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COMBUSTION AND FUEL CHARACTERIZATION OF COAL-WATER FUELS

Volume 4
Commercial Scale Atomizer and Burner Evaluation of Coal-Water Fuels

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I. INTRODUCTION

Recently the technology of coal-water fuel (CWF) combustion has advanced from fundamental laboratory and small-scale combustion studies to the study of large-scale practical combustors. A number of organizations have carried out many experimental studies on CWF in pilot to industrial scale combustion systems. These experiments have included work performed by government, industrial, and academic laboratories. Some of the fundamental studies have broadened the basic data base on CWF technology, while several larger scale demonstration programs have begun to advance the commercialization of this technology. However, most of the commercialization studies have been too limited in scope to allow the private sector to fully assess the potential for widespread utilization of CWF as an alternative to conventional fuel oils or natural gas. On the practical side, for the successful commercialization of CWF technology in the boiler marketplace, it is important that CWF can be produced, handled, and combusted in a cost effective manner in industrial scale systems.

The U.S. Department of Energy, Pittsburgh Energy Technology Center, entered into a CWF research contract with Combustion Engineering, Inc. in 1982. The program, entitled "Combustion and Fuel Characterization of Coal-Water Fuels" (Contract DE-AC22-82 PC 50271), was a multiple phase, multi-year effort with the overall objective of establishing a broad, commercially useable engineering data base for CWF technology. The data generated as a result of the contract would allow the private sector to make decisions on the technical, economic, and environmental feasibility of using CWF as a prime alternative fuel. The study also intended to provide the incentive for the private sector to continue and expand the development of stable, cost effective CWFs which can be transported, stored, and distributed the same way as conventional fuel oils, and which will burn reliably with minimum pollutant emissions.

The program was structured into three major projects that addressed both utility and industrial applications:

1. CWF Combustion Characteristics
2. CWF Rheology
3. Plant Equipment Selection and Performance

The first two projects were conducted by a team from Combustion Engineering (C-E) and Gulf Research and Development Company (GRDC). The third was carried out by TRW.

The CWF Combustion Characteristics phase embodied multiple tasks which focused on key aspects of CWF combustion properties. This report summarizes studies conducted under Task 4 of the subject program. The overall objective of Task 4 was to quantify CWF atomization and combustion properties utilizing industrial/utility scale equipment.

Task 4 was broken down into two major phases of study. The first phase involved the selection and detailed performance characterization of several commercially available burners designed for use with CWF. Burners were comparatively evaluated with a single CWF reference formulation, using both cold flow atomization testing and combustion performance testing. These comparative burner tests were conducted at a scale of 25 million Btu/hr heat input.

The second phase of study under Task 4 focused on identifying combustion performance differences between various commercially oriented CWF formulations. A suitable burner design from the first phase of study under Task 4 was selected and scaled up to a 50×10^6 Btu/hr heat input rating for use as a reference test bed for comparatively evaluating the atomization and combustion properties of five different CWF formulations.

This report (Volume 4) provides a general overview of Task 4 and it's principal results and conclusions. Other information regarding technical approaches, test equipment, test procedures, test data and analyses relating to the remaining aspects of the work from each individual task are provided in the following volumes:

Volume 1 -	All Tasks:	Final Summary Report
Volume 2 -	Task 1 and Task 3	Selection and Procurement of Candidate Coal-Water Fuels with Commercial Potential
Volume 3 -	Task 2:	Bench-Scale Characterization of Chemical, Physical and Combustion Properties of Coal-Water Fuels
Volume 5 -	Task 5:	Pilot-Scale Ash Deposition and Performance Testing of Coal-Water Fuels
Volume 6 -	Task 6:	Commercial Application and Economics of Coal-Water Fuels

II. BURNER SELECTION

Burner designs evaluated under the first phase of Task 4 were selected based on manufacturers' current market share, suppliers' manufacturing capabilities, and previous experience with slurry fuels. A burner's impact on project budget and test schedule was also considered in making the final decision on burner selection. Selected burner designs were required to comply with the following guidelines in order to ensure that the candidate CWF burners were commercially viable and could be installed in C-E's test furnace:

Capacity - 25 x 10^6 Btu/Hr Heat Input

Atomizing Air Temperature - ambient

Atomizing Steam/Air Pressure - less than 250 psig

Atomizing Steam Temperature - no greater than 20°F of superheat (i.e., 425°F @ 250 psig)

Atomizing Steam/Air Mass Flowrate - less than 700 lbs/hr

Burner Register Pressure Drop - less than 16" water column (W.C.) @ 600°F

Burner Ignition Energy Requirements - less than 5 x 10^6 Btu/hr Heat Input

Flame Diameter - less than 8 ft

Flame Length - less than 12 ft

Burner Register Diameter - less than 5 ft

Burner Register Depth - (i.e., depth of windbox) - less than 4 ft

Requests for test burners were sent to sixteen manufacturers, and nine proposals were received. The nine proposals represented a wide range of burner register and atomizer design concepts.

Four burner designs were finally selected from the group of nine potential candidates; the four burners selected represented four unique design approaches. The burners, described in the following section, are referred to by code in order to preserve the anonymity of the participating burner manufacturers.

HIGH SWIRL WALL-FIRED BURNER

The design of this burner features a central primary air register, which houses a primary air swirler through which a portion of the combustion air is passed (Figure 1). This swirling air exits the burner register through a refractory lined divergent exit nozzle. The primary air register is centrally located within an annular secondary air register through which the remainder of the combustion air is passed. This air register is equipped with co-rotational swirl vanes, which impart additional swirl to the total combustion air flow.

The atomizer for this burner is of the air-assisted, "Y - jet" type, specifically developed for CWF firing (Figure 2). The fuel stream is directed into a pressurized air stream. The shear forces which develop at the fuel/air interface initiate fuel stream atomization. The atomizer features tungsten carbide inserts in critical wear areas to extend atomizer life and maintain specified performance.

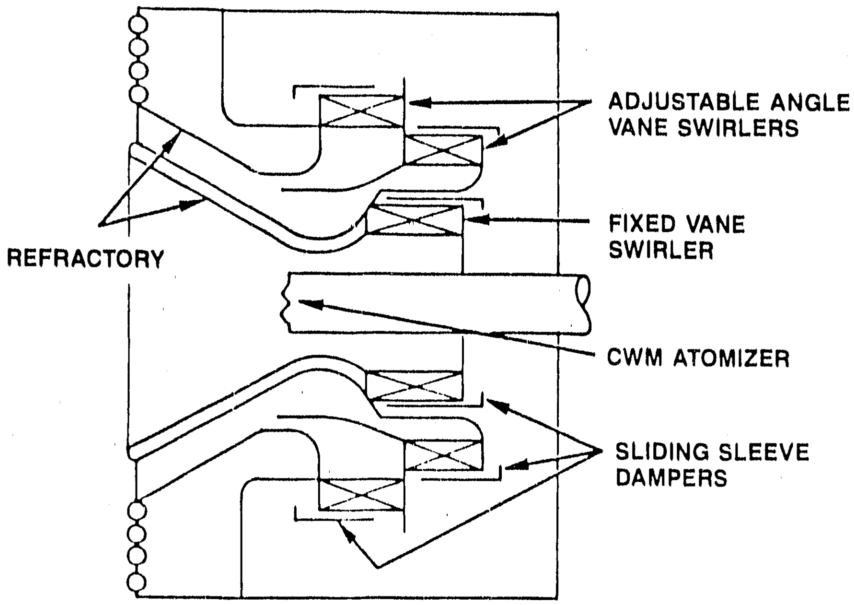

FIGURE 1: SCHEMATIC OF HIGH SWIRL WALL-FIRED BURNER

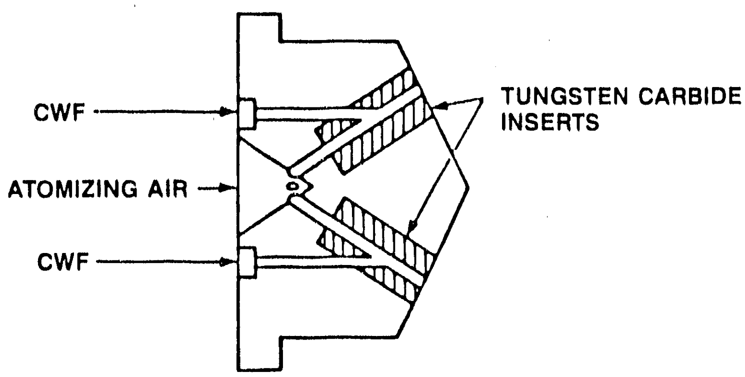

FIGURE 2: "Y" JET ATOMIZER

REFRACTORY CHAMBER BURNER

The refractory chamber burner's design (Figure 3) features swirled primary combustion air in the refractory lined combustion chamber. A portion of the primary air passes through a centrally located vane swirler into the combustion chamber. The remainder of the primary air passes through a series of "tunnels" between the primary air register and the combustion chamber. These "tunnels" are angled such that they impart additional swirl to what can be referred to as secondary combustion air. Additional combustion air is added downstream to help complete combustion.

The atomizer for this burner is of the external mix, air assisted variety. Pressurized air is directed radially inward towards a central fuel stream. Shear forces at the fuel/air interface initiate atomization of the fuel stream. A general schematic of this atomizer is shown in Figure 4.

TANGENTIAL FIRING BURNER

This burner is a swirl stabilized unit configured for tangential corner firing (Figure 5). The principal elements of the burner are: a refractory-lined divergent nozzle, a fixed vane tangential swirler through which the primary combustion air stream is passed and secondary combustion air nozzles above and below the burner through which the balance of the combustion air is ducted (unswirled). The atomizer for this burner is of the air-assisted "Y-jet" type and was identical to the atomizer used in the HSWF burner (Figure 2).

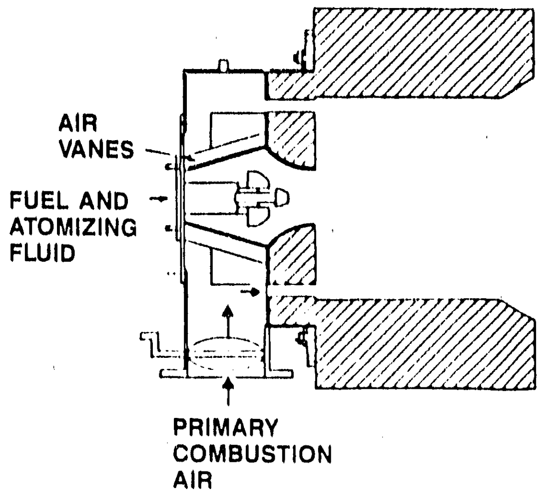

FIGURE 3: SCHEMATIC OF REFRACTORY CHAMBER BURNER

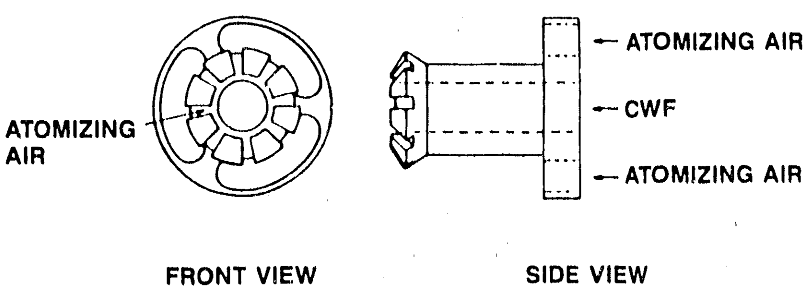

FIGURE 4: CWF ATOMIZER

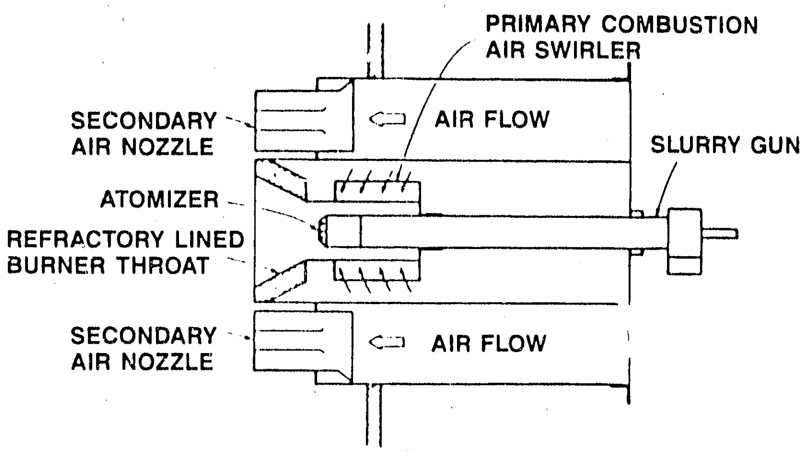

FIGURE 5: SCHEMATIC OF TANGENTIALLY FIRED BURNER

REFRACTORY/REGISTER BURNER

The refractory/register burner (Figure 6) utilizes a single air plenum for its source of combustion air. Primary air passes through an adjustable angle vane swirler, into the register tunnel and out through a refractory quarl. Secondary air is added through an annulus around the burner quarl. A slotted metal cone located on the end of the CWF gun acts as a bluff body to help stabilize the flame. The atomizer for this burner is of the air-assisted "Y-jet" variety (Figure 7).

