The Effects Of Coal Particle Size And High-Throughput On The Performance Of The 20 Hwt MHD Coal Combustor

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THE EFFECTS OF COAL PARTICLE SIZE AND HIGH-THROUGHPUT ON THE PERFORMANCE OF THE 20 MW_t MHD COAL COMBUSTOR

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ABSTRACT

A series of parametric tests were performed to evaluate the performance sensitivity of a nominal 20 MW_t slagging MHD coal combustor to both coal particle size and thermal throughput. All tests were performed using an existing 24 inch diameter slagging combustor. Montana Rosebud Seam coal was used for all the tests and 2900^{o}F vitiated air was nominally used as the oxidizer. The effects of particle size on slagging stage heat loss, slag recovery and carbon losses to the slag are presented. We also present and discuss the effects of throughput (combustion intensity) and swirl number on heat loss and slag capture.

INTRODUCTION

Since 1975, TRW has been developing high pressure, high slag rejection coal combustors that would meet the requirements specified by the U.S. Department of Energy (DOE) for MHD applications. Coal combustors with nominal power ratings of 10, 20 and more recently, 50 MW_t have been designed, fabricated and successfully tested at TRW. In particular, the 20 MW_t combustor has been extensively tested (1, 2) in the past and its performance characterized as a function of stoichiometric ratio, air preheat level (both oil and coal vitiation) and level of oxygen enrichment. Figure 1 shows an isometric view of the two stage combustor. The first stage is a confined vortex flow combustion chamber where pulverized coal is burnt under substoichiometric conditions. Partial oxidation of the coal as well as slag rejection takes place in the first stage. Final oxidation and seed addition takes place in the second stage where the plasma required for efficient MHD power generation is produced. Proper design and operation of the first (or slagging) stage is critical by virtue of its function (heterogeneous combustion and slag separation) and of its size which is significantly larger than that of the second stage, thus accounting for the largest fraction of the heat losses.

Since early development testing it had been recognized by TRW that selection of the coal grind (particle size and distribution) was important in determining the performance of the first stage. Indeed, whereas small particle sizes ensure in-flight combustion (as contrasted to wall burning) of the coal, from the point of view of slag particle centrifugation to the walls, large particle sizes should be favored. Accordingly a series of tests was conducted as described hereafter, aimed specifically at evaluating the combustor performance sensitivity to coal particle distribution.

A second important aspect of MHD coal combustor development relates to the sizing and scaling of the combustor. Indeed a factor of 5 to 10 scale-up is required for early commercial applications and consequently the effects of the combustor size and its possible limitations on performance need also to be investigated. The present paper describes the results of tests where the throughput of the 24 inch diameter combustor was varied in the range of 15 to 30 MW_t and the performance dependence on flow rate is analyzed.

EFFECT OF COAL PARTICLE SIZE ON COMBUSTOR PERFORMANCE

The objective of this test series was to determine the performance sensitivity of the 20 MW_t coal combustor to coal particle size and distribution using the existing test hardware and an available stock of pulverized coal. A total of 11 tests were conducted under the following test conditions:

Air Preheat Temperature	2900^{o}F
Total Thermal Input	20 MW_t
Chamber Pressure	6.0 atmos
Oxygen Enrichment	23.0% at inlet
First Stage Equivalence Ratio	.69
Test Time	60 Min.

Test Set Up

The 20 MW_t combustor installation on the test stand at FETS is shown in Figures 2 and 3. The coal-fired vitiator from the low preheat development test series was left in place, however the unit itself was not utilized. The tests were conducted with the nominal 2900^{o}F preheat provided by the oil-fired vitiator.

Test Coals

All of the tests were performed using existing stocks of pulverized Montana Rosebud Seam coal. Tables 1 and 2 show the typical moisture, ash and sieve analysis of the coals used. Differences in the coal moisture content and ash content were recognized but were unavoidable. Figure 4 shows the particle size distributions for the various coals used for this test series.

The "endurance test coal" is from the same lot used for the 1981 20 MW_t coal combustor endurance test series. The endurance test "classified" coal was obtained by separating the coal into approximately two equal lots with a cyclone separator. The lot with the larger size particles was labeled as "coarse" coal and the remainder as "fine" coal.

The "CDIF coal" was obtained from the Component Development and Integration Facility (CDIF) located in Butte, Montana. The coal was processed as part of the CDIF coal grinding equipment checkout work.

The "PETC coal" used for this series was delivered to TRW in 1980 from the Pittsburgh Energy Technology Center (PETC) for use during the combustor demonstration test phase. The coal is Montana Rosebud Seam coal with a nominal grind classification of 80-200 mesh. In-house sieve analysis indicates the distribution in actuality approximates a 50-325 grind.

Table 1. Coal Analysis - Dry Basis

TEST	MOISTURE (%)	ASH (%)	HEATING VALUE BTU/LB	C (%)	H (%)	N (%)	Cl (%)	S (%)	O (%)	O/F	SO_3(ASH) (%)	T_{250} (^oF)
161	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
162	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
163	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
164	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
166	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
167	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
168	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
169	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
170	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
171	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
172	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
173	18.2	10.3	-----	-----	----	---	---	----	-----	-----	-----	----
174	18.2	10.3	-----	-----	----	---	---	----	-----	-----	-----	----
176	----	----	-----	-----	----	---	---	----	-----	-----	-----	----
177	----	----	-----	-----	----	---	---	----	-----	-----	-----	----
178-179	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
180	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
181	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
182	20.28	17.35	10628	62.86	4.10	.88	.06	.78	13.97	2.008	9.27	2640
183	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
184	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
185	22.69	15.38	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
186	22.08	14.74	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
188	22.01	14.99	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
189	21.55	16.52	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
195	22.60	15.17	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480
196	22.60	15.13	11008	64.44	4.32	.91	.04	1.06	13.85	2.070	10.94	2480

Table 2. Test Coal Description

	ENDURANCE TEST COAL			CDIF	PETC	
	CLASSIFIED* FINE	CLASSIFIED* COARSE	AS RECEIVED	AS RECEIVED	AS RECEIVED	CLASSIFIED* COARSE
TYPE	MONTANA ROSEBUD	MONTANA ROSEBUD	MONTANA ROSEBUD	MONTANA ROSEBUD	MONTANA ROSEBUD	MONTANA ROSEBUD
MOISTURE (%)	20.3	5.84	22.7	18.2	8.36	8.87
ASH (%) DRY BASIS	17.35	12.85	15.38	10.3	11.26	10.87
PARTICLE SIZE DISTRIBUTION (WEIGHT PERCENT)						
<12 MESH	0.276	.00	.00	.045	.00	.00
12-20	.1324	.0277	.022	.178	.0331	.0296
20-60	.0806	3.101	1.584	14.300	.1113	.1787
60-80	.0911	7.507	3.778	10.787	.3796	.516
80-100	.2172	8.758	4.275	6.723	.9360	1.003
100-200	1.828	53.234	29.125	31.572	26.822	35.178
200-230	2.584	10.779	7.237	6.911	12.363	15.279
230-270	3.393	6.324	7.624	4.211	6.877	16.138
270-325	1.564	2.155	1.590	1.261	2.286	5.176
325-500	31.004	7.279	21.439	14.277	26.443	24.867
500- >	59.075	.832	23.324	9.730	23.747	1.630

* "Classified" coal was obtained by separating the respective "as received" lot of coal into the coarse group and the fine group.

