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GRANULAR BED FILTER DEVELOPMENT PROGRAM
PHASE II

Quarterly Report for July–September 1981

By
K. Phillips
J. Ferguson
C. Spangler

January 1982
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Combustion Power Company, Inc.
Menlo Park, California

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ABSTRACT

The Department of Energy is sponsoring a multiphase program to investigate the filtration potential of the moving bed granular filter (GBF) for application in pressurized high temperature energy conversion systems. Phase I, which has been completed, included the development of a mathematical model, a cold flow parametric test series in a 1800 ACFM GBF, and investigations of potential dust plugging problems at the inlet screen. During the experimental program, collection efficiencies of 99% and filter outlet loadings less than .005 gr/acf were demonstrated.

The objectives of Phase II are to investigate the effects of elevated temperature and coal combustion particulate on GBF filtration performance; to continue development of the analytical model to reflect the high temperature effects; to optimize filter internal configuration; to perform parametric and long duration tests to characterize the effects of filter design improvements on filtration efficiencies; and to conduct an economic analysis of full scale filters for PFB service. A secondary objective is to evaluate the effect of combustion additives in reducing the alkali concentration in the outlet from the GBF.

Earlier Phase II hot flow testing confirmed that the original GBF design incorporating inlet and outlet screens exhibited a tendency for extensive and irreversible ash plugging. That has led to an alternate design of the GBF internals which eliminated the inlet and outlet screens. This screenless GBF has undergone cold and hot flow tests with collection efficiencies equal to the screened GBF and without ash plugging problems. All current development work under Phase II objectives is being carried out using the screenless configuration.

This report updates the work accomplished in the development of the three-dimensional axisymmetrical model, describes the hot flow test set-up and the particulate and alkali sampling equipment and procedures, includes the test plan for hot flow testing, and reports the results of system checkout following equipment modifications.

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I. SUMMARY OF PROJECT STATUS

The current Granular Bed Filter (GBF) Development Program is a continuation of a two-phase program which began in February 1977. Phase I was devoted to ambient temperature studies of granular filtration phenomena and included construction and testing of a 3000 acfm (maximum) ambient temperature pilot scale GBF, development of a mathematical model for GBF collection performance and experimental bench scale granular filtration studies in support of this modeling effort. This work was previously reported as "GRANULAR BED FILTER DEVELOPMENT PROGRAM, FINAL REPORT #FE-2579-19, April 1978."

Phase II of the program commenced in September 1978 and consists of contract tasks 4 through 9, the current status of which are summarized below.

Task 4 is a continuation of the theoretical analysis, analytical model, and GBF optimization work commenced in Phase I but as applied to high temperature and high pressure applications. Early Phase II hot flow testing of the screened (crossflow) GBF showed extensive and irreversible ash plugging of the inlet screen which led to an alternative screenless design. This configuration change required additional experimental data and new computer model media flow experiments have been completed and reported previously. Development of the governing equations is in progress with completion of an operational model expected by January 1982.

Task 5 includes the test setup and modifications required for each hot flow test under Tasks 6 and 7. The latest modifications for the upcoming tests are described in Section II along with the system checkout results.

Task 6 includes all Phase II hot flow parametric and short duration GBF tests. The last two series of tests, P671 and P672, are planned for October and December. The test plan is presented in Section II.

Task 7 includes a 1000-hour test which was completed in February 1980 and reported previously. General program management and report preparation are also included under Task 7.

Task 8 was cancelled by contract modification M013 after partial completion of a design of a high pressure GBF for testing at high pressure and high temperature.

Task 9 includes an economic analysis and performance analysis of a full scale GBF. Work is scheduled to commence on this task in October after receipt of reference plant data from DOE.

Figure 1 Control Volume used for Determining the Suspended Particle Concentration

II. TECHNICAL PROGRESS

A. Three Dimensional GBF Model: The Finite Difference Development Of The Coupled Particulate Capture Equations

Introduction

The granular bed filter model consists of three governing equations which describe the gas flow and collection of particles for an axisymmetric geometry. In previous reports, the development of the governing equations and physical processes involved in particle capture have been described. In addition, the finite difference equations, solution technique and preliminary results of solving for the gas flow field have been reported. The next step in the completion of the computer model is the development of the finite difference equations which describe particle capture thus giving the solution for the suspended or adhering particle concentration. This solution, combined with the gas flow solution, gives a complete description of the filter's performance.

The primary result of GBF model will be the estimation of the particulate concentration either captured or suspended as a function of location within the filtration bed. To achieve this result the two coupled differential equations describing the suspended and captured particle concentrations must be solved iteratively. First, the suspended particle concentration is found by integrating the governing equations along streamlines. This is done for reasons of stability. Then with this result the adhering particle concentration is computed using the Crank-Nicolson finite difference form of the governing equation. Then the suspended particle concentration is re-evaluated and the process repeated until the change in the two concentrations is below some acceptable value. The finite difference equations required for this process are developed here.

Suspended Particle Concentration

During the development of the conventional finite difference expression, using backward differences and the Taylor Series expansion for the derivatives in the governing equation, it was found that the resulting computational scheme had stability problems which were potentially unsolvable. Therefore it was decided to integrate the governing equation along streamlines. This reduces the partial differential equation to an ordinary differential equation that does not have computational instabilities in its finite difference form. However, such a method has its difficulties causing odd geometries to be solved to attain the correct control volume.

The finite difference expression is best developed by considering the control volume shown in Figure 1. The volume consists of the "square" element shown rotated around the centerline of the model. The volume is bounded by the streamlines ψ_1 and ψ_2 and annular planes perpendicular to the streamline passing through the center of the cross section illustrated. Consequently, suspended particles enter and leave the element only through

the perpendicular plane normal to the center streamline. Within the element, particles are either captured or re-entrained by the gas stream. This is pictured schematically in the figure and labeled with the term $(J-R) N_c (\text{Vol})$. At steady state, the difference between the particles entering and leaving the element must equal the rate of particle capture minus the rate of particle re-entrainment. Mathematically, this is expressed as

$$(NpU)_i A_i - [(NpU)_i + \frac{\partial}{\partial \ell} (NpU)_i d\ell] A_o = (J-R) N_c \text{Vol}.$$

Approximating the derivative with

$$\frac{\partial}{\partial \ell} (NpU)_i = [(NpU)_o - (NpU)_i] / d\ell$$

and using the gas continuity relation (assuming constant temperature and pressure)

$$A_i U_i = A_o U_o - 2\pi(\psi_2 - \psi_1) = Q$$

the equation may be rewritten as

$$Np_o = Np_i - (J-R) \frac{N_c (\text{Vol})}{2\pi(\psi_2 - \psi_1)} \quad (\text{eq. 1})$$

This particular finite difference expression does not have a stability requirement. The only difficult task is computing the annular volume of the element.