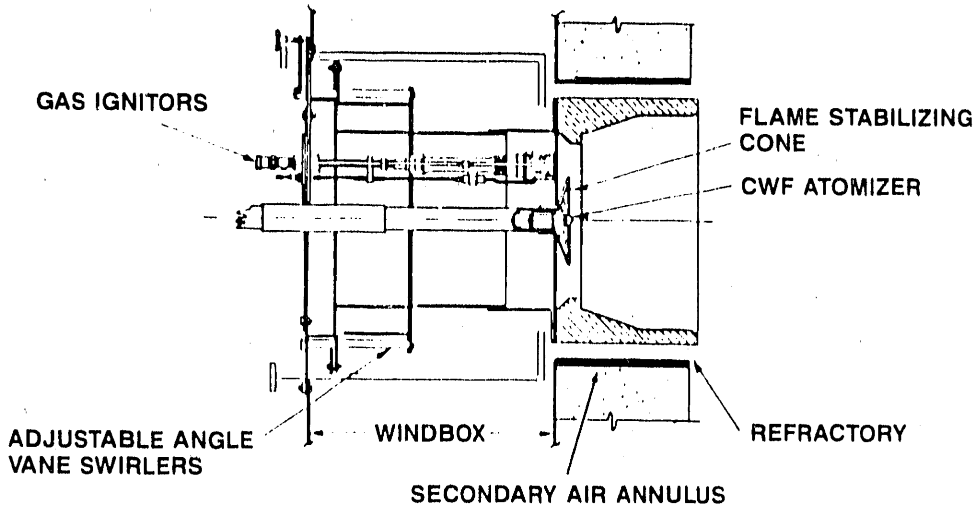

FIGURE 6: SCHEMATIC OF REFRACTORY/REGISTER BURNER

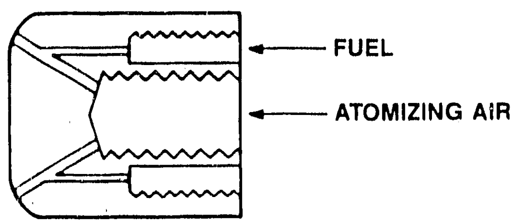

FIGURE 7: REFRACTORY REGISTER BURNER CWF ATOMIZER

III. REFERENCE CWF ANALYSIS

In order to obtain performance data that could be directly compared, each burner was tested with a reference CWF that was produced with the same coal by an established fuel manufacturer. The coals considered for this baseline fuel were all high-volatile, low sulfur bituminous coals from the Eastern United States. Splash Dam coal mined in Buchanan County, Virginia and beneficiated to 5.5% by weight ash was selected and used to produce all 90,000 gallons of the reference CWF used in the program.

The analysis of the Splash Dam coal is typical of high volatile eastern bituminous coals. Volatile matter content of the fuel was approximately 29% on a dry basis. The CWF had a solids loading of approximately 70% and a higher heating value of 10,145 Btu/lb. Additional properties of the reference CWF are summarized below:

TABLE 1
REFERENCE CWF DATA

	As-Received	Dry Basis
Proximate, Wt %		
Moisture (Total)	29.5	--
Volatile Matter	20.7	29.4
Fixed Carbon (Diff.)	45.9	65.1
Ash	3.9	5.5
Total	100.0	100.0
HHV, Btu/lb	10,145	14,390

TABLE 1 (CONTINUED)

	As-Received	Dry Basis
Ultimate, Wt %		
Moisture (Total)	29.5	--
Hydrogen	3.5	5.0
Carbon	57.4	81.4
Sulfur	.8	1.1
Nitrogen	1.1	1.6
Oxygen (Diff.)	3.8	5.4
Ash	3.9	5.5
	100.0	100.0
CWF Screen Analysis		
+60 mesh (250 1)	0.1%	
60x100 mesh (250x150lm)	0.9%	
100x200 mesh (150x75lm)	3.8%	
200x325 mesh (75x45lm)	8.9%	
Coal Particle Mass Median Diameter (lm)	15	
(1) Viscosity @ 100 sec^{-1}	640 centipoise	
(1) Power Law Exp.	1.4	
(2) Viscosity @ 1100 sec^{-1}	983 centipoise	
(2) Viscosity @ 2000 sec^{-1}	1700 centipoise	
(2) Viscosity @ 4000 sec^{-1}	2850 centipoise	
(3) Viscosity @ 1100 sec^{-1}	1250 centipoise	
(3) Viscosity @ 1500 sec^{-1}	2137 centipoise	
Density	1.21 grams/cubic centimeter	

Note:

(1) Rotational Viscometer @ 20°C

(2) Extrusion Rheometer @ Room Temp.

(3) Variable High Shear Viscometer @ 68-75°F

IV. PRELIMINARY PERFORMANCE OBJECTIVES (PPOs)

C-E defined Preliminary Performance Objectives (PPOs) in order for the burner manufacturers to have consistent performance targets. The goal throughout the burner test program was to objectively compare designable performance characteristics to actual burner performance. The PPOs were as follows:

Combustion air preheat temperature: less than 500°F

Excess combustion air requirements: less than 40% @ 100% load

Turndown without support fuel: greater than 4:1

Ignition requirements: less than 20% of full load heat input in a cold boiler for 30 minutes

Carbon conversion efficiency: greater than 98% at 100% load

Confirmed scanner signal over turndown range

No excessive burner coking during 8 hour test

No atomizer pluggage during 8 hour test

Atomized spray droplet mass median diameter should be less than 200 microns @ 100% load

Atomizer assist fluid consumption: less than 0.25 lbs/lb of fuel at 100% load

Windbox air pressure: less than 16 inches WC @ 100% load

V. RELATIVE ATOMIZER PERFORMANCE (COLD FLOW)

The comparative burner test program was initiated following identification of participating burner designs and performance targets. The first set of tests, described in this section, centered on quantifying the performance of each burner's CWF atomizer. Since it is generally accepted that atomization quality highly influences CWF combustion properties, tests were conducted in order to identify spray quality differences between each generically different atomizer design.

CWF spray droplet size has been shown to have a direct impact on CWF ignition properties. CWF devolatilization and ignition is delayed in proportion to the time required for droplet heating and drying. Since droplet heating and drying times can increase exponentially with spray droplet diameter (1) it is vital that spray droplet diameters be minimized in order to improve CWF ignition characteristics.

CWF spray droplet diameter can also influence combustion in terms of carbon conversion efficiency. Several studies have indicated that coal particles contained within an atomized CWF droplet tend to agglomerate during drying and devolatilization and produce a single char particle proportional in size to the original droplet diameter (2). The carbon burnout time required for a given char particle is proportional to its diameter (3). It therefore appears that spray droplet size can directly influence carbon conversion efficiency by influencing the timeframe required for complete char particle combustion.

All tests were conducted in C-E's Atomizer Test Facility (ATF). A schematic of the facility is shown in Figure 8. The facility is uniquely configured to obtain spray droplet size distribution and droplet ballistics (velocity and trajectory) information. The facility operates in a cold flow (non-combustion) mode and can be

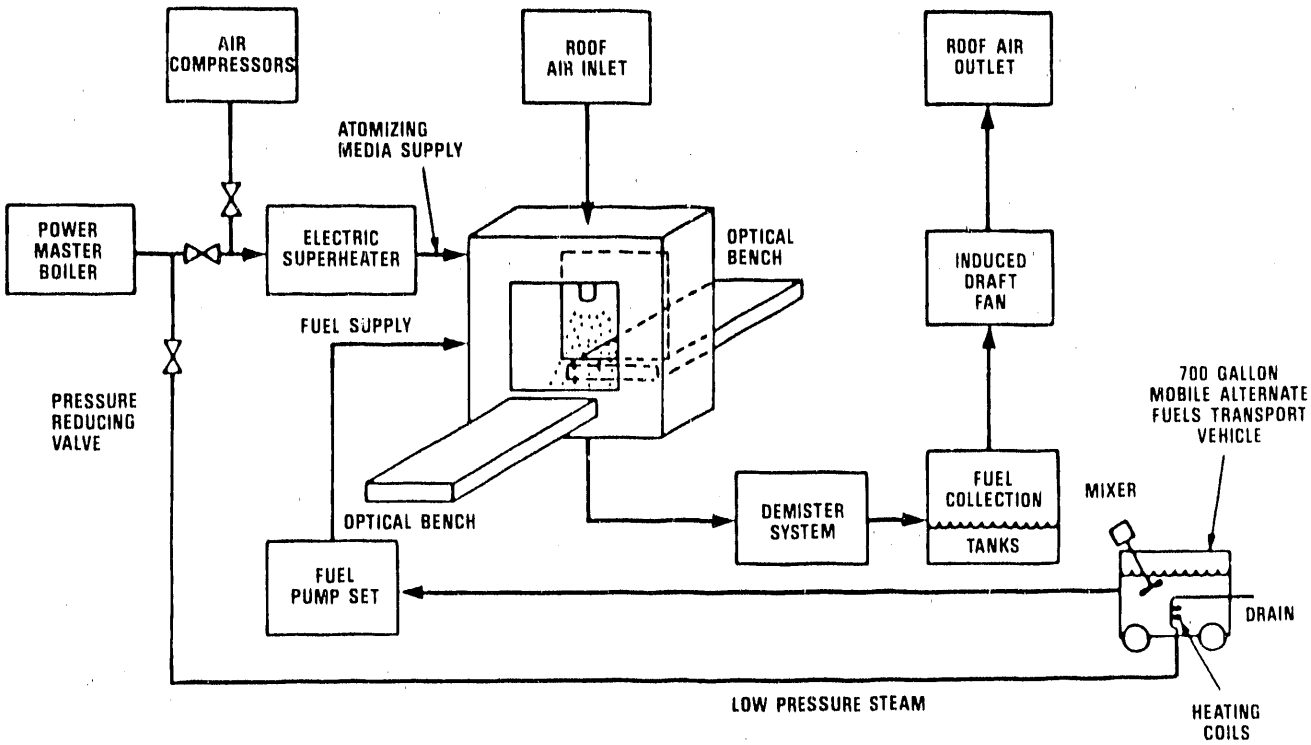

FIGURE 8: ATOMIZER TEST FACILITY

used to quantify any atomizer's performance. The facility has been integral to research programs at C-E which have resulted in development of optimized atomizers for use in CWF burners, residual oil burners, and emissions control (dry scrubber) systems.

Two non-intrusive, optically based techniques are employed in the ATF to quantify spray quality. A laser diffraction based instrument (Malvern 2600) is used to determine spray droplet size distribution. Droplet size distribution can be determined using either Rosin-Rammler model based software or model-independent algorithms. The Rosin-Rammler software was exclusively employed during the subject test program. Size distribution histograms were summarized and reported in terms of spray droplet mass median diameter (MMD) and the weight percentage of droplets which exceeded 300 microns in diameter. These comparatively large diameter droplets are believed to have a negative impact on both CWF ignition and carbon conversion, based on pulverized coal firing practices (4). Many investigators believed that minimizing the population of droplets exceeding 300 microns in diameter can improve CWF ignition and carbon conversion efficiency.

