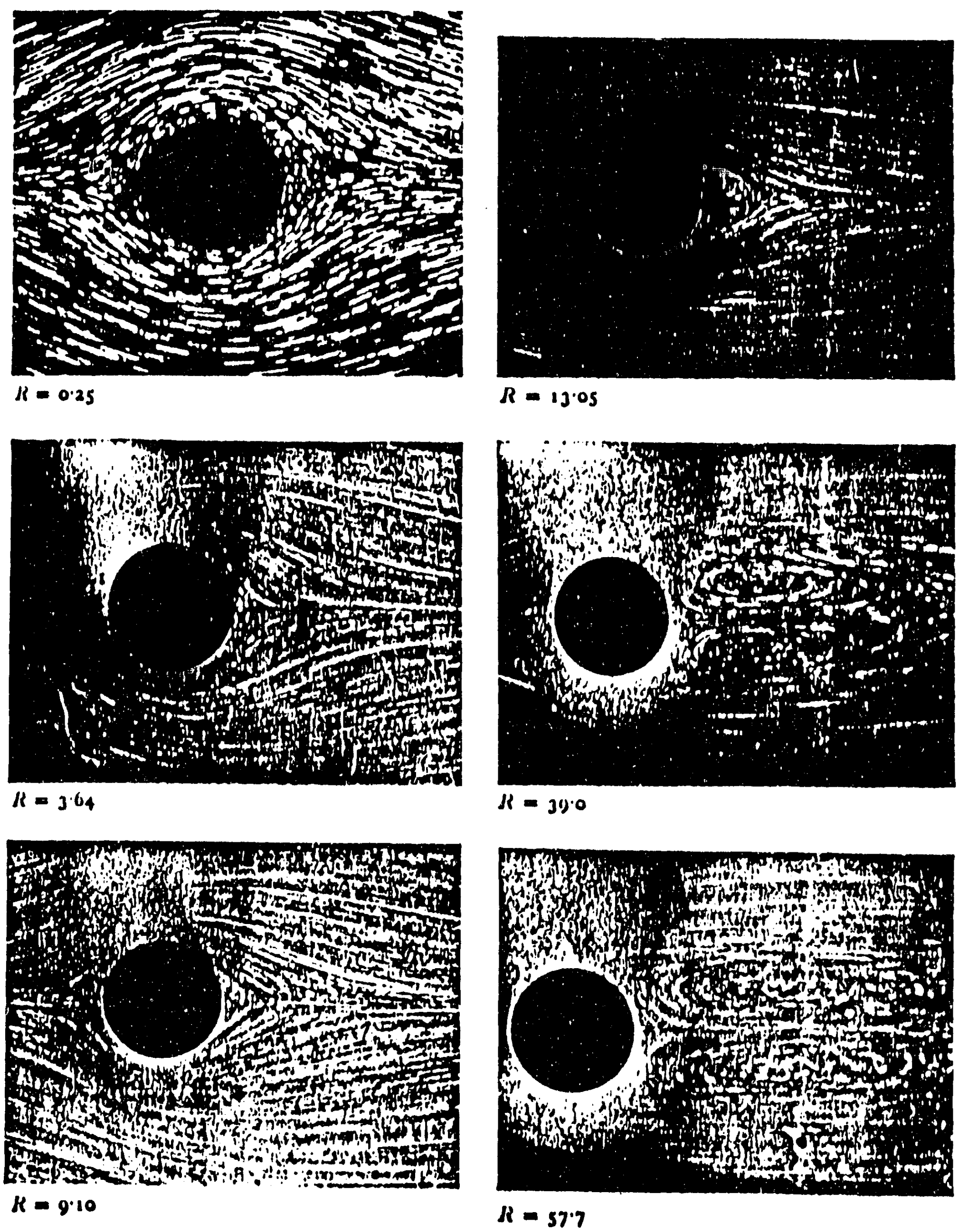
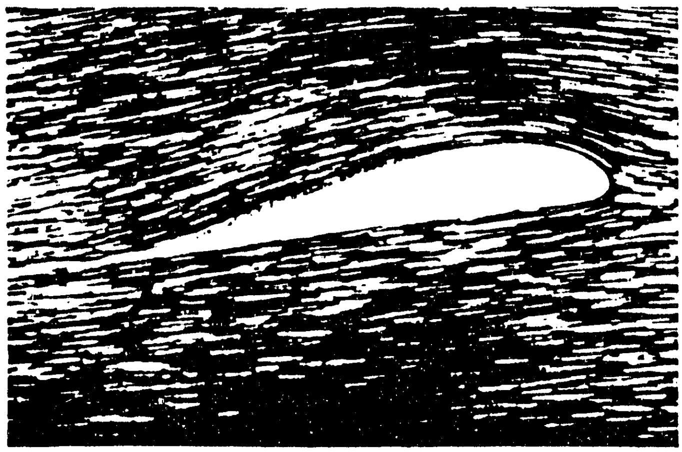


