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# Performance Analysis of a Screenless (Counter-Current) Granular Bed Filter on a Subpilot-Scale PFBC, Volume I

**Final Report**

**K.B. Wilson**
**J.C. Haas**

October 1989

Work Performed Under Contract No.: DE-AC21-84MC21335

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Combustion Power Company, Inc.
Menlo Park, California

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1020 Marsh Road, Suite 100
Menlo Park, California 94025

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This research effort was made possible by the hard work and dedication of the above METC personnel and the staff of New York University, Antonio Ferri Laboratories. We at Combustion Power Company appreciate the opportunity to operate our filter at NYU. The entire NYU staff is acknowledged for their work, in particular Dr. Victor Zakkay, Laboratory Director; Mr. Jack Spiegel, Laboratory Supervisor; and Mr. George Lipsky, Laboratory Project Manager.

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## EXECUTIVE SUMMARY

The U.S. Department of Energy sponsored this program to develop and test the Granular Bed Filter (GBF) as part of the overall program to develop coal-fired, pressurized fluidized-bed combustors to be used in combined-cycle power generating systems. In these systems a portion of the electricity is generated using a gas turbine driven by the high-temperature, high-pressure combustion gas. A hot gas cleanup train, such as the Granular Bed Filter, must be installed before the gas turbine to prevent erosion of turbine materials and deposition of particulate within the turbine. Meeting New Source Performance Standards (NSPS) with this filter is also required to eliminate need for post-turbine particulate removal. Furthermore, it has also been shown that alkali (sodium and potassium) in trace amounts can harm gas turbine materials. The GBF was evaluated for removal of these contaminants.

The purpose of this work was to obtain information on the operational and economic feasibility of the Granular Bed Filter when applied to a pressurized fluidized-bed combustor (PFBC) as a high-temperature, high-pressure particle control device. In this program, experimental data was obtained on the design and operational life of critical components, an experimental sequence was conducted on a subpilot-scale GBF test module, and an update of a commercial-scale design was completed based on experimental data.

There were three tasks in this program. Conclusions reached in each task are reported in respective sections.

SECTION I - Life-Critical Component Testing:

The objective was to provide a sound basis for assessing the design and predicting the operational life of GBF components under PFBC conditions. Testing was carried out at the Combustion Power Company high pressure test facility in Menlo Park, California. Components supporting GBF operation in a PFBC subpilot plant were designed, built and operated. About 500 hours of testing was completed. Results showed that all components were ready for subsequent operation at the New York University subpilot-scale PFBC facility.

SECTION II - Granular Bed Filter Testing at New York University:

The objective was to successfully remove particulates to the required levels over the entire test period (200 hours) without operational or component failure. These requirements are determined by the chosen gas turbine, the process design, and NSPS requirements. According to Stone & Webster Engineering Corporation, gas turbines can normally tolerate

100-200 ppmw particles up to 5 micron size without erosion. Particles larger than 5 micron should not exceed 8 ppmw with only 1 ppmw exceeding 10 micron. NYU test results showed that GBF collection efficiencies for the moderate and larger particle sizes above is not much different than the collection efficiency below 5 micron. Meeting the NSPS environmental limit of 29 ppmw is actually less restrictive than turbine tolerance limits. Results from the last two tests at NYU averaged 7 ppmw and 4 ppmw for particle loading at the GBF outlet, respectively. Media size was 2 mm for tests yielding 7 ppmw at the GBF outlet and 3 mm for tests yielding 4 ppm at the GBF outlet. Alkalis were removed with high efficiency but due to high temperature drop across the filter during measurements (200-300°F), removal was probably due to alkali condensation.

## SECTION III - Commercial-Size Granular Bed Filter:

The objective for this task was to estimate capital, installation, and operating costs of a Granular Bed Filter based on the concepts and principles developed in testing. A commercial-size design is based on the Philip Sporn PFBC Repowering Project. This is a proposed 330 MWe net power plant located in New Haven, West Virginia. The design proposed is in response to a Memorandum of Technical Requirements prepared by the Stone & Webster Engineering Corporation, Boston, Massachusetts. The hot gas cleanup train is designed for 2,885,000 lb/hr PFBC gas flow at 1550°F and 215 psia (168,525 ACFM) with a particulate loading of 500 to 2500 ppmw. In this design, 80 granular bed filter elements are divided among four pressure containment vessels that are 18' in diameter and 90' tall. The installed cost of the GBF system is $24,207,000 or $144 per ACFM in 1989 dollars.

Tests in the late 1970's and early 1980's of a subpilot-scale filter element at atmospheric pressure and at a temperature of about 1600°F demonstrated successful operation over a 1500-hour test period. Particle collection efficiencies of 99 percent were obtained and degradation of the collection media did not occur. The filter also operated successfully under upset conditions (inlet particle loadings 10 times normal and inlet gas flow rates 25 percent higher than normal). Testing at New York University demonstrated stable GBF operation downstream of a coal-fired PFBC at high temperature and pressure. Particulate was removed under steady-state and upset conditions to below the NSPS requirements and turbine tolerance limits.

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* - .03 lb/$10^6$ Btu NSPS limit, approximate conversion based on:
HHV of coal = 12,223 Btu/lb
1 lb coal requires 12.5 lb combustion gas
ppm = parts per million by mass

# SECTION I

# TEST REPORT

# FOR

# LIFE-CRITICAL COMPONENTS

# AND

# CRITICAL DESIGN PARAMETERS

# 1.0 INTRODUCTION

## 1.1 Purpose

Components of the Granular Bed Filter were chosen to be tested at Combustion Power Company (CPC). These components included the media circulation and ash handling systems. Tests were performed on these components and systems to assess their suitability for use in the high temperature, high pressure sub-pilot PFBC test facility located at New York University (NYU) in Westbury, NY. In addition, critical design parameters were tested for the purpose of quantifying these parameters for operation at NYU. Results from this testing were used to assess the suitability of this equipment for operation at NYU and for scale-up to commercial size equipment.

A nominal five hundred hours of testing included 1) identification of the operating envelope for high temperature, high pressure media circulation system, 2) demonstration of the pressure reduction system for ash-laden lift-air, 3) determination of ash concentration limits in the media, and 4) measurements of equipment erosion and media attrition.

## 1.2 Objectives

The objectives of the test program were:

- Demonstration of the operation of the media circulation system components and the ash handling system components.
- Identification of the operating envelope for this high pressure media circulation system.
- Determination of choking velocity for GBF media as a function of pressure and temperature.
- Reconciliation of existing media transport model with resulting data.
- Demonstration of the double airlock system for discharging ash from the pressurized baghouse.
- Identification of likely wear areas and measurement of media attrition.

## 2.0 TEST EQUIPMENT

To address the critical attributes of high pressure solids circulation and ash removal in the subpilot-scale test module, a test system was constructed for operation at CPC. The capacity and construction of the system was identical to that proposed for testing at New York University (NYU) so that it could be used in both installations. It was designed to operate from 1 to 10 atm and circulate 2 mm and 3 mm media at up to 100 lb/min utilizing 4 to 18 lb/min transport air. Dust addition capability of up to 1 lb/min was provided. Indirect heating allowed assessment of temperature trends in the range from 60F to about 550F. Provisions for measurement of erosion were made.

### 2.1 Test Module Configuration

Equipment installed at CPC comprised only a portion of the GBF equipment. The complete GBF gas cleanup system consists of three main subsystems:

- The granular bed filter element in which the particulates are removed from the incoming gas stream.
- The media circulation system which continually withdraws dirty media from the apex of the element cone and returns cleaned media to the top of the element.
- The ash handling system which transports the particulate separated from the media to the ash storage bin.

Life-critical component testing at CPC included construction and testing on the latter two systems listed above; that is, the media circulation and the ash handling systems.

A process flow diagram is shown on Figure 2-1. System pressurization was by use of a DOE-owned compressor regulated such that pressures could be maintained within the range of 4-8 atm. In place of the filter vessel was a GBF simulation vessel that acted as a receiver for both the system pressurizing air and the ash, much like the filter vessel itself. Heat was added to the test system by passing hot combustion gases through a heat exchanger mounted just downstream of the boost blower. The boost blower was a rotary vane compressor that was limited to a 300F maximum inlet temperature up to 10 atm. To achieve this blower inlet temperature and stay above the expected dewpoint of the high pressure flue gas at the baghouse, two heat exchangers were necessary. The heat exchanger upstream of the baghouse was sized to lower circulation gases to 500F using air for cooling. Downstream of the baghouse a water-cooled heat exchanger cooled circulation gases to 300F or less. To remove any condensation and to protect the boost blower in case of a baghouse failure, a coalescing type air filter was installed just upstream of the boost blower.

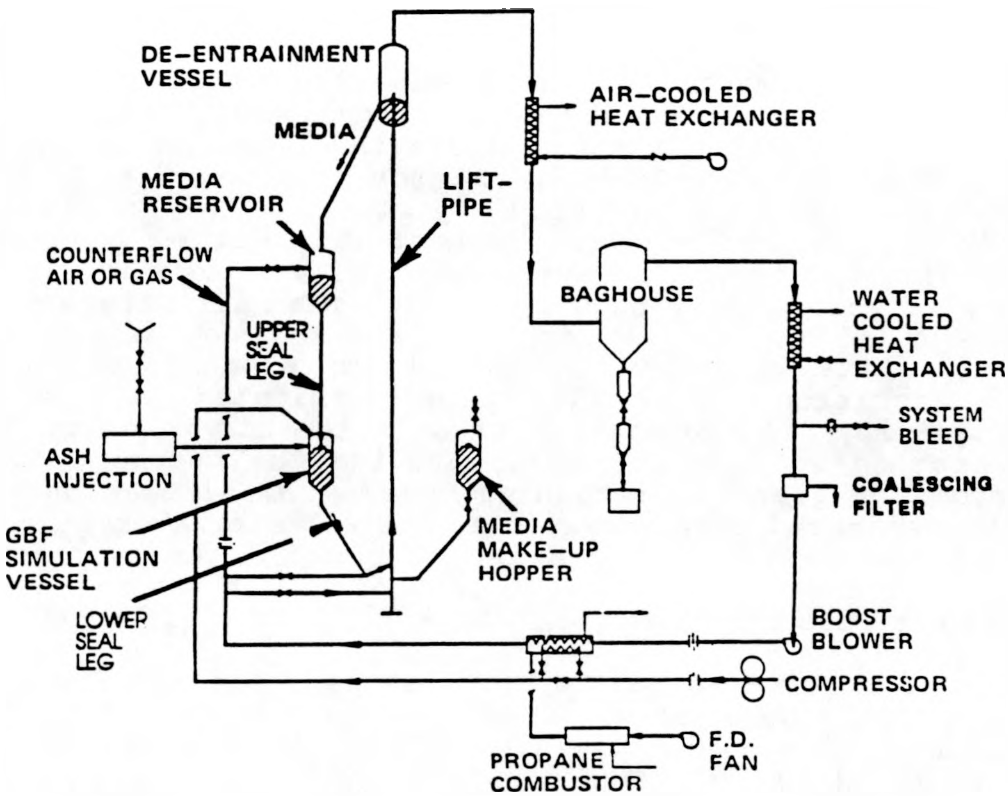


**Figure 2-1. Process Flow Diagram for Critical Component Testing**

High alumina filter media, 2 or 3 mm diameter granules, flowed continuously from the filter simulation vessel. Ash could be injected depending on the test. Media was pneumatically circulated at a rate of 10-60 lb/min up the 2" diameter lift-pipe. As the ash-laden filter media was transported vertically through the lift pipe, the media was cleaned. At the top of the lift pipe, a de-entrainment vessel separated the cleaned filter media from the now ash-laden transport gas by air velocity classification. The cleaned filter media then flowed by gravity to a media reservoir located above the GBF simulation vessel.

The airflow requirements of the pneumatic system depended on operating pressure and temperature conditions. The airflow control system could provide the optimal operating point under variable process conditions. See Appendix IA for the description of the media transport model developed by Combustion Power during development of the low pressure, commercial, gravel bed filters (Grace, 1979). The pneumatic system control was arranged to limit the media lift velocity to under 20 ft/sec in an air stream flowing in the range of 40 to 100 ft/sec depending on pressure and temperature. This was to minimize both containment wall erosion and media attrition. The lift pipe terminated into a large diameter, gravity disengagement section. The air velocity in the expanded section was controlled to provide the cutpoint for the size of media or granules returning to the GBF simulation vessel and for the separated dust conveyed to the ash storage system. The function of the counterflow gas into the media reservoir was to block separated dust particles from returning with the media to the GBF simulation vessel.

The media reservoir was sized to provide space for media inventory to compensate for media volume variations due to heat up, cool down and ash accumulation on the media. The seal leg between the media reservoir and GBF simulation vessel limited gas leakage under conditions of differing pressure.

The hot, particulate-laden transport gas leaving the de-entrainment vessel was cooled and sent to a pressurized baghouse for ash removal. Cooling was achieved first by radiation in a 40 ft long uninsulated steel pipe, then by convection in an air-cooled heat exchanger. Temperature entering the baghouse was nominally 500F. Care was taken in the design of the air-cooled heat exchanger to keep the inside tube walls above the circulation gas dewpoint, otherwise the ash-laden transport gases would quickly foul the heat exchanger.

The collected dust from the baghouse was transported to a disposal bin by a double lockhopper arrangement. The cleaned transport gas was recompressed and circulated back to the media transport system. The transport gas at CPC was compressed air that was being recirculated through the closed transport gas system. At NYU, PFBC flue gas was used for media and ash transport.

Figure 2-2 shows an elevation view of both the CPC critical component test system and the NYU pilot-scale filter. These views are shown in a single plane for clarity, but are depicted somewhat to scale vertically, to give an idea of the physical differences. The 10 foot height difference between the NYU and CPC test facilities saved cost in the support structure at CPC and in the GBF simulation vessel. Operational differences due to this change are discussed in section 5.0.

For successful operation, the media circulation and ash handling systems must exhibit the following key features;

- The media returns clean (dust free) into the GBF simulation vessel.
- Plug flow of media in the seal legs restricts gas flow from the GBF simulation vessel into the circulation system.
- Media is cleaned while hot, and returned to the GBF simulation vessel at the lowest possible heat loss.
- The lift gas transports the separated particulates to the ash removal equipment.
- The pressure in the circulation system is controlled, as necessary, to assist ash removal from the filter, utilizing pressure balancing techniques.

## 2.2 Pressure Balancing

There are two methods available for balancing pressure in the circulation loop. If the system bleed valve shown in Figure 2-1 is closed, the system pressures come to equilibrium without outside influence. The GBF circulation system is sealed to everything except the GBF (or the GBF simulation vessel), and the pressures adjust to the filter pressure. Lift-pipe pressure drop is divided across the lower and upper seal legs. Since these seals are merely columns of media, some gas leakage will occur up the lower seal leg into the filter and from the filter up into the media reservoir. The velocity of these leakage gases, however small it is, may cause ash to dislodge from the media and concentrate at the lower apex of the filter cone. This ash may continue to build up until it causes media circulation problems. Since media in the upper seal leg (above the filter) is clean, leakage countercurrent to media flow is not harmful as long as gravity flow and distribution is unencumbered.

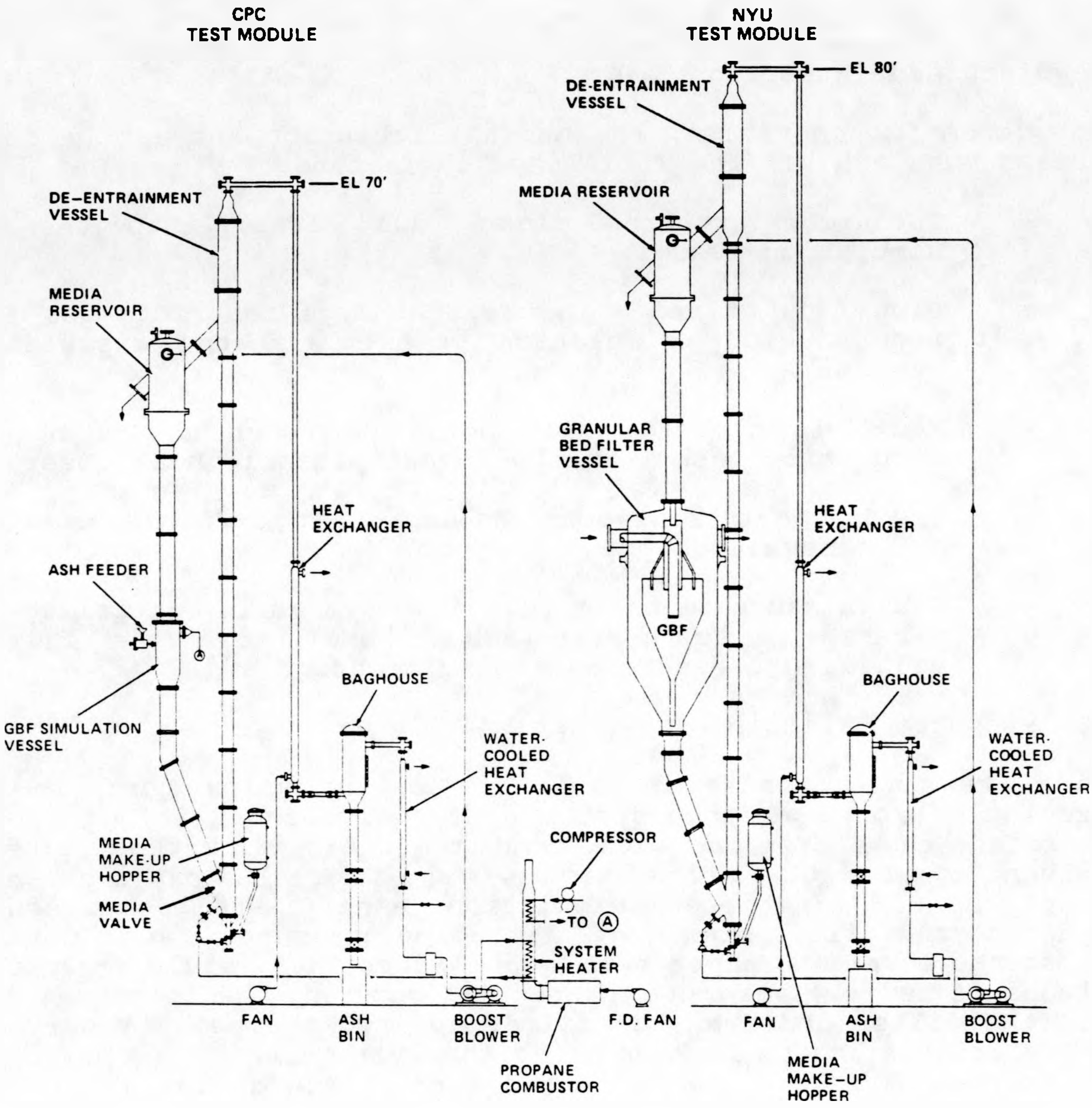


**Figure 2-2. Test Facilities Installed at CPC and NYU**

The system is designed so that the pressure at the bottom of the lift pipe can be made equal to or slightly less than the GBF element outlet pressure. This was achieved by a technique called "artificial" pressure balancing in early work but simply referred to as "pressure balancing" in later work. It allowed the seal leg full of ash-laden media to operate at essentially zero reverse air flow, a condition which enhances ash flow from the filter cone into the seal leg.

To achieve artificial pressure balancing in the test module, a small amount of circulation gas was bled to atmosphere just downstream of the water-cooled heat exchanger. The gas bled came from the filter and flowed up through the upper seal leg and down through the lower seal leg to the bleed point. It is the elimination of upward flow of gas in the lower seal leg that avoids ash removal problems. The pressure drop across the upper seal leg could be made equal to the lift-pipe pressure drop if the pressure drop across the lower seal leg was zero. The length of the seal legs defined the actual bleed air flow.

## 3.0 TEST METHODS

The test plan originally proposed (January, 1985) was revised to increase the test matrix. Primarily, parametric testing was expanded to include temperature as a variable in characterizing the media circulation system. A method was also devised to mechanically measure circulation rates so they could be compared with the theoretical values. Instead of running selected points within the test matrix (latin-square matrix), all matrix test points were verified.

The general test plan is presented below. Detailed steps to implement the test plan are contained in Appendix IB. A piping and instrument diagram is included in Appendix IB to aid in interpretation.

### 3.1 Equipment Checkout and Shakedown

Critical equipment was verified to operate within specified guidelines. Instrumentation was checked and calibrated. The system was brought on line in a careful manner to prevent unintentional damage due to operators not being familiar with the system. Operator training was included. Procedures involved:

- Pneumatic pressure (leak) testing.
- Checking for cooling water flow.
- Checking for cooling air flow.
- Measuring combustion air capability for the propane combustor.
- Setting up the baghouse pulse air system.
- Checking level switches, thermocouples and pressure gauges.
- Bringing the boost blower on-line.
- Checking pressurized operation (without filter media).

### 3.2 Pressure Reduction Test

Prior to operation of the test lift pipe system, the ash pressure reduction system consisting of two Kamyr ball valves in series was checked out at ambient temperature and various pressure levels. Operation was evaluated and a final system design developed from these operations. Operation of the pressure reduction system was observed closely during the remaining test sequences.

### 3.3 Operating Envelope Parametric Tests

This test series consisted of approximately 110 short-term parametric tests addressing the following independent variables:

| Variable | No. of Setpoints |
|---|---|
| System Pressure | 2-3 |
| System Temperature | 3 |
| Lift Air Rate | 3 |
| Media Circulation Rate | 4 |
| Pressure Balance Profile | 2 |

Generation of data sets to fulfill parametric testing requirements was completed as follows: 1) A temperature and pressure level were achieved. 2) A lift-air rate was chosen and verified. 3) Media circulation was set at four levels over a wide range as measured by lift-pipe pressure drop and verified by mechanical means. 4) Lift-pipe air flow was reset and four more media circulation rates set and verified.

At the conclusion of the data set at each temperature and pressure level, the pressure balance profile was altered at preselected levels of lift-air flow and media rates. This adjustment was made by bleeding circulation gases to atmosphere downstream of the water-cooled heat exchanger. This technique produced an "artificial" pressure balance profile characterized by reversing the pressure drop across the lower seal leg such that leakage air flowed from the GBF simulation vessel to media valve. Measurements included: time to reach equilibrium, bleed gas flowrate, and notations on circulation system characteristics. Prior to moving to different temperatures and/or pressures, a choking test was completed by lowering lift-air flow until media collapse was imminent.

One objective of the parametric tests was to identify an optimum lift-pipe airflow for transporting the media-air mix based on temperature and pressure. This optimum flow was intended to be a balance between the following circulation characteristics:

a. Maintaining a reliable circulation (a safe distance away from choking).

b. Circulating in a region where small changes in lift- pipe airflow do not significantly change lift-pipe pressure drop; thus giving a false indication of circulating rate.

c. Circulating with high enough velocity to maintain adequate separation of ash from media.

d. Circulating with low enough velocity to minimize wear and attrition.

Figure 3-1 shows a theoretical plot of optimum lift-pipe air flows. This plot was generated by utilizing the media transport model described in Appendix IA. Priority was assigned to minimizing velocities of the media and transport air. At the time this graph was generated, choking was not felt to be a problem and neither was ash-media separation.

### 3.4 Choking Tests

Media entering the lift pipe too rapidly can choke off the transport air. Conversely, if the transport air flow is too low to move media up the lift pipe, media will accumulate and also choke off the transport air. By lowering lift-pipe airflow, choking airflow or velocity could be estimated but in practice, choking was usually caused by a surge in media flow.

The choking velocity at each temperature and pressure level was determined as a part of each test matrix. This characteristic was weakly dependent on steady media flow and in practice was difficult to identify precisely. As the lift-pipe approached a choking condition, the lift-pipe pressure drop fluctuated widely and actual media rates changed too fast to measure with our equipment. Knowing the choking velocity is useful for defining the difference between the optimum lift-air rate and choking lift-air rate. The optimum lift-air rate allows a reasonable margin from choking but maintains lift-air velocity and media velocity at moderate levels to minimize erosion and attrition.

### 3.5 Ash Concentration Tests

A short series of tests was conducted to identify the concentration of ash in the filter media which resulted in operational difficulties with the recirculation system. Media circulation rate was set at a low rate (15-20 lb/min) and the ash input rate increased in steps to simulate ash loading in the media. Tests were run at pressure with the circulation system cold and heated. Observations were made of pressure drops on the upper and lower seal legs as this would indicate if ash was being fed into the media without upsetting circulation. The baghouse and ash discharge equipment was monitored to indicate if ash was being removed.

### 3.6 Erosion and Attrition Tests

Before and after the entire series, refractory thicknesses at critical areas (media injection point, de-entrainment vessel, lift pipe joints) were measured. In addition, the weight of 2 mm media was monitored to determine if any attrition had taken place. Upon completion, the circulation system was disassembled, inspected for wear and made ready for shipment to NYU.

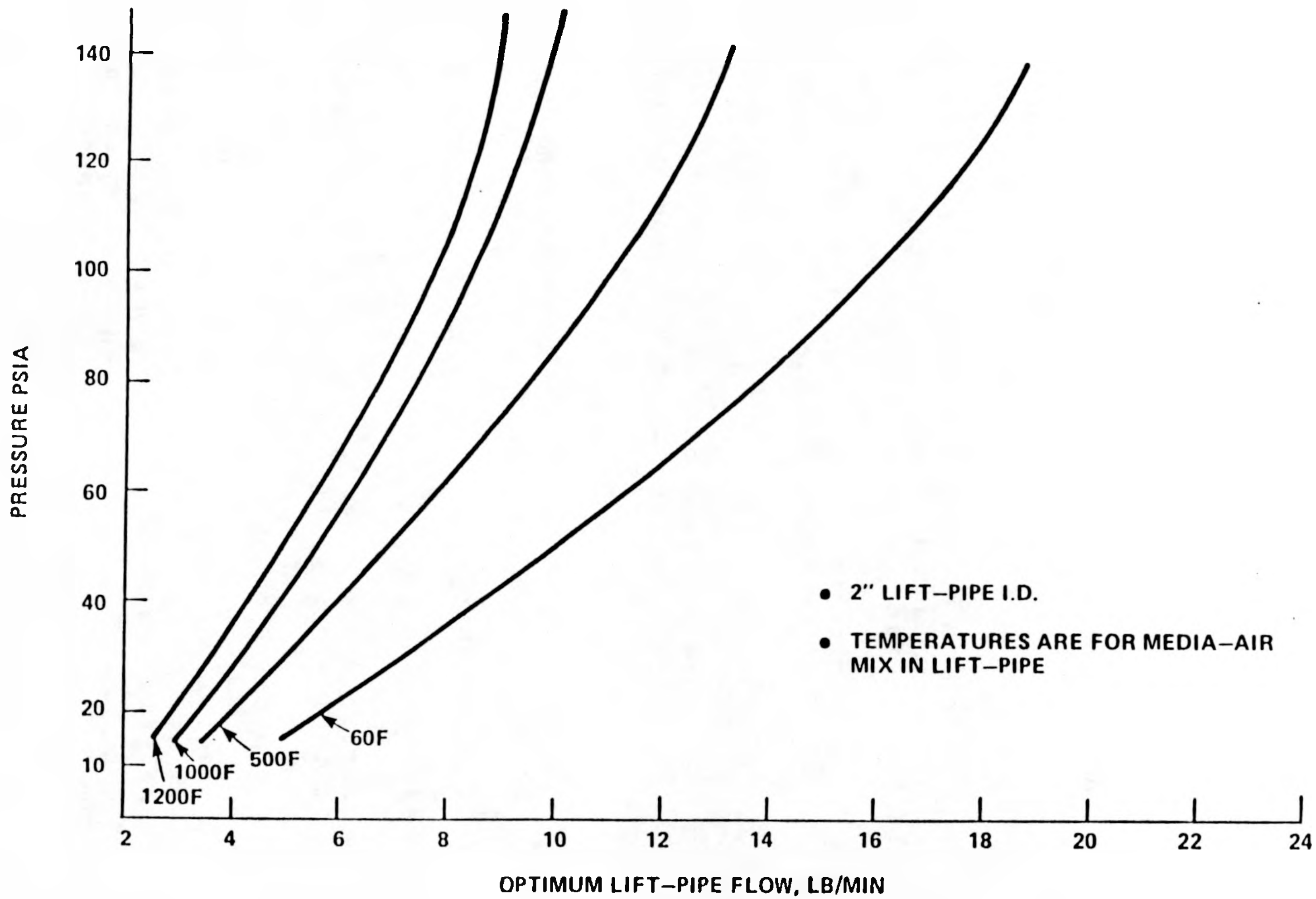


**Figure 3-1. Theoretical Optimum Lift-Pipe Air Rates**

## 3.7 Alternate Media Tests (3mm)

A study, supported by the GBF computer model, showed a scaled-up design utilizing 3 mm media is economically and technically attractive. By utilizing 3 mm media and a 6' diameter filter element instead of 5', the gas capacity through the filter can be nearly doubled at a modest cost difference. Although the study did not identify 3 mm media as the optimum size both technically and economically, it was shown that it was a more effective alternate than the base design with 2 mm media.

Tests were run to characterize 3 mm media in the Test Module at CPC. No design changes were required to handle the 3 mm media.

The media chosen was suggested by DOE. It was a sintered bauxite, spherical media available from the Norton-Alcoa Company. The material specifications were as follows:

a. Size distribution to be Norton-Alcoa size 6 made to ANSI B74.12-1976 Standard Table 2 limits which are:

    0% on a 3 1/2 mesh (USA Standard Sieves)
    20% max on a 5 mesh
    40% min thru 5 on 6 mesh
    70% cumulative min thru 5 mesh retained on 6 and 7 mesh
    3% max thru 8 mesh

b. Chemical composition to be according to Norton-Alcoa Product Code 1711, Sintered Bauxite, which is as follows:

| Chemical Name | Wt.% TYP | Common Name |
|---|---|---|
| Aluminum Oxide, $Al_2O_3$ | 75.9 | Alumina |
| Silicon Oxide, $SiO_2$ | 16.0 | Silica |
| Ferric Oxide, $Fe_2O_3$ | 4.0 | Iron |
| Titanium Oxide, $TiO_2$ | 3.1 | Titania |

c. Physical Properties

| | |
|---|---|
| Specific Gravity | 3.0-3.3 |
| Bulk Density | 130 lb/CF (Approximately) |
| Material Shape | Spherical, slightly uneven surface, no sharp edges, no broken spheres |
| Material Color | Brownish gray |
| Melting Point | >2000°C |

## 4.0 TEST RESULTS

Parametric tests were completed at CPC that compared measured and theoretical media circulation rates. These tests were run at different combinations of temperature, pressure, transport air flow, and media circulation rate. Other tests were run to observe the ash carrying capability of the media, the operation of the ash discharge system, and the characteristic of operation with larger (3 mm vs. 2 mm) media. A summary of results follows:

- Early parametric tests showed remarkable agreement between measured and theoretical circulating rates. Some disparity was noted at lower airflows. See Section 4.1 and 4.6.

- Continued parametric tests showed increased divergence between measured and theoretical circulation rates. Refractory wear in the lift pipe was suspected. Disassembly and inspection of the lift pipe showed abnormal wear in two unrelated areas identified in Section 4.6. Because refractory wear was significantly diminished in adjacent areas, defective materials or installation was suspected. Refractory was repaired prior to delivery of equipment to NYU.

- Tests showed that a very small amount of air could be bled from the circulation loop at the baghouse and result in a pressure profile favorable to moving ash and media in the same direction out of the filter. This technique is called "artificial" pressure balancing and was used during operation at NYU.

- Ash was loaded and circulated with the media to the 5-6% range (ash-to-media by weight). This coincided with expected results. These same ash loading tests suggested ash could easily bridge in the baghouse and double airlock discharge system. Steps were taken to insure reliable ash discharge at NYU.

- Media circulation, as evidenced by lift-pipe pressure drop, started and stopped in a reliable and controllable fashion. It was smooth and steady in the desired ranges.

- The de-entrainment vessel design was insensitive to all imposed changes in pressure, temperature and flow rate. Ash separation from media was achieved. Media carryover towards the baghouse was not detected even though occasional operator error resulted in velocities 25% above design.

- Heat exchangers performed adequately during this test series but were not really challenged to operate at capacity. We did not have enough heat input capability at CPC to assess the performance of the air-cooled and water-cooled heat exchangers. This was expected; also, it does not concern CPC because these heat exchangers are of standard design.

- Baghouse operation and pulsing had no adverse affect on the circulation system. A steady pressure drop across the coalescing filter downstream of the baghouse, responsive only to changes in air flow rates, indicated efficient baghouse operation.

- The ash pressure letdown system (sequencing the Kamyr ball valves) did not affect the circulation system. There was no fugitive dust problem at the ash collection barrel as all leakage gases were exhausted through a standard air filter.

- The boost blower was a sliding vane compressor. It provided a reliable and steady source of media transport air at a pressure rise of 6-10 psi. It was a positive displacement type machine so it automatically adjusted for pressure changes. It was run during periods of both stable and changing system pressures with no difficulties. The blower was attached to a mechanical type variable speed drive. Speeds were infinitely variable between about 725 rpm to 1700 rpm. Furthermore, the combinations of temperature, pressure, and media lift requirements all required blower speeds in a fairly narrow range above 50 psig. Only circulation at atmospheric conditions required a high blower speed, near 1700 rpm, to supply the necessary transport gas.

- At each unique level of temperature and pressure there appeared to be a range of optimum lift-pipe airflows as opposed to a single point. Choking (media collapse in the lift pipe) occurred at 50-75% of optimum lift-pipe air flows. In practice, this is quite a safe gap.

- Operation with 3 mm media produced results expected in that only about 5% more circulation air flow was necessary to transport the media. Otherwise 3 mm media behaved much the same as the 2 mm media from the transport standpoint. From the filtration standpoint, the minimum fluidizing velocity of 3 mm media is about 33% higher than 2 mm media at 1600°F and 10 atm which means that 33% more gas flow can be handled at the same percentage of minimum fluidization velocity. It is possible that a deeper filtration bed will be needed if 3 mm media is to remove particulate as effectively as 2 mm media; although, this was not indicated by demonstration tests at NYU.

## 4.1 Operating Envelope Parametric Tests

Media circulation rates were measured physically and compared with theoretical rates. Physical measurements were performed with a media follower. This was a 1/4" diameter metal rod with a 2" diameter disk attached to the bottom that rode the media downward in the media reservoir. The rod was sealed through the top of the media reservoir so an operator could follow its progress. Media flow through the media reservoir was even throughout the cross-section as confirmed by testing. This allowed for a simple calculation for media circulation rate knowing the media reservoir cross-sectional area, the rate at which media moved downward, and media bulk density. Parametric tests were run at different combinations of temperature, pressure, transport air flowrate, and media circulation rate. The data sets generated were:

PARAMETRIC TESTS

| DATA SET I.D. | LIFT-PIPE TEMP @ TOP (°F) ±20°F | LIFT-PIPE PRES @ TOP (PSIG) ±5 PSIG | NOMINAL TRANSPORT-AIR FLOW, LB/MIN | | |
|---|---|---|---|---|---|
| | | | SETPOINT 1 | SETPOINT 2 | SETPOINT 3 |
| 1 | 60 | ATM | 5.0 | 6.0 | 7.0 |
| 2 | 60 | 50 | 11.5 | 12.5 | 14.5 |
| 3 | 60 | 90 | 16.0 | 19.0 | 22.0 |
| 4A | 400 | ATM | 3.8 | 4.25 | 5.0 |
| 5A | 400 | 50 | 11.0 | 9.5 | 8.5 |
| 6A | 400 | 90 | 12.0 | 14.0 | 16.5 |
| 5 | 550 | 50 | 8.0 | 9.0 | 10.5 |
| 9A | 550 | 90 | 11.0 | 13.0 | 15.0 |

Setpoint 1 transport airflows are the theoretical optimum lift-pipe air rates plotted on Figure 3-1.

The planned data set at atmospheric pressure and 550F was deleted because temperature could not be maintained. At the low pressure, the corresponding low mass flow of circulating gases did not contain enough heat to overcome convective losses from the circulating system.

Data from two of the eight data sets is shown plotted on Figures 4-1 and 4-2. Measured circulation rates are overlayed on a plot of theoretical circulation rates. Some agreement and some disparity is apparent by inspection of the data presented.

Figure 4-1 for Data Set 2 shows only reasonable agreement between theoretical and measured media rates at the highest lift-pipe airflows. Figure 4-2 for Data Set 3 shows remarkable agreement at the highest two lift-pipe airflows, M2 and M3, but disparity at the

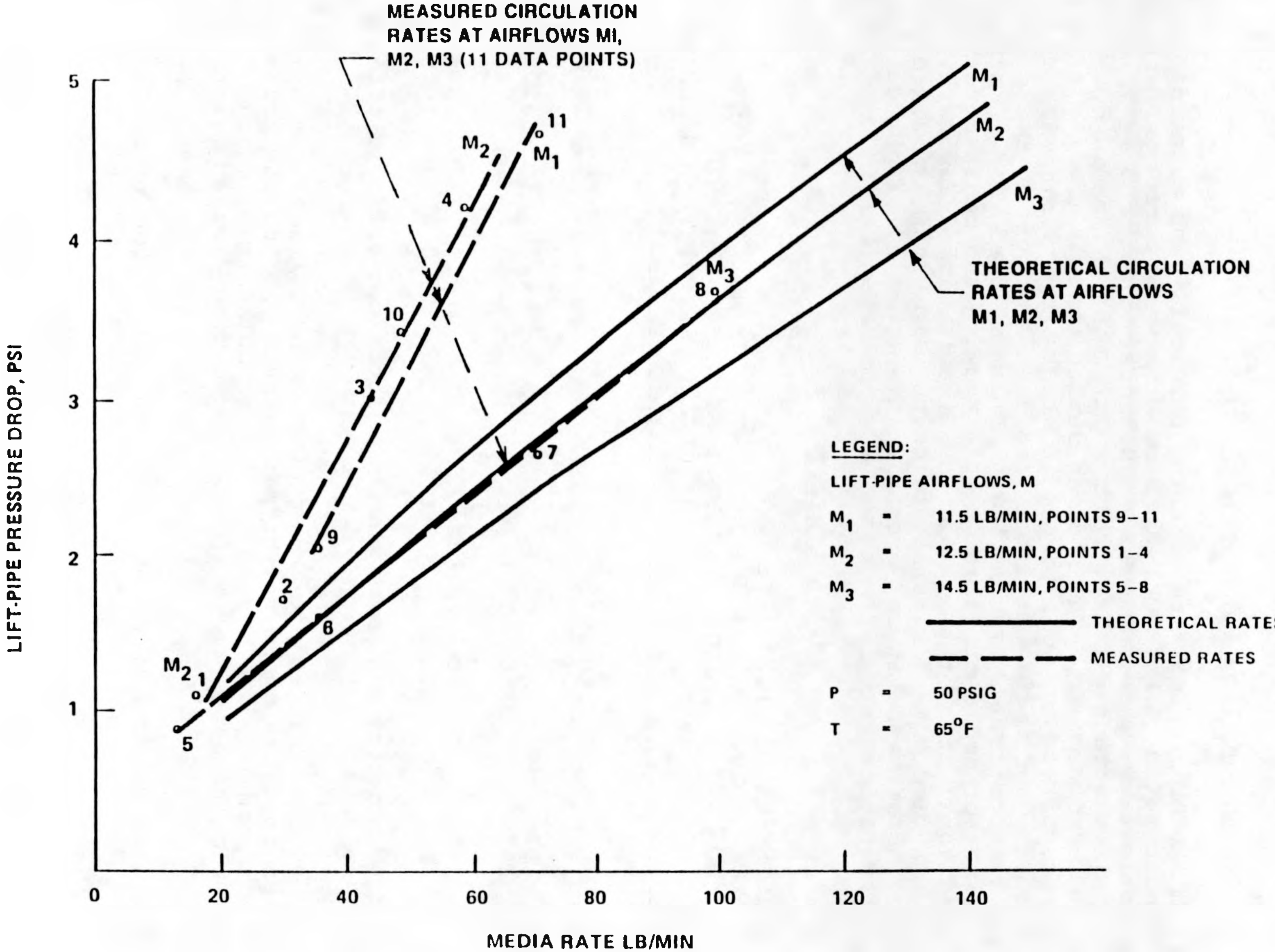


Figure 4-1. Media Rates in 2" ID Lift-Pipe, Data Set 2

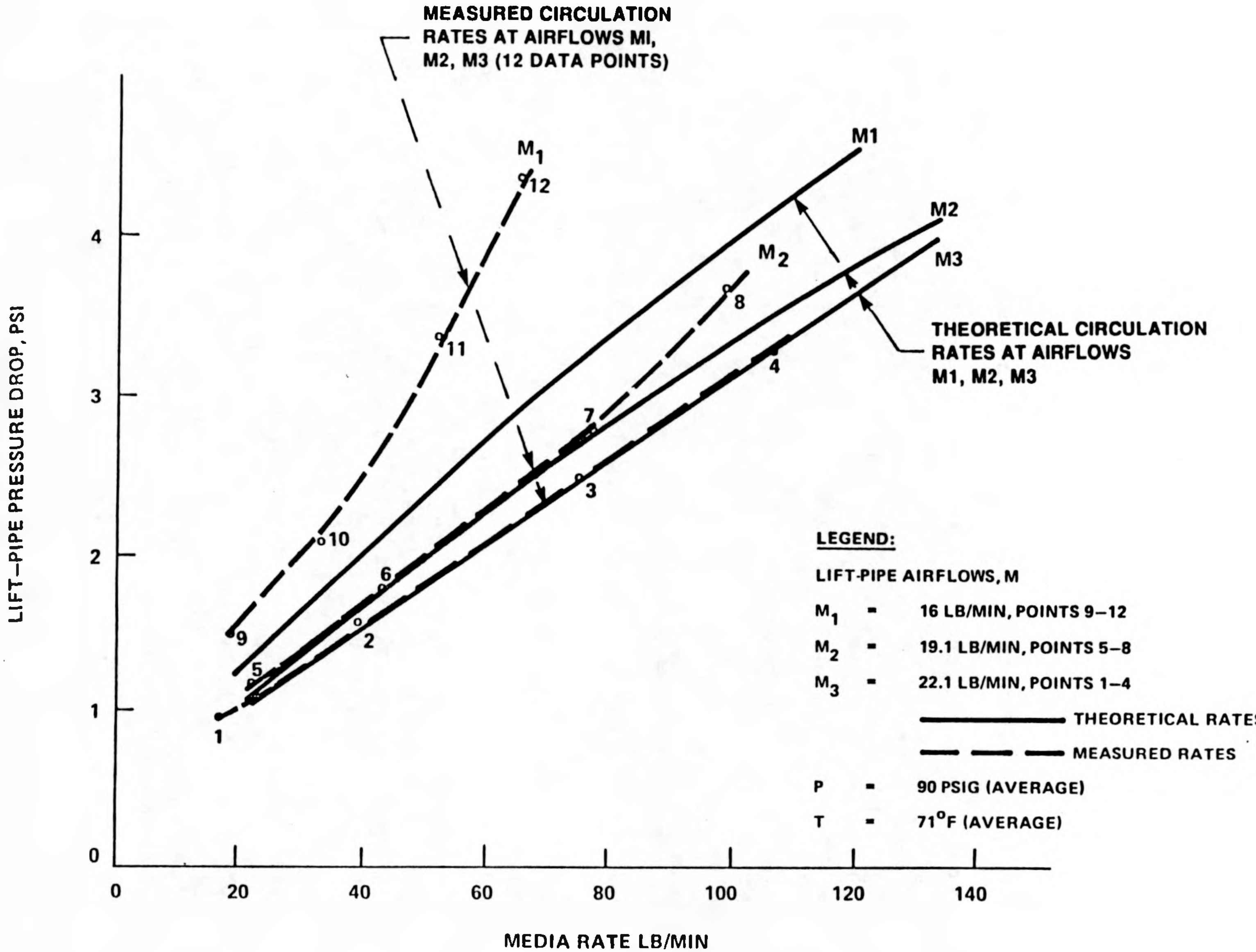


**Figure 4-2. Media Rates in 2" I.D. Lift-Pipe, Data Set 3**

lowest airflow. The remaining data sets generally followed the pattern shown on Figure 4-1 in that all measured circulation rates fell to the left of the respective theoretical rates. The reason for this disparity was not well understood until the circulation system was disassembled for inspection at the end of the test series. At this time, abnormal wear was discovered in one of the lift-pipe segments. This wear could account for the poor agreement between measured and theoretical circulation rates especially in later data sets.

As a result, the data gathered can only be used to reconcile the existing media transport model (Appendix IA) in general terms. Early tests showed, as shown on Figures 4-1 and 4-2, good agreement between measured and theoretical media rates but only at higher transport airflows. Even this data could be biased by the abnormally worn lift-pipe section mentioned above. Nevertheless, the early tests indicate that the media transport model does generate information that, at the very least, is a good place to start. CPC used the media transport model to predict lift-pipe flow characteristics for operation at NYU. This prediction is presented in Section 5.0 and subsequently verified during NYU operation.

## 4.2 Choking Tests (Media Collapse)

Choking (also discussed in Appendix IA) is the velocity at which the column of solids can no longer maintain smooth upward flow. In practice, this point is difficult to pinpoint because the instability of the transport process near choking is reflected in the instrumentation. Furthermore, once the media flow was allowed to collapse to a column of static voidage, recovery required draining media from the bottom of the seal leg. (Note: It was later discovered during NYU testing that a choked lift pipe could be cleared on-line a high percentage of the time, say 90%.) During testing, choking was designated to be at the lowest lift-pipe air flow at which media would transport. This point was found by lowering transport airflow until the lift-pipe pressure drop fluctuated widely (2-5 psi) and, in the operator's opinion, lowering the airflow further would result in complete loss of media circulation. As the lift-pipe pressure drop fluctuated widely, so did the transport airflow, making data indications imprecise. Data on choking airflow is tabulated below and compared with the minimum amount of transport air contemplated for vertical transport at the reported pressure and temperature.

DATA ON CHOKING AIRFLOW

| Lift-Pipe @ Top Press. (Psig) | Temp (°F) | Min. Transport Airflow (lb/min) | Choked Airflow (lb/min) | % Choked to Min. Transport % |
|---|---|---|---|---|
| 50 | 65 | 11.7 | 8.4 | 72 |
| 54 | 386 | 8.5 | 5.7 | 67 |
| 47 | 491 | 8.3 | 5.3 | 64 |
| 96 | 70 | 16.0 | 10.6 | 66 |
| 95 | 386 | 12.2 | 8.5 | 70 |
| 95 | 556 | 11.0 | 7.8 | 71 |

Since the operators didn't allow the media column to collapse to static voidage during the choking test, it is likely that the choked airflow is somewhat lower then reported. In instances when the lift pipe completely choked, the lift pipe pressure drop climbed to a high level, in the range of 10 to 25 psi depending on how much media got trapped in the lift pipe.

In the choking airflow test, lowering the airflow to 70% of the initial flow resulted in a flow orifice pressure drop about 50% of initial. This is quite a substantial change and made accurate gauge reading difficult. Furthermore, the media column did not collapse without plenty of warning in that the flow became highly unstable. The conclusion is that choking occurs sufficiently far enough away from minimum transport flow and with enough warning that it should not prove to be a problem. (Note: During subsequent testing at NYU, it was found that choking almost always occurred because an upset or operator error resulted in a surge of media entering the lift pipe which choked off airflow. This condition was not foreseen.)

4.3 <u>Pressure Balancing</u>

The "pressure balance profile" variable refers to two qualitative types of leakage. The first is characterized by allowing leakage flow up the lower seal leg. This leakage is in the opposite direction of the media and ash flow, and will occur without any adjustments to the system. This may be referred to as a "normal" pressure balance. The other type of leakage is characterized by inducing leakage flow down the lower seal leg and is referred to as an "artificial" pressure balance mode. This leakage is in the same direction as the media and ash flow and may aid in filter operation.

To create the "artificial" pressure balance condition, air was exhausted in a controlled manner just downstream of the water-cooled heat exchanger to impose a pressure drop of 0.5 to 1.0 psi across the lower seal leg (GBF simulation vessel to media valve). It took 15 to 30 minutes to achieve equilibrium after opening the system bleed valve. Changing the circulation rate by adjusting the lift-pipe pressure drop would affect pressure balance so the operator had to be careful about making this transition. Once adjustment had been completed, the test module ran steadily. The amount of air exhausted to atmosphere was 0.6 to 1.0 lb/min for a filter element sized for at least 250 lb/min of PFBC flue gas. Among other factors, the amount of air bled to the atmosphere depends on the length of seal legs. With longer seal legs, less air would need to be bled to atmosphere to achieve the desired seal-leg, pressure profile, but overall system height increases.

4.4 Ash Pressure Reduction Tests (High Pressure Baghouse Ash Discharge to Atmosphere)

Leakage tests on the 4" Kamyr valves for ash handling received from the government indicated two of the three valves to be in fairly good condition. At 99 psi pressure differential across each closed valve, the leakages measured were:

| Valve Serial # | Individual Valve Leakage, SCFH |
|---|---|
| K1044 | 30 |
| K1045 | 5 |
| K2059 | 1 |

The two best valves, K1045 and K2059 were bolted in series and the leakage across both closed valves measured at 0.3 and 0.4 SCFH for two separate tests. This leakage is .004% of the lift-pipe air flow, and did not have any apparent effect on circulation as expected.

When ash is discharged from the baghouse, the double lock hopper arrangement built with the Kamyr valves above would be cycled. The cycle utilized pressure from the circulation system. The action of bleeding pressurized gas into the lockhopper isolated between the two Kamyr valves could conceivably upset media circulation. This upset did not occur, probably because gas was bled slowly from the circulation loop through a control orifice.

4.5 Ash Concentration Tests

The purpose of these tests was to determine if there was a maximum ash/media ratio for successful circulation. Testing in the late 1970's and early 1980's on the atmospheric GBF filter suggested a maximum of 17:1 media to ash ratio, or about 6% ash in media by weight. Above this ash loading, it was felt that difficulties would be experienced pneumatically circulating the mixture. To recreate the characteristics of ash loaded media, an ash feeder was installed and operated as shown on Figure 4-3. The ash feeder loaded ash into media just above a conical transition that was

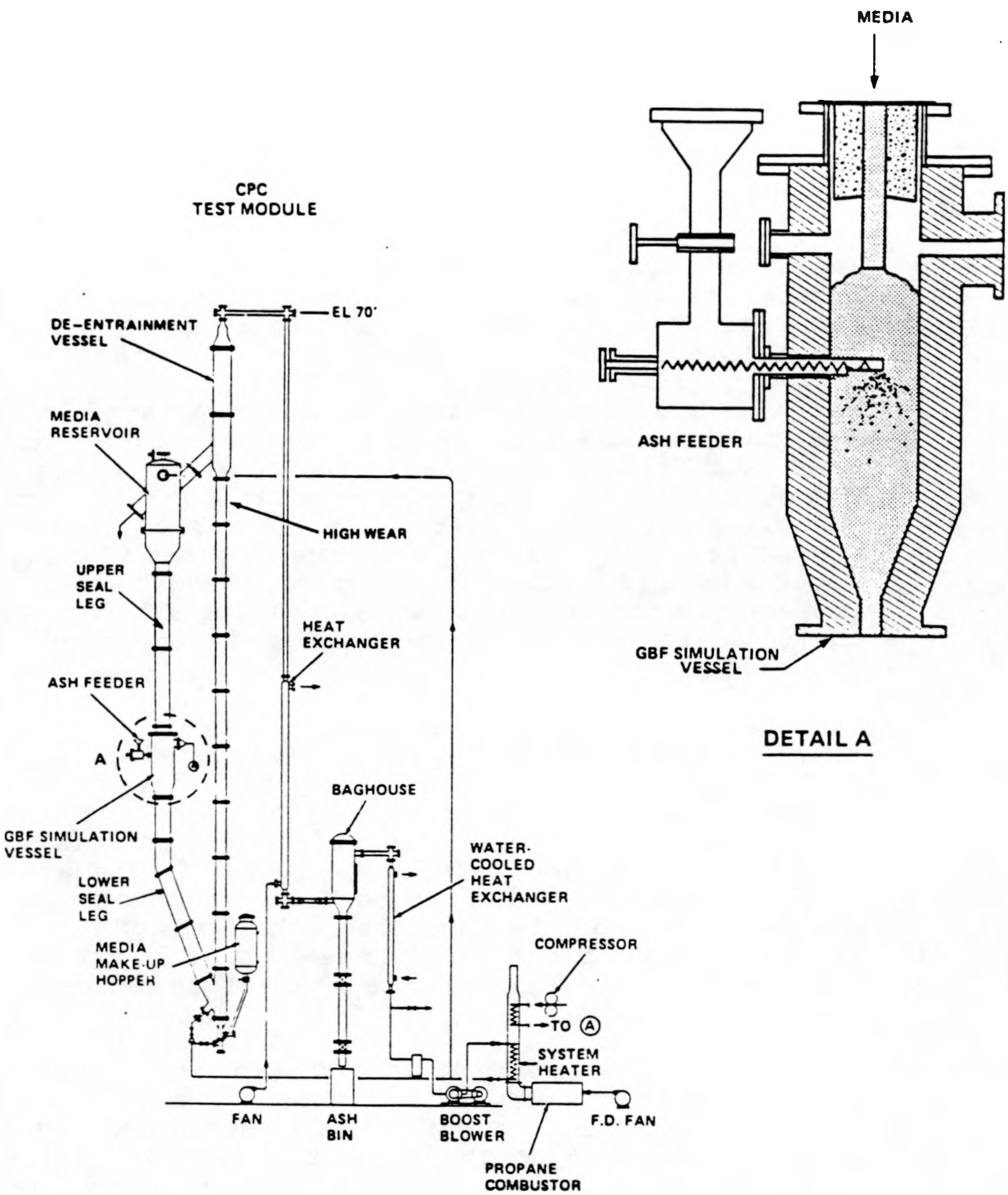


**Figure 4-3. Ash Feeder Location & Operation at CPC**

identical to the GBF ash/media outlet into the lower seal leg. The plan was to conduct one-hour ash loading tests on a heated and pressurized system. Ash was to be added at 2%, 5%, 10% and 15% of media circulation rate (by weight). Observations were to be made on a normally pressure balanced system and an artificially pressure balance system. Note that all testing on the near-atmospheric pressure, high temperature filter (1977-1982) had been done on an artificially pressure balanced system (Guillory, 1983).

Results were:

1) The first test, back in April, 1986, suggested that a normal pressure balance would not work well as bridging occurred at the top of the lift pipe, but problems with the ash feeder halted testing.

2) Tests in the last quarter of 1986 showed again that with a normal pressure balance, the ash substitute (Kaolin and Catalytic Cracker ash) tended to accumulate, at all ash rates, at the bottom of the cone in the GBF simulation vessel. Remember that normal pressure balance is characterized by lift-pipe transport gases leaking up the lower seal leg towards GBF simulation vessel. This leakage gas can, theoretically, prevent ash from entering the seal leg because the terminal velocity of the ash is exceeded.

3) Other tests in the last quarter of 1986 showed that ash could be successfully circulated with media up to about a 5% ash/media mix if the system was artificially pressure balanced. This is equivalent to 8000 ppmw ash in the NYU full flow of 15000 lb/hr process gas assuming a media circulation rate of 40 lb/min. The artificial pressure balance is characterized by inducing leakage gases to flow down the seal leg out of the GBF simulation vessel. Down flow of leakage gas into the seal leg induces ash flow through the apex of the cone into the seal-leg.

4) The ash concentration tests showed that difficulties could be experienced with bridging of ash at the baghouse and ash hoppers. To assure this is not a problem at NYU, a manual override to the automatic system was installed along with some pneumatic blasters. The manual override function was accomplished by building an auxiliary panel with the necessary pushbuttons, gauges and static lights to monitor the ash unloading process. Pneumatic blasters were controlled by pushbuttons on this panel and were installed in the baghouse hopper and the lower ends of each ash hopper. The panel was used at CPC before shipping to NYU. Heat tracing was added to the baghouse hopper and both ash hoppers at NYU.

## 4.6 Erosion and Attrition

### Erosion

Part of the testing included observation of erosion on refractory-lined pipe. To provide baseline data, measurements were made on the refractory ID at selected locations. These locations were chosen according to erosion potential. Four measurements were made around the refractory diameter to establish baseline data. These measurements were made with dial calipers at the ends of pipe segments and at equipment inlets/outlets. On disassembly, the same place were checked for dimensional changes. These same areas were measured after NYU testing to get the longest term data possible for predicting wear.

In some areas, such as in the media reservoir and the upper section of the de-entrainment vessel, very little wear was evident as the spiral indentations from the refractory installation forms were still clearly visible. This should be expected in the media reservoir as media movement is very slow (1-2 inches per minute) and little wear had been expected. On the other hand, in the de-entrainment vessel, media motion is quite turbulent and some wear had been expected.

Measurements on the nominally 3" I.D. seal-legs showed negligible wear that was not measurable over the test period. In the seal legs located beneath the media reservoir and GBF simulation vessel, the media moves by gravity at 2-10 inches per minute so the potential for wear is relatively low.

The lift pipe, nominally 2" I.D., was noticeably worn in all sections. Even though measurements showed that the diameter generally increased from 1% to 5%, the inside surface had roughened appreciably and there were crevices to about 1/2" deep in some areas. The higher wear areas were at the bottom and top of the lift pipe with one very notable exception. A central lift pipe section, the fourth one up from the media valve, was unevenly worn to 4"-5" I.D. See Figure 4-4 for location. The 5' long section of pipe below and above this section were worn about the same as all the other sections. Furthermore, based on CPC experience with commercial media lift systems, wear is usually concentrated in the media valve area and the lower 10' of lift pipe. This section was about 25' above media injection.

Our conclusion is that there was some imperfection with the materials or installation in that section. (Note: Subsequent experience at NYU confirmed this to be true.) The refractory installers were inclined to agree until they were reminded about their guarantee. The top section of lift pipe was worn a little more than the average. This section, located on Figure 4-4, was heavily creviced and roughened; although the ID had increased only about 5%. This section, along with the one described above, were relined for operation at NYU. The same materials and installation techniques originally used were utilized. Both sections showed wear at normal rates at NYU indicating that abnormal wear was a materials problem as opposed to a process problem.

The abnormally large diameter in the central section of lift pipe accounts for the disparity between measured and theoretical circulation rates. Apparently as media circulation was started, media would begin to occupy this section in higher concentration than in adjacent sections. This would increase pressure drop. As media circulation increased, so did the media concentration in this section. One might picture an equilibrium being reached where media enters the worn section, bounces around, and "fluidizes" its way to the upper surface where it is picked up in the off gas. Earlier in the test series this sort of wear was theorized for the media valve or shortly above, based on the observed discrepancy between measured and theoretical circulation rates, but was not found on inspection. This means that all parametric data, except that gathered very early in the testing, is not representative of the actual system. Fortunately, measured and theoretical circulation rates were in reasonable agreement in early testing. We are still confident that we can predict lift-pipe pressure drop vs. circulation rate with reasonable accuracy.

At NYU, physical measurements of circulation rates confirmed the theoretical values. This was accomplished by applying the media follower used at CPC, with minor redesign, and spot checking media rates.

One other area of abnormal refractory wear was found in the media return pipe attached to the de-entrainment vessel. Here the 3 1/2" ID surface wore unevenly to about 4". The refractory appearance was much like the abnormally worn lift pipe. The fact that the wear was much less here than in the lift pipe is consistent with the potential for erosion in this area. Interestingly, the adjacent section of the media return pipe, attached to the media reservoir, was unaffected. This further reinforces the hypothesis that some defect in materials or installation affected the refractory performance. This area was patched by inserting a 316 SS sleeve that restored the 3-1/2" ID.

The performance of the refractory lining in the lift pipe raises some suspicion on its suitability for commercial use. It is possible to explain the minor increase in diameter, the crevice forming, and even the abnormal loss of refractory on problems due to the scale of the work. Forming and pouring a good castable refractory mix to a 2" I.D. is a challenge. If the I.D. was 6" as in commercial-scale, good workmanship would be more easily achieved because of more work space. Nevertheless, we felt it would be wise to investigate other approaches to lining the lift pipe. For operation at NYU, two new 5' long lift-pipe segments were

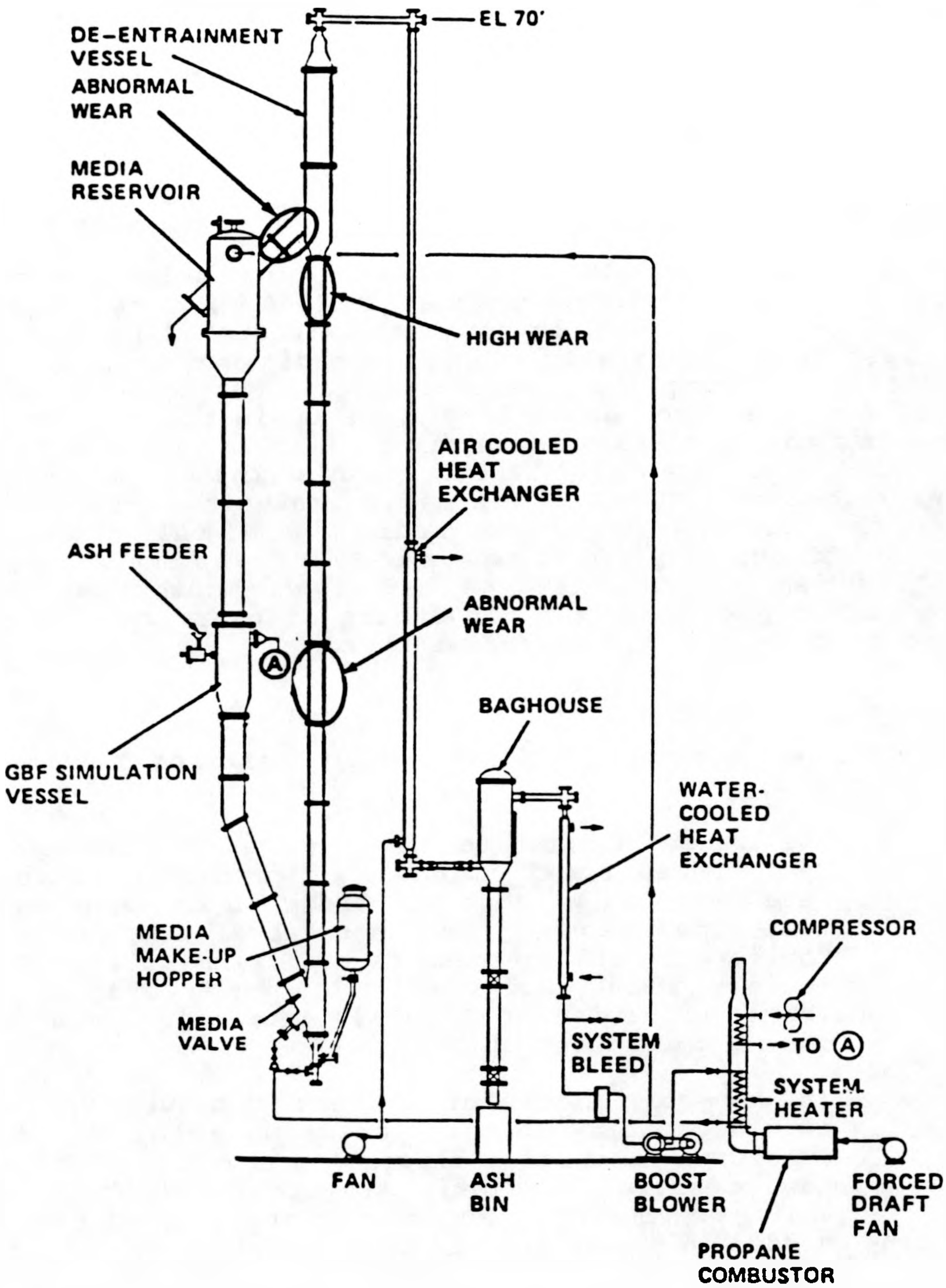


Figure 4-4. Areas of Wear from Life-Critical Component Testing

lined with silicon oxynitride bonded, silicon carbide sleeves backed up by medium density (30 lb/cf) insulating refractory. These new lift-pipe segments were priced competitively with the original refractory-lined spools; although delivery was longer. The plan was to complete one 50-hour test at NYU with the original, refractory-lined spools. Then two of these were to be replaced by the silicon carbide-lined spools. (Note: It turned out that we replaced more than just two spools at NYU but this was not contemplated beforehand.)

