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EFFLUENT CHARACTERIZATION FROM A CONICAL PRESSURIZED FLUID BED

by R. J. Priem, R. J. Rollbuhler, and R. W. Patch
Lewis Research Center
Cleveland, Ohio 44135

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R. J. Priem, R. J. Rollbuhler, and R. W. Patch

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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A major unknown in the use of a pressurized coal burning fluidized bed (PFB) providing gases for driving a gas turbine is the turbine blade lifetime due to corrosion and erosion. Studies on erosion and/or corrosion rates in gas turbines have been conducted at the NASA-Lewis Research Center.[1,2] However, very little data are available to predict erosion and corrosion rates produced by the effluent from a PFB. To assess the potential of alloys developed for aeronautical applications to resist this environment it was decided in 1975 to build a coal burning fluidized bed that could be used to measure erosion and corrosion rates.

To obtain useable corrosion and erosion results it was considered necessary to have data with several levels of particulate matter in the hot gases. One level of particulate loading would have to be as low as possible so that ideally no erosion and only corrosion would occur. For this reason a conical fluidized bed was used to obtain some degree of filtration through the top of the bed which would not be highly fluidized. This would minimize the filtration required for the hot gases or conversely the amount of particulate matter in the hot gases after a given level of filtration by cyclones and/or filters.

This paper describes the data obtained in the first 138 hours of testing to characterize the effluent from the bed at different test conditions. It represents 31 different tests over a range of bed heights coal flows, air flows, limestone flows, and pressure. These tests were made to determine the best operating conditions prior to using the bed to determine erosion and corrosion rates of typical turbine blade materials. The erosion and corrosion rate data are described in another paper at this conference.[3] The design and operating range of the fluid bed have been described in reference 4.

EQUIPMENT AND INSTRUMENTATION

The pressurized fluid bed combustor and associated systems are shown in a simplified schematic drawing in figure 1. The combustor or reactor is conical in shape with a 4^{o} taper angle. It is about 10 feet tall internally and has an 8.9 inch internal diameter (≈ 0.4 ft^2 area) at the bottom and 21 inch internal diameter (≈ 2.2 ft^2 area) at the top. The reactor is made of carbon steel with a liner consisting of 3/4 inch of Kaowool and 5 inches of ceramic. There are six ports spaced vertically on the side of the reactor. A solids removal auger can be located in any one of the ports to maintain the level of solids inside the reactor no higher than that port. Thus the bed volume can be held to values ranging from 1 to 9 cubic feet.

A valve in the reactor exhaust gas vent line is used to control the reactor absolute pressure at any desired value between 1 and 7 atmospheres. An automatic controller monitors the reactor pressure and opens or closes the vent line to maintain the desired pressure.

A mixture of coal and limestone is injected into the bottom of the reactor using high pressure air as a transport media. The coal, nominally 800 microns median size, is metered from its supply hopper into the blending auger along with nominal 1600 micron limestone. The resulting limestone to coal ratio can be varied from 0.05 to 0.35. The coal and limestone mixture travels to the reactor through a double hopper system such that the fuel feed hopper is always pressurized slightly higher than the reactor. The fuel feed hopper weight is monitored to determine the fuel flow rate. The fuel flow is controlled by the rotational speed of the fuel metering screw.

Pressurized air flows into the bottom of the reactor through a grid plate containing nine bubble caps with four holes in each cap. For our program the air was at ambient temperature, however, the air can pass through an exhaust gas heat exchanger to increase the temperature to 700^{o} F prior to entering the reactor.

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The reactor bed temperature was maintained at a desired level by controlling the coal flow. Heat was removed from the bed via water-cooled heat exchangers. The heat exchangers are tubes mounted horizontally in the bed. The tubes are mounted in banks of 7, 8, or 9 tubes per bank at given levels in the bed. The amount of heat removed is a function of how many banks of levels of heat exchangers have been installed. For our tests three banks at 7 tubes per bank were installed in the bottom 2 feet of the bed.

In order to heat the bed up initially to the combustion temperature of the coal a torch was mounted in the bottom side of the reactor. It burned metered quantities of natural gas and air to bring the temperature in the bottom of the bed up to 1400° F. At this temperature the coal is introduced into the bed. As soon as coal burning is detected (increasing bed temperatures) the torch is extinguished.

The products of combustion, after leaving the fluidized bed, can follow two paths (see fig. 1). One path is through the number 5 heat exchanger and solids separator and then out the pressure control valve to the atmosphere. The other path is from the reactor through a test section for making erosion and corrosion studies, and then through parallel heat exchangers and solid separators (Anderson Ibek cyclones); after which the gases exit to the atmosphere through the pressure control valve. The solids collected in the various separators flow through double hoppers, sealed such that the reactor pressure is not released as the solids are dumped.

The facility instrumentation permitted viewing and monitoring what was occurring inside the reactor during the tests. This was done by a television camera looking down through a port in the top of the reactor. Because there was no lighting inside the reactor a televised picture was seen only when the top of the bed was hotter than 1200° F (i.e., incandescent).

Some 180 parameters were instrumented and the resulting test signals were reduced to engineering terms. The instrumentation used was the standard type strain gage pressure transducers, thermocouples, turbine type and venturi flowmeters, and weight determining load cells. A gas analyzer was used to measure the composition of the gases from the reactor. The gases were analyzed for hydrocarbons, nitrogen oxides, carbon dioxide, carbon monoxide, oxygen, and sulfur dioxide. The sample line was kept over 300° F to prevent condensation. Between tests the gas analyzer system was purged with nitrogen gas. The gas analyzer was calibrated every 12 hours using gases of known composition.