Figure 4-19 Streamlines of Steady Flow Past a Circular Cylinder



(a)

(b)

Figure 4-20 Flow Past an Aerofoil

layer separation occurs not far downstream from this point, the boundary layer here adjoins to very little of the upper surface and the aerofoil is said to be 'stalled', the term being associated with accompanying severe reduction in lift on the aerofoil. Alignment of aerofoil probe with stream is difficult in the gas sampling, and the probe may not perform as what it is expected.

The second approach of gas sampling in multiphase flows is to use inert gas purge of the probe to eliminate particulate clogging. This method has been widely used in the adjustment of combustion performance of utility steam generators where the sampling environment is close to the present situation.

Recommendations

Streamline design of the probe is a very complicated task with regard to both fabrication and application. Flow Visualization results have demonstrated that even with aerofoil design, the flow will still be strongly disturbed if the aerofoil is not well aligned with the flow stream. Moreover, the environment where the probe is to be applied is loaded not only with particulates but also possibly some metal or non-metal vapor which is tend to condensate on cooler surfaces.

However, the flow pattern shown in Figure 4-16 indicates that the flow recirculation may help to alleviate the rate of particle carryover. This is illustrated conceptually in Figure 4-21. As the particles approach to the port inlet, the parallel flow pattern generated by the recirculating flow will keep the particles from getting into the sampling port. As the particles move to the right corner of the port, the flow turns rapidly 90 degree upwards. The centrifugal force produced by the sudden change of flow direction along with particle inertia serves as a separation mechanism to prevent particles being carried into the sampling port. Nevertheless, some of the particles will inevitably be carried into the sampling port. Part of the particles will be carried by the recirculating flow back down to the port inlet results in a secondary separation. Further, since the flow rate of the gas sample is low, the velocity in the sampling port may be smaller than the terminal velocity of some coarse particles. As a result, these particles may fall down due to the gravitational force and join the circulating flow The number flux of particles eventually getting into the sample probe is expected to be low.

Therefore, it is recommended that the existing sample probe be used but pulled half way back into the wall. In addition, if the probe can possibly be purged periodically with inert gas such as nitrogen, carbon dioxide, etc., the service duration of the sample probe could be further increased.

4.1.2 Task 1.2 - Component Fabrication

No major component fabrication was conducted during this reporting period.