Particle Capture and Re-entrainment

Expressions for the rates of particle capture and re-entrainment have been derived previously (see: January-March Quarterly Report). The expressions are:

$$J = (\alpha N_a + \beta) N_p$$

$$R = \gamma N_a$$

where

$$\alpha = \pi d_p^2 \frac{3\pi A_g U d_p}{8 d_c} n_p$$

$$\beta = \frac{\pi}{4} d_o^2 U_{nc}$$

$$\gamma = C \frac{\partial V_c}{\partial r} + \frac{\partial U_c}{\partial z}$$

For the control volume used in deriving the finite difference expression, the capture and re-entrainment terms are evaluated at the midpoint of the control volume. N_p and N_a in the capture and re-entrainment expressions are

$$N_p = \frac{1}{2} (Np_i + Np_o)$$

$$N_a = \frac{1}{2} (Na_i + Na_o)$$

Using the above relations, the finite difference expression for the suspended particle concentration at the outlet of the control volume is

$$Np_o = \frac{2Np_i - \{(\alpha Na + \beta)Np_i - 2\gamma Na\} \frac{Vol}{2\pi(\Psi_2 - \Psi_1)}}{2 + (\alpha Na + \beta) \frac{Vol}{2\pi(\Psi_2 - \Psi_1)}}$$

Computational Method

In practice the streamlines do not conveniently pass from node to node of the finite difference grid. Therefore, a hybrid method is used to determine the suspended particle concentration at each node location. The method uses the streamline that passes through the node, for which the suspended particle concentration is being calculated, and streamlines that lie half way to either side. The locations upstream of where the stream lines cross node to node boundaries is then found to form a control volume from which the suspended and adhering particle concentration entering the control volume can be interpolated from nearby nodes. An example of such a control volume is shown in Figure 2. Once the particle concentration is found for the node the process is repeated progressing from the GBF inlet boundary to the exit of the filter.

Adhering Particle Concentration

The governing differential equation from which the adhering particle concentration is computed has been derived previously by applying the conservation of mass principle around a control volume. The governing equation is (non-dimensional)

$$\frac{\partial}{\partial z} (Ug Np + Uc Na) + \frac{1}{r} \frac{\partial}{\partial r} r (Vg Np + Vc Na) = 0$$

The finite difference form of the equation used to compute the adhering particle concentration results from approximating the derivatives midway between nodes in the z direction and at the nodes in the r direction. This approach leads to a finite difference scheme which is often referred to as the Crank-Nicolson method. The method is inherently stable.

The finite difference equation is best developed using the control volume shown in Figure 3. The number of particles entering and leaving the control volume is shown at each face. At steady state, conservation of mass gives

$$\begin{aligned} & (NaVc)_{i,j} A_b + (NpVg)_{i,j} A_b + (NpUg)_r A_r + (NaUc)_r A_r \\ & = (NaVc)_{i-1,j} A_{t-1,j} + (NpVg)_{i-1,j} A_t + (NpUg)_z A_z + (NaUc)_z A_z \end{aligned}$$

Figure 2 Relationship between the Suspended Particle Control Volume and the Finite Difference Grid

Figure 3 The Control Volume used for Determining the Adhering Particle Concentration

Using the following interpolations for the suspended and adhering particle concentrations at the left and right hand boundaries of the control volume,

$$(NaUc)_r = \frac{1}{4} Uc_r (Na_{i,j} + Na_{i,j+1} + Na_{i-1,j} + Na_{i-1,j+1})$$

$$(NaUc)_\ell = \frac{1}{4} Uc_\ell (Na_{i,j} + Na_{i,j-1} + Na_{i-1,j} + Na_{i-1,j-1})$$

$$(NpUg)_r = \frac{1}{4} Ug_r (Np_{i,j} + Np_{i,j+1} + Np_{i-1,j} + Np_{i-1,j+1})$$

$$(NpUg)_\ell = \frac{1}{4} Ug_\ell (Np_{i,j} + Np_{i,j-1} + Np_{i-1,j} + Np_{i-1,j-1})$$

the above equation expressing the conservation of mass provides one equation for the three unknowns $Na_{i,j-1}$, $Na_{i,j}$ and $Na_{i,j+1}$. All other variables are known including the values of Na at the previous level $i-1$. Two other equations can be written similar to this one for the nodes to the right and left. However, this also introduces two more unknowns. The process is repeated until the nodes at either boundary are reached. At each boundary an additional equation is obtained without introducing any new unknowns. A system of n equations with n unknowns results, where n is the number of nodes in the i -th level of the finite difference grid. The simultaneous equations are then solved using Gaussian elimination.

Computational Method

The adhering particle concentration is first computed one grid division from the media inlet (gas exit) of the filter. The boundary condition specifies the adhering particle concentration at the media inlet. The complete solution is obtained by progressing from this boundary one grid spacing at a time through the filter solving the system of simultaneous equations at each step. As mentioned previously the method is inherently stable.

Summary

Finite difference equations have been derived from which the suspended and adhering particle concentrations can be computed. The schemes are each individually stable and should pose no conceptual problems in programming.

NOTATION

A	- Area
Ag	- Happel hydrodynamic constant
dc	- Collector diameter
dp	- Particle diameter
J	- Rate of particle capture
ℓ	- Length of control volume element
Na	- Number of adhering particles per collector
Np	- Suspended particle number concentration
Nc	- Number density of collectors
R	- Rate of particle re-entrainment
U	- Gas velocity
Uc	- Collector radial velocity
Ug	- Gas radial velocity
Vc	- Collector vertical velocity
Vg	- Gas vertical velocity
Vol	- Volume of element
α	- Particle to particulate capture coefficient
β	- Clean grain capture coefficient
γ	- Re-entrainment coefficient
Nc	- "Clean grain" capture efficiency
Np	- Particle-particle capture efficiency

Subscripts

i - Inlet of control volume; node index

j - Node index

o - Outlet of control volume

z - Left face of control volume

r - Right face of control volume

B. Hot Flow Test Set-Up

All hot flow testing for the GBF development program has been conducted in Combustion Power Company's 5 ft² atmospheric fluid bed combustion facility. This facility has a flow capacity of 2000 ACFM at 1600 F and contains a granular bed filter which has gone through several configuration changes during the development program. For the upcoming test program (two 200 hour tests described in Section II D) several changes to the GBF have been made plus modifications to other components of the facility. These changes were described previously in the January-March 1981 quarterly report. A description of the facility follows along with identification of the changes. A schematic of the system is shown in Figure 4.