Media Attrition

Measurements on the attrition of the 2 mm media indicate very little loss. Out of the approximately 2300 lb of media in the CPC test module, only 50-100 lb remained unaccounted for. This could have been loss during maintenance as media was spilled from time to time and not completely accounted for. Furthermore, any change of media in the circulation loop shows up in the media reservoir. Data shows that the media inventory oscillated within a 35 lb range over a 200 hour interval. In other words, the media loss was less than 35 lb over 200 hours. A sieve analysis of the 2 mm media showed that out of a ton of used media sieved, only 0.4 lb was less than 20 mesh and only 3.6 lb was over 1/8". The small material was much like sand. The large material was comprised of mainly refractory chunks with a minor amount of oversized media. This showed that very little media was broken.

## 4.7 3 MM Media Characterization (vs. 2 MM)

Findings from parametric and ash loading tests of 3 mm media are as follows:

- The transport air rates were increased only about 5% over that needed for 2 mm media as predicted. Media rates were measured without knowledge of the abnormally worn lift-pipe segment as described in section 4.5. Consistent with the results utilizing 2 mm media, actual media rates fell well below theoretical rates. Characterization of 3 mm media transport was completed during operations at NYU.

- It was confirmed that the boost blower did not have enough capacity to circulate 3 mm media at atmospheric pressure. The boost blower has a variable speed drive. Low pressure circulation requires a high speed (more volume). During 3 mm media testing, some pressure was needed in the system (25 psig) in order to circulate cold media.

- Catalytic cracker ash was fed into the 3 mm media at 2% by weight of the media rate. The rate chosen was 0.4 lb/min ash in 20 lb/min media. The media was heated to 400F and ash was fed for about 1 hour with the system pressure balanced to induce air leakage in the same direction as media flow in the lower seal leg. The ash discharge system was run in the manual mode with indications that the pneumatic blasters encouraged better ash removal.

- Ash deposits were found in the GBF simulation vessel on the conical transition surface. It is not known if this affected circulation rate. Furthermore, because of the way the ash was fed, it was not known if we would experience the same problem in the filter element at NYU. Subsequent testing at NYU indicated there were no ash deposits in the GBF element cone. No problems with media flow out of the cone occurred and no deposits were found during inspections.

## 5.0 APPLICATION TO SUB-PILOT PLANT TESTING (NYU)

Figure 2-2 shows a scaled schematic of the equipment developed and tested at CPC along with the NYU equipment. As depicted on this schematic, the majority of Life-Critical Test components from CPC testing were transferred to NYU for reuse. In particular, the following components were installed at NYU without modification:

- Media Reservoir
- De-entrainment vessel
- Water and air-cooled heat exchangers
- Pressurized baghouse
- Ash pressure let-down valves and hoppers
- Boost blower
- Media makeup hopper
- Refractory lined seal legs
- Refractory lined lift pipe (plus two new sections)
- Control panels

The difference between the CPC and NYU test modules was 1) the addition of the granular bed filter test module to replace the GBF simulation vessel and ash feeder, and 2) the deletion of the system heater. At New York University, the filter was tested along with the above listed media circulation and ash handling components.

### 5.1 Equipment Specifications

Components developed for use for both the Life-Critical Component test program (at CPC) and the Sub-pilot Test Series (at NYU) are described below:

a. Media Circulation System

The media circulation system includes the piping and equipment in which the ceramic media spheres flow. These items shown previously on Figure 2-2 include the dirty media seal leg, lift pipe, de-entrainment vessel, return leg and media reservoir.

The lift pipes and seal legs were made from numerous short sections of refractory-lined pipe. Lift pipe segments were 12" standard wall pipe lined with two layers of castable refractory down to a 2" inside diameter (I.D.). The insulation layer is a soft castable block mix. The hard face is a 3" thick layer of abrasion resistant castable. This installation was performed using common materials but special techniques developed for producing refractory-lined pipe. Forms were made from heavy cardboard tubes centered in the pipe with plywood forms. Each section of finished pipe was checked for accurate centering and straightness of the resultant refractory-lined hole. Tools used for checking included bolthole sized tapered pins and a light-gauge plate drilled to the proper bolt circle and containing an alignment hole in the center. The intent was to produce refractory-lined pipe with the I.D. centered within flange bolt circle. With this fact proven, the flange bolt holes could be used with the tapered pins to line up 5' sections of pipe so the I.D.'s at each flange interface lined up. The tolerance chosen for alignment was ±1/16" based on engineering judgment. The refractory installation job proved adequate and no work had to be rejected.

Installation of the piping was completed by lining up match marks on the component flanges and then lining up boltholes with two tapered pins per joint. Proof of proper alignment was achieved by sliding a 1-15/16" diameter wooden dowel past each mating flange. The dowel had an adjustable length PVC pipe handle for convenience. In the few predictable instances that alignment was not immediate, minor levering at the boltholes accomplished the desired result. The same tapered pins were used on each flange. As bolts are normally 1/8" smaller in diameter than the boltholes, there is some adjustment allowable at the flanges. Seal legs were made by lining 14" pipe to a 3" I.D. The same principles were utilized.

b. De-entrainment Vessel

The design of the de-entrainment vessel which separates media and ash by velocity was patterned after equipment developed in the high temperature, low pressure testing at CPC. The 2" I.D. lift pipe was extended into the bottom of the de-entrainment vessel as a stainless steel pipe. The remainder of the vessel body acted like an air classifier in that the gas velocity was adjusted to allow media to drop out of the gas stream while ash was carried upward. Baffles near the top exit prevented media escape in the event of an unusually high gas velocity.

c. Media-Reservoir

In low pressure GBF testing at CPC, the media reservoir was an integral part of the filter vessel. For high pressure operation, the media reservoir was physically separated from the filter vessel to minimize gas leakage between the filter and circulation system, and to lay groundwork for scaling up to a commercial-size filter. It is sized to provide space for media inventory to compensate for media volume variations due to heat up, cool down, and ash accumulation on the media.

d. Media Valve

Media circulation experience in previous GBF testing and in commercial filter design (300-500°F and atmospheric pressure) formed the basis for configuration and sizing of the media valve, lift pipe and seal legs. Media is injected into the lift pipe at an upward angle to minimize the direction change and inner surface wear.

e. Particulate-Laden Gas Handling Equipment

Ash handling equipment downstream of the de-entrainment vessel is standard equipment available with only a few special considerations.

From the de-entrainment vessel, the 1000-1200F particulate-laden gas was radiation cooled in a 40'-50' long run of 2" pipe. The gas entered an air-cooled heat exchanger at 700-800°F and was cooled to 500°F. The thermal design of the heat exchanger maintained internal tube temperatures above circulation gas dewpoint under the anticipated operating conditions. The heat exchanger was a standard pipe-within-a-pipe type unit installed vertically so that particulate dropped through with minimal fouling of the inner wall.

The 500°F, 150 psig baghouse is a pulse jet type unit sized with a conservative air-to-cloth ratio of 2.6:1. Four 4' long, 4-1/2" O.D. filter bags were be housed in an ASME pressure vessel. The baghouse dimensions are 24" O.D. by about 80" tall. Pulse air pressure will be 60-90 psi above system pressure.

This baghouse is of standard, ASME pressure vessel construction utilizing commonly available, fiberglass bags. A higher temperature baghouse was not considered for two main reasons. First, we did not want to accept the risk of working with seldom used, developmental type baghouse bag materials. The fiberglass material chosen is widely used in industry and power plants (Huyck). Second, it was necessary to ultimately lower the circulation gas temperature to 300°F as that was the limitation of the boost blower. The interim 500°F at the baghouse was chosen to avoid baghouse condensation problems with flue gas as a transport medium. At 300°F, there will be condensation.

The water-cooled heat exchanger downstream of the baghouse was sized to lower circulation-gas temperature to 300°F. It was a small pipe-within-a-pipe unit. Any condensation formed was collected downstream of the heat exchanger in a coalescing type compressed air filter.

f. Ash Unloading

The ash unloading valves and sequencing is patterned after similar systems for high pressure cyclones utilized in developmental PFBC exhaust systems. The basic concept of utilizing two chambers in series with pressure equalization valves to feed ash from one pressure to another is proven. However, when the pressure differential is 150 psi, special design considerations are necessary.

The design utilizes two 4" Kaymr ball valves in series. These valves are cylinder operated both to open and to close. Position switches confirm the valve status.

g. Boost Blower

The boost blower choice of a rotary vane compressor operating well within its pressure and temperature range resulted from a comprehensive study of candidate machines.

The boost blower circulates lift air or gas in the range of 9-16 lb/min at an inlet pressure of about 140 psig. Pressure rise is 8-10 psi.

The devices considered for moving the circulation gas besides the rotary vane compressor were: 1) reciprocating compressor, 2) lobe-type positive dispacement blower and 3) eductor. The reciprocating compressor was eliminated because of cost and because of potentially pulsing flow and difficulty handling wet gases. The lobe type blower would have been ideal as it could handle the wet gas, would have performed much the same as the vane compressor as it was also a positive displacement machine, and did not need oil injection into the circulation air stream for lubrication. The drawback was cost. At $35,000 it could not compete with the vane compressor at $12,000. Eductor control appeared complex because a high pressure motive air source would have been necessary to boost the pressure of the circulating gases and this motive air would have had to be generated and then controlled to provide the necessary pressure and then exhausted to allow precise lift pipe and counterflow air as the remainder. Furthermore, controls would have had to be flexible enough to account for operation at all combinations of pressure, temperature and changing pressure drop in the circulation loop. At the initial consideration, this task appeared overwhelming, and as a result this device was not seriously considered.

Both the rotary vane compressor and the lobe-type blower inherently adjust to changing pressure drops within the range expected (5-20 psi) and can be supplied with variable speed drives to precisely adjust flow for temperature and pressure over a 3 to 1 range. The drawback with both of these machines was the temperature limitation of 250°F to 300°F. This limitation is based on bearing and lubrication design.

h. Instrumentation and Control

The Test Module was manually controlled and instrumented to maintain the system process parameters at specified setpoints, to provide system status and safe operation and to perform the required ash removal functions. Figure 5-1 shows details of instrumentation and controls of the system.

Flow, temperature and pressure requirements were arranged to give complete definition of system operation at all times. Some redundant measurements were provided to check data. Control was from small, locally mounted panels at the base of the unit.

The control system had four major control loops. They were:

Lift Pipe Delta P. This loop maintained the lift pipe pressure drop (linearly related to the media circulation rate) at the specified setpoint by modulating the position of the media injector gas valve. The setpoint is selected based on the test point and the control is manual.

Lift-Gas Flow. This loop maintained the gas flow through the lift pipe at the specified setpoint by bypassing the excess gas flow delivered around the boost blower or to the counterflow area (top of the media reservoir). The setpoint for this loop was selected based on operating conditions (pressure and temperature) to minimize the media velocity in the lift pipe.

Particulate Removal Airlocks

This was an automatically or manually sequenced operation controlled from the main panel. The steps were:

- Both ball valves started off closed while ash accumulated in the upper ash holding vessel.

- At the electronic start signal, timer or manually initiated, a pressure balancing valve opened to bleed system pressure into the lower ash holding vessel. A pressure switch proved status.

- The upper ball valve opened and ash fell at equal pressure into the lower ash holding vessel.

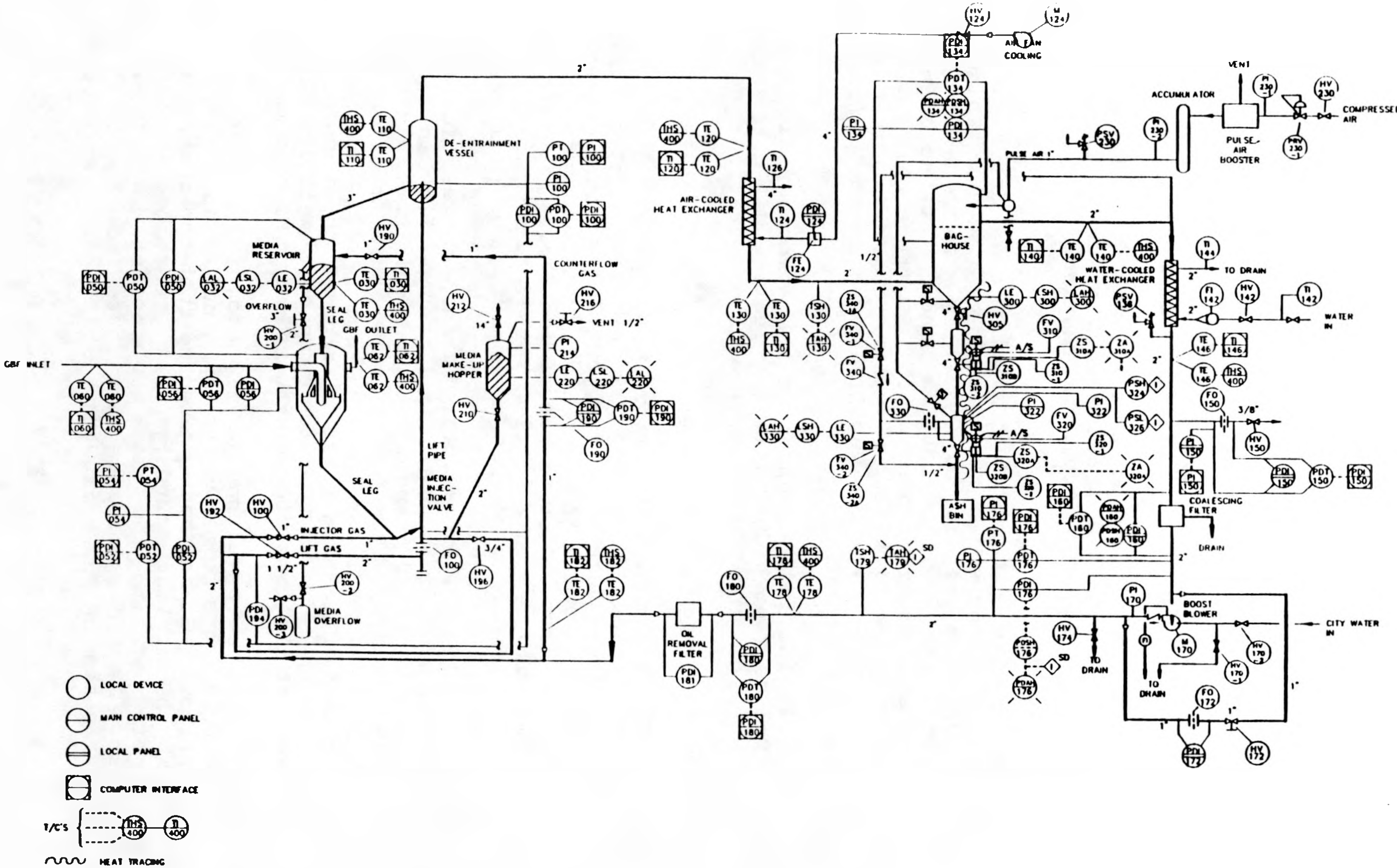


**Figure 5-1. P&ID New York University Test Module**

- After the upper ball valve closed to isolate the lower ash holding vessel, a bleed valve opened to exhaust pressure to the atmosphere. Desired pressure was proven by a switch.

- The lower ball valve opened to discharge ash at atmospheric pressure into the ash holding bin.

- The sequence ended after the lower ball valve closed. A timer restarted the sequence after a chosen delay. Also the sequence could be restarted manually at any time.

- To provide additional flexibility, a manual override panel was provided for operation at NYU. This panel allowed the operator to physically step the ash unloading system through the above sequence. Status lights and gauges confirmed progress. Furthermore, pushbutton control was provided for pneumatic blasters that jar sticky ash loose from metal surfaces in the baghouse and both ash hoppers.

A small air filter is mounted on the atmospheric collection ash barrel to remove dust from any leakage gas during normal operation or during the ash discharging operation.

## 5.2 Circulating System Characteristics

One purpose of the circulation system tests performed at CPC was to identify an optimum lift-pipe flow at each temperature and pressure. This unique amount of transport air was to be determined by balancing factors that favor a high transport gas flow with those factors that favor a low transport gas flow. Favoring a high transport flow would be consideration for avoiding choking (media collapse). Also favoring a high transport rate (and velocity) would be achieving enough turbulence for adequate ash-media separation. Another factor favoring transport velocity tending towards the high side is maintaining lift-pipe flow in the range where small transport air changes do not significantly affect the transport pressure drop. As shown in the media transport model, Appendix IA, lift-pipe flows in the region below minimum will result in rapidly increasing pressure drop as the transport rate approaches choking. Favoring a low transport velocity would be minimizing wear of the lift-pipe lining and attrition of the media.

Figure 5-2 shows the envelopes of transport air rates explored during parametric tests compared with original estimates of optimum lift-pipe airflows. It has been presented that the choking airflow is 50-75% of the minimum boundary of the envelope. Because of this, fear of operating too close to choking is not a strong consideration. We did experience wear, but since a wide range of flows were imposed on the lift pipe and close examination was

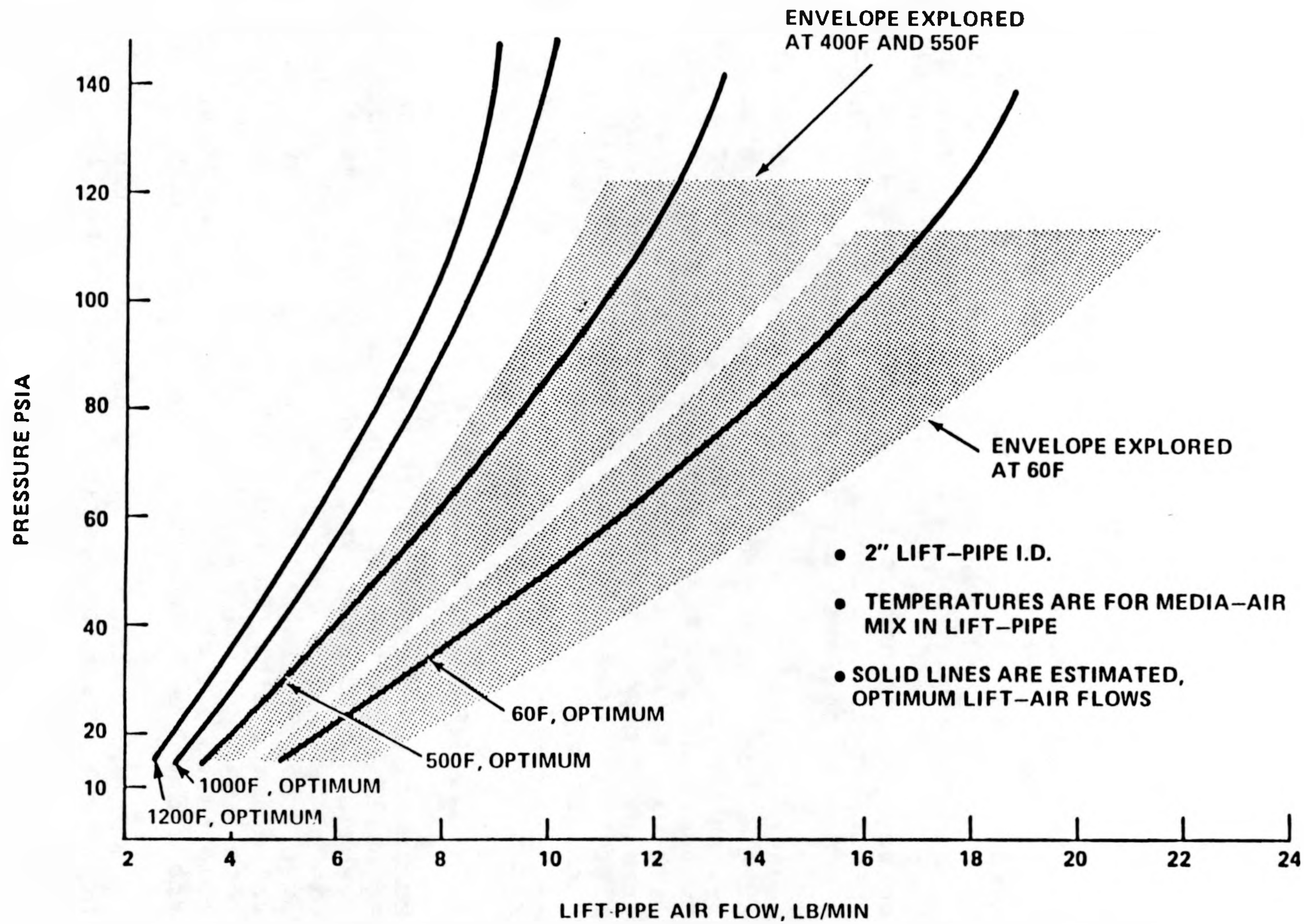


Figure 5-2. Comparison of Estimated Optimum Lift-Pipe Air Flow with Ranges Tested

performed only before and after the test series, we could not correlate wear with velocity. Ash loading tests were not detailed enough to explore the effect of transport velocity.

Furthermore, we knew at the outset, that the test program would be too restrictive to do any more than give indications of the range of optimum lift-pipe airflow rates. The conclusion is that the first estimate was reasonable. The same basis was used to choose base-line transport air rates for testing at NYU. During operation at NYU, the envelopes of acceptable lift-air rates at temperature and pressure were less narrow than tested at CPC. Based on the average envelope value being slightly greater than the estimated optimum, NYU was run between the estimated optimum and about 1 lb/min to the right. See Figure 5-3. This corresponds to a theoretical media velocity of 10-15 ft/sec. The slight difference between the transport flue gas at NYU and the transport air at CPC is not expected to be significant as the molecular weight of each gas mix is the same within a few percent.

Because of the taller lift pipe at NYU as compared to that tested at CPC, the media pressure drop characteristic changed. Figure 5-4 shows the effect of the 10' height difference on the lift-pipe pressure drop. The comparison is theoretical and is based on a lift-gas flow rate from Figure 5-3. Based on the lift-pipe transport model, the velocity of gas and media at the top of the lift pipe does not change because of the height difference. Consequently, lift-pipe height has no effect on optimum lift-gas rates. Tests at NYU compared the theoretical with measured media rates.

### 5.3 Ash Handling Equipment

During tests at CPC, ash removed at the baghouse showed a tendency to build up in the conical hoppers of the baghouse and ash holding vessels. Automatic cycling of the ash pressure let-down equipment did not reliably remove ash. A new panel was built to manually step the double airlock pressure letdown system through the unloading cycle. Pneumatic blasters were added in the baghouse and both ash holding vessels. These devices release a pulse of compressed air on demand into hopper cones to break ash loose from the sidewalls. This system was successfully tested at CPC.

At NYU, heat tracing was added to the baghouse hopper and ash hoppers. Prior to operation, these vessels were warmed to about 400F so condensation did not form to attract ash.

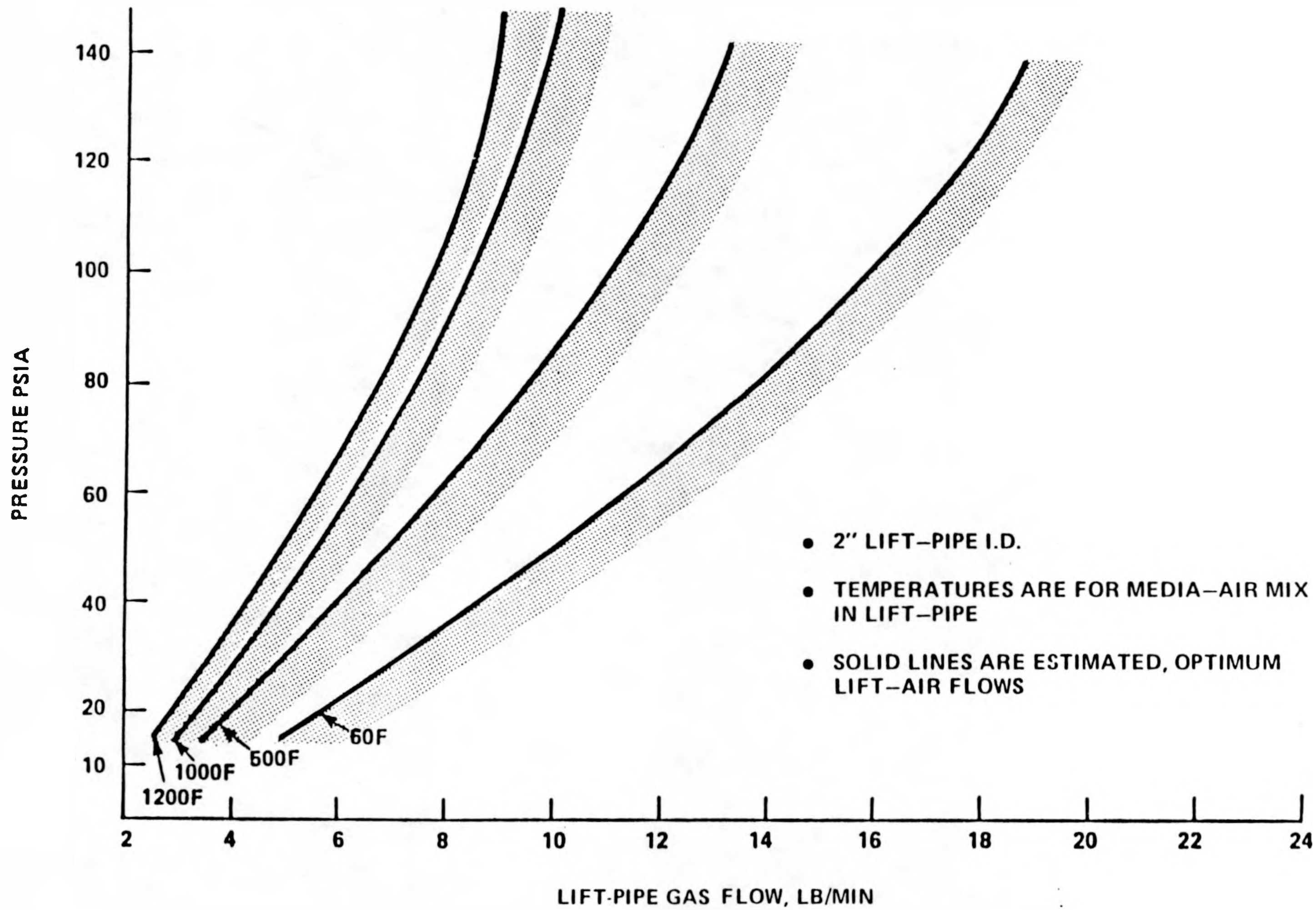


**Figure 5-3. Targeted Lift-Pipe Flow at NYU**

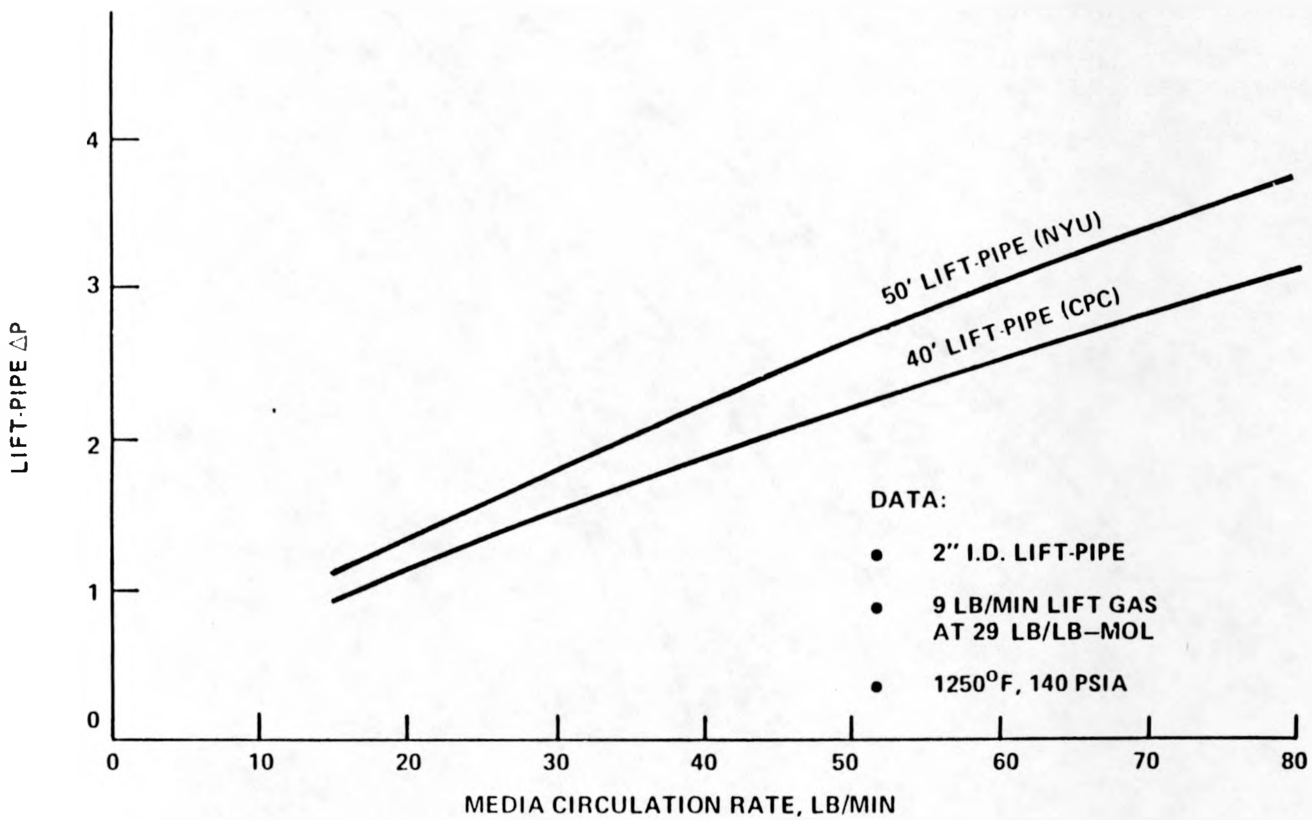


**Figure 5-4. Impact of Height on Lift-Pipe Operation (Theoretical)**

## 5.4 Pressure Balancing

This technique was used to insure ash removal at NYU. During tests at CPC, pressure balancing was easy to achieve. A surprisingly small amount of circulation system air had to be vented to reverse the airflow down the lower seal leg. Recall that without pressure balancing the lift-pipe pressure drop is divided between the lower and upper seal leg (below and above the GBF simulation vessel respectively). By venting circulation gas to atmosphere downstream of the baghouse, a subtle change in the pressure profile in the circulation system occurs. One effect is that leakage air (or gas) flows down the lower seal leg instead of up. As shown by testing at CPC, altering the pressure profile within the circulation system could be accomplished without upset, and could aid in removing ash from the GBF.

## 5.5 Lift-Pipe Refractory Options

For testing at NYU, the two worn sections of lift-pipe shown on Figure 4-4 were restored to their original state. In conformance with the original specification, A.P. Green Lo-Abrade castable refractory was installed to a 2" I.D. and backed up by Castable block mix. Refractory was then dried in an oven by controlled heating to 600F.

With measurable wear and crevice forming evident in the lift pipe, an alternate approach to the wear lining was investigated. Two new 5' long lift-pipe segments were lined with silicon oxynitride bonded, silicon carbide sleeves backed up by medium density (50 lb/CF) insulating refractory. These new lift-pipe segments were priced competitively with the original refractory-lined segments; although delivery was longer. Originally, the plan was to replace the two 5' lift-pipe segments just above the media valve with the silicon carbine-lined segments after the first test at NYU. This plan was altered when it was discovered that wear was more of a problem than first estimated. See Section II for more information.

## 5.6 2 mm vs. 3 mm Media Operation

Most of the Life-Critical Component testing was performed using 2 mm media. This was the baseline size utilized in all previous filter tests. Circulation and ash loading tests on the larger 3 mm media showed that it could be substituted for the 2 mm media. No modifications were made to the equipment to handle 3 mm media. As a result of these successful operations, some testing at NYU was planned utilizing 3 mm media. Favorable results at NYU will have economic impact in that it will be shown possible to substantially increase gas throughput to the filter with modest design changes and little cost increase.

## 6.0 CONCLUSIONS

The 500-hour, critical component test sequence at CPC has served to demonstrate the operation of the media circulation and ash handling components. Objectives have been met to identify the operating envelope for high temperature, high pressure media circulation; to partially reconcile the media transport model with actual data; to observe the effects of gas leakage through the seal legs; to determine limitations on ash/media concentrations; to identify wear problems; and to check for media attrition.

Data has been presented that formed the basis for choosing the flow of transport gas in the lift pipe at NYU. The same transport gas model can be used to predict flow rates for commercial sized lift pipes. Media circulation has been studied at rates proposed for operation at NYU under pressure and temperature. An abnormal wear problem prevented good agreement between theoretical and actual circulation rates, so further measurements were completed during NYU testing. Complete reconciliation of the media transport model with actual data must be completed based on data from NYU operations. In the meantime, enough data has been gathered from testing at CPC to generate confidence in the ability to predict lift-pipe transport characteristics at various pressures and temperatures.

It was found that if seal-leg leakage gases are allowed to flow counter-current to ash, accumulation of ash at the top of the seal leg may occur. Under an artificial pressure balance arrangement, the ash flow and leakage gases can be forced in the same downward direction. This enhances ash removal from the filter and is a technique that was utilized at NYU.

Ash collected in the pressurized baghouse is sequenced through unloading valves to an atmospheric bin. The basic ash unloading system worked adequately, although it sometimes plugged with ash. Modifications were made to insure reliable ash unloading. These modifications were: a) Adding a manual sequence to allow a pause if necessary to clear ash, b) Adding pneumatic blasters to stir the ash in hopper bottoms, c) Installing heat tracing on bin hoppers so they operate above the condensation temperature. These approaches are common for ash handling systems. The same tests that identified the ash unloading difficulties demonstrated that ash could be loaded to 5-6% of the media circulation rate by weight.

The refractory lining of the circulation system performed satisfactorily except in the lift pipe. There was a 1-5% increase in diameter and formation of surface crevices that caused concern. Two new lift-pipe segments were lined with silicon carbide sleeves. The new segments were scheduled to replace existing segments at NYU after the first 50-hour test.

Equipment and operating data from critical component testing at CPC was used in the 200-hour, NYU test sequence. Tests at NYU concentrated on assessing the particulate removal efficiency of the GBF in the environment of an actual PFBC exhaust. Parametric tests were conducted at 9-10 atm, utilizing 2 mm and 3 mm media and various media circulation rates. A single operating point was chosen for a long-term (100-hour) steady-state test.

# 7.0 REFERENCES

Guillory, J.L. et al, "Granular Bed Filter Development Program, Phase II", Final Report, Issued by Combustion Power Company, May 1983, Report No. AC21-77ET10373.

Grace, D.S. et al, Electrostatic Enhancement of Moving-Bed Granular Filtration, 2nd Symposium on the Transfer and Utilization of Particulate Control Technology (July 1979)

## SECTION II

# FINAL TEST REPORT
# GRANULAR BED FILTER TESTING
# AT NEW YORK UNIVERSITY

## ABSTRACT

The purpose of this test program was to obtain information on the operational feasibilty of the granular bed filter as a high temperature, high pressure (HTHP) particle and alkali control device for pressurized fluidized-bed combustion (PFBC) applications. During 1988, subpilot-scale filter testing was completed at the New York University subpilot-scale PFBC located in Westbury, New York. The filter media utilized was 2 mm and 3 mm spherical alumina beads. Collection of ash was primarily by impaction. Ash-laden media was continuously removed from the filter, cleaned and returned by a pneumatic process. Under investigation was the suitability of this pneumatic process and the particle removal efficiency of the granular bed filter.

Major accomplishments were:

- Successful completion of the planned performance tests. The NYU test facility consists of a coal-fired 30" I.D. combustor, capable of operating up to 10 atmospheres at 1500-1600°F with 20-30% excess air.

- Filter performance with 2 mm media: inlet particulate, 70-6400 ppmw; outlet particulate 1-20 ppmw; >99% efficiency; pressure drop steady at less than 1 psi.

- Filter performance with 3 mm media: inlet particulate, 160-1570 ppmw; outlet particulate 1-11 ppmw; >99% efficiency; pressure drop steady at less than 1 psi.

- Solved isolated filter operation problems related to PFBC pressure excursions, refractory wear and media flow.

# 1.0 INTRODUCTION

Subpilot-scale testing was performed on a Granular Bed Filter (GBF) installed on a coal fired, pressurized fluidized bed at New York University, Westbury, New York. Tests were run up to 115 psig and 1600°F. These tests were run under contract with the Department of Energy (DOE) to assess GBF performance as a high temperature, high pressure, particle control device and to acquire data for scale-up to commercial size.

Three shakedown and five performance evaluation tests were carried out from October 1987 to June 1988. All but the last test were performed with 2 mm diameter alumina granules as filter media. In the last test, 3 mm diameter media was used. The flue gas flow rate through the filter was varied between 6000 and 14000 lb/hr.

The ability of the GBF to capture both particulate and alkali from the PFBC exhaust stream was evaluated by isokinetic sampling of the inlet and outlet of the GBF for particulate and alkali loadings. The particulate sampling system consisted of a total filter and a cascade impactor. The total filter collected all the dust in the flue gas sample. In the impactor, the particles collected were separated according to their size. Alkali emissions were measured using two techniques, a total vapor condensation method and an on-line alkali monitor sampling method.

The testing demonstrated stable GBF operation downstream of the PFBC at high temperature and high pressure. Furthermore, particulate removal was achieved to greater than 99% efficiency and to below the requirements of the New Source Performance Standards (NSPS) and gas turbine tolerance limits. The average emissions from the last test series was .004 lb/million BTU compared to a NSPS limit of .030 lb/million BTU. Data from the cascade impactors may have not been completely valid but indicated turbine tolerance limits, which depend on the particulate size distribution, were met.

Alkali removal across the GBF was quite high, generally greater than 90%, but measurements were taken with high temperature drops across the filter and the alkali sampling system. Because alkali reduction was likely due to vapor condensation which will not occur at commercial size, the results were invalidated. Other tests showed that alkali could be removed in the GBF (Guillory, 1983).

## 1.1 Objectives

The specific objective of the subpilot-scale test sequence was to successfully remove particles to meet NSPS and turbine tolerance limits over the entire test period without operational or component failure. Detail objectives were as follows:

- To evaluate the dust collection efficiency of the GBF under actual PFBC operating conditions.

- To study the alkali capture efficiency of the GBF media.

- To identify problems, if any, associated with moving media in the filter.

- To study the effect of varying the media flow rate, and to perform tests with 2 and 3 mm media.

- To identify any interface problems between the GBF and the PFBC.

## 1.2 Lower Pressure GBF Tests

Tests of a subpilot-scale filter element at atmospheric pressure and at a temperature of about 1600°F demonstrated successful operation over a 1500-hour test period. Collection efficiencies of 99% were obtained and degradation of the collection media did not occur. The filter also operated successfully under upset conditions (inlet particulate loadings 10 times normal and inlet gas flow rates 25% higher than normal) (Guillory, 1983).

## 2.0 TEST FACILITY

Figure 2-1 contains a schematic view of the granular bed filter developed and tested at low pressure and high temperature (Guillory, 1983). The filter was 5' in diameter and utilized 2 mm (nominal) spherical alumina granules as filter media. For testing at New York University, the filtration portion of the device was reproduced and installed in an existing Government-owned pressure vessel as shown on Figure 2-2. The filter media used for testing at New York University was the identical 2 mm media saved from low pressure developmental testing at Combustion Power and a new 3 mm (nominal) alumina material procured for parametric testing at higher gas flows.

Referring to Figures 2-1 and 2-2, particulate laden gas is introduced into the center of a downward moving bed of granules which acts as the cleaning media. The gas initially moves cocurrently, then cross-flow before reversing its direction upward, counter-current to the direction of the movement of filter media. Particulate collection activity in these zones depicted in Figure 2-1 is as follows:

- Cocurrent-flow zone: At the particle-laden gas inlet, 90% of the solids are removed by a small portion of the media. The result is a particle cake which promotes even more ash collection. The rapidly moving media in this region and the shear layers near the boundaries promote tumbling and mixing of the media. This action keeps the ash from sticking either to itself or to the media. Thus, a large amount of re-entrainment of the ash occurs in this area of high media and gas motion.

- Cross-flow zone: The adjacent cross-flow zone recaptures most of this ash carrying it back into the high velocity core where the ash is literally drawn down and out of the filter vessel with the media.

- Counterflow zone: Here, the final ash collection-polishing takes place. The GBF is a true counterflow device in that exhaust gases exit through the cleanest media. In fact, one can always design with additional layers of media at the exit to increase cleanup effectiveness.

Angle of repose surfaces are affected by the media shape, media friction, dust concentration, dust flow characteristics, gas velocity, gas flow direction and gas pressure. At the gas-to-media contact area below the inlet duct, the dust and gas flows tend to increase the angle of repose of the media. The local maximum gas velocity at the inlet is quite high, resulting in very high capture efficiencies.

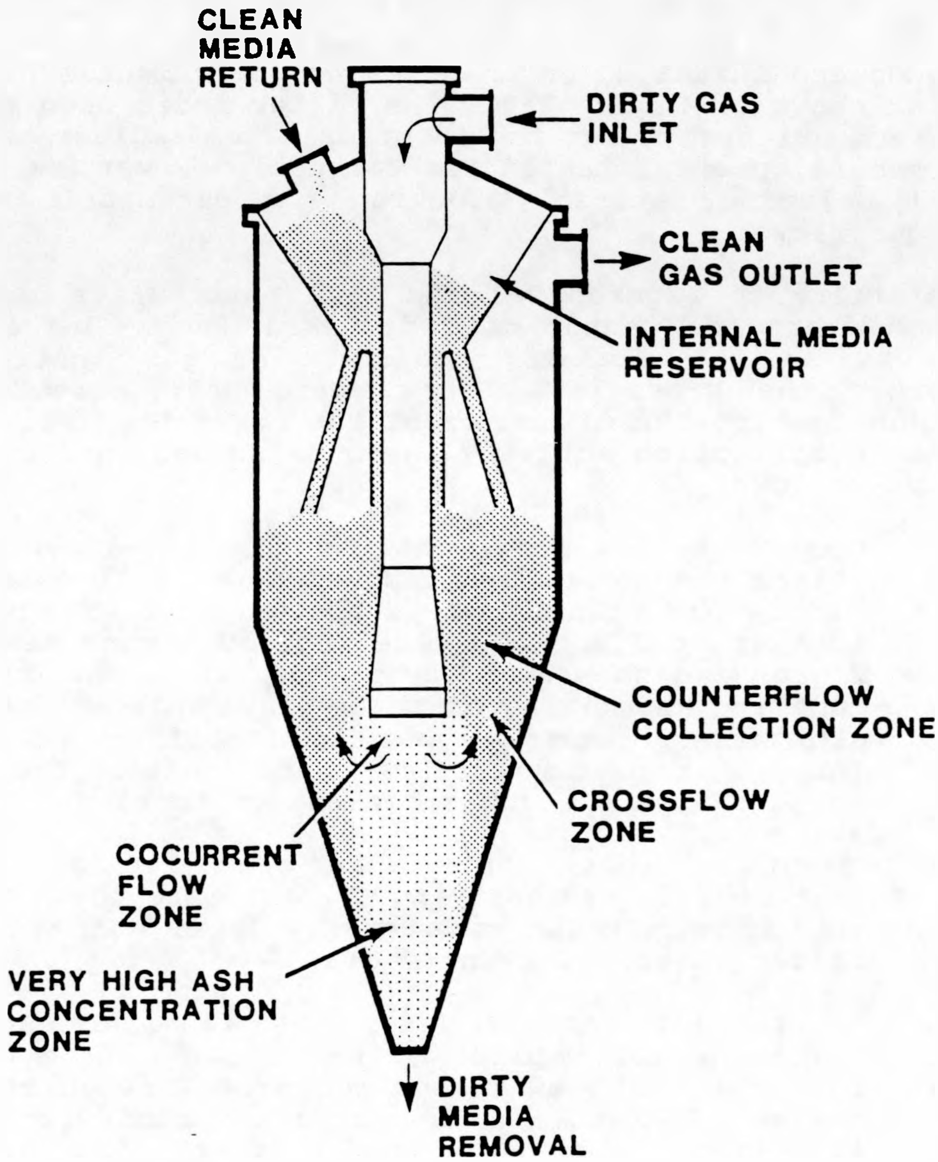


Figure 2-1. Screenless Counterflow Granular Filter Bed

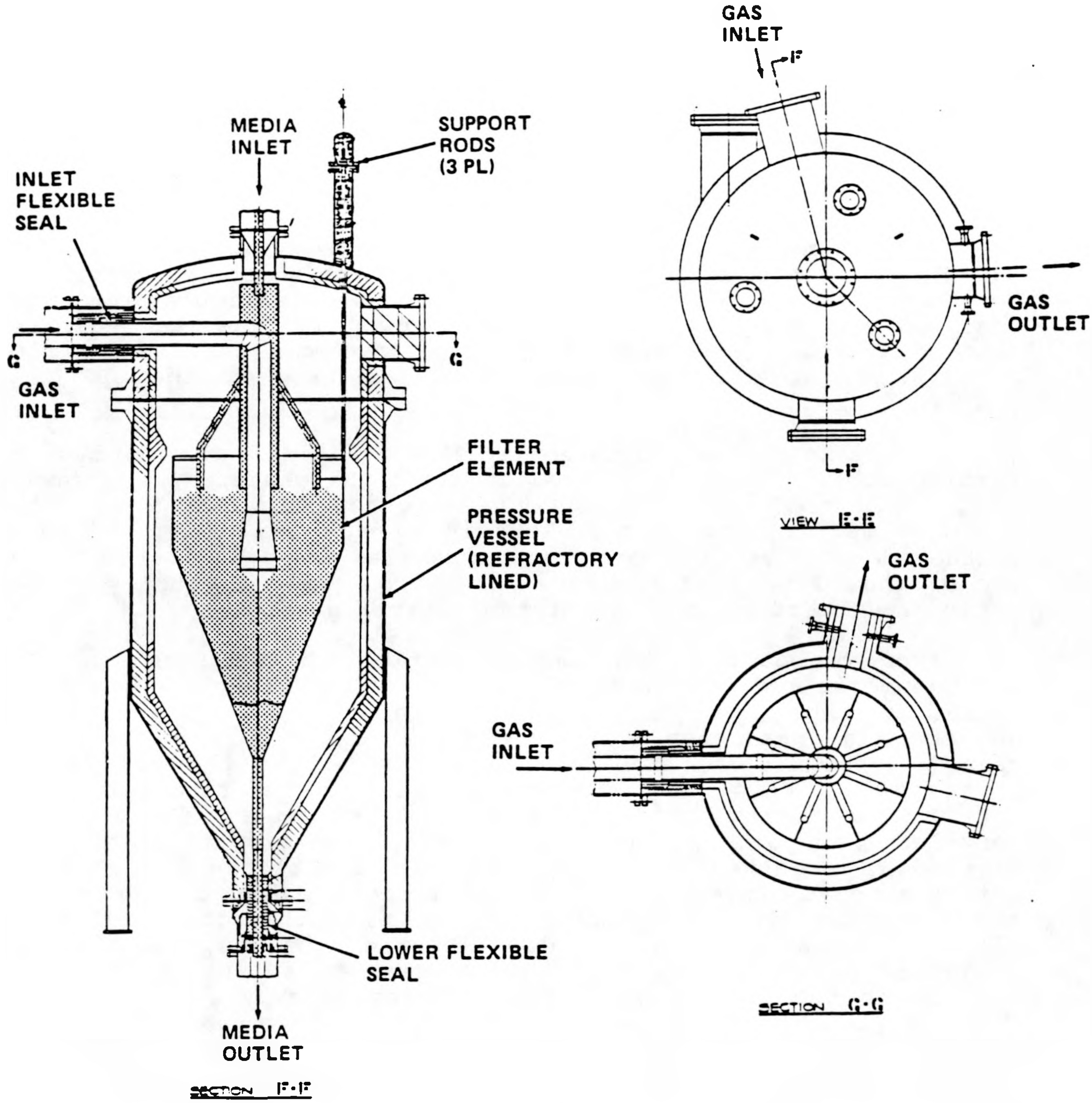


Figure 2-2. Granular Bed Filter Installation

The top surface variations created by the free angle of repose presents preferential flow areas at the low points. The design must provide for high/low variations within a fixed percentage of design bed depth which is the vertical distance between the central gas inlet duct exit and the media distribution pipes. As depicted in Figures 2-1 and 2-2, the high/low point variations are controlled by the spacing of the media distribution pipes.

Even, non-shear type media flow is desired in the counterflow gas-flow area of the filter. Media flow in this zone is controlled by the conical bin design. Various cone configurations were analyzed and evaluated at Combustion Power and results indicated that a steep, single angle cone provides the best media flow pattern. A 40° included angle cone was used in the GBF test module.

Figure 2-3 shows the schematic flow diagram of the GBF system. Particulate-laden gas is introduced into the center of a downward moving bed of 2 mm or 3 mm alumina granules which act as the cleaning media. Fine particulate in the gas stream is collected in the downward moving bed. Clean granules are distributed to the top of the filter and flow downward through eight equally spaced pipes and the outer annulus of the central gas inlet.

From the bottom of the conical section, the ash laden granules are pneumatically conveyed and cleaned in a 2" lift pipe. At the top of the lift pipe, the granules disengage from the transport gas and the fine particles. The clean granules return to the media reservoir from which they are redistributed to the top of the moving bed. The filter media is circulated at a rate between 20 and 60 lb/min using nominally 11 lb/min of transport flue gas. The recycled transport gas with the entrained dust is cooled and then cleaned in a conventional baghouse at 500°F before the flue gas enters a boost blower at 300°F which makes up the pressure drop in the lift pipe and the baghouse. Note that in the commercial-scale plant, heat recovery is included. Part of the recycled flue gas is vented just downstream of the baghouse to adjust the pressure profile in the filter and media circulation system. By venting flue gas downstream of both the upper and lower seal legs, the pressure in the entire circulation system (lift pipe to baghouse) can be maintained slightly less than the pressure in the filter. Under this condition, leakage gas moves down the lower seal leg which enhances flow of the ash and media out of the filter element and into the lift pipe. The captured dust is collected in a pressurized baghouse and removed by a lockhopper system.

Figure 2-4 shows the GBF system to scale, shown in a single plane for clarity. At NYU the equipment was arranged in an area 12' x 15' and was about 80' tall.

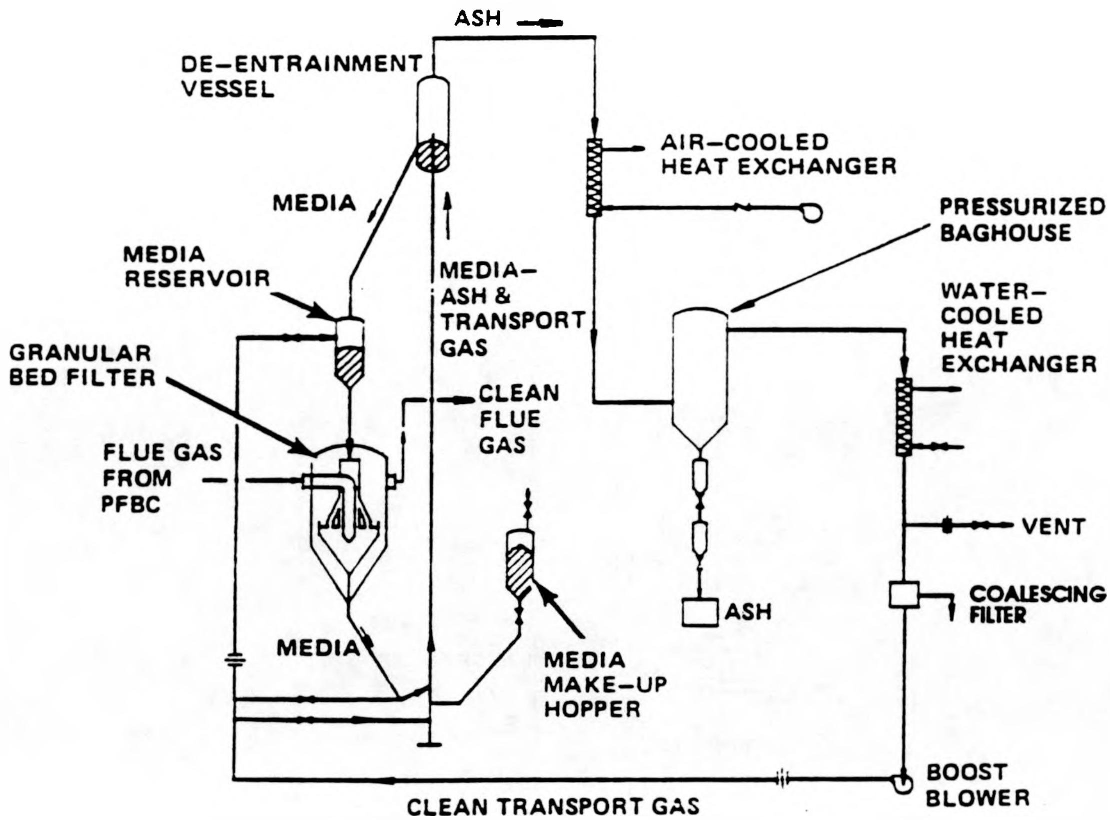


Figure 2-3. Granular Bed Filter System

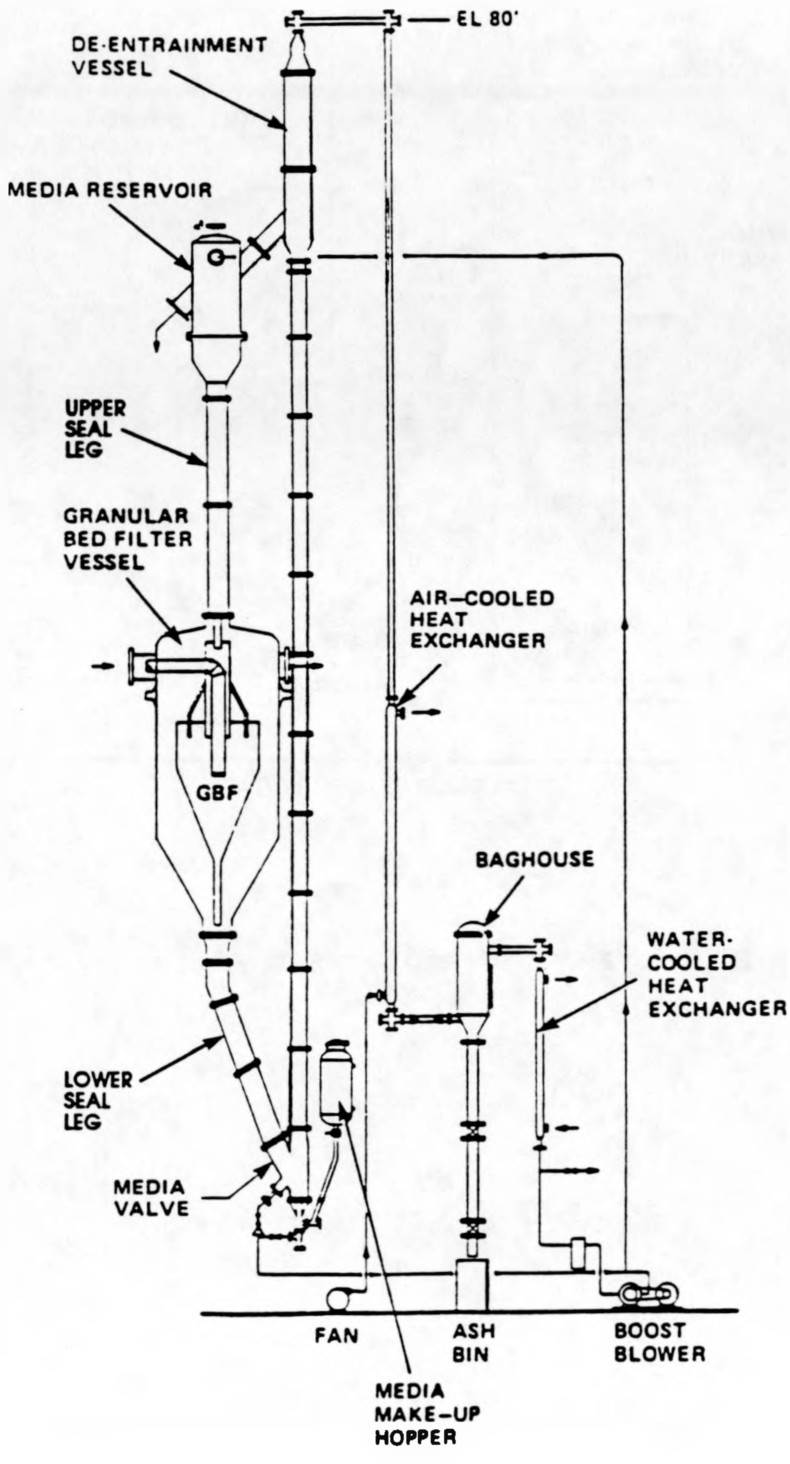


Figure 2-4. GBF Test Facility at NYU

## 2.1 GBF Equipment

### 2.1.1 Filter

The arrangement of the filter element within the pressure vessel is shown on Figure 2-2. In the filtering regime, the critical relationship between components is identical to the developmental filter tested at low pressure at Combustion Power. The intent was to preserve the gas flow distribution through the cocurrent-flow, cross-flow, and counterflow collection zones. Media distribution to the filter body has been altered significantly as can be seen by comparing Figures 2-1 and 2-2. Moving the media reservoir out of the filter has advantages in the commercial-scale design.

Relocating the media reservoir to above the filter element saves valuable space in a pressure containment vessel. Furthermore, the media feed pipe from the remote reservoir creates a low-leakage seal between the filter element and the media circulation system. Minor pressure differences between these two zones can exist without upsetting media flow or particulate capture.

At the filter inlet, a flexible seal absorbs small horizontal and vertical movements from thermal expansion. The basis of the seal is a metal bellows to absorb the thermal movements of the inlet ducting and to maintain a positive seal against gas leakage around the filter bed. At the media outlet, another flexible seal absorbs considerable (about 3-1/2") vertical thermal expansion. This metal bellows is also insulated from the 1600°F environment. Type 316 stainless steel materials was used in fabrication of both metal bellows.

The approach to supporting the filter element within the pressure vessel is patterned after common industrial approaches to supporting metal components inside refractory-lined furnaces. The support rods are carefully designed to allow a temperature gradient along the rod which is steep enough not to allow overheated support points. Heat loss due to this support configuration is quite modest, only a few percent of the total heat loss. The limiting factor is the small cross section of the rods.

### 2.1.2 Media Circulation System

The media circulation system includes the piping and equipment in which the ceramic media spheres travel. These items shown previously on Figure 2-4 include the lower seal leg, lift pipe, de-entrainment vessel, return leg, media reservoir, and upper seal leg.

The lift pipes and seal legs were originally made from numerous short sections of refractory-lined pipe. Lift pipe segments were 12" standard wall pipe lined with two layers of castable refractory down to a 2" inside diameter (I.D.). The insulation layer is a soft castable block mix. The hard face was a 3" thick layer of abrasion resistant castable. Each section of finished pipe was check for accurate centering and straightness of the resultant refractory-lined hole. Tools used for checking included bolthole sized tapered pins and a light-gauge plate drilled to the proper bolt circle and containing an alignment hole in the center. The intent was to produce refractory-lined pipe with the I.D. centered within flange bolt circle. With this arrangement, the flange bolt holes could be used with the tapered pins to line up 5' sections of pipe so the I.D.'s at each flange interface lined up. The tolerance chosen for alignment was ±1/16".

Some of the refractory lined sections were replaced during operation at NYU. Two replacement sections were lined with 1" thick silicon carbide sleeves backed by 60 $lb/ft^3$ insulating castable. Three replacement sections were lined with stainless steel pipe backed by the same castable.

### 2.1.3 De-entrainment Vessel

The design of the de-entrainment vessel which separates media and ash by velocity was patterned after equipment developed in the high-temperature, low-pressure testing at CPC. The 2" I.D. lift pipe was extended into the bottom of the de-entrainment vessel as a stainless steel pipe. The remainder of the vessel body acted like an air classifier in that the gas velocity was adjusted to allow media to drop out of the gas stream while ash was carried upward. Baffles near the top exit prevented media escape in the event of an unusually high gas velocity.

### 2.1.4 Media-Reservoir

In low pressure GBF testing at CPC, the media reservoir was an integral part of the filter vessel. For high pressure operation, the media reservoir was physically separated from the filter vessel to minimize gas leakage between the filter and circulation system, and to lay groundwork for scaling up to a commercial-size filter.

### 2.1.5 Media Valve

Media circulation experience in previous GBF testing and in commercial filter design (300-500°F and atmospheric pressure) formed the basis for configuration and sizing of the media valve, lift pipe and seal legs.

### 2.1.6 Particulate Laden Gas Handling Equipment

Ash handling equipment downstream of the de-entrainment vessel is standard equipment available with only a few special considerations.

From the de-entrainment vessel, the 1000-1200°F particulate-laden gas was radiation cooled in a 50' long run of 2" pipe. The gas entered an air-cooled heat exchanger at 700-800°F and was cooled to 500°F. The thermal design of the heat exchanger maintained internal tube temperatures above circulation gas dewpoint under the operating conditions. The heat exchanger was a standard pipe-within-a-pipe type unit installed vertically so that particulate dropped through the minimal fouling of the inner wall. Nevertheless impact cleaning was required during operation.

The baghouse was a pulse jet type unit sized with a conservative air-to-cloth ratio of 2.6 to 1. Four 4' long filter bags were housed in an ASME pressure vessel. The baghouse dimensions were 24" O.D. by about 80" tall. Pulse air pressure was about 60 psi above system pressure.

The water-cooled heat exchanger downstream of the baghouse was sized to lower circulation-gas temperature to 300°F. It was a small pipe-within-a-pipe unit. Condensation formed was collected downstream of the heat exchanger in a coalescing type compressed air filter.

### 2.1.7 Ash Unloading

The ash unloading valves and sequencing was patterned after similar systems for high pressure cyclones utilized in developmental PFBC exhaust systems. The basic concept of utilizing two chambers in series with pressure equalization valves to feed ash from one pressure to another is proven. However, when the pressure differential is 100 psi, special design considerations were necessary.

The design proposed utilized two 4" Kamyr ball valves in series. These valves were cylinder operated both to open and to close. Position switches confirm the valve status.