All the test instrument signals were channeled to a data logger in the facility control room. The data logger compared the input signals with limits and if the signals were outside the limits alarm circuits were energized. These circuits not only sounded an alarm but for key parameters in extreme conditions, shut down the facility. The facility controls work through a programmable controller which can be set to operate in a semi-automatic mode. Signals from both the programmable controller and data logger are periodically sent to a data collector located in our Data Processing Center for tape recording. The recorded data is later processed by a computer and the engineering results are printed out in a predetermined format.

EXPERIMENTAL PROCEDURE

Testing involved making a series of tests over a range of operating conditions to characterize the reactor effluents and efficiency of operation. All variations were made keeping in mind that ultimate operation of the bed had to be suitable for long duration turbine blade material testing.

The chief variables in the test program were reactor air flow, coal flow, limestone flow, reactor volume (bed height), pressure, and test duration. Other parameters of major concern that were varied when the above were varied are: superficial velocities in the bed, coal/air ratio, limestone/coal ratio, and bed temperature. The major dependent parameters were exhaust gas composition, exhaust gas solids content and size, sulfur removal efficiency, coal combustion efficiency, vertical bed temperature profiles, exhaust gas temperatures, and operational stability.

The same type of coal and limestone were used for all the tests. The coal was Champion (Pittsburgh seam number 8) and had a nominal 2 percent moisture, 8 percent ash, 37 percent volatile matter, and 53 percent fixed carbon. The sulfur content of the coal was 2 percent and the higher heating value was 13,560 Btu per pound (dry basis). The limestone was from Grove City, Virginia, and contained 97 percent calcium carbonate. The mesh size was -7, +18 as initially loaded in the hoppers. Coal and limestone size distributions as measured from samples taken after the metering screws are shown in figure 2.

Prior to the start of a test the reactor was filled with limestone to the desired level. Pure limestone was used to fill the reactor only for the first test; thereafter the residual bed material from previous tests was used to get the desired bed level. The bed heat exchangers were installed and the instrumentation checked. The alarm circuit lines were checked and appropriate portions of the system were pressure checked.

At the start of a test series the bed had to be heated to at least 1400° F before injection of the fuel. This usually could be done in less than an hour. The fuel flow and reactor air flow were gradually increased as the torch flows were reduced. During this time the exhaust gases were vented out heat exchangers and separator number 5. When the coal started burning, the pressure control valve was adjusted to give the desired reactor pressure. When the desired operating conditions had been attained, separator and heat exchanger number 5 were closed and heat exchangers and separators numbers 1 to 4 were opened. This allowed the hot test gases to go through the materials test chamber.

During the test the data logger checked each of the 180 data parameters once every 35 seconds for out-of-limit conditions. On 30 minute intervals the data logger output was sent to the data collector for later computer processing.

It was planned to operate at a given set of test conditions until stable operating behavior was apparent for an hour or more. Some tests lasted for 3 hours and others extended for as long as 8 hours. During this period, recorded data was taken approximately every half hour. The final test data for each test were attained from averaging data taken during that portion of the test that was considered stable. In this program 31 tests were made in which one or more parameters were varied and over 300 data readings were used in data averaging. The 31 tests and conditions associated with each test are listed in table I.

Prior to the termination of a given test a portion of the exhaust gases coming from air heater number 1 was directed through separator number 6, a stainless steel mesh filter (with a 0.5 micron nominal rating) and then through a flowmeter before venting to the atmosphere. The size and quantity of particles coming from the reactor was defined as the sum of the material collected in the number 6 separator and filter. Other samples taken during the tests were coal, limestone, fuel, discharge of solids from the reactor via the auger, and flyash from the separators. These samples were later analyzed for particle size and chemical composition.

At the shutdown the fuel flow was stopped and the air kept flowing until the bed temperature dropped below 800° F. Air was then turned off and the bed allowed to cool down to ambient temperature. If the bed appeared to be operating peculiarly the bed fill was dumped and the bottom of the reactor was removed for inspection of the interior.

CHEMICAL AND SIZE ANALYSIS

Chemical analysis was used to estimate the fractions of ash, ash-free char, uncalcined limestone, calcined limestone, and sulfated limestone in the flyash (elutriated with the gases from the bed) and discharge (solids withdrawn from the bed by the auger). The procedure required analysis of raw coal, limestone, flyash, and discharge samples. For consistency, standard ASTM methods of coal analysis were used on all four types of samples.

The estimation procedure required a number of assumptions: (1) both the calcium and magnesium in the limestone were fully calcined before the calcium could be sulfated, (2) the removal of sulfur by the limestone resulted in no compounds other than calcium sulfate, (3) sulfur in the ash was unchanged from raw coal ash, (4) there was no sulfur in coal volatiles, (5) the sulfur in the ash-free char was the same as in the fixed carbon fraction of raw coal, (6) there were no coal volatiles in the solid effluents, (7) the calcium, magnesium, sodium, and potassium in the ash were not combined as sulfates or carbonates except for possibly the sulfur originally in the ash, and (8) any sulfur originally in the limestone remained there as undetermined compounds. Consequently, the coal was analyzed for silica, ash, ash containing sulfur trioxide, volatiles, and total sulfur. The limestone was analyzed for silica, lime, carbon dioxide, total sulfur, and magnesia. The effluent solids were analyzed for silica, lime, carbon dioxide, and total sulfur. This resulted in five equations in five unknowns which were solved by algebraic and matrix methods to give weight fractions of ash, ash-free char, uncalcined limestone, calcined limestone and sulfated limestone. The effluent material that was originally introduced into the bed as coal was the ash and ash-free char. The effluent material that was originally introduced into the bed as limestone was the sum of the uncalcined limestone, calcined limestone, and sulfated limestone.

