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Comparisons of Micronized Coal, Pulverized Coal and No. 6 Oil for Gas/Oil Utility and Industrial Boiler Firing

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ABSTRACT *What minimum coal particle size is necessary for micronized coal to work? What happens in the closed spaced convection passes of a gas/oil fired boiler when burning coal? This paper will detail combustion research undertaken by Old Ben Coal Company and performed by Riley Stoker Research Center to answer these questions. Furnace heat flux / temperature profiles are investigated and compared to No. 6 oil firing. Ash deposition and aerodynamics are investigated. A unique observation of the effect of excess* O_2 *on heat flux is also described as a result of this testing. Finally, conclusions are drawn regarding the use of micronized coal as a substitute fuel for gas/oil designed boilers.*

INTRODUCTION

There had been much work done in proving that micronized could burn and replace oil and gas in industrial and utility boilers. [1] However, there was a significant degree of uncertainty with regard to what level fineness was sufficient to be able to burn the micronized coal in a gas/oil boiler without a derating. In an effort to evaluate the potential of micronized coal as a future market for Old Ben, the following testing was undertaken at the Riley Pilot Scale Research Facility (PSCF) in Worcester, Massachusetts.

OBJECTIVES

The testing program was designed to answer the following questions:

* What is the effect of coal sizing on carbon burnout, heat flux, flue gas furnace exit temperature and ash particle size?
* What is the effect of ash particle size on convection ash settling, slagging, fouling, and erosion over varying flue gas velocity ranges?
* What is the minimum coal particle size percent passing a 325 mesh (44 micron) sieve acceptable for the conversion of a gas/oil boiler without a derating or pressure part modifications?
* How will NO_x generation vary over the varying firing conditions with particle size and excess air?
* What effect does excess air have on the overall system?

TEST METHODOLOGY

High quality eastern coal from Old Ben's Mine No. 20 was delivered to Riley Research for the combustion tests. The proximate analysis of the Old Ben coal used was: Moisture, 4.4%; Ash, 6.2%; Volatile, 32.9% and Fixed Carbon, 56.5%. To meet the testing objectives three coal size tests were needed. Test 1 burned a typical pulverized coal with 60% passing a 325 mesh screen and an average particle size of 33 microns (8% > 100 mesh). Test 2 burned a fine pulverized coal with 75% passing a 325 mesh and an average particle size of 22 microns (less than 1% > 100 mesh). Test 3 burned a micronized coal at 90% passing a 325 mesh screen with an average particle size of 14.7 microns (99.97% < 100 mesh). Following the coal combustion tests, one test using Number 6 oil was run by Riley and used as a comparison.

Prior to each test day the Schultz-Oneill pulverizer was adjusted to produce the desired coal size distribution. Enough coal was then ground into the pulverizer hopper to conduct the scheduled tests. A natural gas ignitor was used to pre-heat the furnace before firing coal. Coal feed was gradually introduced and as full load was approached the ignitor was removed. When stable conditions were achieved with 15% excess air, measurements were conducted to determine furnace gas temperatures, wall heat flux, flue gas particle size and carbon burnout. The sampling locations are shown on Figure 1. In addition to these more specialized measurements, on-line instrumentation provided