Test Results

A total of 26 combustor test firings were executed of which 11 separate coal firings were performed to evaluate the effects of coal size or size distribution on combustor performance. Approximately eleven (11.4) hours of coal combustor test time were accumulated during this test series. All of the tests were nominally of one hour duration. In all cases, the test run was initiated with the combustor wall fully slagged at the start of the test run to maximize test results uniformity.

The average first stage heat loss was noted to decrease with the finer coal grind as shown in Figure 5. The anomalously high first stage heat loss shown for the tests with the coarse coal was attributed to both increased wall burning (as opposed to in-flight burning) of the coal particles and to the loss of the protective slag layer during the test. Significant variations in the heat loss were noted during the test, indicating that large wall areas were losing slag cover during the run. Post test observation of the combustor walls indeed revealed large uncovered areas. Also, examination of the slag indicated that it was very porous with low mechanical strength. The lack of good slag coverage is attributed to the low mechanical strength of the slag combined, possibly, with the worn down condition of the slag retention pins. The measured average heat flux for the chamber section, slag dump section and the volute section has been plotted as a function of coal particle size distribution in Figure 6. The higher heat flux with the coarse coal grind is believed to be the result of an increase in wall burning of the injected coal. The reason for the heat flux "cross over" at the 46% point has not been determined.

The measured slag recovery performance as a function of coal particle size has been plotted and is presented in Figure 7. The slag recovery number has been corrected for the loss of the non-condensible volatiles (SO_3). All of the tests were performed with the available stock of Montana Rosebud Seam coal. Although it was recognized that the tests should be performed using coal processed and dried from a single lot, the logistics, costs and time requirements were beyond the scope of this test program.

The maximum slag recovery was achieved with the coal having 46 wt. % of the coal particles smaller than 270 mesh. The slag recovery decreased from 85% (max.) to 60% as the fine particle content was increased to 90%. A slight drop-off in slag recovery was also noted at the other extreme end (10 wt. % smaller than 270 mesh) using classified and dried coal (see Figure 7 and Table 2). The low combustor slag recovery noted with the finer coal grinds is believed to be the result of the higher percentage of small slag droplets formed during the combustion of fine coal. The small slag droplets are entrained in the combustion gas flow and carried out of the slag recovery zone or first stage. The lower slag capture noted with the "coarse" coal is tentatively attributed to localized stripping of slag layer. It is hypothesized that the stripped slag becomes airborne and escapes the combustor. The slag stripping hypothesis is consistant in part with the higher heat loss with the coarse coal. The increase in unburned coal in the captured slag as a function of coal particle size is shown in Figure 8. It is evident from the test data that as the percentage of larger coal particle size is increased, the coal particle residence time becomes insuffecent to achieve complete in-flight combustion. Coal that is entrained in the slag and not consumed in the wall burning process is rejected along with the molten slag.

HIGH THROUGHPUT TESTING

The specific objective of this test program was to achieve a greater knowledge of the combustor scaling laws. This test series consisted of 11 tests accumulating 9.95 test hours of coal burn time. Each test was nominally 1.0 hour long. Pulverized Montana Rosebud coal was used for all tests. The test approach was to incrementally increase the total thermal input to the combustor at nearly constant operating conditions (ϕ_1, preheat) and measure the change in the combustor performance (i.e., heat loss, carbon loss and slag rejection).

Test Results

The nominal first stage operating parameters for this test series are listed in Table 3. Table 4 presents the test conditions and test results for the 11 tests which comprise the high throughput test series. The general appearance of the chamber slag and chamber slag coverage for this portion of the test program is shown in Figure 9. The slag layer is about 1/4 to 1/2 inch thick and has a glassy surface texture.

Table 3. Operating Parameters

Air Preheat Temperature	- 2900^{o}F
ϕ_1	- .65
Wt % Oxygen	- 23.0
Air Inlet Velocity	- 280 Ft/Sec

The heat loss from the combustor was calculated by measuring the flow rate and temperature rise of the cooling water in the various circuits. Typically, the total combustor first stage heat loss was found to be of the order of 1500 BTU/sec. The relative heat loss is defined as the ratio of the heat loss to the thermal input from the coal and oil. A simplified model which accounts for convection and radiation yields a heat loss dependence of the form shown as Equation (A) for the specific test condition:

$$Q\ (\%) \simeq \frac{1.07}{\alpha} + \frac{116}{MW_t} \qquad \text{(A)}$$

The first term of Equation (A) arises from convective losses and the second term from radiative losses, which are assumed constant for constant operating conditions. The parameter α is equal to the ratio of the actual oxidizer inlet area to the maximum area.

Table 4. Test Summary

TEST NUMBER	TEST DATE	COAL BURN TIME (MINUTES)	COAL TYPE	PREHEAT TEMPERATURE (^oF)	% OXYGEN (WT %)	ϕ_1	ϕ_2	CHAMBER PRESSURE PSIA	TOTAL THERMAL INPUT MW_T	HEAT LOSS - PERCENT CFV	HEAT LOSS - PERCENT FIRST STAGE	HEAT LOSS - PERCENT SECOND STAGE	SLAG RECOVERY* %
136	3/24/82	60	↑	2840	23.1	.716	.977	55.0	15.3	-	8.36	2.9	74.4
137	3/25/82	59		2840	23.3	.708	.966	55.0	15.5	-	7.70	3.0	79.7
149	4/20/82	43	MONTANA	2864	22.9	.685	.943	58.4	15.9	-	12.80	-	62.4
171	1/5/83	60	ROSEBUD	2550	22.0	.69	.90	71.0	18.0	3.9	9.60	2.3	75.2
172	1/5/83	71	NOMINAL	2465	23.0	71	.92	73.0	18.9	3.8	9.40	1.9	79.5
183	2/2/83	61	80-200	2553	23.0	.70	.90	76.0	20.4	3.8	7.80	2.1	84.3
184	2/3/83	60	MESH	2550	23.0	.69	.90	55.0	14.8	4.3	8.60	2.2	80.3
185	2/7/83	21	AS REC'D	2657	23.0	.65	.86	84.2	25.3	2.95	7.00	1.89	79.08
189	2/15/83	61	MOISTURE	2845	23.0	.66	.77	84.3	25.5	4.1	7.22	1.79	73.7
195	3/14/83	49		2609	23.0	.69	.90	78.0	30.9	3.27	6.26	2.6	47.7
196	3/15/83	52	↓	2609	23.0	.69	.91	77.0	30.2	3.5	6.07	2.62	63.0

*CORRECTED FOR MOISTURE AND SO_3 LOSS

Figure 10 shows a comparison between measured and calculated heat loss. The two solid curves in Figure 10 represent the calculated relative heat loss for air inlet areas of 48% and 100% of maximum respectively. These two curves bracket the measured relative heat loss with the exception of test #184. The reason for the poor correlation of test #184 has not been determined. The combustor heat loss data essentially corroborates the assumptions of Equation (A). To a first approximation, radiative heat loss is the dominant loss mechanism.