### 2.1.8 Boost Blower

The boost blower choice of a rotary vane compressor operating well within its pressure and temperature range results from a comprehensive study of candidate machines. The boost blower will handle circulation air of 10-20 lb/min at an inlet pressure up to 150 psig. Pressure rise was 8-10 psi normally and 25 psi maximum.

## 2.2 GBF Instrumentation and Control

The test module was manually controlled and instrumented to maintain the system process parameters at specified setpoints, to provide system status and safe operation and to perform the required ash removal functions. Figure 2-5 shows details of instrumentation and controls of the system.

Flow, temperature and pressure requirements were arranged to give complete definition of system operation at all times. Some redundant measurements were provided to check data. Controls were mounted in small, panel located at the base of the GBF unit.

The control system had four major control loops. They were:

### 2.2.1 Lift Pipe Delta P (PDI-100)

This loop maintained the lift pipe pressure drop (linearly related to the media circulation rate) at the specified setpoint by modulating the position of the media injector gas valve. The setpoint was selected based on the test point.

### 2.2.2 Lift-Gas Flow

This loop maintained the gas flow through the lift pipe at the specified setpoint by adjustments of boost blower speed. The setpoint for this loop was selected based on operating conditions in the de-entrainment vessel (pressure PI-100, and temperature TI-110) to minimize the media velocity in the lift pipe.

### 2.2.3 Particulate Removal Airlock

This was an automatically sequenced operation controlled from the main panel. The steps were:

a. Both ball valves (FV-310 and FV-320) start off closed while ash accumulated in the upper ash holding vessel.

b. Once an hour, at operator initiation, a pressure balancing valve (FV-340-1) opened to bleed system pressure into the lower ash holding vessel. A pressure switch (FSH-324) proved status.

c. The upper ball valve (FV-310) opened and ash fell at equal pressure into the lower ash holding vessel. The operator activated a pneumatic blaster to assure ash movement.

d. After the upper ball valve (FV-310) closed to isolate the lower ash holding vessel, a bleed valve (FV-340-2) opened to exhaust pressure to the atmosphere. Desired pressure was proven by a switch (PSL-326).

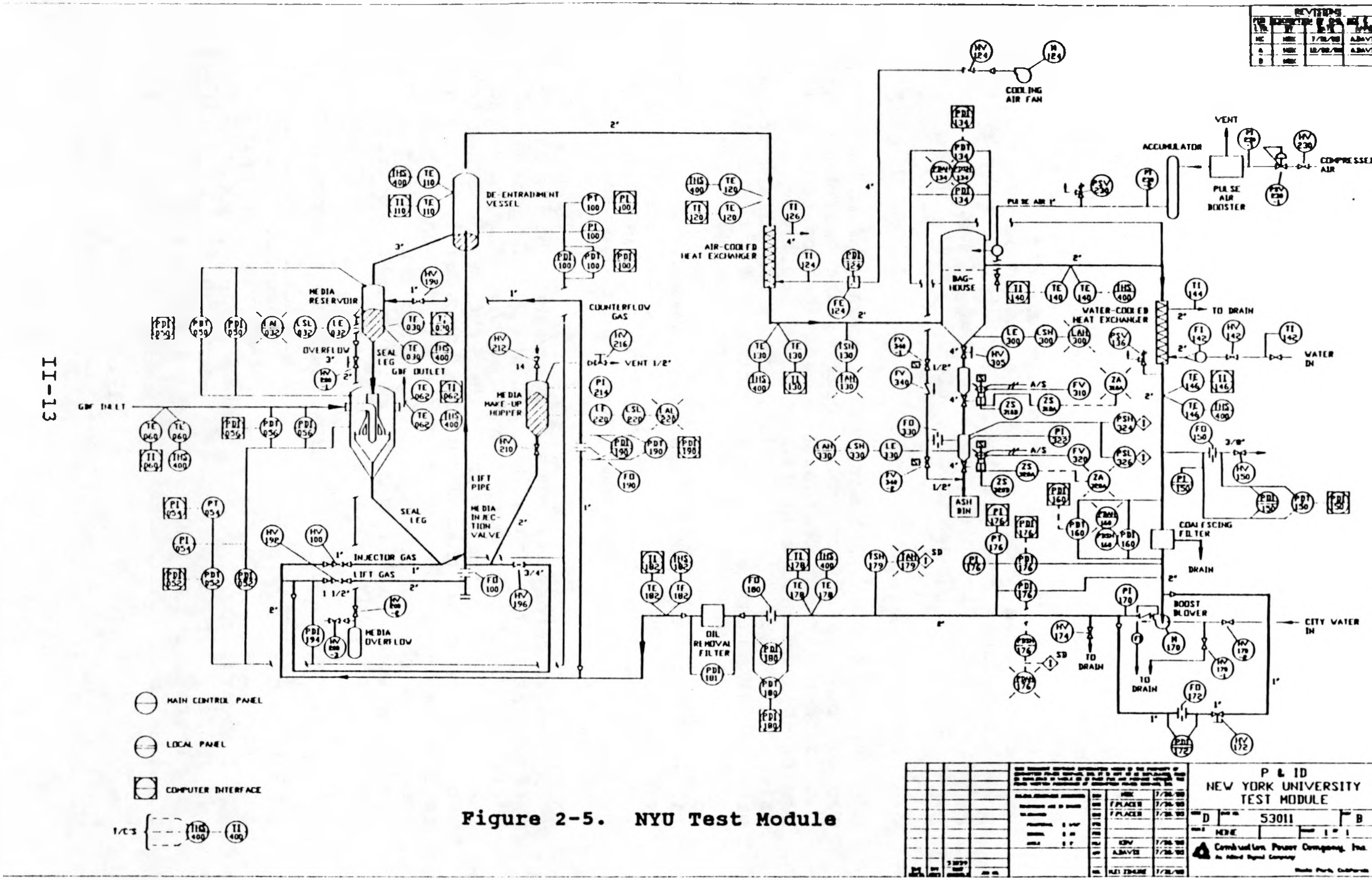


Figure 2-5. NYU Test Module

e. The lower ball valve (FV-320) opened to discharge ash at atmospheric pressure into the ash holding bin. The operator activated a pneumatic blaster to assure ash movement.

f. The sequence ended after the lower ball valve (FV-320) closed.

#### 2.2.4 Pressure Balancing

A hand valve (HV-150) was provided at the water-cooled heat exchanger outlet (boost blower inlet) to bleed circulation gases to atmosphere. This allows the pressure drop across the lower GBF simulation vessel seal leg to be adjusted as desired. Control is possible because pressure in the lift pipe can be relieved to the point where gas is forced to bleed out of the granular bed filter in an upward and downward direction.

### 2.3 PFBC Test Equipment

Figure 2-6 shows a simplified schematic of the NYU test unit. Two to four diesel driven air compressors operated against one or two sonic nozzles. The nozzle downstream of the GBF was designed for open or closed operation and was referred to as the on-off valve. The bypass nozzle was fitted with an air-cooled plug and precise plug positioning equipment but was typically not used to modulate pressure. Nozzle sizes were chosen prior to a test series to divide the PFBC gas flow, which was near constant, between the filter device and the bypass. Pressure changes during operation were made by adjusting the flow from the compressor bank. The unobstructed sonic nozzles were used to measure gas flow based on nozzle diameter, upstream pressure (above about 28 psia) and temperature.

The two kerosene combustors were used during start-up to first preheat the filter and then start the PFBC. This allowed a filter heat-up at 200°F/hr which protected the refractory and superalloy steelwork from thermal shock. The PFBC was designed to preheat to 1600°F in no more than about two hours as there is no auxiliary fuel system. For one series of tests, all the PFBC generated fuel gas passed through the GBF. During other series of tests, some PFBC generated gas was bypassed. Typical PFBC operating parameters are shown on Table 2-I.

**TABLE 2-I. NYU OPERATING PARAMETERS**

| | | |
|---|---|---|
| Flue Gas Flow | 12000-16000 | lb/hr |
| Pressure | 60-135 | psig |
| Temperature | 1400-1650 | °F |
| Excess Air | 20-30 | % |
| Particulate to GBF | 100-3000 | ppmw |

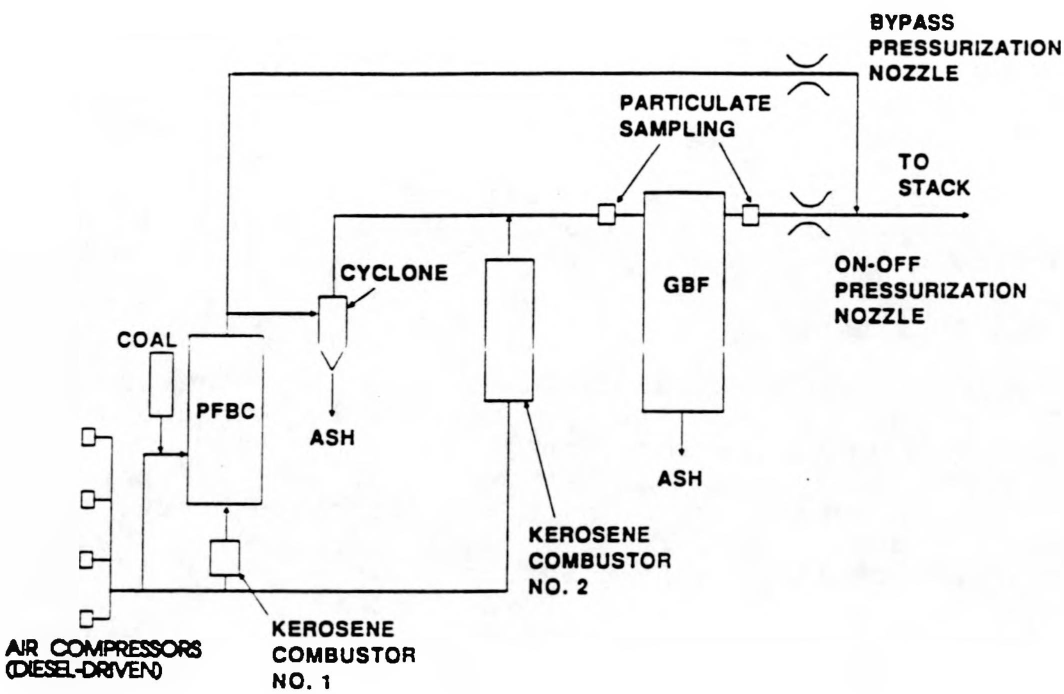


Figure 2-6. NYU Test Equipment

The fluidized-bed combustor is 30" I.D. and 20' tall with horizontal water tubes coiled within the bed. Figure 2-7 shows the configuration of the PFBC lower section.

## 2.4 Computer-Based Data Acquisition System

An Analog Devices Inc. Macsym 350 computer system is used for data acquisition. The data acquisition system is capable of handling 60 thermocouples, 32 current and 16 voltage signals, and a 2-channel event counter for totalizing. Additional functions are 32 channels each of digital input and output including 120 VAC and 3-32 VDC sensing and control by means of solid state double throw relay contacts. The system updates every 12 seconds, logs data every 60 seconds and prints out a data summary every 1 to 5 minutes as selected.

## 2.5 Sampling Systems

To monitor the performance of the PFBC and the Granular Bed Filter, flue gas is continually sampled before and after the granular bed filter. The location of the sampling station is shown in Figure 2-6. The sampling system is made up of particulate, alkali, and gas subsystems. These are described below.

### 2.5.1 Particulate Sampling System

Two sampling systems were utilized. The first was a total filter, i.e. grab sampling system, and the second was a cascade impactor system. Both systems were used at the inlet and outlet of the GBF. Schematic representation of the grab and impactor sampling systems are shown in Figure 2-8 and 2-9.

The grab and impactor sampling schemes are basically similar in design. Each system consists of the following components:

1. An isokinetic sampling probe.

2. A dust collection device (Balston filter or cascade impactor) housed in an electric oven that maintains its temperature at about 450°F.

3. A water-cooled heat exchanger to cool down the sample gas before it flows through the rotameter.

4. A coalescing filter to remove the condensate from the sampling gas, located after the water-cooled heat exchanger.

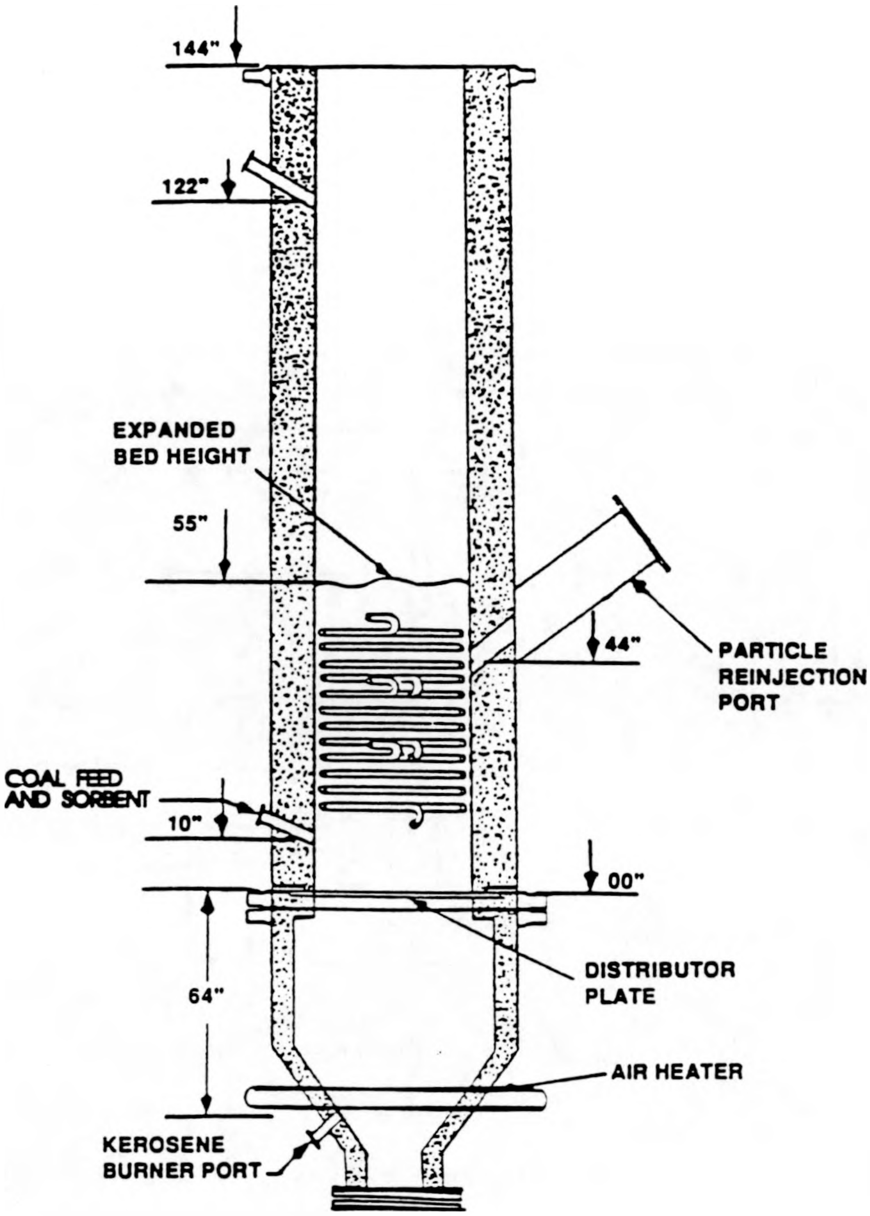


Figure 2-7. PFBC Lower Section (NYU)

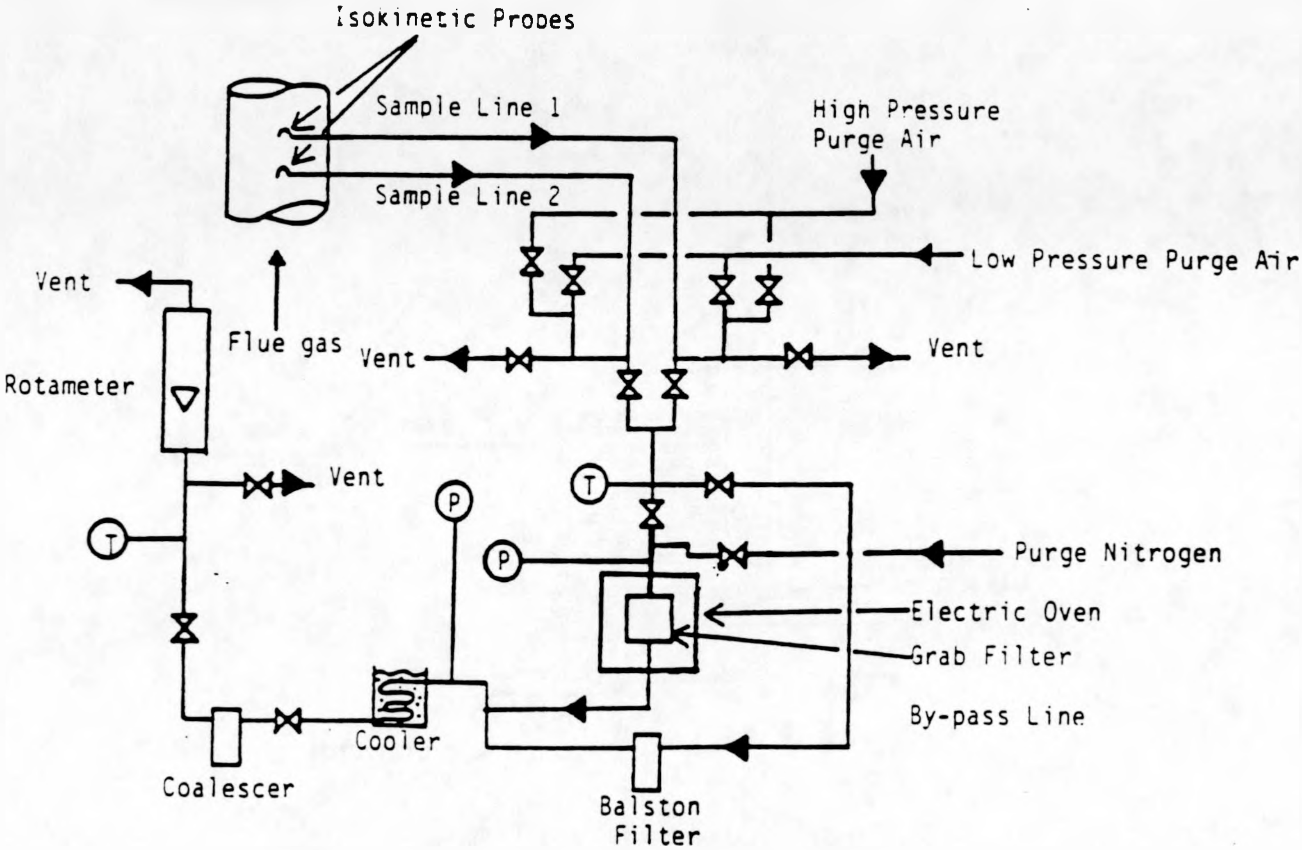


**Figure 2-8. Inlet/Outlet Particulate Grab Sampling System**

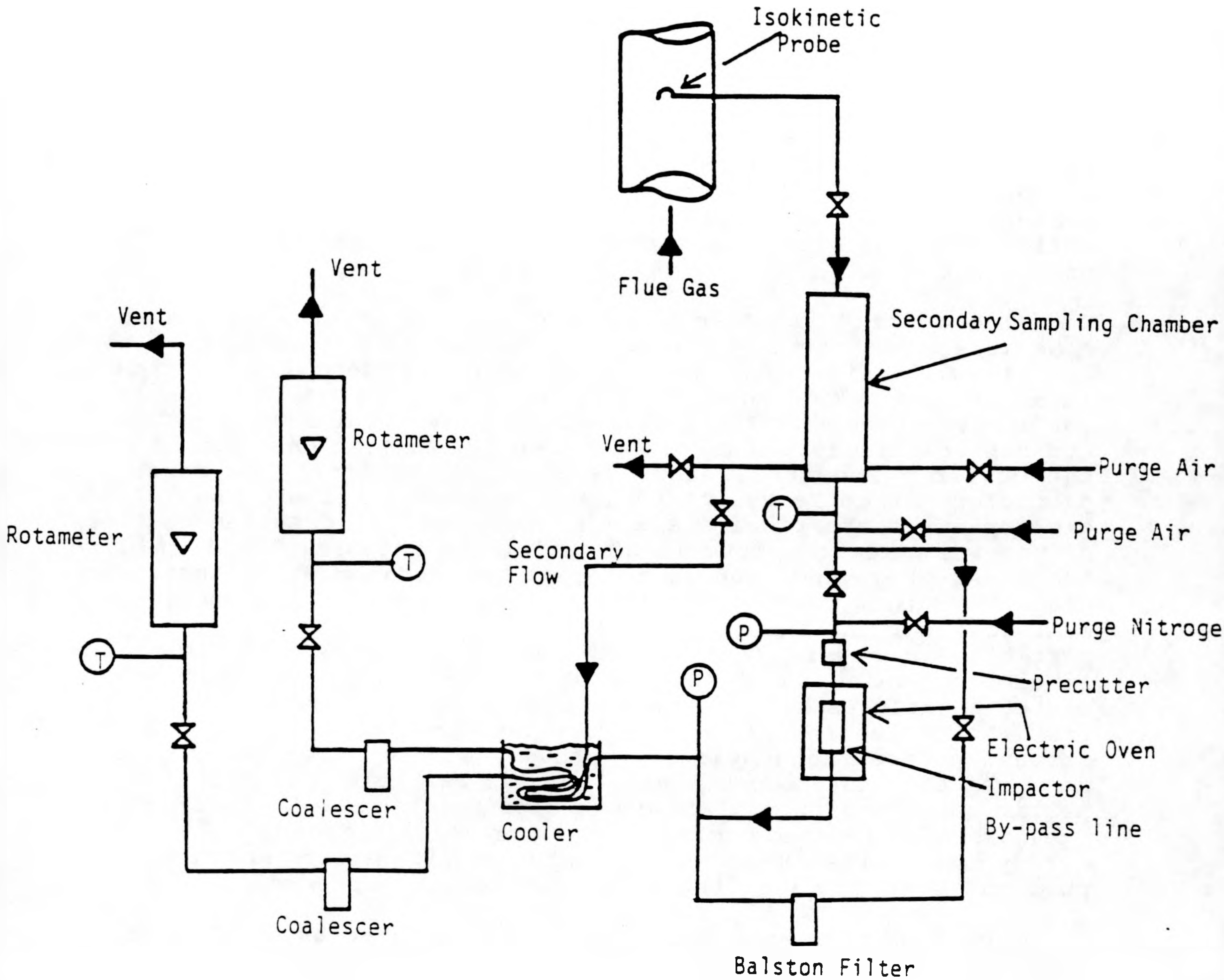


Figure 2-9. Inlet/Outlet Impactor Particulate Sampling System

Ideally, the collection of the dust should be done at the same condition as that of the main gas stream. Due to limitations of the dust collection device and temperature rating of the valves located in the sampling line, dust collection was done at a lower temperature (about 450°F) while maintaining the pressure close to system pressure.

Effective grab sampling requires essentially total filtration of dust within the microfiber structure of a suitably housed filter. Balston grade CH tubular filter elements were used. The microfiber filter tubes were sealed at one end and housed in a stainless steel casing. The filter tubes have filtration efficiencies of 98% (retention of 0.1 $\mu$m particles) at temperature of up to 900°F.

The cascade impactor is an inertial separation device which classifies the particles in a gas stream into a number of size fractions. Basically a cascade impactor is made up of a series of impaction stages as shown in Figure 2-10. The collection plates for stages other than the first and last are donut shaped, allowing for particle impaction upon the outside with flue gas flow through the center. The final stage is a filter holder. The remaining particles not collected at various stages are filtered out of the gas stream at the final stage. A precutter is installed upstream of the impactor to remove larger particles which may tend to blind the first stage and lead to material re-entrainment to the second stage. In this matter, the impactor can handle the expected high dust loading. As the flue gas passes through a given stage, large particles possessing sufficient inertia to cross the gas stream lines and impact on the collecting surface are collected on the plate. Particles having lower momentum will follow the gas stream past the collection plate. In the cascade impactor, the flue gas stream passes sequentially through several impaction stages designed to remove successively smaller particles, thus collecting particles in a series of discrete size fractions. In this manner, the cascade impactor classifies particles according to their aerodynamic size which takes into consideration not only the physical size but also the shape and density of particles.

The impactors employed at NYU were designed by the University of Washington. Two model types of cascade impactors were in use. The model Mark 5, which has eleven-stages (with gas flow rate in the range of 0.2 to 0.8 acfm) was designed for higher dust loadings. It was installed in the inlet test section to handle the higher dust loading around 1500 ppmw, entering the GBF. A seven-stage cascade impactor, Mark 3 was installed at the outlet test section.

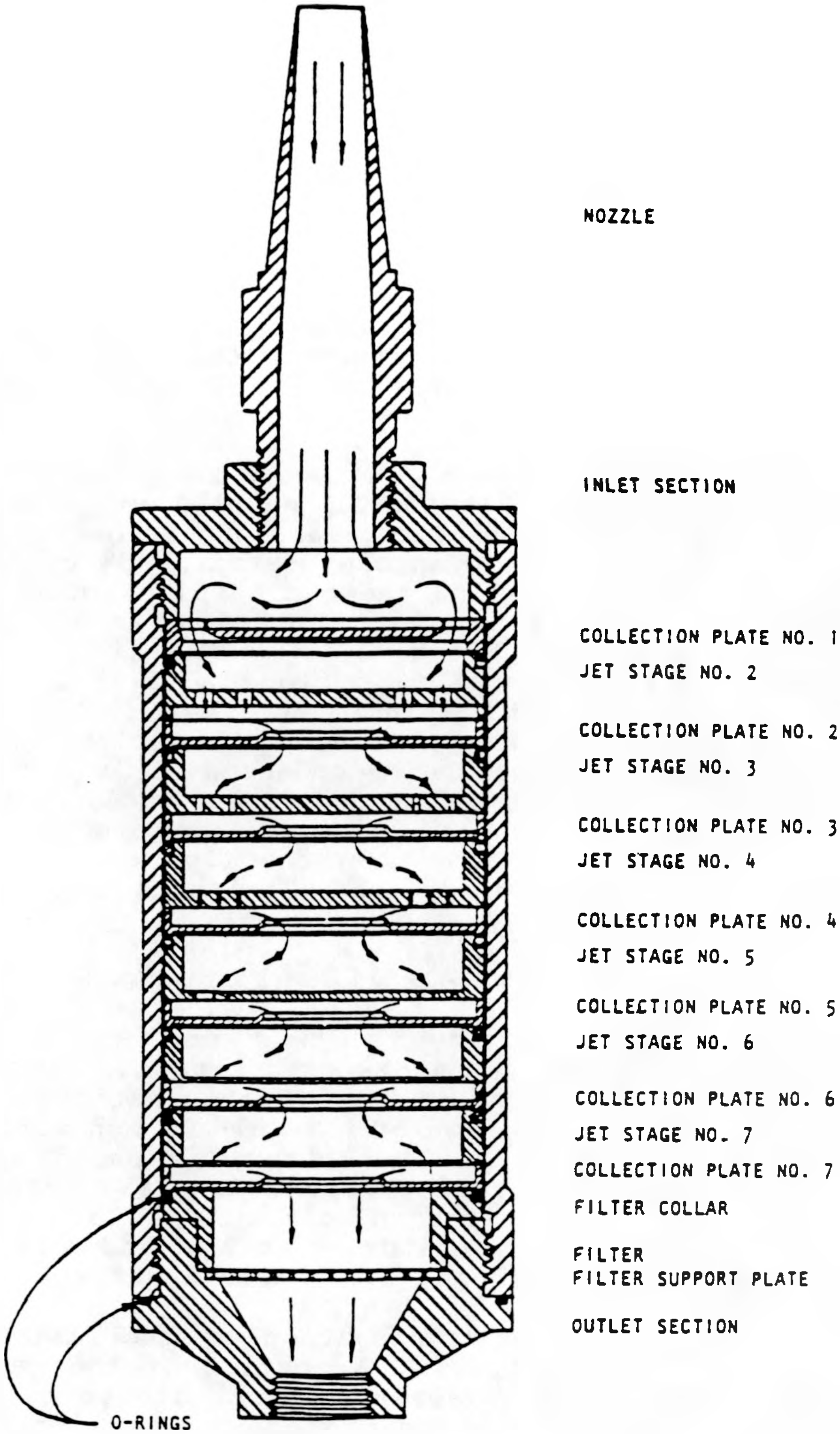


**Figure 2-10. Cross Section of Mark 3 Cascade Impactor**

Approximately, four times the required impactor sample rate was extracted isokinetically from the test section into a 1.25" O.D., 38" long secondary sampling chamber shown in Figure 2-11 and from this chamber, the required quantity was then isokinetically sampled at a lower flow rate (see Figure 2-9).

### 2.5.2 Alkali Sampling Systems

Two techniques were used to measure the alkali content in the flue gas. One was the NYU total vapor condensation alkali system (NYU Alkali System). The other is the METC/INEL on-line alkali system.

For the NYU alkali system, both the inlet to the GBF and the outlet of the GBF were isokinetically sampled using "S" probes (see Figure 2-6 for the location of the sampling probes). The flue gas was separated from the dust in tiny "Stairmand" cyclones located in a pressure vessel close to the gas sampling point as shown on Figure 2-12. The cyclones were heated to near the flue gas temperature using external heaters augmented with flue gas flowing around the outside surface of the cyclones. In this manner, alkali condensation on the dust particles inside the cyclone was minimized. The clean flue gas leaving the cyclones was precooled in a water heat exchanger and condensed in a stainless steel chiller. The flue gas leaving the condenser was scrubbed of alkali in distilled water gas bubblers. The condensate was analyzed and the vapor phase alkali content in the flue gas was calculated. Also, the alkali content in the Stairmand cyclone dust was determined.

#### 2.5.2.1 METC/INEL On-Line Alkali Monitoring System

The alkali monitor employed in this work was the second of two latest generation alkali monitors produced for Morgantown Energy Technology Center (METC) by the Idaho National Engineering Laboratory (INEL). The design of this alkali monitor, referred to herein as the METC/INEL alkali monitor, is based upon, but not identical to, that of the fiber optic alkali monitors developed earlier by METC. The first of the METC/INEL instruments was applied earlier for alkali monitoring at PFBC and coal gasification facilities in England (Fantom, 1987; Haas and Eckels, 1988).

The basic principle of operation of the METC/INEL on-line alkali monitor is as follows: A portion of the gas stream for which alkali concentration determinations are to be performed is introduced into a propane/oxygen flame. There, the sodium and potassium containing species are vaporized and the sodium and potassium present in the subject hot-gas stream are determined by measuring the intensities of the characteristic atomic emission lines of the excited sodium and potassium atoms.

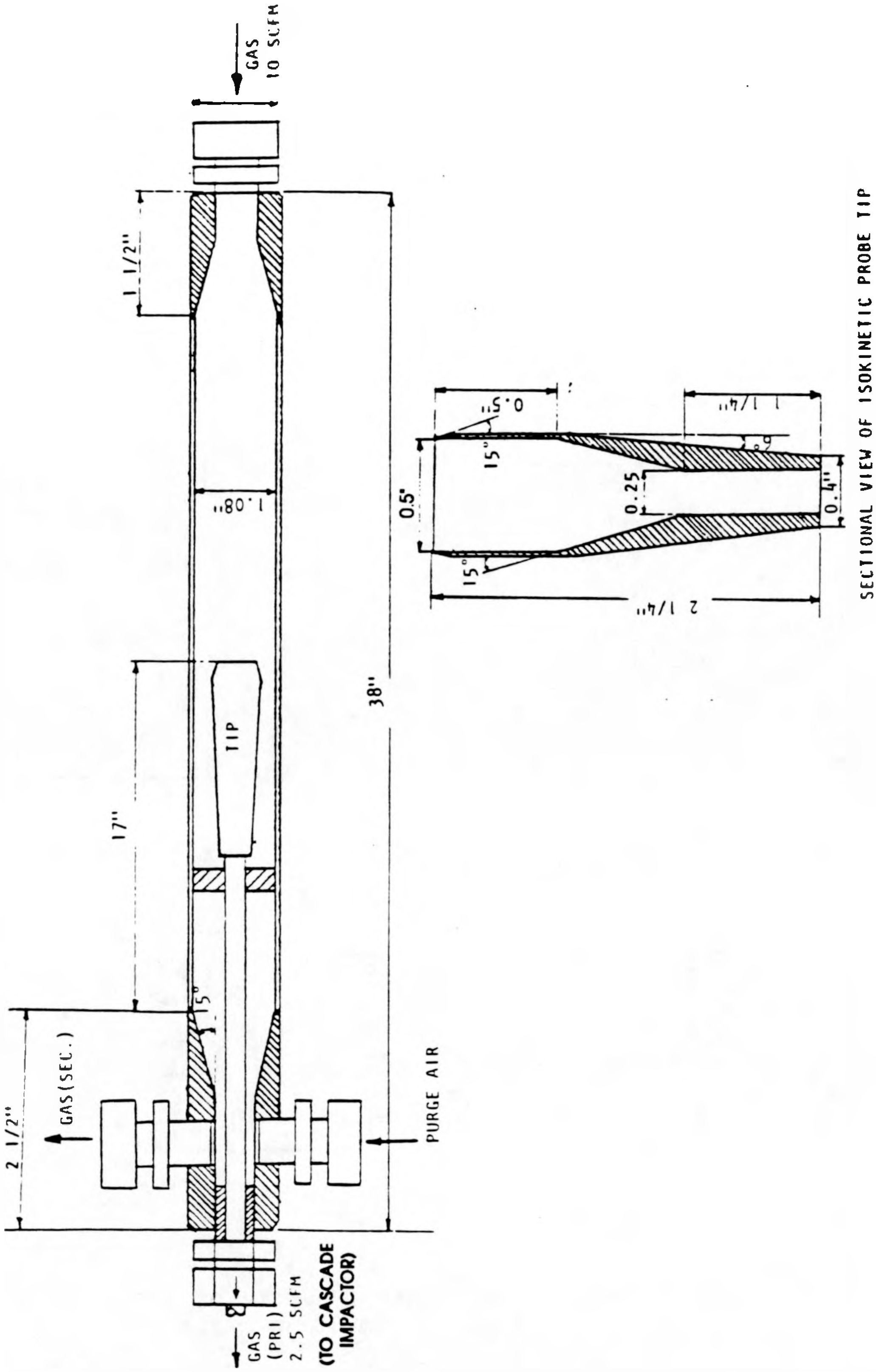


Figure 2-11. Secondary Sampling Chamber for Cascade Impactor System

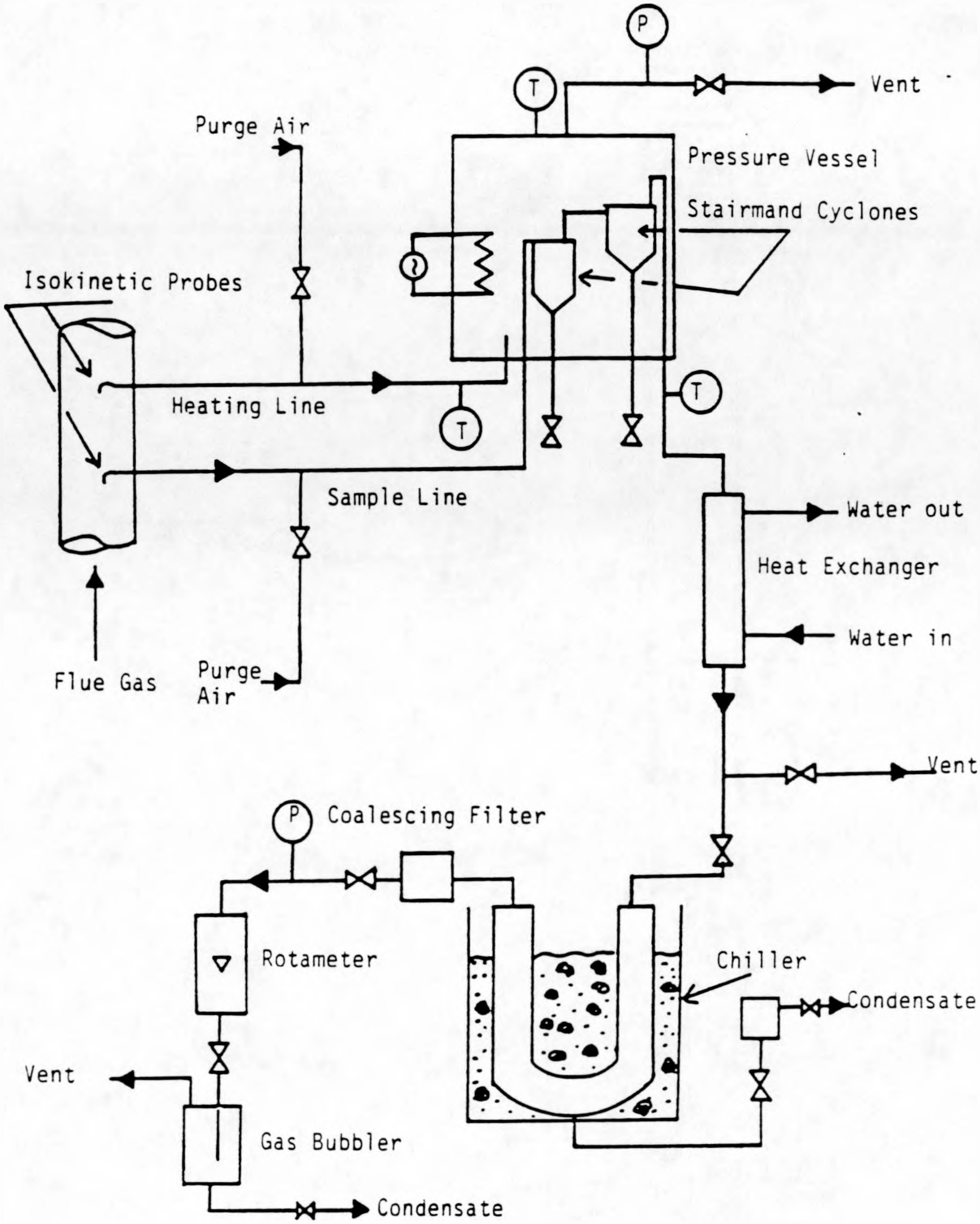


**Figure 2-12. Schematic Diagram of NYU Alkali Sampling System**

The alkali monitor is connected to a small computer with software to provide a level of automation for data acquisition and recording, for computations involved in instrument calibration and determination of concentrations, and for real time display of the analytical results. Details concerning the manner in which the alkali monitors were operated were determined by interactive commands that the operator types at the instrument console and by answers the operator types in response to questions displayed at the console.

The alkali monitor is calibrated by measurements of the emission intensities that are observed when known flow rates of hot surrogate sample gas streams containing known concentrations of sodium and potassium are introduced into the flame. Known concentrations of the elements are produced in the surrogate sample streams by nebulization of aqueous reference solutions containing known concentrations of sodium and potassium sulfates.

The hot-gas sampling system was designed to provide conformance to previously published guidelines for continuous representative sampling for hot-gas alkali monitoring (Haas et al., 1986); the double flue gas is sampled isokinetically with an S probe into a secondary sampling chamber. From here, it is again sampled isokinetically at a rate of about 22 $ft^3/hr$, measured at the entrance to the burner. A sketch showing details of the installation of the primary sampling probe, the expansion chamber and secondary sampling probe, the flame excitation/optical detection unit, and the calibration unit of the METC/INEL alkali monitor system is given in Figure 2-13.

The sample gas lines, the calibration stream gas line, and the high temperature shut-off and control valves were heat traced and heavily insulated with Kaowool insulation in an attempt to maintain sample stream temperatures equal to or greater than the flue gas temperature at the entrance to the primary sampling probe. As indicated in Figure 2-13 the heat tracing consisted of several 1/8 inch diameter 600 watts ARI heaters (supplied by ARI Industries, Addison, Illinois) each wired to a single section of sample line and each controlled by a separate temperature controller (with a range of 0 - 2000°F).

### 2.5.3 Gas Sampling

The flue gas analysis system had on-line analyzers for $SO_2$, $CO_2$, CO, $O_2$, and NO measurements. The system consisted of: 1) isokinetic sampling probes located in the freeboard, the inlet test section to the GBF, the outlet test section downstream of the GBF, the by-pass line and one after the terminal cyclone; 2) a conditioning unit to remove all the dust and water vapor from the flue gas using a permapure dryer and to reduce flue gas pressure to the instruments and 3) gas analyzers which could be calibrated

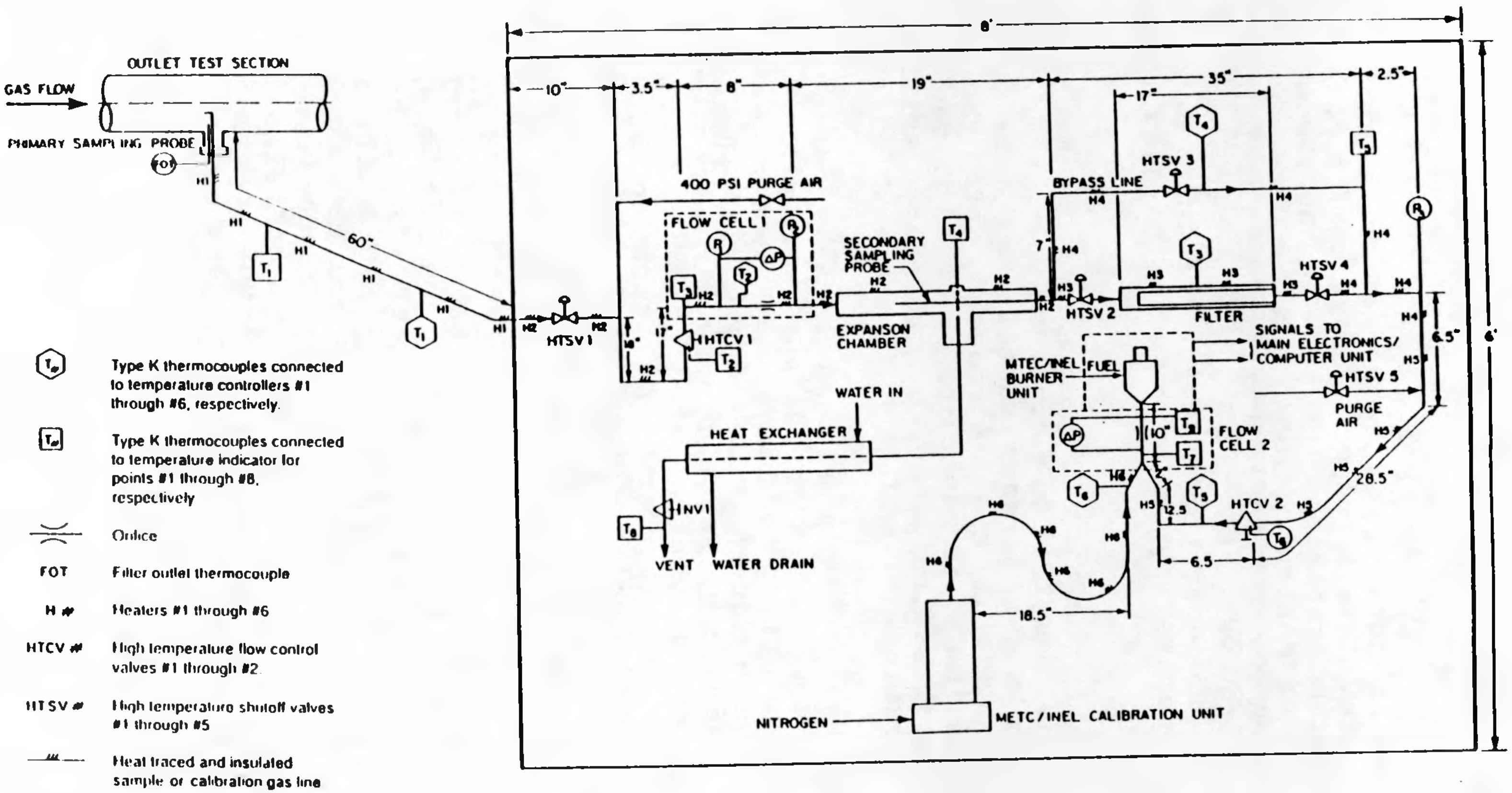


Figure 2-13. METC/INEL Alkali System

using bottled calibrating gas mixtures of the appropriate gases. The mini dryers were used where the moisture content in the flue gas was high. The mini dryers operate on the same principle as the permapure dryers. The line from the gas conditioning room to the control room where the analyzers were located was heat traced. The $CO_2$, CO and NO were measured using non-dispersed infrared techniques whereas $SO_2$ and $O_2$ were measured using UV fluorescence and zirconia cell electrochemical techniques respectively. Detailed layout of the gas analysis system is presented in Figure 2-14. The gas sampling isokinetic probe were similar in design to the alkali sampling probes.

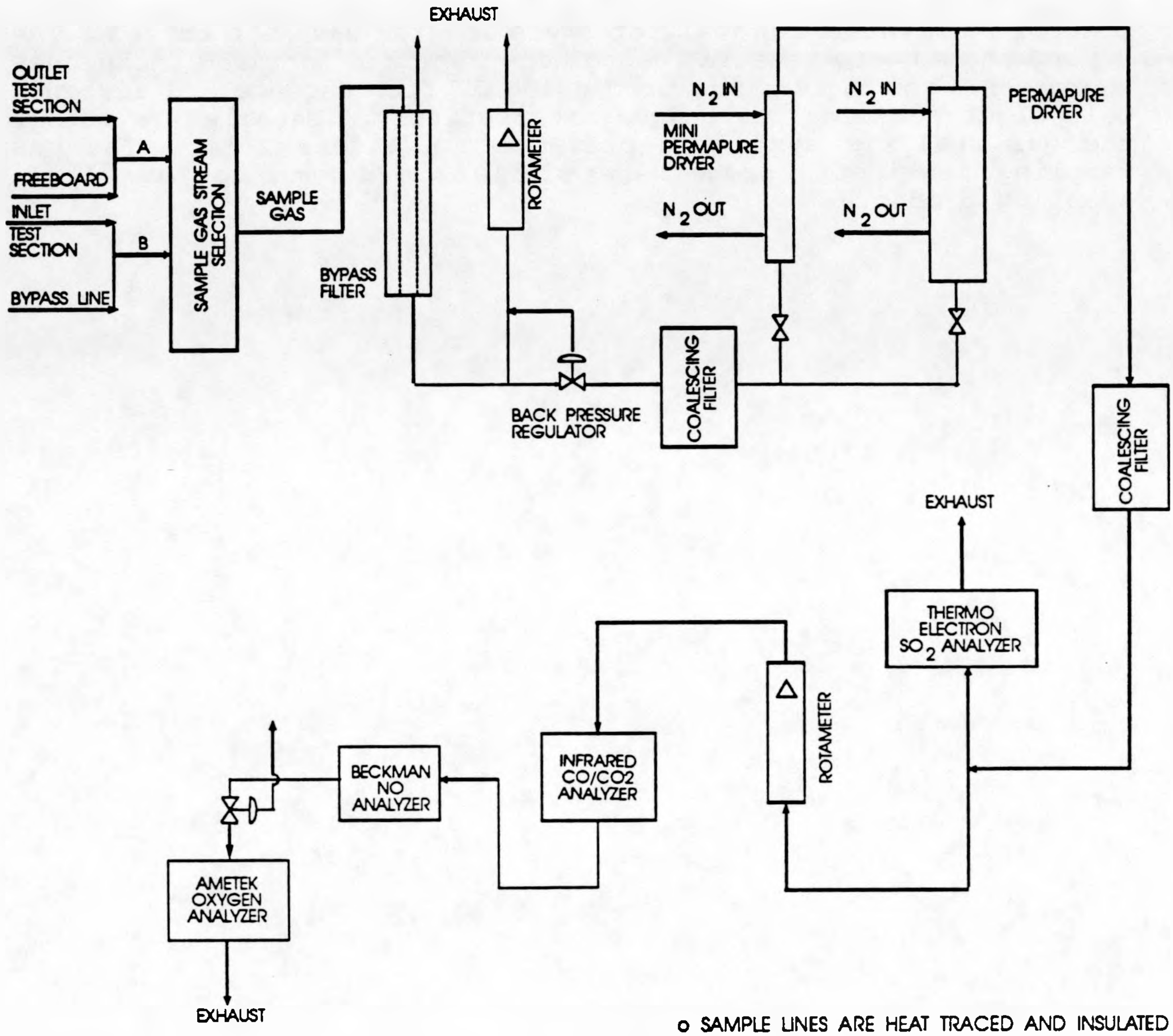


**Figure 2-14. Layout of Gas Analysis System**

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## 3.0 OPERATING AND TEST PROCEDURES

Start-up, operating and test procedures evolved over the first few tests, although the objectives always remained the same. These objectives were:

- Minimize thermal stresses to the superalloy steel components of the granular bed filter and to the unprotected refractory lining by changing temperature at less than 200°F/hr whenever possible.
- Maintain gas flow to the GBF to below 40% minimum fluidization during preheat and to less than 35% minimum fluidization during changeover to coal to avoid bubbling of media.
- Minimize condensation in the media and ash handling system especially during times of particulate removal to assure continuous media and ash movement.
- Avoid condensation in the PFBC primary cyclone which could lead to pluggage.
- Limit pressure changes to 2 psi/minute to allow the GBF operator to keep up with manual control adjustments.

Early start-ups involved use of the system bypass during firing off of the kerosene burners and during the start of coal firing. This practice was changed when it was learned that rapid depressurization while the system was totally on bypass (on-off valve closed) could result in loss of GBF media. This loss of media on rapid depressurization, in excess of 15 psi/minute, would not occur with the on-off valve open. See Figure 2-6 for reference. Preheating without the use of the bypass valve meant that PFBC flue gases passed through the GBF at all times even during periods of poor combustion as one would expect at the initiation of coal combustion. This general mode of operation had precedence during GBF development testing at Combustion Power (Guillory, 1983). There was no bypass on the low pressure, high temperature GBF tested at Combustion Power.

Figure 3-1 shows a history of test parameters from a typical test, HG-204. Regions marked on this graph are explained below.

### 3.1 Start-Up

A few hours prior to GBF preheat, heat tracing at the baghouse and lockhoppers was started. Prior to pressurization, the boost blower was energized and media circulation commenced. Media circulation rate at this time was immaterial. With pressure

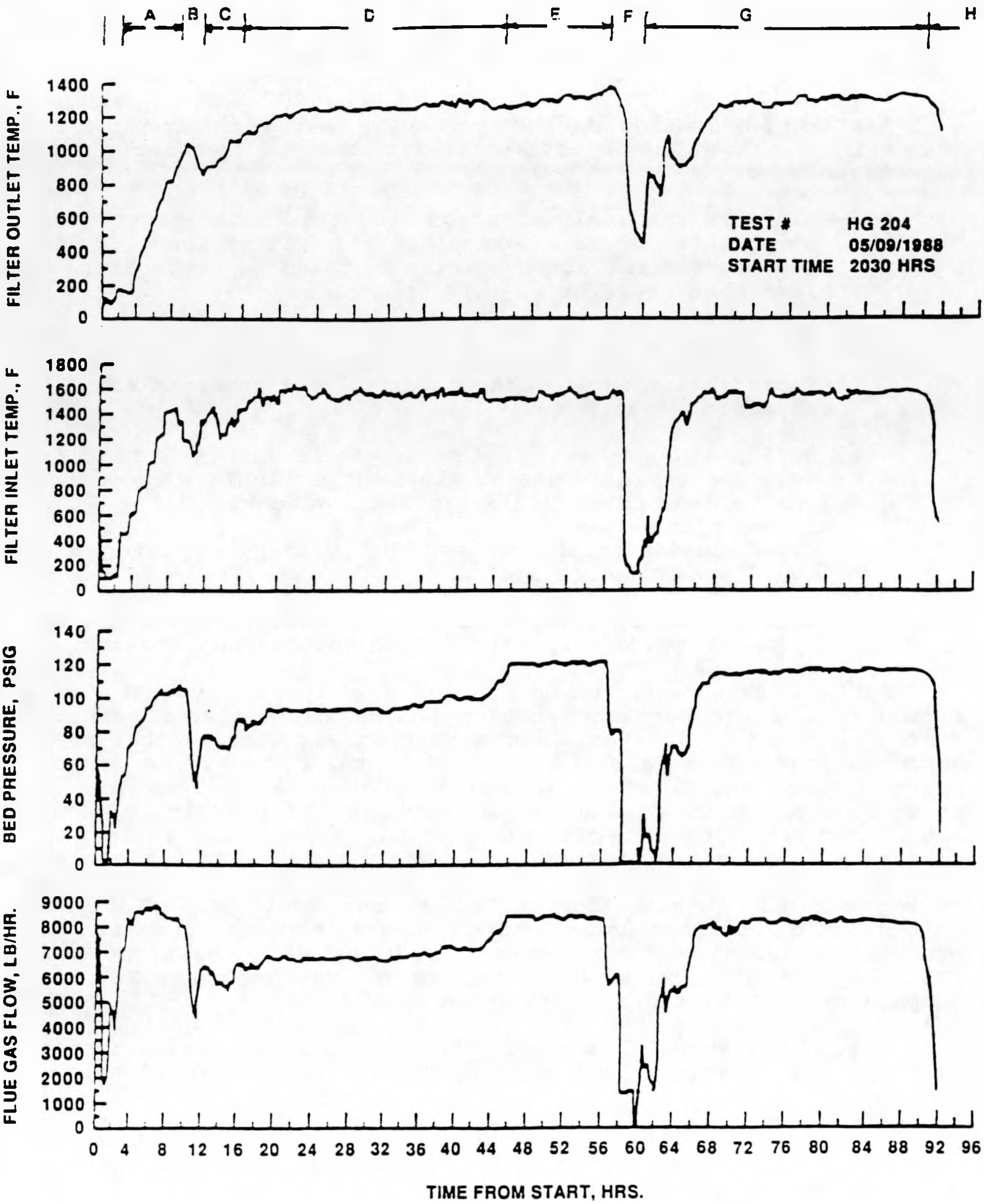



Figure 3-1. Typical Operating Curves for PFBC-GBF System

stabilized near 25 psig, the GBF preheat combustor (#2) was brought on-line with flow typically through the bypass valve. When the temperature was steady at 300-350°F, changeover to the GBF commenced by slowly opening the on-off valve while slowly closing the bypass. In later tests, the use of the bypass valve during kerosene combustor light-off was discontinued as NYU operators gained confidence in proper operation.

After the kerosene combustor was ignited, both fill and vent (manual bypass) valves on the primary cyclone dust lockhopper were opened to allow some of the flue gas to flow through and preheat the primary cyclone system to prevent moisture condensation inside the cyclone. These valves were closed once the cyclone system had been heated to approximately 400°F.

With operation at the kerosene combustor and primary cyclone stabilized, the media circulation rate was maintained in the 50-70 lb/min range. This relatively high circulation rate increased the heat-up rate of the circulation system.

When the temperature of the media transport air exceeded 400°F at the inlet to the GBF baghouse, the cooling air to the air-cooled heat exchanger upstream of the baghouse was started. This reduced the media transport air temperature to below 400°F. The water-cooled heat exchanger upstream of the booster blower was operated when the inlet media transport air temperature at the inlet of the booster blower exceeded 200°F to protect the blower from overheating. The kerosene firing rate was controlled to obtain a heat-up of the GBF at a rate not exceeding 200°F/hr. The preheating process was continued until the GBF outlet temperature stabilized (with the GBF inlet temperature at approximately 1300°F) and the media reservoir temperature was above 500°F. With 500°F in the media reservoir, there was assurance that no portion of the circulation system was below dewpoint (300-350°F). This phase of preheat is shown as region "A" in Figure 3-1.

After preheat, and with the on-off valve remaining fully open, the bypass valve was slowly opened. This operation took place over 20 minutes to minimize pressure transients. With pressure at about 40 psig and the GBF inlet temperature reduced to 1100°F, the start-up of the PFBC began. This is shown as region "B" in Figure 3-1. Note the drop in pressure as the bypass valve was opened.

With 16" of used bed material in the fluidized bed, water flow established to the in-bed tubes, and fluidizing air established to the PFBC, the lower kerosene burner was started up. Adjustments were made at the GBF preheat kerosene burner to maintain the guidelines on temperature and pressure changes. Within 30 minutes the PFBC was heated to 1000°F and coal feed commenced. At 1200°F in the PFBC, the lower kerosene combustor was shut down and the GBF preheat combustor also shut down except for a small amount of cooling air. The result is shown as region "C" in Figure 3-1. At the end of "C", the GBF preheat combustor was shut down. The PFBC continued to heat to 1650°F at which time sorbent feed was increased to build up the fluidized bed height from 6' to 8'. This is shown as the first few hours of region "D" on Figure 3-1.

## 3.2 Operation

At near steady state, the bed temperature and pressure were maintained at 1600-1650°F and 90-120 psig, respectively. The sorbent feed rate was generally maintained constant in order to maintain the bed height and $SO_2$ emission levels at the desired values; although higher sorbent rates were sometimes initiated to increase the dust loading to the GBF.

The media circulation rate of the GBF was maintained within the range of 20-60 lb/min. During the steady state period, the GBF inlet and outlet were sampled for flue gas particulate and alkali concentrations and gas composition. The bed and GBF temperatures as well as pressures were continuously recorded and stored in the computer. Minute by minute printouts of data were available.

Two regions of steady state are shown on Figure 3-1 as "D" and "E". Some PFBC bed material was being loaded at the beginning of "D" (first 4-6 hours). Other than that, operation was stable. In region "E", the pressure was increased by raising gas flow. GBF outlet temperature was rising slowly throughout this later period.

The GBF test plan consisted of a series of 50-hour parametric tests and a long-term (100-hour) steady state test. Gas flows were set prior to a test by choice of on-off and bypass nozzles. During each parametric test, a constant circulation rate was maintained for 16-24 hours while data was gathered to determine if the GBF collection efficiency could be related to media circulation rate. Data gathered at different pressures as shown on Figure 3-1 was not part of the original test plan but occurred due to uncertainty over particulate sampling data at the specific time. Detailed test objectives and test plans are presented in Section 4.0.

## 3.3 Shutdown

It was very difficult to control shutdowns to allow slow temperature and pressure drop. The coal feed rate could be lowered to drop PFBC temperature to only 1400-1450°F. Below that temperature, the quality of coal combustion was poor; consequently, coal was shut off followed by fairly rapid pressure and temperature drop. Depressurization was made more gradual by coordinated closing of the bypass and/or on-off valve as the bed temperature and air flow decreased. In Figure 3-1, regions "F" and "H" show shutdowns. Region "F" was a shutdown to take care of a GBF media circulation problem.

Pressure was lowered at instantaneous rates of over 20 psi/minute. Filter inlet temperature dropped 912°F from 1612°F in 12 minutes (76°F/min.). During the shutdown at "H", the pressure drop came closer to averaging 2 psi/minute although the instantaneous rate approached 10 psi/minute. Temperature drop at the filter inlet was still high at almost 50°F/minute between 1570°F and 620°F. Maintaining a 2 psi/minute pressure change and a 200°F/hour temperature change was very difficult during shutdowns at NYU.

Filter media was circulated for 10-12 hours after shutdown to remove ash from the granules. This operation was not always continuous but usually occurred within 30 hours after shutdown depending on the availability of manpower. This procedure was necessary prior to the next start-up to avoid handling ash during the condensation phase.

## 3.4 Transient Operation

PFBC upsets occurred during operation; such as a kerosene combustor trip, loss of coal feed, primary cyclone plugging, diesel compressor trip, and electric power loss. These upsets usually involved a pressure loss, then regain, and if the upset lasted for some time, the GBF inlet temperature also fell. Usually upsets were obvious, but in any case, the NYU operator notified the GBF operator. Media circulation could be lowered to 20-30 lb/min to maintain GBF and circulation system temperature to some extent. After HG-203, manual controls were installed to assist in handling pressure transients. These controls bypassed seal-leg leakage between the GBF and circulation system; consequently, the desired pressure profile could be restored more quickly than before. When pressure, temperature and gas flow changed slowly as during most of "D", "E" and "G" the GBF operated with very little manual intervention. More details on transient operation is presented in the section on GBF Test Summaries.

## 4.0 SUMMARY OF GBF TESTS

### 4.1 Test Plans

The objective of the testing was to remove PFBC generated particulate to proposed limits without operational or component failure. Proposed limits for particulate were the New Source Performance Standards for coal fired boilers (.03 lb/$10^6$ Btu) and turbine tolerance limits (defined in Section 5.0). Testing was divided into shakedown and performance tests. Shakedown tests were necessary to prove the PFBC and GBF equipment operational prior to committing manpower and materials to the longer term performance test. For shakedown tests, the GBF and PFBC were preheated and operated only long enough to check out equipment and procedures. Preheat on kerosene demonstrated GBF operation at varying temperatures and pressures. Coal was burned to observe GBF operation under ash loading to check out the coal feed equipment and to confirm particulate and alkali sampling procedures. Typically, coal was burned for no more than 4-6 hours. Kittanning bituminous coal was used as fuel and dolomite as sorbent. Ultimate and proximate analysis of the coal and chemical analysis of the dolomite are presented in Appendix IIA.

Performance testing was further divided into parametric testing and steady-state testing. Parametric tests, lasting up to 50 hours each, and were planned to study filter operation under various parametric combinations of process variables as follows:

- Media Size: 2 mm & 3 mm diameter
- Gas Flow: 25% and 50% minimum fluidization of media
- Pressure: 1-9 ATM (14.7-135 psia)
- Temperature: 60°F - 1600°F
- Dust Loading: 1000-2000 PPMW
- Media Circulation Rate: 20-60 lb/min

Media saved from GBF developmental tests at Combustion Power Company was used for the earlier tests at NYU. This media was 2 mm alumina granules that were nearly spherical. The last performance test was devoted to investigating operation with the larger, 3 mm media which allowed higher gas throughput. Filter gas flow was lowered to 25% minimum fluidization after the first few tests because of difficulty tolerating PFBC upsets while operating at 50% minimum fluidization. Temperature and pressure varied over a wide range due to start up and shutdown; although particulate and alkali sampling was ordinarily done at 8-9 ATM pressure and 1500-1600°F filter inlet temperature. The range of dust loading was estimated at 1000-2000 PPMW based on previous experience at NYU and proved to be reasonable even though actual dust loadings measured from less than 200 PPMW to over 6000 PPMW.

In the 50-hour parametric tests, circulation rates were changed periodically to observe effects on filter operation and ash collection efficiency. All parametric tests were started at a high circulation rate (60 lb/min) in case particulate loadings were much higher than expected. The first two or three particulate grab samples were analyzed qualitatively to the point where results appeared reasonable and consistent. Our original plan was to collect three valid particulate grab samples at each level of circulation and then move on to the next level of circulation. This proved to be difficult as inlet and outlet loadings were not consistent. Furthermore, for the GBF to respond to a change in circulation rates may take as many as three total changes of media in the filter. The time required for media to travel once around the filter circulation loop is tabulated below.

| Circulation Rate (lb/min) | Time for One Circulation (hours) |
|---|---|
| 30 | 7.2 |
| 45 | 4.8 |
| 60 | 3.6 |

In a parametric test that lasted 40-50 hours it was not possible to circulate long enough or take enough particulate samples to assure that sampling truly reflected steady-state operation in relation to media circulation rate.