Coal and Additive Feed System

A new supply of Illinois No. 6 coal was procured as fuel for this test and will be processed to a size fraction $\frac{1}{4}$ -0 inch. The coal will be fed from a hopper onto a calibrated K-TRON weigh belt feeder which will be manually controlled at a rate to produce the desired system temperatures. From the weigh belt, the coal passes through a rotary airlock into the fluidizing air line and is pneumatically transported into the fluid bed.

The SO₂ sorbent additive to be used is dolomite (Dolowhite No. 6), nominal particle size 0.09-0.14 in., procured from Kaiser Minerals. This additive will be used as received without processing, and will be fed using a small calibrated BIF screw feeder which will discharge directly into the area just above the rotary airlock. The additive will mix with the coal and will be pneumatically transported into the fluid bed.

The alkali suppressant additive will also be fed into the area just above the rotary airlock using a separate calibrated Acrison screw feeder. This additive will mix with the coal and dolomite, pass through the rotary airlock, and be pneumatically transported into the fluid bed.

Main Air Blower

All low pressure air required for the GBF tests (the fluidization air and the GBF media lift air) will be supplied by a six-stage centrifugal blower. Air flows to the FBC and GBF media lift system are manually controlled for the desired rates.

Fluid Bed Combustor

The FBC has a 5 sq ft bed area with a conical bottom section into which the fluidizing air and additives enter and where the major portion of the combustion process occurs. The vertical height from the top of the cone to the combustor outlet is 15 ft. The FBC is constructed with a carbon steel shell, 4 $\frac{1}{4}$ " insulating refractory and 4 $\frac{1}{2}$ " low abrasion refractory. One new 54-3/4 in. high combustor section was added during modifications to increase freeboard height. The bed material will be 800 lb of 2 mm alumina beads.

Figure 4 CPC Moving Bed Granular Filter Pilot System Schematic

Recycle and Separator Cyclones

Two stages of cyclones will be used. The first cyclone is a refractory lined recycle cyclone which recycles the larger elutriated combustor particulate back into the combustor.

The second cyclone is of stainless steel construction and separates the larger particles (10-20 μm) from the gas stream. This cyclone was designed specifically for this test program with a reverse flow section to improve the exit gas stream flow characteristics and thus eliminate the spiral-ash pattern. A schematic of this cyclone is shown in Figure 5.

Hot Gas Ducts

The GBF inlet and outlet ducts were modified and re-routed. The outlet duct diameter was decreased from 8-in. diameter to 6-in. diameter and a new orifice plate installed to monitor gas flowrates. Two pitot ports have been installed 90-degrees apart on both the inlet and outlet ducts just downstream of the respective sample ports. The flow profile of each duct will be determined at ambient conditions during the tests using both an "S" and Kiel pitot tube at an airflow rate of nominally 1600 acfm. The 8-in. inlet duct will be traversed at seven points in the horizontal and vertical positions. The 6-in. outlet duct will be traversed at five points horizontally and vertically. The ambient flow profile data will be compared for different operating conditions. Both ducts were re-routed to provide ample space for new sampling ports.

Granular Bed Filter

The upper fluid bed media cleanup system was removed and the lift pipe shortened by 8 ft. The GBF internals were modified to add a 14 cu ft media inventory hopper with eight media distribution legs and a modified gas inlet duct. The inlet duct termination was modified to be similar to the cold flow design which was effective in minimizing ash deposition and provided uniform air flow distribution. The GBF will be filled with 13,000 lb of 2mm alumina beads. A schematic of the GBF is shown in Figure 6.

The entire GBF was raised 4½ ft, and the lower two-angle cone was modified by deleting the 60-degree cone section and extending the 70-degree cone to its apex. This resulted in a 1½ ft longer GBF seal leg, which is expected to improve media circulation performance.

Instrumentation and Control System

Pressure, flow, and temperature measurement locations are shown in Figure 7. All pressure and flow measurements will be connected to readout instruments on the main control panel. Appropriate calibration curves will be developed for required flow measurements. Selected pressures and flows

Figure 5 Schematic of Separator Cyclone Design

Figure 6 Schematic of Moving Screenless Granular Bed Filter

TEMPERATURE

TEMPERATURE		
MODEL # - T/C LOCATION		
DIAL NO	TF	THERMOCOUPLE LOCATION
1	100	FBC AIR SUPPLY FROM BLOWER
2	120A	FBC LOWER CONE
3	120B	FBC MIDDLE CONE
4	120C	FBC UPPER CONE
5	120E	FBC LOWER FREEBOARD
6	120F	FBC UPPER FREEBOARD
7	120G	FBC UPPER FREEBOARD
8	125	PREHEAT BURNER EXIT
9	130A	DIPLEG CYCLONE (UPSTREAM)
10	130B	DIPLEG CYCLONE (MIDDLE)
11	130C	DIPLEG CYCLONE (DOWNSTREAM)
12	131	RECYCLE CYCLONE EXIT
13	123	INLET SAMPLING PORT (GBF)
14	123	GBF INLET
15	140	LOWER BURNER
16	141	LOWER BURNER EXIT
17	182	GBF MEDIA LIFT TRANSPORT LUNER
18	185	GBF MEDIA LIFT TRANSPORT UPPER
19	171A	GBF MEDIA LOWER (ISIN)
20	171B	GBF MEDIA LOWER (ISIN)
21	177	GBF FREEBOARD
22	173	GBF FREEBOARD
23	175	GBF OUTLET
24	178	OUTLET SAMPLING PORT (GBF)
25	178	GBF MEDIA INVENTORY VESSEL
26	178	GBF MEDIA INVENTORY VESSEL
27	178	GBF MEDIA INVENTORY VESSEL
28	181	DISCHARGE VESSEL EXIT
29	183	BAGHOUSE