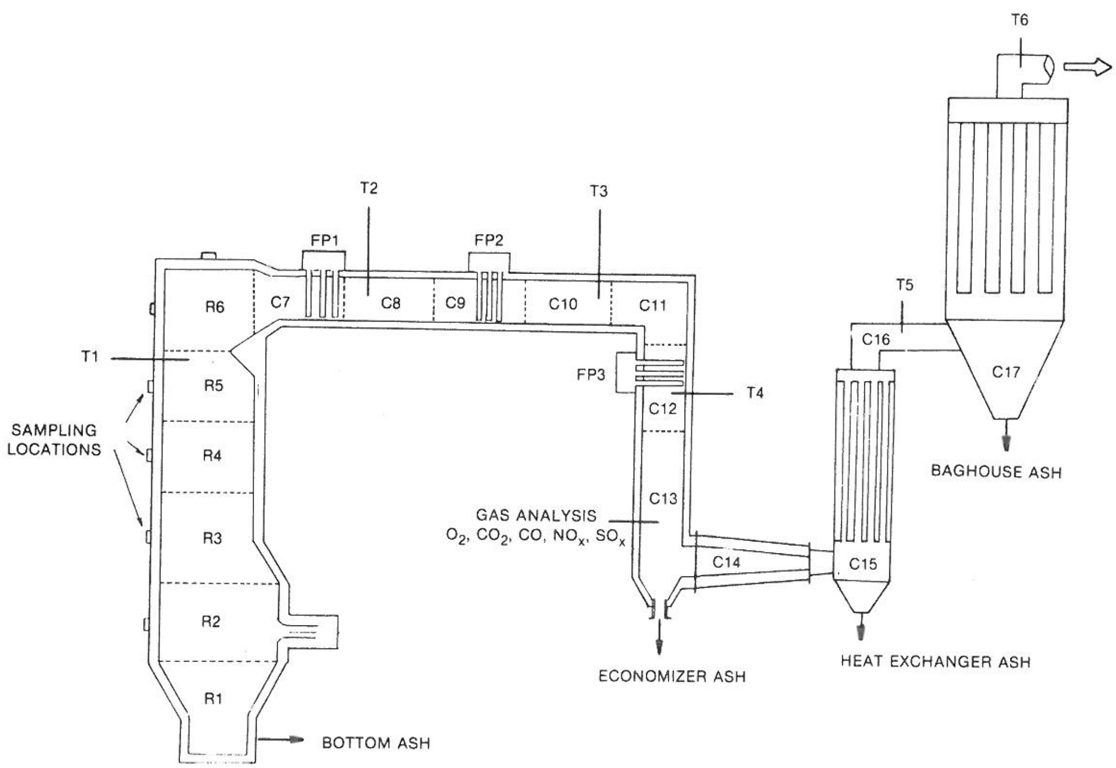

Figure 1. Riley PSCF Schematic

measurements, on-line instrumentation provided furnace operating data and flue gas composition at regular intervals during the test. After approximately eight hours of operation at 15% excess air, test were conducted to determine the effect of excess air on furnace exit gas temperatures, heat flux and NO_x emissions. These measurements were also conducted at 10 and 20 percent excess air levels.

The day after each test was used to recover particulate samples from the facility. The ash collection hoppers in the facility are also indicated in Figure 1. Analysis of these samples was conducted to determine: particulate mass distribution, size distribution and carbon content. The measurement techniques used during the test program are described in the following sections. A description of the specific pieces of testing equipment will not be included herein.

Coal Size Distribution

Two methods were used to obtain pulverized coal samples for size analysis. Samples were aspirated from the coal transport line prior to the pulverized coal baghouse. In addition, grab samples were obtained from the baghouse hopper while discharging into the pulverized coal bin. Multiple samples were obtained to reduce statistical bias. Coal size distributions were determined by standard sieve analysis and by light scattering using a Leeds and Northrop Microtrack Particle Analyzer.

Furnace Gas Temperatures

Temperatures in the radiant furnace were measured at section R1 through R6. The measurements were performed with a water-cooled high velocity temperature (HVT) probe. Furnace gas was drawn over a thermocouple surrounded by a ceramic shield to prevent radiative exchange with the cooler furnace walls. In addition, an unshielded, K-type thermocouple was used to measure the furnace exit gas temperature. This thermocouple reads lower than true furnace gas temperature due to re-radiation, but, is an indicator of furnace conditions.

Furnace Heat Flux

The heat flux to the furnace walls was measured at Sections R2 through R5, using a water-cooled total heat flux meter developed by the International Flame Research Foundation. The probes were usually mounted at sections R3 and R4, but as time and sampling ports became available, the probes were moved to sections R2 and R5. In addition to the total heat flux measurements, an ellipsoidal radiometer was used to measure the radiative heat flux at section R2.

Flue Gas Particle Size

Particle loading and size distribution were measured at section R5 just prior to the transition from the vertical radiant furnace to the horizontal convective pass. The sample was withdrawn isokinetically from a single point at the center of the flow field. A four foot water-cooled probe with a heat traced liner was used to direct the flue gas-particulate sample to a four stage Anderson high capacity impactor. The system eliminates bends for particulate deposition and allows control of the flue gas temperature entering the impactor. The Anderson HCSS impactor fractionates particulates into four ranges allowing separate analysis of each fraction. Gram quantities of each size fraction can be obtained, allowing reasonably long sampling times in heavily ladened flue gas. Along with the impactor, a complete impinger system with pump and dry gas meter are incorporated for moisture removal and sample flow rate control.

Carbon Burnout

The extent of combustion as a function of furnace residence time was measured by withdrawing particulate samples and analyzing for carbon content. The size segregated particulate samples obtained from the particle sizing system were analyzed to obtain carbon burnout at Section R5. Samples were also taken from Section R3 and R4 by a wet sampling train at these locations. The sampling velocities here, were matched as closely as possible with the fluctuating velocities in the lower furnace regions. A water spray was introduced near the probe tip to quench further carbon reaction in the sampling probe. Particulate matter was collected in a two liter impinger which was later filtered and dried for analysis.