A high speed, double image photographic technique was also employed in the ATF in order to characterize differences in spray droplet ballistics between the generically different test atomizers. A stroboscopic light source, capable of producing two intense, short duration (one microsecond), light flashes, is used to illuminate an area of interest in the atomizer's spray. Using a high resolution, short depth of field (6 millimeter) camera, double exposure shadow graphic images of the droplets are recorded. Measurements of the time delay between flashes as well as measurements of the distance between double exposure droplet images are used to determine droplet velocity. Droplet trajectories are readily determined by observing the flight path of the droplets with respect to the camera's orientation.

The ATF and the optical diagnostic techniques used by C-E are described in detail in Reference 5. All of the atomizers tested in this program were of the twin-fluid air-assisted type. Twin fluid atomizers utilize the energy contributed by the atomizing fluid to initiate breakup of the fuel stream into more readily combustible droplets. The quantity and/or quality of the atomizing medium defines the total energy available to initiate atomization and strongly influences generated spray quality. The quantity of atomizing media used is normally reported as the ratio of atomizing media to fuel (A/F) mass flow ratio. The following summarized how influential A/F mass flow ratio is on each respective CWF atomizer design.

Table 2 outlines spray quality observations made as a result of this test program. All three of the atomizers tested met the PPO criteria of less than 200 microns MMD at an A/F ratio of less than 0.25. However, there were significant differences in spray quality and fuel and air pressures between atomizers. Overall, the HSWF atomizer produced significantly finer sprays at any given A/F ratio. For example, at an A/F ratio of 0.20, the HSWF atomizer produced an MMD of about 60 microns while the REF and REF/REG atomizer produced MMD's of 145-155 microns (Figure 9). Similar although less pronounced trends are shown in the 50% and 25% load curves (Figures 10 and 11).

Table 2 also summarizes droplet top size information derived from droplet size distribution data for each atomizer tested. As can be seen in the table, at 100% load, the HSWF/TAN atomizer produced negligible (<1%) droplets above 300 microns, while the REF and REF/REG atomizers produced 5.5% to 8.7%, and 14% to 18%, respectively, in the greater than 300 micron range. Similar trends can be seen in the data presented for 50% and 25% loads. This data correlates directly with the combustion results, as will be discussed later.

TABLE 2

SPRAY QUALITY OBSERVATIONS

	Firing Rate 100% = $25x10^6$ BTU/hr heat input	Atomizing Media/ Fuel Mass Flow Rate (A/F)	Spray Droplet Mass Median Diameter (MMD) (Microns)	% By Weight Of Spray Droplets >300 Microns in Diameter
HSWF & TAN	100%	.27-.10	51-91	.01-.12
REF	100%	.65-.37	98-143	5.5-8.7
REF/REG	100%	.19-.09	142-175	14-18
HSWF & TAN	50%	.59-.28	48-63	.00-.09
REF	50%	1.37-.31	70-94	1.0-5.1
REF/REG	50%	.37-.22	92-137	10-15
HSWF & TAN	25%	1.29-.65	46-52	.04-.33
REF	25%	2.7-.62	41-87	.26-1.28
REF/REG	25%	.88-.47	81-117	5-12

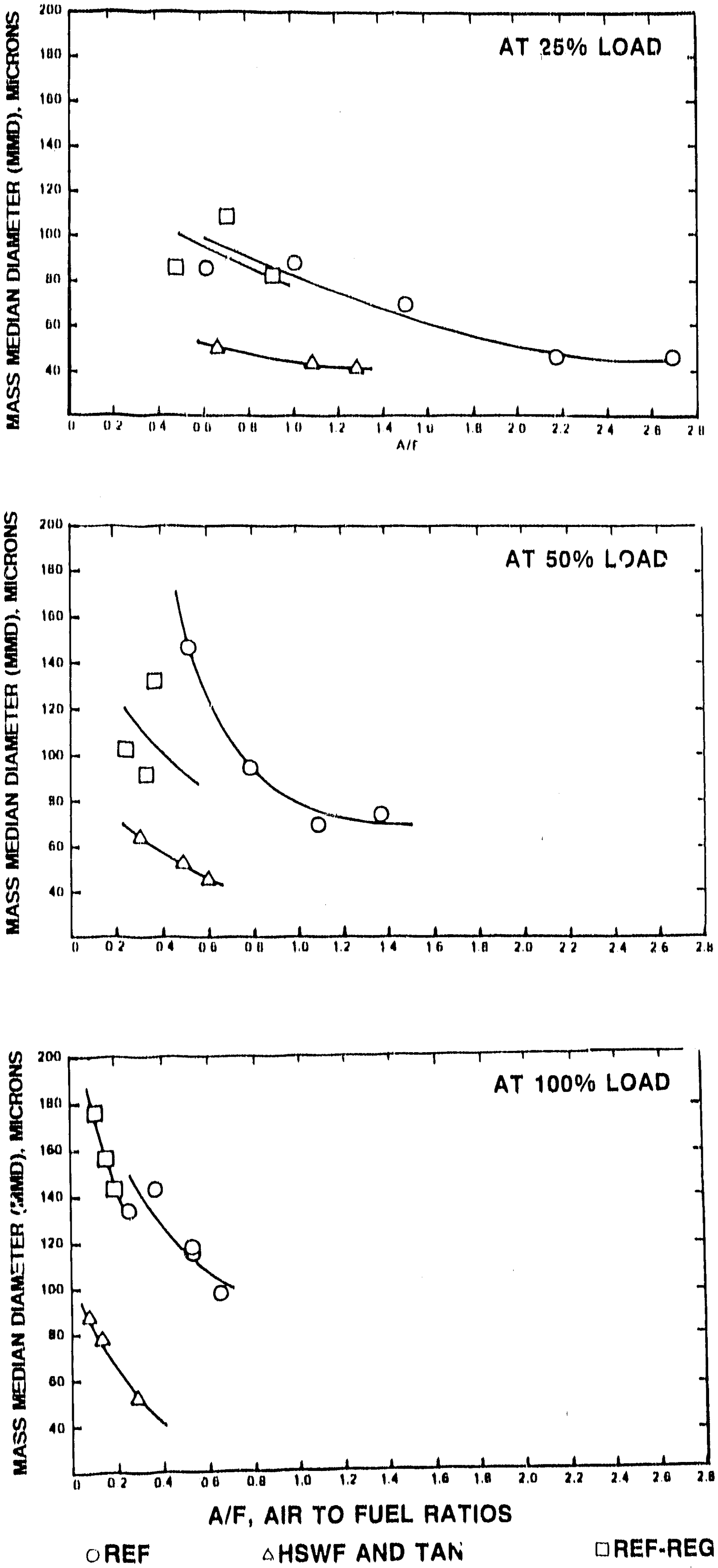

FIGURE 9 COMPARISON OF MASS MEAN DIAMETER VERSUS ATOMIZING MEDIA/FUEL (A/F) MASS FLOW RATIOS FOR CWF BURNERS

Droplet Ballistics

As previously mentioned, a high speed, double exposure photographic system was employed in the ATF in order to quantify relative differences, if any, in spray droplet ballistics between the generic atomizer designs. Photographs were taken of the spray at a location 24" axially downstream of the atomizer. Sampling at this location assured that complete atomization (i.e., the formation of spherical droplets from fragmented fuel ligaments) was achieved before the photographic sampling volume. The sampling location was also identical to that used for definition of the CWF spray droplet size distribution using the laser diffraction technique.

The photographic technique used permitted the determination of droplet velocity as a function of droplet diameter. Definition of the droplet size/velocity relationship is important for defining the near-burner aerodynamics required for effective combustion. Burner aerodynamics can, to a certain extent, be adjusted to accommodate high velocity droplets by increasing the size or strength of the combustion air recirculation zone. Carbon burnout and burner ignition stability can be favorably influenced by minimizing the number of high momentum droplets which move rapidly out of the burner's primary aerodynamic recirculation zone.

Figure 10 summarizes diameter vs. velocity information obtained for the HSWF, TAN, and REF atomizers. In general, detected droplet velocities ranged between 2-13 meters/sec; the REF atomizer tended to generate somewhat higher velocities on average. This could possibly be attributed to the fact that the REF atomizer's operating A/F ratio was over twice that of the HSWF/TAN atomizer (0.5 vs. 0.2). The greater momentum of the REF atomizer's air assist stream

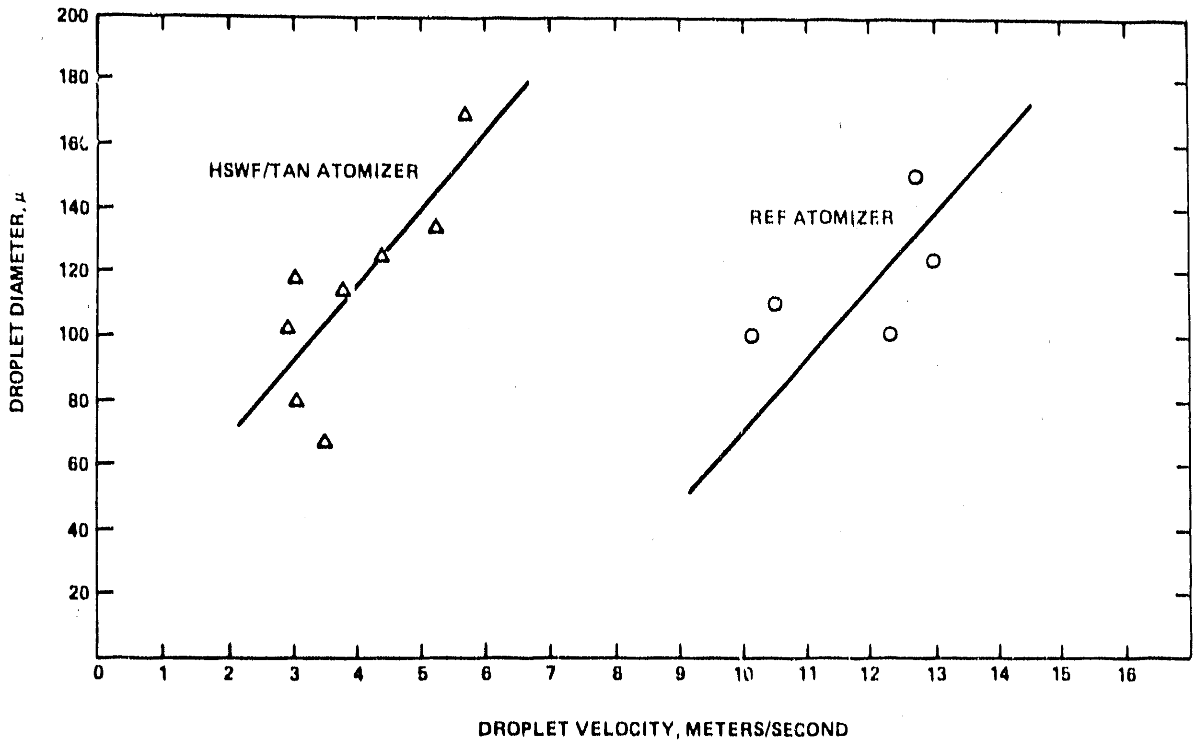

FIGURE 10: DROPLET VELOCITY VERSUS DROPLET DIAMETER AT 100% LOAD

as compared with that of the HSWF/TAN atomizers may increase the total momentum (mass, velocity product) of the partially atomized fuel stream issuing from the REF atomizer. This may increase measured droplet velocities downstream of the atomizer exit.

It should also be noted that droplet trajectories for the HSWF, TAN, and REF atomizers tended to predictably follow the streamlines of a freely expanding jet.

Ballistics data for the REF/REG atomizer is unavailable due to an instrumentation failure, however, it is likely that droplet velocities and trajectories are similar to those observed for the HSWF and TAN atomizers, as the atomizer designs are generically similar and the operating A/F ratios are in a similar range.