PRESSURE

PRESSURES	
ID	NAME
PI 100	FBC FLUIDIZING AIR PRESSURE
PI 108	FBC AIR FLOW-ORIFICE ΔP
PI 130	FBC BOTTOM CONE PRESSURE
PI 131	FREEBOARD PRESSURE
PDI 121	RECYCLE CYCLONE ΔP
PDI 172	SECOND STAGE CYCLONE ΔP
PI 176	GBF INLET PRESSURE
PDI 170	GBF ΔP
PDI 161	SEAL LEG ΔP
PI 180	LIFT PIPE PRESSURE
PDI 180	LIFT PIPE ΔP
PDI 180A	LIFT PIPE ΔP
PI 131	EXHAUST DUCT ORIFICE PRESSURE
PI 176	EXHAUST DUCT ORIFICE ΔP
PI 181	VENT LINE PRESSURE
PI 172B	PREHEAT BURNER ORIFICE ΔP
PI 140	LIFT AIR PIDI ΔP

Figure 7 Pressure and Temperature Instrumentation

will be continuously recorded on a trend recorder. Temperature measurements will be connected to a selector switch and readout unit and to a 24-channel recorder for continuous recording. An opacity monitor will be installed in the exhaust duct downstream of the GBF. This monitor will be connected to the trend recorder for continuous on-line recording.

The electrical control system is still essentially the same as that used during the previous GBF tests except for the deletion of unused systems, such as the upper fluid bed and the data acquisition system. All motor and most flow controls are located on a central operator's control panel near the pressure and temperature readout units. An illuminated view panel serves as an operational status board showing equipment status, pressure and temperature locations, and visual alarms. System safety is monitored with audio and visual alarms for such items as burner flameout, over-temperature and over-pressure conditions, and low media circulation.

Preheat System

At the start of a test, the FBC will be heated with the preheat propane burner until the bed temperature reaches 1000 F when coal feed will be started. The preheat burner is an Eclipse thermal blast air heater capable of heating up to 400 scfm air to the preheat system operating limit of 1500 F. Propane will be supplied from a 500-gal storage tank at the demand rate of 2 to 4 scfm at 30 psi.

Particulate, Alkali, and Gas Sampling Systems.

Major changes have been made to these systems since the last test series. The hot gas ducts were modified to provide longer straight run sections for particulate sampling, new 4-in. diameter sample ports were installed, new pitot tube ports were installed and new "S" and Kiel pitot tubes procured. New design particulate and alkali sample probes were fabricated, and several new high temperature sample train components were procured, e.g., two impactors, two pre-impactors, three filter holders, plus ancillary equipment. All sampling probes will be heated in the sample port using a propane air heater to pass clean hot gas over the probes. The gas analysis system is described by Table I and Figure 8.

TABLE I

Specific Gas Analyzers utilized in the CPC Gas Monitoring System

GAS COMPONENT	ANALYZER MANUFACTURER & MODEL	TYPE OF ANALYZER	AVAILABLE DETECTION RANGES (VOL. CONCENTRATION, DRY BASIS)*	COMMENTS
CO ₂	BECKMAN 864	NON-DISPERSIVE INFRARED	1 to 25% *	NON-LINEAR LOWER CONCENTRATION RANGE (0.5%-5%) ALSO AVAILABLE.
O ₂	TELEDYNE 346A	ELECTROCHEMICAL	1 to 25% 0.5 to 10% * 0.25 to 5%	BECKMAN 715 ANALYZER AVAILABLE AS BACKUP UNIT (0.5%-5% & 1%-25%).
CO	ANARAD 500	NON-DISPERSIVE INFRARED	10 to 500 PPM* 50 to 5000 PPM	BECKMAN 864 ANALYZER AVAILABLE AS BACKUP UNIT (10-1000 PPM).
SO ₂	DUPONT 400	UV ABSORPTION	10 to 500 PPM 100 to 5000 PPM	SO ₃ REMOVED VIA CONDENSER SYSTEM.
NO	THERMO ELECTRON 10 A	CHEMILUMINESCENCE	5 to 250 PPM* 25 to 1000 PPM	NO ₂ TYPICALLY REMOVED BY CONDENSER SYSTEM. BY ALTERING SAMPLING SYSTEM, ANALYZER CAN ALSO DETECT AND MEASURE NO ₂ AND/OR TOTAL NO _x .
C _x H _y AS CH ₄ (HYDRO-CARBONS)	BECKMAN 400	FLAME IONIZATION DETECTOR, HYDRO-GEN FUEL	5 to 100 PPM* 25 to 1000 PPM 100 to 10,000 PPM AS METHANE, i.e., CH ₄ .	DETECTS COMBUSTIBLES UP TO APPROXIMATELY C ₅ . HEAVIER HYDROCARBONS ARE REMOVED IN THE CONDENSER SYSTEM.

* Indicated ranges are the standard ranges utilized. Other ranges can be utilized with proper calibrations if sufficient planning time is allowed for ordering calibration gases.

Response Times: The response times for the IR, UV, FID, and chemiluminescence type analyzers are less than one second for 90% of full scale, while the electrochemical type (i.e., O₂) is ten seconds for 90% of full scale. With the recorder response times of 0.25 second for 100% of full scale, the total response times are determined by the analyzers. The sampling system has a total internal volume of approximately 0.2 cu ft, resulting in a delay of 30-35 seconds from duct to analyzer. Thus, the total gas monitoring system records the composition in less than 45 seconds after the gas sample is extracted from the duct.

Figure 8 CPC Gas Monitoring System Schematic

C. Particulate And Alkali Sampling Equipment

The design and construction of the particulate and alkali sampling probes were completed during this reporting period. Minor changes were incorporated in the design concept as reported on in the April-June 1981 quarterly report. The final design is shown pictorially in Figure 9. The principle changes made to the design concept included; (1) installing the sample port isolation ball valve short-coupled to the gas duct, (2) locating the hot gas probe heating lines to the upstream side of the isolation ball valve, (3) addition of a probe preheat burner, (4) deleting the front end probe seal on all the sampling probes, (5) modifying the alkali probe to sample the "total alkali" method in lieu of the "filtered vapor" method.