Convective Tube Fouling

After each combustion test the three convective tube banks, designated FP1 (16—2.5″ tubes on 3″ spacings in a 4 × 4 array), FP2 (9—2″ tubes on 4″ spacings in a 3 × 3 array) and FP3 (9 extended surface 2″ tubes with .75″ extended surface at 3 fins per inch in a 3 × 3 array), were removed to recover deposited particulate for analysis. The total mass deposited, it's size distribution and carbon content were determined. Deposits were removed from the tube surface using a loop of piano wire for probes FP1 and FP2 and using a brush between the fins of probe FP3. Probe FP3 was also acetone rinsed to remove inaccessible deposits.

Ash Collection

Ash collected throughout the facility was recovered and weighed. In addition, samples from the economizer hopper, heat exchanger hopper and baghouse hopper were obtained and analyzed for size and carbon content. Bulk samples were reduced by combining multiple grab samples then rolling and quartering to provide a representative sample for analysis. Ash hopper locations are also shown on Figure 1. The ash and slag deposited on the furnace walls was removed as much as possible and combined with the bottom ash sample. After the economizer hopper catch was recovered, ash settled in the horizontal and vertical sections of the convective pass was swept into the economizer hopper and recovered. The heat exchanger tubes were also brushed to recover deposited material. Separate weights were obtained for bottom ash, convective pass ash, heat exchanger ash and baghouse ash, in order to compare the mass and size distribution through various sections of the furnace.

TEST SUMMARY AND RESULTS

Tests No. 1 and No. 2 were carried out with only minor difficulties and all data was able to be collected. Fine coal agglomeration problems were encountered with test No. 3. Therefore the test was terminated prior to the collection of all data. During test 3, these agglomerating tendencies of the finest ground coal (90% through 325 mesh) caused severe fluctuations in micronized coal flow from the pulverized coal storage hopper to the burner. Rapping and two system modifications did not improve the condition. A number of micronized coal flameouts and a significant amount of low (less than 1% O_2) excess air firing were experienced. As a result, the data available from Test No. 3 with micronized coal must be considered in this light.

The following will summarize the test results based on the objectives defined above:

COAL SIZE AFFECT

Carbon Burnout

Carbon utilization increased with the finer coal grinds. Fly ash carbon losses were found to be 4.5% for test 1 (60% < 325 mesh) and 3.9% for test 2 (75% < 325 mesh). Test 3 (90% < 325 mesh) showed an increase in carbon loss. The latter was attributed to lower loads, reduced furnace temperatures and flame instabilities associated with erratic coal flow.

Although the temperatures and residence time of the PSCF are representative of full scale combustors, the carbon loss obtained for test 1 and 2 should not be considered representative of oil designed units converted to micronized coal grinds. The scaled down burner results in the inefficiencies observed. However, the comparison of micronized coal results with oil fired data provide an extremely valuable insight into the applicability of micronized coal.

Heat Flux

Heat flux measurements in the radiant furnace during Tests 1 and 2 are compared with those for oil in Figure 2. Increased heat flux in the lower furnace for the finer grind results from an increased combustion rate and burner zone temperature. For Test 1, the higher heat flux is in Zone 4 and slightly higher in Zone 3. In Test 2, the heat flux in Zone 2 is higher. If the heat flux line for test 2 is extended toward the bottom of Zone 2, the heat flux could tend to be significantly higher at the same BTU/hr rates and excess air. Comparison to the oil curve indicates oil to have a higher lower furnace heat flux. However, the curves for the oil and 75% < 325 mesh micronized coal are fairly similar.

For a gas/oil boiler, heat must be released as soon as possible within the furnace to take full advantage of the total effective projected radiant surface to achieve the lowest possible furnace flue gas exit temperature without going below that temperature necessary for maintenance of superheat/reheat temperatures, if applicable. Based on heat flux data represented in Figure 2 and flame length observed during Test 3 (90% < 325 mesh), micronized coal could be expected to be equal or better than oil at grinds producing 80 to 90% less than 325 mesh.

Flame Length

During Tests 1, 2 and 3, there was a visible difference in flame length and volume. For the standard grind coal, the flame size, as a percent of flame envelope, was between 70-80%. For Test 2 (75% < 325 mesh) the flame size was 50-60% of the flame envelope. For Test 3 (90% < 325 mesh) it was 30-35% of the flame envelope. Observations during the oil test showed a flame length and volume equal to about 25-33% of the flame envelope. During Test No. 3 a load of only 2.5 million BTU/hr was achieved at a 1.3 stoichiometry. With a decreased O_2, an increase in the BTU input would probably not affect the flame size appreciably.

During Test 1, there was a high concentration of sparklers at the flame extremities. Sparklers were also observed being carried over into the first section of convection tubes. These sparklers were not observed in Test 2 or 3.