VI. COMPARATIVE COMBUSTION PERFORMANCE OF EACH GENERIC BURNER SYSTEM

The overall objective of this portion of the project was to measure the combustion characteristics of each burner type, so that the potential commerciality of each generic burner design for retrofit to oil-designed units could be assessed. Preliminary Performance Objectives (PPO) previously established to provide performance targets for each burner vendor were used as guidelines.

Each burner was initially evaluated through a series of preliminary tests to identify potential performance problems which could be corrected prior to detailed performance characterization. The preliminary tests included cold flow atomization testing, combination shakedown/optimization testing and an abbreviated performance characterization. Following the preliminary tests, each burner manufacturer was provided the opportunity to modify equipment. The burners then underwent more detailed combustion performance testing.

All burners were evaluated with the same reference fuel in the same test furnace. The Industrial Scale Burner Test Facility (ISBTF) employed throughout this testing simulates a front wall, horizontal fired industrial type boiler environment. Figure 11 outlines the physical appearance of this facility. The combustion chamber of the facility is surrounded by an atmospheric pressure water jacket. Chamber wall temperatures can be adjusted by the addition or removal of refractory panels to allow simulation of specific heat release profiles and furnace temperatures.

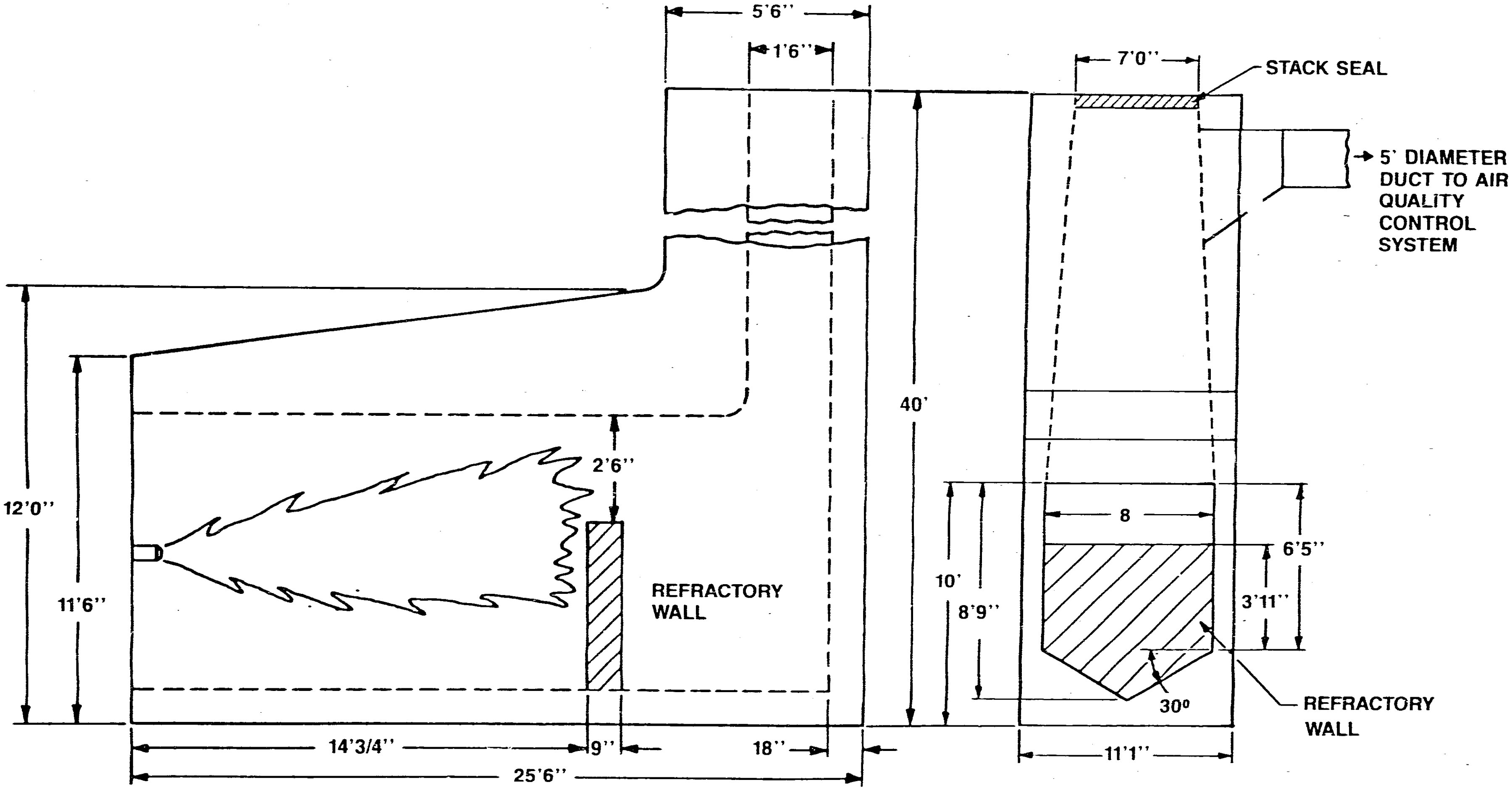

FIGURE 11: INDUSTRIAL-SCALE BURNER TEST FACILITY

For the combustion testing, a volumetric heat release rate of approximately 30,000 Btu/hr-ft^3 was chosen as being representative of the majority of the oil-fired boilers and process heaters which have the greatest potential for CWF retrofit. To obtain this heat release rate, a refractory brick wall was constructed 14 feet downstream of the furnace front wall. A layer of blanket refractory insulation was added to the ISBTF walls and ceiling to obtain furnace outlet temperatures on the order of 2400 to 2500°F. Fuel particle residence times are estimated to be on the order of 1.7 seconds, utilizing a plug flow approximation for bulk gas velocity.

Flue gases are channeled from the ISBTF to a venturi rod scrubber. This scrubber is used during all combustion testing to meet local and federal air quality standards for SO_2 and particulate emissions.

The ISBTF is capable of a maximum firing rate of 72×10^6 Btu/hr on typical oils and 50×10^6 Btu/hr on coals or coal-based fuels. Support equipment consisting of solid fuel pulverization and storage facilities and slurry fuel handling facilities provide capabilities for a wide range of fuel types and their associated firing equipment.

Facility instrumentation employed during the subject project included:

- Flue gas constituent monitors for CO_2, CO, O_2, NO_x, and SO_2

- Flue gas particulate collection equipment (EPA Method 5)

- Heat Flux instrumentation

- Suction pyrometers for gas temperature measurements.

A primary performance criteria for most potential CWF burner users will be carbon conversion efficiency (CCE), since CCE is influential in determining the economics of CWF conversion. The PPO target was to achieve greater than 98% CCE at $25x10^6$ Btu/hr (100% of full load) heat input. The performance of each burner with respect to CCE was determined principally by analysis of flue gas constituents (O_2, CO_2, and CO). CCE's determined by flue gas analysis were also confirmed at selected test points by analysis of isokinetically-obtained fly ash samples for carbon content.

The HSWF burner was capable of achieving CCE levels greater than 97% at 100% load, while the TAN burner was capable of CCE's greater than 99% when operating at 100% load conditions. The HSWF burner's performance with respect to CCE nearly met the PPO target, while the TAN burners performance exceeded PPO expectations. The REF/REG burners, using the best atomizer supplied by the burner vendor, was capable of CCE's in excess of the PPO target level of 98%, contrasting with the REF burner which achieved CCE's on the order of 86% at 100% load firing conditions. CCE for the REF burner improved at reduced firing rates (to the 95% level). However, it appeared that the REF burner would benefit from additional development in order to improve CCE.

All four burners were sensitive to excess air level. Increasing excess combustion air tended to improve CCE in all cases. Figure 12 summarizes the measured effect of excess air on CCE. Note that all tested burners can operate within the PPO target of 40% excess air.

Several tests were conducted in order to quantify the effect that combustion air preheat has on burner operation. The PPO target for preheat called for combustion air temperature not to exceed 500°F, derived primarily from conversion economics considerations. (Economics of conversion to CWF improve when burners require minimal levels of combustion air preheat.)

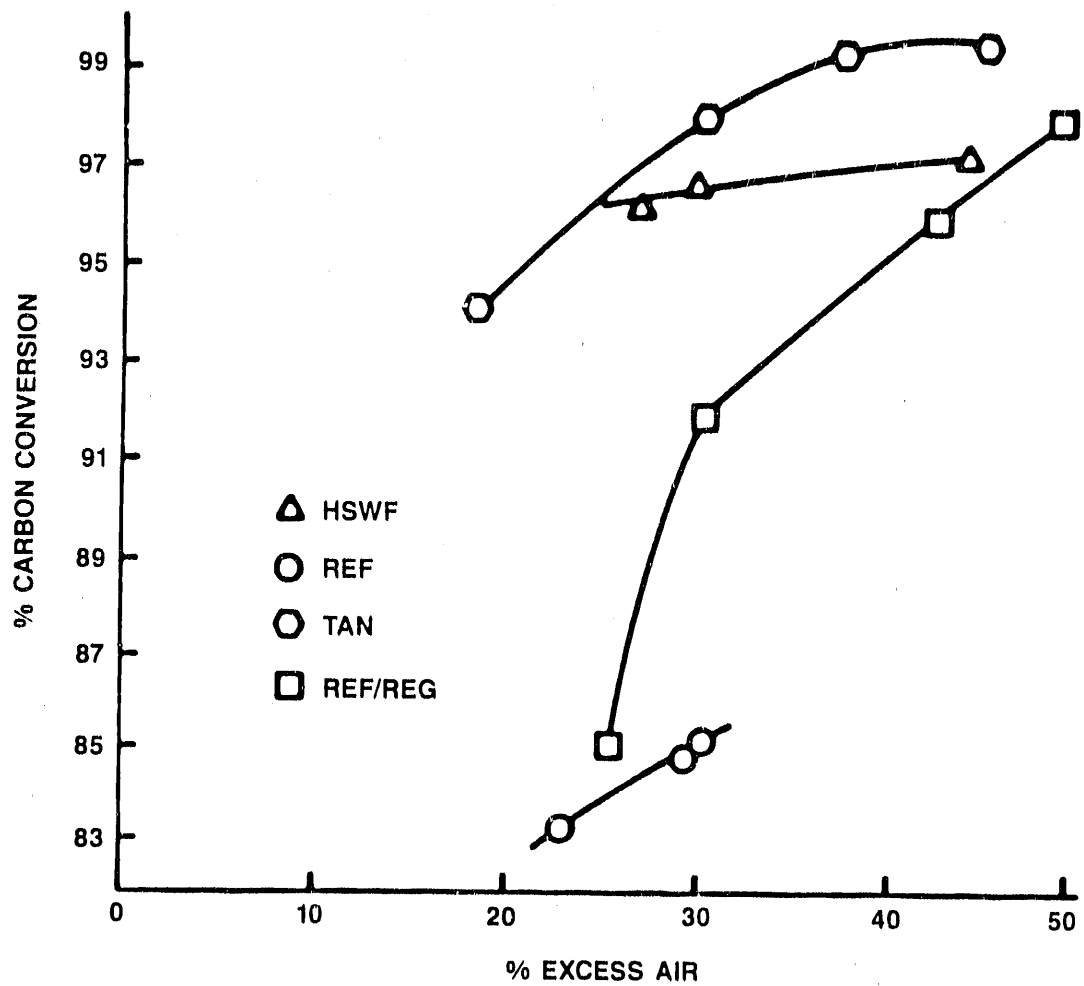

FIGURE 12: COMPARATIVE COMBUSTION RESULTS

While combustion air preheat can influence a number of burner performance parameters, it's influence can be most readily seen by observing relative flame stability. Air preheat affects flame stability through its impact on fuel ignition properties. With this in mind, each burner's flame stability was assessed at various combustion air temperatures.

The HSWF burner operated with acceptable flame stability at combustion air temperatures as low as 300°F. It should be noted that CCE degraded by 0.4% when the HSWF burner was operated with combustion air temperatures below 500°F.

The TAN burner was capable of operation at combustion air temperatures down to 250°F. Data from this testing indicated that CCE was not affected by combustion air temperature for the TAN burner over a temperature range of 250°F-600°F.

