ICP-1068

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**INTERIM EXPERIMENTAL RESULTS:
PRIMARY GRAPHITE BURNER TESTING
WITHOUT FINES RECYCLE**

W.B. Palmer

ALLIED CHEMICAL CORPORATION
IDAHO CHEMICAL PROGRAMS-OPERATIONS OFFICE
IDAHO NATIONAL ENGINEERING LABORATORY
Idaho Falls, Idaho 83401

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ABSTRACT

A 4-inch diameter, fluidized-bed burner was used to test primary burning of HTGR graphite fuel. The results of fifteen runs which were made to test the effect of fluidizing velocity, feed rate, bed temperature, and bed depth on fines generation and combustion efficiency are reported.

SUMMARY

During reprocessing of HTGR fuel, the large graphite fuel elements are crushed to less than 3/16-inch particle size and burned in a fluidized-bed burner. Fluidized-bed burning consumes matrix graphite and liberates silicon carbide coated fuel particles for subsequent reprocessing.

A series of 15 tests was completed at ICPP to establish the operability of a 4-inch diameter pilot-plant primary burner when using filters located in an external filter pot. The effect of fluidizing velocity, feed rate, bed temperature, and bed weight (depth) on combustion efficiency and fines generation was studied during the tests. The range of variables tested was: fluidizing velocity - 1.45 to 3.58 ft/sec, graphite feed rate - 100 to 200% of stoichiometric (based on the fluidizing oxygen flowrate), bed temperature - 800 to 900°C, and starting bed weight - 2500 to 4500 grams of TRISO particles. The external filters performed satisfactorily during the testing; no burn through of the filters or filter plugging occurred.

The test results showed that for best burner operation in the range of variables studied (1) the fluidizing velocity should be as low as the required throughput will allow, (2) the feed rate should be as high as possible (but consistent with good fluidization of the large graphite pieces), (3) the bed temperature should be as high as burner construction material will allow, and (4) the bed should be as deep as possible without excessive slugging.

CONTENTS

	Page
ABSTRACT	ii
SUMMARY	iii
I. INTRODUCTION	1
II. EQUIPMENT AND PROCEDURES	2
III. OPERATING CONDITIONS AND RESULTS	9
IV. DISCUSSION OF RESULTS	22
V. CONCLUSIONS AND RECOMMENDATIONS	27

FIGURES

1. Schematic Diagram of Pilot-Plant Primary Burner	3
2. Nozzle-Venturi Assembly for Filter Blowback System	4
3. Primary Burner Distributor Plate	6
4. CO Torch Installed in Primary Burner	7
5. Effect of Fluidizing Velocity on Combustion Efficiency	14
6. Effect of Feed Rate on Combustion Efficiency	15
7. Effect of Bed Temperature on Combustion Efficiency	16
8. Effect of Bed Weight on Combustion Efficiency	17
9. Effect of Fluidizing Velocity on Fines Elutriation	18
10. Effect of Feed Rate on Fines Elutriation	19
11. Effect of Bed Temperature on Fines Elutriation	20
12. Effect of Bed Weight on Fines Elutriation	21

TABLES

	Page
I. SUMMARY OF OPERATING CONDITIONS FOR PRIMARY GRAPHITE BURNER TESTING	10
II. SUMMARY OF RUN RESULTS FOR PRIMARY GRAPHITE BURNER TESTING	11
III. SUMMARY OF MASS BALANCE CALCULATIONS	12

INTERIM EXPERIMENTAL RESULTS:
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I. INTRODUCTION

Proposed reprocessing of Ft. St. Vrain fuel calls for whole block crushing to -3/16-inch size by a series of three crushers. The crushed material will then be fed to the primary burner for burning the graphite matrix. The exposed fissile and fertile particles will then be separated, crushed, burned, and leached to recover the uranium and thorium.

Ideally, the primary burner should burn all the matrix graphite from the fissile and fertile particles. However, whole block crushing generates significant quantities of graphite fines; fines are also generated during burning of the larger graphite pieces. Graphite fines are very light and elutriate rapidly from the fluidized bed before and during burning. During previous primary burning studies, a sintered-metal filter was installed in the burner vapor space to retain the fines in the burner. The in-vessel filters resulted in filter burn through and excessive filter plugging. The sintered-metal filters were contained in an external filter chamber during the current test series. The fines were collected continuously from the filter chamber, but fines recycle to the burner was not attempted.