Changes 1 through 4 were made to reduce the length and complexity of the probes for operational reasons and to improve preheat control. The change to the "total alkali" method was due to difficulty in finding suitable high temperature (1500 F) filters.

The inlet and outlet duct particle sample ports installed are similar except for the size of the duct on which they are installed. The GBF inlet duct is eight inch diameter schedule 40 pipe and the outlet duct is six inch diameter schedule 10 pipe. On both installations the sample ports are installed horizontally with the isolation ball valve flange connected to the duct flange nominally 3" from the outer circumference of the gas duct. The sample port and isolation ball valves have a minimum 4 inch I.D., with the sample port overall length aft of the ball valve of 28 inches. The sample port contains a 2 inch hot gas inlet and outlet line for sample probe pre-heat. Hot gas for probe pre-heat is supplied by a propane air blast heater capable of providing in excess of 200 acfm air at 1600 F to both sample ports simultaneously. For probe heatup, the probe is inserted into the sample port with the nozzle near the closed isolation ball. Clean hot gas then flows around the sampling probe until the desired probe temperatures are achieved.

The sample trains are of three configurations: one for particulate loading, one for particulate size distribution and one for alkali capture. The aft end of the sample train's probe is typical for all three configurations. This aft section mates with a filter holder located in the same position for all three sample trains to provide a common connection for interchangeability. In addition, the aft end contains a packing gland connector to mate with the sample port and outlet connections for thermocouples and sample flow lines to the flow control unit. The aft probe sections are the same for both the inlet and outlet ducts. Three aft probe sections were fabricated to optimize sample train turnaround time between samples. The sample flow control consoles to be used are existing units used for all previous EPA-5 and Andersen impactor sampling. These units have been completely refurbished and necessary components calibrated.

Figure 9 Particulate and Alkali Sample Train

The particulate loading sample probes (Figure 10) were fabricated to be compatible for sampling in accordance with EPA Method-5. The inlet duct sample probe will contain a nozzle, nozzle guide and filter holder. The outlet duct probe is the same as the inlet except for the different nozzles used. The inlet and outlet duct nozzles have been sized to extract the sample flow at isokinetic flow conditions.

The size distribution sampling probe (Figure 11) consists of a pre-impactor, an APT impactor and filter holder. Two pre-impactors were fabricated from a design procured from Southern Research Institute. One of the pre-impactors will be used for inlet duct sampling and the other for the outlet duct sampling. These pre-impactors are essentially rectangular boxes 1-9/16" x 2-1/8" with an inlet tapered nozzle and outlet tube. The inlet tapered nozzle was appropriately sized for the duct in which it will be used. Two five-stage cascade impactors as shown were procured from Air Pollution Technology, Inc. (APT), one for the inlet and one for the outlet, together with 22 orifice plates of 13 different hole size and pattern configurations. Selected orifice plates will be arranged in the appropriate impactor to capture and characterize particulate size at the various test conditions.

The alkali sampling probe is designed to use the same impingers and flow control module components as those used for the loading and size distribution sampling probes. The casing is identical except for a larger access (cutout) opening. The front probe section contains a nozzle, nozzle guide and filter holder. The interior surfaces of the nozzle and probe section back to and including the front half of the filter holder will be gold plated to ensure an inert non-reactive surface exposed to the alkali vapors. The nozzle has been sized to sample isokinetically. The filter for collecting the "total alkalis" is a silver foil type filter pad. Only one alkali probe has been fabricated for sampling the GBF outlet duct only.

Figure 10 Particulate Loading Sampling Probe

Figure 11 Size Distribution Sampling Probe

D. Test Plan

Introduction

The screenless Granular Bed Filter (GBF) design was first tested under cold flow conditions in November, 1978 followed by hot flow testing in January, 1979. During the period February through April 1979, additional cold flow and hot flow parametric tests were run to check out configuration improvements and to determine the limits of operations and optimum operating points. During the period May, 1979 to February, 1980 a 1,000 hour test was run in four segments (100, 200, 300 and 400 hours) to quantify corrosion, erosion, and deposition effects on metal coupons and a cascade section. The results showed no evidence of erosion, but there was heavy deposition in the duct upstream of the GBF and minor deposition in the cascade. The highest temperature in the filter was 1550 F, slightly under the planned temperature of 1600 F due to duct, cyclone, and GBF heat losses. Particulate removal efficiency averaged over 99% for inlet loadings of 0.4 to 1.0 gr/acf. The combined results of these tests revealed problems requiring further development, namely:

- Fractional efficiency data were unreliable, since up to 60% of the inlet impactor sample was collected in the nozzle and probe and, thus, it was not sized by the impactor stages.
- Representative inlet duct particulate samples may not have been taken due to a spinning flow pattern.
- The data from the impactors was processed for low temperature conditions which, in accordance with Marple's cut point theory, introduces significant errors at high temperature.
- The media cleanup system was overly complex in that an external fluid bed was required.
- The GBF had a double-angled cone section which caused undesirable media flow profiles as shown by subsequent cold flow tests.
- The GBF internal media distribution system created peaks and valleys in the media bed surface that limited throughput due to potential "blowthrough."
- Heat losses prevented operating the GBF safely at 1600 F due to the high upstream temperatures required.

During 1977-1978, Combustion Power Company ran a series of tests for the Weyerhaeuser Company to demonstrate the effectiveness of an alumino-silicate additive in suppressing reactive alkalis in the adiabatic fluid

bed combustion of wood. The results indicated above 90% suppression of reactive alkali and a significant reduction in corrosion of turbine blade alloy coupons located downstream of the GBF. Under the current GBF development program, the effectiveness of the same aluminosilicate additive will be evaluated in the fluid bed combustion of high sulfur coal, along with the particulate capture performance of the GBF.

Objectives

The objectives of the final test series are:

- To evaluate configuration improvements to the GBF media distribution system, cone shape, media cleanup system, and media inventory system.
- To obtain more reliable fractional efficiency and total loading data through improved particulate sampling methods and data processing.
- To obtain baseline alkali emission data without the use of aluminosilicate additive in the combustor.
- To evaluate the alkali suppression effectiveness of selected aluminosilicate additive to the combustor.
- To provide hot flow experimental data to verify the 3-D analytical model.
- To obtain particulate capture and alkaline emission data with the GBF operating at 1600 F.