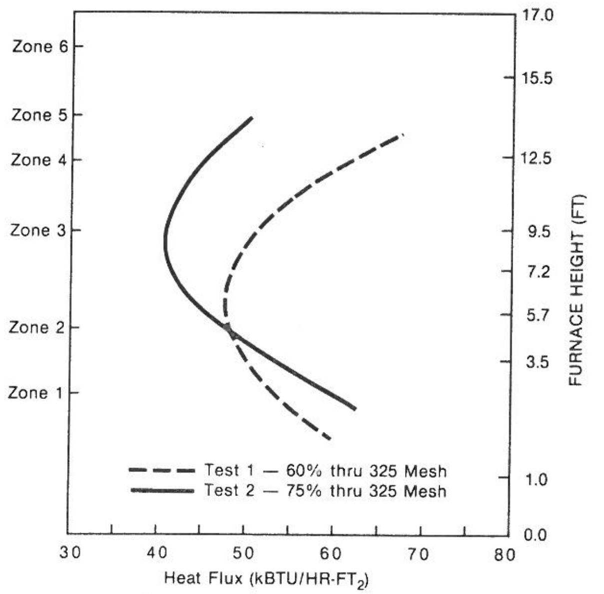

Figure 2. Effect of Coal Size on Furnace Heat Flux

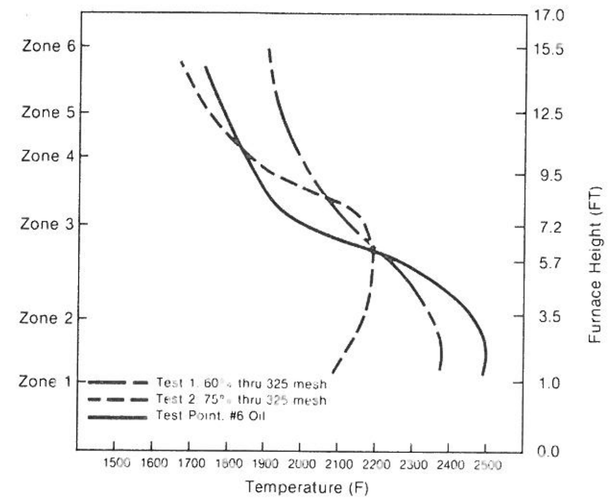

Figure 3. Effect of Coal Size on Furnace Gas Temperatures

FURNACE EXIT FLUE GAS TEMPERATURE (FEGT)

The flue gas temperature distributions measured by HVT probes in the radiant furnace are presented in Figure 3. It is evident that the finer grind coal burns faster and produce higher temperatures in the burning zones. The increased radiant heat transfer in the lower furnace exit gas temperatures. The increased slag accumulations in the burner region during Test 2 resulted from these high burner zone temperatures. The high surface temperatures induced by the refractory lining and the close proximity of the burner to the side walls, encourages the development of slag in the test furnace. Whether or not slag would develop in the burner region of a water cooled furnace is not known. The slagging plate installed on the rear wall of the test furnace, which was maintained at temperatures representative of water wall furnaces, showed a decrease in slag deposition with finer coal grinds.

Compared to oil firing, coal tests 1 and 2 showed higher temperatures from furnace Zone 2 to furnace Zone 3. Test 2 coal (75% < 325 mesh) furnace temperatures approximate those for oil firing between furnace Zone 3 and Zone 6 (Furnace Exit). Higher upper furnace temperatures are seen with the Test 1 coal at (60% < 325 mesh).

The increased heat release in the lower furnace improved energy transfer results and reduced FEGT to those approaching oil for the finer grind coals. A 200°F temperature difference was observed between the standard grind, Test 1, and the coarse micronized coal, Test 2. Test 3 data was not obtained. However, furnace exit gas temperatures are expected to be lower than those for oil. With the expected lower FEGT for fine micronized coal, there could be some concern for maintaining superheat/reheat temperatures. This could become a particular concern for original coal designed units.

Ash Particle Size

The average particle size of flue gas and ash hopper particulate samples are shown in Table 1. For Test 1 there was about 10% greater than 100 microns compared to only about 3% greater than 100 microns for the coarse micronized coal at the furnace exit location. No data was collected for the fine micronized coal test.

When looking at concentrations by sizes, the economizer and heat exchange hoppers are not efficient for capture of small particles and differences between the tests are not apparent below 10 microns. In the larger particle sizes differences in particle sizes are more apparent with much lower particulate capture form the finer grinds. For the baghouse, efficient for the capture of small particle sizes, an increased loading of the smaller particle sizes is noted for Test 3. There was not much difference in the amounts of total ash per pound of coal between Test 1 and test 2. The discussion of the settling and deposition to follow will provide additional information on this point.