The long-term test (100 hours) was planned for a single circulation rate but at two pressure levels. For the first 20-30 hours, conditions from the previous test were re-established to determine if the same particulate sampling results were received. The final 50-70 hours were devoted to a single, steady-state demonstration of longer-term behavior.

Table 4-I summarizes planned conditions for shakedown and performance tests. "HS" was NYU's code to designate a hot shakedown test; "HG" designated a planned hot gas performance test.

## 4.2 Shakedown & Performance Test Results

Three shakedown and five performance tests were performed between October 1987 and June 1988. A summary of test dates and operating hours is shown on Table 4-II. Brief test summaries follow. Test reports are included in Appendix IIB.

### 4.2.1 Shakedown Test HS-201

The first shakedown test consisted of a kerosene preheat of the GBF. Operation was with 2 mm media at near 50% minimum fluidization. Preheat was delayed because of difficulty igniting the kerosene combustor. The test started about 4:00 am on a Friday morning and ended later that day as no second shift was scheduled for the PFBC. The GBF was operational for preheat, but instrument and electrical problems were identified.

#### 4.2.2 Shakedown Test HS-202

Operation was with 2 mm media at near 50% minimum fluidization. A normal GBF preheat was followed by an attempt to fire coal. A plugged coal feed line prevented coal feed and NYU efforts to clear the fuel line backflowed media out of the GBF. Media backflowed because pressure was released through the bypass valve while the filter was isolated by the on-off valve. Since this backflow would not occur with the on-off valve open, operating procedures were changed. Subsequent startups of the PFBC were accomplished with the on-off valve open. This solved the media backflow problem and demonstrated the ability of the GBF to handle the products of poor combustion during startup.

#### 4.2.3 Performance Test HG-201

Again the filter was operated with 2 mm media at near 50% minimum fluidization. After about 1-1/2 hours of coal combustion the primary cyclone just downstream of the PFBC plugged up. Pulsing high pressure air up through the cyclone ash drain pipe caused a large amount of cyclone ash to enter the GBF. This surge of ash caused the GBF media to bubble as it blinded off the filter at the gas/media interface.

As a result of this test the filter element was modified to contain bubbled media and some repairs were made as a result of earlier tests. PFBC and primary cyclone modifications were also completed in hopes of averting a repeat of the problem.

#### 4.2.4 Shakedown Test HS-203

Because the PFBC and GBF both had considerable modifications, another shakedown test was scheduled. Operation was with 2 mm media at near 50% minimum fluidization. This test was completed through 4 1/2 hours of coal combustion, but was halted prematurely because NYU still had problems with primary cyclone dust drain. Particulate and alkali measurements were completed. A post-test inspection indicated that filter media had bubbled sometime during the test, but it was decided to try the same basic test parameters again in the following performance test.

A summary of shakedown test conditions is presented in Table 4-III.

TABLE 4-I. SUMMARY: PLANNED CONDITIONS FOR SHAKEDOWN AND PERFORMANCE TESTS

| Test# | GBF Temperature (F) | GBF Pressure (psig) | Coal Firing (hrs) | Media Circulation Rate (lb/min) | GBF Gas Flow (lb/hr) | Media Dia. (mm) |
|---|---|---|---|---|---|---|
| HS-201 | 1550 - 1600 | 115 - 130 | 5 - 10 | 20 - 60 | 15000 | 2 |
| HS-202 | 1550 - 1600 | 115 - 130 | 5 - 10 | 20 - 60 | 15000 | 2 |
| HS-203 | 1550 - 1600 | 115 - 130 | 5 - 10 | 20 - 60 | 15000 | 2 |
| HG-201 | 1550 - 1600 | 115 - 130 | 40 - 50 | 30, 45, 60 | 15000 | 2 |
| HG-202 | 1550 - 1600 | 115 - 130 | 40 - 50 | 30, 45, 60 | 15000 | 2 |
| HG-203 | 1550 - 1600 | 115 - 130 | 40 - 50 | 30, 45, 60 | 7500 | 2 |
| HG-204A | 1475 - 1550 | 90 - 100 | 20 - 30[2] | 30[1] | 7500 | 2 |
| HG-204B | 1550 - 1600 | 115 - 130 | 50 - 70[2] | 30[1] | 7500 | 2 |
| HG-205 | 1550 - 1600 | 115 - 130 | 40 - 50 | 30, 45, 60 | 12500 | 3 |

(1) Media circulation rate chosen from HG-203 operation.

(2) Coal firing was divided into two pressure levels. The lower level was to verify particulate sampling from HG-203.

TABLE 4-II. SUMMARY OF KEROSENE COMBUSTOR AND PFBC OPERATION HOURS

| Test Date | Test No. | Kerosene[1] (hrs) | Coal (hrs) | Total PFBC Operation[2] (hrs) | Prime Reason for Termination of Test |
|---|---|---|---|---|---|
| 10/16/87 | HS-201 | 9.82 | 0 | 0 | Late start. No planned PFBC manpower. |
| 10/27/87 | HS-202 | 16.07 | 0 | 1.65 | Unsuccessful efforts to unplug PFBC coal feedline led to GBF problems. |
| 02/18/88 | HS-203 | 13.53 | 4.57 | 6.53 | Problem with primary cyclone dust drain system. |
| 11/31/87 | HG-201 | 28.40 | 2.97 | 11.75 | Bubbling of GBF media due to sudden infusion of dust that blocked the primary cyclone. |
| 03/01/88 | HG-202 | 21.92 | 13.30 | 19.80 | Poor PFBC operation. Bubbling of GBF media. |
| 04/12/88 | HG-203 | 13.00 | 42.70 | 46.60 | Scheduled shut-down. |
| 05/09/88 | HG-204 | 10.93 | 74.15 | 75.82 | Scheduled shut-down. |
| 06/06/88 | HG-205 | 14.15 | 47.22 | 53.07 | Scheduled shut-down. |

(1) Kerosene combustor or lower plenum burner.
(2) Coal and fluidizing air.

**TABLE 4-III. SUMMARY OF TEST CONDITIONS FOR SHAKEDOWN TESTS**

| Test# | PFBC Bed Temp. (F) | PFBC Bed Press. (psig) | Operation on Coal (hrs) | Gas Sampling | | | GBF Operation | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Grab | Impactor | Alkali | Gas Flow (lb/hr) | Inlet Temp(F) | Outlet Temp(F) | Granules Dia.(mm) |
| HS-201 | (1) | 58 | 0 | NO | NO | NO | 11203 | 963 | 718 | 2 |
| HS-202 | (1) | 72 | 0 | NO | NO | YES | 11489 | 1422 | 1118 | 2 |
| HS-203 | 1573 | 85 | 4.33 | YES | NO | YES | 15442 | 1415 | 1112 | 2 |

(1) PFBC not operated

### 4.2.5 Performance Test HG-202

Operation was with 2 mm media at near 50% minimum fluidization. There were two tries to establish GBF operation on coal-derived flue gas. PFBC combustion was poor and there were many upsets which ultimately made GBF operation at this capacity not possible. Continued deterioration of GBF circulation system refractory was also a problem.

After this test the gas flow to the GBF was reduced to 25% minimum fluidization. Worn areas of upper seal-leg refractory were covered with a stainless steel sheath. It was becoming clear that some hard face refractory was substantially below advertised quality.

### 4.2.6 Performance Test HG-203

Operation was with 2 mm media but GBF gas flow was reduced to 25% minimum fluidization by bypassing one-half PFBC flue gas around the GBF. This was a good test for the GBF from an operational standpoint. PFBC problems including primary cyclone plugging and nuisance electric power losses prevented consistent results from particulate sampling. This test provided good data on GBF operation under upset conditions.

### 4.2.7 Performance Test HG-204

The first segment of this test recreated the operating conditions from HG-203 as more particulate sampling was needed for NYU to check and perfect their procedures. This test was also very successful with coal combustion for 74 hours and more consistent particulate sampling than in previous tests.

A single loss of media circulation because of media valve pluggage caused one brief shutdown. Pluggage was first attributed to broken pieces of refractory, but after the following test it appeared more likely that ash had agglomerated to plug the media valve. Agglomeration was due to moisture and boost blower oil in the circulation gases.

Outlet loadings were measured at 1-16 PPMW which is well below NSPS which translates to about 29 PPMW (see Section III).

### 4.2.8 Performance Test HG-205

Operation was at 31% minimum fluidization with 3 mm media. Particulate sampling seemed more consistent at the filter inlet in that it matched closely with alternate measurement from the GBF baghouse catch. Outlet loadings were 1-10 PPMW. This very successful test included 47 hours of coal combustion but was interrupted by loss of media circulation due to ash agglomeration in the media valve from moisture and oil. Had another test been ran, this problem would have been eliminated by filtering moisture and oil from media valve injector gases.

The performance test results are summarized on Table 4-IV and discussed in detail in Appendix IIB.

## TABLE 4-IV. SUMMARY OF TEST RESULTS FOR PERFORMANCE TESTING

| | HG-201 | HG-202 | HG-203 | HG-204 | HG-205 |
|---|---|---|---|---|---|
| Media Size, MM | 2 | 2 | 2 | 2 | 2 |
| GBF Pressure, psig | 85.7 | 58 | 87.8 | 105.7 | 117.5 |
| Temperature | | | | | |
| • GBF Inlet (AVG) | 1127 | 1173 | 1513 | 1536 | 1561 |
| • GBF Outlet (MAX)(1) | 900 | 950 | 1310 | 1330 | 1450 |
| Coal Flow Rate, lb/hr | 959 | 711 | 1052 | 1170 | 1104 |
| GBF Gas Flow, lb/hr | 13740 | 10140 | 6478 | 7500 | 12834 |
| • % min Fluidization | 48 | 46 | 25 | 25 | 31 |
| • Face Velocity, ft/sec | 1.2 | 1.2 | .67 | .66 | 1.0 |
| Filter Press. Drop, IWC | 30-60 | 33-40 | 27-33 | 24-30 | 18-22 |
| Media Rate, lb/min | 20-40 | 20-40 | 25-65 | 20-70 | 20-70 |
| Ash Loading | | | | | |
| • No. of Measurements | ---- | 1 | 11 | 26 | 17 |
| • GBF Inlet | ---- | 1500 | 27-6355 | 80-2800 | 160-1600 |
| • GBF Outlet | ---- | 60 | 0-30 | 3-16 | 1-10 |
| • Emissions, lb/$10^6$ Btu | ---- | .060 | 0-.030 | .003-.013 | .001-.010 |
| GBF EFF %(2) | ---- | 96 | 96.5-99.9 | 94.3-99.9 | 98-99.8 |
| Alkali Measurements | | | | | |
| • NYU | No | Yes | Yes | Yes | Yes |
| • METC/INEL | No | No | No | Yes | Yes |

(1) Estimated outlet temperature at steady-state.

(2) Disregarding inlet loadings measured below 200 ppmw.

## 5.0 GBF PERFORMANCE RESULTS

This section contains discussions of data gathered during testing. A complete data listing is presented in the following Appendices:

- APPENDIX IIC Southern Research Institute Report on New York University Particulate Sampling
- APPENDIX IID: Particulate and Alkali Data
- APPENDIX IIE: Comparison Between the Weight of Particulate Collected by the GBF and that Estimated From the Grab Data
- APPENDIX IIF: Average Flue Gas Composition Downstream of GBF

### 5.1 Particulate Sampling

Equipment for collecting particulate, both for total dust loadings (grab samples) and for size distribution (impactors) is described in Section 2.0. It is shown that in both inlet and outlet sampling, a portion of the process gas is removed from the main duct and routed through relatively long tubing to the particulate sampling device. This equipment and the laboratory techniques utilized were reviewed by Southern Research Institute. Their findings indicate possible errors could exist with measurements; more likely with impactor data than with grab sampling.

For the entire Southern Research Institute report, refer to Appendix IIC. Some of the salient points are as follows:

- There was evidence that part of the particulate transport system ran below dewpoint as some impactor substrates showed indications of being wet.
- There was no final filters on impactors. Therefore, no data was available on material smaller than the cut diameter of the last impactor stage.
- The transport lines to the samples were relatively long and unheated. This could cause problems with condensation and periodic agglomeration and re-entrainment of ash.
- There was also potential deposition in sample lines because of the long tortuous path from the process ducts to the sample collection devices. These sample ducts included bends and needle valves. This could affect the

measured loadings and size distribution as ash deposited re-entrained, agglomerated, and broke up.

On the basis of this information, grab sampling is reported and interpreted with some caution. Impactor data is reported, but interpretation is minimal due to questions on its validity. This data is presented in Appendix IID and discussed in the following section.

### 5.1.1 Total Particulate Loadings

The GBF inlet dust concentration depends heavily on the efficiency of the primary cyclone and the manner in which the flue gas stream leaving the primary cyclone is split between the bypass and the GBF. The flue gas stream exiting from the primary cyclone maintains its vorticity after it leaves the cyclone vortex tube and requires some distance from the cyclone exit for its vorticity to be dissipated. The dust concentration may not be uniformly distributed inside the flue gas as it leaves the vortex tube. If the flue gas is therefore split at a distance not greater than the distance necessary for its vorticity to be dissipated, the dust concentrations in the two streams may not be uniformly split in terms of concentration and particle size distribution. In the present piping configuration, the filter inlet line is perpendicular to the direction of flow coming out of primary cyclone and the bypass line is in the direction of flow. Consequently, the dust concentration entering the GBF could be lower and probably biased in size in comparison to the dust flowing through the bypass line. The lower dust concentration would result from the tendency of particulate to ignore the 90° turn at the tee into the GBF. Just how the size distribution could be biased is a subject of speculation. This, in addition to errors introduced by: 1) sampling technique and equipment as discussed above, 2) variations in the equilibrium bed particle size distribution, 3) bed height along with fluidization activity, and 4) the irregular draining of the primary cyclone to remove collected dust, could add to the fluctuation in the inlet dust loading to the GBF. In addition, the sorbent feed rate was changed during testing to increase or decrease the dust loading to the GBF. It is therefore not entirely accurate to attribute the fluctuations in the GBF inlet dust loading to any particular cause; although NYU felt that the splitting of the flue gas stream and the intermittent feeding of the sorbent contributed most significantly to the unsteady nature of the particulate loading entering the GBF.

The high dust loadings measure during runs 203-G4 to 203-G6 (See Table 5-I) was due to the malfunction of the primary cyclone dust let down system which prevented the cyclone from being drained. This caused accumulation of dust inside the primary cyclone and subsequent re-entrainment of dust. After the cyclone

**TABLE 5-I PARTICULATE LOADING INTO AND OUT OF GBF FOR TEST HG-203 FROM GRAB SAMPLING**

| Run No. | Flue Gas Flow in to GBF | GBF Inlet Dust Concentration | | GBF Outlet Dust Concentration | | Efficiency % |
|---|---|---|---|---|---|---|
| | lb/hr | ppmw | lb/MBtu | ppmw | lb/MBtu | |
| 203-G1 | 6445 | 930.8 | 0.901 | 19.30 | 0.019 | 97.9 |
| 203-G2 | 6322 | 27.3(1) | 0.026 | 0.00 | 0.000 | -- |
| 203-G3 | 6223 | 71.3(1) | 0.067 | 0.46 | 0.000 | 99.4 |
| 203-G4 | 6302 | 3440.0 | 3.254 | 0.54 | 0.001 | 99.9 |
| 203-G5 | 6251 | 6355.0 | 5.964 | 0.79 | 0.001 | 99.9 |
| 203-G6 | 6338 | 4027.0 | 3.832 | 2.33 | 0.002 | 99.9 |
| 203-G7 | 6383 | 1235.0 | 1.184 | 3.20 | 0.003 | 99.7 |
| 203-G8 | 6411 | 892.0 | 0.859 | 31.60 | 0.030 | 96.5 |
| 203-G9 | 6486 | 174.5(1) | 0.170 | 19.43 | 0.019 | 88.9 |
| 203-G10 | 6618 | 178.8(1) | 0.177 | 15.30 | 0.015 | 91.4 |
| 203-G11 | 6678 | 258.7 | 0.258 | 8.23 | 0.008 | 96.7 |
| Avg. (Total) | | 1599 | 1.517 | 9.20 | .009 | 97.0 |
| Avg. (less G2, G3, G9, & G10) | | 2448 | 2.322 | 12.2 | .014 | 98.6 |

(1) Low measured inlet loadings are likely erroneous.

dust let down system was cleared, the cyclone operated properly and the inlet dust loading to the GBF dropped to a lower value. During this time, the GBF was able to accommodate the sudden increase in the dust loading with a very high collection efficiency of 99.9%. At the conclusion of the test, all dust collected by the GBF was weighed and an average inlet particulate loading was calculated by dividing the ash collected over time by the average flue gas flow. The result was 1750 lb ash per million lb of flue gas or 1750 ppmw. This compares well with 1599 ppmw as the average GBF inlet concentration reported on Table 5-I. Regardless, this was the first large set of grab samples taken in the test program and some data points may be erroneous. Inlet loadings below 200 ppmw seem suspiciously low considering the NYU PFBC system.

Figure 5-1 is a composite plot from test HG-204 comparing inlet and outlet particulate loadings with media circulation rate and time. On the graph for GBF inlet loading both the grab sample data and GBF ash capture data is plotted. GBF ash capture was calculated by periodically weighing the ash removal by the GBF and averaging it over the time period and dividing by the average heat input to yield a result in pounds of particulate per million Btu of coal input. Details are presented in Appendix IIE. These results should compare very closely to grab sample data; the only difference being the filter efficiency as a divisor (about 99%). It is clear that the results from these two methods for estimating inlet loading do not compare well, and since weighing ash collected in a barrel is fairly straight forward, Combustion Power suspects that the NYU grab sample measurements at the GBF inlet were low in some cases.

Also plotted on the curve for GBF outlet loading is the NSPS particulate emission limit for fossil fuel fired power plants of .03 $lb/10^6$ Btu. Measured outlet loadings were well below this limit. Comparison of inlet and outlet loadings does not show any clear trend. Outlet loadings were uniformly low after about 50 hours from the start of measurements and this coincides with a higher media circulation rate. During low pressure, high temperature developmental testing at Combustion Power, higher circulation rates resulted in higher outlet loadings so this observed trend at NYU may not be real. The fluctuation in the outlet loading may simply be due to experimental error.

Figure 5-2 shows GBF inlet and outlet particulate loadings plotted against media circulation rate and time for test HG-205. Here the agreement between GBF ash capture and grab sample loading is reasonable. This gives credibility to the inlet grab sample measurements. Outlet loadings were more uniform and lower than HG-204. There was some expectation that with the 3 mm media utilized for HG-205 vs. 2 mm for HG-204 that outlet loadings would change. The apparent lower outlet loadings for HG-205 were not expected, but could be due to characteristics of the 3 mm media mix. This media actually ranged from 2.4 to 4.0 mm diameter and

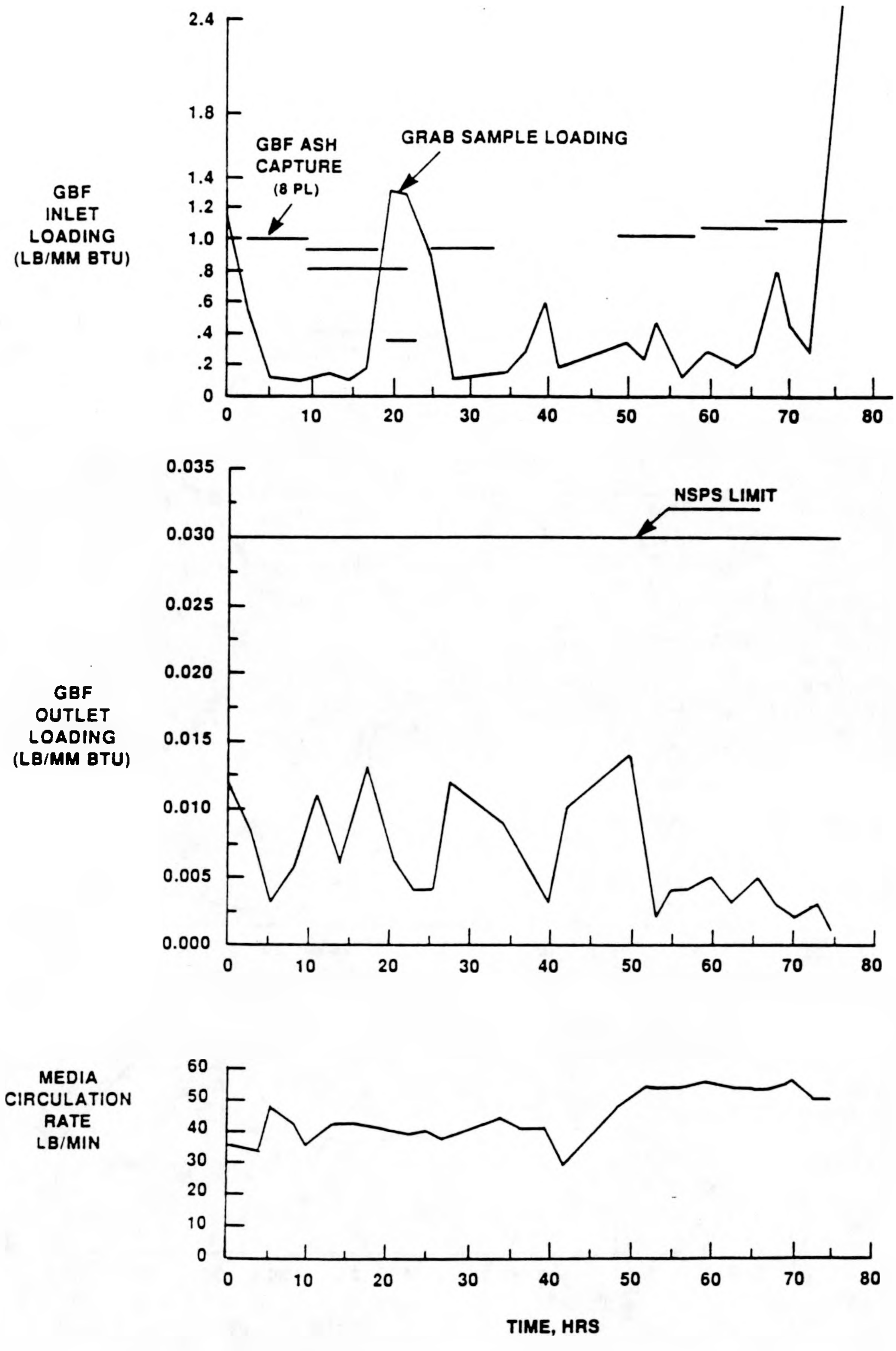



Figure 5-1. HG-204 GBF Inlet & Outlet Particulate Concentration vs. Media Circulation Rate and Time

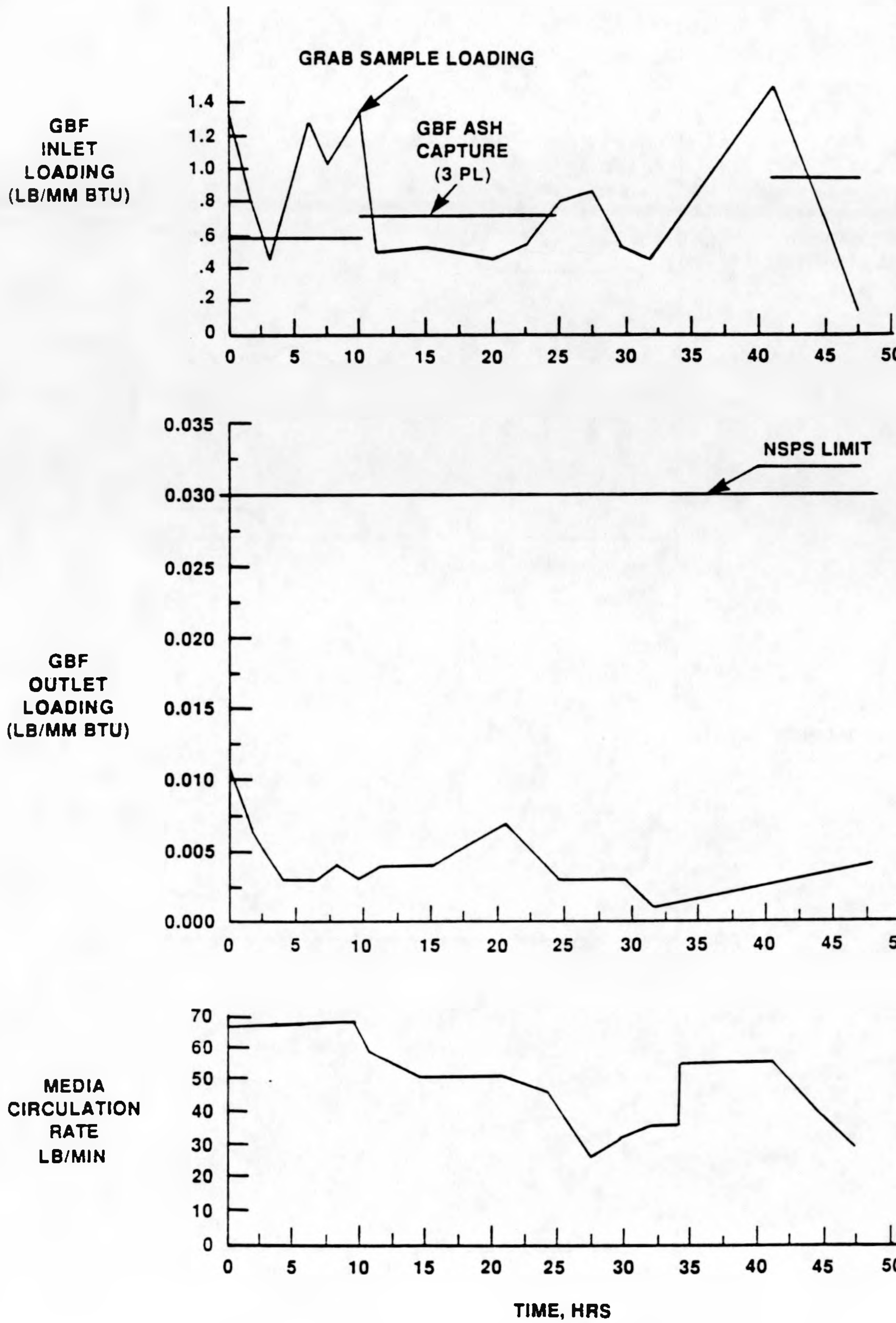



Figure 5-2. HG-205 GBF Inlet and Outlet Particulate Concentration vs. Media Circulation and Time

probably packed differently from the 2 mm media that was quite evenly sized at 1.9 to 2.1 mm. There is no clear trend shown between inlet and outlet loadings and media circulation rate in HG-205 which could be due to short time that the circulation rate was held constant.

It was shown in low pressure developmental testing that encompassed thousands of hours that lower circulation rates decreased outlet loading (Guillory, 1983). It was expected that this trend would also be shown at high pressure but the short test period did not allow for confirmation.

The dust capturing efficiency of the GBF is sensitive to the inlet dust loading. Figure 5-3 shows that for HG-204, there were considerable inlet grab sampling measurements below 200 ppmw; and since the outlet loading averaged 7 ppmw, the efficiency calculation yields biased results. In Figure 5-1, it was shown that low inlet GBF loadings measured by grab sampling may not be representative. If, we somewhat arbitrarily disregard all data associated with inlet loadings below 200 ppmw, the average collection efficiency for HG-204 is 98.6%. If we assume that the inlet loading averages 1000 ppm as suggested by the GBF ash capture (Figure 5-1) then, using 7 ppmw as the average outlet loading, the GBF collection efficiency averages 99.3% for HG-204. During HG-205 (3 mm media) inlet grab sample measurements were generally above 500 ppmw; consequently, the calculated filter efficiency were not biased as much by low measured inlet loadings as shown on Figure 5-4. For HG-205 the average filter efficiency by grab sampling was 99.4%. By averaging the weight of ash collected by the GBF (GBF ash capture from Figure 5-2) and averaging the GBF outlet loadings from grab sampling (4 ppmw), the filter efficiency averages 99.5%.

### 5.1.2 Size Analysis of Grab Sample

The size distributions of the dust entering the GBF are presented for tests HG-204 and HG-205 in Figures 5-5 and 5-6 respectively, based on coulter counter analysis. The size distribution of the dust leaving the GBF are not presented because the weight of the grab samples taken was too small to be analyzed. For test HG-204 sample 204-G24 reflects the state of the bed particle size distribution at that time according to NYU. In test HG-205, both 205-G6 and 205-G15 (see Figure 5-6) samples appear to be slightly coarser than HG-205-G12 sample but the difference is not as pronounced as those of test HG-204. The variation in this data demonstrates the range of particle sizes entering the GBF.

The size distributions of the dust collected by the GBF and sampled from the high pressure baghouse catch during Tests HG-204 and HG-205 is presented in Figure 5-7. These size distributions are not only similar but fall within the same range defined by the size distributions at the filter inlet shown on Figures 5-5 and 5-6.

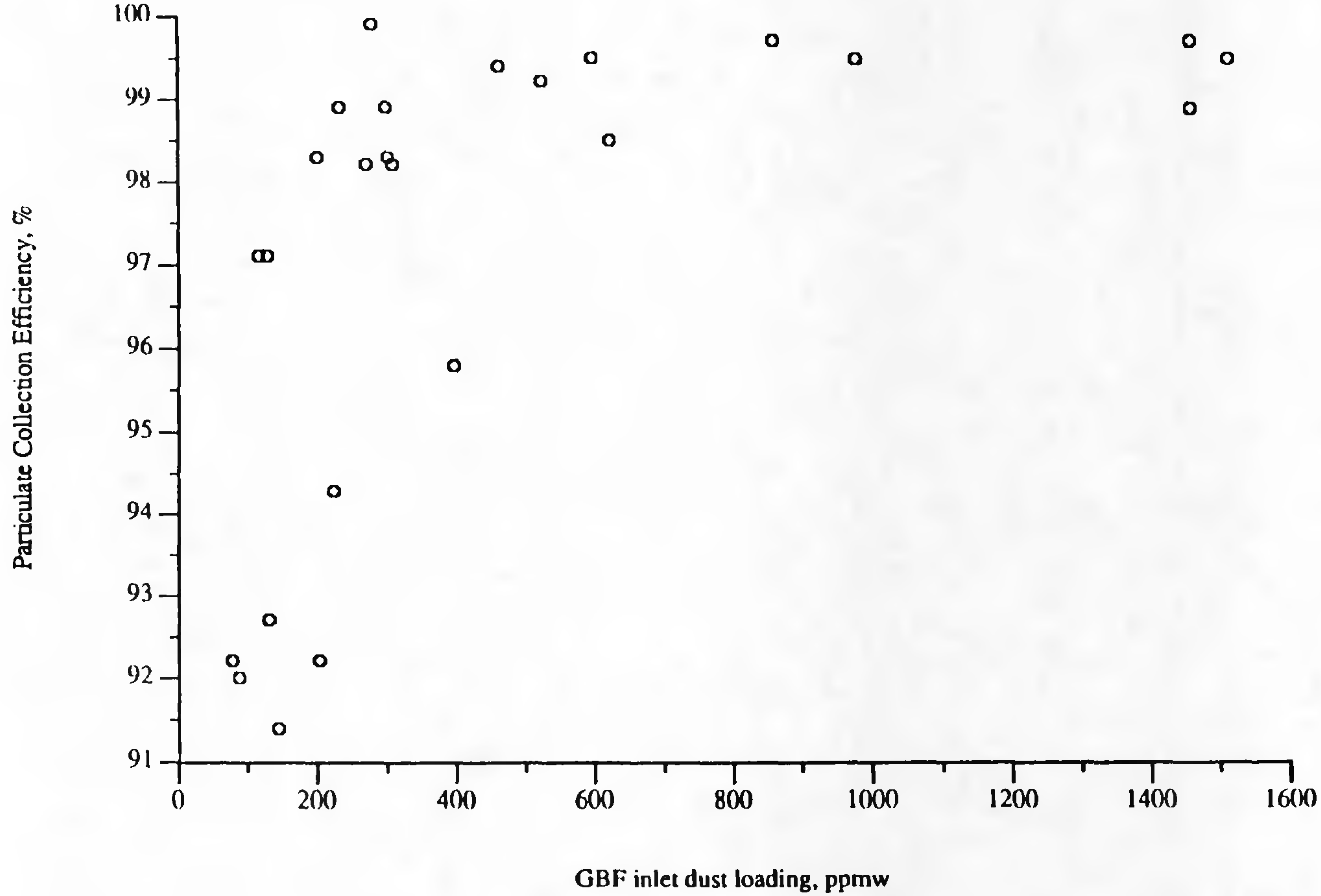



**Figure 5-3. Effect of Inlet Particulate Loading on GBF Collection Efficiency, HG-204**

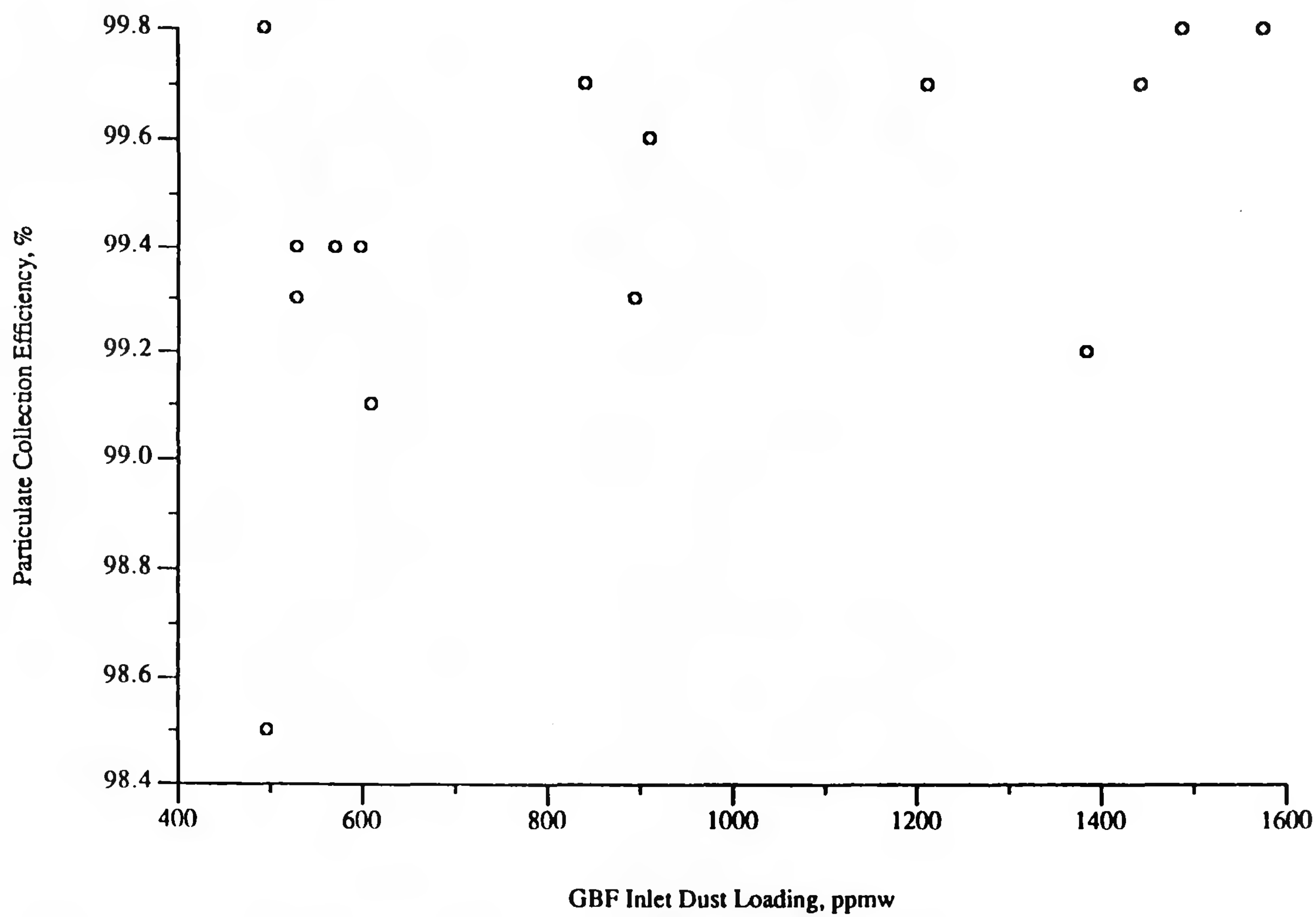



**Figure 5-4. Effect of Inlet Particulate Loading on GBF Collection Efficiency, HG-205**

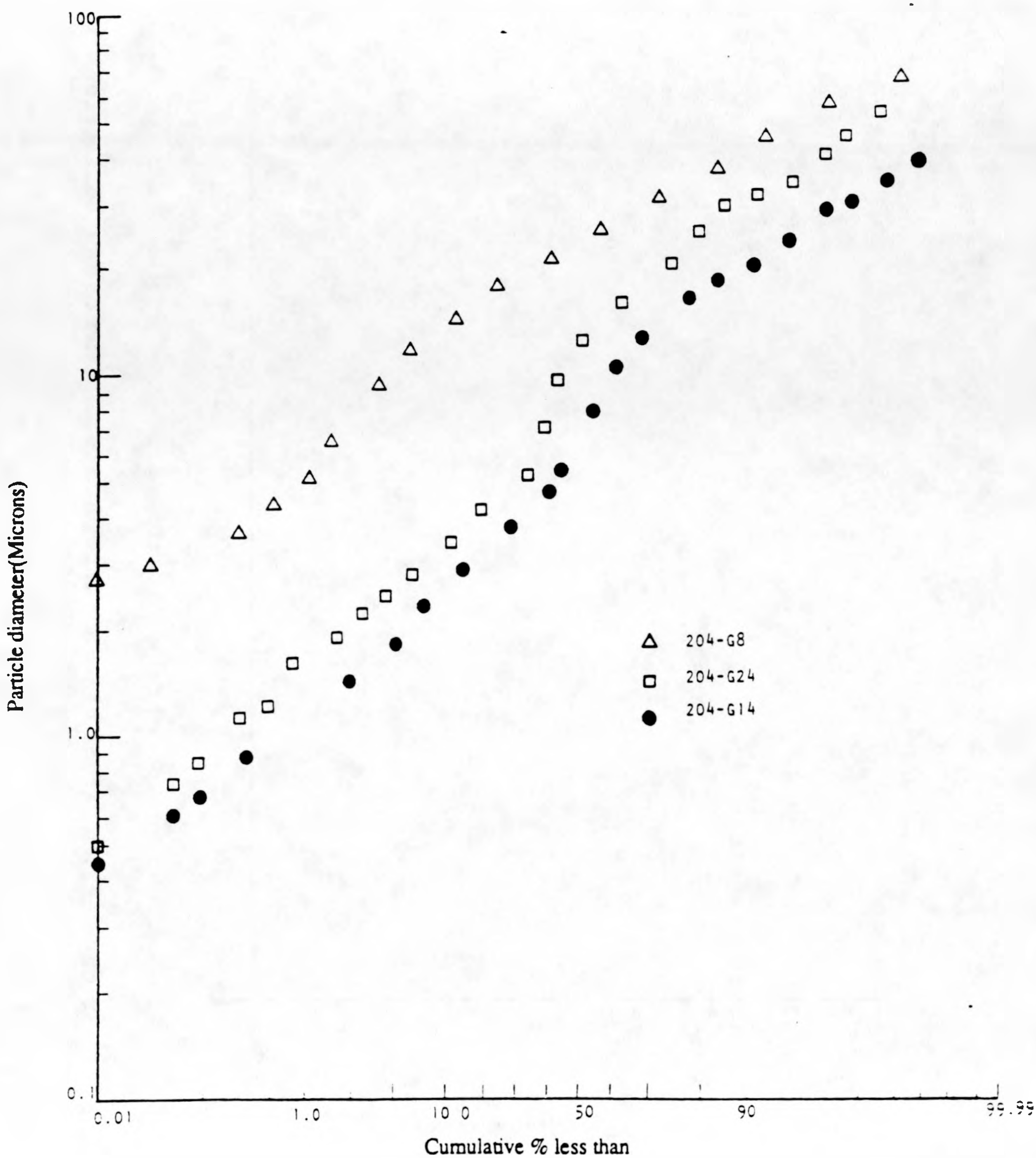



**Figure 5-5. Particle Size Distribution of the Dust Entering the GBF During Test HG-204 (Coulter Counter)**

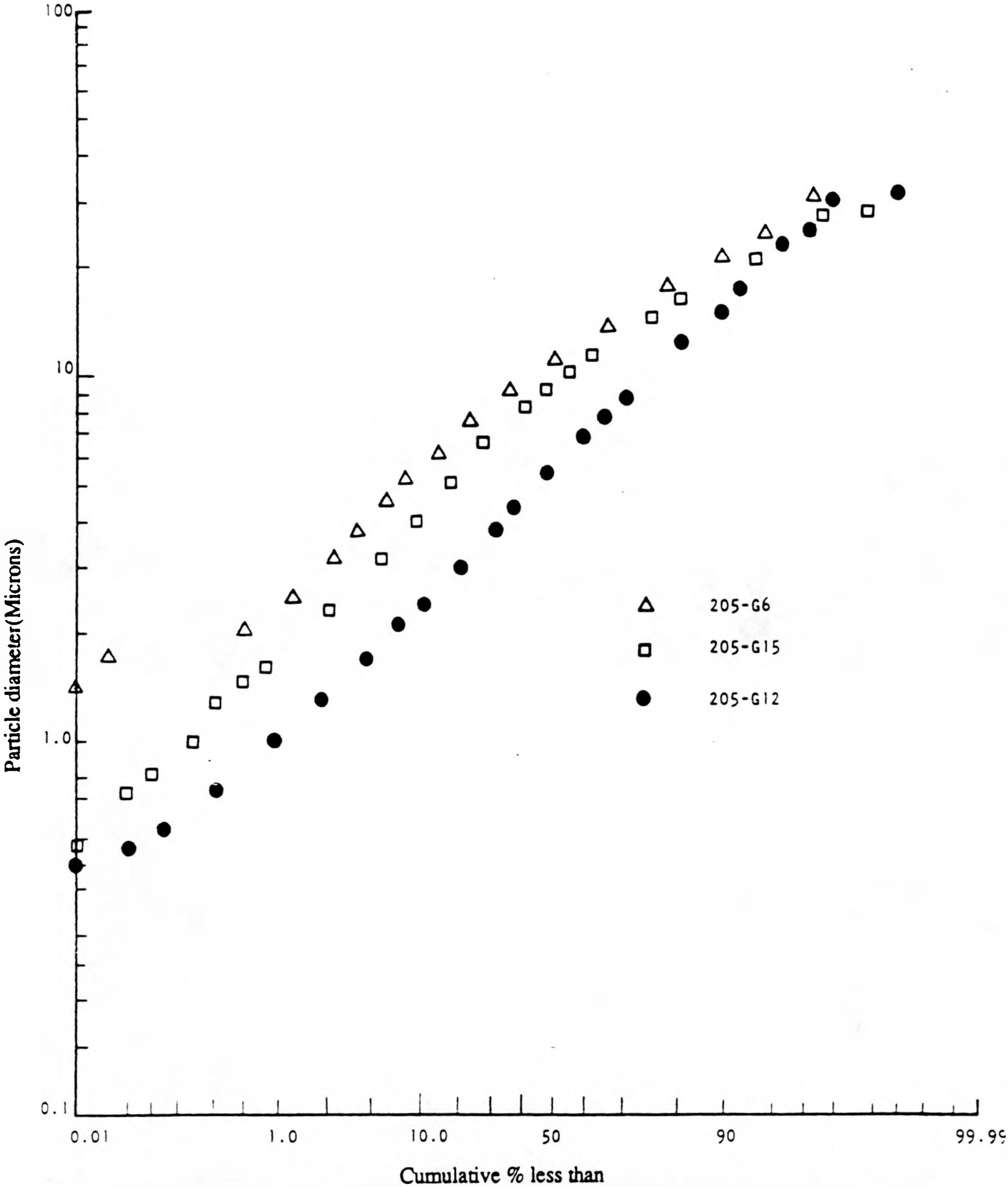



Figure 5-6. Particle Size Distribution of the Dust Entering the GBF During Test HG-205 (Coulter Counter)

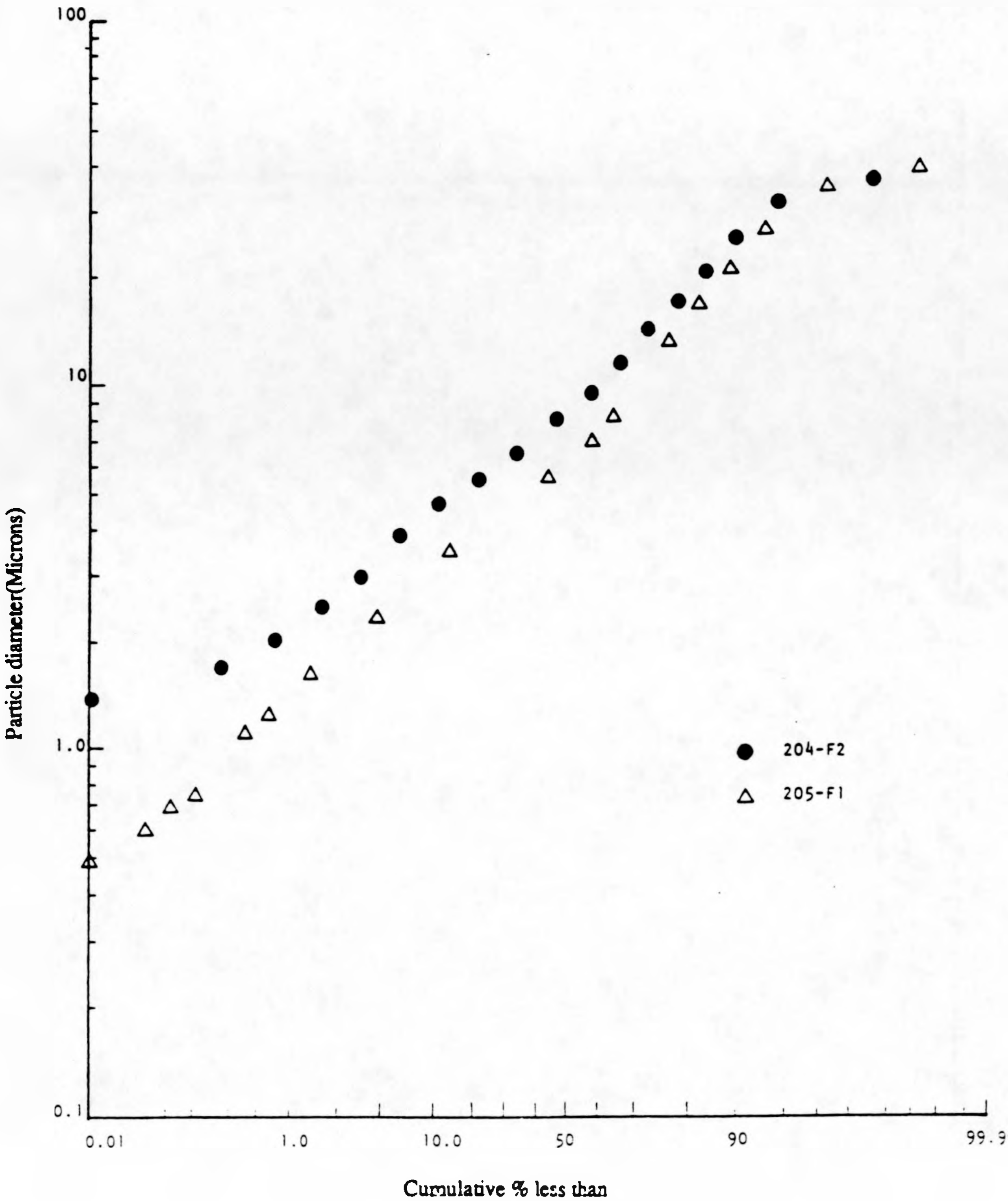



Figure 5-7. Particle Size Distribution of the Dust Collected by the GBF, HG-204 and HG-205 (Coulter Counter)

The geometric mean diameters of the grab samples are presented in Table 5-II. Impactor data is included for comparison. Again it is shown that the size of particulate collected upstream of the GBF and within the GBF is similar. Impactor data was gathered and interpreted on a completely difference basis from the coulter counter data; consequently, comparisons can only be made roughly.

### 5.1.3 Analysis of Impactor Data

The impactor data was analyzed using a computer program developed by the University of Washington. Input to the program includes the weight of the particulate collected on each stage in the cascade impactor; sampling conditions such as flue gas flow rate; and process gas temperature, pressure and composition. The program then computes the aerodynamic particle diameter for each collecting stage in the cascade impactor and the size fraction collected on each stage. By the use of cubic spline interpolation technique, the size distribution is divided up into narrow intervals of 0.2 $\mu$m ranging from zero to 50 $\mu$m and the results are tabulated as particle diameter, mass fraction and cumulative fraction corresponding to each particle size. The program also fits the particle size distribution to a log normal distribution and outputs the geometric mean diameter and the geometric standard deviation. An example of the output from the computer program, together with the input data is presented in Figure 5-8. Detailed results of all the tests are presented in Appendix IID.

Interpretation of the impactor data is very difficult because of all the potential errors that could be introduced from deficiencies in equipment and procedures. In the example shown on Figure 5-8, the mass mean particle size calculated at the filter outlet is 4.7 $\mu$m. This is quite small but still may be biased on the large side if, as suggested by Southern Research Institute, some of the large fraction collected was agglomerates that re-entrained from the walls of the sampling duct. Furthermore, although the data did not detect particles larger than 20 micron, the cubic spline extrapolation predicts some to exist.

This tendency of the cubic spline extrapolation to predict particle sizes greater than the maximum aerodynamic sizes calculated is a known limitation. According to NYU, who gathered the data, the aerodynamic diameter calculation's may place an upper limit on size distribution. Realizing the limitations of their equipment and procedures, NYU claims that only size distributions predicted up to 15 micron will be accurate for analyzing the performance of the GBF. For particle size distributions above 15 microns, the extrapolated data will be erroneous as the parent data input to the cubic spline program does not have particle sizes beyond 15 to 18 microns. In any filter application, particles larger than 15 microns have a high probability of being collected with high efficiency.

**TABLE 5-II. MEAN DIAMETER OF PARTICULATE ENTERING, LEAVING AND COLLECTED BY GBF**

| RUN# | METHOD | FILTER INLET | | FILTER DRAIN | | FILTER OUTLET |
|---|---|---|---|---|---|---|
| | | $d_p (\mu m)$ | Std.Dev. | $d_p (\mu m)$ | Std.Dev. | $d_p (\mu m)$ |
| HG204-G8 | Grab/Coulter | $20.0^G$ | 1.54 | - | - | - |
| HG204-G14 | Grab/Coulter | $4.8^G$ | 2.0 | - | - | - |
| HG204-G24 | Grab/Coulter | $7.2^G$ | 2.4 | - | - | - |
| HG204-I1 | Impactor | $21.0^M$ | - | - | - | $4.7^M$ |
| HG204-I2 | Impactor | $8.0^M$ | - | - | - | $2.8^M$ |
| HG204-I3 | Impactor | $22.0^M$ | - | - | - | $2.8^M$ |
| HG204-I4 | Impactor | $19.9^M$ | - | - | - | $1.8^M$ |
| HG204-F2 | Coulter | - | - | $5.6^G$ | 1.63 | - |
| HG205-G6 | Grab/Coulter | $10.0^G$ | 1.82 | - | - | - |
| HG205-G12 | Grab/Coulter | $4.8^G$ | 2.2 | - | - | - |
| HG205-G15 | Grab/Coulter | $8.6^G$ | 2.2 | - | - | - |
| HG205-I3 | Impactor | $12.0^M$ | - | - | - | $1.7^M$ |
| HG205-I4 | Impactor | $16.0^M$ | - | - | - | $1.6^M$ |
| HG205-I5 | Impactor | $16.5^M$ | - | - | - | - |
| HG205-I6 | Impactor | $21.0^M$ | - | - | - | $2.4^M$ |
| HG205-I7 | Impactor | $7.5^M$ | - | - | - | $2.6^M$ |
| HG205-F1 | Coulter | - | - | $7.0^G$ | 1.81 | - |

$^G$ Refers to geometric mean diameter (Coulter Counter).

$^M$ Refers to mass mean diameter (Impactor Measurements).

**** RESULTS ****

| | | |
|---|---|---|
| DATE OF TEST | 05/10/88 | |
| TIME OF TEST | 1815 | |
| LOCATION OF TEST | NYU-PFBC | |
| TEST NUMBER | 204 - | |
| RUN NUMBER | 1-O | |
| ACTUAL FLOW RATE (STACK CONDITIONS) | | 0.249 CFM |
| FLOW RATE (STANDARD CONDITIONS) | | 0.995 CFM |
| PERCENT ISOKINETIC SAMPLING | | 0.00 % |

VISCOSITY OF GAS STREAM 0.0002503 GRAMS/CM-SEC

| STAGE | CCF | DP(CLAS AERO) | DP(IMP AERO) | CUM FRACTION |
|---|---|---|---|---|
| 1 | 1.004 | 11.300 | 11.320 | 0.6833 |
| 2 | 1.002 | 19.605 | 19.625 | 0.5833 |
| 3 | 1.005 | 7.996 | 8.016 | 0.5250 |
| 4 | 1.010 | 4.179 | 4.199 | 0.4750 |
| 5 | 1.017 | 2.427 | 2.447 | 0.3583 |
| 6 | 1.029 | 1.381 | 1.401 | 0.1250 |
| 7 | 1.051 | 0.795 | 0.815 | 0.0333 |

NOTE: THE MASS ON STAGES 1 AND 2 WILL BE COMBINED AND ASSIGNED TO THE OUTPUT ON STAGE 1 , FOR SPLINE FITTING ANALYSIS.

TOTAL MASS PER DRY NORMAL CUBIC METER 7.7445 MG/CUBIC METER

PART. DIAM. TYPE C (I=IMP AERO, C=CLAS AERO, P=PHYSICAL)

| PARTICLE SIZE (MICRONS) | CUMFR (STD. DEV.) | CUMFR (PER CENT) | CUM. MASS (MG/DRY N.CU.METER) | dM/dLOG D |
|---|---|---|---|---|
| 0.20 | -3.3199 | 0.0 | 0.004 | 0.031 |
| 0.25 | -3.0796 | 0.1 | 0.008 | 0.067 |
| 0.40 | -2.5735 | 0.5 | 0.039 | 0.279 |
| 0.50 | -2.3332 | 1.0 | 0.076 | 0.504 |
| 0.75 | -1.8965 | 2.9 | 0.224 | 1.268 |
| 1.00 | -1.5682 | 5.8 | 0.452 | 2.477 |
| 1.50 | -1.0296 | 15.2 | 1.174 | 6.256 |
| 2.00 | -0.6019 | 27.4 | 2.119 | 8.280 |
| 2.50 | -0.3324 | 37.0 | 2.864 | 6.548 |
| 4.00 | -0.0730 | 47.1 | 3.647 | 1.804 |
| 5.00 | -0.0296 | 48.8 | 3.781 | 1.100 |
| 7.50 | 0.0436 | 51.7 | 4.007 | 1.918 |
| 10.00 | 0.1524 | 56.1 | 4.341 | 3.228 |
| 15.00 | 0.4192 | 66.2 | 5.130 | 4.817 |
| 20.00 | 0.6326 | 73.6 | 5.704 | 4.336 |
| 25.00 | 0.7995 | 78.8 | 6.103 | 3.886 |
| 40.00 | 1.1588 | 87.7 | 6.790 | 2.839 |
| 50.00 | 1.3355 | 90.9 | 7.041 | 2.344 |

**Figure 5-8. Particle Size Analysis (Outlet)**

**** INPUT DATA ****

| | | |
|---|---|---|
| DATE OF TEST | 05/10/88 | |
| TIME OF TEST | 1815 | |
| LOCATION OF TEST | NYU-PFBC | |
| TEST NUMBER | 204 | |
| PART. DIAM. TYPE | C | (I=IMP AERO, C=CLAS AERO, P=PHYSICAL) |
| TEST TYPE | OUTLET | |
| RUN NUMBER | 1-0 - FILE NAME: B:T204R1-I.OUT | |
| REMARKS: | | |
| IMPACTOR TYPE | UW3NYU | |

| | |
|---|---|
| WATER VAPOR | 3.00% |
| CARBON DIOXIDE | 14.77% |
| CARBON MONOXIDE | 0.00% |
| OXYGEN | 4.34% |
| SULFUR DIOXIDE | 0.00% |
| NITROGEN | 80.89% |
| PARTICLE DENSITY | 1.00 GRAMS/CM^3 |

| | | |
|---|---|---|
| GAS METER VOLUME | 13.260 | CUBIC FEET |
| IMPACTOR DELTA P | 0.00 | INCHES HG |
| ORIFICE DELTA P | 0.00 | INCHES H2O |
| STACK PRESS. (BELOW ATMOS.) | 0.00 | INCHES H2O |
| BAROMETRIC PRESS. | %208.89 | INCHES HG |
| STACK TEMPERATURE | 432.9 | DEGREES F |
| METER TEMPERATURE | 432.9 | DEGREES F |
| IMPACTOR TEMPERATURE | 432.9 | DEGREES F |
| SAMPLE TIME | 55.00 | MINUTES |
| AV. VELOCITY OF STACK GAS | 0.00 | FEET/MINUTE |
| GAS METER PRESSURE | 0.00 | IN HG |
| NOZZLE DIAMETER | 0.43 | INCHES |
| MAXIMUM AERODYN. DIAMETER | 1000.00 | MICRONS |

| | |
|---|---|
| MASS GAIN ON STAGE 1 | 3.80 MG |
| MASS GAIN ON STAGE 2 | 1.20 MG |
| MASS GAIN ON STAGE 3 | 0.70 MG |
| MASS GAIN ON STAGE 4 | 0.60 MG |
| MASS GAIN ON STAGE 5 | 1.40 MG |
| MASS GAIN ON STAGE 6 | 2.80 MG |
| MASS GAIN ON STAGE 7 | 1.10 MG |
| MASS GAIN ON FINAL FILTER | 0.40 MG |

**Figure 5-8. Particle Size Analysis (Outlet) (Continued)**

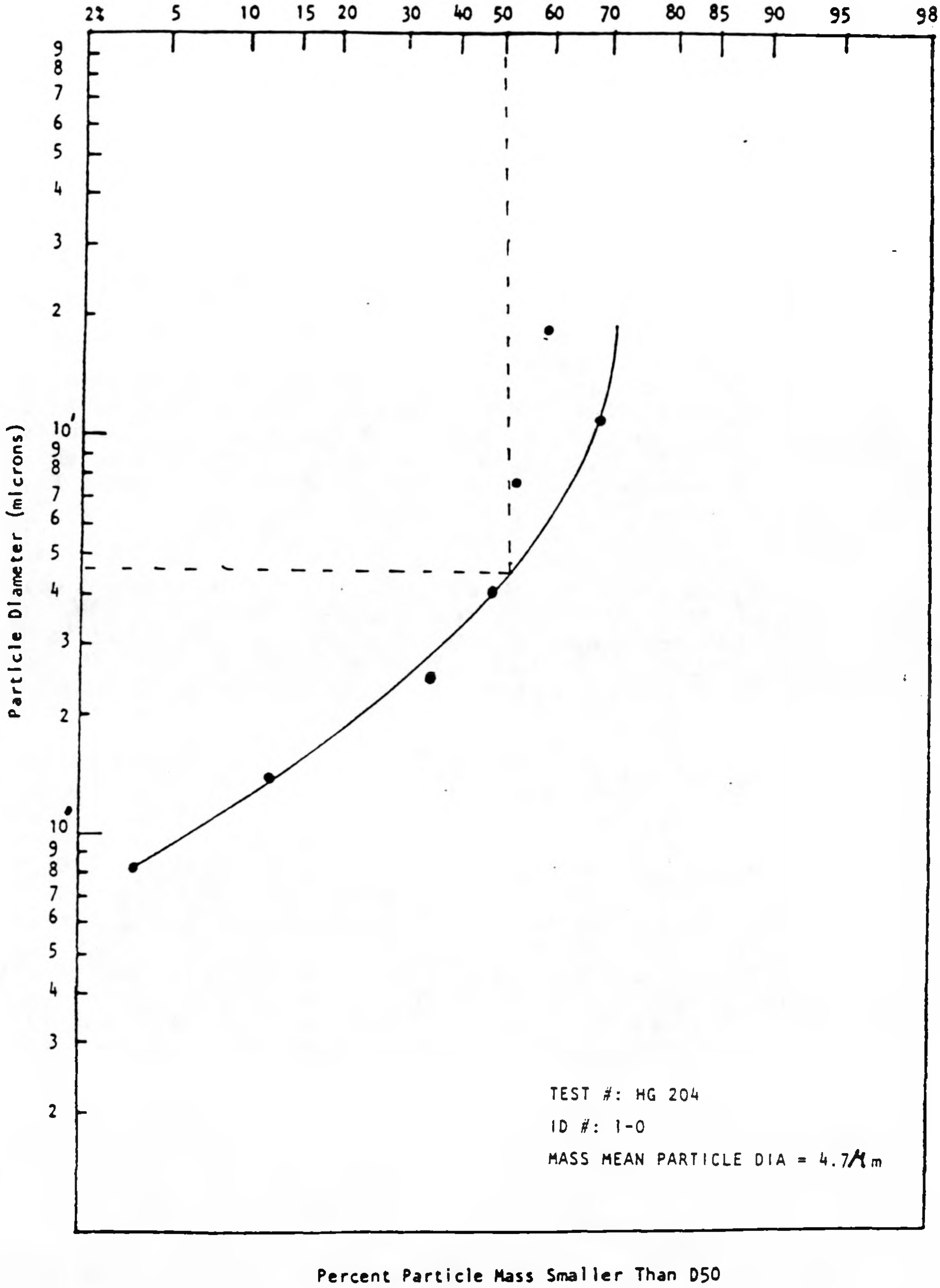



Figure 5-8. Particle Size Analysis (Outlet) (Continued)

The average particle size distribution at the inlet and outlet of the GBF for tests HG-204 and HG-205 are presented in Figures 5-9 and 5-10 respectively. The data presented in these figures were obtained from isokinetic sampling of the flue gas at the inlet and outlet of the GBF using Washington University's Cascade Impactor design. The results show the outlet dust to be an order of magnitude finer than the inlet dust for test HG-204. For test HG-205, the outlet appears to be finer than the inlet in particle sizes under 1 $\mu m$ and above 10 $\mu m$. The outlet dust contained the same proportion of particle sizes between 1 and 10 $\mu m$. Particle collection efficiency is plotted in Figure 5-11 as the grade efficiency versus particle size for the GBF during test HG-204 using 2 mm media and Figure 5-12 for test HG-205 using 3 mm media. The GBF was able to collect very small particles (less than 2 $\mu m$) with high efficiency. The GBF grade efficiency tended to increase with particle size up to 6 microns for the 2 mm GBF media and 5 microns for the 3 mm GBF media. Grade efficiency was actually calculated as discrete points but reported as a range. This is because of the uncertainty associated with the accuracy of the NYU data.