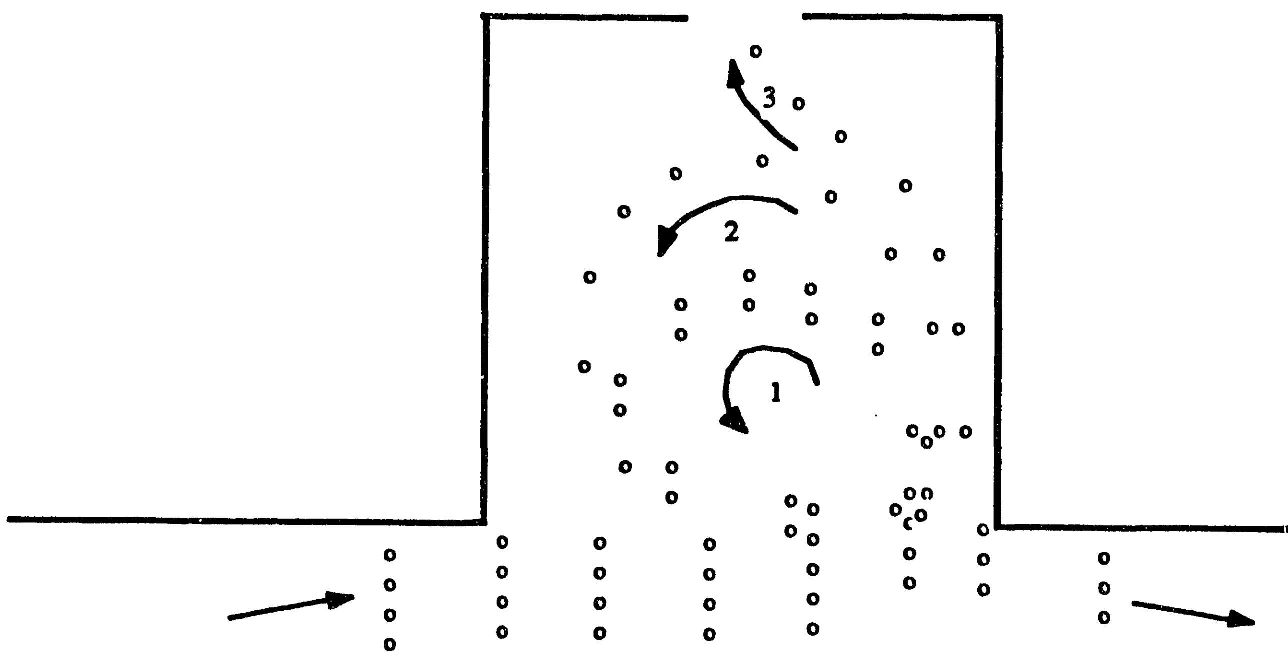


Figure 4-21 Conceptual Diagram of Particle Separation in the Sampling Port

4.1.3 Task 1.3 - Component Integration

Batch and Coal Handling, Feeding, and Injection Subsystem

The existing coal feed system was dismantled, cleaned and refurbished, and reassembled for the upcoming tests. The coal tank was also cleaned of residue coal which had caked-up on the tank walls.

CRV and Melter Assembly Modifications

Modifications to the precombustors are underway to remove the slag pots. Because the focus of the program is to use flyash as the feedstock for the glass making process, there is no concern for contaminating the glass with the coal slag. Therefore, the slag pots are being removed and a refractory floor is being built in the bottom of the precombustors to allow the coal slag to flow directly into the CRV.

Refractory repairs to the separator/reservoir were completed. Also minor modifications to the refractory around the view ports in the separator/reservoir have been completed to eliminate overheating observed in these areas during previous test runs.

4.2 Task 2 - Perform Preliminary System Tests

4.2.1 Task 2.1 - Test Plan

Work on the Test Plan was suspended pending approval of documentation required under the National Environmental Policy Act (NEPA)

4.2.2 Task 2.2 - System Tests

Preliminary system tests were scheduled for this quarter. However, testing has been delayed pending NEPA approval.

4.3 Task 3 - Perform Proof-of-Concept Tests

This task is not scheduled to begin until the beginning of September 1992.

4.4 Task 4 - Evaluate Economics/Prepare Commercialization Plan

This task was not scheduled to begin until the forth quarter of 1993; however, Contract Change No. M003 has allowed work to begin early.

The economic evaluation of commercial scale CMS processes has begun. In order to accurately estimate the cost of the primary process vessels, preliminary designs for 25, 50, and 100 ton/day systems have been started under Task 1. These designs will be the basis for the development of detailed equipment lists, system energy requirements, and building and land requirements. Also detailed foundation and structural steel designs are being developed and the costs of these components are being estimated. This data will serve as input data to the life cycle cost analysis. This economic evaluation of the commercial CMS system will be an integral part of the commercialization plan.