The REF burner and REF/REG burners operated stably at the combustion air temperature of 500°F, but the REF burner's flame stability deteriorated at temperatures below 500°F. The REF/REG burner vendor did not recommend burner operation with combustion air temperature below 500°F, due to expected flame stability problems.

The PPO target for burner turndown was for each burner to achieve a firing rate turndown ratio in excess of 4 to 1 without any support fuel or supplementary ignition sources. The test burners' turndown performance was found to vary widely. For example, the REF burner was capable of achieving 4 to 1 turndown with acceptable flame stability, while the HSWF burner and TAN burner achieved turndowns of 2.5 to 1 and 2 to 1, respectively. The REF/REG burner's turndown was limited to 1.5 to 1 at best.

The PPO target for burner ignition energy was that each burner should achieve stable operation after providing ignition support energy equivalent to 20% of full load heat input ($5x10^6$ Btu/hr) for a period of time not to exceed 30 minutes in a cold boiler. It should be noted that all burners in the test program were successful in meeting this ignition energy guideline.

Combustion air windbox pressure requirements were noted for each generic burner. It is desirable from an overall plant efficiency standpoint to minimize burner windbox pressure. The PPO target was for each burner to not exceed 16 inches water column windbox pressure. Relative ranking of the burners with respect to operating windbox pressures were 1) TAN (5.1" W.C. @ 44% excess air), 2) HSWF (9.8" W.C. @ 44% excess air), 3) REF (17" W.C. @ 30% excess air) and 4) REF/REG (19.5" W.C. @ 48% excess air).

Flame scanners are an integral component in burner management and safety systems. Tests were conducted to quantify relative compatibility of each burner's flame scanning system to CWF firing. Two generic flame detection systems were employed by the burner vendors participating in these tests. The HSWF and TAN burners used a visible light intensity/frequency monitor, while the REF and REF/REG burners used infrared detectors. Based on this test program, it appears that both visible light intensity/frequency monitors and infrared scanners can be successfully employed with CWF firing systems.

A factor which may limit the potential for CWF burner retrofit is that additional burner/boiler maintenance may be required as compared with existing oil fired burners. The reason for this concern derives from the fact that the pulverized coal in CWF's contains varying quantities of mineral matter in the form of ash. This ash is potentially erosive and can form deposits on burner/boiler surfaces. Two PPO targets were established with respect to the above: 1) that no excessive coking (deposition) occurred on burner surfaces during eight hours of steady burner operation and 2) that no atomizer pluggage or erosion occurred after eight hours of steady burner operation.

No burner coking or deposition was observed with either the HSWF or TAN burners. Some limited deposition was observed with both the REF and REF/REG burners. However, the deposition observed did not impede burner operation.

The HSWF, TAN, and REF atomizers did not experience any atomizer pluggage or erosion over eight hours of burner operation. These atomizers were fabricated of erosion resistant materials specifically for application to CWF. The REF/REG burner's atomizers tended to wear after only three hours of operation. However, the atomizers were fabricated of carbon steel, which is not particularly erosion resistant. Had the REF/REG atomizers been fabricated with erosion resistant materials, then REF/REG atomizer life would have improved dramatically.

The final PPO burner performance target addressed atomizer energy consumption requirements. All burners in the test program employed air-assisted atomizers; compressed air is used to provide fuel atomization energy. Since the amount of compressed air required for atomization effects overall plant efficiency, a PPO target limit was set for atomizer air consumption. Atomizer air consumption is normally expressed as an atomizing air to fuel (A/F) mass flow ratio. The PPO target was set at the A/F ratio of 0.25. This ratio was consistent with air consumption guidelines set by EPRI (Ref 5) for CWF atomization.

A/F ratio has a first order effect on atomization quality; atomization quality improves with increases in A/F ratio. This phenomena was observed for all burners in the test program.

Optimum burner performance was achieved at the following A/F ratios:

Burner Type	A/F Ratio Range
HSWF	0.19 - 0.22
REF	0.53 - 0.55
TAN	0.19 - 0.22
REF/REG	0.19 - 0.29

It is clear in reviewing the above that the HSWF and TAN atomizers met the PPO guideline, and the REF/REG atomizer for the most part operated within an acceptable A/F ratio range. The REF atomizer only operated at A/F ratio's which exceeded the PPO limitation.

In summary, all burners in the program were capable of firing the reference CWF. However, each burner demonstrated unique performance characteristics. No tested burner concept could be deemed wholly inadequate for CWF service. The HSWF and TAN designs appear suitable for immediate commercial CWF retrofit application. The REF and REF/REG burners demonstrated promising performance, but would benefit from further development. It should be noted that the REF and REF/REG burner manufacturers had no significant experience with CWF firing prior to this test program.

VII. BURNER SELECTION FOR $50x10^6$ BTU/HR

Having quantified the relative performance of each $25x10^6$ Btu/hr generic burner design, the project's focus centered on selecting a generic burner design for application to the multiple CWF formulation test program to follow. These tests were to be conducted at a 100% load heat input of $50x10^6$ Btu/hr. Therefore, the burner design selected would require scaling to a $50x10^6$ Btu/hr heat input capacity. Specific burner selection criteria included:

1) Burner design suitability to a wide range of boiler retrofit applications.
2) Burner design compatibility with PPO levels of performance
3) Impact of burner delivery on project schedule
4) Impact of burner selection on project budget

Due mostly to consideration of the first criterion, the High-Swirl Wall Fired (HSWF) Burner was chosen for application to the multiple CWF formulation test program. The HSWF generic design is suitable for use in a variety of CWF retrofit situations. It was determined that a $50x10^6$ Btu/hr HSWF burner could be integrated into the project with positive impacts of both project budget and schedule. In addition, the HSWF burner design operated within most PPO target performance levels.

The HSWF burner manufacturer fabricated a $50x10^6$ Btu/hr capacity burner with improvements to the design with respect to minimizing required burner windbox pressure. Specifically, the tertiary air swirler was eliminated from the design, which effectively allowed the burner to operate at windbox pressures below those previously observed (i.e., less than 9.8" W.C. @ 44% excess air). A schematic of the $50x10^6$ Btu/hr HSWF burner is shown in Figure 13.

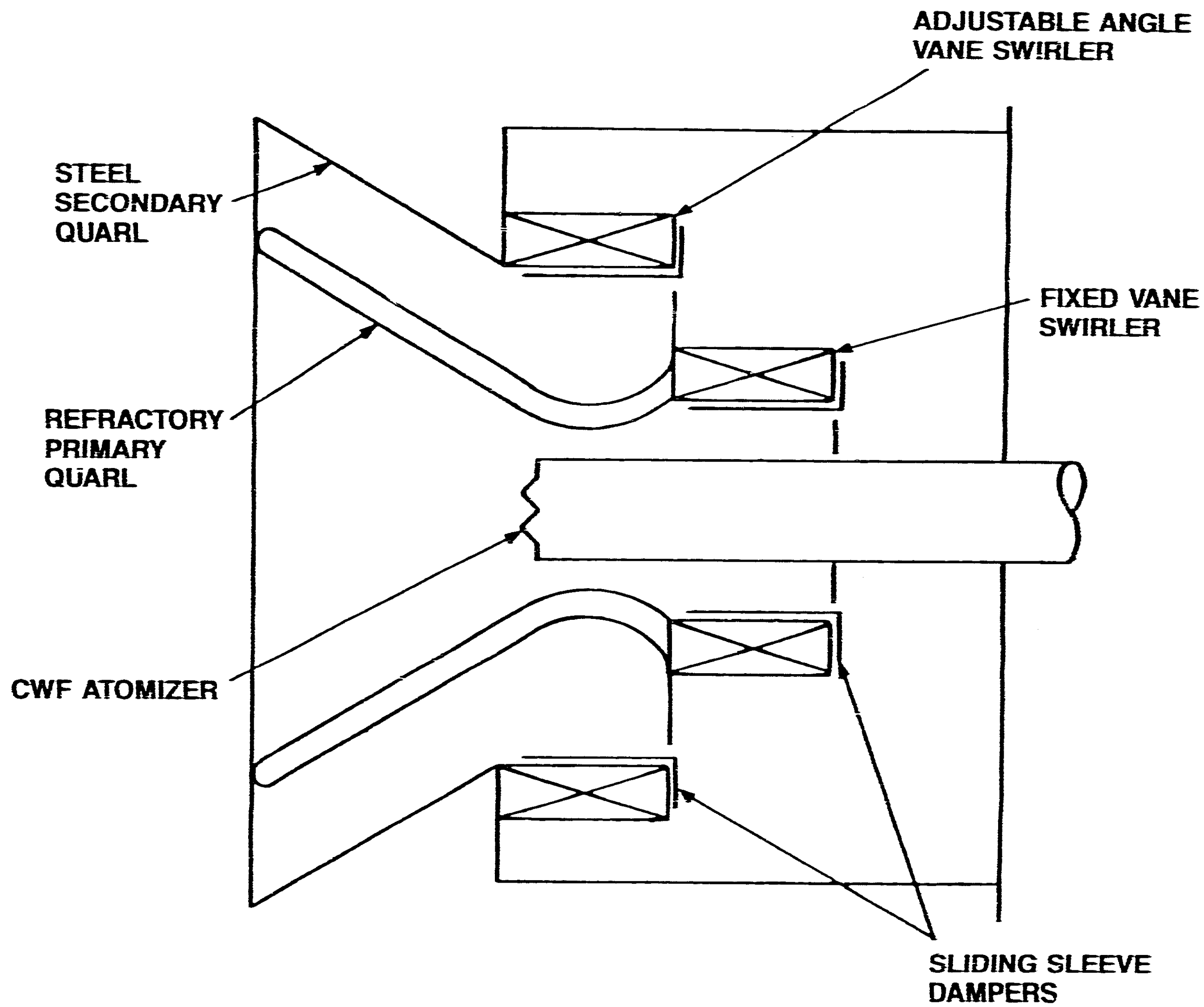

FIGURE 13: 50×10^6 BTU/HR HIGH SWIRL WALL-FIRED BURNER

VIII. LABORATORY ANALYSIS OF TEST CWFS

The overall objective of this portion of the project was to characterize and compare the performance of five different coal-water fuel (CWF) formulations which have commercial potential for replacing conventional premium fuels in industrial and utility boilers. Direct comparisons between each fuel's relative performance could be drawn since the testing environment (i.e., burner and test furnace) for each fuel was held constant. The information gathered as a result of the project can be used by potential users to assess the technical feasibility of utilizing CWFs sourced from several commercial suppliers who employ differing formulation approaches.

A detailed laboratory analysis program was initially carried out to characterize the five chosen CWFs in terms of their chemical and rheological properties. All CWFs chosen were formulated with high volatile A bituminous coals from mines in the eastern U.S.

Identifying codes, summarized below, were assigned to the fuels in the program. These codes identify a specific CWF's coal type, ash level, and vendor. The vendors are identified by code letter to preserve their anonymity:

Fuel Identifier	Coal Type	% Ash (Dry Basis)	Vendor Code
SD63C	Splash Dam	6.3	C
SD52A	Splash Dam	5.2	A
CG53C	Cedar Grove	5.3	C
UF62C	Upper Freeport	6.2	C
SD71F	Splash Dam	7.1	F

Laboratory evaluation of these fuels included the following characterization tests:

1) Solids content
2) Proximate analysis
3) Ultimate analysis
4) Higher heating value
5) Ash Fusibility
6) Ash Composition
7) Screen Size Analysis
8) Low shear viscosity (Haake viscometer) (Ambient Temperature Fuel)
9) High shear viscosity (Burell viscometer) (Ambient Temperature and Heated Fuel)

Note that no attempt was made to characterize any commercial additives which typically comprise about 1% by weight of most CWF mixtures in order to prevent settling or enhance rheological properties. These additive packages are considered proprietary by the respective fuel manufacturers.

In addition, it should be noted that all testing in this program was conducted on fuels in their as-delivered states (i.e., no dilution).

Table 3 presents a tabulated summary of the major results from the laboratory testing phase. The discussion which follows highlights key fuel characteristics which can impact a fuel's ability to atomize and combust efficiently.