The slag recovery data is shown plotted as a function of thermal input per unit chamber pressure (MW/P) in Figure 11. As indicated, slag recovery is maximum near MW/P equal to 3.8 or at about 23 MW_t at nominal 6 atm. pressure. We note however that as the throughput is increased at constant oxidizer inlet velocity, the swirl number decreases, so that the decrease in slag recovery at high throughput may be due to the decrease in swirl number. Replotting the slag recovery values as a function of swirl number (Figure 12) shows what appears to be either an asymptote at about 80% recovery for a swirl number greater than about 6 for this test series or possibly a maximum point at S = 6.0 depending on how the data is interpreted. A semi-empirical slag recovery correlation equation was derived to assist in the interpretation of the slag recovery data and takes the form:

$$\eta = \eta_{Tap}\,\eta_{Escape} \qquad \text{(B)}$$

The equation is valid for $\eta_{Tap} \leq 1.0$ and swirl number $S \leq 6.0$. For $S > 6.0$, S is assumed constant. η_{Tap} is a simple geometric slag capture term and η_{Escape} is an ash particle escape term. The variables are:

$$\eta_{Tap} = \frac{2d}{\pi D}\left[1 + \left(\frac{S}{2}\right)^2\right]^{\frac{1}{2}} \quad \text{(C)}$$

$$\eta_{Escape} = \left[1 - F_a\right]^{\frac{A\tau_g}{S^2\left(L/D_e\right)^2}} \quad \text{(D)}$$

S = Swirl number
d = Slag Tap diameter (d = 12.0 inch)
D = Chamber diameter (D = 24 inch)
D_e = Baffle diameter (D_e = 12 inch)
L = Chamber length
τ_g = Plug flow gas residence time (sec)
A = Constant dependent on coal and ash properties
F_a = Ash fraction below a given particle size

Since the plug flow gas residence time τ_g is inversely proportional to MW_t/P at constant first stage conditions, the constant A can be determined by simply plotting the term ln $(\eta/\eta_{Tap})/\ln(1-F_a)$ as a function of $P/MW_t S^2$. The slope of the line will yield A. This was done and the results are shown in Figure 12 for two values of MW_t/P (MW_t/P = 5.8 and 3.8). The most noteworthy feature of Equation B is that it yields a maximum value which is comparable to the test data. At small swirl numbers, slag capture is limited by slag spill-over whereas as the swirl is increased small particle carry-over and spill-over become comparable in magnitude.

CONCLUSIONS

A total of 11 tests were conducted with the 20 MW_t coal combusor with the specific objective of empirically evaluating combustor performance sensitivity to coal particle size distribution. The test results can be summarized as follows:

- The slag recovery efficiency peaks with the nominal 80 - 200 mesh coal which contains 46% by weight particles smaller than 270 mesh.

- The reduction in slag recovery efficiency with an increasing percentage of fine coal particles does not appear to be directly proportional to the fine coal particle content.

- The data indicates an increasing trend in unburned coal carryover with the captured slag as the particle size is increased.

- The first stage heat loss increases with the increase in coal particle size.

The 24 inch diameter combustor was operated in the range 15 to 31 MW_t. The results of the tests may be summarized as follows:

- o Increasing the thermal throughput, decreases the relative heat losses.
- o Increasing the combustion intensity first increases and then decreases the slag recovery when the combustor is operated at constant inlet velocity (decreasing swirl).
- o Increasing the swirl number increases in general the slag recovery.

ACKNOWLEDGEMENT

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2. Bauer, J. M., Iwata, H., "Development of Slagging Coal Combustors for MHD Applications", 19th Symposium - Engineering Aspects of MHD, University of Tennessee Space Institute, Tullahoma, Tennessee, June 1981.