Test Conditions

Two test series will be run in the Model #4 fluid bed facility (described in Section II B). The first test, P671, will be run without the use of alkali suppression additive, thereby providing reference data for comparison with the second test, P672, which will use an alkali suppression additive. Both tests will be similar in all other process conditions and cover 200 hours of operation, at least 100 hours of which will be at steady state conditions. Included in each test is a period of operation at very high particulate loadings (~ 3 gr/acf) to the GBF in order to evaluate its performance under upset conditions (such as plugging of the upstream collectors).

The planned operating conditions for both tests are:

GBF Inlet Temperature	1600 F
GBF Inlet Gas Flow	1600 ACFM

Inlet Particulate Loading	0.5 gr/acf
Media Circulation Rate	~ 25 lb/min
Fuel	Illinois #6 coal
Sorbent	Dolomite (Kaiser DOLOWHITE #6)
Alkali Suppression Additive	Kaolin-based aluminosilicate (P672 only)
Recycle	Yes

Data Recording and Samples

A continuous record of all significant test events will be made in the operator's log book. All log entries will be preceded by an elapsed time entry for chronological reference. All pressure and temperature data available from the control panel will be manually logged on data sheets hourly. At this same hourly logging period the coal rate, dolomite rate, kaolin rate, and gas analysis data will be manually recorded on data sheets.

In addition to the hourly logging of data, a log will be maintained of all solid inputs and outputs, i.e., coal, dolomite, kaolin, collected ash, and feeder valve blowback dust (fine feed material collected by dustkop system).

Selected temperatures which will provide key temperature histories will be continuously recorded on a multipoint temperature recorder. Selected pressures, ΔP 's, opacity and flows and all gas analysis data (O_2 , CO , CO_2 , SO_2 and NO) will also be recorded continuously on trace recorders.

Particulate, alkali, and solid input and output samples will be taken during periods of the tests as shown in the following table.

SAMPLES MATRIX

Sample	Day	Preheat		Normal Loading					High Loading	
		1	2	3	4	5	6	7	8	9
EPA-5 Inlet			x	x	x	x	x	x	x	x
EPA-5 Outlet				x	x	x	x	x	x	x
APT Impactor Inlet			x		x	x	x	x		
APT Impactor Outlet					x	x	x	x		
Alkali Outlet				x	x	x	x	x		
Coal				x	x	x	x	x		
Dolomite				x	x	x	x	x		
Kaolin (P672 only)				x	x	x	x	x		
Separator Cyclone Ash				x	x	x	x	x		
GBF Ash				x	x	x	x	x		
FBC Bed Material				x	x	x	x	x		

Data Reduction and Analysis

Raw process information from each test will be delivered principally in the form of hand-logged hourly operating data sets. In addition, selected parameters for which trends, as well as absolute values provide critical real-time operating information (e.g., filter pressure drop) will be automatically recorded on continuous analog strip charts and made available as backup to the hand-logged data. All hand-logged data will be transferred to magnetic tape storage and plotted in order to uncover any obvious typographical errors but will not be edited further unless comparison of these plots with corresponding strip-chart data (where possible) indicates an error in the original record.

This computer file will be used in conjunction with a data reduction program to convert the recorded data to meaningful engineering units. The derived parameters will be:

- Gas flowrate to GBF
- Media circulation rate

These calculated data will be recorded in a second file along with the following measurements taken directly from the log sheets:

- Filter pressure drop
- Filter temperature (inlet and outlet)
- Outlet capacity

Gravimetric particulate samples will be processed by standard laboratory methods and reduced to the usual loading units using a CPC-developed computer program based on conventional EPA Method 5 calculations.*

Size classification samples will be taken with new APT impaction classifiers specifically selected for high-temperature sampling. While the laboratory and calculation techniques for handling such data are qualitatively similar to that employed in connection with the Andersen classifiers used in previous tests, CPC has acquired and set up on an in-house computer the Southern Research Institute Cascade Impactor Data Reduction (CIDR) program, which performs basic data reduction incorporating the "Marple Theory" Reynolds number effect on plate cut size determination, calculates grade efficiencies, and includes a statistical analysis when multiple samples are available.

In order to present the performance of the filter in simple tabular form, as well as provide input to the analytical model, each test will be reduced to a representative set of parameters (average GBF temperature, etc.). In order to do this objectively, the data set for each test will be

* This program has been used for all previous particulate data reduction associated with GBF testing at CPC.

analyzed to locate the "best" steady-state operating period.* Since there is likely to be relatively few complete particle samples compared to the number of process variable records during the steady state period, simple averages of overall and grade collection efficiencies will be taken as representative of the test, although plots of these collection efficiencies versus elapsed time will be made to illustrate any trends that might be present.

As a further check on major measurements, simple energy/mass balances around the combustor-cyclone system during the steady-state period of each test will be conducted to confirm that those measurements critical to a description of GBF performance (e.g., gas flowrate, temperature, and ash loading) are consistent with independent measurements such as fuel flow, O_2 level, and separator cyclone removal. The degree to which these redundant measurements agree will be taken as an indication of the uncertainty in determining the major independent variables.

Evaluation of alkali emissions in the GBF exhaust gases will be based upon 1) the collection of total aerosol samples via extractive methods from the exhaust gases and subsequent laboratory analyses for alkali content, and 2) the collection of representative feed and product samples from the total system and subsequent laboratory determinations of elemental compositions. A series of samples will be collected during the steady-state operation periods of both the test with coal and dolomite only (i.e., baseline conditions) and the test with addition of aluminosilicate to suppress reactive alkalis.

Due to the temperature of the final filter (nominally 500-700 F) and method of collecting, the extracted total aerosol samples will include alkali compounds in all phases including solid particulates, solidified liquids, and condensed vapors. The total-alkali content of the samples will be determined by atomic absorption analyses via a fluoroboro acid matrix ("AA/FBAM") and the water soluble fraction will be determined by AA on the water leached fraction. From the process data (i.e., temperature, pressure, flow, and gas composition) and feed and product solids rates during the steady state periods, a mass balance of the total system will be computed and subsequently converted to the individual alkalis and other elemental balances from laboratory analyses of selected feed and product samples via AA/FBAM and ICAP**/FBMA procedures.

* Roughly defined as the maximum period of continuous operation during which

$$\frac{s}{\sqrt{n}} < 0.05 \bar{x}$$

for each major variable. s is the standard deviation of the period, n is the number of data records, and $\bar{x}$ is the average of data over the period.