Higher heating values of coal, flyash, and discharge were measured in a bomb calorimeter using ASTM procedures. However, the flyash and discharge had such low heating values that complete combustion was not always obtained. The ASTM procedure calls for adding benzoic acid to the sample in such cases. However, benzoid acid tended to react with the carbonates in the sample before ignition causing erroneous heating values to be obtained. To circumvent this difficulty heavy mineral oil of known heating value was used instead of benzoic acid. All higher heating values were converted to lower heating values before calculating combustion efficiency.

Solids sampled were analyzed for size using a Fisher-Wheeler Sieve Shaker with the following screens:

Mesh	Passing particles of micron size	Mesh	Passing particles of micron size
8	2380	40	420
10	2000	45	354
12	1680	50	297
14	1410	80	179
16	1190	200	74
18	1000	270	53
20	841	325	44
25	707	400	27
30	595	500	25
35	500		

The quantity of solids on each screen was weighed to determine the size distributions.

For sizes between 25 and 2 microns an Andreason Sedimentation Pipet was used. Weighed samples were mixed with alcohol and introduced to the pipet and the resulting emulsions were withdrawn at measured time intervals and at a measured depth. The emulsions were then dried and weighed. Sizes were calculated from Stokes Law according to the falling velocity of the particles. Sizes calculated for each group were checked and verified by microscopic photographs at ×350 enlargements.

EXPERIMENTAL RESULTS

A summary of the experimental results obtained in this program are given in table II. The minimum, maximum, and average values observed over the entire range of test conditions are given. Results of correlations to determine how test conditions influenced the experimental results are presented in the Correlations Section.

The gas analysis to determine exhaust gas composition showed a wide variation in the SO_2 and NO_x concentrations. All the values for NO_x were below the EPA standard of 0.7 pound/MBtu with the average value of 0.34 being half the standard. The maximum observed level of SO_2 was 1.75 pounds/MBtu which is above the EPA standard of 1.2 pounds/MBtu. The average value, however, was 0.63 pound/MBtu, which is half of the standard. The unburned hydrocarbon and CO levels were all very low resulting in combustion efficiencies, based on gas analysis greater than 99.9 percent. The percent sulfur captured based on gas analysis, showed that the minimum level of 53 percent and average value of 79 percent are below the desired operating levels of 90 percent capture. Tests were made with sulfur capture efficiencies greater than 99 percent. As will be shown later these high capture efficiencies were not obtained with high limestone to sulfur ratios.

Measured heat transfer coefficients to the water cooled tubes varied between 45 and 65 Btu/(hr)(^{o}F)(ft^2) with an average value of 55. This agrees very well with the data that has been observed by other investigators.[5] Heat transfer coefficients were also calculated from thermocouples imbedded in the ceramic wall of the bed. Two thermocouples are located a known radial distance from the bed wall. Using the thermoconductivity of the ceramic a heat transfer coefficient was calculated for the walls. These coefficients were found to be 1.7 Btu/(hr)(^{o}F)(ft^2) at the bottom of the bed and 5.6 at the top. These results gave very good agreement with the total heat that was absorbed by the water used to cool the various external metal sections of the bed. The much lower heat transfer coefficients to the walls, compared to the water cooling tubes is believed to be a result of a thicker boundary layer and less particle motion on the walls as compared to the horizontal tubes.

Overall bed pressure drop varied from 0.45 to 5.56 psi and as expected was very dependent on bed height. In the conical bed the pressure drop is not equal to that required to support the total weight of the bed material as some of the weight is supported by the walls. As flow is increased with a conical bed the pressure drop decreases as more material is moved to the top of the bed. The injector pressure drop varied from 0.9 to 16.8 psi.

Analysis of the solid contents in the gases from the bed showed that the conical bed has a lower level of particulate matter in the gases than that observed with cylindrical beds. Solids content varied from 1.0 grains/standard cubic foot of gas (gr/SCF) to 3.4 with an average of 2.0. This is considerably lower than the values reported at this meeting[5,6,7] with cylindrical PFB's. This is also reflected in the fraction of solids that are carried over in the gases. Our results showed that between 15.2 and 48.7 percent of the combined weight of ash, sulfur, and limestone (called the flyash/solids in ratio) was removed along with the gases from the reactor, with an average value of 27.6 percent. This is considerably lower than the 50 percent bed material elutriated with a 2½ ft/sec bed velocity and 90 percent with a 7½ ft/sec velocity in the Leatherhead tests.[5] Combustion efficiencies as determined by the carbon content in the solids showed excellent performance of the conical bed (all the efficiencies were greater than 97 percent with an average of 99 percent).

Size distributions for the particles carried with the gases from the bed are shown in figure 3. The weight of solids carried in a unit weight of gas (grains/SCF) for particles smaller than a given size was used so that all the data could be shown on one graph. These results show that all the particles carried over with the gases were smaller than 300 microns, with an average size of approximately 60 microns. Particulates in the gases coming from the Anderson-Ibek cyclones are given in figure 4. These results show that after one stage of separation the exhaust gas solids content has been reduced to between 0.7 and 0.5 gr/SCF with an average of 0.25. This compares reasonably well with the EPA requirements of approximately 0.08 gr/SCF. The average size of the effluent material passing through the cyclone was 15 microns with a maximum size of 40 microns. Comparing the results shown in figures 3 and 4 indicates that the separators were removing 90 percent of the 30 micron material, 50 percent of the 20 microns and very little below 10 microns. This is not considered a high efficiency cyclone. A cyclone with a 90 percent removal efficiency in the 6 to 10 micron size would reduce the particulate loading to less than 0.02 gr/SCF which is the requirements given for the turbine by Curtiss Wright.[8] Cyclone manufacturers claim that a 90 percent collection can be achieved in this size range. (A high temperature cyclone and ceramic filter are being installed in the Lewis Facility to attain these low particulate loading levels for future turbine materials tests.)