The specification for permissible dust loading to the gas turbine varies from manufacturer to manufacturer. A recent projected turbine tolerance limit for particulate matter is shown in Figure 5-13 (METC, 1985) as a plot of cumulative dust loading versus particle size. Also plotted in the figure are the GBF inlet and outlet cumulative dust loadings obtained from grab and cascade impactor measurements. The projected gas turbine tolerance band is also shown. Within the envelope for "projected turbine limit" is plotted data presented in a specification for a PFBC combined cycle power plant (Stone & Webster, 1989). The cumulative outlet dust loading out of the GBF falls below the projected turbine tolerance band suggesting that the dust loading out of the GBF will meet the projected turbine limit and more important, it is fine in grain and can thus be tolerated by the gas turbine.

The dust leaving the PFBC passes through a single stage cyclone before it enters the GBF. The cumulative dust distribution at the GBF inlet plotted in Figure 5-13 clusters around the projected line for single stage cyclone exhaust dust.

### 5.1.4 Particulate Chemical Composition

A comparison between the chemical composition of the dust at the inlet of the GBF and that collected by the GBF for test HG-204 is shown in Table 5-III and Table 5-IV for HG-205. Also presented in these Tables are the bed material and primary cyclone capture dust chemical compositions. Apparently the dolomite material is composed of larger particles as considerable CaO and MgO is present

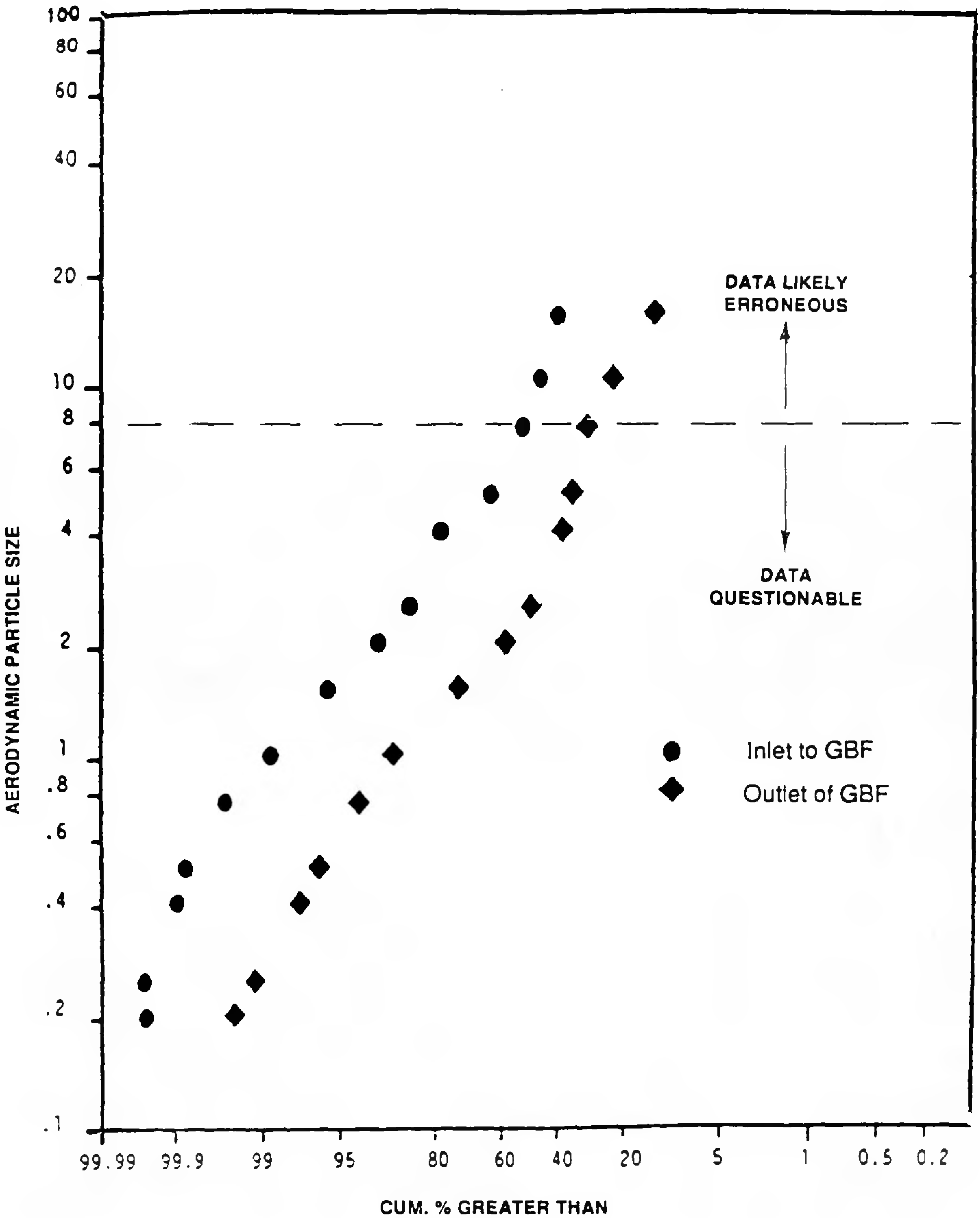



Figure 5-9. Particle Size Distribution at the Inlet and Outlet of the GBF for Fine Particulates for Test Run #HG-204

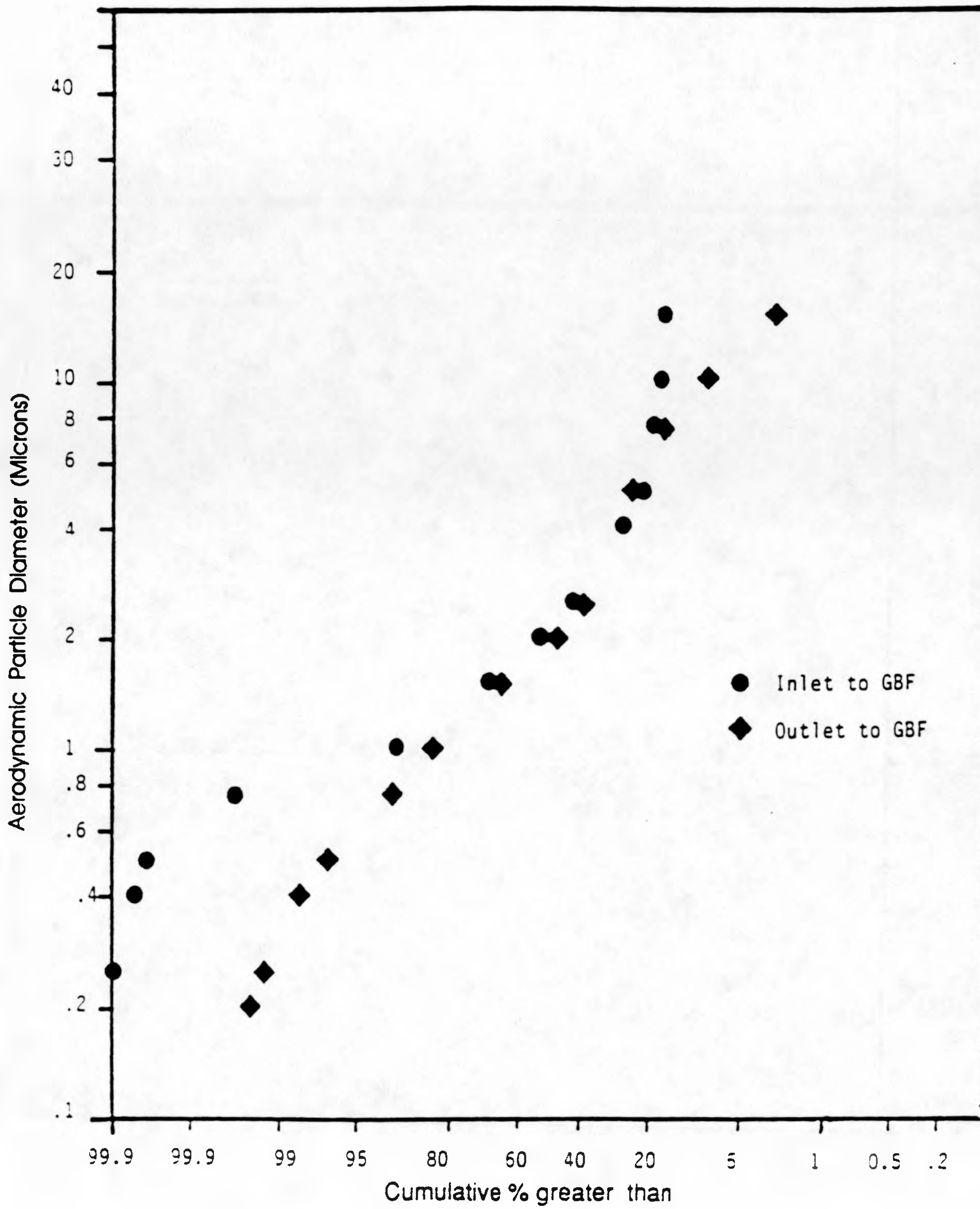



**Figure 5-10. Particle Size Distribution at the Inlet and Outlet of the GBF for Fine Particulates for Test Run #HG-205**

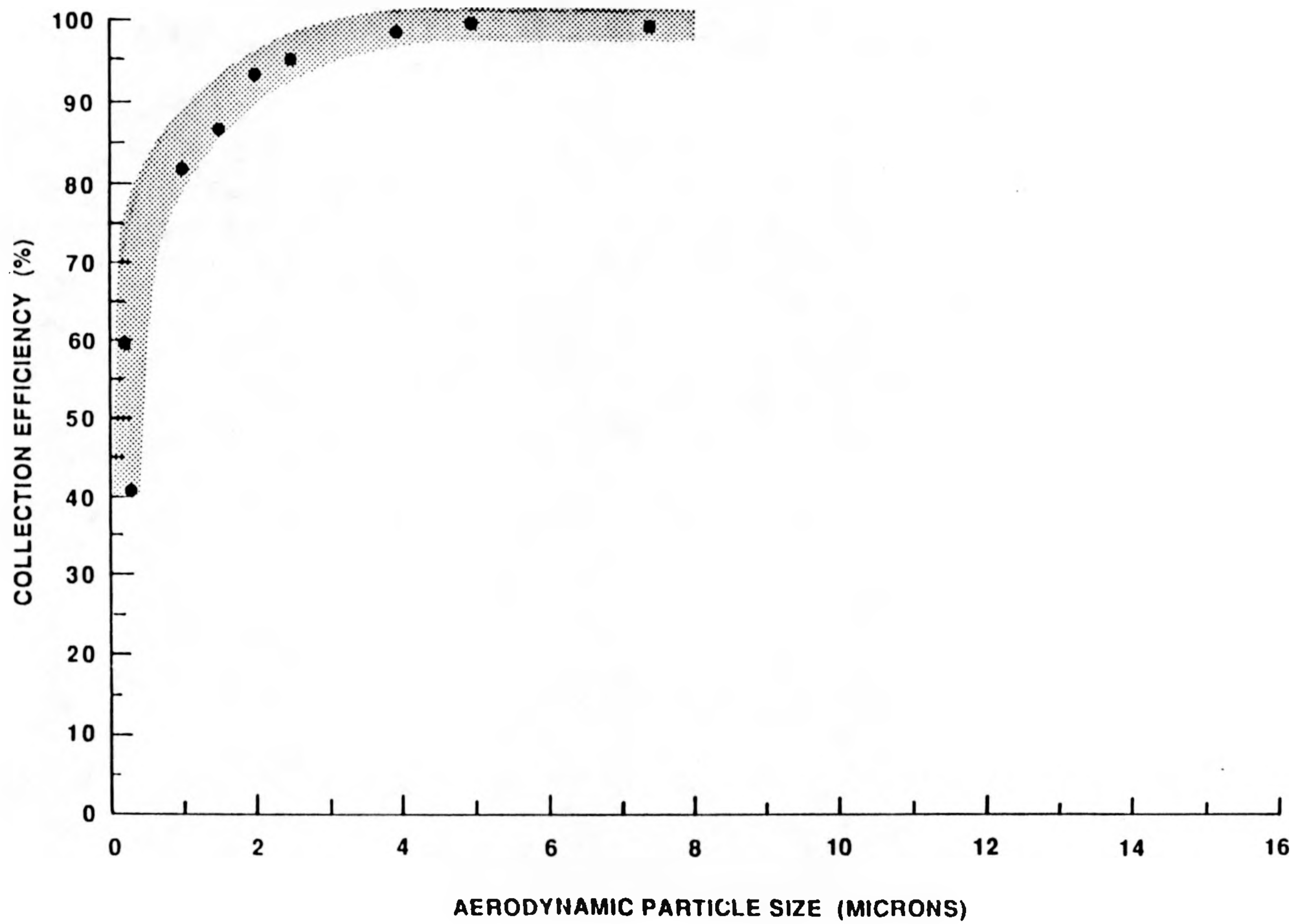



Figure 5-11. GBF Collection Efficiency vs. Particle Size Using Cascade Impactor, HG-204

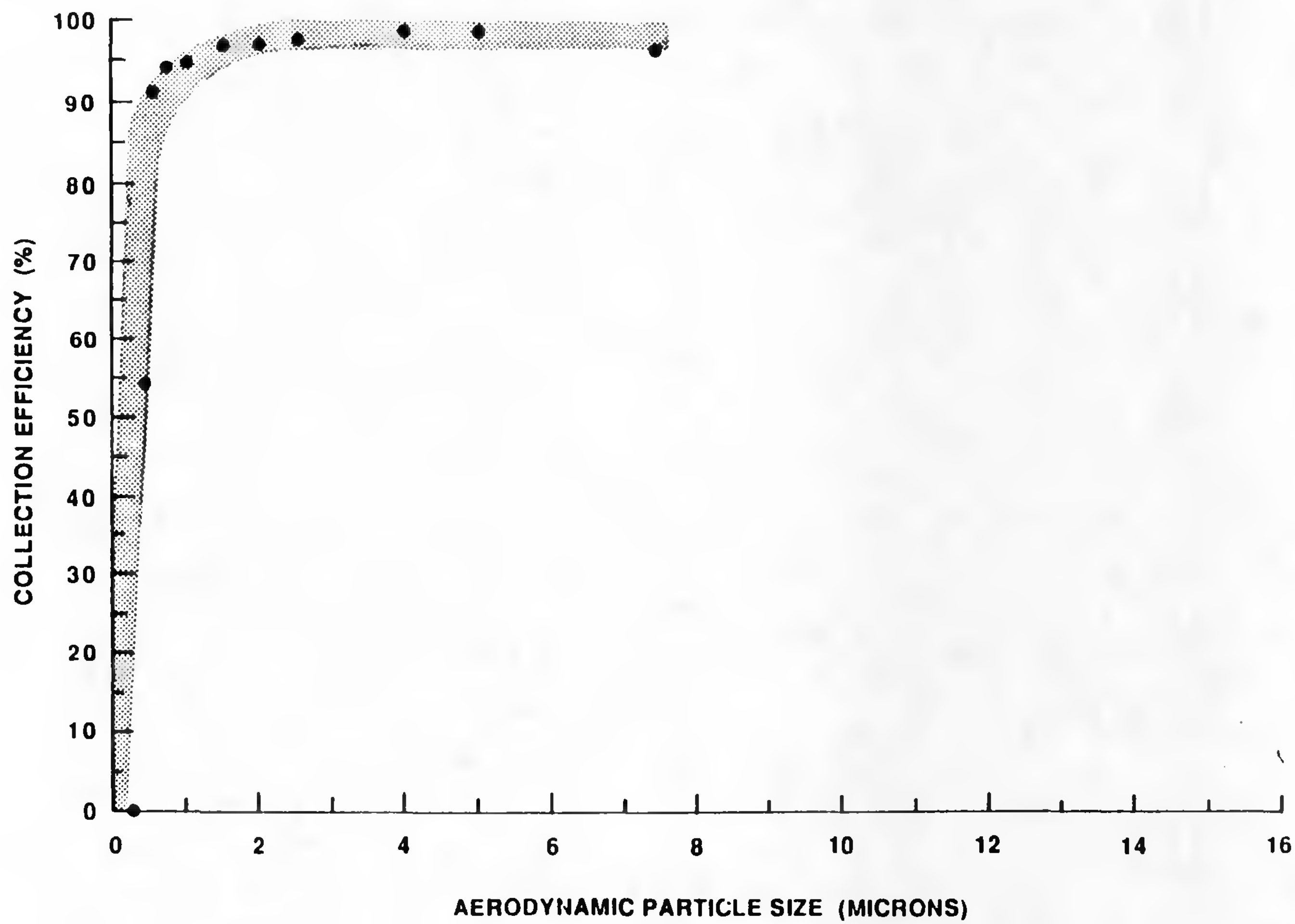



Figure 5-12. GBF Collection Efficiency vs. Particle Size Using Cascade Impactor, HG-205

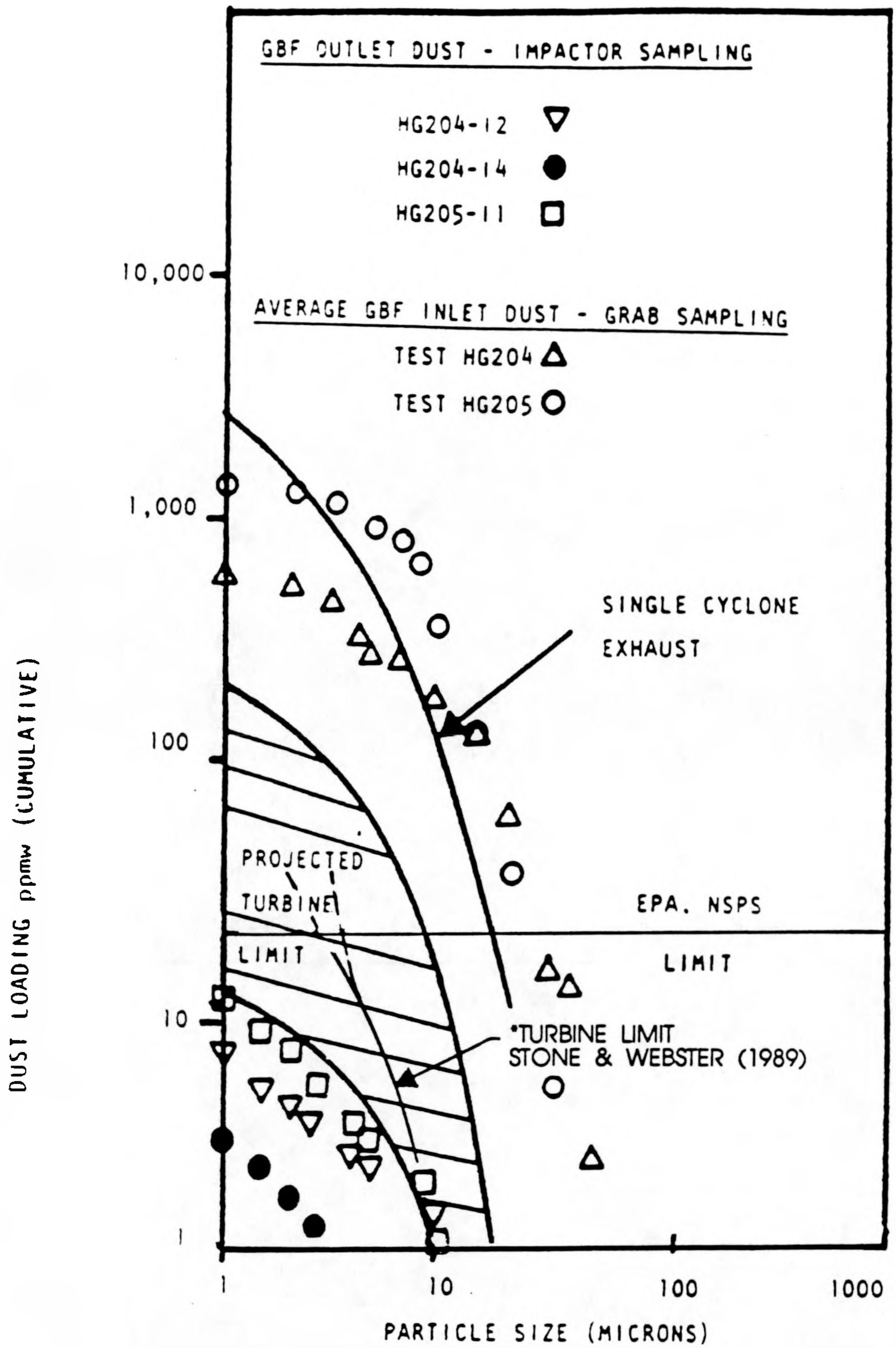



**Figure 5-13. Relationship Between Particle Size and Particle Concentration for Turbine Tolerances for the Granular Bed Filter**

**TABLE 5-III CHEMICAL COMPOSITION OF VARIOUS PARTICLE STREAMS DURING TEST HG-204**

| Component | Bed Material Capture | Primary Cyclone | Inlet to GBF | Particulate Collected by GBF |
|---|---|---|---|---|
| C | 3.51 | 6.23 | 7.90 | 0.41(7.90*) |
| CaO | 34.25 | 35.03 | 21.29 | 19.72(18.24*) |
| $K_2O$ | 0.09 | 0.16 | 1.25 | 1.41(1.30*) |
| $Na_2O$ | 0.46 | 0.27 | 1.12 | 0.97(0.90*) |
| $P_2O_5$ | 0.04 | 0.09 | 0.26 | 0.41(.38*) |
| $SiO_2$ | 1.81 | 7.36 | 19.24 | 25.56(23.6*) |
| $Al_2O_3$ | 1.46 | 4.00 | 14.01 | 17.67(16.3*) |
| $Fe_2O_3$ | 0.76 | 2.95 | 4.80 | 4.93(4.56*) |
| $TiO_2$ | 0.07 | 0.19 | 0.65 | 1.01(.93*) |
| MgO | 29.38 | 25.34 | 12.83 | 9.51(8.79*) |
| $SO_3$ | 19.35 | 8.09 | 12.06 | 18.38(17.00*) |
| $CO_2$ | 8.84 | 10.3 | 4.59 | ----- |

* Corrected for carbon loss

**TABLE 5-IV. CHEMICAL COMPOSITION OF VARIOUS PARTICLE STREAMS DURING TEST HG-205**

| Component | Bed Material Capture | Primary Cyclone | Inlet to GBF | Particulate Collected by GBF |
|---|---|---|---|---|
| C | 3.42 | 5.90 | 5.94 | 0.17(5.94*) |
| $CaO$ | 35.89 | 40.97 | 18.48 | 18.27(17.2*) |
| $K_2O$ | 0.07 | 0.08 | 1.75 | 1.43(1.35*) |
| $Na_2O$ | 0.43 | 0.38 | 1.40 | 2.04(1.92*) |
| $P_2O_5$ | 0.04 | 0.15 | 0.53 | 0.50(.47*) |
| $SiO_2$ | 2.13 | 7.88 | 28.17 | 29.52(27.81*) |
| $Al_2O_3$ | 1.01 | 3.27 | 18.49 | 19.59(18.46*) |
| $Fe_2O_3$ | 0.46 | 2.53 | 4.81 | 4.89(4.61*) |
| $TiO_2$ | 0.09 | 0.23 | 0.87 | 0.90(.85*) |
| $MgO$ | 27.13 | 23.08 | 7.97 | 6.29(5.93*) |
| $SO_3$ | 21.02 | 4.80 | 10.85 | 16.39(15.44*) |
| $CO_2$ | 8.31 | 10.73 | 0.74 | ----- |

* Corrected for carbon loss

in the primary cyclone ash and less of these compounds are present at the GBF inlet. Large particulate is preferentially removed in the primary cyclone. There is a significant decrease in carbon content of the ash as it passes through the filter. Since the ash collected by the GBF is held in the filter at temperature for 4-8 hours before it enters the ash removal system, the carbon most likely oxidized while residing in the filter. The values in the parenthesis in Tables 5-III and 5-IV have been adjusted for carbon loss assuming that the carbon content is the same as that in the GBF inlet particulate. This helps to highlight any other significant chemical change across the filter. The only significant chemical change detected between the filter inlet and dust collected is in the $SO_3$ content. This is probably because sulfur reacted dolomite is very small in size and passes through the cyclone, but it is also possible that some conversion of gaseous $SO_2$ to sulfur bearing solids is taking place within the filter.

## 5.2 Alkali Concentrations

To prolong the gas turbine life, it is not only necessary to reduce the dust loading and particle size, but also to reduce alkali (sodium and potassium) concentration in the flue gas to acceptable levels. General Electric has recommended that the total alkali concentration reaching the gas turbine should be less than 24 ppbw (General Electric, 1980). This limit may not be valid for coal based alkali but could be used as a gas turbine guideline until a better alkali specification is defined for coal-derived combustion gases.

Investigations performed by Combustion Power during Phase II of the GBF developmental program showed that alkalis can be removed by aluminosilicates (Guillory, 1983). Alumina and silica are present in the coal ash as shown on Tables 5-III and 5-IV, and some fraction of this material should be available as reactive aluminosilicate. The reaction forms a high melting point sodium or potassium aluminosilicate solid. The GBF media also contains alumina and silica and may be partially reactive. Furthermore, combustion additives could be used to boost the presence of reactive aluminosilicates; although, this was not investigated at NYU.

The effectiveness of the GBF to remove alkali from PFBC flue gas stream was studied during the GBF performance tests by measuring the alkali concentration in the flue gas entering and leaving the GBF. As discussed earlier in section 2.5, two techniques, namely, NYU alkali and METC/INEL on-line alkali methods were utilized to determine the alkali concentration in the flue gas. The NYU total condensation technique was used to sample flue gas entering and leaving the GBF whereas the METC/INEL on-line alkali monitor measured the alkali content in the GBF exhaust only.

### 5.2.1 Alkali Vapor Concentration Measured by NYU Total Vapor Condensation Method

Vapor alkali measurements performed during three performance tests, namely HG-203, HG-204 and HG-205 are summarized in Table 5-V, together with the average bed temperature and pressure. The results of the on-line METC/INEL vapor phase alkali measurements during the same period as the NYU vapor phase alkali measurement are also presented in this table.

The total vapor phase alkali emissions from the PFBC (upstream of the GBF) far exceed the 24 ppbw limit recommended by GE for gas turbines. The results presented in Table 5-V are 3 to 35 times higher than the recommended limit at the GBF inlet. However, after the flue gas is passed through the GBF, the total vapor phase alkali concentration dropped by several order of magnitude. The outlet alkali vapor phase concentration ranged from 3 to 20 ppbw, well below the turbine tolerance limit of 24 ppbw in all the measurements except for run number 205-1 whose value of 72 ppbw exceeded the 24 ppbw limit. The results of the NYU condensate sampling system predominantly indicated that the GBF reduced the total alkali level in the PFBC exhaust gas stream by over 98%. The moisture condensate from the flue gas was found to be more acidic at the outlet than at the inlet. At the low temperature end of the gas turbine, the flue gas which is rich in acid gases could condense if right conditions exist and cause acid corrosion of turbine blades.

The mechanism by which the GBF getters alkali from the hot-gas stream is a combination of condensation and reaction. The alkali compounds condensed on the PFBC dust collected by the GBF because of the large temperature drop across the GBF and reacted with the alumina of the coal ash, GBF media, or the GBF refractory wall to form alumino silicates according to the following reaction mechanism (Zakkay et al., 1984):

$$2NaCl + 3SiO_2 + H_2O \longrightarrow Na_2O.3SiO_2 + 2HCl$$

$$Na_2SO_4 + 3SiO_2 \longleftrightarrow Na_2O.3SiO_2 + SO_2 + 0.5O_2$$

$$Na_23SiO_2 + Al_2O_3 \longleftrightarrow Na_2O.Al_2O_3.2SiO_2 + SiO_2$$

Sodium and potassium vapors are present in very small concentrations, in the parts per billion range, as shown on Table 5-V. Therefore removal of these vapors are difficult to detect by changes in $Na_2O$ or $K_2O$ concentrations in the ash or on the GBF media. This is exactly the case as shown on Tables 5-III and 5-IV where there is no trend showing alkali removal on the ash. Likewise, even though alkali could have condensed on the GBF media as the GBF outlet temperature dropped 100 to 300°F below inlet temperature, x-ray fluorescence diffraction measurements of the 2 mm diameter GBF media taken during an earlier test, HG-203, showed

TABLE 5-V. SUMMARY OF ALKALI CONCENTRATION MEASUREMENT RESULTS

| Run No. | Date | Measurement Period | Avg.Bed Temp (F) | Avg.Bed Press (psig) | Avg.GBF Temp. Inlet (F) | Avg.GBF Temp. Outlet (F) | Alkali Concentration(ppbw) GBF Inlet NYU Method Na | K | GBF Outlet NYU Method Na | K | GBF Alkali Gettering Efficiency % | Avg. GBF Outlet METC/INEL Na (ppbw) | K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 203-1 | Apr 14 | 19:47-20:40 | 1526 | 86.1 | 1494 | 1178 | 97.5 | 87.5 | <2.0 | 2.0 | 97.8 | nm | nm |
| 203-2 | Apr 14 | 22:06-22:50 | 1522 | 87.8 | 1524 | 1232 | 135 | 129 | <4.4 | 2.6 | 97.4 | nm | nm |
| 203-3 | Apr 14 | 23:06-23:46 | 1498 | 88.2 | 1509 | 1224 | 43.6 | 42.1 | <2.7 | 2.8 | 93.6 | nm | nm |
| 203-4 | Apr 15 | 12:20-12:52 | 1493 | 87.5 | 1504 | 1212 | 63.6 | 89.0 | 8.9 | 7.4 | 89.3 | nm | nm |
| 203-5 | Apr 15 | 12:55-14:07 | 1514 | 87.2 | 1496 | 1198 | 67.6 | 143 | 2.9 | 2.5 | 97.4 | nm | nm |
| 204-1 | May 10 | 16:28-17:25 | 1571 | 93.2 | 1542 | 1198 | 109 | 161 | * | * | * | <4 | 85 |
| 204-2 | May 10 | 18:08-19:20 | 1576 | 92.1 | 1582 | 1225 | 61 | 131 | 1.9 | 2.2 | 97.9 | <4 | 85 |
| 204-3 | May 11 | 12:11-13:20 | 1524 | 99.7 | 1534 | 1275 | 172 | 273 | 1.5 | 1.5 | 99.3 | nm | nm |
| 204-4 | May 12 | 16:03-17:03 | 1600 | 110 | 1519 | 1195 | 37 | 67 | 14.3 | 5.5 | 81.0 | <4 | 130 |
| 204-5 | May 12 | 17:45-18:25 | 1536 | 112.9 | 1525 | 1231 | 187 | 164 | 6.3 | 3.9 | 97.1 | <4 | 115 |
| 204-6 | May 13 | 07:18-08:06 | 1525 | 113.3 | 1559 | 1271 | 66 | 91 | 3.1 | 2.0 | 96.8 | nm | nm |
| 205-1 | Jun 7 | 11:38-12:30 | 1518 | 108.8 | 1560 | 1271 | 216 | 289 | 41 | 31 | 85.7 | nm | nm |
| 205-2 | Jun 7 | 14:30-15:05 | 1511 | 112.6 | 1606 | 1348 | 352 | 282 | 17 | 3 | 96.9 | nm | nm |
| 205-3 | Jun 7 | 17:31-18:08 | 1566 | 117.5 | 1593 | 1367 | 174 | 165 | 4 | 3 | 97.9 | nm | nm |
| 205-4 | Jun 8 | 10:15-10:58 | 1489 | 117.9 | 1561 | 1363 | 423 | 424 | 3 | 1 | 99.5 | nm | nm |
| 205-5 | Jun 8 | 15:07-15:45 | 1514 | 120.2 | 1554 | 1397 | 270 | 236 | 2 | 2 | 99.2 | <4 | <4 |
| 205-6 | Jun 9 | 09:55-10:45 | 1544 | 108.2 | 1382 | 1234 | 307 | 347 | 5 | 3 | 98.8 | <4 | <4 |

* - Analysis not available. Sample bottle was broken in transit.
nm - Not measured.

no change in the potassium content (sodium content was not reported) of the granules. The $K_2O$ content before and after the test remained constant at 0.3%. Electron probe analysis even showed some decrease in the potassium content in the media after the test, while the sodium concentration remained constant at 0.5%. This is because the alkali concentration is so low in comparison with the weight of media in the filter that it would take thousands of hours of operation for a change in concentration of alkali in the media to show up. Unfortunately, the high temperature drop across the filter precludes any conclusion regarding alkali removal other than by condensation. Other data is needed to show the potential of the GBF as an alkali removal device. This subject was directly investigated during low pressure, high temperature developmental testing (Guillory, 1983).

### 5.2.2 Alkali Vapor Concentration Measured by METC/INEL Alkali Monitor

The real time alkali monitoring reported on here was conducted in two sessions during tests HG-204 and HG-205. These two sessions included approximately 23 hours and 14 hours of real time alkali monitoring, respectively. Results are presented on Table 5-V and discussed below.

The METC/INEL alkali monitor was first calibrated with solutions of known concentrations of sodium (Na) and potassium (K). Calibration equations developed between species intensity using least square curve fitting techniques were later used for the determination of the concentrations of sodium and potassium in the sampled gas.

During the sampling period, the flue gas temperature entering the burner was maintained as high as possible to prevent alkali condensation in the sampling line. The temperature of sample gas and sample line was measured by thermocouples and maintained by electrical heater. The flue gas temperature at the entrance to the burner was maintained on the average above 1000°F. (Note: Some alkali probably condensed in line at this temp.)

Figure 5-14 is a graph of a typical real-time alkali results obtained with the METC/INEL instrument. Additional results are presented in Appendix IID. The results shown are from measurements for the period between 16:00 and 18:00 on May 12, 1988 test HG-204. During that period, except for brief periods following each dump of the PFBC primary cyclone ash hopper, which occurred every 20 minutes beginning at 16:00, the measured sodium levels were less than one half the lower limit of the calibration and the measured potassium levels were between 100 and 200 ppbw. The lowest concentration that can be reported with a degree of reasonable confidence is approximately 4 ppbw. Measured concentrations that were less than 1 ppbw are not plotted. The higher sodium and potassium levels that were observed following each dump of the ash

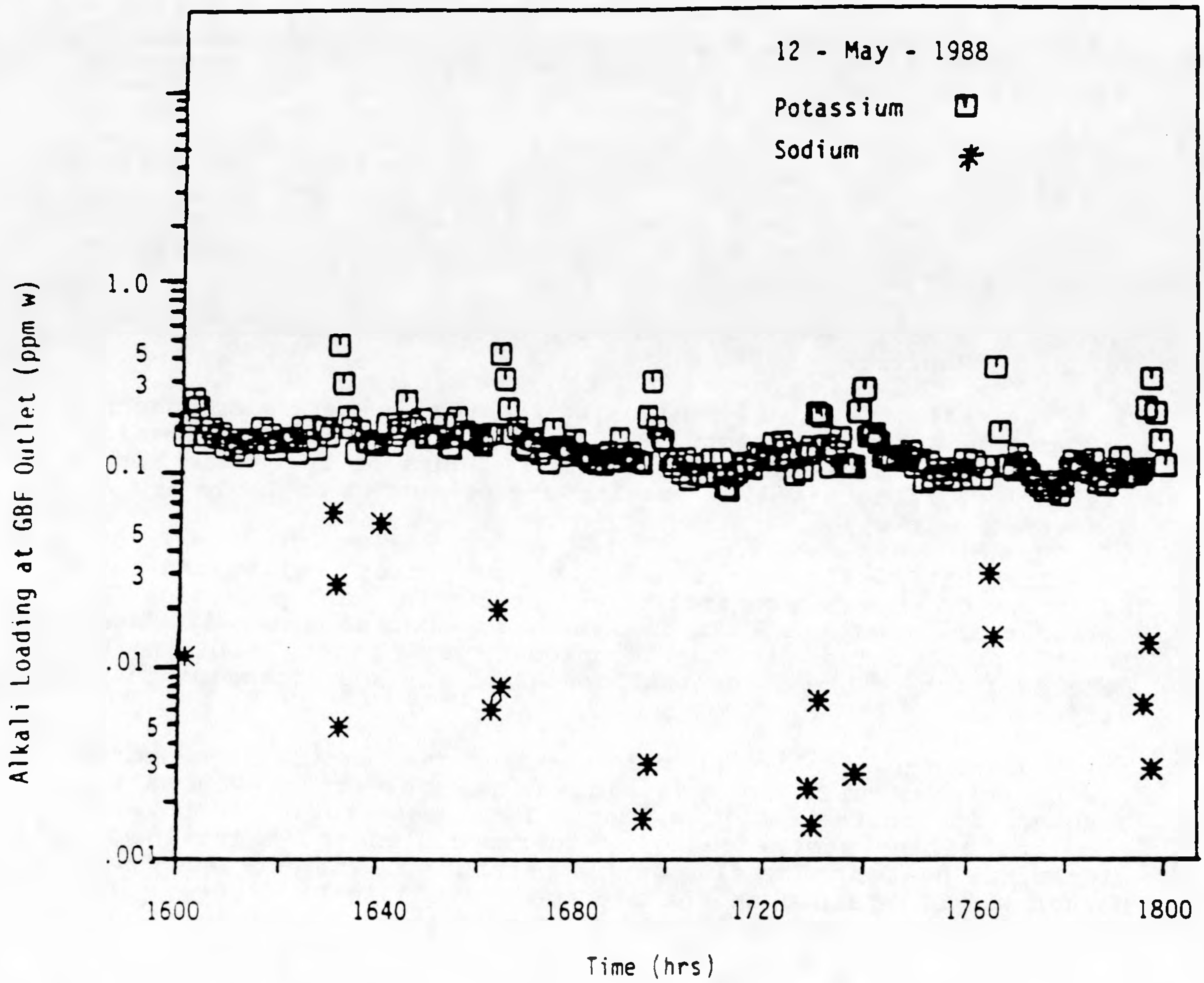



**Figure 5-14. Typical Analytical Results from METC/INEL Alkali Monitor**

hopper do not indicate higher alkali levels in the hot-gas sample stream, but were caused by sodium and potassium containing particulates that drifted from the ash dump area of the facility and were swept into the flame of the alkali monitor. METC/INEL sodium results were less than 4 ppbw for both the HG-204 and HG-205 measurements; potassium results were between 30 and 200 ppbw for the HG-204 session and less than 4 ppbw for the HG-205 session.

Most of the METC/INEL alkali monitoring results reported here are total alkali, i.e., alkali present in particulates and gaseous components of the hot-gas sample stream. A hot-gas filter was employed for some of the alkali measurements, in an attempt to distinguish between "vapor phase" alkali concentrations and total alkali concentrations, but the total alkali and particulate loadings of the unfiltered sample stream were so low at that time that no decrease in alkali level was observed when the switch was made from the unfiltered stream to the filtered stream.

Except for brief, identifiable periods in which dust from the terminal cyclone and dumping of the ash hopper drifted into the alkali monitor flame, the GBF outlet sodium concentrations measured with the METC/INEL alkali monitor were less than 4 ppbw; with similar exceptions, the GBF outlet potassium concentrations were between less than 4 and 200 ppbw. The alkali monitor results for sodium were consistently lower than the alkali monitor results for potassium.

The METC/INEL results shown on Table 5-V generally show that there is more potassium in the GBF outlet stream than obtained by the NYU total condensation method. On the other hand, the sodium content in the GBF outlet stream appears to be lower to those measured by the NYU technique. In fact, the data presented in Table 5-V conveys the impression that the METC/INEL monitor does not appear to have sufficient sensitivity for quantitative measurement of sodium. The higher potassium content during test HG-204 could be due to dust particles entering the METC/INEL burner as explained earlier. Alkali condensation in the sampling lines for both NYU and METC/INEL sampling systems could introduce error in the alkali measurements, however, this has not as yet been quantified.

## 5.3 Filter Gas and Ash Capacity

Developmental Granular Bed Filter testing at low pressures was performed at gas flows around 30% of the minimum fluidizing velocity of the filter media. Tests at NYU were proposed at 25% and 50% minimum fluidization. As the mass flow corresponding to 50% minimum fluidization was close to full NYU capacity (15,000 lb/hr), tests at this rate were performed first.

To put this into perspective, Table 5-VI compares the key filter operating parameters at these different conditions. It was the intent of the contract to challenge the filter outside the low pressure operating envelope. At the full NYU gas flow condition, this was the case, especially with projected ash rates. In the shakedown of February 17-19, (HS-203) limited sampling yielded a dust loading of 1500 ppmw at the filter inlet and 60 ppmw at the outlet for a 96% filter efficiency and over 99% efficiency when the cyclone and filter are considered together.

**TABLE 5-VI. GBF DESIGN PARAMETERS**

| | Low Pressure | Contractual Goal | Full NYU Gas Flow | One-Half NYU Gas Flow |
|---|---|---|---|---|
| % MIN. FLUIDIZATION | 28 - 33 | 25 - 50 | 40 - 52 | 25 - 30 |
| ASH RATE, LB/MIN | .10 - .16 | .29 | .5 - 1.1 | .01 - .3 (.8 MAX) |
| ASH LOADING, PPMW | 1500-40,000 | 1200 | 500-2000 | 100-6400 |
| % ASH IN MEDIA | .5 - 1.0 | 6 | 2 | .1 - 1.0 (2% MAX) |
| CIRCULATION RATE LB/MIN | 20 - 40 | 20 - 40 | 30 - 60 | 20 - 60 |

While these results were promising, other aspects of the filter operation suggested it was being operated beyond its capacity. During this test, the filter went into a bubbling mode after a pressure excursion. We know from sub-scale tests at Combustion Power (Guillory, 1983) that there is non-uniform gas flow through the media. At full NYU gas flow this non-uniformity, coupled with ash concentration and PFBC upsets resulted in bubbling the filter bed as described above. Bubbling (fluidization) of the filter media diminishes the ash capturing capability of the filter.

To build some margin to take into account non-uniform gas flow, varying ash rates and PFBC upsets, the flue gas flow to the filter was reduced to one-half full NYU gas flow or to about 25% minimum fluidizing velocity of the filter media for test HG-203. This change brought the key parameters more in line with the levels tested at low pressure. Based on the good results achieved at 25% minimum fluidization during test HG-203 and HG-204, capacity was increased for HG-205 by, first, changing to a larger size media and, second, by operating at 31% minimum fluidization. The combined effect of this change was a 67% increase in flow through the filter element with no loss in filtration efficiency. Based on this success, operation with larger media, 4 mm, to slightly higher percentages of minimum fluidization velocities (35-37%) are proposed.

Part of the objectives during Life-Critical Component testing was to evaluate the media circulation system under high ash loadings. The purpose was to determine if media circulation problems would be experienced at a certain threshold loadings of ash in media. From developmental testing at low pressure, high temperature, researchers at Combustion Power identified a limit of 6% ash in media by weight. A high value for this parameter would allow low circulation rate and, subsequently, smaller lift-pipes and circulation systems. The 6% level was achieved in Life-Critical Component testing and confirmation was desirable under PFBC conditions. A related parameter, the ash rate removed by the GBF is needed to size the baghouse, baghouse hopper and ash pressure letdown equipment.

A number of times the percentage of ash in the media approached 1% but only once did it approach 2%, and this was during HG-203 when the inlet loading was 6355 ppmw. Basically the media valve would not operate steady enough at very low circulation rates to allow challenging this parameter. The ash rate removed by the filter did approach the contractual target of .29 lb/min, and in one case the target was exceeded by a wide margin. This was also during HG-203 when the high inlet loading was experienced due to primary cyclone pluggage. Experience prior to NYU testing showed that a very high percentage of ash in the media could result in difficulty moving the ash out of the filter and into the media valve. No media flow problems at NYU were attributed to the loading of ash in the media as expected.

## 5.4 Performance of Circulation System Materials

Filter media and ash was pneumatically transported up the lift pipe and separated in the de-entrainment vessel. Media tumbled by gravity back to the media reservoir and then was fed by plug flow back to the filter through the upper seal leg. From the filter outlet cone media and ash traveled by plug flow down to the media valve and was injected into the lift pipe. This equipment comprises the refractory-lined portion of the circulation system that was investigated for wear.

### 5.4.1 Refractory Lined Lift Pipe

To provide baseline data, measurements were made on the refractory inside diameter at selected locations on lift-pipe and seal-leg segments. Four measurements were made around the refractory diameter with dial calipers at each end of the pipe or equipment. On disassembly, the same areas were checked for dimensional changes. To eliminate as many variables as possible the same person made all measurements. Regardless, even with the most of care, repeated measurements at the same location could vary by 5/1000 inch. Because of this difficulty and because of the relatively short test periods, the information and conclusions are only approximate.

At the beginning of construction (10/85), all segments were refractory lined. The hot face lining was 2 1/2" of A.P. Green Lo-Abrade and the back-up lining was 2 1/2" of A.P. Green castable block mix. Some refractory lined lift-pipe segments were later replaced with silicon carbide or stainless steel-lined segments. Figure 5-15 shows the final disposition of lift-pipe spools.

Segment of lift pipe and seal leg were identified by stamping letters on the flanges, sometimes double, as in "A-A" for the "A" end of segment A-B. Along with the stamped letters was a match-mark groove that was used to align segments. Refractory measurements were referenced to the match-marks. The exception was the new silicon carbide lined segments that replaced segments "R-S" and "T-U". These segments were marked with chalk, "1-2" and "3-4".

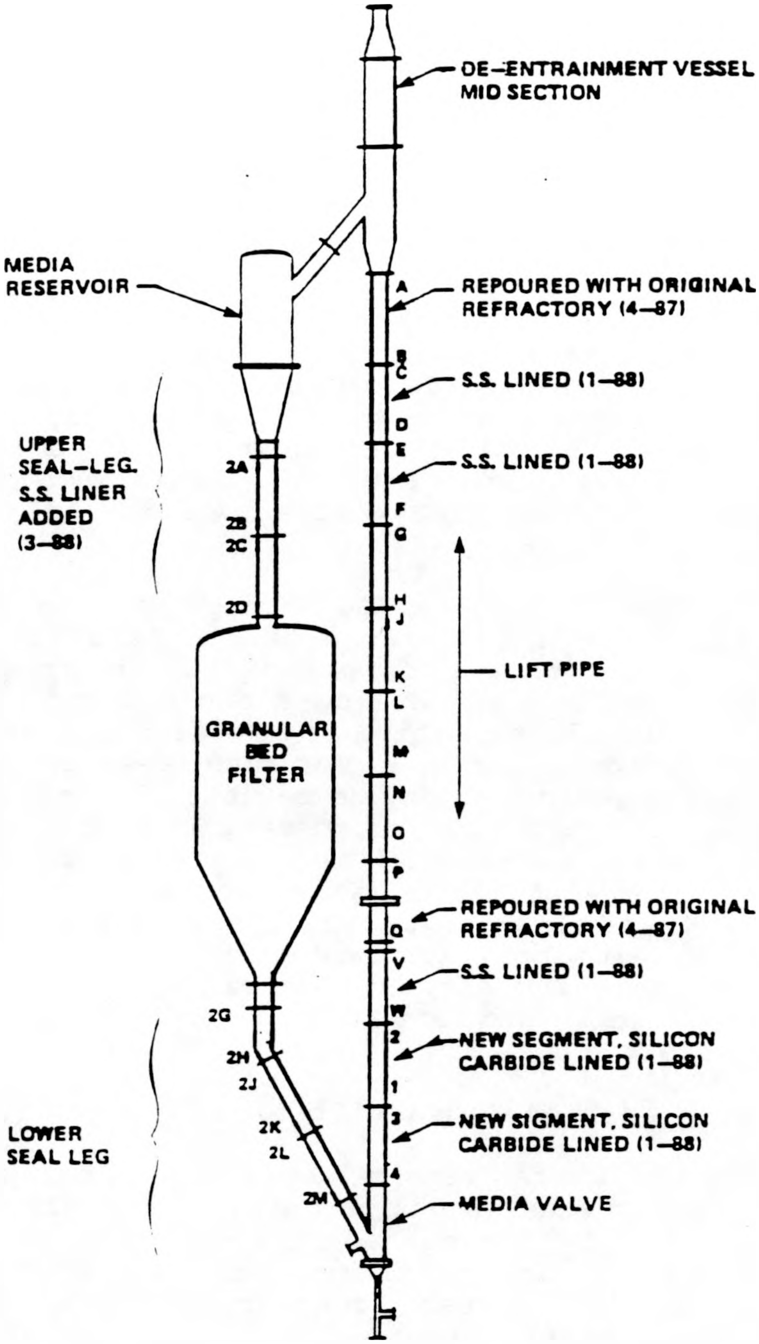
Table 5-VII shows the summarized data on wear. Base dates reflect that two segments were relined prior to use at NYU. The service hours are rounded off and are expected to be accurate within ±20%. Diameters listed are averages of the four measurements taken at each location rounded off to the nearest 1/1000 inch. Wear rates are based on an 8760 hour year.

**TABLE 5-VII**

**LIFT PIPE REFRACTORY WEAR**

| Wear Point | Base Date | Service Hours | AVG. DIAMETER New | Used | % Diam. Change | Wear (Mils/yr) |
|---|---|---|---|---|---|---|
| P-P | 4/28/87 | 400 | 2.008" | 2.023" | .78 | 172 |
| G-G | 10/24/85 | 900 | 1.994" | 2.090" | 4.83 | 468 |
| O-O | 10/24/85 | 900 | 1.976 | 2.054" | 3.95 | 380 |
| B-B | 4/28/87 | 400 | 2.013 | 2.047 | 1.71 | 375 |
| 2J | 10/24/85 | 900 | 2.992 | 2.999 | .22 | 126 |
| 2M | 10/24/85 | 900 | 2.997 | 2.989 | NEG | NIL |
| DEV MID | 10/24/85 | 900 | 8.001 | 7.966 | NEG | NIL |
| MEDIA RESEV INLET | 10/24/85 | 900 | 3.603 | 3.668 | 1.8 | 316 |

NEG = Negligible
DEV = De-entrainment Vessel




ALL SEGMENTS IDENTIFIED ABOVE WERE LINED WITH REFRACTORY PRIOR TO TESTING AT COMBUSTION POWER IN 1985 EXCEPT AS NOTED.

Figure 5-15. Post NYU Status of Refractory-Lined Equipment

At best, the data shows high wear of the lift-pipe refractory linings. For example, section "P-Q" had been redone with the original materials prior to installation at NYU. The replacement lining appeared to be in very good shape after NYU testing as it was still fairly smooth on the interior. (Other segments showed crevice formation and increased roughness.) Measurements at the end marked "P-P" showed there actually was some wear; although not as high as in other locations.

In general, all segments of refractory-lined lift pipe wore not only in diameter but also developed deep crevices (up to 1/2") and increased roughness. As shown on Figure 5-15, five lift-pipe segments are relined on the dates shown. All segments appeared serviceable at the end of the NYU test series except segment N-O which was judged unsuitable for further use due to a more advance state of crevice formation.

Wear in the lower seal legs (2G through 2M) was minimal except for at localized areas not shown on the table above. Fiberscope inspection during the test series indicated wear at the flange areas (2J, 2K-2L, and 2M) and at locations midway between flanges 2J-2K and 2L-2M. Visual inspections on final disassembly indicated the wear at the flange interfaces was not as severe as previously thought. Through the fiberscope, we saw the gap between the flange refractory interfaces and some rounding of the refractory corners (about 1/2"). These discontinuities appeared major through the fiberscope, but minor on direct visual inspection. From the ends of sections 2J-2K and 2L-2M we could determine that there was some refractory missing at about the mid-point of each segment. The wear was in the form of a circumferential groove 1/2" to 1" wide and at least 1/2" deep. Through the fiberscope, this had appeared 2 to 3 times larger.

### 5.4.2 Silicon Carbide-Lined Lift Pipes

The lining in these segments was a 1" thick cylinder of silicon oxynitride bonded silicon carbide for the hot face and medium density (60 $lb/ft^3$) castable insulation for the back-up lining. In each 5' segment there were two pieces of silicon carbide installed that butted together near the center of the segment. Stainless steel bars held the silicon carbide cylinders in place, see Figure 5-16.

Table 5-VIII shows results of the measurements taken to determine wear. The service hours is accurate to ±15%. The diameters listed are averages of the four measurements taken at each location rounded off to the nearest 1/1000 inch. Wear rates are based on an 8760 hour year.

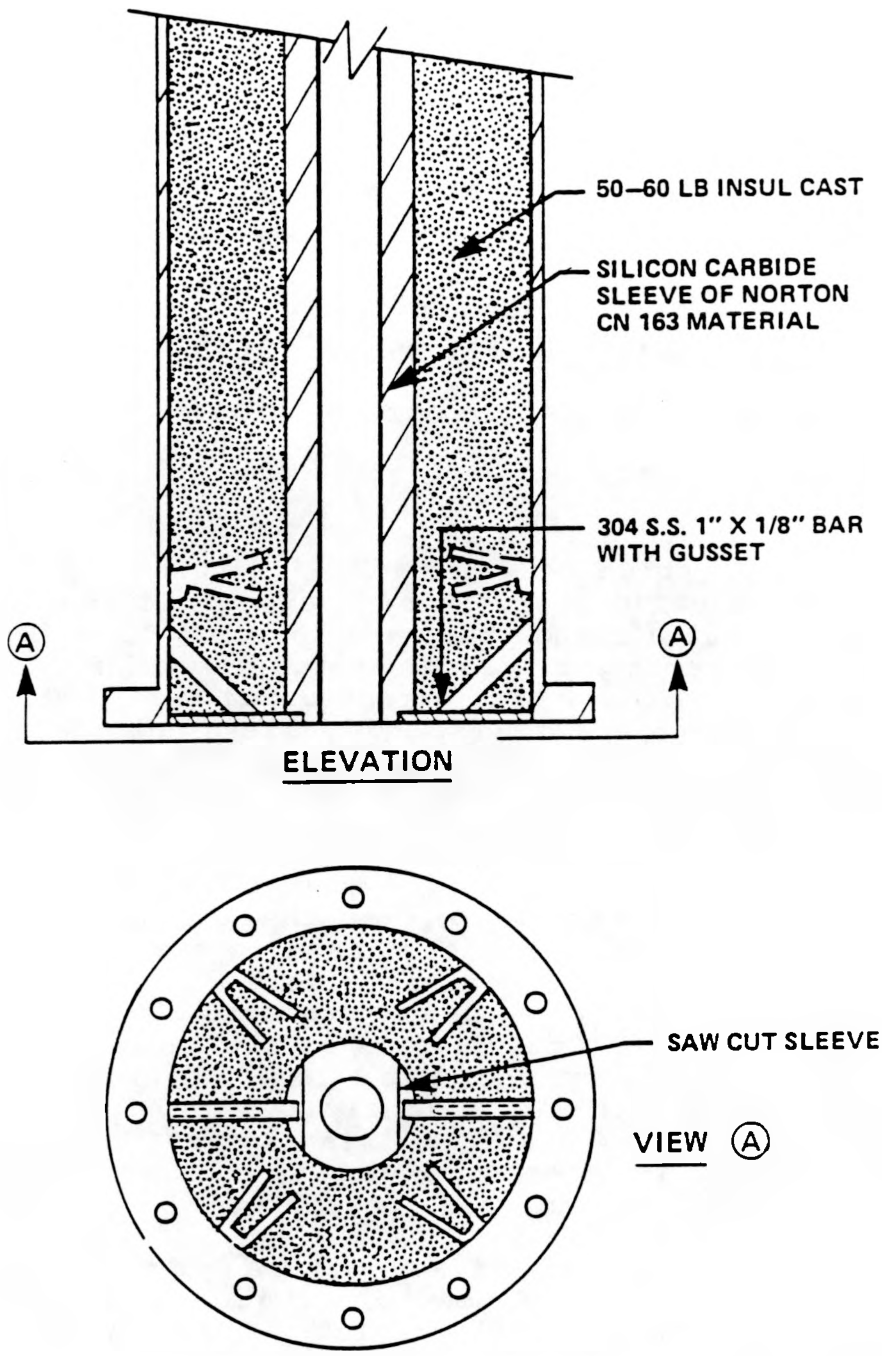



Figure 5-16. Silicon Carbide Lined Lift Pipe

**TABLE 5-VIII**

**WEAR OF SILICON CARBIDE LINED PIPES**

| Wear Point | Base Date | Service Hours | AVG. DIAMETER New | Used | % Diam. Change | Wear (Mils/yr) |
|---|---|---|---|---|---|---|
| 1 | 2/88 | 300 | 2.025 | 2.033 | .42 | 93 |
| 2 | 2/88 | 300 | 2.029 | 2.040 | .54 | 120 |
| 3 | 2/88 | 300 | 2.032 | 2.037 | .22 | 49 |
| 4 | 2/88 | 300 | 2.021 | 2.041 | 1.01 | 224 |

The silicon carbide wear data is difficult to interpret. It was clear from visual comparison of the new and used surfaces of silicon carbide that a change had taken place. The new surface had a roughness characterized by close, sharp, minute projections. The used surface had a texture that appeared rougher in the sense that the distance between the hills and valleys on the surface had increased but the sharp edges were rounded off. Furthermore, the hills and valleys were more widely spaced in the used condition than the roughness of the new surface.

The wear rates projected to a year of service vary widely. One reason, as mentioned above, is the difficulty in getting repeatable measurements. Another reason is that the measurements were taken in the first few inches of the lining from each end. Wear due to misalignment of adjacent segments could bias readings. The apparent high wear at point 4 was due to misalignment with the media valve. The alignment tool was 1 15/16" diameter for the lift pipe. This, along with the slightly oversized silicon carbide sleeves could allow up to 3/32" misalignment assuming a good refractory surface in the media valve, which it was not. A misalignment up to 1/8" was quite possible.

A wear test of 300 hours may not be representative of the actual yearly wear. It is possible that the new surface wore rapidly to a more stable configuration. Future wear could be at a different, perhaps slower rate.

The corners of the silicon carbide sleeves were broken away irregularly. This was not only observed at the ends of the segments, but also at the butted joints of the sleeves inside the segments. On the number "2" end of segment "1-2" the stainless steel bracing for the liner was bent outwards. Within this segment, the butted joint of the silicon carbide sleeves had opened up about 1/4". One of the liner sections apparently expanded and deformed the bracing at the "2" end by about this same "1/4". Also within this segment a slight kink developed where the two silicon carbide sleeves met; although the alignment tool passed through easily. The design of the silicon carbide supporting components should be reviewed prior to fabrication of additional segments or commercial sized segments.

#### 5.4.3 Stainless Steel Lined Lift Pipe

Baseline measurements on the stainless steel lined pipe were not made since this lining was not intended to be a wear-resistant lining. Measurements were taken after operation for 300 hours since it appeared that the stainless steel did not wear significantly. Figure 5-17 shows the design of the stainless steel lining. On the ends closest to the expansion joints, the inside diameters ranged from 2.030" to 2.045" on segments "V-W" and "C-D". This is less than the standard diameter of 2" Sch 40 pipe which is 2.067". The same is true on the end opposite the expansion joint as the final diameters ranged from 1.995" to 2.065". The pipe probably shrunk due to the heat from welding on the bracing. Unfortunately, because of the pipe shrinkage, no conclusions can be made on wear.

On segment "E-F", the liner on the expansion joint end was distorted to a somewhat square cross-section probably from welding. The pipe was flattened in the periphery by the support bars. Measurements across the inside of the pipe ranged from 1.956" to 2.031". This minor distortion did not cause any problems.

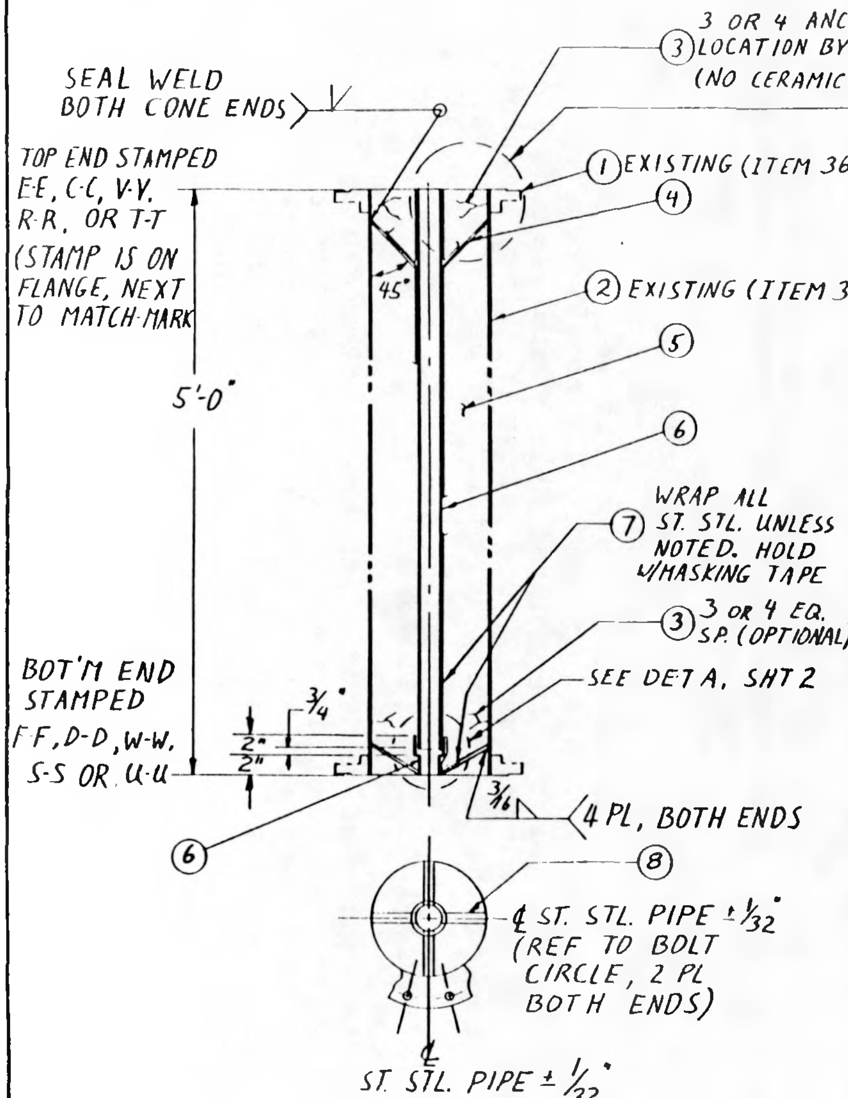
The only visible wear was on the expansion joint end of segment "C-D". Misalignment with the segment just below "C-D" was the reason for the wear spot along 20% of the circumference and extending along the pipe axis about 3". About .040" was worn at the deepest point from the wall thickness of .154" nominally. This was the only visible wear on these segments. All the expansion joints in the stainless steel segments were fouled with ash and media as expected. This apparently did not affect the function of the expansion joint. In general, the stainless steel lined lift pipes looked surprisingly good after testing, considering the condition of the refractory-lined lift pipes.