TABLE 3
SUMMARY OF LABORATORY FUEL ANALYSIS

	SD63C	SD52A	CG53C	UF62C	SD71F
% Solids (by weight)	69.7	69.9	70.1	69.9	70.8
Coal Size Distribution					
+50 Mesh (300 microns)	0.0	Trace	Trace	0.0	0.6
+100 Mesh (150 microns)	0.2	2.8	1.4	0.1	3.7
Average Mass Median Diameter (microns)	6.5	31.0	27.0	6.5	30.0
Coal Volatile Matter (weight percent moisture free)	29.5	29.3	30.5	37.8	30.4
Ash Content (weight percent moisture free)	6.3	5.2	5.3	6.2	7.1
Higher Heating Value (Btu/lb) (moisture free)	14215	14560	14260	13920	14275
Higher Heating Value (Btu/lb) (as received)	9900	10180	9999	9735	10105
A. Viscosity (cp. @ 100 sec^{-1} shear rate) (ambient temp.)(Haake)	610	1459	1459	989	1533
B. Viscosity (cp. @ 3000 sec^{-1} shear rate) (ambient temp.)(Burrell)	710	850	860	1300	630
B. Power Law Index (Burrell)	1.4	1.07	1.07	1.37	1.07
B. Viscosity (cp. @ 2000 sec^{-1} shear rate) (135°F) (Burrell)	500	150	610	220	970

Coal particle size distribution and coal particle top size can impact on combustion performance in conventional pulverized coal firing (4). Finer coal grinds enhance combustion as they promote fuel/air mixing through an increase in fuel surface area. Assuming the same analysis held true for CWF firing, (disregarding atomization/agglomeration mechanisms for the moment) one could presume that finer grind CWF's would combust more readily and completely than coarser grind fuels.

Figure 14 presents a comparison of the coal particle size distribution (Rosin-Rammler Analysis) for the five CWF fuels tested. The five fuels fall into two major categories as delineated by their respective coal particle size distributions. Fuels UF62C and SD63C can be considered microfine CWF's, with coal particle mass median diameters approximately equal to 6.5 microns. Fuels SD52A, SD71F, and CG53C are considered standard grind CWF's with coal particle MMD's ranging from 27 to 31 microns. Assuming the base coals were fired in a dry, pulverized state (again ignoring any agglomeration phenomena), the microfine coals would probably fire at higher levels of carbon conversion efficiency than would the more conventional grind coals, all other factors being equal.

The value of volatile matter content is used as an indication of coal classification and ignitability, and, in general, high volatile matter content (approx. 30% or above) is desirable in coal firing as it enhances fuel ignition and flame stability. Figure 15 presents a comparison of the volatile matter content for the five fuels. As can be seen, all of the fuels have essentially identical volatile matter content, with the exception of UF62C which has a somewhat higher value. Thus, it can be expected that all of the base coals would have good ignition characteristics and will maintain good flame stability if fired as dry pulverized fuels.

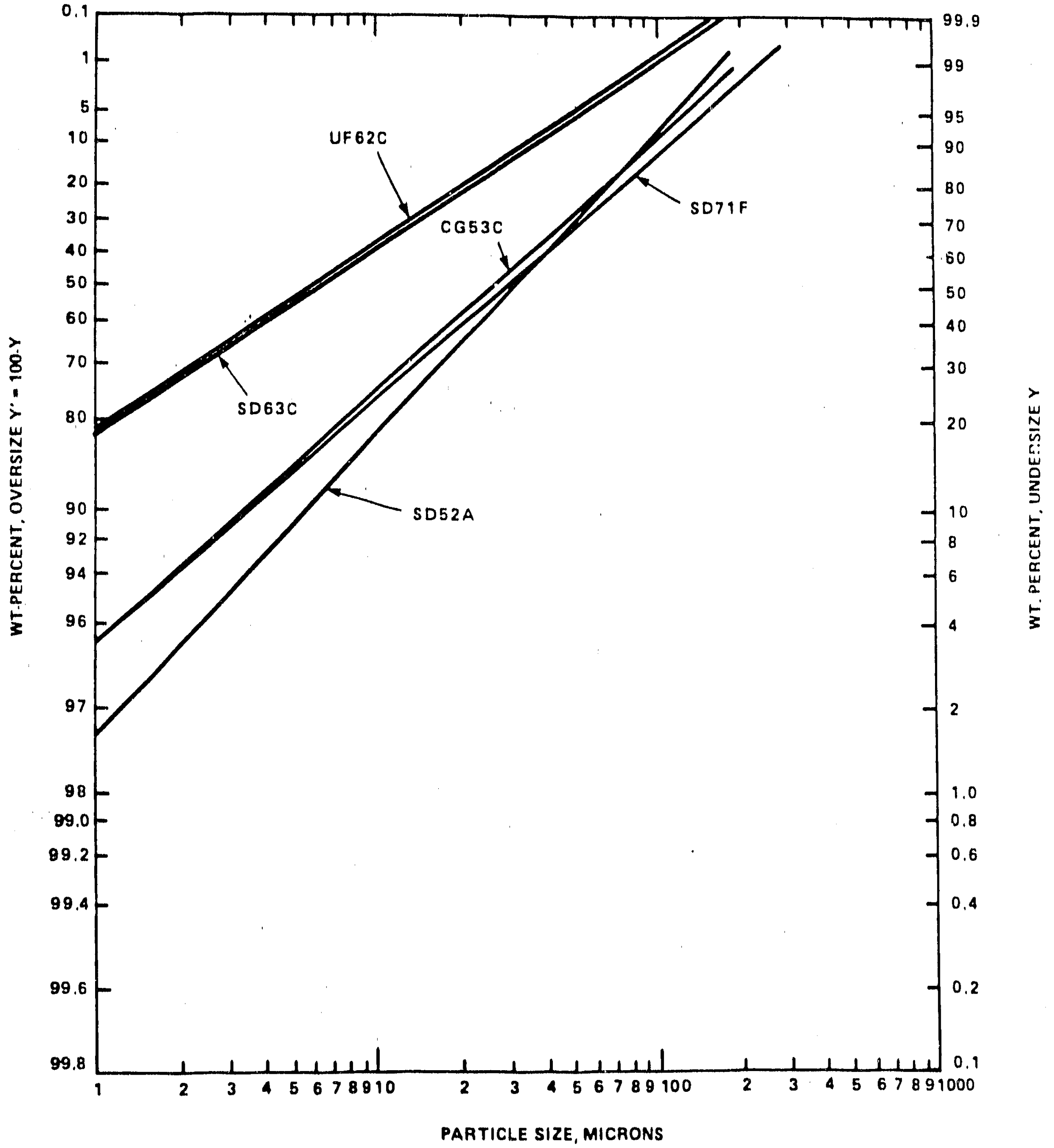

FIGURE 14: COMPARISON OF THE COAL PARTICLE SIZE DISTRIBUTION FOR THE FIVE CWF'S TESTED

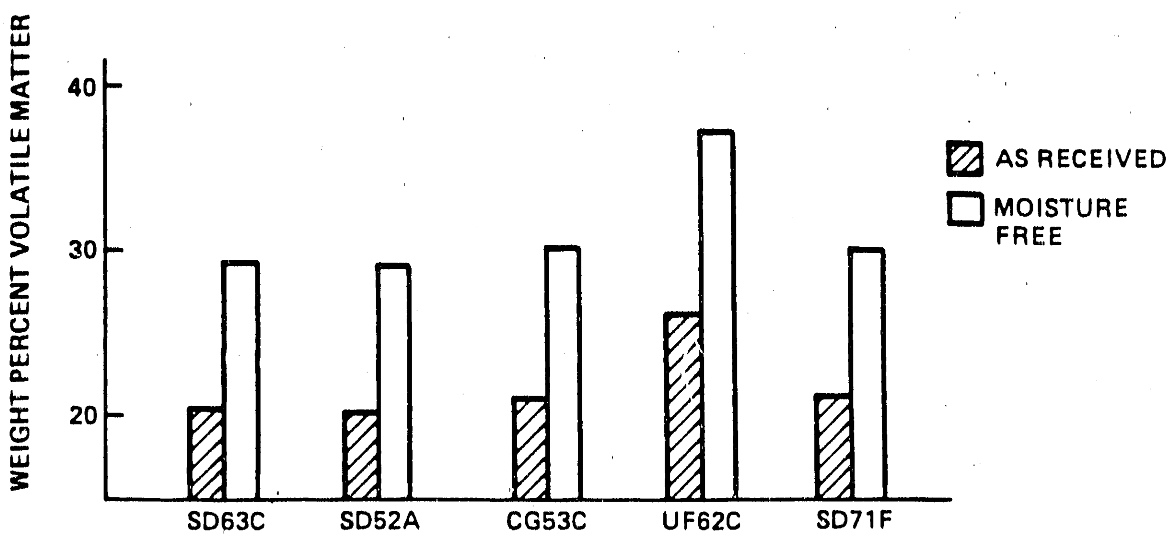

FIGURE 15: COMPARISON OF VOLATILE MATTER

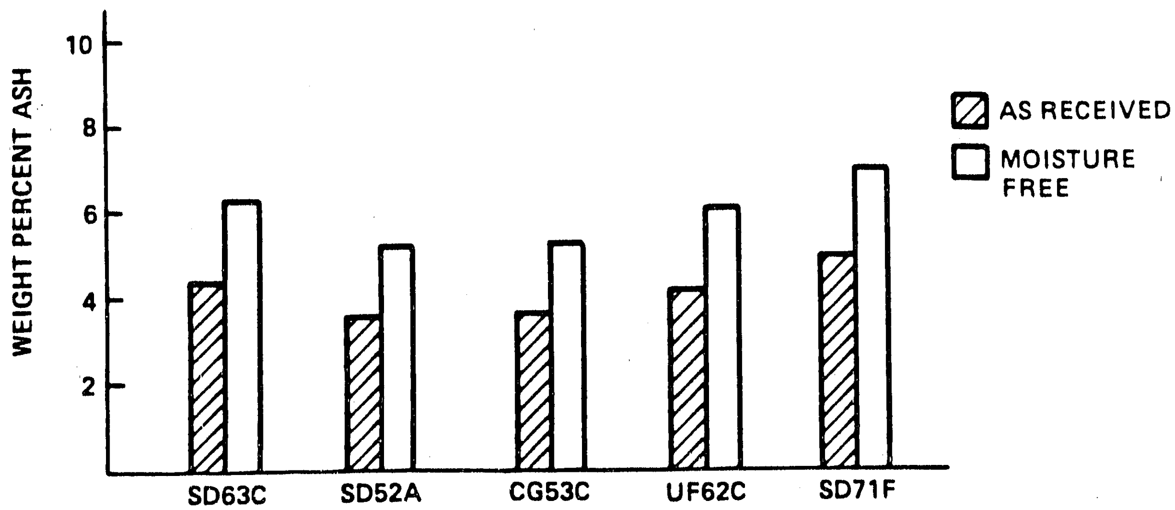

FIGURE 16: COMPARISON OF ASH CONTENT

Ash composition and ash content are important variables in any CWF formulation, since boiler convection tube erosion is directly related to these factors. Convective tube erosion resulting from flyash generated during combustion must be a major consideration when retrofitting boilers designed for low ash level fuels to higher ash level CWF firing. Several investigators (6,7) have indicated that the potential for boiler pressure part erosion could be a significant load limiting factor, and would adversely affect the economics of CWF conversion in some cases.

Most commercial CWF vendors beneficiate the base coals utilized in CWF's in order to minimize the impact of increased fuel ash content on both tube erosion and boiler flyash collection systems. Thus, all parent coals in this study were beneficiated to some degree prior to CWF production. Figure 16 shows a comparison of the ash levels for the five fuels on an as-received and moisture- free basis. As can be seen in Figure 16, ash levels ranged from 5.2 to 7.1% by weight on a dry basis. A study of the impact of CWF ash composition and ash level on boiler tube erosion was beyond this scope of work. However, studies have been reported elsewhere (7,8) which characterize the effects of CWF ash on erosion.