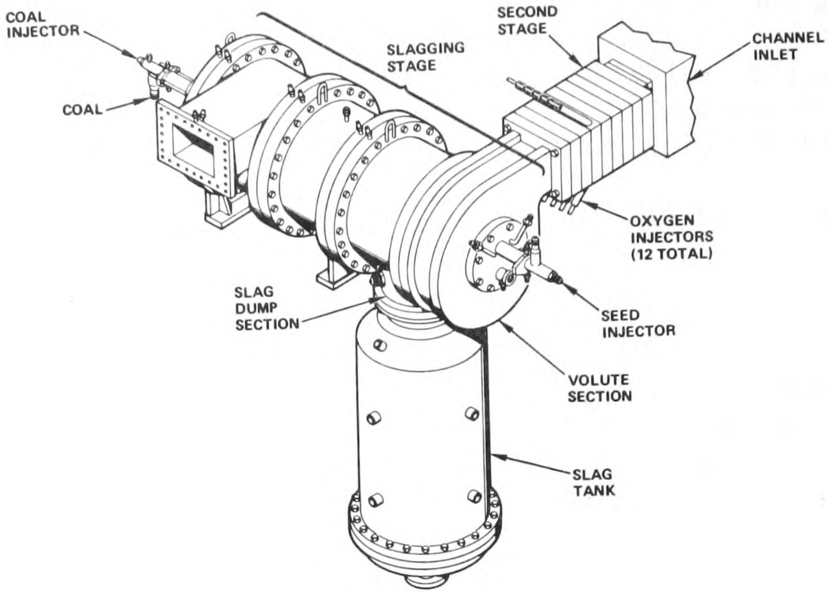

Figure 1. 20 MW_t Combustor for Integrated Test

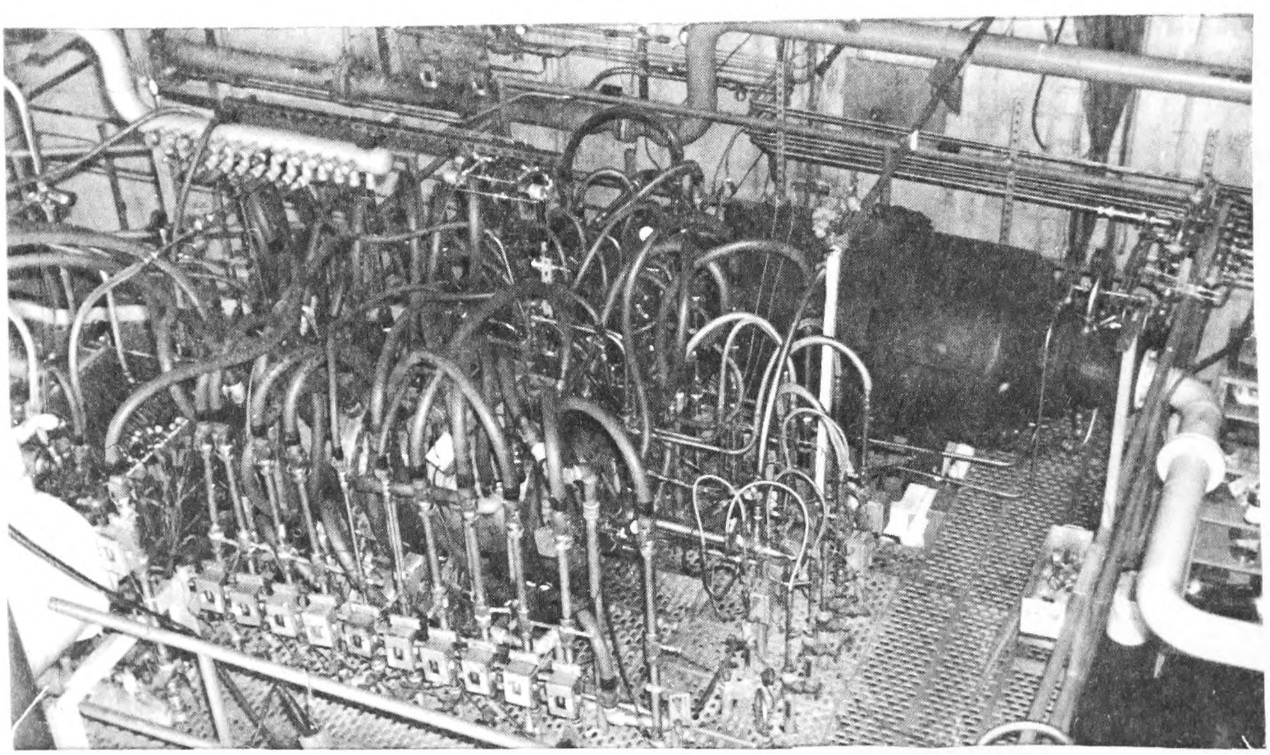

Figure 2. 20 MW_t Combustor Assembly

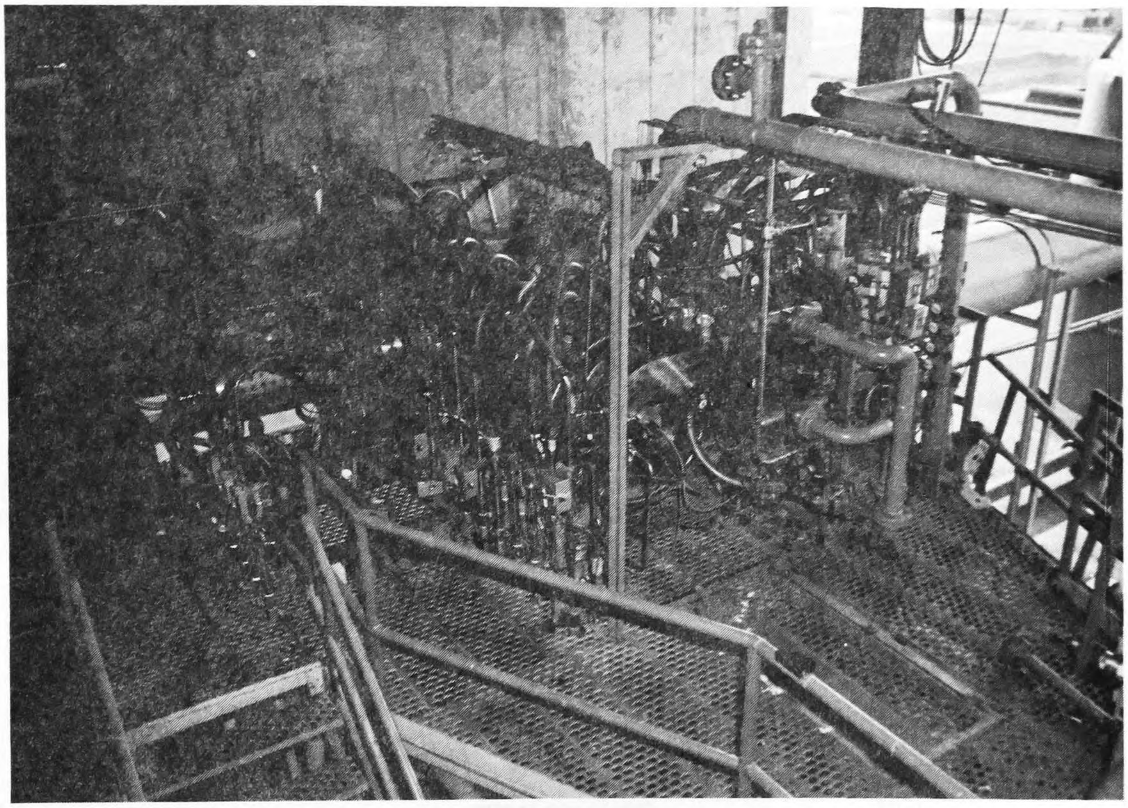