TABLE 1
ASH PARTICLE SIZE AND COLLECTION RATES

Average Particle Size (micron)			
Sample Location	Test 1	Test 2	Test 3
1. Flue Gas (R5)	11.0	7.6	—
2. Economizer	84.9	69.6	26.3
3. Heat Exchanger	96.3	59.8	26.7
4. Baghouse	33.4	18.2	14.7
Normalized Collection (lbs. ash/lbs. coal)			
Sample Location	Test 1	Test 2	Test 3
1. Flue Gas (R5)	—	—	—
2. Economizer	0.020	0.007	0.004
3. Heat Exchanger	0.006	0.006	0.001
4. Baghouse	0.087	0.082	0.109

ASH SIZE EFFECT

Settling and Deposition

Tube bank deposition is a result of complex interactions between tube bank flow aerodynamics and the chemical/physical structure of the flue gas particulate and condensibles. Table 2 is a summary of representative flue gas velocities and deposition rates for the three tests. Comparing Test 2 to

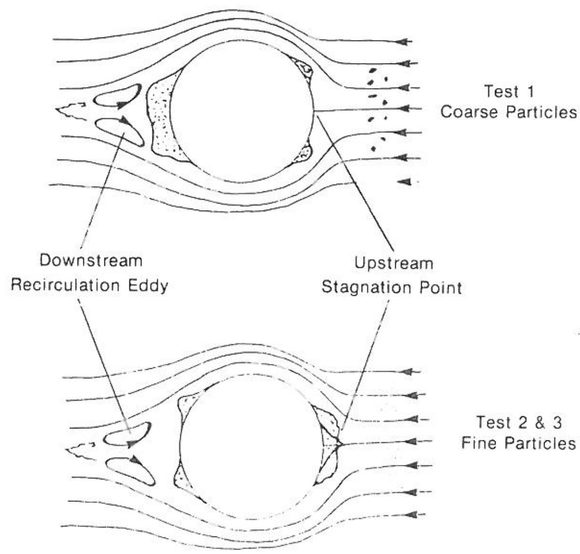

Figure 4. Comparison of Deposit Structure

TABLE 2
PROBE DEPOSITS SUMMARY

Test Number	1	2	3
Coal Grind (% < 43 μm)	60	75	90
Coal Fired (lb)	2792	2141	1797
Mean Flue Gas Particle Size (μm)	11.0	7.6	—
Fouling Probe 1:			
Flue Gas Velocity (FPS)	87.1	79.6	59.2
Total Deposit (lb)	.8691	.6702	.7560
Mean Particle Size (μm)	7.22	8.46	8.25
Combustible (%)	.8	4.8	2.6
Lb Deposit/Lb Coal Fired	3.113×10^{-4}	3.130×10^{-4}	4.207×10^{-4}
Fouling Probe 2:			
FG Velocity	23.5	24.5	18.5
Total Deposit (lb)	.1798	.1444	.0897
Mean Particle Size (μm)	10.19	10.04	10.55
Combustible (%)	1.1	1.6	6.1
Lb Deposit/Lb Coal Fired	6.440×10^{-5}	6.774×10^{-5}	4.992×10^{-5}
Fouling Probe 3:			
FB Velocity	21.2	20.6	19.9
Total Deposit (lb)	.3662	.4579	.3790
Mean Particle Size (μm)	13.56	15.6	16.15
Combustible (%)	3.7	5.7	18.8
Lb Deposit/Lb Coal Fired	1.312×10^{-4}	2.139×10^{-4}	2.109×10^{-4}
Slagging Probe 1:			
Total Deposit (lb)	.0835	.0595	1.2247
Probe 1,2,3			
Total Deposit (lb)	1.4151	1.2725	1.2247
Slagging Probe 1:			
Total Deposit (lb)	.0835	.0595	
Lb Deposit/Lb Coal	2.99×10^{-5}	2.78×10^{-5}	

Test 1, on a normalized pound per pound of coal fired, there is about the same amount of deposit on the first two probes and an increased amount on the economizer probe. Test 3 did not follow this trend.

A cursory review of the data would tend to simply state: that the deposition rate of ash increase with decreasing ash particle size. However, when tube bank temperatures and velocities are considered, the changes in the ash viscosity and aerodynamics of the system reduce the influence of particle size on the deposition rate in the convection sections tested. This was indicated by the location of the deposition on the tubes during the three tests.

Figure 4 is a sketch of the relative deposit locations for the three tests. During Test 1 the deposit location was concentrated on the down stream side of the tubes. The deposit during the finer grind test was reversed with the deposit concentrated on the up stream side of the tubes. The presence of larger particles in the flue gas during Test 1 may have helped prevent the formation of the up stream deposit in that case. We believe work done by Drs. Beer and Sarofim at MIT, [2] tends to agree with this finding.

The inability to collect meaningful information from the fine micronized coal test has severely limited the ability to draw conclusions regarding the deposition of ash when using micronized coal. Decreases in flue gas temperature and velocity give good reason for an optimistic outlook with finer grind coals.