Viscosity is a measure of a fluid's resistance to flow. Fluids are typically categorized as being either Newtonian or non-Newtonian in nature. Newtonian fluids are characterized by viscosities that are independent of shear rate while non-Newtonian fluids exhibit viscosities that are shear dependent. Most conventional petroleum based boiler fuels are Newtonian fluids. Consequently, their transport flow characteristics, which relate to viscosity under low shear conditions, and, to a certain extent, their atomization characteristics, which can be related to viscosity at much higher shear rates, can be analytically predicted with shear viscosity information derived at a single shear rate. This is not the case with CWF's, since most CWF's exhibit non-Newtonian behavior, as did the five fuels studied in this program. This fact complicates the analytical prediction of viscosity related CWF characteristics, such as piping pressure losses and atomization quality.

In order to characterize the complex non-Newtonian rheology of the five CWF's, a series of parametric viscosity measurements was made. These measurements were conducted over a range of shear rates from $100sec^{-1}$ to $8000sec^{-1}$. This range of shear rates may be considered fairly representative of the flow regimes a CWF may be exposed to when being handled (pumped) from a storage tank to a boiler and then subsequently atomized within the burner's atomizer. A sensitivity study was also conducted in order to define the impact of temperature on CWF rheology. Viscosity measurements were made at a constant shear rate ($2000sec^{-1}$) over a range of CWF temperatures from 75°F to 160°F.

The low shear ($100\ sec^{-1}$) viscosity data, as measured by a Haake Rotovisco Viscometer, were summarized in Table 3. Figure 17 presents the high shear viscosity data obtained with a Burrell high shear viscometer. As can be seen, the fuels are clearly non-Newtonian with each fuel being dilatent in nature. Of the five fuels, fuels SD63C and UF62C exhibited the highest degree of dilatency with power law indices of 1.4 and 1.37. The other three fuels showed identical degrees of dilatency, each having a power law index of 1.07. Note that fuel UF62C had the highest range of high shear viscosity (from 1075 to 1475 centipoise) and that fuel SD71F had the lowest range (between 620 and 700 centipoise).

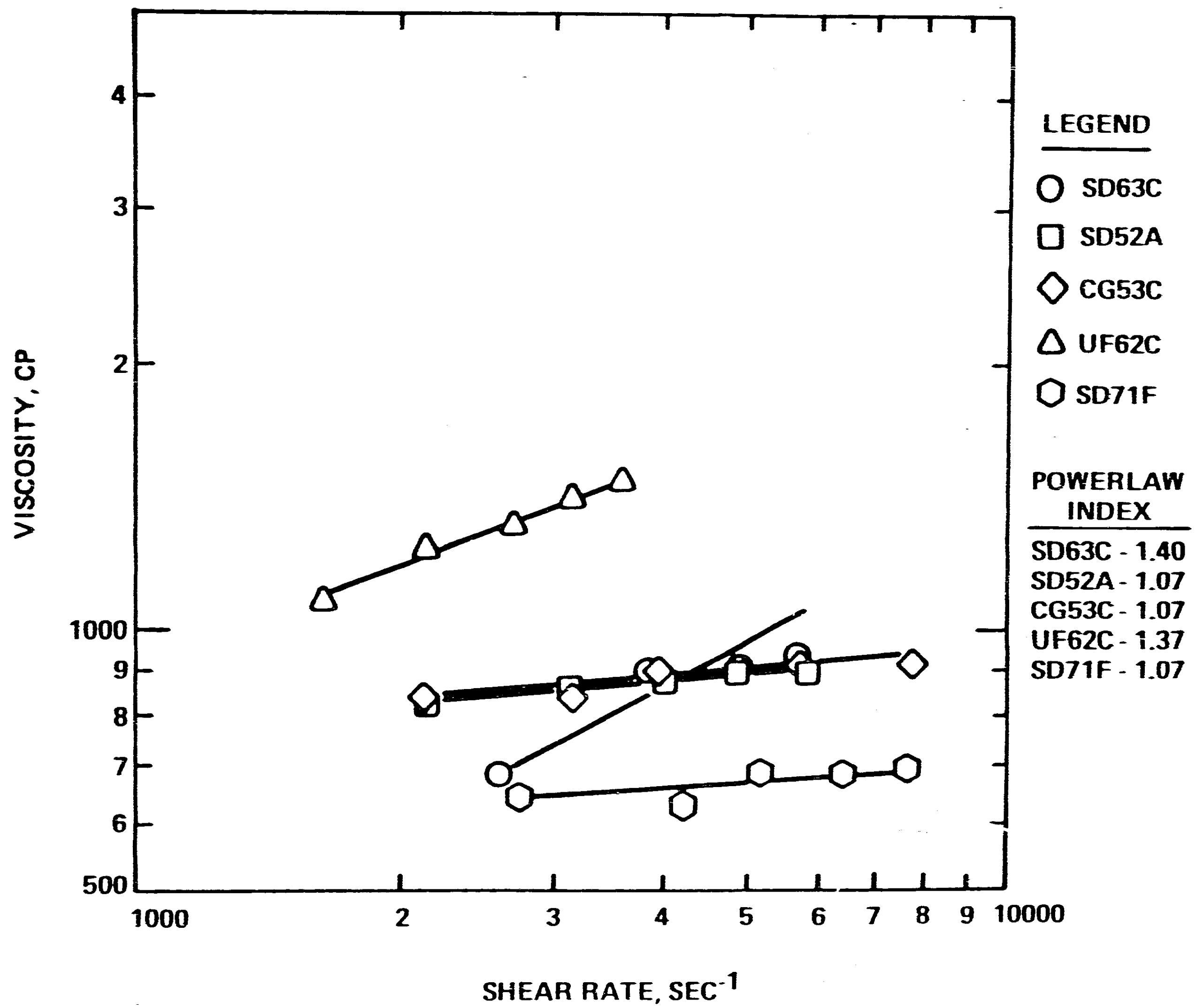

FIGURE 17: CWF VISCOSITY DETERMINED AT SHEAR RATES GREATER THAN 1000 SEC^{-1}

Viscosity has been shown (9) to have a first order effect on the atomization quality of Newtonian fluids. CWF atomizer's typically operate at high shear rates (>5000sec^{-1}). Assuming that high shear viscosity also has a first order effect on CWF atomization and disregarding any other influences, one could make the prediction that fuel SD71F would atomize more finely and combust more readily than would fuel UF62C.

Figure 18 presents a comparison of high shear viscosity values as a function of temperature, ranging from 75 to 160°F, for the five fuels. These measurements were performed by the Adelphi Center for Energy Studies with the fuel samples sent directly from each vendor. As shown, all of the fuels, with the exception of UF62C, exhibited viscosities that were highly dependent on fuel temperature, with viscosity generally decreasing as temperature was increased. The sample of fuel UF62C analyzed by Adelphi underwent settling and it is likely that the shear viscosity data obtained are not representative.

IX. ATOMIZATION CHARACTERIZATION

Most CWF investigations to date have identified the fuel atomization process as critical to efficient combustion. The situation is analogous to firing conventional liquid fuels. That is, fine fuel sprays enhance ignition and carbon conversion efficiency as compared with fuel sprays having a relatively significant population of large diameter droplets.

A parametric study was conducted in order to quantify the effect that various CWF formulations would have on atomization quality. This testing was carried out on the five CWF's in this program using Combustion Engineering's Atomizer Test Facility (ATF) described in previous sections of this report. Performance comparisons can be drawn between each fuel as all CWF's were atomized under identical conditions using the same 50x10^6 Btu/hr, Y-jet CWF nozzle.

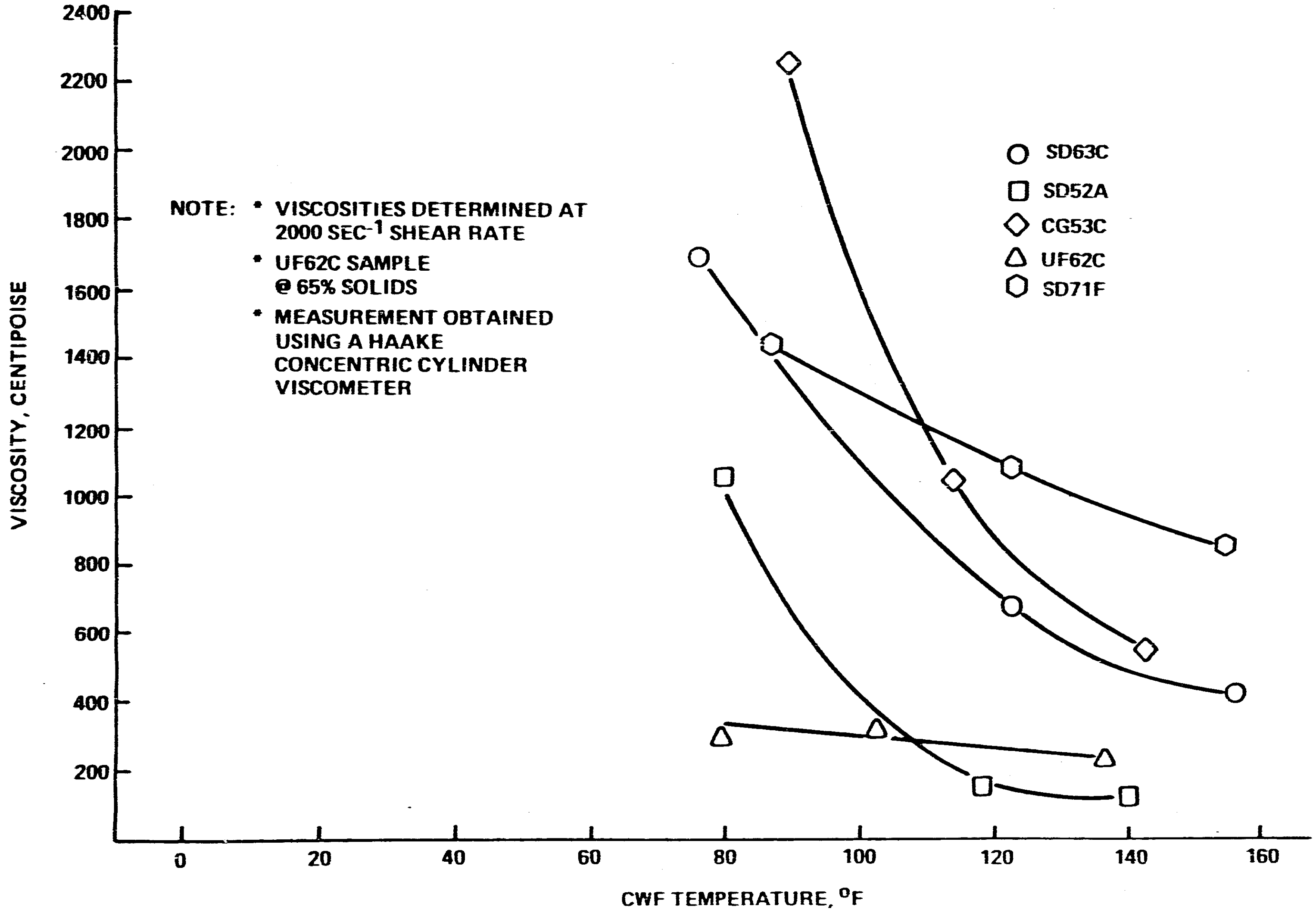

FIGURE 18: CWF VISCOSITY vs TEMPERATURE

In general, to reach any valid conclusions on atomization performance, a set of performance criteria for CWF must be established by which a comparison can be made with experimental data. Specifically, performance objectives in terms of droplet size distribution and atomizer energy consumption need to be developed. During the burner evaluation phase of this program, Combustion Engineering established a number of Preliminary Performance Objectives (PPO's) in order for the burner manufacturers to have established design targets.

In the specific area of atomizer design, it was deemed desirable to have: 1) An atomized spray droplet mass median diameter (MMD) of less than 200 microns at 100% load, 2) less than 1% by weight of total spray droplets exceeding 300 microns in diameter and 3) An atomizer assist fluid consumption ratio (A/F) of less than 0.25 lb air/lb fuel at 100% of full load firing rate.