Figure 3. 20 MW_t Combustor Assembly

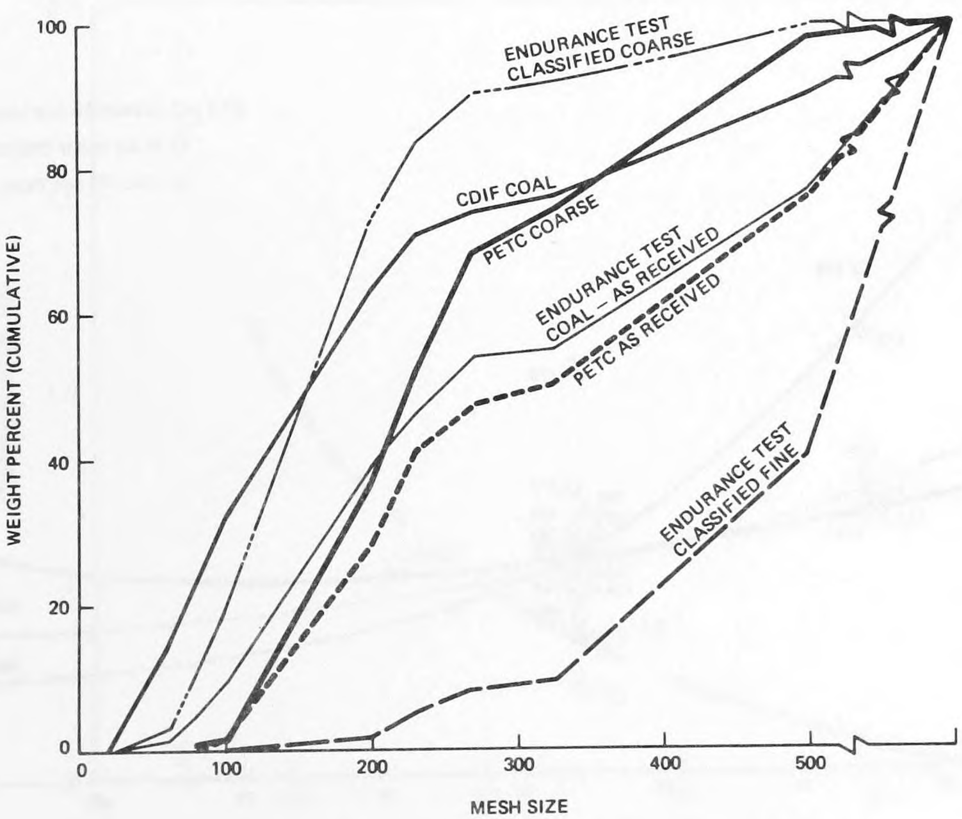

Figure 4. Coal Particle Size Distribution

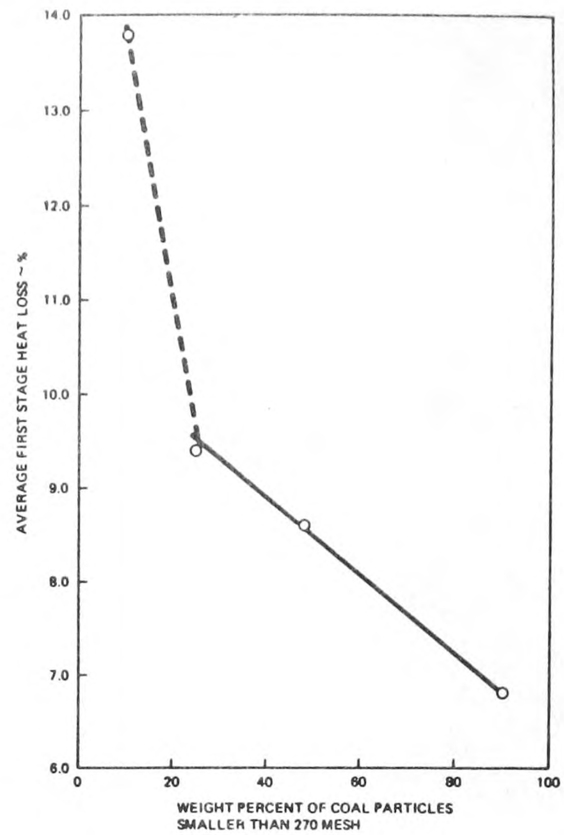

Figure 5. Effect of Coal Particle Size Distribution on Average First Stage Heat Loss