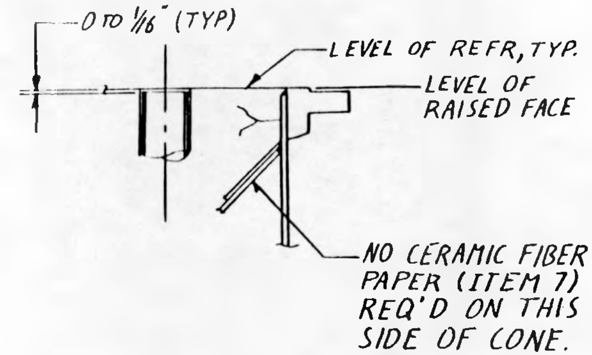
### 5.5 Circulation System Operation

The amount of gas needed to transport media up the lift pipe depends on media size, media shape, temperature and pressure. Combustion Power has a media transport model that has been in use for quite some time, and is known to work well at atmospheric conditions. This model was used extensively in development of the commercial gravel bed filter (Grace, 1979) and was further utilized in generating media transport parameters for the testing of Life-Critical Components. In Life Critical Component testing a family of operating curves was confirmed to be applicable for 2 mm media as temperature and pressure changed (refer to Section I). To effect these changes in lift-pipe flow, the boost blower had a

**Figure 5-17a. Stainless Steel Lined Lift Pipe Segments**

| LTR | REVISIONS DESCRIPTION | DATE | APP |
|---|---|---|---|
| | | | |




NOTES:

1. AFFECTS MODS. TO PIPE SPOOLS STAMPED E-F C-D & V-W.

| QTY REQ | QTY REQ | PART NO | NAME | STOCK SIZE | MATERIAL DESCRIPTION | EST WEIGHT | ITEM NO |
|---|---|---|---|---|---|---|---|
| | 1 | | ROLLED BAR OR TUBE | | 316 OR 316L | | 10 |
| | 1 | | TUBE | 3" O.D. x .12" THK. x 2 1/4" LG | ASTM A-312-316L | | 9 |
| | 4 | | BAR | 1" x 3/16" THK | ASTM A-240-316 | | 8 |
| | AR | | CERAMIC FIBER PAPER | 1/8" THK, 5 Ø' | A.P. GREEN INSWOOL-HP or EQ | | 7 |
| | 1 | | PIPE | 2" SCH 40 x 5'-0" LG | ASTM A-312 TP316L | | 6 |
| | 200 LB | | REFRACTORY INSULATION | 50 LB/CF | VSL-50 (A.P. GREEN) RS-3 OR RS-3B (RESCO) | | 5 |
| | 1 | | CONE | 10 GA. THK | ASTM A-240-316 | | 4 |
| | AR | | ANCHOR | BY REFR CONTRACTOR | | | 3 |
| | REF | | PIPE | 12" x .375 THK | ASTM A-53 GR B | | 2 |
| | REF | | FLANGE | 12" 150 LB RFSO | ASTM A-105 | | 1 |
| | -1 | | | LIST OF MATERIAL | | | |

FOR NEXT ASSY AND USAGE DATA SEE ENGRG RECORDS

DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES/MILLIMETERS
TOLERANCES
FRACTIONAL ± .88
DECIMAL ± .83
MM ± 1.6
ANGLE ±

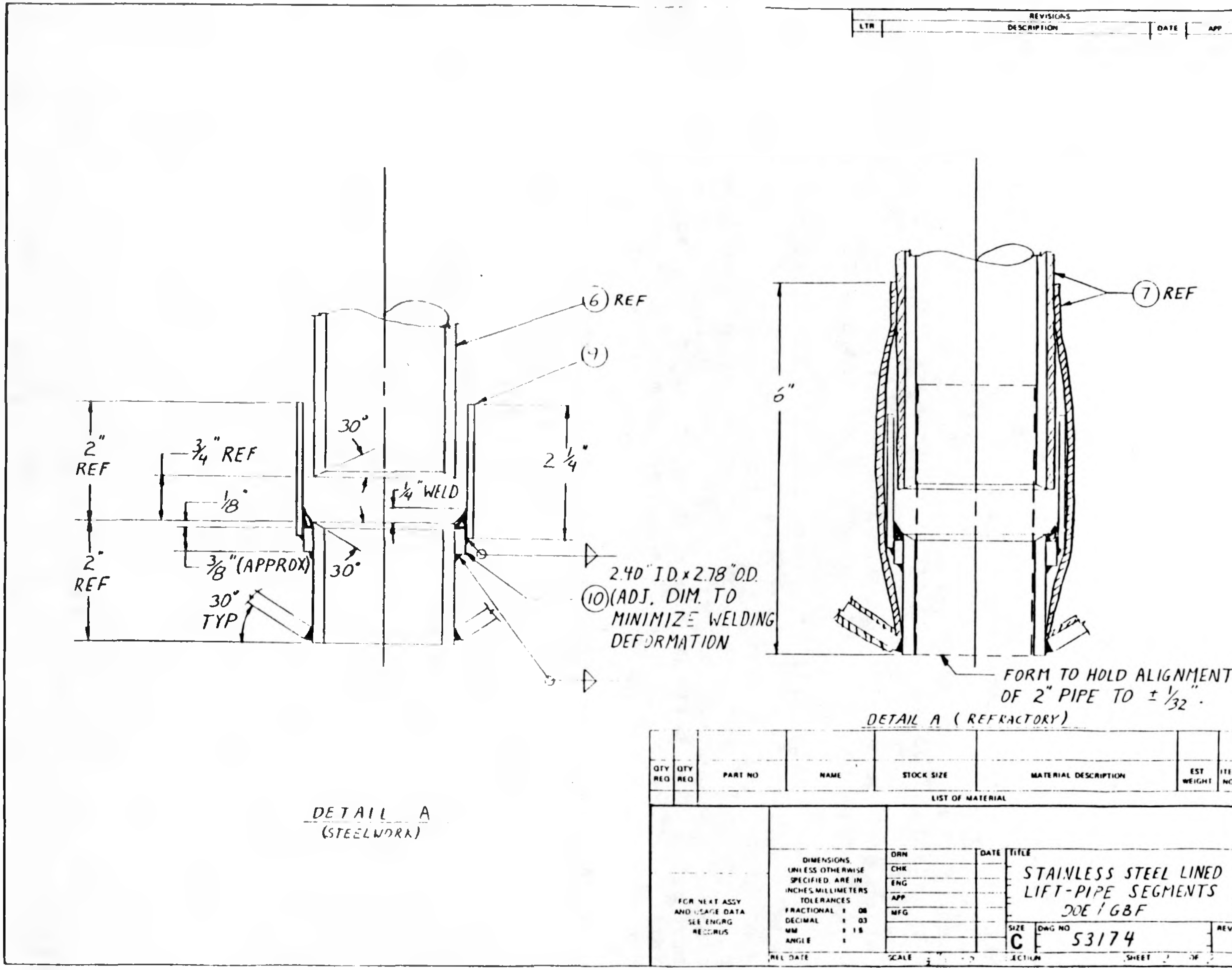
DRN K [illegible] | CHK J33 | ENG | APP K [illegible] | MFG

REL DATE 12-4-87 | SCALE 1 1/2" = 1'-0

TITLE: STAINLESS STEEL LINED LIFT-PIPE SEGMENTS DOE/GBF

SIZE C | DWG NO 53174 | REV

SECTION | SHEET 1 OF 2


REVISIONS
LTR
DESCRIPTION
DATE
APP
(6) REF
(9)
2" REF
3/4" REF
1/8"
30°
1/4" WELD
2 1/4"
2" REF
3/8" (APPROX)
30°
30° TYP
2.40" I.D. x 2.78" O.D.
(10) (ADJ. DIM. TO MINIMIZE WELDING DEFORMATION
DETAIL A (STEELWORK)
(7) REF
6"
FORM TO HOLD ALIGNMENT OF 2" PIPE TO ± 1/32".
DETAIL A (REFRACTORY)
QTY REQ
PART NO
NAME
STOCK SIZE
MATERIAL DESCRIPTION
EST WEIGHT
ITEM NO
LIST OF MATERIAL
FOR NEXT ASSY AND USAGE DATA SEE ENGRG RECORDS
DIMENSIONS UNLESS OTHERWISE SPECIFIED ARE IN INCHES MILLIMETERS
TOLERANCES
FRACTIONAL
DECIMAL
MM
ANGLE
DRN
CHK
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APP
MFG
DATE
TITLE
STAINLESS STEEL LINED LIFT-PIPE SEGMENTS
DOE / GBF
SIZE C
DWG NO 53174
REV
SCALE
SHEET

manually adjustable, variable speed drive. This relationship was used on all 2 mm media tests.

The utilization of 3 mm media for filtration, vs. 2 mm media, required an adjustment of the parameters for circulating and cleaning media. From Life-Critical Component Testing at Combustion Power previous to the operation at NYU, the basis for optimizing the transport air was formulated. Operation at NYU on 2 mm media yielded validity to this basis which was to exceed the terminal (free fall) velocity of the media by 10-20 fps. As a result, a family of curves was generated for 3 mm media to link the optimum lift pipe flow to temperature and pressure. Figure 5-18 shows this relationship. To achieve the proper amount of transport gas, the speed of the boost blower was adjusted. This adjustment proved to be substantial between atmospheric pressure and 50 psig but rather minor above 50 psig and with temperature. It is the information plotted on Figure 5-18 that would be needed to automatically adjust the lift pipe gas flow in a computer controlled GBF.

In addition to lift-pipe transport gas, another parameter that needed adjustment in response to temperature and pressure was counterflow gas. This is the gas flow that prevents ash from drifting back into the media reservoir from the de-entrainment vessel. The amount can vary widely and still be effective, but some basis for setting the flow must be generated. With 2 mm media, the setpoint was 30% of the minimum fluidization velocity of the media. Because the capacity of the boost blower plus other circulation system components was to be challenged by the additional mass flow needed for 3 mm media, the basis for counterflow air was revised to 20% minimum fluidization. The resulting family of curves are shown on Figure 5-19. This resulted in only a modest increase in counterflow gas (10%) over that utilized with 2 mm media. Thus the velocity in the counterflow air pipe (between the media reservoir and de-entrainment vessel) was much the same for both media sizes. There was no indication that this adjustment affected filter performance.

In practice, the operator visually interpolated between temperatures and pressures for setpoints of both counterflow and lift-pipe gas flows. Both parameters were calculated from transmitter data and displayed on a computer console screen at NYU for reference.

Media circulation rates were measured throughout all tests by mechanical means for comparison to theoretical values. The theoretical ranges take into account the different pressures and temperatures at which data was taken. At a single pressure and temperature, the relationship between media circulation rate and pressure drop is a single line. In earlier testing at NYU, there was a wide divergence between measured and theoretical circulation rates; sometimes up to 2:1. Prior to HG-203 the lift pipe was repaired by replacing badly worn refractory lined segments. Still,

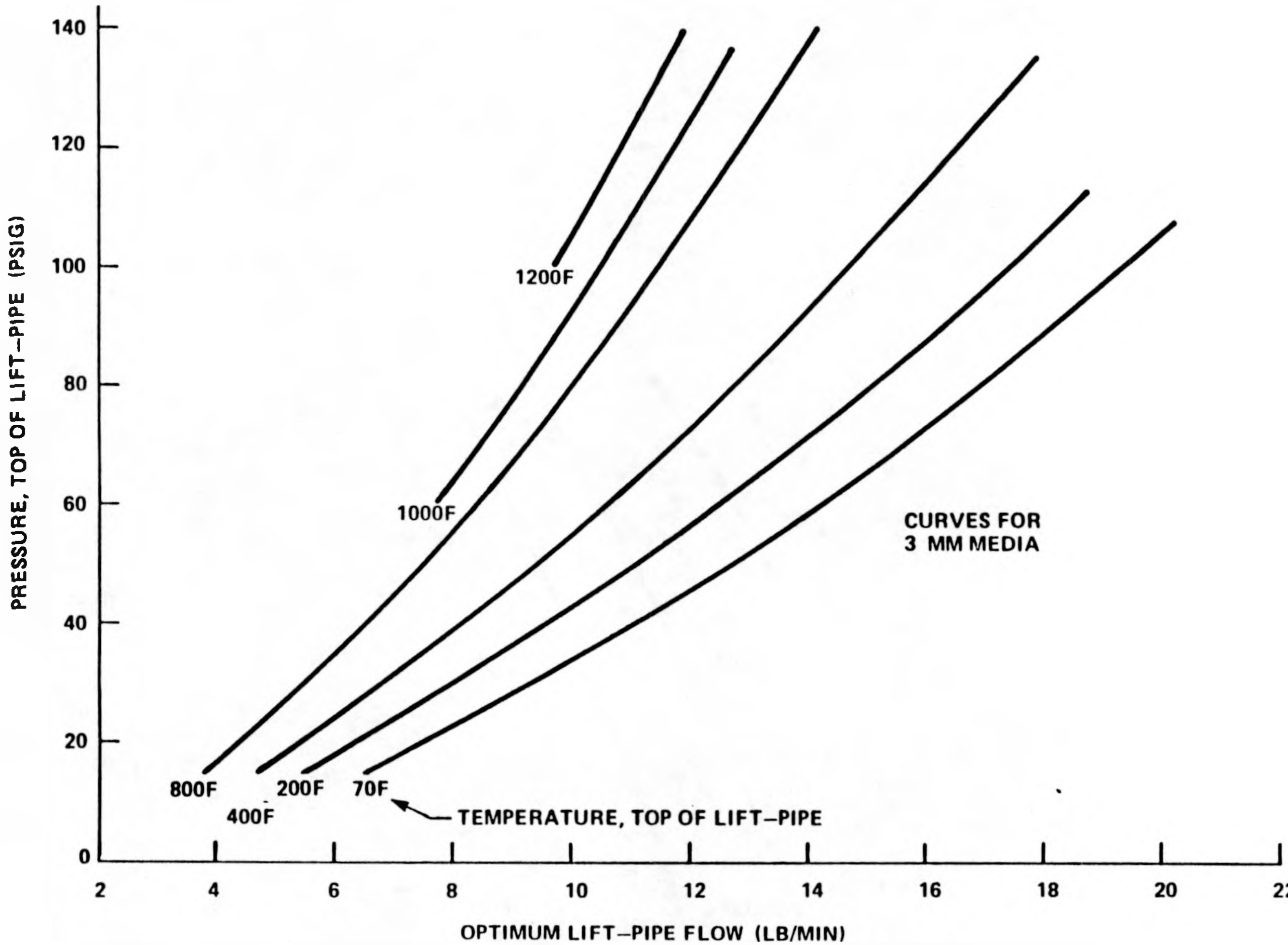



Figure 5-18. Theoretical Optimum Lift-Pipe Transport Gas

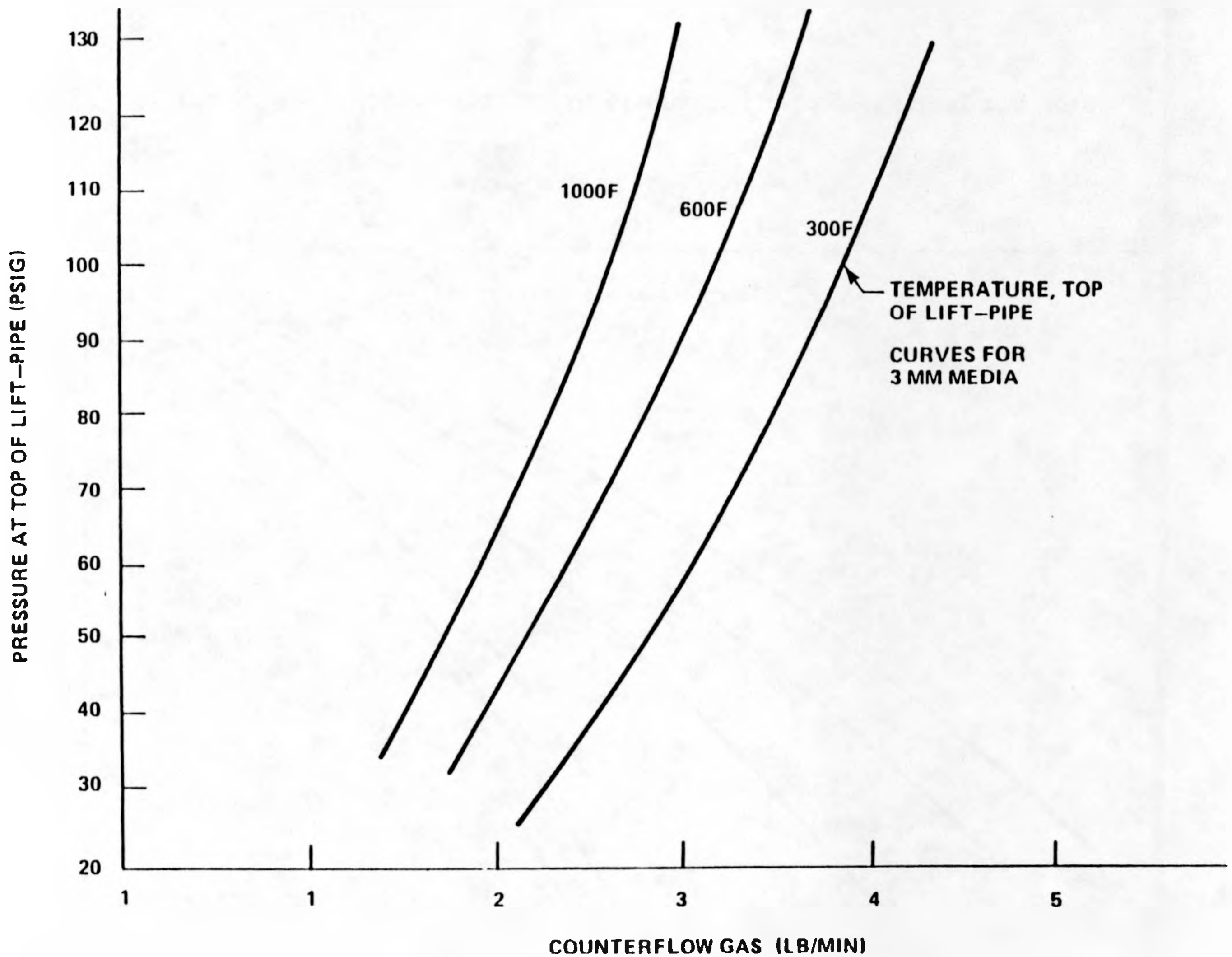



Figure 5-19. Counterflow Gas Setpoint

during HG-203, 204 and 205, 5 out of 10 lift pipe segments had the original refractory lining and there was some concern that these would continue to deteriorate and affect media circulation. These wear problems are discussed from the standpoint of wear rates in Section 5.4. From the standpoint of performance, the measured and theoretical rates are compared in Figures 5-20 and 5-21.

Both graphs generally show good agreement between measured and theoretical values. This indicates that the lift-pipe wear problem exhibited in earlier tests has been brought under control. Figure 5-20 is from data taken in test HG-204. Plotted data indicates the lift pipe performance is close to the theoretical model. This was data gathered shortly after the lift pipe was refurbished. Data on Figure 5-21 comes from the last GBF performance test, HG-205. With the exception of two data points, the agreement is good. The cluster of data just above the theoretical range can be explained by continued refractory wear when compared to the data on Figure 5-20. Wear generated very rough refractory surfaces evidenced by crevices up to 1/2" deep and roughness to 1/4".

Occasionally very high circulation rates are measured at an unusually low pressure drop, like the one out beyond 80 lb/min on Figure 5-21 (See also Figure 5-20, HG-204). These could be errors in measurement; although this was not evident. The unusually low circulation rate, at 28 lb/min on Figure 5-21 is probably due to errors initiated by minor damage to the mechanical device used to measure media flow. The damage could cause the device to move more slowly than the media, thus yielding low circulation rates. To be more precise, the device consists of a rod with a disk on one end that followed the media level in the media reservoir. Timing the drop of media in this mass flow type hopper yielded a media circulation rate. The rod had become bowed so if the operator was not careful, the device could be arranged to scrape along the side wall of the media reservoir. Evidently the damage to the media follower occurred early in test HG-205. Regardless of the minor difficulties in gathering data, there was remarkable agreement between measured and theoretical circulation rates.

## 5.6 Post-Test Inspection

After the test series at NYU, the GBF equipment was disassembled for inspection. The condition of the lift pipe was reported on in detail in Section 5.4. Other items were as follows:

- FILTER ELEMENT (Figure 2-2)

  Prior to disassembly, this was inspected for ash deposits. The inlet duct was coated with ash up to 1/2" thick, but this ash was loose and easily brushed away. There was no sign of ash agglomeration.

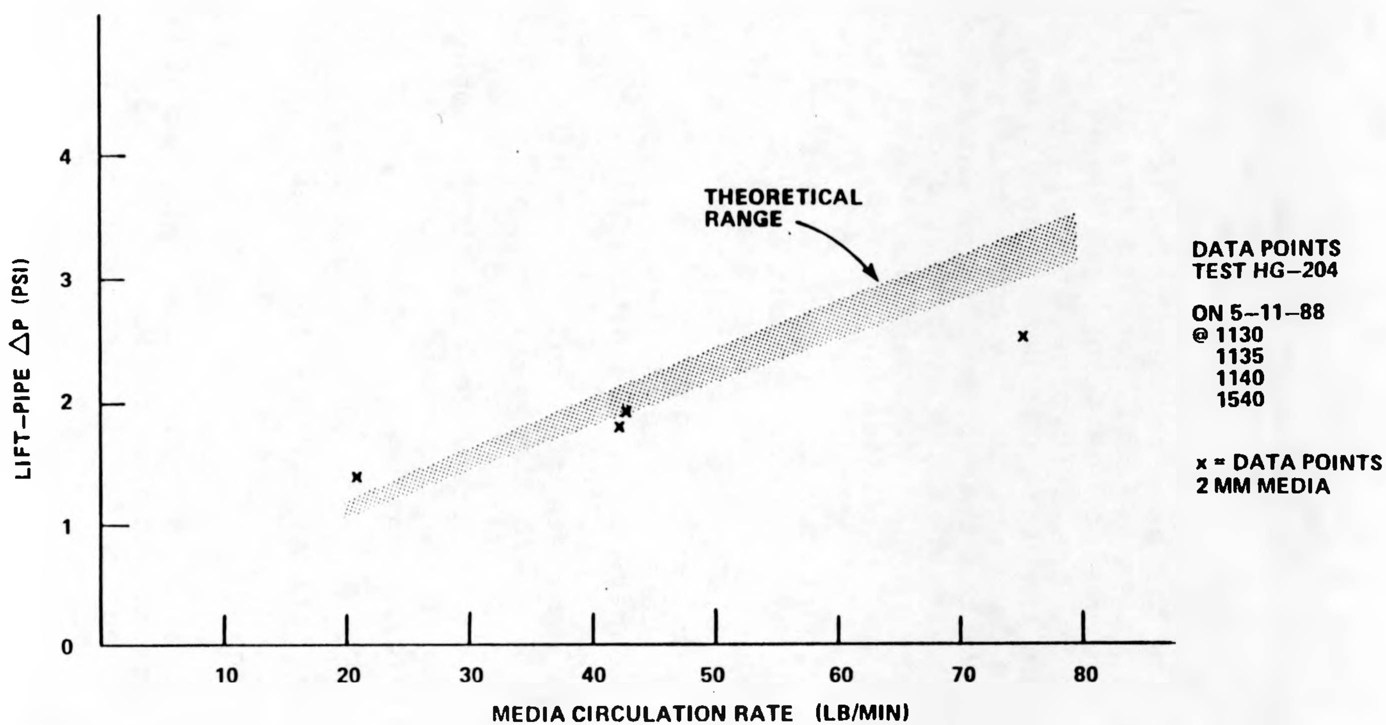



Figure 5-20. Media Transport at NYU (Early in Test HG-204)

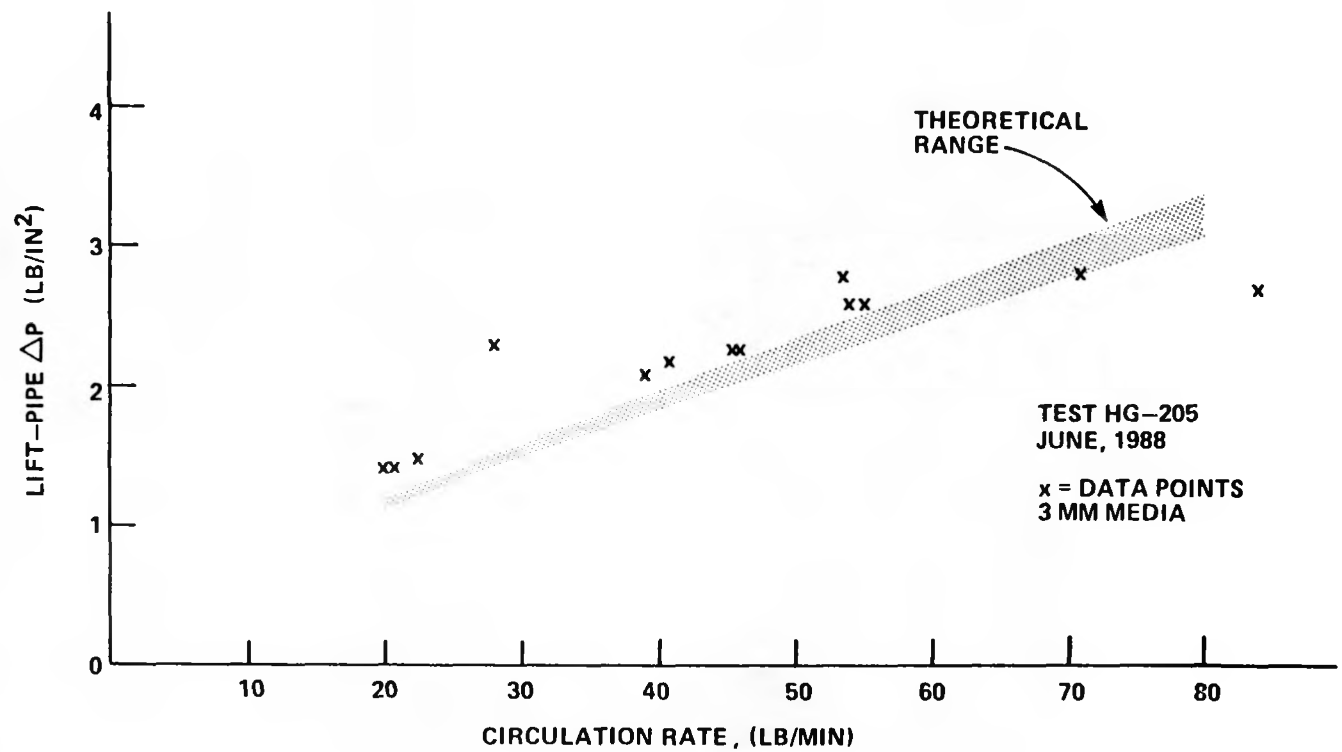



Figure 5-21. Media Transport at NYU, HG-205

On disassembly, the filter element appeared in generally good condition. There was no visible distortion. The original Inconel 800 HT material was noticeably clearer than the 316 SS material which was subsequently added to extend the height of the filter element. The 316 SS material appeared mottled and oxidized but no loose scale was in evidence.

- LOWER FLEXIBLE SEAL INSERT (Figure 2-2)

The lower flexible seal at the bottom of the filter vessel had failed apparently due to the effects of overheating and corrosion. This condition may have been caused by the lack of insulation along the full length of the seal and consequent overheating of the 316 SS bellows material. This insulation was mistakenly left out by the fabricator. Condensation collecting in the lower vessel could have aggravated the situation. The lower portion of the bellows which was protected by Kaowool rope insulation was in noticeably better condition than the uninsulated upper portion. (It is noted that the upper flexible seal at the gas inlet to the filter vessel is insulated along its entire length and experienced no deterioration). The Kaowool packing on the lower seal leg at the bottom of the filter vessel apparently acted as a backup seal and permitted successful filter operation.

- FILTER VESSEL HEAD (Figure 2-2)

The inside of the Combustion Power vessel head appeared in generally good condition with refractory essentially intact but with the usual cracking in evidence.

- INLET FLEXIBLE SEAL (Figure 2-2)

This component was in good condition except that it suffered some scrapes probably during removal. Recall that this item had been reworked in December of 1987 because the bellows had been deformed due to overpressurizing. It is notable that despite the subsequent pressure upsets, the bellows was unaffected.

- UPPER SEAL-LEG INSERT (Figure 5-15)

The stainless steel liner added to renew the surface in segments 2A-2B, 2C-2D was in good condition.

- CARBON STEEL PIPE

As part of the media circulation system, there was some 2" and smaller steel pipe (ASTM A-53 Gr B). Corrosion of this pipe was apparent based on the debris collected in the coalescing filter downstream of the pipe. On disassembly, it was discovered that this corrosion was not too vigorous as metal wastage was minimal.

In summary, observations on disassembly revealed information fairly consistent with operational characteristics. As expected, the lift pipe was worn, but not catastrophically. The only real surprise was the condition of the lower flexible seal. This problem can be eliminated by redesign. Most components could be reused in a system of similar capacity for limited use. For long term use (in excess of 400 hours) the remaining refractory-lined lift-pipe segments should be relined and the media valve refractory renewed.

## 5.7 Upset Responses

Upsets that occurred during operation fall under four categories: pressure, temperature, gas flow, and ash flow.

### 5.7.1 Pressure Changes

Pressure in the media circulation system changes with the GBF pressure. Gases leak through the upper and lower seal legs to bring equilibrium. When pressure is steady for a few minutes, equilibrium is approached and circulation system operation is steady. Pressure changes up to 2 psi/minute could be absorbed easily at NYU.

Rapid pressure changes occurred at NYU for many reasons. Sometimes upsets were operator induced, and sometimes upsets were caused by equipment malfunction. Pressure changes at NYU greater than 4 psi/minute caused some upset. The greater the rate of pressure change, the more severe the upset and the higher potential for filter problems.

A pressure rise is potentially most harmful. This causes gas to flow down the lower seal leg (GBF to media valve) and will increase the circulation rate 10-30% for pressure changes greater than 4 psi/minute. A diligent operator can cope with the change by adjusting the hand valve for media injector air. During a pressure rise, the pressure drop across the upper seal leg increase as gas flows upward. With the badly worn refractory and enough leakage velocity to retard media, as was the case during some early tests, bridging was initiated. These bridges could be broken by two methods. One was by momentarily turning off the circulation and the boost blower to allow the pressure difference to diminish and the other was to utilize the pneumatic blaster in the baghouse while on-line to accomplish the same pressure reversal.

It was also observed that a rapidly rising pressure could increase filter pressure drop. This could have been from an increase in ash loading as pockets of ash were stirred loosed from the primary cyclone and ducting. Alternately, the primary cyclone efficiency could be degraded. Additionally, the unsteady-state gas flow due to rising pressure is added to the steady-state gas flow creating a high instantaneous gas flow.

To cope with rapid pressure rises, piping and valves were added after test HG-202 to connect the GBF outlet to the circulation system baghouse outlet. When a rising pressure increases the pressure drop across the upper seal leg beyond about 4 psi, the operator opened the solenoid operated ball valve connecting the GBF pressure vessel to the baghouse outlet. This allowed pressure equalizing gases to bypass the seal legs and quickly restore the proper pressure profile. This could be automated with a pressure switch, but due to the tight schedule, materials on hand were utilized.

Rapid pressure drops were relatively easy to tolerate. The only concern is that the circulation can be slowed 10-30% due to pressure drop greater than 4 psi/minute. As long as the on-off valve was open there was no danger of media backflow as occurred during Test HS-202 with the on-off valve closed. To cope with rapid pressure drop, the system bleed valve, used for artificial balancing, was opened to re-establish the proper pressure profile.

The biggest nuisance is that the seal-leg gauges could be pegged during pressure changes. If the incidence was severe enough, the accuracy of the gauge could deteriorate. The gauge on the lower seal leg was most sensitive to rapid pressure drop. Transmitters in parallel with the gauges did not seem to be affected.

To illustrate filter response during a rapid pressure change, an example from Test HG-203 is shown on Figure 5-22. During this test, three power failures occurred that resulted in rapid pressure drops when the power went off followed by rapid pressure rises when the power came back on. This illustration is from the third power failure. By this time, the operator was familiar with his response so system perturbations caused by operator error were minimal. At 41 minutes after the zero hour on Figure 5-22, filter pressure dropped from 81.7 psig to 55.2 psig in 2-3 minutes at an instantaneous rate of at least 24 psi/minute. Recovery to 80.8 psig occurred in 2-3 minutes at an instantaneous rate of at least 18 psi/minute. The filter pressure drop (GBF DP) decreased to .05 psi on pressure loss and increased to 2.05 psi on recovery. During this test, flow was divided equally between the filter and bypass. There was concern that large pressure drop could cause backflow of gas and media from the filter element as during HS-202 but this did not occur as the GBF pressure drop did not go negative. The sudden jump in GBF pressure drop on recovery whether due to high transient gas flow and/or a high transient ash flow probably caused the media to bubble as the GBF pressure drop at minimum fluidization is about 2.0 psi. Media circulation rate, indicated

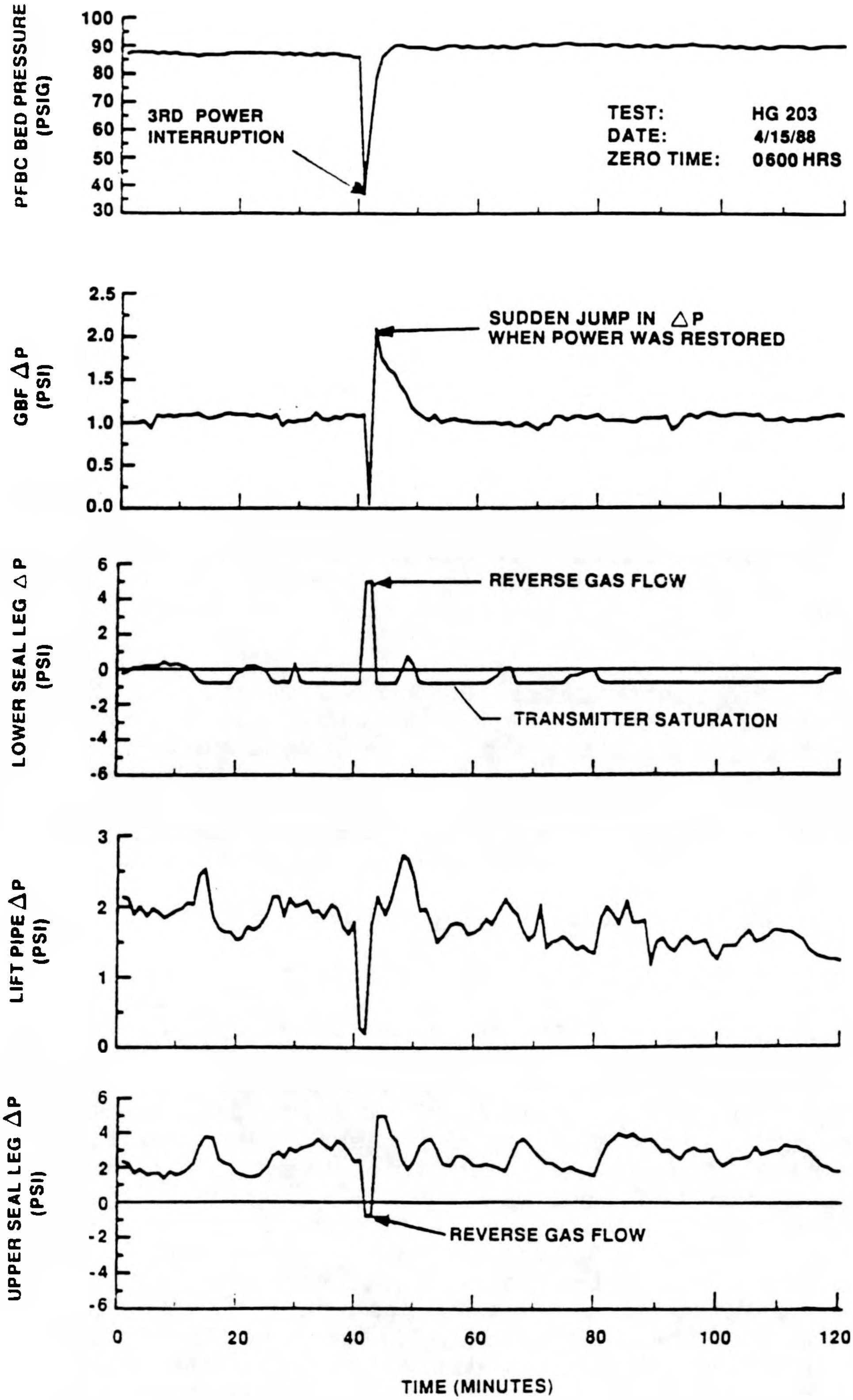



Figure 5-22. GBF Performance Curves for HG-203 Showing System Response to the Third Electrical Power Interruption

by lift-pipe pressure drop, decreased to near zero and then recovered. Likely, the GBF pressure change influenced the drop and rise in circulation rate but operator response also played a part especially in the aftermath at 50 minutes after zero time. Herethe operator increased circulation rate to about 2.8 psi lift-pipe pressure drop to hasten the recovery of the GBF pressure drop. Upper and lower seal-leg responses were typical as the pressure in the circulation system momentarily became higher than the filter pressure. It should be clear from comparison of these traces before and after the pressure upset that no lasting filter problem occurred. More information on filter response during pressure upsets is in Appendix IIB.

### 5.7.2 Gas Flow Changes

Changes in pressure were always accompanied by changes in gas flow and vice versa. Changes in ash loading usually occurred with little change in gas flow but gas flow perturbations could affect ash flow.

Early performance tests (HG-201 & 202) and all shakedown tests were attempted at near 50% minimum fluidization. At this capacity the GBF entered a bubbling mode during pressure or ash flow upsets. In two of five cases, upsets that led to bubbling of filter media ultimately led to shutdowns. This bubbling indicated that the combined gas flow and ash flow (and storage) capacity of the filter had been exceeded. In later tests at 25% minimum fluidization, pressure upsets sometimes caused the filter to bubble but only momentarily and then followed by recovery.

Unfortunately, it was not possible to isolate a gas flow change from which to draw conclusions. The pressure upsets that occurred during HG-203 during power interruptions served well in studying pressure upsets. From the flow standpoint, these upsets do not yield conclusive data. For example, it could be assumed that on pressure recovery, the GBF pressure drop was completely due to the transient gas flow as gas rushed past the filter to bring pressure back up to normal. This transient gas flow would then be responsible for the increase in GBF pressure drop on recovery. Under this assumption, the filter gas flow increased to rates equivalent to 57%, 143% and 68% of minimum fluidization for the first, second, and third power interruption, respectively. This spread in results indicates that something other than gas flow was responsible for the increase in filter pressure drop during these upsets. Perhaps stored ash dislodged from low velocity zones in the ductwork or cyclone. Maybe the gas/media interface at the filter inlet changed in configuration during the pressure drop that preceeded the pressure rise.

Shakedown test HS-202 came to an end when pressure induced flow changes transported media from the filter into the inlet ducting. During this incident, the on-off valve downstream of the filter was closed. On pressure drop, gas could only back flow through the filter to relieve (See Appendix IIA for details). Combustion Power's conclusion was that his backflow could occur if the velocity in the GBF inlet was greater than minimum fluidization of the media. During HG-203 when PFBC gas flow was divided near equally between the filter and bypass there was speculation that a rapid pressure drop could result in a similar occurrence. Combustion Power made a rough estimate based on component volumes and sonic nozzle sizes that showed the on-off sonic nozzle capable of venting pressure from 100 psig to 40 psig at 1400°F in 30 seconds. This capacity, in excess of 100 psi/minute, was much greater than the drop in pressure that occurred during power interruption. Subsequent operation with pressure upsets during power loss (HG-203) proved that media backflow would not occur on pressure loss in excess of 32.5 psi/minute. Note that these conclusions are highly site specific and depend on equipment volumes, equipment arrangement, pressure, temperature and vent point.

### 5.7.3 Temperature Changes

It was normally possible to keep temperature changes to within 200°F/hr. Exceptions occurred often during startup, shutdown and upsets. Figure 5-23 shows one typical upset where coal flow to the PFBC was interrupted. Perturbations such as this occurred for one reason or another once or twice during each test. For example, during HG-204, temperature dropped from 1612°F to 700°F in 12 minutes. This was followed by a rise from 644°F to 1050°F in 20 minutes. Filter temperature exceeded 1600°F many times during the test series and peaked out at 1625°F. There were no detrimental effects due to these upsets.

### 5.7.4 Ash Flow

Ash loading into the filter was expected to be 1200-1500 ppmw. During HG-203 GBF inlet loadings were measured at 3440 ppmw, 6355 ppmw and 4027 ppmw during consecutive grab sample measurements. These high loadings were due to a plugged primary cyclone. During this time the ash loading in the filter rose to 2% (ash rate to media rate by weight). No special problems with GBF operation were noted during these several hours. In fact Combustion Power operators were unaware that the inlet loading was of this magnitude until well after the test was over.

At the end of HG-204 the ash loading was intentionally increased by feeding a high amount of dolomite sorbent. This increased ash loading lasted for about one hour with one grab sample measurement indicating 2800 ppmw. During this time the circulation rate was held constant at about 35 lb/min giving an ash loading of 1%. Only a minimal change in filter pressure drop occurred during this time (about 5%).

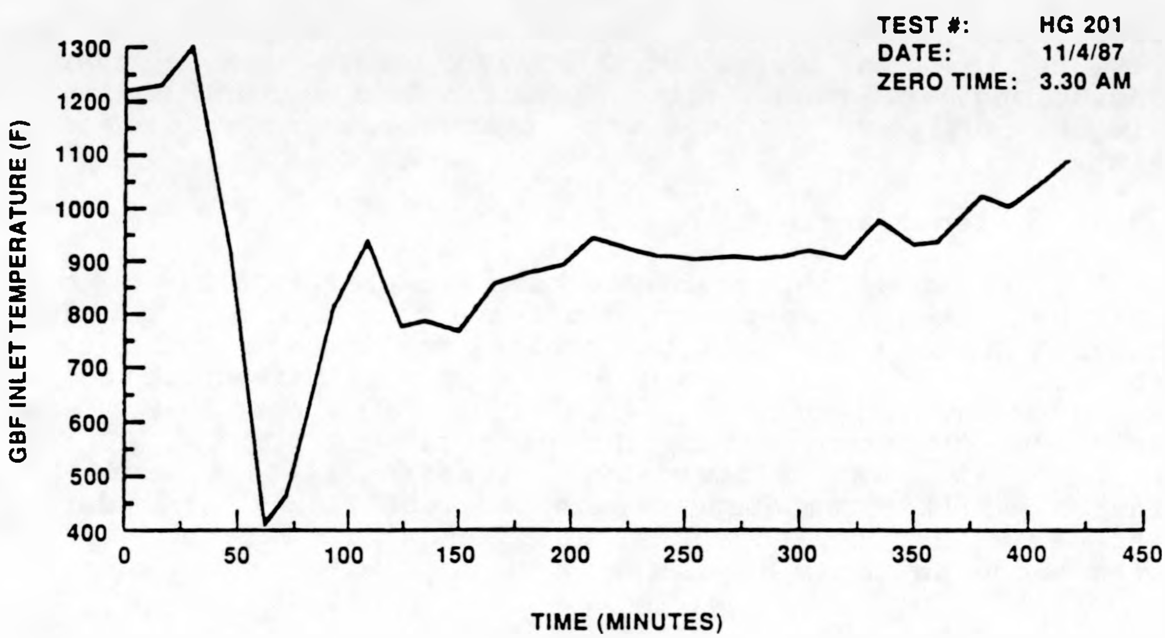



Figure 5-23. GBF Inlet Temperature Change vs. Time for HG-201

Based on operation during HG-203 and tests during HG-204, it was concluded that ash rates could be increased 4 to 6 times normal rates without causing filter problems.

During HG-203, a test was performed to determine how long the media circulation could be turned off during PFBC operation before filter pressure drop increase high enough to cause filter media bubbling (2 psi). Operation during this test is shown on Figure 5-24. At 38 minutes after zero hour of 1400 hrs. on 4/15/88, circulation was stopped. The boost blower was also shut down to preserve heat in the circulation system. At 49 minutes, the test was repeated.

Without media flow, ash builds up in the GBF causing the pressure drop to rise. The results showed that the GBF pressure drop would rise from 1.0 psi to 1.4 psi in 6-7 minutes without media circulation. Once circulation was restored the filter pressure drop returned to 1 psi in about 2 minutes. The results depended heavily on how much ash was being generated by the PFBC during the test. Grab sample measurements showed the ash loading was about 2000 ppmw just prior to the test which appeared moderately high for the NYU combustor. Therefore it was concluded that the GBF media circulation could be turned off for up to 7 minutes without filter problems.

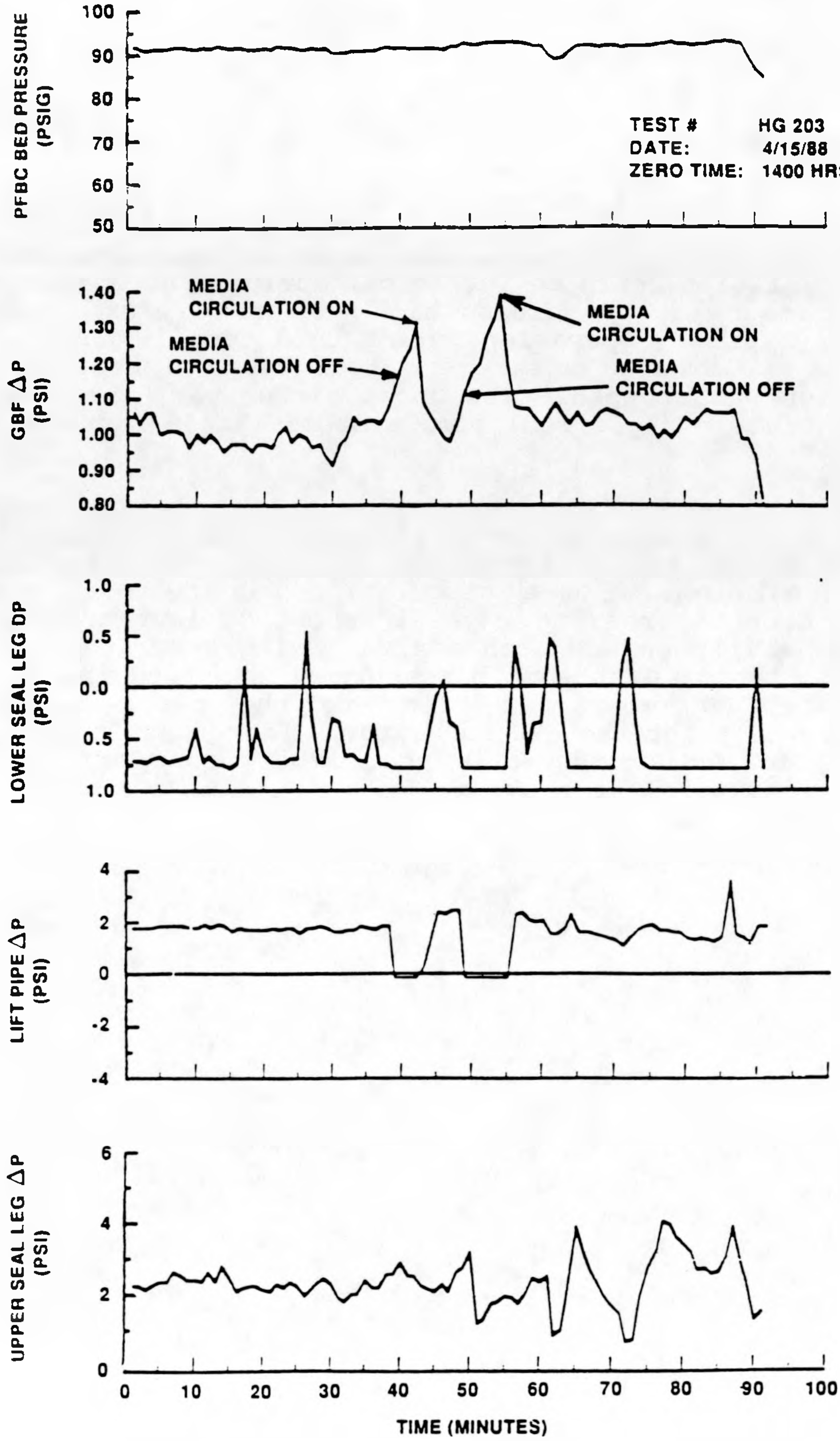



Figure 5-24. GBF Performance Curves for HG-203 Showing the Effect of Turning Off Circulation

## 6.0 CONCLUSIONS

The screenless granular bed filter has been successfully tested under high temperature, high pressure conditions at New York University. Kittanning bituminous coal containing 5-8% ash was fired in the PFBC. Sulfur sorbent was Ohio lime dolomite. Five performance tests were run at NYU. Data from two of these tests is reported in Tables 6-I and 6-II.

Table 6-I compares low pressure GBF data with the contractural targets and actual results. The early prototype filter had the same critical dimensions as the NYU test module but was tested at low pressure; thus, not all parameters are directly comparable. The low pressure performance tests and NYU tests including HG-204, used identical 2 mm media. These results compare closely except for pressure. Flows through the filters are only comparable when referenced to minimum fluidizing velocity of the media. Temperatures reported for the NYU tests are typical for near steady state conditions, and indicate the heat loss experienced across the test module. These heat losses were anticipated as a result of the small pilot-plant scale. The lower heat loss on HG-205 was due to higher gas flow. In a commercial-scale unit, the temperature drop across the filter would be much less. Filter pressure drop depends mainly on gas flows, ash concentration and media circulation rate. It is normally steady since the media is circulated and cleaned continuously.

**TABLE 6-I. GBF OPERATING PARAMETERS**

| PARAMETER | LOW PRESSURE GBF TESTS | CONTRACTUAL TARGET | REPRESENTATIVE NYU TESTS HG-204 | HG-205 |
|---|---|---|---|---|
| MEDIA SIZE | 2 | 2-3 | 2 | 3 |
| PRESSURE, PSIG | 1-4 | 90-135 | 90-115 | 105-115 |
| TEMPERATURE | | | | |
| GBF IN (TYP) | 1550 | 1550-1700 | 1550 | 1550 |
| GBF OUT (TYP) | -- | -- | 1350 | 1450 |
| FLOW | | | | |
| GAS TO GBF, LB/HR | 2000 | 7200-14,400 | 7200 | 12,515 |
| % MIN. FLUIDIZATION | 28-33 | 25-50 | 25 | 31 |
| FILTER PRESSURE DROP, IWC | 25-30 | -- | 24-30 | 18-22 |
| MEDIA CIRCULATION RATE LB/MIN | 20-40 | 20-40 | 20-70 | 20-70 |

Particulate sampling results are shown on Table 6-II. The amount of ash entering the filter could be roughly controlled by adjusting sorbent feed to the PFBC. For HG-204 inlet loadings below 200 ppmw at the inlet were suspect since this data was not consistent with ash loadings estimated by the ash collected by the GBF. Therefore, the averages shown for HG-204 are for 18 of 26 samples during 74 hours of operation where inlet loadings were greater than 200 ppmw. For HG-205 there was 17 samples collected over 47 hours of operation. Having gained a general idea of how sorbent rates affected filter ash loadings, the ash input rate was raised to a high level during HG-204 (2800 ppmw) to observe the filter response. There was only a slight rise in pressure drop across the filter (1-2 IWC) during this one-hour period.

**TABLE 6-II. PARTICULATE SAMPLING RESULTS**

| PARAMETER | LOW PRESSURE GBF TESTS | CONTRACTURAL TARGET | REPRESENTATIVE NYU TESTS HG-204 | REPRESENTATIVE NYU TESTS HG-205 |
|---|---|---|---|---|
| ASH CONCENTRATION | | | | |
| @ GBF INLET, PPMW | 1500-40,000 | -- | 80-2800 | 160-1600 |
| o AVG | -- | ≤ 1200 | 560 | 860 |
| @ GBF OUTLET, PPMW | 30-60 | 12 | 3-16 | 1-10 |
| o AVG | -- | - | 7 | 4 |
| EMISSIONS LB/$10^6$ BTU | -- | < .03 LB/$10^6$ BTU | .003-.013 | .001-.010 |
| o AVG | | (NSPS) | .008 | .004 |
| COLLECTION EFF % | 98-99.2 | 99 | 94.3-99.9 | 98-99.8 |
| o AVG | -- | - | 98.6 | 99.7 |
| ASH COLLECTION RATE LB/HR | 3-72 | 17 | .5-17 | 2-20 |
| % ASH IN MEDIA | .1-4.3 | 6 | .03-1.0 | .1-1.0 |

Outlet loadings meet New Source Performance Standards (NSPS) of .03 lb/million Btu and also will most likely meet turbine tolerance limits which actually can be more restrictive at large particulate sizes. With 3 mm media (HG-205) the outlet loadings were expected to increase over that measured at 2 mm (HG-204). One explanation for the higher efficiency of 3 mm media is that it was composed of alumina spheres ranging between 2.4 and 4.0 mm. The 2 mm media was more uniform at 1.9 to 2.0 mm. More opportunity for ash collection (by impaction, etc.) could exist with the wider size range of media than with an evenly sized media bed. Another explanation is that the higher gas velocity permitted by the larger media increased particulate collection by impaction.

The percent of ash in the media compares the ash collection rate to the media circulation rate. Although anticipated at NYU, it was not possible to circulate media slow enough to challenge the contractural target of 6% ash in the media. Other testing on this parameter was carried out at Combustion Power Company and demonstrated 6% as achievable (Wilson, 1987). At NYU, some experiments involved no media circulation for various time periods, but this does not directly correlate to this parameter.

Other operating characteristics of the GBF are:

- Media circulation rates were close to predicted values based on the mathematical model of the lift-pipe.

- The media/ash separation in the de-entrainment vessel appeared adequate. Apparently, the media was cleaned to the same degree on each circulation.

- There was no measurable breakage or attrition of media. Used media contained very little fractured material.

- Rapid pressure changes were tolerated although the upset would change the circulation rate and alter the desired pressure profile. In one special case, a rapid loss of pressure shut down the filter. These problems were typically a mere nuisance and could be accounted for in a control system and by careful PFBC system design and operation.

- Rapid temperature changes were tolerated. In HG-204 a drop of 912°F from 1612°F in 12 minutes was followed by a 400°F rise in 20 minutes between 644°F to 1050°F. Inlet temperatures to 1625°F were recorded. There were no problems due to temperature upsets which did occur during every test. Temperature changes to 200°F/hour were requested.

- Filter media bubbling (fluidization) occurred in some NYU tests immediately following a PFBC upset. These upsets which resulted in surges of pressure level and ash rate were compensated for by lowering the filter capacity to 25-31% minimum fluidization. Capacity near the original level of 50% minimum fluidization may have been possible without such severe PFBC upsets.

- Plugging of the media valve with ash resulted in occasional shutdowns. In the last test, the problem was isolated to flue gas condensate and boost blower oil in the media valve control air; an easily solved problem in future designs by heating and/or filtering injector gas.

- Heat exchanger fouling upstream of pressurized baghouse needs to be addressed. There are many conventional solutions.

- Refractory wear, mainly on the lift-pipe was solved with silicon carbide lined transport pipe. Possibly an overkill, but one of a myriad of solutions.

- Alkali (sodium and potassium) were reduced to very low levels (averaging less than 10 ppbw), but this could be due to alkali condensation as well as absorption.

- Auxiliary equipment: Baghouse, lockhoppers, boost blower, etc. operated with minimal problems.

- Media circulation could be stopped and restarted when desired.

In summary, stable GBF operation was achieved downstream of a coal-fired PFBC simulating a gas turbine based power plant. Particulate removal to below NSPS and turbine tolerance limits was demonstrated.

## 7.0 REFERENCES


Guillory, J.L., et al, Granular Bed Filter Development Program, Phase II, DOE Report DOE/ED/10373-T10 (Combustion Power Company, Menlo Park, CA) (May 1983)

Haas, W.J., Jr. and D.E. Eckels, Real Time Monitoring of Sodium and Potassium Concentrations in Flue Gas Produced During July and August 1987 Coal Combustion/Hot Gas Clean Up Studies at the Grimethorpe (England) PFBC Establishment, U.S. Department of Energy Research and Development, Report IS-4956, 1988.

Haas, J.J., Jr. and D.E. Eckels, S.H.D. Lee and K.M. Myles, Hot Gas Alkali Determination, Proc. 6th Annual Contractors Meeting on Contaminant Control in Coal-Derived Gas Streams, (K.E. Markel and D.C. Cicero Eds), June 1986, 343-353. DOE/METC-86/6042.

Zakkay, V., et al, Construction and Utilization of a Large Scale Coal-Fired PFB Facility, Fossil Energy, Report No. DOE/MC/14322-1800 (DE 850136850), August, 1985.

General Electric, PFB Coal-Fired Combined Cycle Development Program, May, 1980, FE-2357-66.

METC, Physical Gas Clean Up Technology Status Report, DOE/METC-86/0239, March, 1985.

Zakkay, V., H. Clisset, A. Ganseh, P. Radhakrishnan and K. Sellakumar, Sulfur retention of North Dakota (Beulah) lignite ash in PFBC, Proc. Int. Cong. on Gas Turbines, Amsterdam, June, 1984.

Grace, D.S., et al, Electrostatic Enhancement of Moving-Bed Granular Filtration, 2nd Symposium on the Transfer and Utilization of Particulate Control Technology (July 1979).

## SECTION III

COMMERCIAL-SIZE

GRANULAR BED FILTER

FOR

330 MW

PHILIP SPORN PLANT PFBC REPOWERING PROJECT

NEW HAVEN, WV

## 1.0 GENERAL APPROACH

The concept of a coal-fired gas turbine in a combined cycle power plant is an advanced technology for producing electricity from coal. Coal is burned at 10-20 atmospheres in a pressurized fluid bed combustor (PFBC) to produce steam to drive a steam turbine while the high temperature, high pressure (HTHP) flue gas drives a gas turbine. This results in a highly efficient, combined cycle power plant. To protect the gas turbine, particulate control is necessary and alkali reduction desirable. Two stages of cyclones are often proposed to protect the gas turbine but particulate and alkali loadings could still be detrimental. Furthermore, particulate loadings cannot be reduced to below New Source Performance Standards (NSPS) levels with cyclones. Advanced HTHP particulate control devices such as the granular bed filter could better protect the gas turbine from particulate and meet NSPS levels; thus eliminating the need for particulate removal downstream of the gas turbine. There is also some potential for lowering alkali levels.

A commercial-scale design of a granular bed filter (GBF) is proposed based on the Philip Sporn PFBC Repowering Project. This is a 330 MW net power plant by American Electric Power (AEP) and is located in New Haven, WV. Scheduled start-up is March 1, 1996. The design proposed in this document is in response to a Memorandum of Technical Requirements prepared by Stone & Webster Engineering Corporation, Boston, Massachusetts. Briefly, this memorandum specifies a filter gas flow of 2,885,000 lb/hr at 1550°F and 215 psia with a dust loading of 500 to 2500 ppm. Design maximum for pressure and temperature are 275 psia and 1640°F. Filter outlet loading is limited to 25 ppm (operating) or 29 ppm (design) based on NSPS limits and certain coal and operational data. Further limits are placed on particulate size entering the turbine and filter pressure and temperature drop (5 psi and 4°F, respectively). See Tables 1-I and 1-II for details.

### 1.1 GBF Configuration:

In all the work completed to date, the GBF has been separated from the combustion equipment. This approach to packaging has advantages in the developmental and commercial scale because the combustion equipment (PFBC) and the granular bed filter can be isolated and accessed separately for inspection and maintenance. This was the basis for the filter configuration developed at Combustion Power Company and proven at New York University. Considerations were given to installing the GBF device inside the PFBC containment vessel as requested by the Memorandum of Technical Requirements. In addition to complicating the access to equipment which could affect availability, the containment vessel did not contain enough room for the GBF elements in the configuration developed to date.

## TABLE 1-I

## SUMMARY OF GRANULAR BED FILTER PERFORMANCE REQUIREMENTS

| | Operating | Design Maximum |
|---|---|---|
| Filter Inlet Temperature, F | 1550 | 1640 |
| Filter Outlet Temperature, F | (1) | 1640 |
| Filter Inlet Pressure, psia | 215 | 275 |
| Filter Differential Pressure, psi | (2) | 5 |
| Combustor Gas Flow, lb/hr | 2,944,000 | |
| Filter Inlet Gas Flow, lb/hr | 2,885,000 | |
| Inlet Dust Loading, ppmw (3) | 500 (3) | 2500 |
| Outlet Dust Loading, ppmw | 25 (4) | 29 (4)(5) |
| PFBC Vessel Internal Pressure, psia | 232 | 275 |
| PFBC Vessel Internal Temperature, F | 575 | 675 |

(1) Heat loss from filter and ductwork shall be kept as low as reasonably possible and shall not exceed 150 $Btu/hr/ft^2$.

(2) Filter differential pressure shall be kept as low as reasonably possible and shall not exceed 5 psi.

(3) Refer to Table 1-II for particle distribution entering the granular bed filter.

(4) 8 ppm limit for 5 micron and larger and 1 ppm limit for 10 micron and larger.

(5) 29 ppmw is based on NSPS limit of .03 $lb/10^6$ Btu. Approximate conversion based on:
HHV of coal = 12,223 Btu/lb
1 lb coal - 12.5 lb combustion gas
ppm = parts per million by mass

## TABLE 1-II

## PARTICLE SIZE DISTRIBUTION ENTERING GRANULAR BED FILTER

| Particle Size Range (micron) | Mean in Size Range (micron) | Fractional Distribution |
|---|---|---|
| 1 - 1.4 | 1.2 | 0.197 |
| 1.4 - 2.0 | 1.7 | 0.389 |
| 2.0 - 2.8 | 2.4 | 0.291 |
| 2.8 - 4.0 | 3.4 | 0.090 |
| 4.0 - 5.6 | 4.8 | 0.020 |
| 5.6 - 8.0 | 6.8 | 0.007 |
| 8.0 - 11.3 | 9.65 | 0.007 |

| | |
|---|---|
| Mean Particle Diameter, micron | 2.1 |
| Estimated dust loading to HTHP filter, ppm (Based on 15,000 ppm bed elutriation fraction) | 500 |
| Primary cyclone differential pressure, psi (approximate) | 2 |

Increasing the size of the PFBC containment vessel was not pursued vigorously because of the logistics perceived in 1) locating and supporting the filtration elements and 2) moving filter media to and from them in this large (60' diameter) enclosure. Further complicating the study was the requirement for an effective 23 psig external pressure on each element which we interpreted as requiring design to the ASME Pressure Vessel Code Section VIII, Division I according to the Memorandum of Technical Requirements. This meant that each GBF element needed to be enclosed in an internally insulated carbon steel vessel. Even without the ASME code as a complication, there was only space enough in the AEP proposed PFBC containment vessel for about 1/2 of the GBF elements needed.

As a result of this preliminary study, a decision was made to consider separate containment vessels for the GBF. The testing at New York University formed the basis for our approach.

Three configurations of packaging were considered for the GBF elements as follows:

Case 1:

Emulating NYU, 128, 5' diameter filter elements could operate at about the same relative capacity achieved at NYU which is about 35% minimum fluidization velocity. (The filter element tested at Combustion Power (Guillory, 1983) and NYU was 5' diameter.) Eight containment vessels would be required, each containing 16 filter elements. The eight filter vessels would be about 14'-0 O.D. and would package in two groups of four each. Each group of four vessels would require a plot of land about 30' square and 155' tall. We felt that the plot plan requirement was high and sought reduction at the expense of height.

Case 2:

A 64 element approach was considered, but the elements would have been 6'-10" diameter. It was felt we should maintain a filter element size closer to the size tested at NYU.

Case 3:

An 80 element approach fell very close to the element size and conditions tested at NYU. This could be accomplished in four containment vessels of 20 elements, each in a plot plan 38' square. This approach is presented.