To determine the source of solids material elutriated from the bed by the gases (flyash) and with the solids removal auger (discharge) the solids were chemically analyzed as described in the Chemical and Size Analysis section. The results of these tests are shown in figure 5. For the average of all the tests 2 pounds of solid were removed by the solids removal auger (discharge) for each pound of solids carried over with the hot gases (flyash). An average of 84 percent of the material in the flyash was originally introduced into the bed as coal and 16 percent was from the limestone (now in the form of calcium sulfate, oxide and carbonate). The discharge material removed by the auger is just the opposite as 84 percent of the material originated from the limestone and 16 percent originated from the coal. This indicates that the solids elutriated by the gases are mainly ash and the discharge from auger is mainly limestone.

The solid size distributions of the material going to the bed and removed from the bed are shown in figure 6 to illustrate what happens in the bed. The relative weight added to the bed (or removed) in a given period of time and size range is plotted against particle size. Particle size is plotted on a log scale to better represent the small size data. Dividing the size range (ΔD) by the diameter D makes the area under the curve represent the total weight in the sample when the abscissa is a log scale, (i.e., the area under the bed discharge is twice the area of the flyash curve). The data for the coal ash represents the size and mass distribution that would be obtained if each coal particle (size distribution given in fig. 2) was reduced to only ash with the particle having the density of pure ash. This reduces the individual coal-ash particle weight to 6 percent of the coal particle weight and the diameter by one-half. These results show that the limestone is reduced in size before it is removed from the bed (approximately by a factor of 2) and the ash particles are reduced in diameter by a factor of 5 (this means that over 100 ash particles are formed from each coal particle).

CORRELATION OF RESULTS

The test series (as described in table I) did not have only one independent variable changed at a time so it is impossible to plot the original data to show how each parameter influenced bed characteristics. Therefore, the experimental data for the tests were correlated with a multiple-linear-regression digital-computer program, based on reference 9, to determine statistically how bed operating conditions influenced the results. In the tests conducted we had five independent variables. These variables could be expressed in several different ways depending on which measurements were used. The various independent parameters considered were (1) bed height, (2) pressure, (3) moles lime/moles sulfur, (4) coal/air ratio over stoichiometric coal/air, (5) superficial air velocity at the bottom of the bed, (6) air flow rate, and (7) bed temperature. Of these only 1 and 3 (bed height and limestone to sulfur ratio) were truly independent. The others were all interdependent and one could select any three of the remaining five variables as the other independent variables. Correlations were made against all combinations of five independent variables and the combination which resulted in the correlation with the highest corrected index of multiple correlation[10] was selected.

The correlations have been used to show the effect of different operating parameters on gas analysis and solids effluent as shown in figure 7. For the data presented here the best correlations were always obtained using five of the following six independent variables: (1) coal/air ratio, (2) lime/sulfur ratio, (3) velocity at the bottom of the bed, (4) bed temperature, (5) pressure, and (6) bed height. Parameters that statistically influenced the data but were not used in the best correlation are indicated by a "PC" (poor correlation) in the figure. An independent parameter that did not statistically influence the data and therefore did not appear in the correlations is indicated by a "NC" (no correlation). To produce each curve in figure 7 a prediction was made using the average value of all independent parameters in the regression equations. Then a particular independent parameter was changed to the lowest and highest value tested in this program to determine what would have happened if only that parameter had been varied in our tests. Thirty-five curves were obtained and are plotted in figure 7.

The gas concentrations shown in figure 7 indicate that all the emissions were decreased and percent sulfur absorbed increased when coal/air ratio, velocity, bed height, pressure, and limestone ratio were increased. The order of importance is as listed above. NO_x was not influenced by the limestone ratio.

The solids elutriated from the bed, solids after the cyclone and solids from the bed that were smaller than 10 microns all decreased with lower coal/air ratios, velocities and increased bed temperature and increased limestone/coal ratio. Solids in the gases from the bed were not influenced by limestone/coal ratio but did improve (less carry-over) with lower bed heights. Combustion efficiency (based on the unburned material in the elutriated solids only; the unburned material in the discharge from the auger was negligible according to the bomb calorimeter) improved with increasing coal/air ratio, velocity, pressure, and limestone/coal ratio. The term flyash/solids in figure 7 is actually the flyash flow divided by the sum of three quantities: (1) limestone feed rate, (2) rate of ash flow in the coal, and (3) rate sulfur flow in the coal. The flyash/solids in ratio decreased with increasing pressure, limestone/coal ratio, temperature and decreasing velocity, and decreasing bed height.

Examining how each independent parameter influenced the results (vertical columns in fig. 7) we see that higher temperatures, pressure, and limestone/coal ratios were beneficial for all parameters. High coal/air ratio, velocity, and bed height were desirable to obtain low gas emissions and high efficiencies but they were undesirable in obtaining low solids content in the gas.