** Inductively coupled plasma emission spectroscopy.

Thus, the soluble-to-insoluble alkali ratios of the GBF emissions and system alkali balance will be utilized as an indication of the conversion of reactive alkali compounds to alkali aluminosilicate combustion additive. (The alkali aluminosilicates are relatively insoluble in water compared to the high solubility of the common alkali compounds found as oxides, hydroxides, chlorides, sulfates, etc., in combustion systems; i.e., the compounds typically referred to as "reactive".)

Selected samples will also be analyzed via x-ray diffraction to identify the molecular composition of the emitted aerosols and related products of the system.

E. System Checkout Results

Test Operations

The Model 4 GBF check-out test was run during the period September 21 through 25, 1981. This was the first hot test of the GBF system since undergoing major modifications. The primary purpose of this test was to check out the recent equipment modifications under hot operating conditions and to check out particulate sampling procedures using the new probes.

Test operations were started (ET=0) on September 21, 1981 with the light off the propane preheat burner. After 80 minutes the bed temperature was 960 F and coal feed (Illinois #6) was started at a low rate. The coal rate was gradually increased until the bed temperature of 1250 F was reached and the preheat burner was turned off. At ET 160, dolomite was started at 0.8 lb/min and fluidizing air flow was adjusted for 5.5 fps. Initially, the media rate was set at 40 lb/min. In an attempt to increase the GBF heat-up rate, media circulation was increased at ET 484 to a rate of 60 to 80 lb/min and the lift pipe temperature maintained 500 to 600 F higher than GBF media temperature. This resulted in a media inventory hopper temperature 100 F above the GBF freeboard temperature. At ET 1435 the fluid bed airflow was increased to 7 fps which increased the GBF inlet temperature to 1500 F with the fluid bed at 1750 F.

It appears that GBF heat-up can be achieved faster with a high media circulation rate and high main air flow. However, higher air flows also contribute to more thermocouple damage, particularly in the combustor, where four thermocouples were eroded away during the period when fluidizing airflow was 7 fps.

At ET 2986, the system airflow was reduced to planned test conditions (6 fps/1600 ACFM) to obtain particle samples. To maintain the GBF inlet temperature at least at 1530 F, the bed temperature was increased to over 1800 F. The temperature history is shown in Figure 12.

Components/Subsystems Performance

a) Instrumentation:

- The propane regulator for the lift pipe burner was replaced because it was limiting flow. It appeared to have a faulty diaphragm.
- The thermocouple selector switch was sloppy, causing much difficulty in obtaining desired temperature readings. The selector condition continued to worsen to where some of the channels were not receiving proper input.

Figure 12 Model 4 GBF Checkout Test Temperatures

- The KTRON (weigh belt conveyor) alarm was not working properly. It failed to respond when the supply hopper ran out of coal.
- Number 4 thermocouple in the fluid bed broke off and was replaced. Thermocouple number 2 became open early in the test and remained inoperative.
- On the third day of testing, the IRCON temperature indicator was checked with a calibrated input and indicated 41 F high. It was also checked against two DORIC units, showing the ICRON high 30-36 F. One of the DORIC units was installed which indicated 5 F high for a (MV) input @ 1000 F. Before the GBF test P671, the MV-temperature calibrator will be calibrated and all temperature indicators will be set properly.
- When the thermocouple indicator switch was at certain positions, the temperature would suddenly drop 40-60 F, hold the new temperature for a few seconds, then return. At first, it was thought the problem was caused by the selector switch, but later the temperature chart recorder was turned off and the temperature indication held steady. This showed that the chart recorder had some feed back influence on the (MV) signal.

b) Recycle Leg:

The recycle leg to the combustor maintained flow continuously, shown by the temperature drops down the leg.

c) Separator Cyclone:

No problems were encountered through the check-out test. A total of 2080 lb of ash were collected for the 3-day test period.

d) Combustor:

No problems were encountered. The combustor operated well due to a consistent feed system. The combustor afterburning was 20-30 F and 50-70 F at 5.5 and 7.0 ft/sec fluidizing velocity respectively.

e) Media Circulation System:

The circulation system behaved well, requiring only occasional adjustments.

f) Feed System:

- The coal supply hopper (just above the KTRON) bridged three times. The problem was solved by turning on the small hopper vibrator.
- The small baghouse connected to the feeder valve provided good suction, keeping the test area free of dust from feeder valve leakage. The dust leakage was 6.5% of the coal and dolomite put into the system. The initial catch from the feeder valve baghouse was approximately 20 lb/hr because it included dust from the pre-checkout combustor refractory cure. From then on, it varied from 5 to 12 lb/hr, depending on the gas flow. The general trend was for the collection rate to increase with gas flow. When feeding metakaolin in addition to coal and dolomite, the collection rate increased from 5 to approximately 7½ lb/hr.
- The coil spring on the KTRON weight conveyor needed to be vacuumed every hour. Twice during testing, the operator noted that the conveyor belt was jamming. Apparently coal and dolomite floating from the feeder valve leakage builds up on the edges of the belt, sometimes forcing the belt alignment to change. The jamming can be avoided by vacuuming the belt edges every two hours. Otherwise the KTRON worked smoothly.
- The coal, dolomite and metakaolin feed systems provided flow rates consistent with the set points.

g) Media Inventory:

It was expected that the filter media level in the supply reservoir would drop due to thermal expansion of the filter. The level was found to be nearly the same at cold or hot conditions.

h) Sampling:

A total of four particulate samples were taken, two EPA-5 inlets, one EPA-5 outlet, and one inlet APT Impactor. Without the metakaolin additive, the inlet loading was 0.3-0.4 g/acf, with the outlet at 0.008 g/acf. The APT Impactor inlet sample was taken during metakaolin addition and indicated a loading of 1.6 gr/acf. This loading is considered invalid due to problems measuring the low sample flow rate required for the Impactor. The preliminary sampling procedures were checked out and found to be satisfactory except for the following changes:

- The EPA-5 (inlet) nozzle diameter will be increased to require a higher velocity gas flow through the filter. This will

achieve a higher, more easily measured sampling line orifice ΔP . The sampling time will be reduced from 40 to 20 minutes due to filter overload.