In Table 1-III below, the capacity parameters are compared for these applications:

**TABLE 1-III**

**Operating Conditions**

| | NYU Test | SPORN Proposal |
|---|---|---|
| Media Diameter Size, mm | 3 | 4 |
| Media Depth, inches | 30 | 40 |
| Face Velocity, fpm | 61 | 72 |
| % Min. Fluidization | 31 | 37 |
| Filter Diam. | 5'-0" | 6'-0" |
| Temperature, °F | 1550 | 1550 |
| Pressure, psia | 125 | 215 |
| Single Element Capacity, lb/hr | 12500 | 36000 |

The filter element for Sporn was sized based on operating conditions instead of design conditions as this resulted in the most conservative design. At the design temperature and pressure for Sporn (1640°F, 275 psia) the filter element will operate at 35% minimum fluidization instead of 37% at operating conditions.

## 2.0 GBF DESIGN

Presented are the process flow diagram for the GBF, a P&ID, general arrangement drawing and filter element detail drawing.

The process flow diagram is based on the operating values for temperature and pressure. One of four filter containment vessels is shown. The lift pipe is common to all four containment vessels as is the de-entrainment vessel, heat exchangers and boost blower. Particulate removed in the four GBF pressure vessels moves with the media to the single, centrally located lift pipe. Media and ash separate in the de-entrainment vessel. The clean media flows by gravity back to the filter vessels while the ash-ladened lift gases flow to the regenerative heat exchanger. Here the gas is cooled to 400-500°F for ash removal in a standard, high pressure baghouse. Transport gases are then further cooled to below dew point at 250-300°F to be recycled by the boost blower. The gas utilized for media transport is filtered flue gas that migrates from the filter into the media circulation system. The coalescing filter upstream of the boost blower protects the boost blower by removing excessive moisture and by monitoring baghouse efficiency. Circulation gases are reheated by the regenerative heat exchanger and distributed to media circulation system. Gases are bled from the circulation system just downstream of the regenerative heat exchanger to adjust the pressure profile in the filter. This assists the removal of ash as follows: By venting flue gas downstream of both the upper and lower seal legs, the pressure in the entire circulation system (lift pipe to baghouse) can be maintained slightly less than the pressure in the filter. Under this condition, leakage gas moves down the lower seal leg which enhances flow of the ash and media out of the filter element and into the lift pipe.

The de-entrainment vessel is arranged to operate with a small amount of media overflowing to the media make-up hopper. The media injector valve from the media make-up hopper can be run periodically or continuously at a low level to maintain a full charge of media in the de-entrainment vessel surge volume. This technique has been employed by Combustion Power in the industrial boiler version of the GBF: Electroscrubber Filter (Grace, 1979). The bleed gas utilized to control the pressure profile is vented to the filter outlet. This allows utilization of the energy in this small gas stream. At New York University, this gas was vented to atmosphere.

Instrumentation and control is shown on the P&ID. The microprocessor-based control concept utilizes information learned from testing at New York University. For example, the speed of the boost blower will be a function of temperature and pressure in the lift pipe.

The general arrangement drawing shows how the filter elements are arranged in the containment vessels. Five levels of four filter elements are connected to a single, centrally located, inlet gas distribution duct. Media is distributed to the filter elements from a distribution hopper at the top of the filter vessel much like the arrangement utilized in the low pressure test element developed and tested at Combustion Power in the early 1980's (Guillory, 1983). The media distribution ducts are 4" diameter and are supported and guided from the central gas distribution duct. Once the clean media enters the filter element, it is further distributed by a central annulus and peripheral pipes identical to the manner utilized at New York University. Ash-laden media is removed from the filter elements by 4" diameter ducts utilizing the same support and guiding arrangement as proposed for the clean media distribution ducts. At the lower flexible seal, media enters a mass flow hopper with each media exit pipe attached to a cylinder to hold these pipes at equal distance from the hopper centerline. Even movement of media through the mass flow hopper equalizes media movement through each filter element.

The flexible seal is an extension of the design utilized at NYU. A metal bellows provides the seal with a packing gland that also serves to center the device as a back-up. Expansion is expected to be about 18" from cold to hot and the expansion joint will be installed preloaded at least 9". This is the same approach used at NYU.

Filter elements will be supported by rods attached to the top head of the containment vessel similar to the configuration employed at NYU. These rods are arranged in two concentric circles with eight rods in each circle. In this manner, each filter element will be supported in four locations whereas only three support locations per element were utilized at NYU. Support rods will be Haynes 556, designed for 2500 psi stress based on 1% creep in 100,000 hours.

Because the central ducting will heat and cool rapidly with changes in PFBC off gas temperature and the supports will not, expansion joints are located in the central gas duct between each level of filter elements. If necessary, these expansion joints can be cooled by GBF system bleed gases.

Seal legs and lift pipe segments are lined with 1" thick silicon carbide sleeves backed up with a combination of light weight and medium weight refractory insulation. Segment length is proposed at 10'.

The internals of the media valve (Figure 2-5) and de-entrainment vessel (Figure 2-6) are scaled-up versions of the designs proposed for other high temperature, high pressure applications. Silicon carbide liners are used in the media valve in the expected wear areas. Abrasion resistant castable refractory is utilized in the upper de-entrainment vessel where it performed well at New York

University. The lower de-entrainment vessel is lined with high alloy steel backed with ceramic fiber insulation. The stainless steel provides a surface that media will move over with less friction than refractory.

Baghouse, heat exchangers and the boost blower package are described by the specifications included in the next section.

**TABLE 2-I**

**Materials**

| Item | Material |
|---|---|
| Filter Containment Vessel | 2" SA-515-70 |
| Containment Vessel Insulation | 6" Thick Ceramic Fiber |
| Filter Vessel Internals | |
| Gas Distribution Duct | Incoloy 800 HT |
| Media Distribution Hopper | Incoloy 800 HT |
| 4" Media Distribution Pipes | Incoloy 800 HT |
| Expansion Joints | Inconel 600 |
| Element Support Rods | Haynes 556, 3 1/4" & 4-1/2" DIA. |
| Media | 4 MM Diam, Alumina |
| Filter Vessel Outlet Shroud | Incoloy 800 HT |
| Mass Flow Hopper | 7/8" SA-515-70 |
| • Liner | 3/16" Incoloy 800 HT & Ceramic Fiber Insl. |
| Seal Legs & Lift Pipes | 1" Silicon Carbide Hard Face 5"-6" Insulation |
| GBF Elements | See Drawing 56213 |
| Media Valve | See Typical Drawing |
| De-entrainment Vessel | See Typical Drawing |
| Heat Exchangers | See Specification |
| Baghouse | See Specification |
| Boost Blower | See Specification |
| Ducting | 3/4" SA-285-C |
| • Liner | 3/16" Incoloy 800 HT over 6" Ceramic Fiber Insulation. |

| | ① PRIMARY CYCLONE EXHAUST | ② GBF INLET | ③ LOWER SEAL LEG | ④ LIFT PIPE SUPPLY | ⑤ INJECTOR VALVE | ⑥ LIFT PIPE | ⑦ INJECTOR VALVE | ⑧ COUNTER-FLOW AIR | ⑨ RETURN LEG | ⑩ DEV OUTLET | ⑪ EXCH #1 INLET GAS | ⑫ EXCH #1 OUTLET GAS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FLOW | | | | | | | | | | | | |
| SOLID, LB/MIN | 120 | 30 | 630 | | | 2520 | | | 600 | 119 | 119 | 119 |
| LIQUID, LB/HR | | | | | | | | | | | | |
| GAS, LB/MIN | 48083 | 12021 | | 700 | 20 | 700 | 10 | 20 | 10 | 770 | 770 | 770 |
| GAS, ACFM | 168525 | 42167 | | 1890 | 80 | 2383 | 28 | 37 | 33 | 2584 | 2460 | 1240 |
| TEMPERATURE, F | 1550 | 1550 | 1542 | 1184 | 1184 | 1484 | 1184 | 1184 | 1441 | 1444 | 1357 | 450 |
| PRESSURE, PSIA | 215.0 | 214.7 | 214.7 | 218.8 | 218.3 | 213.7 | 218.8 | 218.8 | 214.0 | 210.1 | 209.8 | 208.0 |

| | ⑬ BAGHOUSE OUTLET | ⑭ EXCH #2 OUTLET GAS | ⑮ COALESCING FILTER OUTLET | ⑯ BLOWER OUTLET | ⑰ EXCH #1 CLEAN GAS INLET | ⑱ EXCH #1 CLEAN GAS OUTLET | ⑲ GBF EXIT | ⑳ EXCH #2 WATER IN | ㉑ EXCH #2 WATER OUT | ㉒ ASH | ㉓ BLEED LINE | ㉔ GBF OUTLET |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FLOW | | | | | | | | | | | | |
| SOLID, LB/MIN | | | | | | | | | | 119 | | |
| LIQUID, LB/HR | | | | | | | | 31350 | 31350 | | | |
| GAS, LB/MIN | 770 | 770 | 770 | 770 | 770 | 770 | 12011 | | | | 60 | 48083 |
| GAS, ACFM | 1235 | 977 | 980 | 928 | 928 | 2186 | 42128 | | | | 118 | 168860 |
| TEMPERATURE, F | 440 | 250 | 250 | 250 | 350 | 1181 | 1542 | 80 | 130 | 400 | 1190 | 1542 |
| PRESSURE, PSIA | 207.8 | 207.3 | 206.3 | 218.0 | 217.8 | 217.1 | 214.0 | 100.00 | | 207.8 | 214.0 | 213.2 |

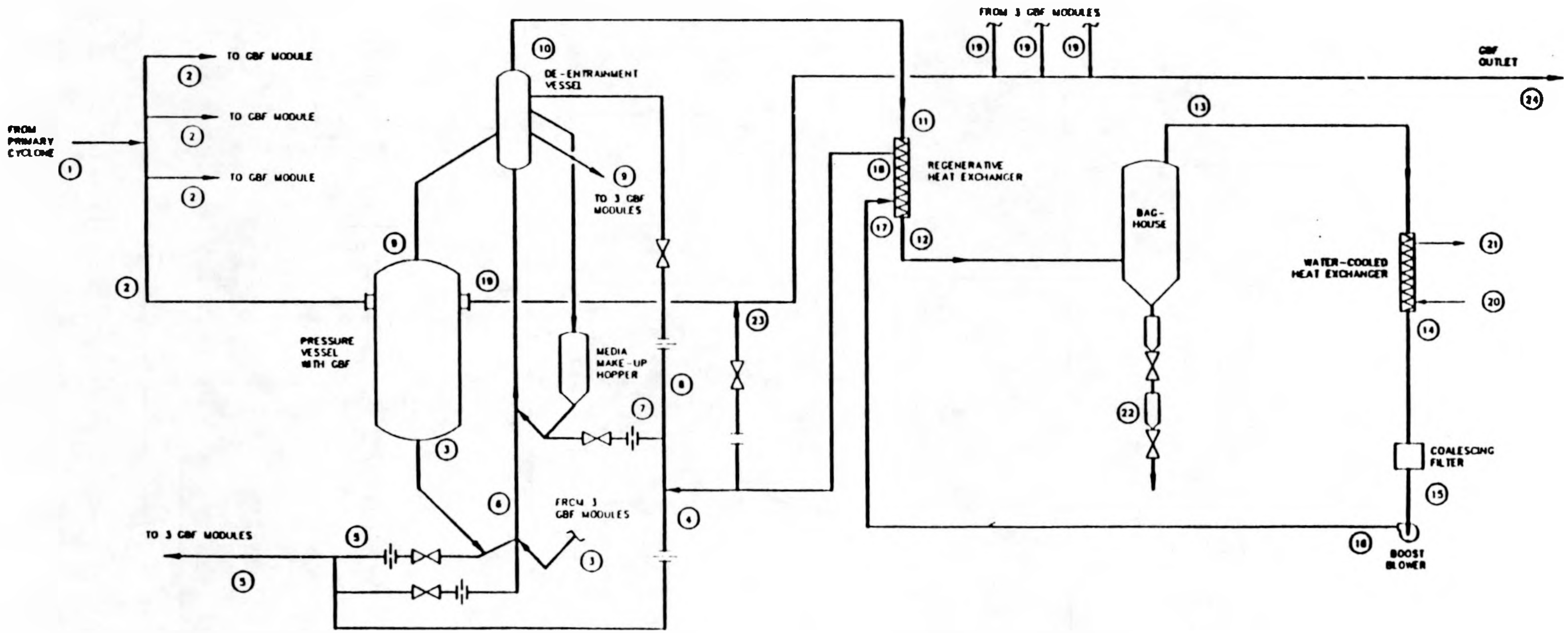



**Figure 2-1 Process Flow Diagram**

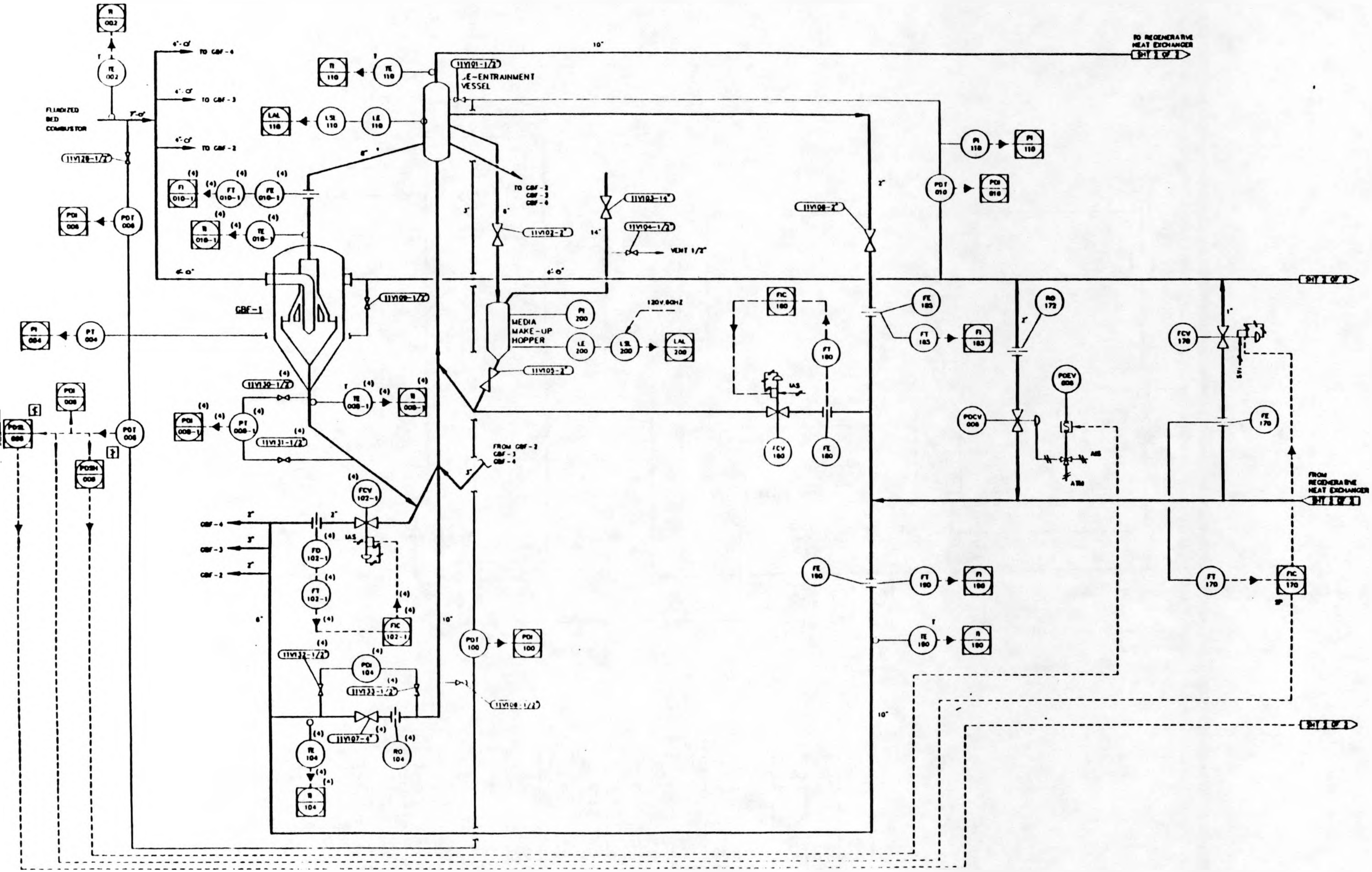



**Figure 2-2. Piping and Instrument Diagram**

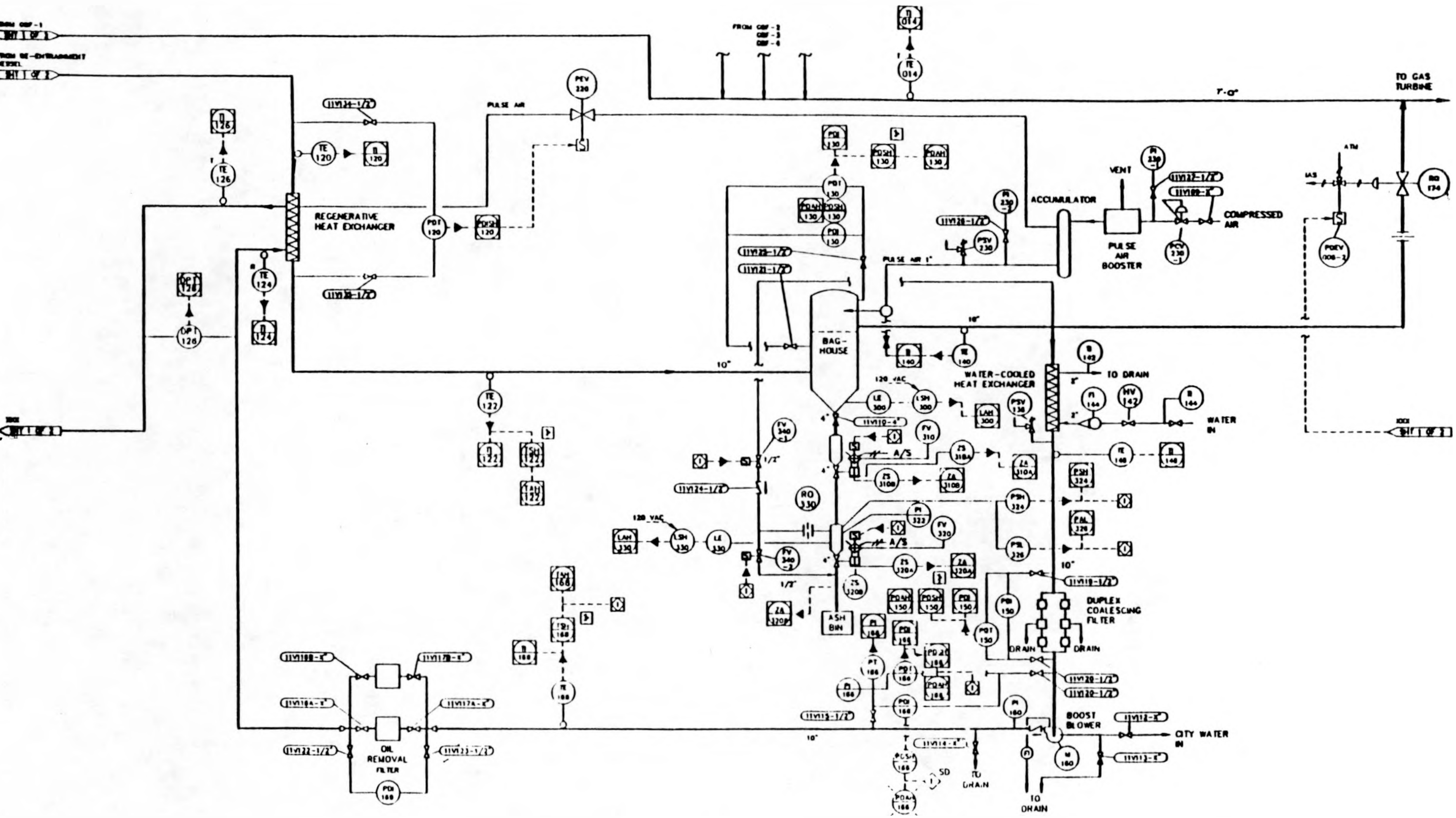



**Figure 2-2. Piping and Instrument Diagram (Cont.)**

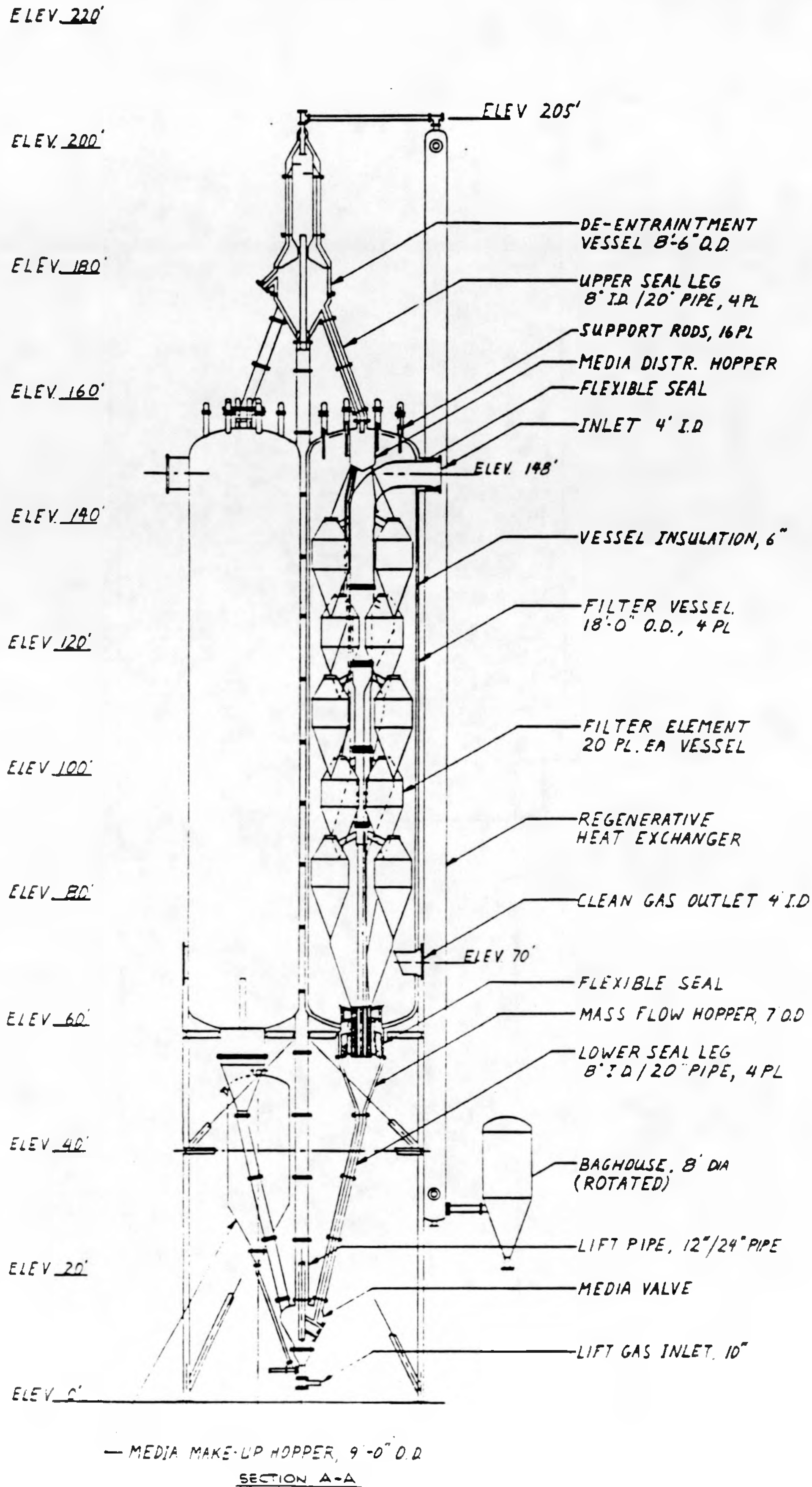



Figure 2-3. General Arrangement

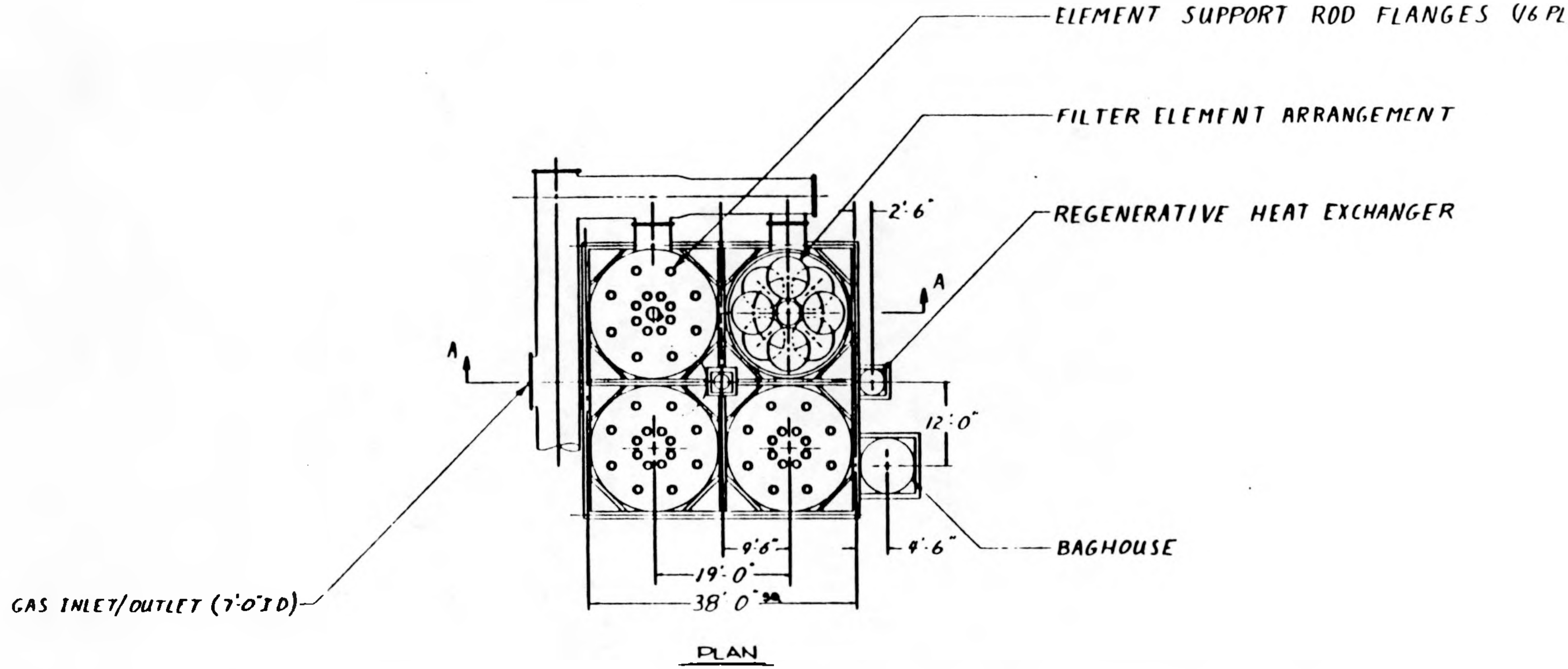



Figure 2-3. General Arrangement (Cont.)

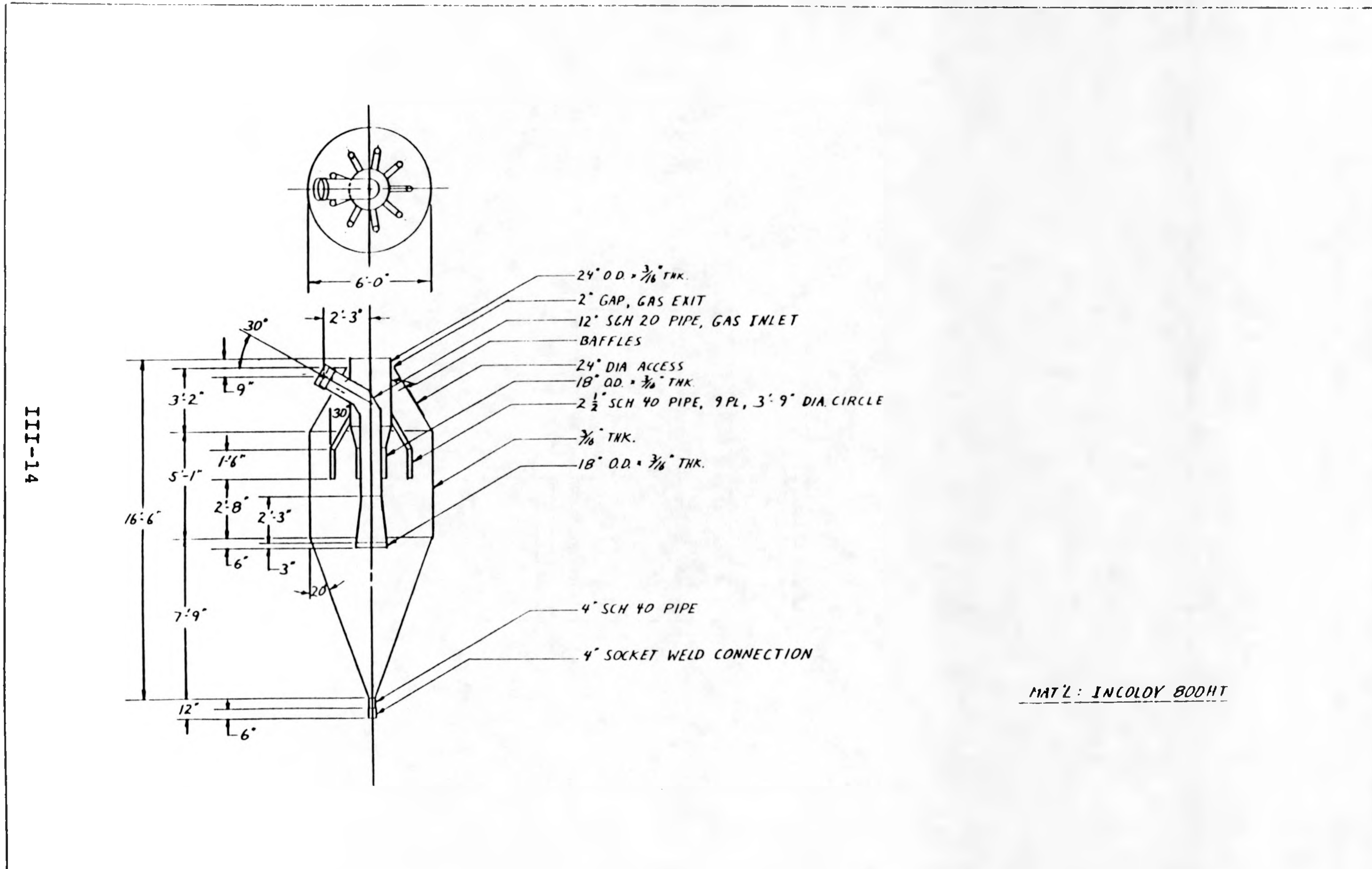
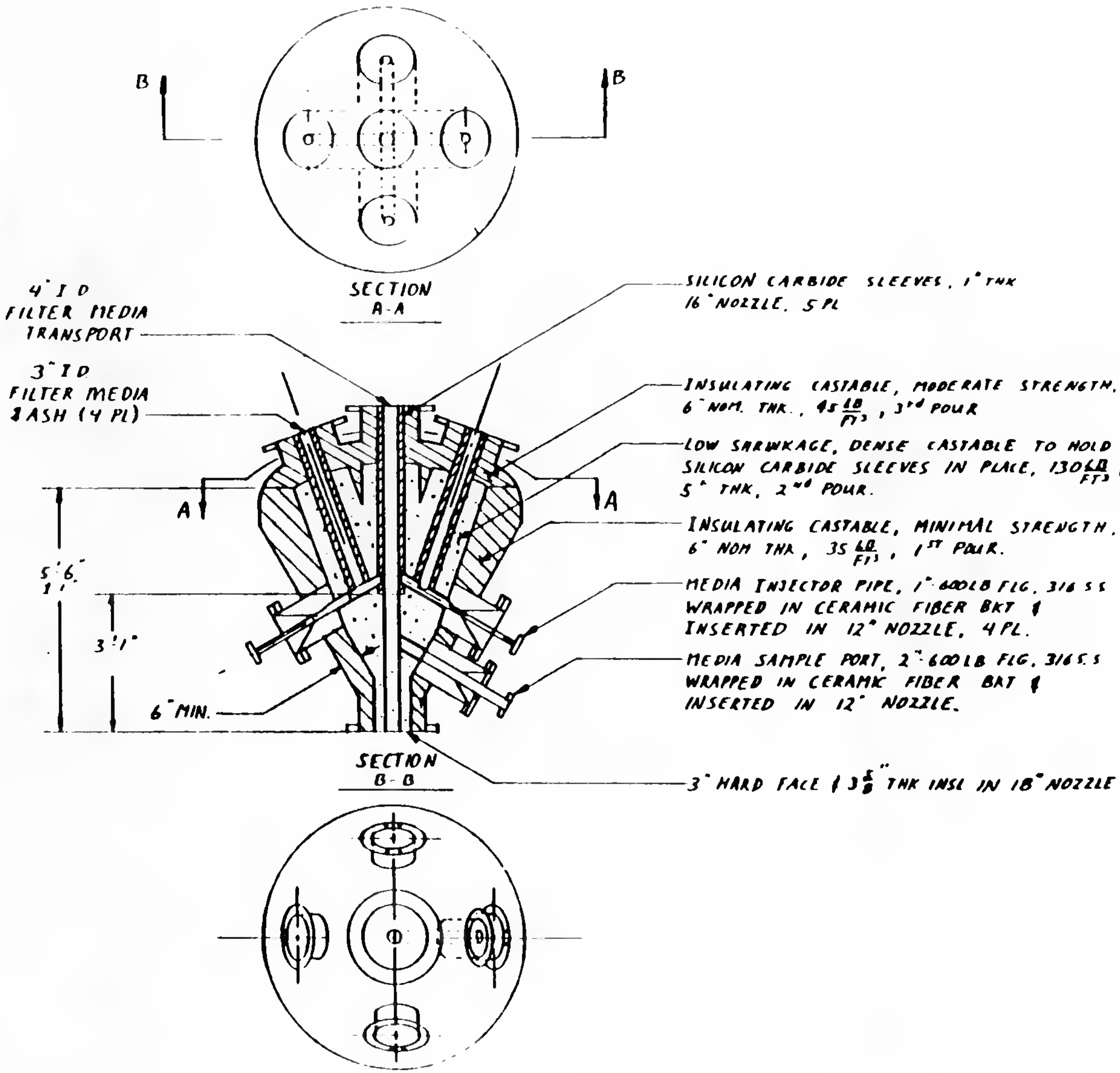
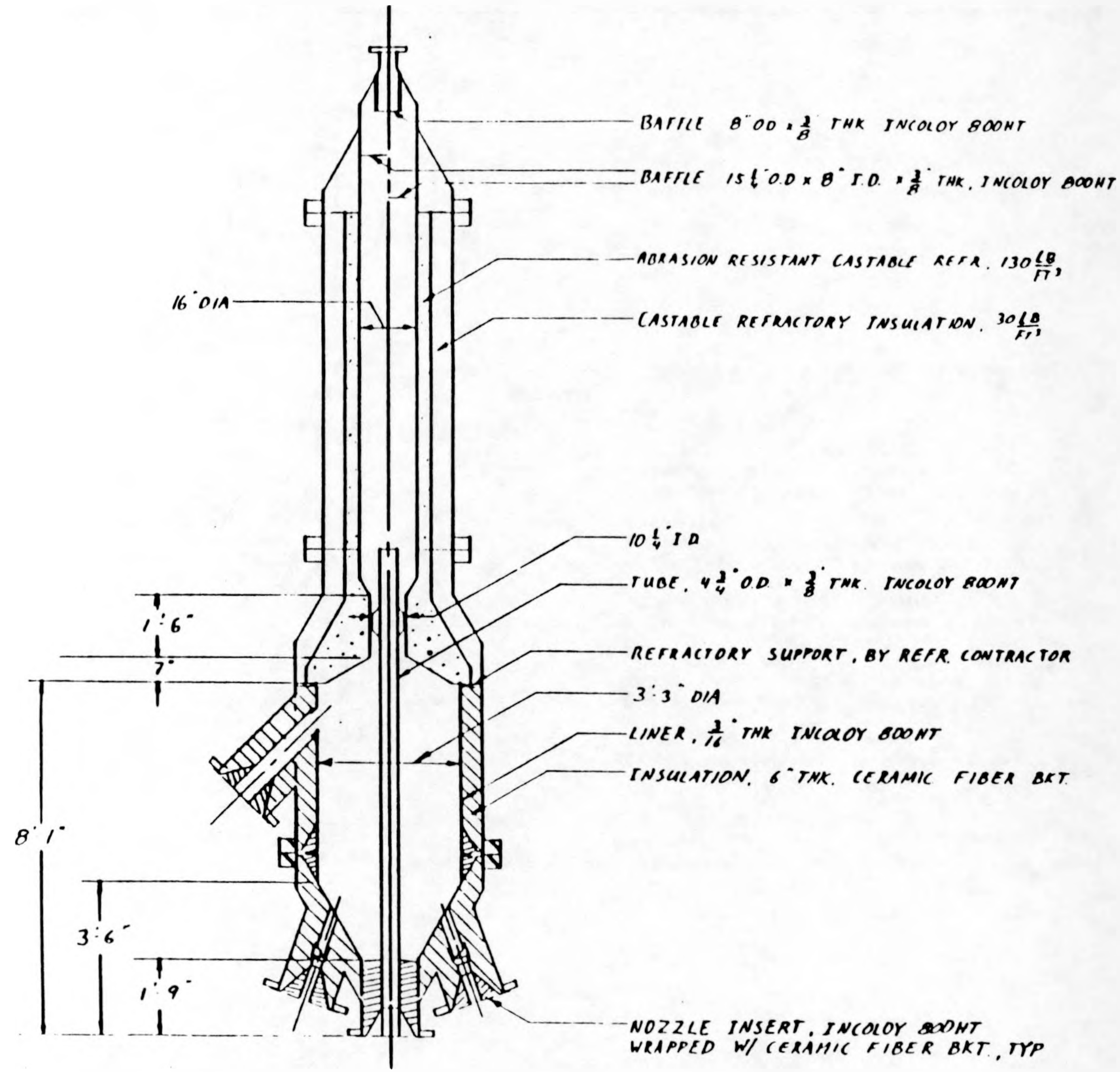



**Figure 2-4. Filter Element**




NOTE: DIMENSIONS NOT APPLICABLE TO SPORN DESIGN

Figure 2-5. Media Valve Refractory




NOTE: DIMENSIONS NOT APPLICABLE TO SPORN DESIGN

**Figure 2-6. De-Entrainment Vessel Refractory**

# 3.0 OPERATION AND MAINTENANCE

## 3.1 Start-Up

The start-up requirements for the granular bed filter are similar to those of the pressurized fluidized bed combustor. A heat-up rate of 200°F/hr should not be exceeded. This rate generally matches refractory suppliers recommendations for heating refractory and promotes even thermal stress free expansion of the filter media containment steelwork and alloy supports.

In the event the temperature does rise quickly as described in the Memorandum of Technical Requirements (from 918°F to 1134°F in 63 sec.), it will be desirable to hold at the higher temperature to maintain the average temperature rise of 200°F/hr.

The GBF can be preheated with the same start-up burner gases utilized to preheat the PFBC. This was the mode of preheat during the 3000 hours of low-pressure GBF testing at Combustion Power (Guillory, 1983). During preheat, media should be circulated at near the maximum rate (2400-3000 lb/min) to bring heat into the media circulation system as fast as possible. Baghouse and other ash handling equipment that is heat traced must be warmed prior to PFBC start-up to minimize condensation in these areas. For the same reason, the water-cooled heat exchanger should not be brought on line until the heat exchanger exit temperature exceeds 250°F. The circulation system is considered heated to above condensation temperature when the media reservoir (part of the de-entrainment vessel) exceeds 550°F.

Pressure during heat up is immaterial as long as the gas flow does not exceed 50% of minimum fluidization. Information on these values which change with pressure and temperature can be built into the microprocessor-based control system. The tests at NYU showed that the manually controlled circulation system was stable if pressure changes were no greater than 2 psi/minute. At higher rates of pressure change, operator intervention was required to hasten the return to equilibrium. It is expected for the commercial-size unit that a similar limit will exist; although with the different size media and seal legs and with automatic control, the value will be higher. Nevertheless, pressure surges can be accommodated as discussed under "transient upsets".

The transition from gas or oil fired preheat burner to coal firing should take place at about 35% minimum fluidization to guard against the possibility of unexpectedly high particulate loadings due to combustion or feed system transients. As system pressure, temperature and flowrate near steady-state desired values, the media circulation rate can be slowed to the desired rate.

### 3.2 Normal Operation w/Load Changes

The media circulation rate (2400 lb/min) is conservatively designed to operate with an ash loading of 1% by weight, ash in media, at an inlet loading of 500 ppmw. This will allow recovery from a short term upset condition of higher inlet loading due to a cyclone malfunctioning. Testing at NYU was up to 2%. Previous cold flow tests, at Combustion Power, showed a granular bed filter is capable of operating with ash loadings as high as 6% ash. (In this case, an ash inlet loading of 2500 ppmw would result in a 6% loading of ash in media at a circulation rate of only 2000 lb/min.) Operationally, if the ash loading to the filter increases, the pressure drop through the filter would start to increase, and then to compensate for the additional ash loading, the media circulation rate is increased. Figure 2-1 shows the lift pipe pressure drop as a function of circulation rate. The test at NYU showed that it was also possible to stop the media for short periods of time to allow for minor adjustments.

The circulation rate is automatically controlled by the quantity of gas used in the media valve injector. The solids flow meter and the lift pipe pressure drop serve as redundant methods for determining media circulation rates. The computer will be programmed to monitor and control the circulation rate of media through each filter vessel.

### 3.3 Shutdown

Generally, the same requirements for temperature and pressure change apply to start-up and shutdown. If pressure changes are limited to a very low rate (at NYU this was 2 psi/min) and temperature changes to 200°F/hr the circulation system will respond with considerable ease, and thermal stresses will be minimized. Higher rate changes in pressure and temperature can be accommodated as routinely occurred during NYU operations without major or lasting problems as will be discussed in the section on transient responses. Automatic controls will adjust boost blower speed and media valve injector air to maintain proper lift pipe flows. The bleed system control valve will adjust to maintain the proper pressure profile throughout the media circulation system. After fuel is shut off to the fluidized bed combustor, media should be circulated at least once through the filter to remove ash collected on the media. This will take about 13 hours at a circulation rate of 2400 lb/min.

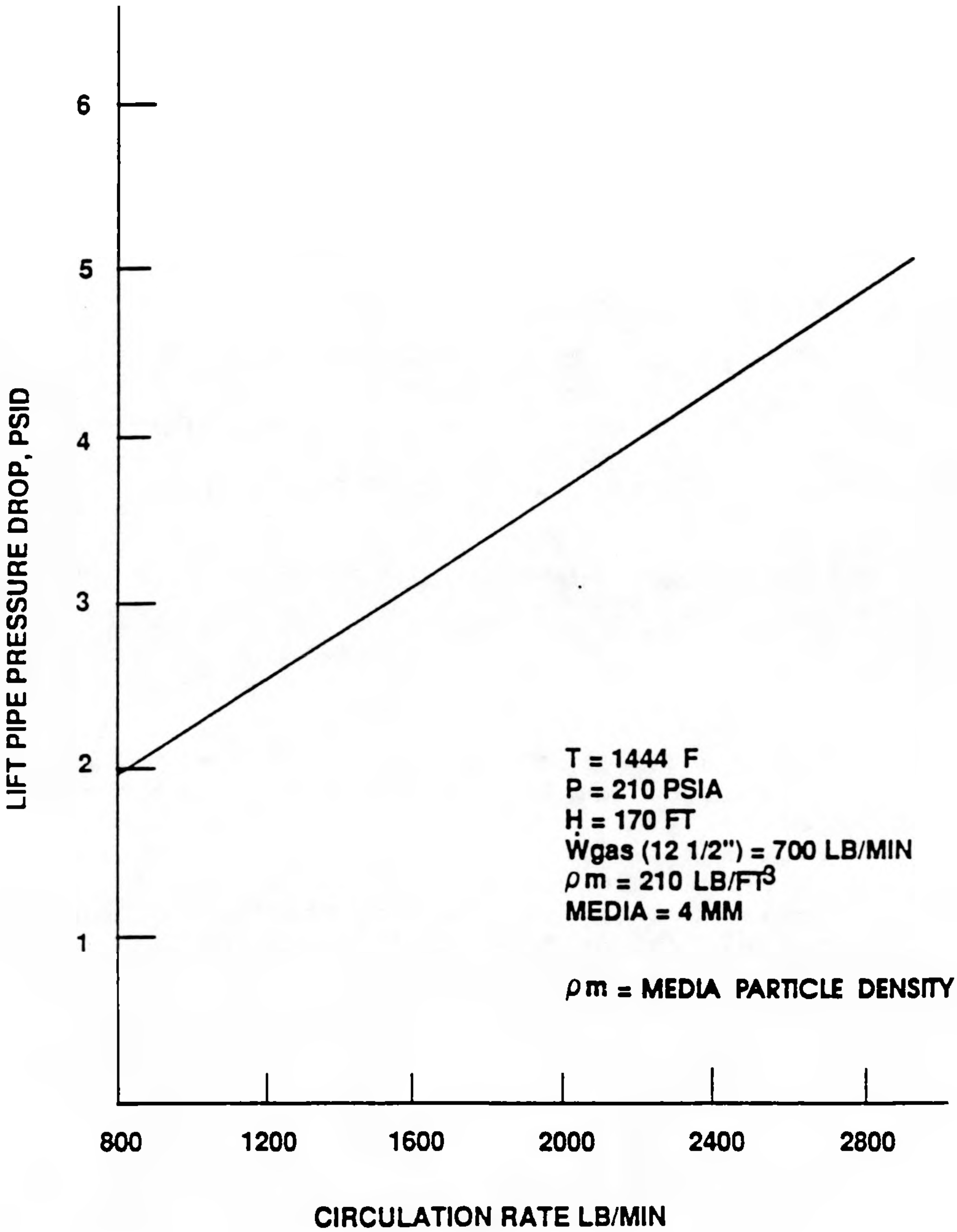



Figure 3-1. Lift Pipe Response to Media Circulation Rate

## 3.4 Transient Upsets

Data on operating transients was estimated by American Electric Power (AEP) based on the Tidd PFBC plant and included in the Memorandum of Technical Requirements by Stone and Webster. AEP assumed this data was conservative if the differentials were assumed for Sporn. These transients are summarized in Table 3-I, below.

**TABLE 3-I**

**OPERATING TRANSIENTS**

| Parameter | Differential | Time |
|---|---|---|
| Pressure(1) | 174 psig to 29 psig = 145 psi (drop) | 450 secs. |
| Pressure(1) | 167 psig to 102 psig = 65 psi (drop) | 50 secs. |
| Temperature(2) | 918°F to 1134°F = 216°F (rise) | 63 secs. |

(1) Gas Turbine Trip Bed Freeboard Conditions
(2) Start-Up: Coal Firing

### 3.4.1 Pressure

Small pressure transients which normally occur during the operation of a pressurized fluidized bed would not cause operational problems with the GBF. The combustor control system will automatically compensate for pressure fluctuations to maintain the correct pressure balance between the granular bed filter elements and the ash removal loop. Referring to the P&ID, (Figure 2-2), flow control valve FCV-170 is automatically modulated to maintain the correct pressure balance between the filter element and the lift pipe. This control loop is expected to adequately control pressure balance even if pressure changes are occurring up to 2, maybe 4 psi/min. Special GBF provisions were made to respond to operational upset in the fluidized bed. PDCV 006 and PDCV 006-2 are set up to provide pressure balance capability for large pressure transients (10-20 psi/min) for which FIC-170 does not compensate. The automatic control system will prevent the back flow of gas through the seal legs into the filter insuring the smooth circulation of media.

The tests at NYU showed that the filter was stable if pressure changes were no greater than 2 psi/minute. Above 4 psi/minute there were minor upsets between in the circulation system as gas flowed through the seal legs to balance the pressure between the filter and media circulation system. Pressure increase tended to increase the circulation rate as gas leakage acted like injector air in the lower seal leg. Pressure increase also added a transient gas flow through the filter that increased the possibility of filter media bubbling. Pressure decrease had an opposite effect. Media circulation would decrease as would the transient gas flow rate. Manual controls and piping similar to the automatic capability described above were added at NYU to help maintain the proper pressure balance between the filter and circulation system. These controls allowed quicker restoration of steady-state pressures during changes.

The pressure transients given in the Memorandum of Technical Requirements would be offset by the automatic controls described above. Response would be as follows:

a) For a pressure drop from 175 to 29 psi in 450 seconds (refer to the P&ID) the pressure vent valve downstream of the baghouse (PDCV-006-2) will open and vent the excess pressure in the circulation system. The automatic controls will maintain circulation although the rate may fluctuate slightly due to any lag in control response. This same lag may affect the pressure balance but operations at NYU show that steady-state can be quickly re-established once the transient subsides.

b) For a pressure drop from 167 to 120 psi in 50 seconds (refer to P&ID) the same control loop as described above responds but in this case the vent valve will not be sized to handle the volume necessary to follow this rapid of a pressure change. Instead, two or three minutes will lapse until the pressure can be re-established near steady state. Even if there is a total loss of media circulation during this transient, no long-lasting or detrimental effects to the GBF are anticipated. It is assumed that this depressurization would occur through the gas turbine and would not cause backflow through the GBF. After the depressurization, the filter would restart automatically, assuming it stopped. The control system would re-establish and maintain the pressure balance between the filter element and the ash removal loop.

### 3.4.2 Temperature

The temperature rise given in the Memorandum of Technical Requirements of 918°F to 1134°F in 63 seconds will not be a problem. It is recommended that temperature be held at the higher level for an hour before continuing preheat.

Note that Combustion Power knows of no portion of the GBF that would be sensitive to a rapid change in temperature either upwards or downwards. Our limit of 200°F/hr is based somewhat on "good practice" recommendations from refractory suppliers and our own experience with high alloy materials in fluid bed design. Certainly our experience at NYU demonstrates that greater rates of temperature change are not detrimental. In addition, the media experienced thermal shock without damage on each circulation at NYU as the lift gases were not preheated. Furthermore, temperature rise and fall during start-up, shutdown and upsets at NYU was often quite abrupt but did not cause damage to the filter steelwork.

A sustained temperature of 2000°F for 15 minutes due to PFBC freeboard afterburning would be greatly absorbed by heating media and containment steelwork. It is estimated that the downstream side of the filter may rise 150-200°F during this transient because of the media's thermal capacitance. The support rods will be further protected from this transient by a layer of insulation. Inlet ductwork is not highly stressed and is configured in thermally stable shapes that should survive this transient without distortion.

### 3.4.3 Flow Transients

A drop in face velocity of 50% from the operating value would not cause any problem. If this is accompanied by a pressure drop, any upset would be due to the pressure transient as described previously.

An increase in face velocity of 50% over the operating valve would increase flow to about 55% of minimum fluidization. At NYU this condition caused bubbling (fluidization) of the media. For Sporn the media is larger and the filter bed deeper. The deeper bed should result in a more even velocity profile at the filter exit which would suppress bubbling. Nevertheless the filter elements for

Sporn are designed to contain bubbled media in the unlikely event that it should occur.

### 3.5 Heat Loss and Pressure Drop

Heat transfer calculations show that there will be a 8°F temperature drop between the inlet and the outlet of the filter. This is due primarily to the large amount of surface area of the GBF and associated subsystems. The heat less was minimized by the use of sufficient insulation to insure that the rate of heat loss is less than the design value of 150 $Btu/hr/ft^2$. Table 1 shows the geometric factors and the thermal conductivity of the insulation used. Table 3-1 also shows the calculated heat loss from the individual components. There was no margin in the heat loss calculations used to predict the exit temperature from the filter. If the rate of heat loss is 10% greater than the calculated value, the filter exit temperature would decrease by less than 1°F.

The total pressure drop through the GBF is estimated to be 32 IWC. Twenty-three IWC pressure drop occurs in each filter element. The rest of the pressure drop is associated with the inlet and outlet ducting. The pressure drop through the ducting could be reduced by increasing duct size which would increase the weight of the filter system. The ducting is designed for a nominal velocity of 60 ft/s which seems to be a reasonable compromise between pressure drop and increased weight.

## TABLE 3-II Heat Loss From Individual Components

HEAT LOSS FROM INDIVIDUAL COMPONENTS

| EQUIPMENT | OD (IN) | LENGTH (FT) | AREA (FT2) | RATE OF HEAT LOSS (BTU/HR/FT2) | HEAT LOSS (BTU/HR) | # | TOTAL HEAT LOS (BTU/HR) |
|---|---|---|---|---|---|---|---|
| INLET DUCT | 72.0 | 16.3 | 306.3 | 157.5 | 48251 | 4 | 193003 |
| GBF | | | | | | | |
| CYCLINDER | 216.0 | 89.0 | 5032.8 | 144.0 | 724905 | 4 | 2899621 |
| CONE | | 0.0 | 0.0 | 144.0 | 0 | 4 | 0 |
| TOP & bottom | | | 661.6 | 144.0 | 95297 | 4 | 381186 |
| TOP SEAL LEG | 20.0 | 25.0 | 130.9 | 149.2 | 19530 | 4 | 78120 |
| LOWER SEAL LEG | 20.0 | 40.0 | 209.4 | 159.8 | 33479 | 4 | 133914 |
| LIFT PIPE | 24.0 | 155.0 | 973.9 | 157.9 | 153741 | 1 | 153741 |
| LIFT PIPE TO HEAT EXCH | 22.8 | 20.0 | 119.4 | 100.3 | 11971 | 1 | 11971 |
| HEAT EXCH TO LIFT PIPE | 22.8 | 150.0 | 895.4 | 79.0 | 70698 | 1 | 70698 |
| BOTTOM DEV | 108.0 | 14.0 | 395.8 | 158.1 | 62597 | 1 | 62597 |
| TOP DEV | 66.0 | 16.0 | 276.5 | 127.7 | 35316 | 1 | 35316 |
| OUTLET DUCT | 72.0 | 16.3 | 306.3 | 156.5 | 47925 | 4 | 191700 |

| | R1 (FT) | R2 (FT) | R3 (FT) | INSULATION THICKNE (IN) | R4 (FT) | K1 | K2 | K3 | Hi | Ho | Ti | To | RATE OF HEAT LOSS BTU/HR/FT2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INLET DUCT | 2.49 | 2.50 | 3.00 | 6.00 | 3.03 | 16.7 | 0.06 | 26 | 20 | 2 | 1551 | 70 | 157.5 |
| LIFT PIPE | 0.50 | 0.58 | 0.97 | 4.68 | 1.00 | 10.8 | 0.06 | 26 | 20 | 2 | 1466 | 70 | 157.9 |
| GBF PRESSURE VESSEL | 8.33 | 8.36 | 8.86 | 6.00 | 9.00 | 16.7 | 0.05 | 26 | 20 | 2 | 1541 | 70 | 144.0 |
| TOP SEAL LEG | 0.33 | 0.42 | 0.80 | 4.56 | 0.83 | 10.8 | 0.06 | 26 | 20 | 2 | 1443 | 70 | 149.2 |
| BOTTOM SEAL LEG | 0.33 | 0.42 | 0.80 | 4.56 | 0.83 | 10.8 | 0.06 | 26 | 20 | 2 | 1541 | 70 | 159.8 |
| BOTTOM DEV | 4.00 | 4.03 | 4.50 | 5.64 | 4.60 | 16.7 | 0.06 | 26 | 20 | 2 | 1443 | 70 | 158.1 |
| TOP DEV | 1.67 | 1.92 | 2.69 | 9.24 | 2.75 | 0.4 | 0.10 | 26 | 20 | 2 | 1446 | 70 | 127.7 |
| DEV TO HEAT EXCH | 0.42 | 0.45 | 0.95 | 6.00 | | 16.6 | 0.05 | | 20 | 2 | 1446 | 70 | 100.3 |
| HEAT EXCH TO LIFT PIPE | 0.42 | 0.45 | 0.95 | 6.00 | | 16.6 | 0.05 | | 20 | 2 | 1154 | 70 | 79.0 |
| OUTLET DUCT | 2.49 | 2.50 | 3.00 | 6.00 | 3.03 | 16.7 | 0.06 | 26 | 20 | 2 | 1541 | 70 | 156.5 |

DEFINITION OF SYMBOLS

| | |
|---|---|
| R1 | INSIDE RADIUS (FT) |
| R2 | OUTSIDE RADIUS OF FIRST LAYER (FT) |
| R3 | OUTSIDE RADIUS OF SECOND LAYER (FT) |
| R4 | OUTSIDE RADIUS (FT) |
| K1 | THERMAL CONDUCTIVITY OF INSIDE LAYER (BTU/HR/FT/F) |
| K2 | THERMAL CONDUCTIVITY OF MIDDLE LAYER (BTU/HR/FT/F) |
| K3 | THERMAL CONDUCTIVITY OF OUTSIDE LAYER (BTU/HR/FT/F) |
| Ho | CONVECTIVE COEFFICIENT OF OUTSIDE SURFACE (BTU/HR/FT2/F) |
| Hi | CONVECTIVE COEFFICIENT OF INSIDE SURFACE (BTU/HR/FT2/F) |
| To | AMBIENT TEMPERATURE (F) |
| Ti | INSIDE FLUID TEMPERATURE (F) |

## 3.6 Filter Efficiency

Figures 3-2, 3-3, and 3-4 show filter efficiencies as a function of actual gas velocity and media diameter for the three particle sizes of .5, 2 and 10 micron respectively. These graphs were prepared based on testing done at Combustion Power Company with 2 MM media at low pressure and high temperature (Guillory, 1983). NYU data is also roughly predicted by these graphs.

The graphs can be used as if they were the filter fractional efficiencies. Inlet loadings can be grouped in three particle ranges: < 1 μm, 1 to 5 μm and > 5 μm and the fractional efficiencies can be applied respectively as follows:

- For .5 μm @ 72 ft/min, 4 mm media (Fig. 3-2) ---→ .995
- For 2 μm @ 72 ft/min, 4 mm media (Fig. 3-3) ---→ .996
- For 10 μm @ 72 ft/min, 4 mm media (Fig. 3-4) ---→ .997

The predicted outlet loading for the Sporn plant is based on Table 1-II which gives a particle size distribution for .5 μm, 2 μm and 10 μm as 19.7%, 79%, and 1.4% respectively after condensing the fractional distribution.

- For .5 μm (<1 μm); (.197) (2500 ppm) (.005) = 2.5
- For 2 μm (1-5 μm); (.79) (2500 ppm) (.004) = 7.9
- For 10 μm (>5 μm); (.014) (2500 ppm) (.003) = .1

Outlet Total = 10.5 ppmw

## 3.7 Alkali Considerations

Measurements at NYU showed 95% to 98% reduction of sodium and potassium across the granular bed filter. Unfortunately during these measurements, there was a 200-300 °F temperature drop across the GBF often due to PFBC upset requiring shutdown and restart. At such high temperature drop one must suspect condensation as a major factor in alkali reduction during these measurements.

At 8°F temperature drop across the filter as predicted for the Sporn plant, condensation of alkali will not be a factor in reduction.