The high solids content in the gases with the high bed height was not anticipated when the test program was initiated. Observations of the bed with the TV cameras indicated that with a high bed we had considerable slugging of the bed and caking at the surface. This resulted in periodic erruptions in the bed surface with considerable solids thrown into the freeboard area. While some of the solids drifted back to the surface, considerable quantities were carried away with the gases. This unstable operation of the bed was not observed with the lower bed heights and consequently less solids were carried over with the gases.

As can be seen from figure 7 the best operation of a bed is obtained by a compromise of many parameters. This compromise for an actual PFB powerplant would be dependent on cost and cleanup equipment used after the combustor. Therefore, it is impossible to state the best operating conditions for all systems on the basis of our tests only. The tests described herein did provide the necessary data to characterize the effluent from the bed before turbine blade materials erosion and corrosion tests were instigated. The conditions selected for the materials test program and the test results are given in reference 3.

Currently, the cone angle in the conical bed is being reduced from 4° to 3° to provide higher velocities and more stable operation at the top of the bed. This will also permit increasing the thickness of the Kaowool insulation to reduce heat losses from the bed (reducing the temperature difference between bed material and gases leaving the reactor). In the future tests will be conducted to characterize the effluents from the new bed. High temperature cyclones and filters are also being installed to reduce the solids content in the combustion gases. After various levels of filtration, these gases will flow through a gas turbine that is being installed for measuring erosion and corrosion rates.

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Table I. Test Conditions

Test number	Approximate bed depth, in.	Test duration, hr	Number valid test readings	Average reactor air flowrate, lb/hr	Average coal to air weight ratio	Average limestone to coal weight ratio	Average bed bottom velocity, ft/sec	Average bed pressure, psia	Average bed temperature, °F
1	97	8.0	10	582	0.065	0.17	4.3	72	1571
2	97	7.5	15	563	.067	.16	3.8	78	1600
3	97	7.3	15	565	.065	.15	4.1	73	1580
4	97	7.5	16	574	.066	.20	4.5	69	1592
5	97	3.4	16	564	.068	.13	4.3	72	1608
6	56	3.4	8	573	.068	.13	4.3	71	1586
7	56	3.4	8	577	.063	.13	3.8	71	1581
8	56	3.8	9	565	.069	.15	4.2	72	1585
9	56	3.5	8	575	.072	.20	4.2	72	1586
10	56	3.5	8	560	.069	.09	4.1	72	1584
11	56	6.5	12	587	.061	.14	4.1	80	1633
12	56	2.5	6	520	.067	.14	4.1	64	1539
13	56	2.5	5	494	.066	.14	4.3	57	1457
14	56	3.5	9	568	.067	.14	4.7	63	1574
15	56	3.5	8	565	.073	.14	5.3	56	1582
16	56	3.5	8	325	.090	.14	4.4	40	1568
17	56	2.5	6	634	.064	.14	4.4	79	1709
18	44	4.0	9	589	.056	.14	4.3	70	1542
19	44	3.5	8	586	.062	.15	4.9	63	1589
20	44	2.5	6	584	.062	.08	4.3	71	1569
21	44	3.5	8	597	.064	.20	4.3	73	1576
22	44	3.0	8	350	.091	.19	4.7	40	1578
23	44	3.0	7	588	.059	.20	5.6	55	1576
24	44	3.0	8	688	.059	.09	4.8	81	1700
25	68	6.0	13	598	.061	.14	7.8	41	1656
26	68	5.5	12	607	.055	.14	5.3	62	1651
27	68	4.5	10	587	.056	.13	3.9	82	1642
28	68	3.5	8	595	.046	.11	3.5	82	1460
29	68	5.5	13	452	.052	.13	2.7	82	1447
30	68	6.0	14	619	.065	.12	4.4	82	1765
31	68	6.5	9	587	.058	.12	4.2	82	1577

Table II. Summary of Experimental Results

Parameter	Minimum value	Maximum value	Average value
Total operating time, hr	---	136	---
Number of tests	---	31	---
Continuous test time, hr	2.0	8.0	4.3
Coal flowrate, lb/hr	23.4	41.3	35.9
Limestone flowrate, lb/hr	2.8	8.3	5.1
Input air flowrate, lb/hr	350	688	556
Combustion gas velocity at bed surface, ft/sec	0.70	2.96	1.64
Gas pressure drop through bed, psid	0.45	5.56	1.60
Overall combustion efficiency, percent of theoretical	96.9	99.9	98.9
Heat transfer coefficient at bed tubes, Btu/(hr)(ft^2)(^oF)	45	65	55
Heat transfer coefficient at bed wall, Btu/(hr)(ft^2)(^oF)	0.8	2.5	1.7
Heat transfer coefficient at wall above bed, Btu/(hr)(ft^2)(^oF)	4.6	7.9	5.6
Solids in combustion gases, grains/SCF	1.00	3.40	2.00
Solids in cyclone exit gases, grains/SCF	0.07	0.50	0.25
Particles <10 micron in exit gas, grains/SCF	0.06	0.38	0.16
Solids in gases/solids to bed, percent	15.2	48.7	27.6
Input calcium/sulfur mole ratio	1.2	3.1	2.2
SO_2 in combustion gases, ppm	2	464	223
SO_2 in combustion gases, lb/MBtu	0.005	1.75	0.63
NO_x in combustion gases, ppm	67	240	177
NO_x in combustion gases, lb/MBtu	0.13	0.68	0.34
CO in combustion gases, ppm	11	100	40
Hydrocarbons in combustion gases, ppm	1	24	6
Sulfur in combustion exit gases, wt.% of input amount	0.2	47	21
Input air pressure drop through grid plate, psid	0.9	16.8	4.9