- The APT Impactor will be modified for the same reason as the EPA-5 inlet probe (sampling gas flow too low for reading orifice ΔP), but in a different manner. A pressure transducer will be connected to make the orifice ΔP reading more sensitive. A calibration curve will relate sampling probe gas flow versus pressure transducer millivolt output.
- The Alkali probe has not been completed and will require some checking out during heat-up for test P671.

i) System Limitations:

The intended test condition of 1600 F GBF Gas inlet temperature at 1600 acfm was not achieved due to heat loss through the ducting between the combustor and granular bed filter. A sketch of the system temperature profile is shown in Figure 13. From the post-test meeting, it was decided to increase the insulation thickness of the ducting.

j) Pitot Tube Traverses:

The GBF inlet and outlet velocity profiles were taken with standard, kiel, and S-pitot tubes and they were consistent with those taken during the pre-checkout combustor refractory cure. Along the horizontal axis of the inlet (parallel to the sampling duct), the standard pitot produced a very flat curve. The kiel profile was steep near the pipe wall just downstream of the sampling port, then flattened out near the midpoint of the duct. The S-pitot profile was flat one-third of the duct diameter, then there was a rapid increase to a new flat profile, which may have affected the pitot profile. The standard pitot may have been less affected because it extends farther upstream where the flow disturbance has not had time to develop.

The vertical traverses (perpendicular to the sampling duct) for the kiel pitot were more symmetrical across the duct diameter. Only half of the S-pitot vertical traverse could be taken due to an interference problem. In general, the profiles did not vary much in shape with the flow rate, only in magnitude.

Figure 13 System Gas & External Temperatures

k) Gas Analysis:

The gas analysis equipment was very steady during the check-out test with the exception of the SO₂ analyzer which started working properly toward the end of the test.

F. The Cascade Impactor Data Reduction System (CIDRS) Program

The CIDRS program was received from Southern Research Institute and installed on CPC's PDP 11/23 computer. Minor changes had to be made to the program so it would run on the PDP computer with the RSX-11M operating system. The data base was also changed to accommodate the APT Impactor to be used for the hot flow tests of the granular bed filter. The main purpose of the program is to reduce raw impactor data to loading and size distribution information for the extracted sample. An important feature of the program is that it incorporates the influence of the jet Reynolds number upon the plate's cut point that was first found by Marple and Liu (1974)*. Most impactation cut point determinations assume the jet Reynolds number does not affect the cut point. This happens to be only true for a limited range of the Reynolds number. The CIDRS program is also capable of computing collection efficiency for a device as a function of particle size. The method utilizes spline fits to the inlet and outlet size distributions from which fractional efficiencies are computed.

Once the CIDRS program became operational, the cut points of the plates purchased from APT were investigated. The program was run a number of times to find each plate's cut point as a function of volumetric flow rate through the impactor. The results are shown in Figure 14 for an impactor temperature of 1000 F. As expected, cut points vary with the square root of the flow rate for the larger size plates. The smaller plates deviate from this pattern and this is attributed to the cut point dependence on Reynolds number. In general, the cut points agree favorably with the cut points furnished by APT.

The effect of temperature on the cut points was also investigated. For an objective evaluation, the mass flow rate through the impactor was kept constant. In this way, the magnitude of the errors caused by changes in impactor temperature during sampling can be quantified. Figure 15 illustrates the results for a pair of plate sizes. Two mass flow rates were chosen that would be typical of the sampling rates in actual use. The investigation revealed that the cut points for each plate changed by approximately one-half micron for a temperature change of 400 F. On a percentage basis this error becomes serious for quantifying submicron particle distributions. However, such large temperature changes during sampling are not expected.

The primary reasons for a plate's cut point insensitivity to changes in temperature appear to be the compensating effects of volumetric flow rate changes and viscosity differences with temperature. As the temperature drops so does the volumetric flow rate thus increasing the cut point. Compensating this effect, is the decrease in viscosity which increases the Stokes number for any given particle thus decreasing the plate cut point. It appears that the effects nearly cancel.

*Marple, V.A. and B.Y.U. Liu, "Characteristics of laminar jet impactors", Environmental Science and Technology 8, 7, 648-654 (1974)

Figure 14 APT Impactor Plate Cutpoints

Figure 15 Sensitivity of Plate Cutpoints to Temperature

Based upon these results concerning the plate cut points, selections were made as to the best impaction stage sequence for the expected impactor operating conditions (T=1000 F, Q=0.110 acfm for the GBF inlet sample, Q=0.499 acfm for the GBF outlet sample). Southern Research Institute suggested selecting stages such that each stage cut point was 2 to 3 times less than the preceding cut point. This method of selection would minimize the collection overlap that occurs between stage cut points due to the non-ideal cut point behavior of the plates. The result is a more accurate indication of the particle size distribution. Southern Research Institute also suggested that one of the largest stage sizes be repeated. This would give an indication of particle bounce if a significant deposit occurs on the repeated stage. In view of these suggestions the plate selections shown in Table II were made. The largest cut point was limited to be equal to or less than the pre-impactor cut point. At both the inlet and outlet of the GBF the pre-impactor was designed to have a cut point of ~ 15 microns. It would also have been desirable to have the cut points of the inlet and outlet stages nearly the same. Unfortunately, this was not possible due to limited availability of plate sizes.

Table II APT Impactor Plate Selection

<u>GBF INLET</u>			<u>GBF OUTLET</u>		
<u>Stage #</u>	<u>Plate #</u>	<u>Cut Point (μm)</u>	<u>Stage #</u>	<u>Plate #</u>	<u>Cut Point (μm)</u>
1	#2	16.0	1	#12	9.2
2	#1 or 7	6.9	2	# 3	4.6
3	#1 or 7	6.9	3	# 3	4.6
4	#5	2.6	4	# 4	1.9
5	#6	1.2	5	# 8	.75
6	#10	.35	6	# 9	.22

III. WORKS PLANNED FOR THE NEXT REPORTING PERIOD

During the period October-December 1981 the following work is planned:

- Deficiencies resulting from the Model #4 checkout test will be corrected.
- The two 200 hour hot flow tests, P671 and P672, will be run.
- Particulate capture performance analysis of the GBF during test P671 and P672 will be completed.
- Solid samples from P671 and P672 will be sent to outside laboratories for elemental analysis for alkali suppression determinations.
- Debugging of the computer solution of the analytical model will complete and verification runs will commence.
- A concept design of a full scale GBF will be initiated.