4.5 Task 5 - Conduct Site Demonstration

Work under this task is not scheduled to begin until the fourth quarter of 1993.

4.6 Task 6 - Decommission Test Facility

This task is not scheduled to begin until the second quarter of 1994.

4.7 Task 7 - Program Management and Reporting

The results of the bid evaluation for the WESP and the recuperator were sent to the DOE Program Manager for review, and he approved the vendor selection in each case.

SECTION 5 - PLANNED ACTIVITIES

5.1 Task - 1 Design, Fabricate, and Integrate Components

5.1.1 Component Design

During the next reporting period the major emphasis will be completing the installation design for the ESP and the recuperator, reline the CRV, and update the control system.

New control logic is being developed using an updated version of Genesis control software. Additional control system hardware (controller boards and power supplies) were also installed in anticipation of the installation of the recuperator and ESP. As-built drawings of the existing control system will be produced and later updated to reflect the new configuration.

The recuperator and wet ESP vendors will be released to begin work on the designs for the equipment. After Vortec reviews and approves the design drawings, Vortec will authorize them and begin fabrication.

5.1.2 Component Fabrication

A close inspection of the CRV showed that some of the refractory on the side wall required replacement. The melter refractory, however, remained in good shape. Therefore, during the next reporting period the CRV refractory will be replaced. The CRV and melter will be removed from the test structure, and the CRV will be disassembled. After documenting the refractory wear, the CRV refractory will be removed. Because previous refractory testing showed that a chrome based refractory resists corrosion better than an AZS when melting ash, it has been decided to replace the hot liner with a chrome based ram refractory. Because the ram has a high thermal conductivity, it will be installed over an insulating layer of fiberfrax board. The installation of the refractory will be conducted by LVR, a refractory installation company, and Zedmark, the refractory supplier.

5.1.3 Component Integration

Integration requirements for the APC assembly will be defined and detailed engineering drawings showing the layout and interconnection of all components and utilities will be developed. Equipment foundation designs will be developed and site work will begin.

5.2 Task 2 - Perform Preliminary System Test

If the Environmental Assessment is approved by DOE during this quarter, than the test plan will be completed and preliminary testing will begin.

5.3 Task 4 - Evaluate Economics/Prepare Commercialization Plan

Preliminary foundation and structural steel designs have been completed and the support steel has been sized for the 100 ton per day commercial CMS. This information will be used to develop the costs for the structural steel. These costs will then be used as input data to the CMS system cost data base currently being developed.

Heat loss calculations will be conducted for various refractory configurations for a commercial 15 ton/day system. Because long refractory life is a primary requirement of a commercial system, the refractory configuration will, in most cases, incorporate fused cast refractory as the hot liner. The fused cast material, however, has a much higher thermal conductivity than the bonded refractory currently used in the test unit. Therefore, the hot liner will be thicker, and will be backed by a layer of thermal insulating fiberfrax. The heat loss calculations will indicate the heat rate for a given configuration and this will allow the calculation of gas flow rates and system heat and mass balances. This information will allow the determination of the optimum refractory configuration for a given commercial application. It will also allow for an accurate estimate of the refractory weight and cost, and the system's life cycle cost.

SECTION 6 - SUMMARY

The design modifications are proceeding as planned. Bid evaluations for the APC system and the recuperator were completed and the vendors were selected and approved by DOE.

Refractory corrosion tests were conducted with both bonded refractory and fused cast refractory. In both cases, it appears that high chrome based refractories preform the best. In addition, a refractory design review was conducted with a refractory vendor and installer and an acceptable commercial-scale refractory was developed. Refractory cost estimates based on this design were also received from the vendors.

Preliminary designs and cost estimates for commercial scale systems are currently being developed and will provide data necessary for the development of a commercialization plan.

The CFD model of the gas sampling probe was completed and the results indicate several possible options to prevent plugging of the probe. Further investigation of commercially available probes is under way.

We expect that the environmental assessment will be completed during the next quarter and that preliminary testing will begin.

SECTION 7 - REPORT DISTRIBUTION LIST

The report distribution list as specified in the contract is as follows:

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