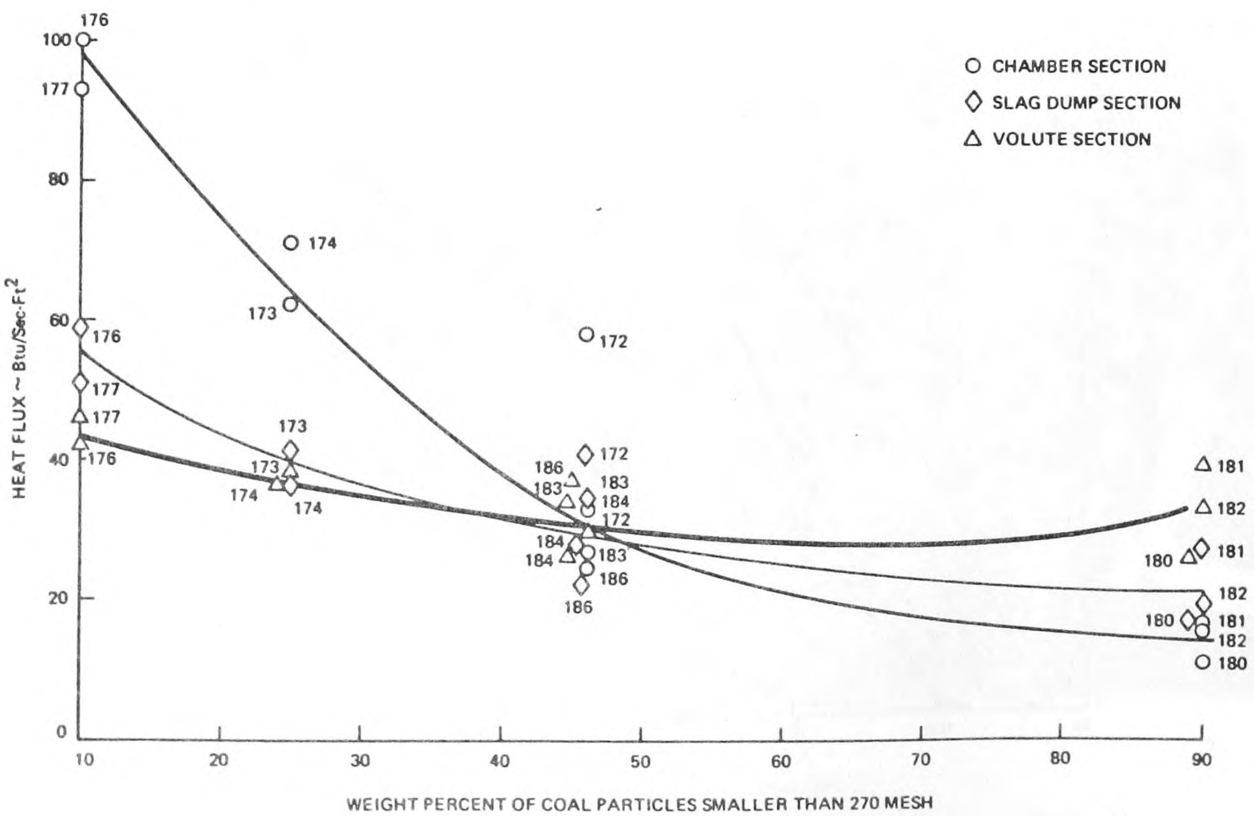

Figure 6. First Stage Heat Flux Distribution

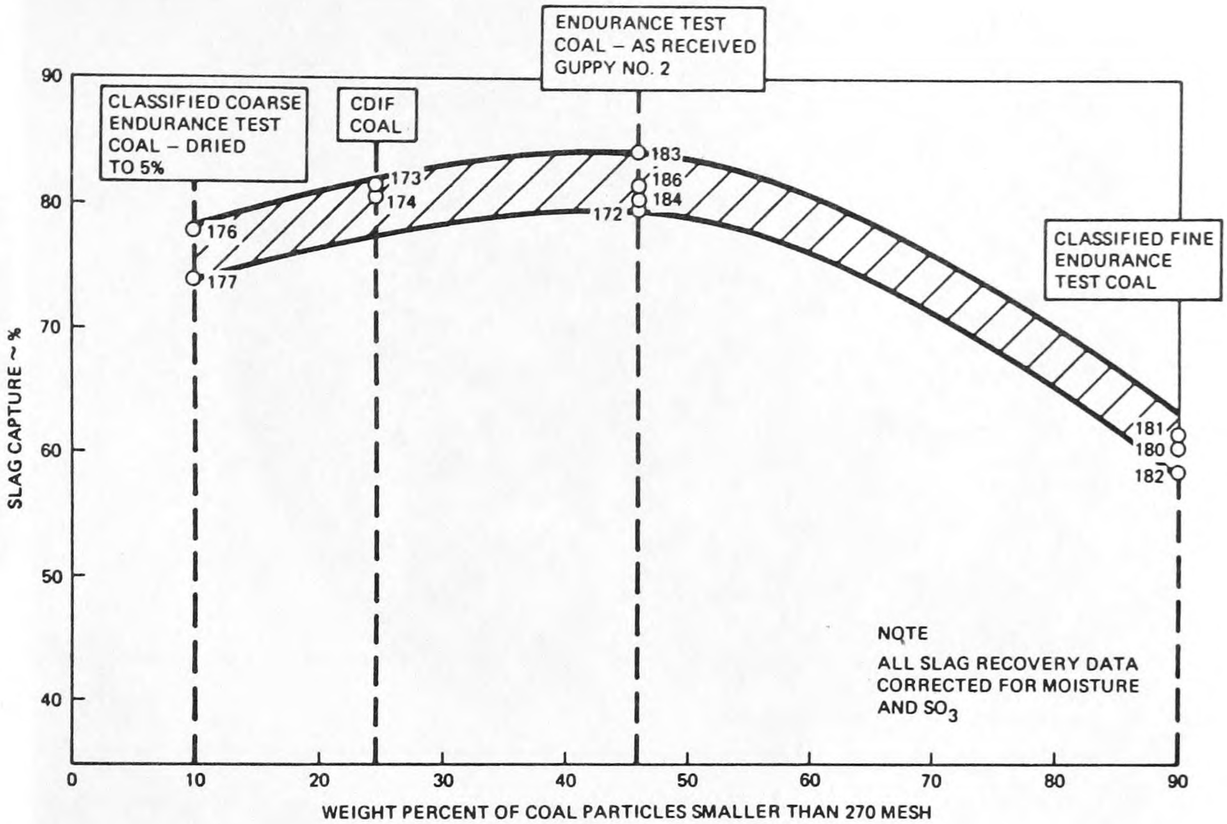

Figure 7. Effects of Coal Particle Size Distribution on Slag Rejection

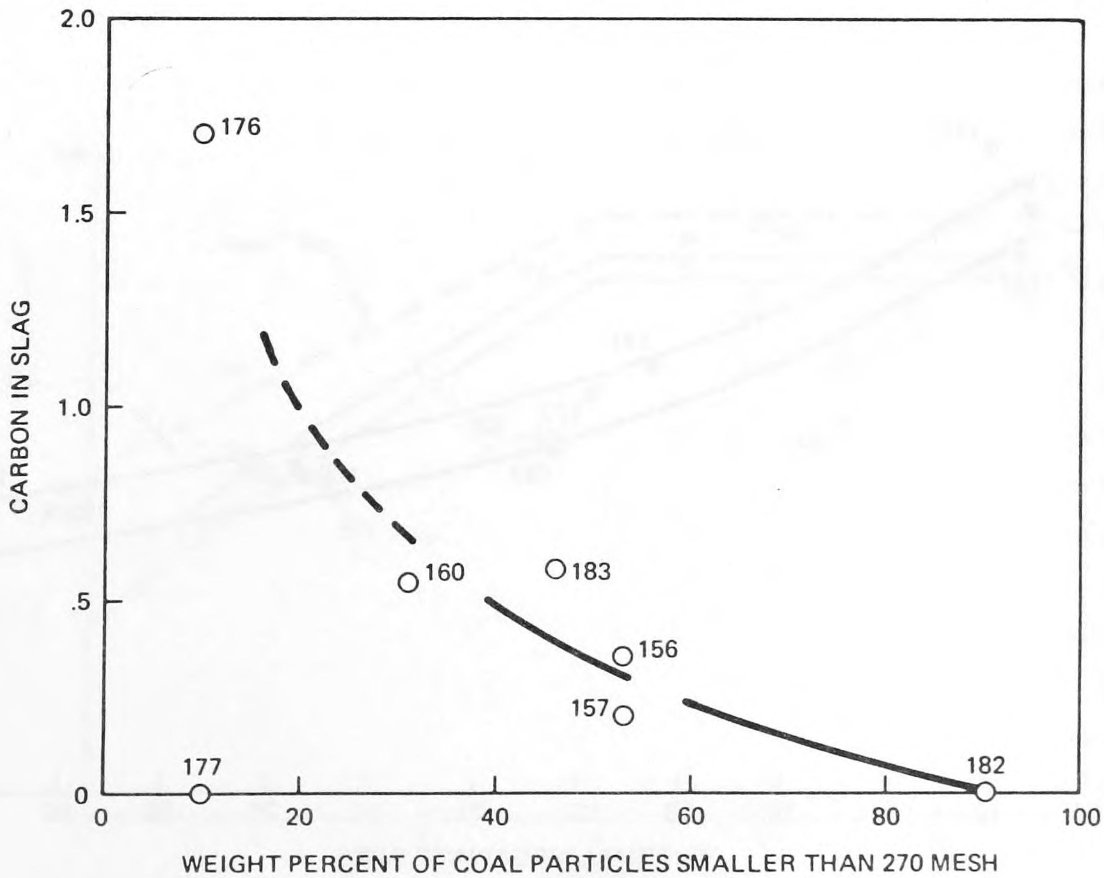