II. EQUIPMENT AND PROCEDURES

A flow diagram of the 4-inch diameter primary graphite burner used for the experimental testing is shown in Figure 1. The system consisted of a feed pot and variable-speed feed auger, a 4-inch diameter burner vessel, an 8-inch diameter filter chamber containing two sintered-metal filters, and a fines pot to collect solids discharged from the filter chamber.

The two sintered-metal filters were 2.75-inches O.D., 18-inches long, 5 μ porosity, and made of 316-L stainless steel. The filters were cleaned by a pulsed blowback system controlled by an automatic timer, giving a 0.1 second pulse every 15 minutes to each of the filters. The blowback air pressure was 75 psig. Details of the venturi blowback assembly are shown in Figure 2.

Figure 1. Schematic Diagram of Pilot-Plant Primary Burner

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ACC-A-1760

Figure 2. Nozzle-Venturi Assembly for Filter Blowback System

The distributor located in the 4-inch diameter fluidizing vessel was a flat plate made from 1/16-inch thick Hastelloy C-276. The plate contained 79 holes; the holes were 0.046 -inch in diameter and were arranged as shown in Figure 3.

Burner startup and supplemental heat was provided by a CO/O₂ combustion torch located in the fluidized bed. A schematic diagram of the torch installed in the burner is shown in Figure 4. The torch was operated by mixing the CO and O₂ in the metal cone and igniting the mixture with a spark. The heating rate was controlled by regulating the CO and O₂ flowrates to the torch.

Analyzers were used to continuously monitor the CO₂, CO, and O₂ concentrations in the off-gas to aid in burner control.

0.060-INCH THICK HASTELLOY C-276 PLATE, 4.5 - INCH OUTSIDE DIAMETER,
79 HOLES - 0.046 INCH DIAMETER

ACC - A - 1772

Figure 3. Primary Burner Distributor Plate

Figure 4. CO Torch Installed in Primary Burner

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The operating procedure was to start the fluidizing air at 1 ft/sec fluidizing velocity. This velocity was held constant during the startup portion of the run by decreasing the fluidizing gas rate as the bed temperature increased. A bed of fissile and fertile particles was then charged to the burner by gravity flow. The torch was ignited and the bed allowed to heat to 600°C. The fluidizing gas was then changed to 100% oxygen at the rate specified for the run and the feed auger was activated to the required rate for the run. The bed temperature continued to increase and when the bed temperature exceeded 800°C, and significant graphite combustion occurred, the torch was deactivated. Bed temperature was controlled at the specified level by passing cooling air through the vessel shroud and/or by adding air to the fluidizing oxygen. Stable conditions were usually attained within 10 minutes after reaching the operating temperature.

During the steady-state portion of the run, the crushed feed (-3/16-inch size, 23.5 wt% fuel rods and 76.5 wt% graphite, 8000 grams/run) was metered to the feed line by a variable-speed auger; feed flowed by gravity into the hot fluidized bed of fissile and fertile particles and unburned graphite. The off-gas passed from the burner to the filter chamber, through the sintered-metal filters, through the HEPA filter, and then to the atmosphere. The fine graphite particles elutriated from the bed were collected on the surface of the sintered-metal filters, periodically displaced from the filter surface by the pulsed blowback system, and continuously collected.

After the feed supply was exhausted, the graphite was allowed to burn from the bed, and the run ended when there was no longer enough graphite in the bed to maintain the burner temperature.

The final fluidized-bed depth was approximately 18 inches except in the last two runs in which the starting bed depth was greater than that for the previous runs.

When the run was completed, the final bed and collected fines were weighed and sampled. The samples were burned to determine their combustible content.

III. OPERATING CONDITIONS AND RESULTS

Fifteen runs were made to test burner operability using the external filters. The run plan was to test the effect of fluidizing velocity, feed rate, bed temperature, and bed depth on combustion efficiency, fines generation, and general burner operability. Fourteen of the runs were successfully completed; one run at low bed temperature ($\sim 800^{\circ}\text{C}$) resulted in the bed being extinguished early; the bed temperature could not be reestablished because of torch ignition problems. (The torch was repaired and has since functioned reliably).

The run conditions are summarized in Table 1 and the results of the runs are summarized in Tables 2 and 3. Run time, weight of fines collected, average off-gas concentrations, calculated combustion efficiencies, wt% combustibles in the final bed and fines, and the average pressure drop across the sintered-metal filters are given in Table 2. Also shown in Table 2 is the sudden temperature rise near the top of the bed which occurred to varying degrees in each of the runs just before burner shutdown, when nearly all of the graphite was burned from the bed.