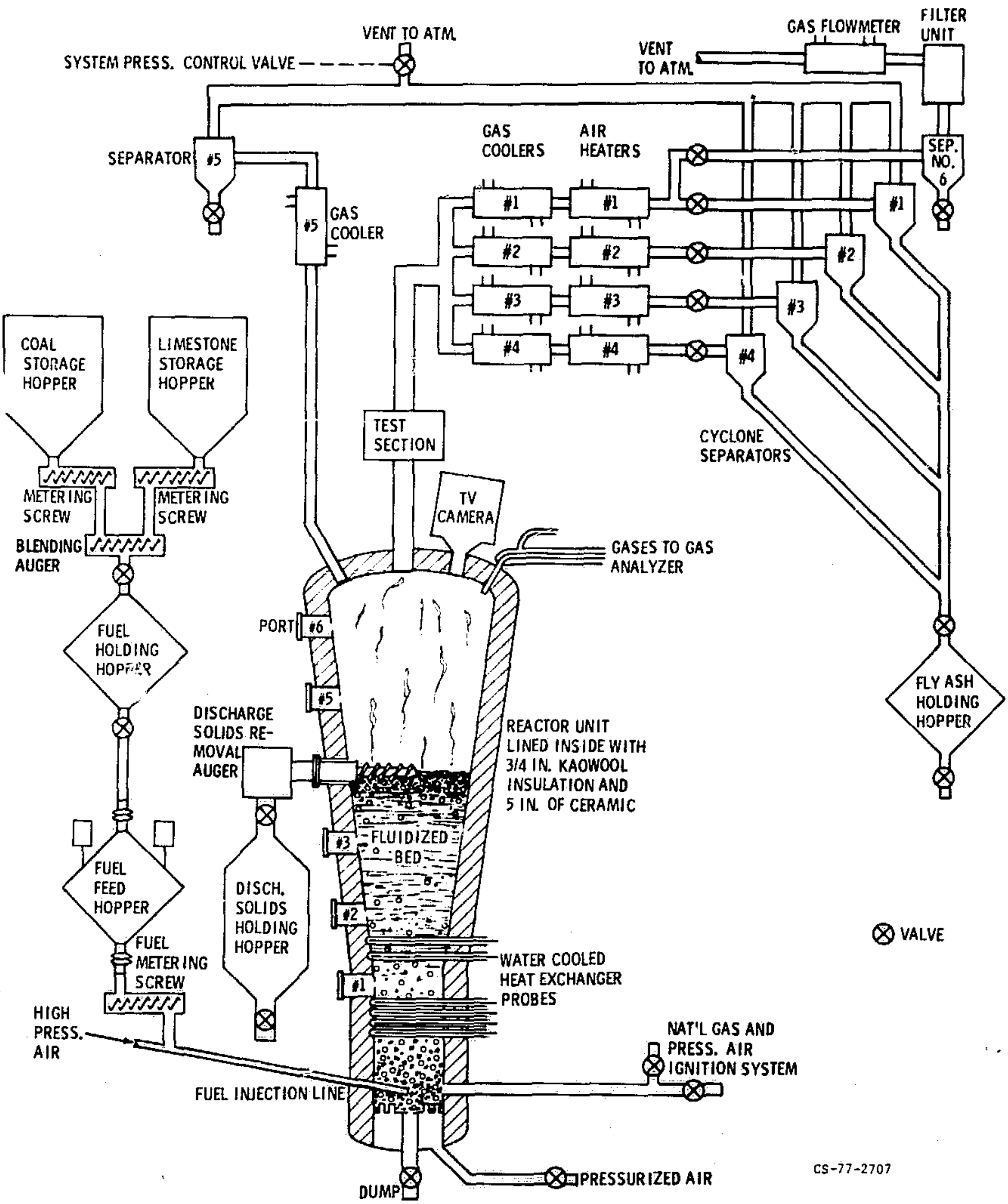

Figure 1. - Schematic of LeRC pressurized fluidized bed combustor.

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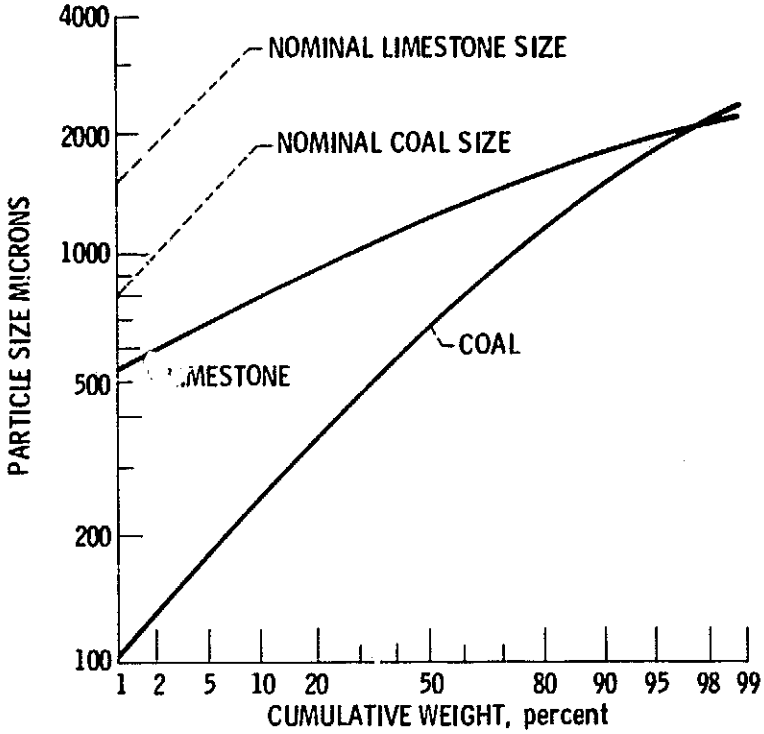

Figure 2. - Coal and limestone size distributions.