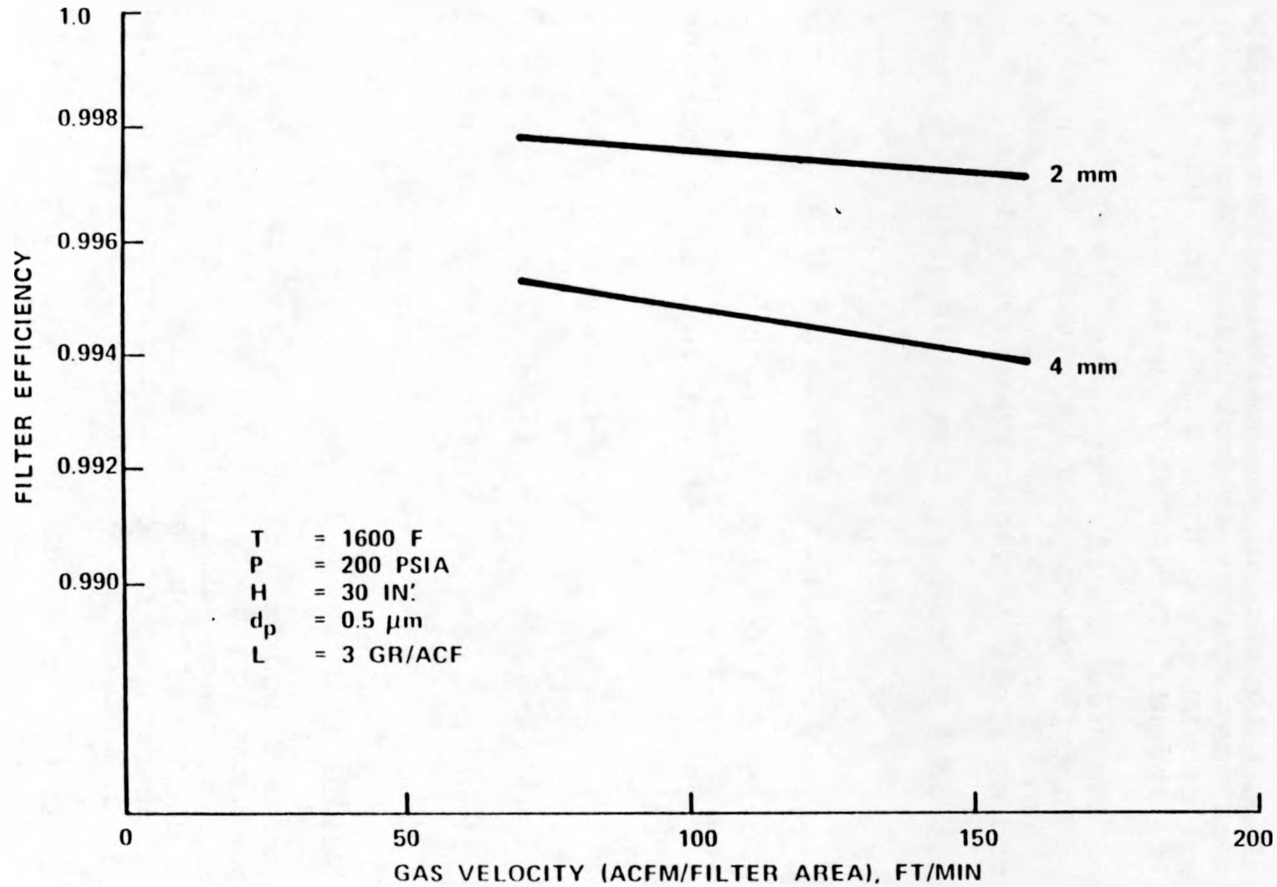



Figure 3-2. Filter Efficiency vs. Gas Velocity and Media Diameter

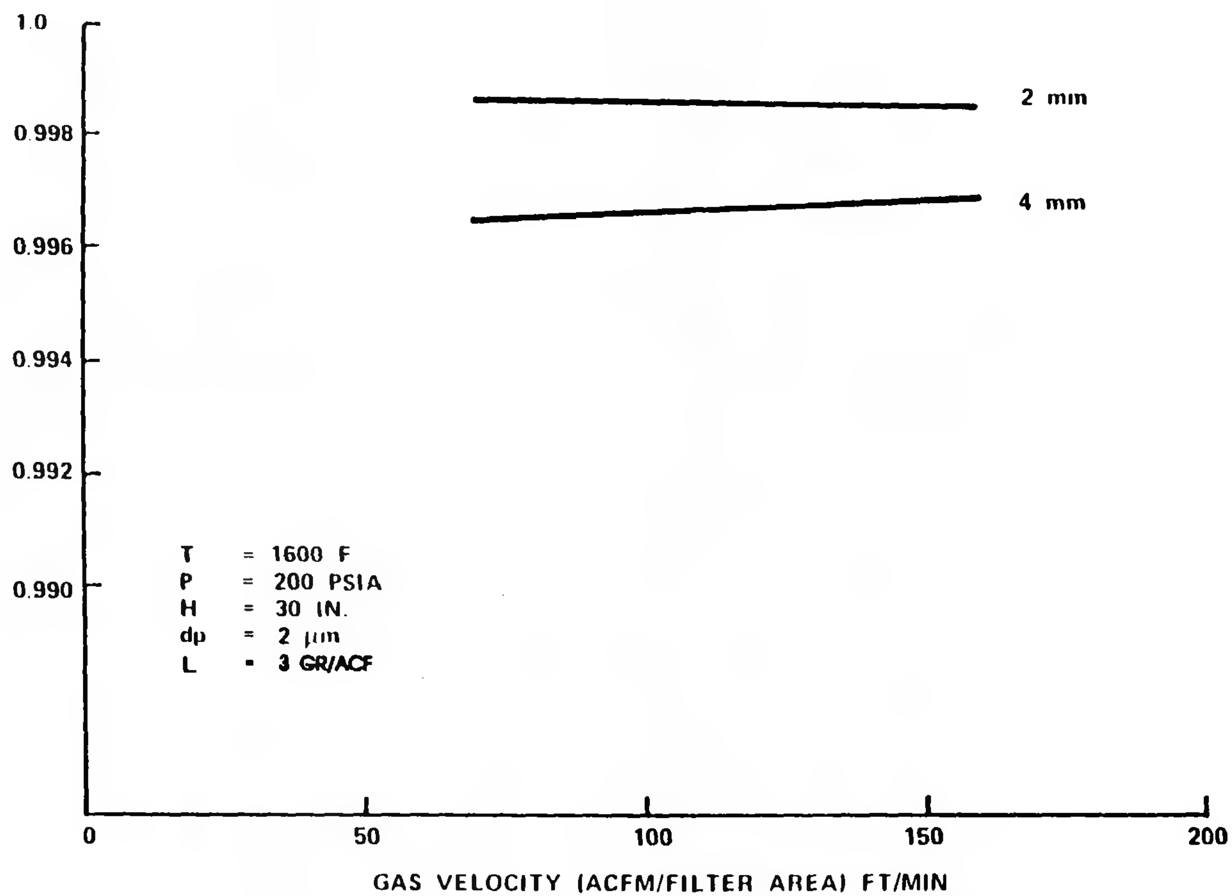



Figure 3-3. Filter Efficiency vs. Gas Velocity and Media Diameter

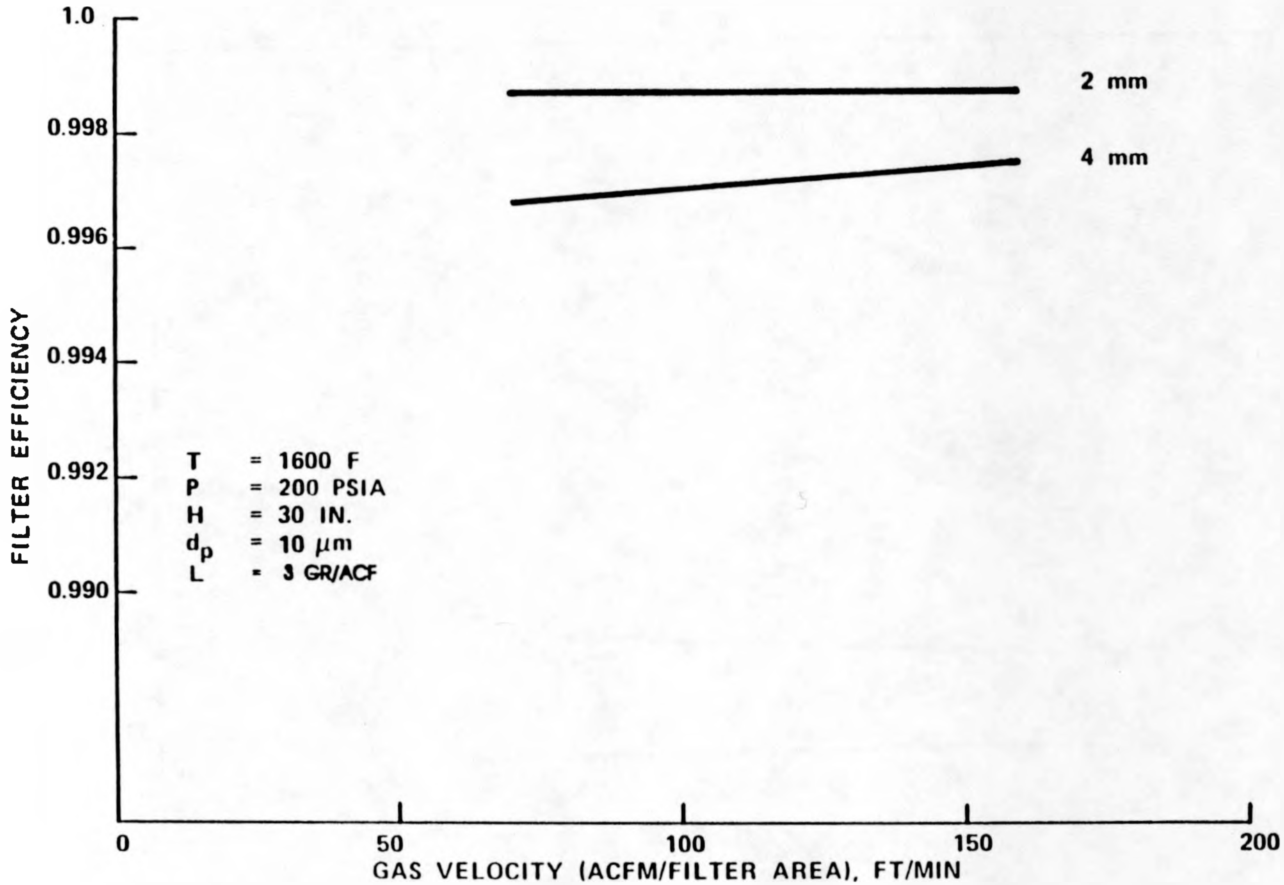



Figure 3-4. Filter Efficiency vs. Gas Velocity and Media Diameter

Combustion Power performed work on reduction of alkalis in fluidized bed exhaust during phase II of the GBF development program (Guillory, 1983). During these tests alkalis were measured upstream and downstream of the GBF and in related tests alloy corrosion was studied. Results showed that aluminosilicates tended to react with alkalis to form stable, high melting point compounds. Alumina and silica are present in the coal ash according to Stone and Webster. Some fraction of this material should be available as reactive aluminosilicate. Furthermore the filter media is an alumina/silica compound and may also be reactive to some extent. Finally, combustion additives can be added to boost the presence of reactive aluminosilicates. Metakaolin was studied in the Combustion Power program.

The tests at Combustion Power indicated that there was a small increase in alkali removal efficiency due to metakaolin additive. Apparently there was sufficient reactive alumina and silica in the Illinois #6 coal ash to convert almost all alkali to inert solid alkali aluminosilicates. In related alkali suppression tests, it was observed that alloy corrosion was definitely reduced by the additive. The study also showed that conversion would even be assisted by high pressure. Thus, it has been shown that the GBF by virtue of the media, coal ash or additive provides a suitable reaction zone for conversion of alkalis to harmless solids.

### 3.8 Maintenance

For the first year after start-up, maintenance outages should occur each 6 months. Based on the findings during these outages, the frequency may be changed to one per year. The first outage will last for 3 or 4 weeks as very detailed inspections are made; thereafter 2 to 3 weeks. These inspections will concentrate on determining the erosion, corrosion and creep rates of the materials. As access can be made to the mass flow hopper, media can be blocked at this point so it will not be necessary to unload media (refer to subsection on loading and unloading media). Media should be unloaded only if there is evidence of deposits forming in the filter elements or media inlet or outlet distribution pipes. (No deposits formed in these areas during NYU testing.) The areas to check for corrosion and erosion are:

- De-entrainment vessel
- Seal legs
- Media valve
- Filter elements
- Expansion bellows
- Circulation piping around boost blower
- Regenerative heat exchanger

Check the de-entrainment vessel for refractory erosion by removing the top section and making observations and measurements. Record information for future reference. A 6" inspection port in the lower de-entrainment section can be removed for observations in this area. The media may or may not be present for this inspection. Major access to the de-entrainment vessel can be achieved by removing successive or combinations of bolted sections.

Upper sections of the seal leg can be removed by supporting the de-entrainment vessel to remove the load on the segments, then unbolting and sliding out segments. There will be flexibility in the piping so a slight gap can be opened up between segment to facilitate removal as was accomplished with segments of lift pipe at NYU. This activity would need to be done only once on a spot check basis until a service life can be confirmed. Seal leg segments can also be checked from the emptied media storage section of the de-entrainment vessel. Access can be by removal of the upper section or optional manway.

Lift pipes and lower seal leg sections can be checked by random removal or by removal of the media valve. The media valve can be lowered slightly by loosening bolts to give the space needed to access segments. By removing the media valve, lower sections of lift-pipe and lower seal leg can be inspected and/or removed. Again this only needs to be done on a spot check basis until service life can be confirmed. As a cross check on lift pipe condition, measured and theoretical values for circulation rate can be compared. A growing divergence indicates lift pipe wear.

The media valve can be inspected by removing media injector piping and the blind flange at the bottom.

Access to the main filter vessels will be necessary to inspect the filter elements. Metal thickness can be inspected ultrasonically with or without media present. Filter elements can be inspected through access port. If desired, individual elements can be drained by opening the media exit port at the lower flexible seal. Supports need to be monitored for creep. Periodic corrections may be necessary.

Expansion bellows should be checked for cracks or corrosion during each inspection of the filter vessel. Bellows at the gas inlet and at the lower flexible seal can be inspected through ports in the respective nozzle shells. Corrosion of the lower flexible seal bellows was observed at NYU; therefore inspection access has been improved and the material upgraded from 316 S.S. to Inconel 625.

Condensation can occur in the piping between the water-cooled heat exchanger and the boost blower, and also downstream of the boost blower. Alloy piping between the coalescing filter and the boost blower will prevent the generation of damaging corrosive particles.

This piping and the remaining carbon steel piping should be checked periodically for unusual corrosion.

Baseline data will need to be gathered on the regenerative heat exchanger. Erosion and corrosion could be a problem as could be deposition (fouling) and the fatigue characteristics of a rapper-type cleaning system.

Normal maintenance is expected for instrumentation and control components. Normal spare parts with respect to thermocouples, controllers and transmitters should be in supply. Valves in service where they open and close against filter media or ash should have spares so they can be replaced during the maintenance shutdowns.

In addition to spare parts for instrumentation and control, spares should be in supply for the baghouse (pulse valves and bags) coalescing filter (filter elements), and oil removal filter (cleanable elements). These items and the boost blower will also have maintenance recommendations generated by their respective manufacturers.

### 3.8.1 Loading Filter Media

The initial charge of media can be loaded and circulated at atmospheric pressure. Otherwise the media make-up hopper can be loaded through pressurization valves. Any time the lower seal legs are empty of media, a few hundred pounds of media will need to be added to each mass flow hopper to establish a seal. Media can be injected into the lift pipe from the make-up hopper at a rate of 1500 lb/min. At the same time, media can be added to the make-up hopper if desired whether at pressure or not. A level switch in the de-entrainment vessel will indicate the filter is full. Excess media will flow back to the media make-up hopper. Loading can be accomplished in 22-24 hours.

### 3.8.2 Unloading Filter Media

Built into the media pipes where the lower flexible seal empties into the mass flow hopper are arrangements for slide-in gates to each of the twenty exits in each filter vessel. If desired, media can be blocked at any time during the unloading process to allow flexibility to empty only specific zones. If these are blocked at the beginning, only the mass flow hopper and lower seal leg will be emptied. One can lower the level of media in the de-entrainment vessel, then block the flow to also empty the lower seal leg. Also selected filter elements can be emptied.

A small sample of media can be emptied into sample pot at pressure and temperature. The pot can then be depressurized and removed from the attachment at the de-entrainment vessel. The lower seal leg can be emptied by closing off all 20 element isolating valves at the lower flexible seal and circulating the media to overflow into the media make-up hopper. Otherwise media unloading must be done at atmospheric pressure and for safety at media temperature below 140°F. This can be accomplished by removing the insert from the media valve injector and emptying media into an appropriate container. To control unloading a high volume of media, a slide gate can be temporarily installed at the injector outlet.

## 4.0 EQUIPMENT SPECIFICATIONS

### 4.1 Baghouse

#### 4.1.1 Summary statement of supply

One high pressure baghouse designed for 265 psig and 1150 ACFM at 450°F with an optional add for 500°F. Unless inconsistent with this specification, the Contractor's standard or usual construction is desired based on the ASME Code, Section VIII, Pressure Vessels, Division I.

#### 4.1.2 Operating Environment

Interior __X__ Exterior _____

Temperature Maximum___100___F

Average____70___F

Minimum____50___F

Relative Humidity Maximum___80%___

Average_________

Minimum___10%___

Elevation __500_Feet Above Sea Level (est)

Wind Load Criteria ____________Maximum Velocity

____________$lb/ft^2$

Average Annual Rainfall____________in/year

Seismic Zone ____________

Location New Haven, West Virginia

_______________________________________________

_______________________________________________

_______________________________________________

#### 4.1.3 Duty Cycle

Daily_______24__________Hours/Day

Weekly_______7__________Days/Week

Yearly ______50__________Weeks/Year

NOTE: This demonstration unit will accumulate up to 7000 hours total operation.

4.1.4 Performance Criteria

a. Service: Remove particulate from flue gas generated by burning coal in a fluid bed combustor.

b. Inlet Volume Flow Rate: 1150 ACFM

c. Inlet Temperature: 450°F maximum (case 1)

500°F maximum (case 2)

d. Inlet Grain Loading: 800 Grains/ACF (119 lb/min)

e. Allowable Pressure Drop: 6 in. $H_2O$ (8" $H_2O$ maximum)

f. Particulate Composition: Molecular: Major - $CaSO_4$, $SiO_2$; Minor - CaO, $Fe_2O_3$; Trace - $CaCO_3$

ASH ANALYSES EXPRESSED AS PERCENT OXIDES

| | (Dolomite) PFBC Cyclone Ash % | (Limestone) PFBC Cyclone Ash % |
|---|---|---|
| $SiO_2$ | 24.3 | 19.4 |
| $Al_2O_3$ | 10.1 | 9.3 |
| $Fe_2O_3$ | 12.3 | 10.1 |
| $TiO_2$ | 0.7 | nd |
| CaO | 20.4 | 26.7 |
| MgO | 10.6 | 1.9 |
| $Na_2O$ | 0.3 | nd |
| $K_2O$ | 1.1 | nd |
| $P_2O_5$ | 0.1 | nd |
| $SO_3$ | 9.9 | 14.8 |
| LOI | 10.2 | 16.9 |
| | 100% | (100) |

Notes: a) Ash analyses for metals tested according to ASTM E-887-82; for sulfur trioxide, ASTM D-3177-84; and for phosphorous pentoxide and ignition loss, ASTM C-311-85.

b) nd = not determined

c) ( ) = assumed

d) Assumed to be blend of primary and secondary cyclone ash.

g. Corrosives: See above, plus some $SO_2$ (less than 50ppm)

h. Size Distribution: See attachment 1

i. Collection Efficiency: 99%

j. Start-up Operation: At atmospheric pressure with air at 60°F to 250°F and up to 2000 ACFM with, typically, a low inlet loading (1-5Gr/ACF).

4.1.5 Mechanical Design Criteria

a. Air/Cloth Ratio: by vendor

b. Filter Cloth Material: by vendor

c. Method of Bag Removal: by vendor

d. Receiving hopper with sides sloping no less than 60° with the horizontal.

e. Collector housing to be constructed of 3/8" (min.) ASME rated steel plate to withstand 265 psig pressure.

f. Support legs are not required. Provide support clips for use by others.

g. Provide access door for bag removal; company prefers a body flange for top bag removal.

h. Provide inlet and outlet flanged connections.

i. Provide 3/4" NPT connection for low level switch.

j. Provide pre-piped compressed air header assembly including diaphragm valves.

k. Provide solenoid valves mounted in NEMA 4 enclosure(s) pre-piped with suitable tubing.

l. Provide automatic electronic sequential timer contained in NEMA 4 enclosure and compatible with 120 VAC power supply.

m. Provide filter cages, bag clamps, and all internal piping.

n. Accessories/Special Equipment
   - Differential pressure gauge
   - Manometer
   - Compressed air pressure gauge
   - Compressed air shut-off valve
   - Compressed air header drain petcock ______ or drain coupling __3/4"__ NPT
   - One complete set filter bags
   - Second (extra) set filter bags. Quote separate.
   - Other ______________________________
     ______________________________

**ATTACHMENT 1**

**PARTICLE SIZE DISTRIBUTION TO BAGHOUSE**

| Particle Size Range (micron) | Mean in Size Range (micron) | Fractional Distribution |
|---|---|---|
| 1 - 1.4 | 1.2 | 0.197 |
| 1.4 - 2.0 | 1.7 | 0.389 |
| 2.0 - 2.8 | 2.4 | 0.291 |
| 2.8 - 4.0 | 3.4 | 0.090 |
| 4.0 - 5.6 | 4.8 | 0.020 |
| 5.6 - 8.0 | 6.8 | 0.007 |
| 8.0 - 11.3 | 9.65 | 0.007 |

| | |
|---|---|
| Mean Particle Diameter, micron | 2.1 |
| Estimated dust loading to HTHP filter, ppm (Based on 15,000 ppm bed elutriation fraction) | 500 |

Total loading is 100-800 gr/ACF

## 4.2 Heat Exchangers

### 4.2.1 Summary statement of supply

Two separate heat exchangers are required to cool combustion flue gas in a high pressure system. This is for a large power plant.

### 4.2.2 Equipment to be Furnished

This specification includes all labor, materials, tools and equipment to supply the equipment as described herein and by the reference drawings. Labor, materials, engineering, etc., not specifically noted herein as required for a complete and functional system for the specific application and which are required for conformity to all pertinent codes and standards, shall be included under this contract.

ITEM 1: Regenerative Heat Exchanger - A multiple pass heat exchanger to cool dirty flue gas to 450° while heating cleaned flue gas to about 1200°F.

ITEM 2: Water Cooled Heat Exchanger - To cool clean flue gas to below the dewpoint from 500 to 250°F.

### 4.2.3 Operating Environment

| | |
|---|---|
| Interior __X__ | Exterior _____ |
| Temperature | Maximum___100___F |
| | Average____70___F |
| | Minimum____50___F |
| Relative Humidity | Maximum___80%___ |
| | Average________ |
| | Minimum___10%__ |
| Elevation | __500__ Feet Above Sea Level |
| Wind Load Criteria | _______N/A_____Maximum Velocity |
| | _______________lb/ft$^2$ |
| Average Annual Rainfall | _______________in/year |
| Seismic Zone | _______________ |

Location New Haven, West Virginia

#### 4.2.4 Duty Cycle

Daily 24 Hours/Day

Weekly 7 Days/Week

Yearly 50 Weeks/Year

#### 4.2.5 Performance Requirements

The same combustion flue gas will be handled by all heat exchangers as follows:

Gas Composition: 20.4 $CO_2$, 6.8 $H_2O$, 68.8 $N_2$, 4.0 $O_2$ (by volume)

Corrosives: from $SO_2$ (50-500 PPM $SO_2$ by volume)

Particulate Loading: Very high upstream of baghouse (119 lb/min) sticky ash and very low downstream of baghouse (.1 lb/min)

ITEM 1: Regenerative Heat Exchanger - The purpose of the regenerative heat exchanger is to minimize heat loss from the granular bed filter. The regenerative heat exchanger cools 48,000 lb/min of dirty lift pipe gas so that particulate can be removed with a conventional baghouse. The cleaned lift gas is then reheated by the same, but ash-free 48,000 lb/min of flue gas in the regenerative heat exchanger. The design inlet temperature on the dirty gas side is 1425°F. As an off design case, this temperature could be as high as 1530°F. The dirty flue gases are cooled to nominally 450°F before entering the baghouse. The outlet temperature of 450°F is not firm. If raising this design temperature to 500°F would also raise the inner tube wall temperature above 225°F, the dew point, then this option should be quoted as an alternate as indicated by case 2 on the data sheet.

One approach is shown in the attachment titled "Regenerative Heat Exchanger". This approach is for a unit sized for 5000 lb/hr. For the 48,000 lb/hr unit a vertical orientation is preferred and 175 ft of elevation is available.

ITEM 2: Water Cooled Heat Exchanger - Since the ash is removed by the baghouse just upstream of this exchanger, condensation on the inside pipe is acceptable. Adjust the inlet temperature to match the outlet temperature chosen for item 2. Carbon steel construction is acceptable, providing a 10 year life can be expected under the corrosive flue gas conditions. See the data sheet.

4.2.6 Mechanical Design Criteria

ITEM 1: The regenerative heat exchanger will have shell and tube construction with the dirty gas passing through vertical tubes and the cleaned gas on the shell side. It is desired to have one tube pass such that the hot dirty gas enters at the top of the exchanger and exits at the bottom of the exchanger. It is expected that the exchanger will be between 150 ft to 175 ft tall. The heat exchanger will have sootblowers and/or impact shakers to remove ash built up on the vertical tube surface. The bottom of the heat exchanger will have a heated ash hopper for the removal of collected ash.

The heat exchanger will be housed in a pressure vessel table to withstand the maximum operating pressure of 265 psig. The heat exchanger is to be insulated such that the heat loss from its surface is less than 150 $BTU/hr/ft^2$. The insulation should be a light weight type such as ceramic fiber to minimize the total weight of the exchanger.

ITEM 2: The water cooled heat exchanger will be a shell and tube type exchanger with the flue gas on the tube side and the water on the shell side.

| | | | | |
|---|---|---|---|---|
| TITLE | HEAT EXCHANGERS | | | |
| | HEAT EXCHANGER DATA SHEET | | | |
| UNIT | REGENERATIVE HEAT EXCHANGER | | CASE 1 | CASE 2 |
| HOT SIDE | Shell or tube | | TUBE | TUBE |
| | Gas flow | lb/hr | 48000 | 48000 |
| | Design pres./temp. | psia/F | 265/1465 | 265/1465 |
| | Operating pres. at inlet | psia | 200 | 200 |
| | Operating pres. at outlet | psia | 198 | 198 |
| | Pressure drop | psi | ~2 | ~2 |
| | Temperature at inlet | F | 1400 | 1400 |
| | Temperature at outlet | F | 500 | 500 |
| | Temperature drop | F | 950 | 900 |
| | Specific heat | Btu/lb/F | 0.281 | 0.283 |
| | Molecular weight | lb/mol | 29.3 | 29.3 |
| | Heat given up | Btu/hr | $12.8 \times 10^6$ | $12.1 \times 10^6$ |
| | Fouling factor (suggested) | hr.sq.ft.F/Btu | 0.025 | 0.025 |
| | | | | |
| *COLD SIDE | Shell or tube | | SHELL | SHELL |
| | Fluid flow (process gas) | lb/hr | 48000 | 48000 |
| | Design pres./temp. | psia/temp | 265/1200 | 265/1200 |
| | Operating pres. at inlet | psia | 262 | 262 |
| | Operating pres. at outlet | psia | 261 | 261 |
| | Pressure drop | psi | 1 | 1 |
| | Temperature at inlet | F | 250 | 250 |
| | Temperature at outlet | F | 1190 | 1140 |
| | Temperature rise | F | 940 | 890 |
| | Specific heat | Btu/lb/F | 0.275 | 0.274 |
| | Molecular weight | lb/mol | 29.3 | 29.3 |
| | Heat absorbed | Btu/hr | $12.4 \times 10^6$ | $11.7 \times 10^6$ |
| | LMTD | | | |
| | Overall ht. tr. coeff. | Btu/hr.sq.ft.F | | |
| | Fouling factor | hr.sq.ft.F/Btu | .005 | .005 |
| | | | | |
| *MECH DATA | Heating surface | sq.ft. | | |
| | Tube diameter | in. | | |
| | min. thickness | in. | | |
| | length | in. | | |
| | material | | | |
| | No. of rows trans. to flow | | | |
| | Transverse spacing | in. | | |
| | No. of rows long. to flow | | | |
| | Longitudinal spacing | in. | | |
| | Fin no/in | | | |
| | height | in. | | |
| | thickness | in. | | |
| | material | | | |

*Vendor to complete as applicable.

| | | | | | |
|---|---|---|---|---|---|
| TITLE | HEAT EXCHANGERS | | | | |
| | HEAT EXCHANGER DATA SHEET | | | | |
| UNIT | WATER COOLED HEAT EXCHANGER | | | | |
| HOT SIDE | Shell or tube | | TUBE | | |
| | Gas flow | lb/hr | 48000 | | |
| | Design pres./temp. | psia/F | 265/350 | | |
| | Operating pres. at inlet | psia | 200 | | |
| | Operating pres. at outlet | psia | 200 | | |
| | Pressure drop | psi | $<.1$ | | |
| | Temperature at inlet | F | 500 | | |
| | Temperature at outlet | F | 250 | | |
| | Temperature drop | F | 250 | | |
| | Specific heat | Btu/lb/F | 0.265 | | |
| | Molecular weight | lb/mol | 29.0 | | |
| | Heat given up | Btu/hr | $3.2 \times 10^6$ | | |
| | Fouling factor (suggested) | hr.sq.ft.F/Btu | | | |
| *COLD SIDE | Shell or tube | | SHELL | | |
| | Fluid flow (process gas) | lb/hr | | | |
| | Design pres./temp. | psia/temp | 40/60 | | |
| | Operating pres. at inlet | psia | 40 | | |
| | Operating pres. at outlet | psia | | | |
| | Pressure drop | psi | | | |
| | Temperature at inlet | F | 60 | | |
| | Temperature at outlet | F | | | |
| | Temperature rise | F | | | |
| | Specific heat | Btu/lb/F | | | |
| | Molecular weight | lb/mol | | | |
| | Heat absorbed | Btu/hr | | | |
| | LMTD | | | | |
| | Overall ht. tr. coeff. | Btu/hr.sq.ft.F | | | |
| | Fouling factor | hr.sq.ft.F/Btu | | | |
| *MECH DATA | Heating surface | sq.ft. | | | |
| | Tube diameter | in. | | | |
| | min. thickness | in. | | | |
| | length | in. | | | |
| | material | | | | |
| | No. of rows trans. to flow | | | | |
| | Transverse spacing | in. | | | |
| | No. of rows long. to flow | | | | |
| | Longitudinal spacing | in. | | | |
| | Fin no/in | | | | |
| | height | in. | | | |
| | thickness | in. | | | |
| | material | | | | |

*Vendor to complete as applicable.

## REGENERATIVE HEAT EXCHANGER

The regenerative heat exchanger is a counter flow heat exchanger with the dirty gas through the tube side and the clean gas passing cross flow through the shell side. The heat exchanger consist of 5 modules in series with each module having 191 ft2 of surface.

The exchanger was designed with the possibility that the ash is of a high fouling type and correspondingly high fouling factors were used in the design. Because of the unknown nature of the ash, two methods of sootblowing will be built into the heat exchanger. The primary sootblowing technique will be rapping. This method proved effective during the GBF test conducted at NYU's high pressure fluidized bed test facility. The other sootblowing method will use high pressure air to individually blow each tube of the heat exchanger.

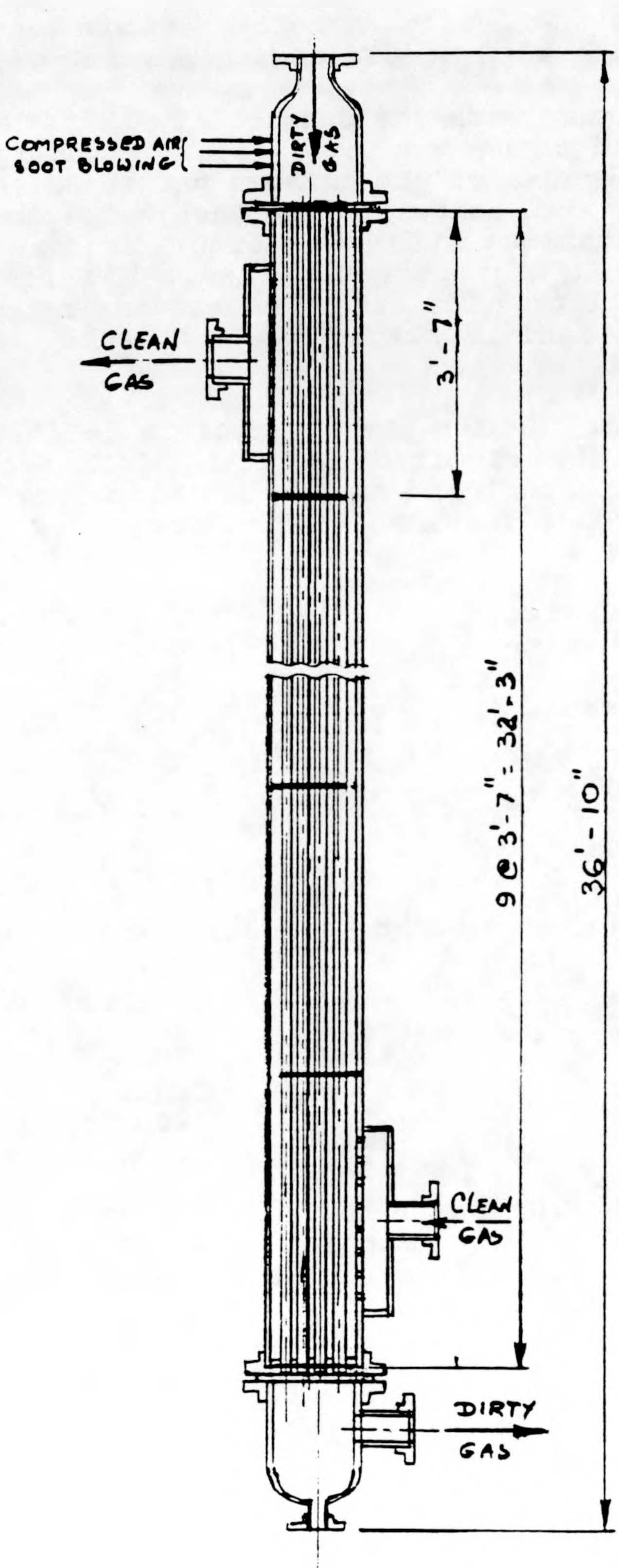
Before entering the final design phase, complete definition of the fuel to be fired will be required including full proximate and ultimate analysis of the coal and ash composition, fouling index, reducing and oxidizing deformation temperatures.

Tube Data:

| | |
|---|---|
| Tube size (heat surface) | 1-1/2" sch40 |
| Tube sheet hole spacing | 2.15"x2.15" |
| Number of tubes per module | 12 (3x4) |
| Tube length per module | 32'-5" |
| Housing size | 12" sch20 |
| Number of modules | 5 |
| Heat surface per module | 191 ft2 |
| Heat surface total | 955 ft2 |

Heat Exchanger Data Total per Set of 5 Modules.

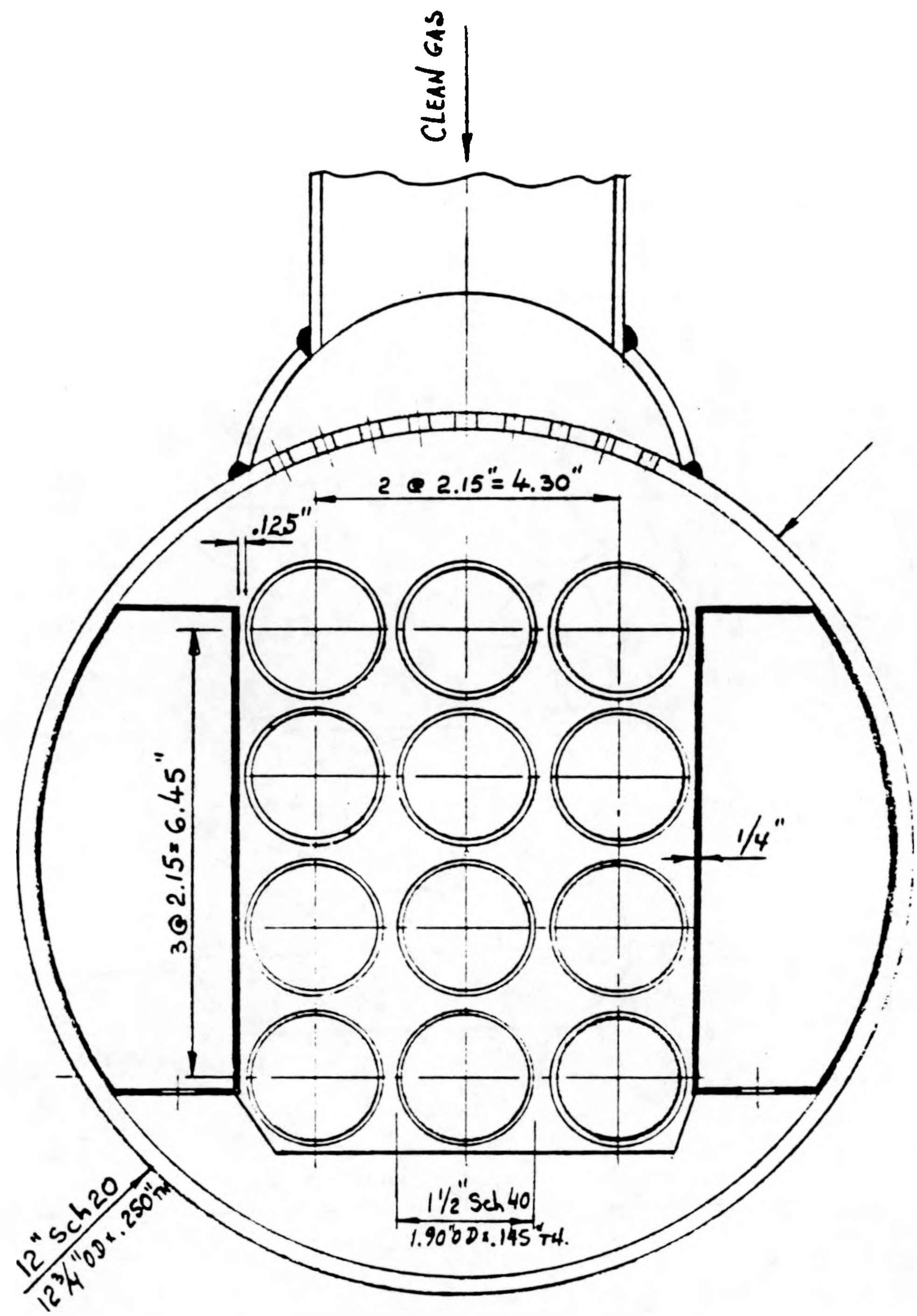
| | | Dirty Gas | Clean Gas |
|---|---|---|---|
| Flow rate | Lb/Hr | 5000 | 5000 |
| Temperature at inlet | F | 1315 | 250 |
| Temperature at outlet | F | 400 | 1175 |
| Pressure at inlet | psia | 165 | 158 |
| Velocity, mean | ft/s | 24.0 | 16.8 |
| Fouling factor | (Hr ft2 F)/Btu | 0.025 | 0.005 |
| Pressure drop | psi | 1.17 | 4.13 |
| Heat absorption rate | Btu/Hr | 1.2 million | |
| Log. mean temp. difference | F | 145 | |
| Heat transfer coefficient: | | | |
| Internal mean | Btu/hr/ft2/F | 28.24 | |
| External mean | Btu/hr/ft2/F | 34.91 | |
| Overall mean | Btu/hr/ft2/F | 9.522 | |
| Heat surface effectiveness factor | | 0.91 | |




HEAT EXCHANGER

HEAT SURface: 191 $FT^2$/MODULE

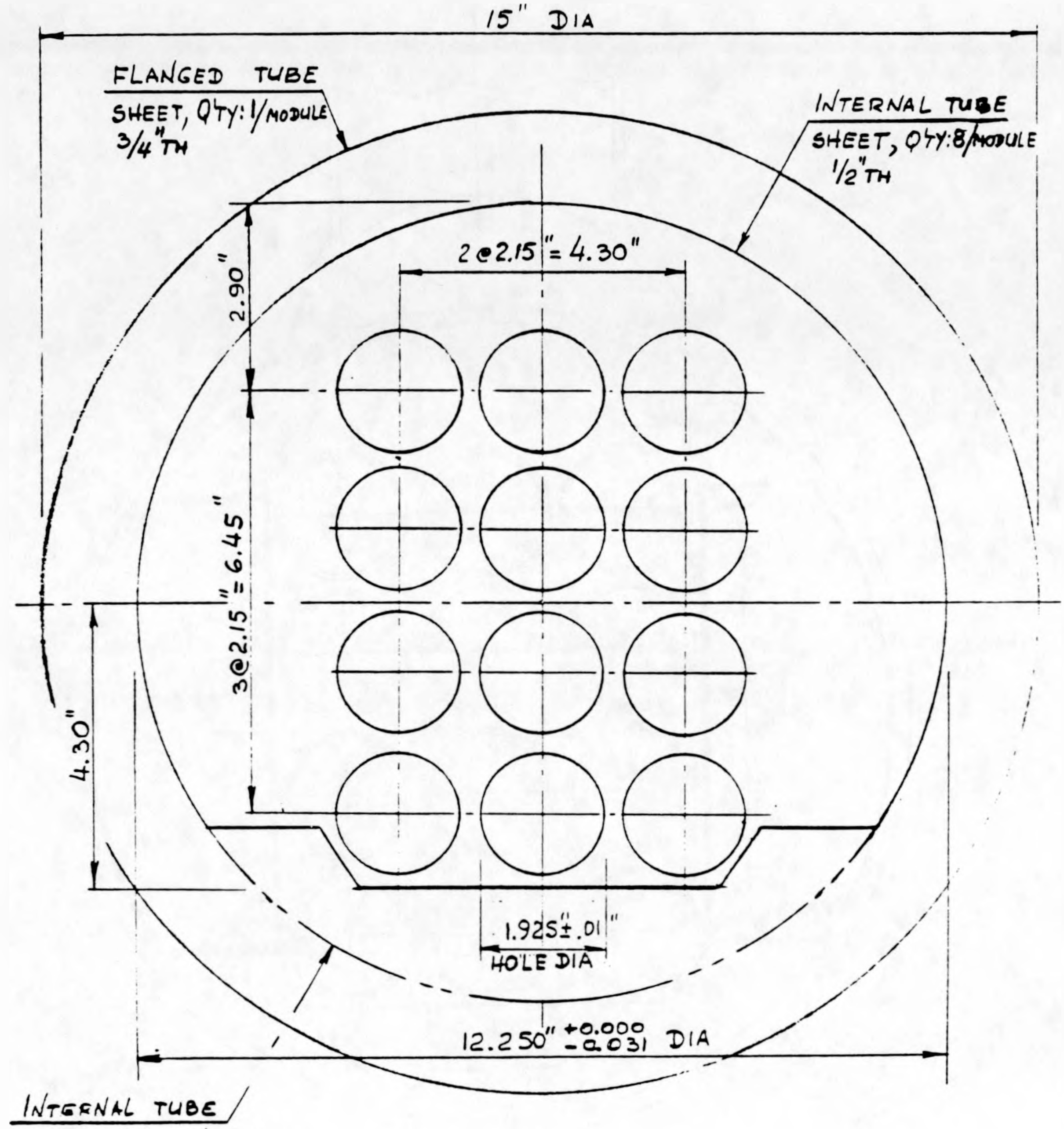
SHEET 1 of 6




HEAT EXCHANGER

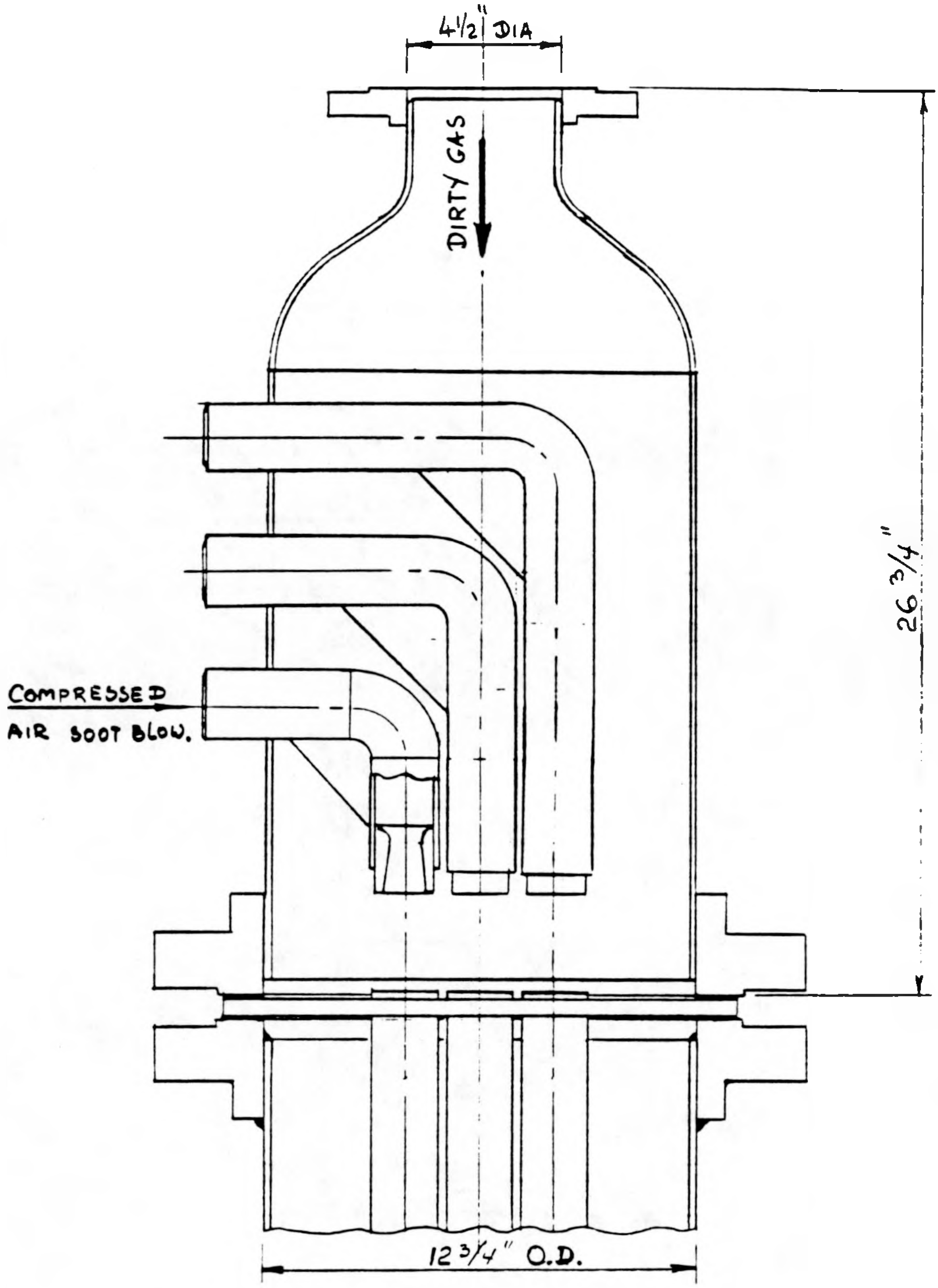
SCALE 1" = 2"

SHEET 2 of 6




TUBE SHEET
SCALE 1"=2"

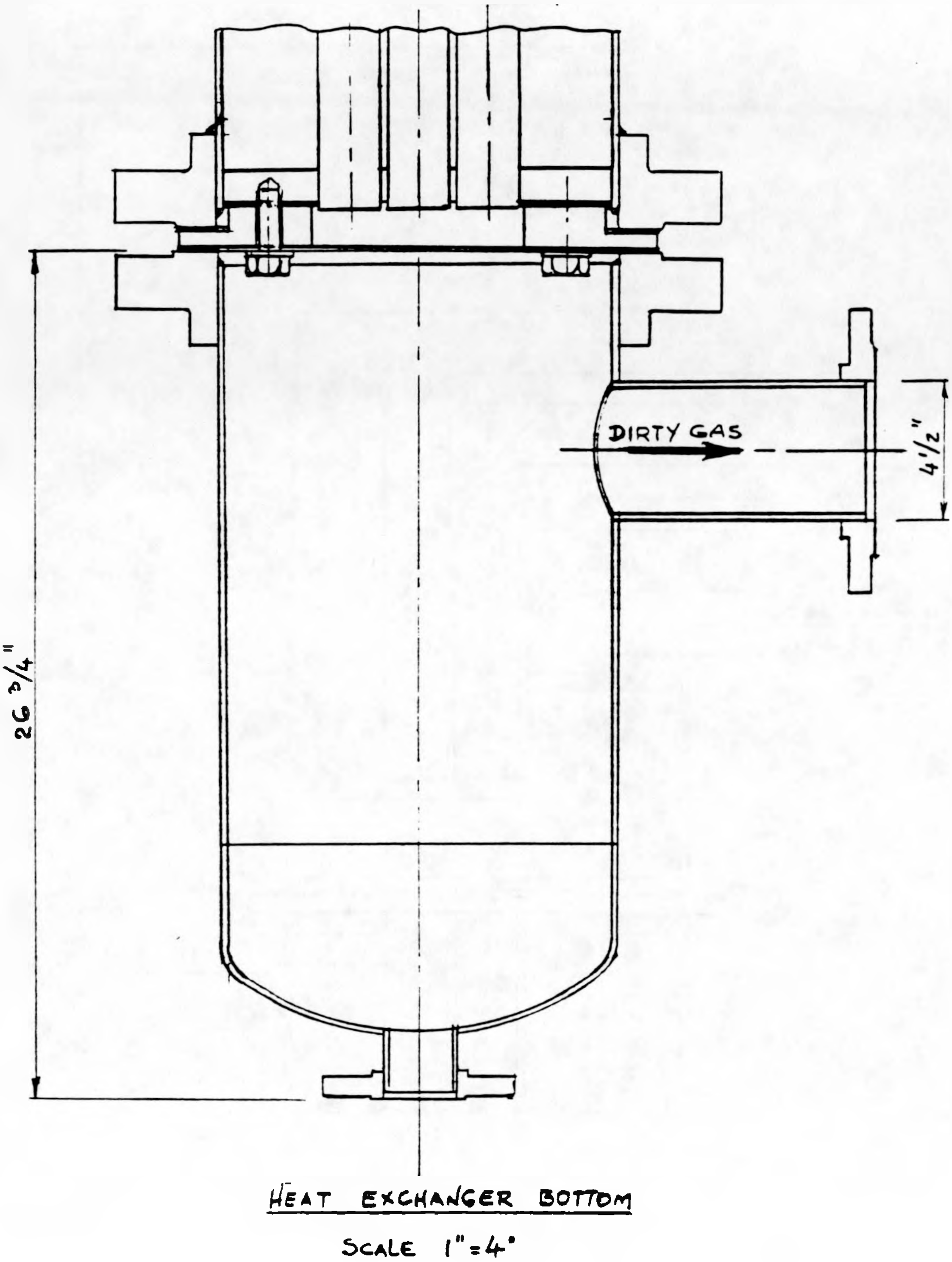
SHEET 3 OF 6




HEAT EXCHANGER TOP

SCALE 1"=4"

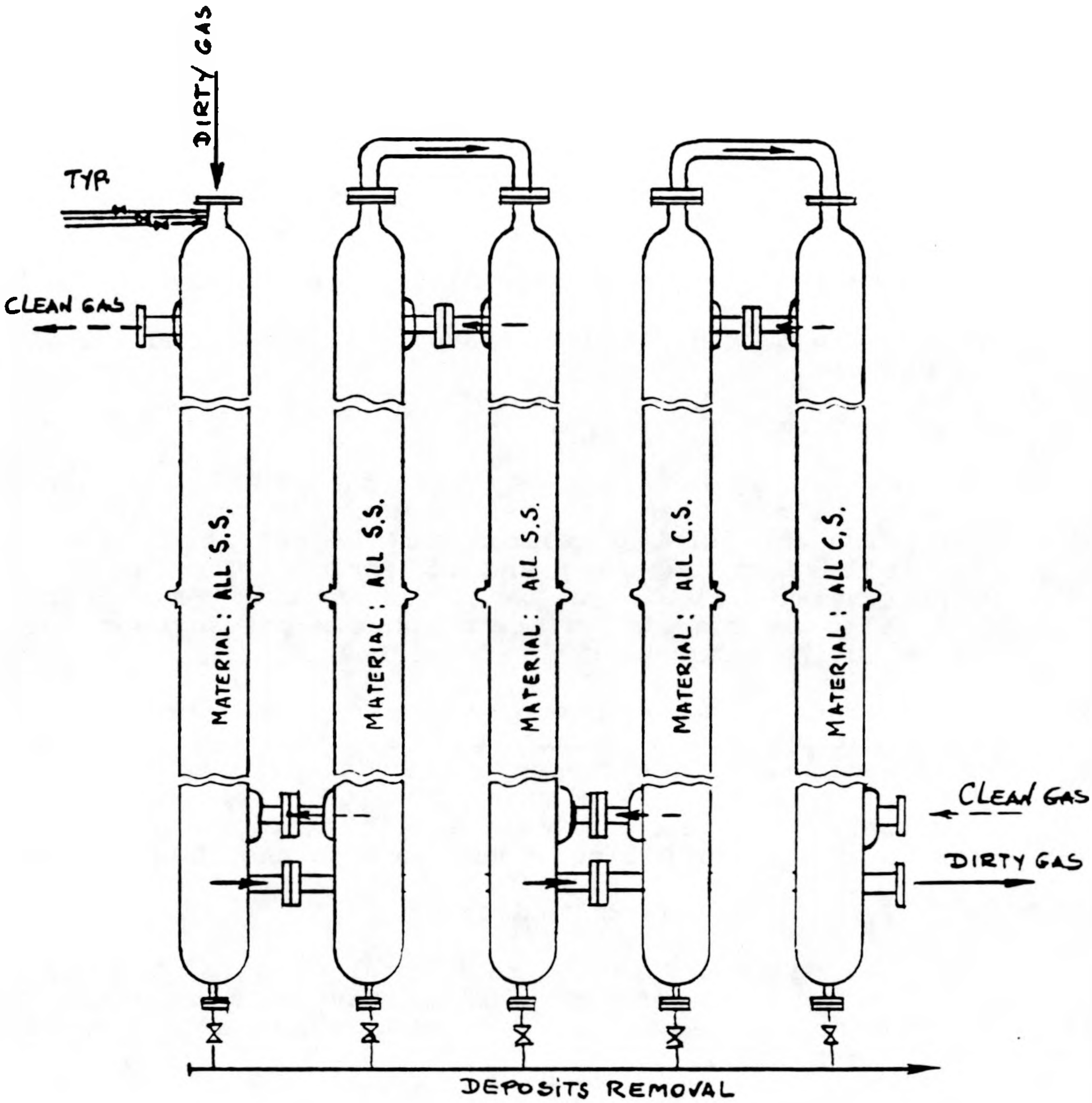
SHEET 4 OF 6




HEAT EXCHANGER BOTTOM

SCALE 1"=4'

SHEET 5 OF 6




HEAT EXCHANGER BATTERY

SHEET 6 OF 6

## 4.3 Boost Blower

This is a preliminary specification for a boost blower to install in a pressured conveying system. 800 lb/min of filtered combustion flue gas must be boosted from 255 PSIG to 265 PSIG.

Considerable latitude in the basic design and furnished equipment exists at this time. The most favorable response will feature:

- o standard equipment proven in similar applications.
- o A complete packaged blower system with drive and normal accessories.

### 4.3.1 Performance Criteria

The preliminary flow rate is 800 lb/min at 255 psig inlet to 265 psig outlet (10 psi pressure rise). During operation the inlet pressures will be set at different levels between 180 psig and 255 psig. The pressure differential will always be 10 psi or less. The blower will also be run at atmospheric pressure at the inlet during startup at a rate of 240 lb/min.

Temperature: A 400°F inlet gas temperature is preferred. Lower temperatures can be accommodated at an inconvenience to the Company, Combustion Power Company. Any gas temperature below about 320°F will be at the dewpoint. The vendor may select the inlet temperature most suitable for his equipment down to the 200°F range.

### 4.3.2 Typical Operating Conditions

The flue gas comes from burning coal or oil. The coal will have sulfur in it so there may be a corrosion problem below the dewpoint. The $SO_2$ concentration could be as high as 100 ppmv.

See the Data Sheet for blower sizing conditions.

### 4.3.3 Blower Configurations considered:

a. Lobe-type blower in a pressure vessel

b. Sliding vane compressor

c. Axial or screw type compressor.

### 4.3.4 Drive

A variable speed drive shall be suitable for adjusting the speed of the blower between start up and the operating flow. Startup flow is 240 lb/hr at 8 psi above ambient at 70 F. Minimum speed ratio is 3:1. Expected speed range is 1716 RPM to 700 RPM but should be confirmed by the manufacture during detail engineering.

### 4.3.5 Accessories

a. Necessary inlet and outlet silencers, if required, for 85 dBA at 3' from any surface.

b. Inlet and outlet flex joint, if necessary.

c. Additional loose seal with mounting instructions, assuming the blower must be mounted in a pressure vessel with the drive shaft protruding through the vessel wall. Cooling water is available as is purge air @ 450 PSIG. Some seal leakage is tolerable; Vendor to state leakage (the preliminary requirement is 0.1 lb/min).

d. Mounting base for blower assembly including pressure vessel if needed.

## 4.4 Computer Control System

### 4.4.1 Scope

The computer control system is based on a Rosemount 8015 and consists of a multivariable control unit that accepts the following inputs and outputs:

- up to 52 Analog Inputs (4-20 mA, 1-5 volts)
- up to 12 Analog Outputs (4-20 mA)
- up to 24 Digital Inputs (Dry Contacts)
- up to 16 Digital Outputs (100 mA @ 24 volts, D.C.)

The equipment included for the multivariable control unit (MVCU) consists of a redundant MVCU main frame, analog and digital terminal boards, and 10 ft interconnecting cable. These items are mounted in an instrument enclosures (Nema 1 design) with front and back access.

Software is included to perform the following functions:

- Generate standard displays
- Allow graphics and trending
- Allow configuration definition
- Generate alarms
- Allow report generation

### 4.4.2 Design Features

The multivariable control unit operates as a redundant system consisting of two identical but separate microcomputer systems. These are identified by nomenclature side "A" and side "B". Normally side "A" is evaluating the assigned control algorithms and driving corresponding outputs, while side "B" is tracking. In the event that side "A" becomes non-functional, as determined by the hardware/software watchdogs, side "B" assumes control through bumpless transfer.

In addition to the above features, the Rosemount model 8015 represents redundant style of analog and digital conditioning module assemblies. Additional conditioning cards can be added at any point in time.

## 5.0 FILTER COST ESTIMATE

### 5.1 Budgetary Price

The cost estimate for the filter includes estimates for equipment, delivery, installation, and commissioning of the filter based on information in Section III. Equipment costs are based on items loaded for delivery (FOB) at the nearest railhead or suitable dock. The large filter vessels are each assumed to be manufactured in one piece and barged to the plant site. Costs for material transportation includes this activity plus an allowance for shipping other listed items to the jobsite by truck or rail as appropriate.

Installation costs are based on moving the large pressure vessels from a barge docked near the plant to the erection point for installation without intermediate storage. Once these pressure vessels are in place, the internals can be installed through the flange for the mass flow hopper. The circulation system and auxiliaries will be installed once the major work is completed inside the pressure vessel.

Costs include a construction subcontractor chosen and managed by Combustion Power Company. Unencumbered access to the filter site is assumed. Construction costs include field mobilization and a field office. Site support by Combustion Power field service personnel is included during construction and start-up.

The budgetary price of the design, procurement and installation of the equipment for a Granular Bed Filter system to handle 2,885,000 lb/hr of gas at 1550F and 215 psia is $<u>24,207,000</u>.

This estimate includes freight, QA/QC, construction management, and start-up support as shown on Table 5-I. See Table 5-II for weights.

Note: Prices are budgetary, based on August 1989 pricing. Sales and use taxes are <u>not</u> included.

**TABLE 5-I**

Sporn Budgetary Cost Estimate

| Description | Material Cost | Inst'l Cost | Sub-Contract |
|---|---|---|---|
| Filter Vessel | $ 2,800,000 | $ 77,000 | |
| Filter Elements | 3,500,000 | 461,000 | |
| Filter Auxiliary: | -- | -- | |
| Vessel Internals | 3,200,000 | 720,000 | |
| Element Supports | 1,860,000 | 185,000 | |
| Piping (External) | 160,000 | 256,000 | |
| Piping (Insulation) | -- | -- | $ 120,000 |
| Filter Media | 1,700,000 | 7,000 | |
| De-Entrainment Vessel | 50,000 | 12,000 | |
| Media Valve | 41,000 | 4,000 | |
| Regen. H & Exchanger | 350,000 | 8,700 | |
| Water Cooled Exchanger | 66,000 | 5,800 | |
| Baghouse | 72,000 | 4,000 | |
| Vessel Refractory | -- | -- | $ 650,000 |
| Boost Blower | 65,000 | 7,700 | |
| Valves | 70,000 | 22,000 | |
| Filter Controls | $ 100,000 | $ 22,000 | |
| Filter Access & Support Steel | 190,000 | 80,000 | |
| Gas Ducts (Inlet & Outlet) | 550,000 | 34,000 | |
| Electric Allowance | 150,000 | 60,000 | |
| Wiring & Controls | 95,000 | 60,000 | |
| Material Transportation (Based on Barging Filter Vessels) | 380,000 | | |
| Craft Start Up Support | | 130,000 | |
| Erection Equipment | | 300,000 | |
| Sub Total | $15,399,000 | $ 2,456,200 | $ 770,000 |
| Sporn Material & Installation Cost | | | 18,625,200 |

| | | | |
|---|---|---|---|
| CPC Engineering & Support Cost | | | |
| Detail Engineering & Design | 6,600 mhs | $ 396,000 | |
| Project Management | 3,300 mhs | 240,000 | |
| Travel/Per Diem | | 18,000 | |
| QA/QC | 800 mhs | 50,000 | |
| Start Up & Support | 3,300 mhs | 220,000 | |
| Travel/Perdiem | | 100,000 | |
| | Sub Total | 320,000 | |
| | | CPC Sub Total | 1,024,000 |
| | | | $19,649,200 |
| | G&A | | 2,357,800 |
| | Margin | | 2,200,000 |
| | Estimated Program Total | | $24,207,000 |

**TABLE 5-II**

**WEIGHTS**

| Quantity | Item | LBS |
|---|---|---|
| 4 | Filter Vessels | 2,100,000 |
| 80 | Filter Elements | 336,000 |
| 4 Lots | Filter Internals & Supports | 462,000 |
| 4 Lots | Vessel Refractory | 36,000 |
| 1 Lot | Filter Media | 2,030,000 |
| 1 | De-Entrainment Vessel | 32,000 |
| 1 | Media Valve | 12,000 |
| 1 | Regenerative Heat Exchanger | 50,000 |
| 1 | Water-Cooled HX | 21,000 |
| 1 | Baghouse | 6,000 |
| 1 | Boost Blower | 10,000 |
| 1 Lot | Piping (External) | 88,000 |
| 1 Lot | Valves | 10,000 |
| 1 Lot | Insulation | 2,000 |
| 1 Lot | Filter Controls | 2,000 |
| 1 Lot | Access & Support Steel | 100,000 |
| 1 Lot | Inlet & Outlet Ducts | 220,000 |
| 1 Lot | Electrical | 3,000 |
| 1 Lot | Wiring & Controls | 3,000 |
| | Total | 5,523,000 |

### 5.2 Size and Operational Data

In the tabulated data below, information is presented pertaining to the GBF equipment size, operation and necessary utilities.

**Filter**

| | |
|---|---|
| Vessel height, ft | 100' |
| Vessel diameter, ft | 18' |
| Inlet nozzle height above reference elevation, ft | 148' |
| Outlet nozzle height above reference elevation, ft | 70' |
| No. of filter elements | 80 |
| Filter blowback reservoir volume, cu ft | -- |
| Filter media volume (GBF), cu ft | 14,500 |
| Filter media weight (GBF), lb | 2,030,000 |
| Media density, $lb/ft^3$ | 140 (bulk) |
| Media minimum fluidizing velocity, ft/sec | 3.3 |

**Hoppers**

| | |
|---|---|
| Number | 1 (baghouse) |
| Volume, each cu ft | 165 |
| Valley angle, degrees from horizontal | 70 |
| Outlet pipe size, in. | 10" |
| Outlet inside diameter, in. | 10" |

**Filter Performance Data**

**Particulate outlet emissions**

| | |
|---|---|
| particulate loading, ppm | 10 |
| particulate mean dia, micron | 2 |
| particle size distribution (expected) | See Section 3.6 |

**Pressure drop, psi**

| | |
|---|---|
| filter clean/dirty, psi | 1 / 1.3 |
| ductwork, psi | .2 |

| | |
|---|---|
| **Filter face velocity, ft/min** | 72 |

**Total electrical load, kVa**

| | |
|---|---|
| connected (PF=.80, EFF=.94) | 86 (150 HP) |
| maximum operating (PF=.80, EFF=.94) | 82 (143 HP) |
| normal operating (PF=.80, EFF=.90) | 26 (44 HP) |
| voltage/phases | 460 / 3 |
| load list | Boost Blower |

Compressed Air Requirements

| | |
|---|---|
| flow rate, scfm | 30 |
| pressure, psig | 15 SCFM at 90 psig/15 SCFM at 350 psig |
| temperature, °F | 60 |
| dewpoint, °F | -40°F |

Operating Manpower

| | |
|---|---|
| 1st shift | .5 |
| 2nd shift | .5 |
| 3rd shift | .25 |

Maintenance

| | |
|---|---|
| Estimated annual outage time, hr/yr for element replacement, cleaning, etc. | 700 1st yr; 350 subsequent |

Reliability/Availability

Expected availability:

| | |
|---|---|
| Filter, hrs/yr | 8000 |
| Auxiliaries, hrs/yr | 8000 |
| Total system, hrs/yr | 8000 |

## 6.0 REFERENCES

Guillory, J. L., et al, Granular Bed Filter Development Program, Phase II, DOE Report DOE/ED/10373-T10 (Combustion Power Company, Menlo Park, California) (May 1983)

Grace, D. S., et al, Electrostatic Enhancement of Moving-Bed Granular Filtration, 2nd Symposium on the Transfer and Utilization of Particulate Control Technology (July 1979)