A mass balance for each run is shown in Table 3. The materials charged to the burner were feed, air, and oxygen at controlled rates. The materials exiting the burner were fines and the off-gas, which was analyzed continuously for CO_2 , CO , and O_2 . The mass balance was made by determining the weight of graphite actually consumed, the weight of graphite which would have produced the amount of CO and CO_2 detected in the off-gas, and the weight of graphite which would have been burned by the amount of oxygen actually consumed during the run. Each of the two theoretical weights were then divided by the actual amount of graphite consumed and multiplied by 100 to obtain the results shown in columns 2 and 3 of Table 3. Column 4 gives the amount of graphite which would have been burned based on averaging the results shown in columns 2 and 3.

During the study, the fluidizing velocity ranged from 1.45 to 3.58 ft/sec; the feed rate was 100% to 200% of stoichiometric (based on the oxygen flowrate); the bed temperature range was from 800°C to 900°C ; the starting bed weights of

TABLE I

SUMMARY OF OPERATING CONDITIONS FOR PRIMARY GRAPHITE BURNER TESTING

Run No.	Maximum Combustion Rate, (A) kg graphite/ hr-ft ²	Bed Temperature, °C	Fluidizing Velocity, (B) ft/sec	Actual Feed Rate, grams/min	Stoichiometric Feed Rate, (C) %	Beginning Bed Weight, grams	Fluidizing Oxygen Rate, scfm
11	15	875	1.5	36	125	2500	1.5
12	20	875	1.8	45	125	2500	2.0
13	25	875	2.3	56	125	2500	2.5
14	30	875	3.1	67	125	2500	3.0
15	35	875	3.6	78	125	2500	3.5
16	25	850	2.2	56	125	2500	2.5
17	25	825	2.2	56	125	2500	2.5
18	25	~ 800	2.2	56	125	2500	2.5
19	25	800	2.1	56	125	2500	2.5
20	25	900	2.3	56	125	2500	2.5
21	25	875	2.2	45	100	2500	2.5
22	25	875	2.2	67	150	2500	2.5
23	25	875	2.2	89	200	2500	2.5
24	25	875	2.2	56	125	3500	2.5
25	25	875	2.2	56	125	4500	2.5

A - Maximum possible combustion rate based on fluidizing oxygen fed to burner.

B - Includes fluidizing oxygen, fluidizing air for cooling, and torch purge air.

C - % of stoichiometric rate assuming complete reaction of the fluidizing O₂ with the feed graphite to form CO₂.

TABLE II

SUMMARY OF RUN RESULTS FOR PRIMARY GRAPHITE BURNER TESTING

Run No.	Run Time, min	Fines Weight, grams	Average Off-Gas Concentration, % CO ₂ - % CO - % O ₂	Combustion Efficiency, ^(B) %	Combustibles in Final bed, wt%	Combustibles in Fines, wt%	Above-Bed Temperature Rise, ^(C) °C	Filter ΔP, psi
11	268	2639	45 - 0.8 - 25	64.7	0.8	94.4	500 - 505	0.2
12	198	2331	61 - 1.3 - 21	74.8	0.7	95.3	560 - 725	0.3
13	161	2344	53 - 2.4 - 17	76.3	1.1	94.7	650 - 790	0.4
14	130	2501	44 - 1.4 - 24	65.9	3.6	95.3	700 - 810	1.2
15	108	2824	41 - 1.3 - 25	63.3	1.3	93.7	800 - 905	1.4
16	160	1619	50 - 2.1 - 25	67.6	2.5	97.2	700 - 975	0.5
17	164	1486	48 - 2.1 - 28	64.3	4.3	97.1	790 - 1060 ^(D)	0.5
18 ^(A)	85	336	---	---	7.5	97.3	---	0.6
19	145	2047	46 - 2.0 - 35	58.2	12.6	95.8	750 - 1060 ^(D)	0.5
20	161	2801	51 - 1.7 - 21	72.0	1.6	96.8	575 - 615	0.6
21	194	4101	48 - 1.3 - 33	59.9	1.1	95.3	550 - 780	0.6
22	138	2020	55 - 3.5 - 16	78.4	0.5	97.3	650 - 695	0.6
23	101	2487	55 - 4.7 - 6	91.5	0.5	96.7	820 - 840	0.7
24	157	3387	51 - 2.3 - 25	68.1	1.2	96.8	730 - 775	0.6
25	157	1805	50 - 2.0 - 24	68.2	0.3	95.8	840 - 870	0.6

A - Run not completed.