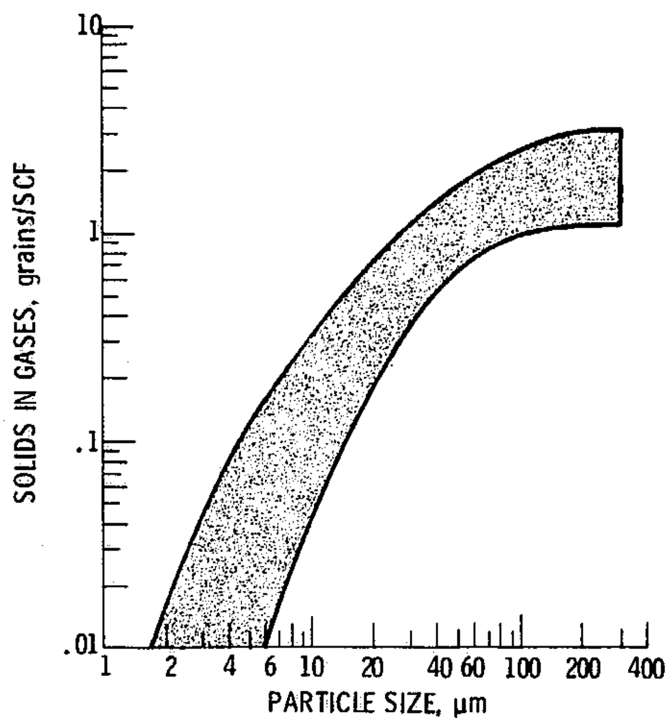

Figure 3. - Particles in gases from bed.

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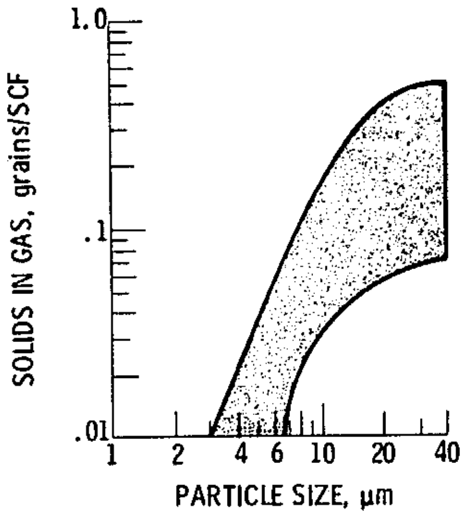

Figure 4. - Particles in gases from cyclone.

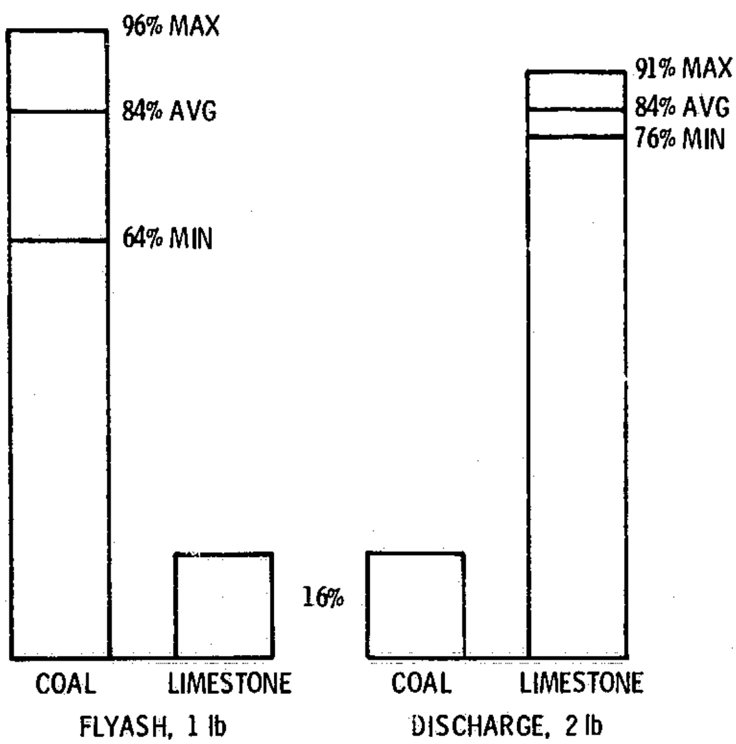

Figure 5. - Source of solids removed from bed.