Figure 8. Carbon Carryover With Slag

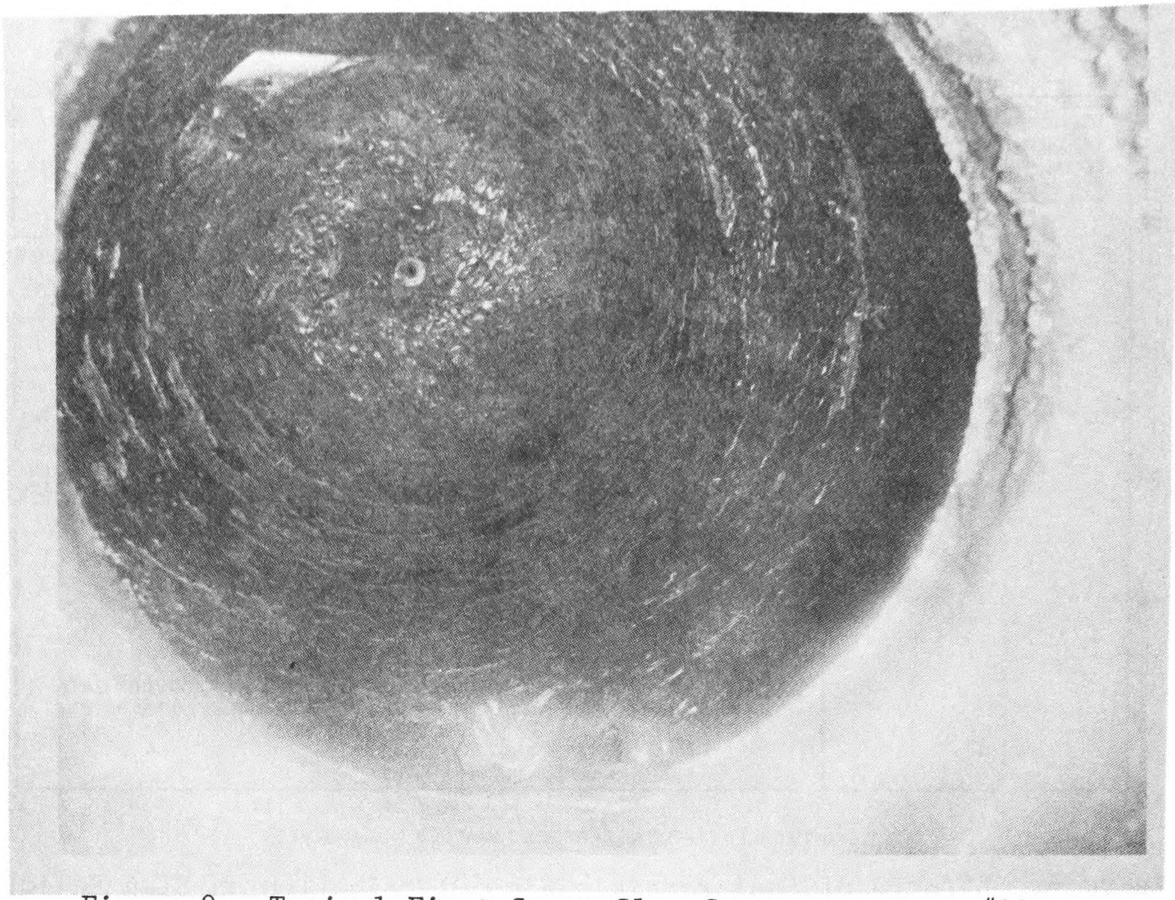

Figure 9. Typical First Stage Slag Coverage - Test #183

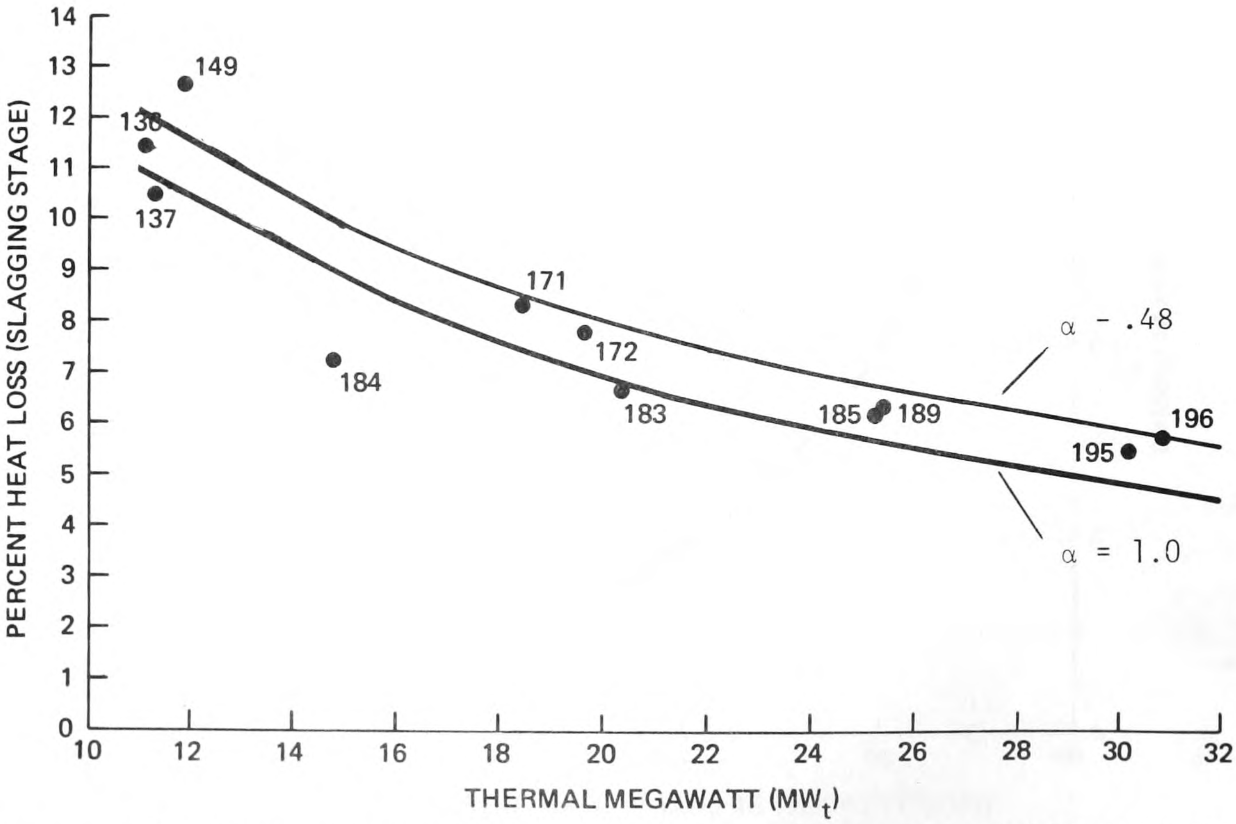

Figure 10. Combustor First Stage Heat Loss Correlation with Thermal Input