B - Defined as $(\% \text{CO}_2 + \% \text{CO}) \times 100 / (\% \text{CO}_2 + \% \text{CO} + \% \text{O}_2)$.

C - Sudden change in upper bed temperature during final burnout of the bed at the end of the run.

D - Reaction was quenched with N₂ when temperature reached 1060°C.

TABLE III

SUMMARY OF MASS BALANCE CALCULATIONS

Run No.	Actual Weight of Graphite Consumed, (A) grams	Percent of Column 1 Based on CO and CO ₂ Production	Percent of Column 1 Based on Oxygen Con- sumption	Weight of Graphite Burned Based on Off-Gas Analysis, grams
11	4051	94	110	4124
12	4359	108	108	4721
13	4346	99	117	4688
14	4189	88	106	4059
15	3866	85	109	3748
16	5071	78	88	4200
17	5204	75	84	4120
18 ^(B)	----	--	---	----
19	4643	70	73	3310
20	3889	104	124	4424
21	2589	173	180	4570
22	4670	81	94	4084
23	4203	65	88	3212
24	3303	118	132	4121
25	4885	77	91	4092

A - Defined as weight of graphite in feed minus weight of graphite in fines.

B - Run 18 not completed.

fiissile and fertile particles were 2500, 3500, and 4500 grams. The results of the combustion efficiency studies are shown in Figures 5 through 8 which give the average off-gas composition and combustion efficiency as a function of the controlled operating variables. For the purposes of this report, the combustion efficiency is defined as the $(CO + CO_2) \times 100 / (CO + CO_2 + O_2)$ ratio. This number is a measure of how efficiently the oxygen is being used by the system. The percent CO_2 in the off-gas would be a good measure of the relative combustion efficiency, except that more nitrogen (torch air, purge air, and fluidizing air) was added in some runs than in others.

The weight of fines elutriated as a function of the controlled variables is shown in Figures 9 through 12. The fines weight plotted is not the total weight of fines elutriated during the run, but only the weight of fines collected after the startup phase of the run was completed. This method eliminated the effects of any variation in the startup procedure or differences in the fines content of the starting beds.

Also plotted in Figures 9 through 12 is weight of fines that would have elutriated (based on the off-gas analyses calculations of Table 3) if there were no fines lodged in the equipment at the end of the run.

Linear, least squares lines have been drawn through both the actual and calculated fines elutriation data in each figure. The solid lines fit the actual weight of fines elutriated, and the dashed lines represent the calculated data points.

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Figure 5. Effect of Fluidizing Velocity on Combustion Efficiency

Figure 6. Effect of Feed Rate on Combustion Efficiency

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Figure 7. Effect of Bed Temperature on Combustion Efficiency

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Figure 8. Effect of Bed Weight on Combustion Efficiency

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Figure 9. Effect of Fluidizing Velocity on Fines Elutriation

Figure 10. Effect of Feed Rate on Fines Elutriation

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Figure 11. Effect of Bed Temperature on Fines Elutriation

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Figure 12. Effect of Bed Weight on Fines Elutriation

IV. DISCUSSION OF RESULTS

The burner and its associated equipment performed satisfactorily during the 15 runs. The CO startup torch failed to ignite during one run, but a minor design change corrected the problem. Plugging or burning of the filters did not occur during the runs. The filter pressure drop remained constant at ~ 0.5 psi throughout all of the runs except Runs 14 and 15 in which the pressure drop increased to as high as 1.5 psi because of the increased fluidizing rate. The filter temperature did not exceed 200°C during the runs.

Burner operability and temperature control was satisfactory at all run conditions except at bed temperatures below 850°C . At the lower bed temperatures any transient condition causing the bed temperature to drop would very often extinguish the burning. Run 18 was made specifically to determine the lowest possible bed temperature at which graphite burning would be self-sustaining in the 4-inch burner. At 770°C the reaction continued, but when the bed temperature was allowed to decrease to 760°C , the temperature continued to drop until all combustion ceased. Burner temperature control was excellent at 900°C .