Slagging and Fouling

Under all test conditions there was only a small amount of deposit on the slagging test panel. However, there was no indication of a potential furnace slagging problem. This was primarily due to the high fusion temperature of the Old Ben coal (H = W + 2700) used for the test. There was about 7% less ash deposited on the slag panel during Test 2 than there was for Test 1. No deposit was observed on the panel for Test 3. These results would tend to complement the observed flame length and volume proportions for the two tests.

With regard to fouling, there was deposition on the fouling probes in each test. Only in Test 1 was there any indication of sintering in the first probe section. Other than this case, the deposits were of a fine powdery deposit that could be easily removed with a light brushing. The coal used for the tests was such that very little fouling would normally be expected. No conclusions can be drawn at this time regarding the utilization of a lower fusion, high fouling coal under similar conditions.

Erosion

In all tests the operating time was not sufficient to make a definitive prediction or draw any conclusions regarding the erosion characteristics of micronized coal. However, the absence of deposition on the tube fronts during Test 1 could be a result of the scrubbing action of the coarser particles inherent with the standard pulverizer grind. This was not seen with the finer grinds and could indicate little or no erosion problems with these grinds.

MINIMUM COAL PARTICLE SIZE NEEDED

Comparison of coal test data with oil test data indicates that micronized coal with 75% < 325 mesh grind closely approaches the heat flux and furnace exit gas temperatures for firing No. 6 oil. These initial results tend to set a minimum 75% < 325 mesh grind sizing as the lower limit for micronized coal firing in a conventional gas/oil designed boiler.

Test 3 at 90% < 325 mesh was never completed. As a result it is impossible to confirm a maximum fineness limit for micronized coal combustion. Until further testing is undertaken it does not seem warranted to require finenesses greater than 90% < 325 mesh. One of the original reasons for looking toward finenesses on the order of 98-99% less than 325 mesh was to carry all the ash through the boiler. These test were inconclusive with regard to any grind size above 75% < 325 mesh. With the ability to add sootblowers, coal fineness on the order of 80 to 90% less than 325 mesh may be sufficient to meet the needs of most gas/oil boiler designs. Further testing is needed in this regard.

NO_x GENERATION

As expected, the results of nitrogen oxide emission measurements during the combustion tests indicated that flue gas NO_2 concentrations increases with stoichiometric ratio for the finer grind coals. However, the rate of increase is less than that for the standard grind coal. The increase surface available for reaction and the resulting increase in combustion intensity and higher temperatures are not as readily affected by reduced oxygen concentrations. This was observed in the CO-O_2 response. The finer coal grinds could be burned at much lower excess air levels before producing a drastic increase in CO.

The results of NO_x measurements corrected to 3% O_2 are presented in Figure 5. The load