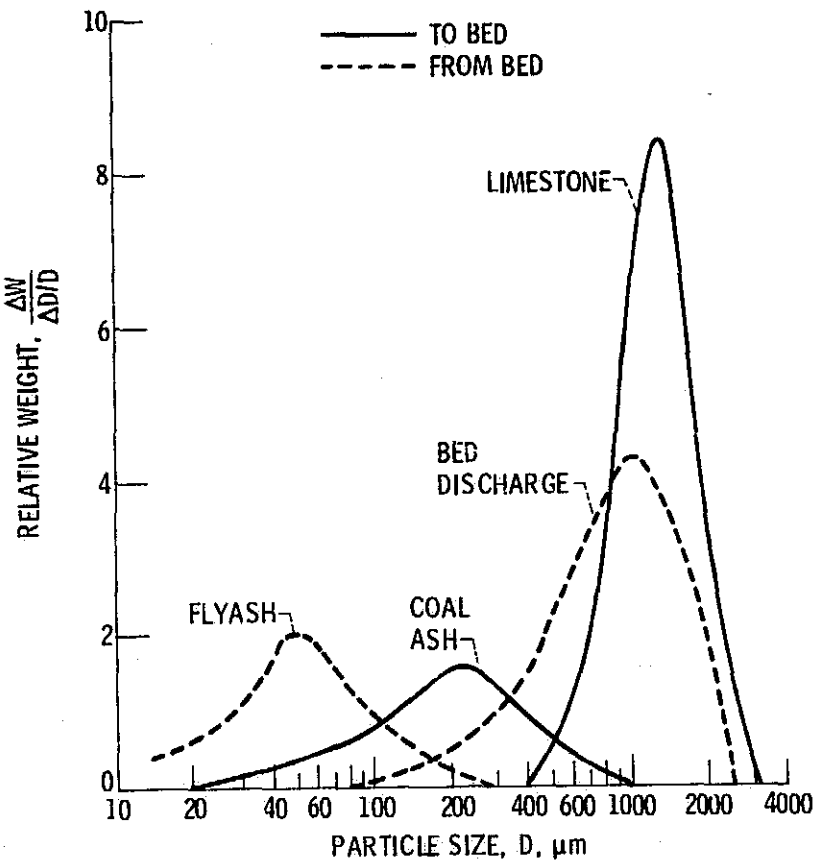

Figure 6. - Solids size distributions.

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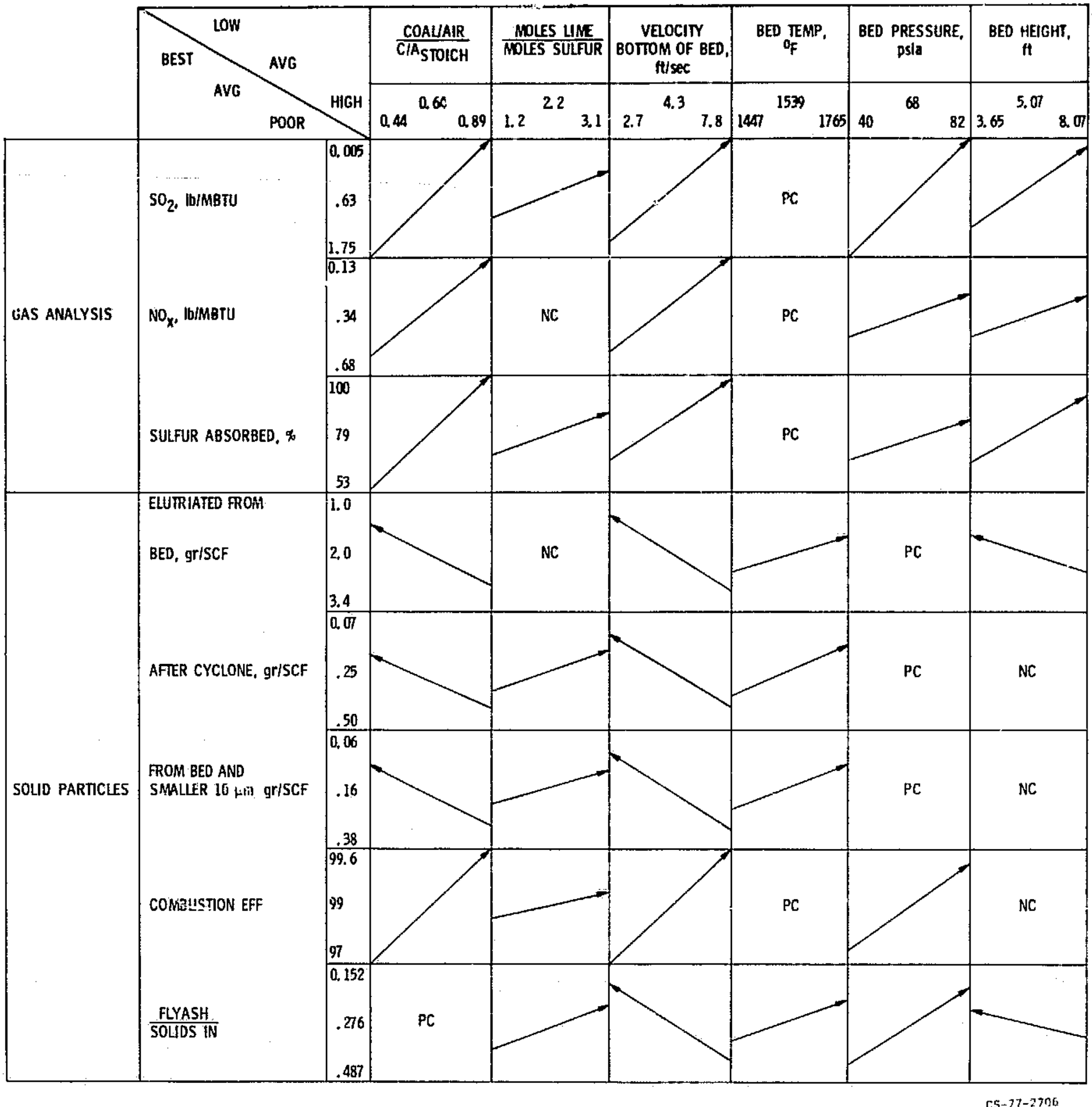

Figure 7. - Data correlation.