Another problem which was very pronounced during the low-temperature runs was a sudden rise in the upper bed temperature at the end of the run. After all the feed was metered to the burner, the graphite remaining in the bed would burn for a few minutes. Just as the temperature in the lower bed began dropping slightly (indicating burning of all the graphite) the upper bed temperature would make the sudden rise shown in Table 2. In most of the runs the temperature did not exceed 900°C , nor did the excursion last more than two minutes, but during the runs at bed temperatures of 800°C and 825°C , the excursions were more serious. The above-bed temperature increased to as high as 1060°C and the reaction had to be quenched with nitrogen. A probable explanation for the temperature excursion is the feed (since it is less dense than the bed material) tends to stratify on top of the bed. During the runs when the lower part of the bed is at 800°C or 825°C , the top of the bed is probably 50°C lower in temperature. Since the O_2 concentration and the temperature are both quite low at the top of the bed, very little combustion occurs, and a layer of feed and fines probably collects in the upper part of the bed. After the graphite in the lower bed is burned, the oxygen concentration

in the off-gas increases sharply; the graphite at the top of the bed burns rapidly; in a few seconds the temperature increases above 900°C. A simple method to prevent the temperature excursions and also make burner operation smoother is to always maintain the bed temperature above 850°C and preferably near 900°C. The sudden temperature rise at the end of the run was only 40°C when the bed was maintained at 900°C compared to a rise of 310°C at a bed temperature of 800°C.

The mass balances given in Table 3 show that the amount of graphite consumed during a run varied from 2589 grams to 5204 grams. The calculated amount burned, based on the off-gas analyses, varied from 65% to 180% of the value in column 1. The combined error in the mass balance calculation method and the off-gas analyses is estimated at $\pm 15\%$; therefore, any runs having numbers in columns 2 and 3 which are outside the range of 85% to 115% have an unreliable mass balance. The greatest problem in obtaining an accurate mass balance during the runs was fines bridging or lodging in the burner or filter pot. The fines were very difficult to empty from the filter pot, and there were undoubtedly some fines left in the equipment after each run. The mass balances for Runs 11 through 15 appear to be reliable, but Runs 16, 17, and 19 indicate that fines were probably lodging in the equipment. Runs 20 and 21 show excess fines emptied from the burner. Runs 22 and 23 again show fines collecting in the equipment and discharged from the equipment in Run 24. Run 25 indicates that fines were probably left in the burner. These results show that the fines elutriation data, which will be discussed, are probably not accurate enough to predict reliable trends.

The burner cooling shroud was able to remove sufficient process heat during normal operation to allow satisfactory bed temperature control, except during Runs 14 and 15 which had very high combustion rates. During Runs 14 and 15, $\sim 16\%$ of the fluidizing gas was air added for internal cooling. The combustion heat was removed easily during Runs 24 and 25, because the increased bed depth provided more cooling surface.

The combustion efficiency reached a maximum at ~ 2.2 ft/sec fluidizing velocity as shown by Figure 5. A probable reason for this is that two effects are interacting. During the lower velocity runs, the increased amount of fluidizing oxygen and feed graphite promoted better combustion because of the

higher oxygen and graphite concentrations in the bed plus better mixing of the bed, but as the velocity increased, these advantages were offset by reduced residence time of both oxygen and fines.

As the stoichiometric feed rate increased, combustion efficiency increased rapidly, as shown in Figure 6. This result indicates that the feed rate of 125% of stoichiometric (mole ratio of graphite to O_2 of 1.25), which was used during most of this series of runs, was too low for maximum combustion efficiency. This result was further proven by the fines generation data. An average of 30.7% of the feed was collected as fines during the 15 runs. Since the feed was 83.6% graphite and the fines were 95.9% graphite (average for the runs), 35.2% of the graphite feed was elutriated from the burner before it was burned. This means the feed rate would have to be at least 155% of stoichiometric to provide enough graphite in the burner for complete O_2 combustion. Since the combustion efficiency was still rising at a stoichiometric feed rate of 200%, it appears that the graphite surface area in the burner was limiting the combustion rate. In future runs, fines recycle should provide sufficient graphite for complete O_2 combustion and sufficient graphite surface area even at a stoichiometric feed rate of 100%.

The combustion efficiency curve reached a maximum at a bed temperature of $\sim 875^\circ C$ as shown in Figure 7. This again is probably due to the interaction of two factors. Below $875^\circ C$ the combustion rate was limited by the bed temperature, but with the higher burning rates at $875^\circ C$ and $900^\circ C$ the amount of graphite in the bed became limiting. If the stoichiometric feed rate had been 200% instead of 125%, the combustion efficiency would undoubtedly have continued to increase sharply at a bed temperature of $900^\circ C$.