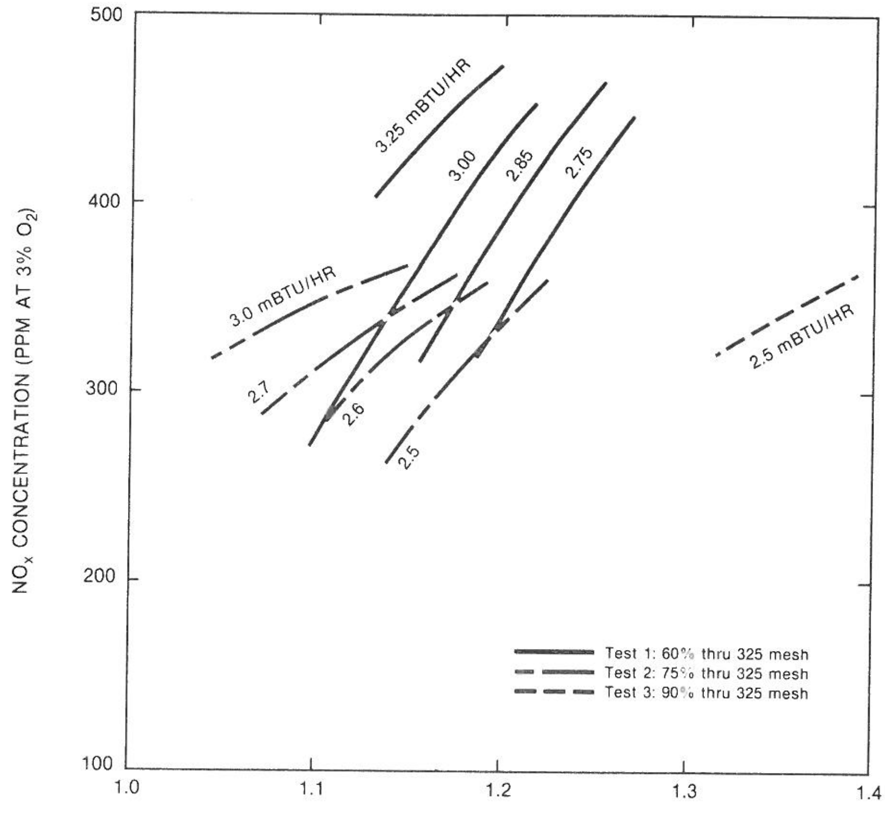

Figure 5. Effect of Excess Air and Coal Size on NO_x Emissions

variations drawn are approximate as there is some spread in the results. The slope of the NO_x (ppm) vs. total stoichiometric ratio indicates that NO_x emissions for the standard coal grind are more sensitive to changes in stoichiometry than are the micronized coal grinds. For Tests 1 and 2 the NO_x emissions are higher for the finer grind coal at a stoichiometric ratio of 1.15. For all other ratios the NO_x emissions are lower for the finer grinds. Only one data point was taken for Test 3 indicating good results for a fairly high stoichiometry of 1.3.

SYSTEM EXCESS AIR EFFECTS

The variation of furnace temperature with excess air was investigated at the standard grind using 2 different excess air levels. Figure 6 indicates that the increase in excess air from 18% to 26% generated a significant change in the temperature profile of the furnace. The expected results would be a slightly displaced curve toward the higher temperatures. The lower temperatures in the Zone 2 to 4 region tend to indicate a much more complex relationship which must include: furnace absorption, flame and gas propagation velocities and heat flux. This is further confirmed in Figure 8.

Figure 7 shows what would be expected as excess air increases FEGT decreases. As indicated by the relative slope of the trend lines, this is more pronounced as particle size decreases. The range of variation among data points for Test 1 compared to Test 2, the finer grind tends to give more predictable results with varying excess air levels.

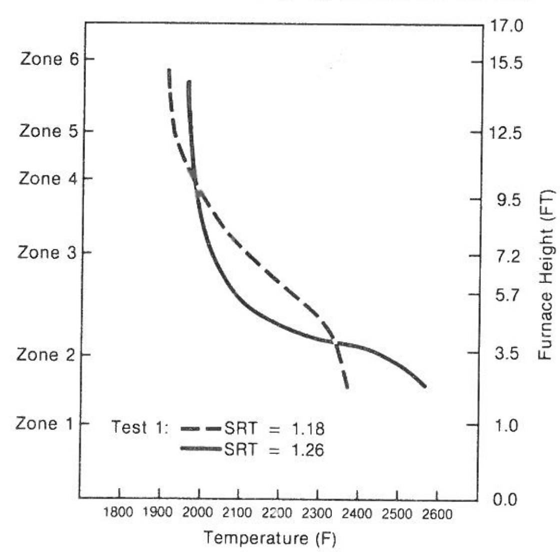

Figure 6. Effect of Excess Air on Furnace Gas Temperatures

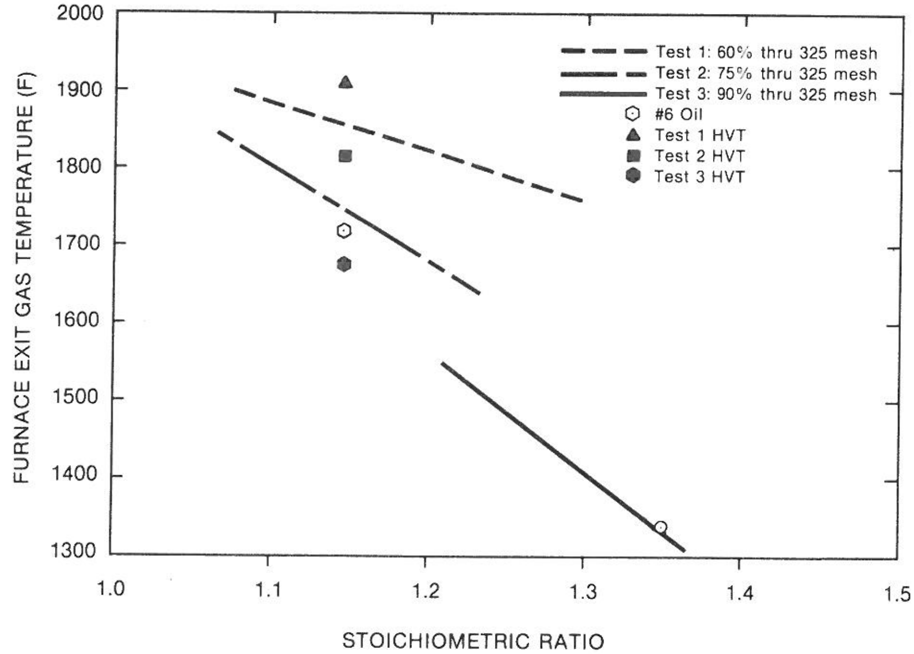

Figure 7. Effect of Excess Air at Varying Fineness on Furnace Exit Gas Temperature