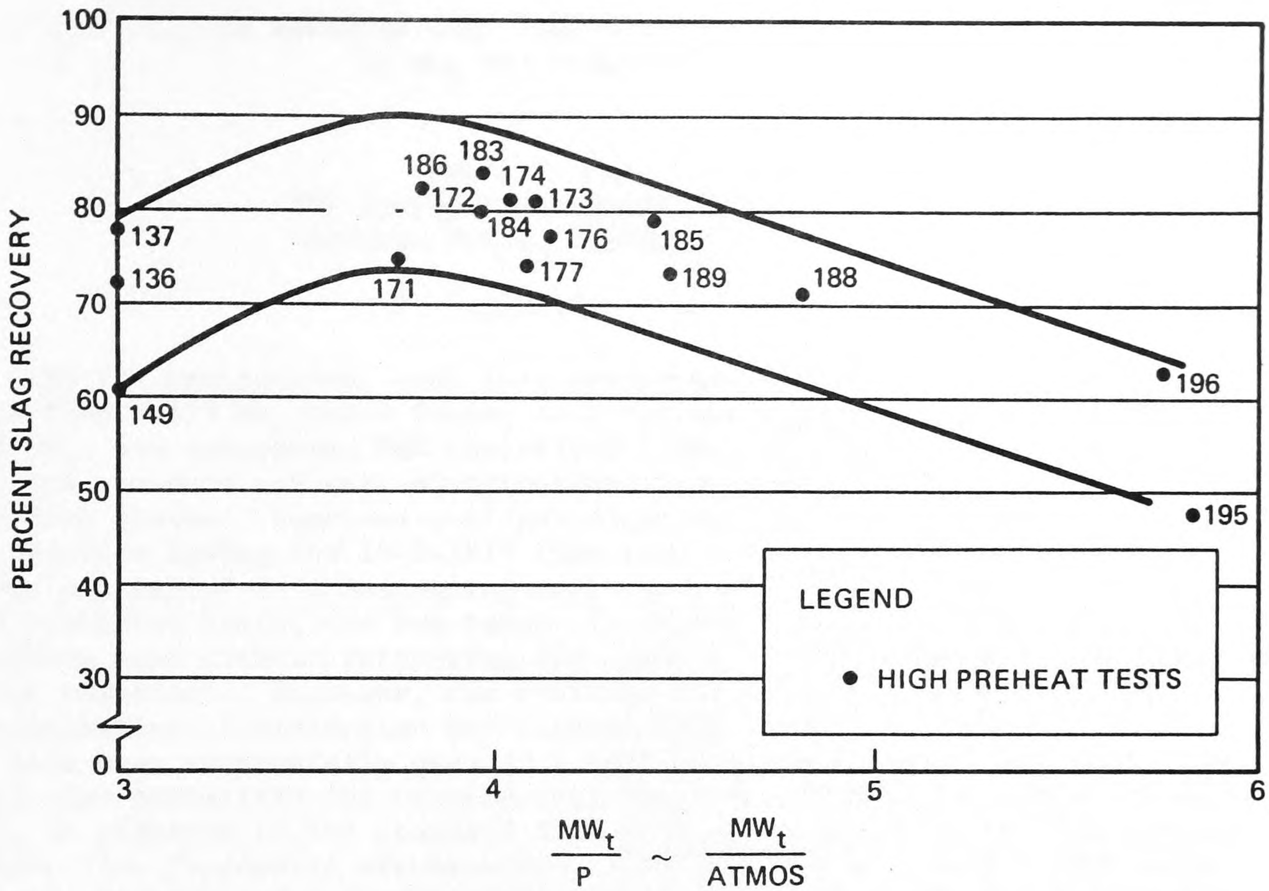

Figure 11. Slag Recovery Correlation with Combustion Intensity

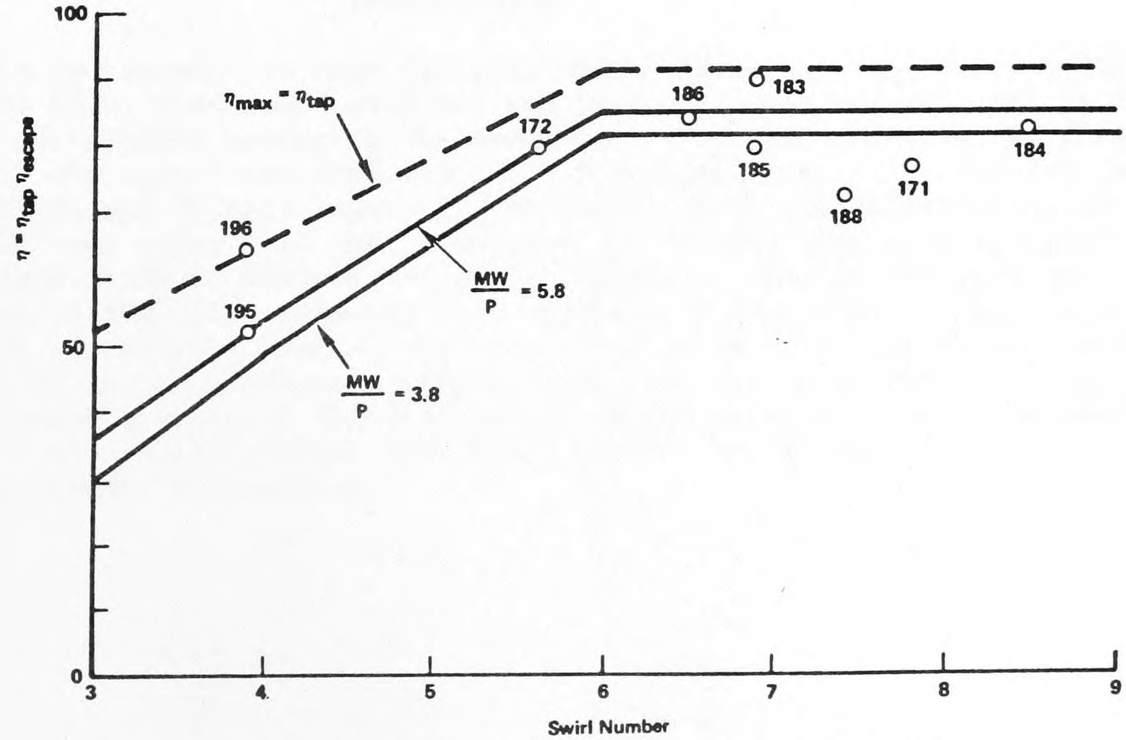

Figure 12. Slag Recovery Correlation with Swirl Number