The beginning bed weight (or bed depth) did not have as great an effect on combustion efficiency as the other variables, Figure 8. A probable reason for the decrease in combustion efficiency with the deeper beds is that with starting bed weights greater than 2500 grams the top of the bed is above the insulated section of the burner and is not as hot as the lower part of the bed. Since the feed material is less dense than the bed, the feed tends to float on top of the bed. If the top of the bed is above the insulation, as it was during both runs with starting beds greater than 2500 grams, a significant part of the feed is probably only at 800 to $850^\circ C$ instead of $875^\circ C$, and the combustion efficiency is lower as indicated in Figure 7.

It was hoped that the weight of the fines elutriated during a run would allow prediction of the fines generation rate at the various run conditions, but as Figures 9 through 12 show, the variance of fines weight from run to run is large, and trends are not accurately predictable. The larger deviation is probably caused by the fines bridging and collecting in the vessels during some runs and being discharged during following runs. Two sets of data are shown on each graph; the circular data points are the actual weight of fines collected during a run, and the square data points are the weight of fines that should have been collected, based on the off-gas analysis. A straight line has been drawn through each set of data on Figures 9 through 12, a solid line through the circular data points and a dashed line through the square points.

The weight of elutriated fines increased with fluidized velocity as shown by Figure 9. This is a reasonable result since as the velocity in the burner increases, the larger fines are blown from the bed and the smaller fines have a shorter residence time to burn. This result also agrees with Figure 5, which shows the combustion efficiency generally decreasing at the high fluidizing rates, which would imply that less graphite was burned and, therefore, more fines were being elutriated.

As the stoichiometric feed rate increased, Figure 10 shows the actual weight of elutriated fines decreased sharply, but the calculated weight of elutriated fines shows just the opposite effect. The reasonable result of increasing the feed rate, and hence the amount of graphite in the bed, is an increase in the amount of fines elutriated from the bed. Run 21, which was made at a stoichiometric feed rate of 100%, shows a mass balance error of 180% (Table 3) which means that far more fines were elutriated than should have been. Disregarding this point, both sets of data agree and show fines elutriation increasing with feed rate.

Although the data points are badly scattered, the actual weight of elutriated fines increased at the higher bed temperatures, as shown in Figure 11. The data points calculated from the off-gas analyses, however, are not badly scattered and show the fines decreasing with increasing bed temperature. The most reasonable result is that the elutriated fines decrease at the higher temperature, since the burning rate is much more rapid.

The actual fines elutriation, as shown by Figure 12, decreased with the deeper fluidized beds. However, this is caused by the extremely low data point obtained for a starting bed weight of 4500 grams. When the mass balance is checked for this run (Run 25), Table 3 shows that more fines probably should have elutriated. If this data point were higher, both sets of data would agree and show elutriated fines increasing with bed depth. This result is reasonable, since as the bed becomes deeper and extends above the insulated section of the bed, the top of the bed becomes significantly cooler. Therefore, the graphite burns much slower and has more time to elutriate. If the upper section of the primary burner were insulated, there would be less fines elutriated from the deeper beds.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were reached as a result of the experimental testing:

1. Sintered-metal filters contained in an external filter pot are satisfactory for separating graphite fines from the primary burner off-gas.
2. The fluidizing velocity in the primary burner should be kept as low as possible to increase fines retention in the bed.
3. The feed rate should be controlled so that there is just enough graphite surface area in the bed to burn the oxygen from the fluidizing gas. Too much graphite in the bed will cause increased fines elutriation and poor fluidization.
4. The bed temperature should be maintained above 850°C and preferably near 900°C to increase combustion efficiency and allow smoother burner operation.
5. Although no conclusions about the effect of bed depth on combustion efficiency and fines elutriation can be drawn from the data, the bed should be as deep as possible to aid in removing the combustion heat. However, too deep a bed (high L/D ratio) will cause excessive slugging and fines carryover.
6. The fines elutriation data was not sufficiently reliable to be conclusive because of fines lodging in the vessels during the runs. The off-gas analyses were reliable and useful in predicting burner responses.

Recommendations based on the experimental testing are:

1. The 4-inch diameter primary burner should be modified to permit testing of the same variables while recycling fines to the burner.
2. Thermocouples should be installed in the burner wall to allow accurate measurement of wall temperatures. The measurements are needed to accurately calculate heat transfer rates.
3. The cooling air capacity of the shroud should be increased so that addition of fluidizing air for internal cooling is not necessary at the higher burning rates.
4. The upper section of the burner should be insulated to maintain an essentially constant bed temperature throughout the depth of the bed.

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