Figure 8, Heat Flux vs. Excess Air, generated some very surprising results. It is generally thought that as stoichiometric ratio (SR) decreases, heat flux increases due to the higher adiabatic flame temperatures. However, the combustion rate, and, therefore, heat flux is also controlled by O_2 concentrations. As SR increases, O_2 concentrations and heat flux would be expected to rise until the excess air begins to cool the flame in excess of the rate of heat flux increase. We might expect an inverted "U" shaped curve for this relationship. The reverse relationship with a flattening or elevation in the center, as seen for Test 2, plotted in this figure was totally unexpected. At this point, other than

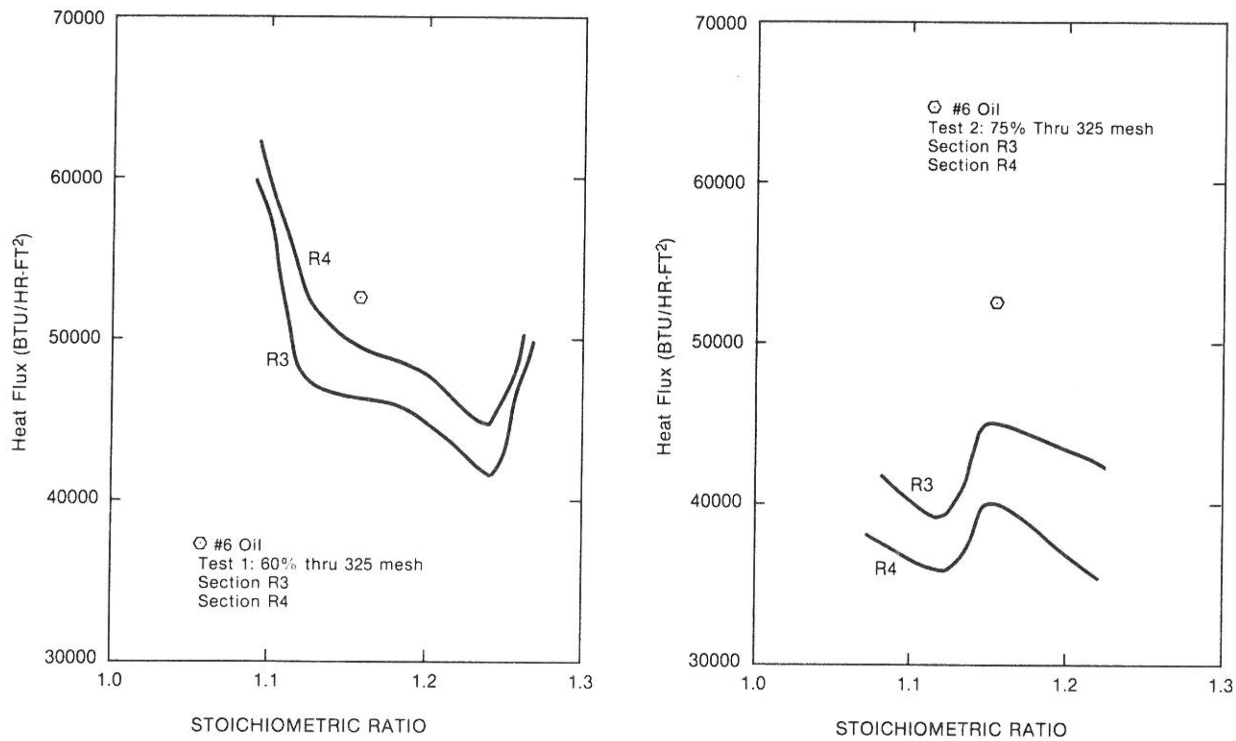

Figure 8. Effect of Excess Air on Furnace Heat Flux

to say it could be a function of multiple particle kinetics and particle density, we are at a loss to explain why this happened.

CONCLUSIONS

This testing was undertaken to answer some relatively practical application questions -- well beyond the standard "Will it burn?" The information generated we believe gives micronized coal a very high probability of success if applied as conversion fuel for oil and gas fired boilers. The characterization of micronized coal in the 80 to 90% < 325 mesh range is indicated to be sufficient to generate oil like temperature results in these units.

Our experiences with fine micronized coal transport from the pulverized coal hopper to the burner and flame shape and size are very similar to those experienced at IGT. [3] We now understand the problem of fine coal transport and believe it can be handled, but remains to be tested.

From the testing, we found that ash deposition will take place in the convection passes of a boiler. Our inability to test the fines grind case significantly limits any conclusions in this regard. More testing is needed.

The information gained from the heat flux and excess air evaluations was totally unexpected and may be of significant benefit for coal performance experimentation and modeling activities.

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