These PPO's were met or exceeded by the HSWF burner's atomizer on a baseline CWF. The atomizer was capable of achieving, on average, a spray droplet mass median diameter of less than 70 microns while meeting the droplet top size and energy consumption criteria outlined above.

The primary focus of this test phase was to determine, for each fuel tested, the effect of A/F ratio on spray droplet MMD, size distribution and topsize. The atomizer test matrix was designed to evaluate atomizer performance over a range of operating conditions with tests conducted at three fuel rates corresponding to 100%, 50%, and 33% load (with 100% load equivalent to a burner firing rate of 50×10^6 Btu/hr). Compressed air was used as the atomizing media and the A/F ratio was systematically varied for each of the three loads.

All spray droplet size measurements were made approximately 150 nozzle diameters downstream of the nozzle exit. Testing at this location ensured that the fuel atomization process was complete and only spherical droplets were present in the measurement volume. Testing of each fuel in the ATF was conducted prior to each fuel being fired in the combustion test phase of the project. Each fuel was delivered in a conventional, pressurized tanker, and 500 gallon samples for ATF testing were drawn from a well mixed storage tank.

Figure 19 presents a comparison of the spray mass median diameter as a function of A/F ratio at 100% load for the five CWF's. Note that, with the exception of fuel UF62C (44 micron MMD), the atomization quality of all the fuels was similar (60 to 70 micron MMD) within the atomizer's recommended A/F operating range of 0.19 to 0.21.

In Figure 20 the entire drop size distribution for each of the five fuels is presented. Note that the droplet size data are derived from the Malvern instrument's Rosin-Rammler analysis routine. Based on this information, each fuel generated fewer than one percent by weight of droplets above 300 microns in diameter, thus meeting the PPO topsize criteria previously stated.

It is apparent from these atomization studies conducted at 100% load as well as at reduced loads that the five CWFs in an isothermal environment generated similar quality sprays, with the exception of UF62C being slightly finer. It is also clear, comparing atomization data to the laboratory fuel analysis summary (Table 3), that atomizations trends did not correlate with viscosity measurements.

In conclusion, based on the isothermal atomization data generated in this study, it appeared, from an atomization viewpoint only, that all fuels, with the exception of UF62C, would combust with nearly equivalent levels of performance. Higher levels of carbon utilization would be expected from fuel UF62C.

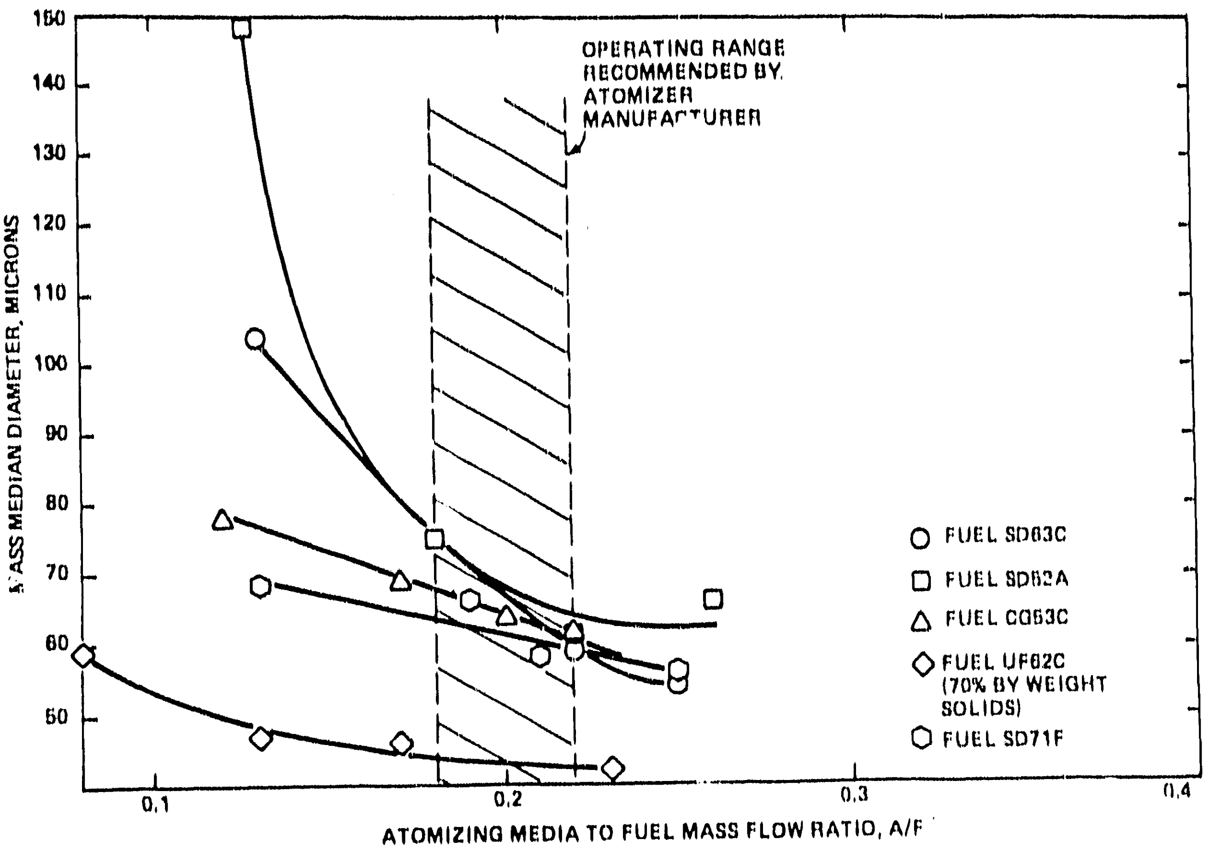

FIGURE 19: SPRAY DROPLET MMD vs A/F RATIOS AT 100% LOAD

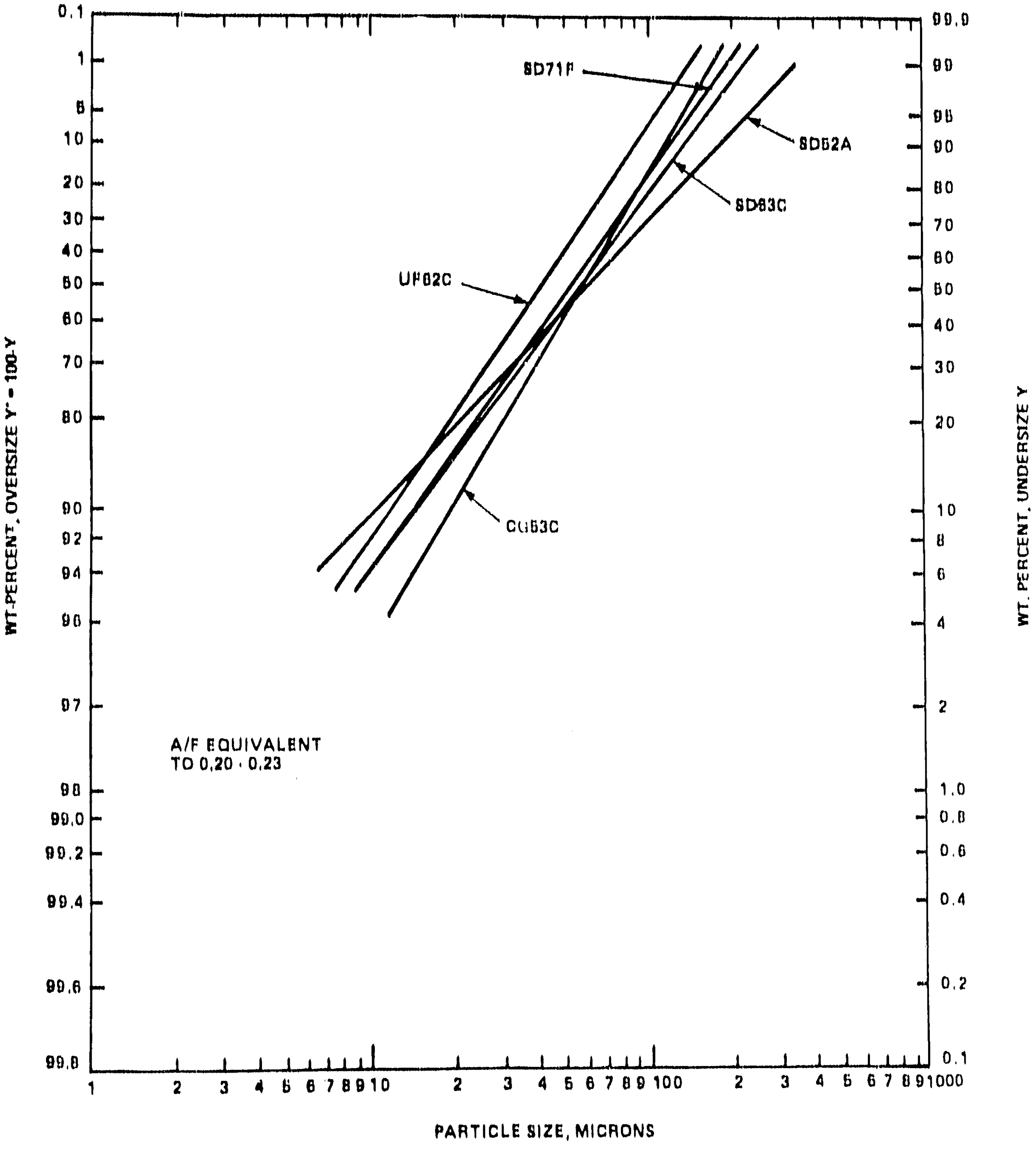

FIGURE 20: SPRAY DROPLET SIZE DISTRIBUTION @ 100% LOAD

X. COMBUSTION CHARACTERIZATION

Subsequent to atomization characterization, each fuel was subjected to a series of detailed parametric firing tests conducted in Combustion Engineering's Industrial Scale Burner Test Facility (ISBTF) using the 50×10^6 Btu/hr HSWF burner.

The primary objective of these tests was to identify and characterize relative differences, if any, between the performance of the five CWF's when the fuels were fired in a simulated boiler environment. Performance differences were quantified thru systematic determination of:

1) Carbon conversion efficiency by flue gas analysis at each test condition.

2) Carbon conversion efficiency by particulate analysis at optimum operating conditions for each load.

3) Flue gas emissions of NO_X, SO_2, and CO.

4) Flame stability and minimum load.

5) Morphology of flyash emissions (scanning electron microscope).

6) Furnace outlet temperatures and peak flame temperatures.

7) The influence of combustion air temperature on combustion efficiency.

8) The effect of varying atomizer A/F ratio on combustion efficiency.

9) Heat flux along the length of the test facility to determine the heat release profile for each fuel tested.

10) Any fuel specific abnormal handling characteristics, such as atomizer or fuel line pluggage, and fuel settling.

The combustion test matrix developed for this program was designed to evaluate the combustion performance of each test fuel over a wide range of operating firing rates and excess air levels. However, in order to compare the performance of each fuel, it was necessary to hold certain operating variables constant to isolate the effect of fuel on combustion performance. Thus, at each test condition the following burner/ atomizer operating variables were held constant between all of the fuels tested:

1) Atomizer A/F ratio - 0.19-0.21 at 100% load
   0.39-0.41 at 50% load
   0.59-0.61 at 33% load

2) Burner Damper Positions

3) Burner Windbox to Furnace Pressure Drop

4) Combustion Air Temperature (500°F)

A complete data set for this test phase is beyond the scope of this report, as a total of 99 individual combustion tests were conducted on the five CWF's. A condensed summary of the data obtained for each of the five CWF's at optimum carbon conversion efficiency levels over the maximum achievable firing rate range is given in Table 4. Note that all fuels, with the exception of SD63A, operated over a 3 to 1 turn down range. Fuel SD63A was limited to a 2 to 1 turn down range. The reason for this is not apparent from a review of either the laboratory fuel characterization study or the atomization study.

TABLE 4

SUMMARY OF COMBUSTION TEST RESULTS @ OPTIMUM CARBON CONVERSION EFFICIENCY CONDITIONS

Fuel Identifier	% Excess Air	% Load	% O_2	% CO_2	CO, ppm Corr. to 3% O_2	SO_2, ppm Corr. to 3% O_2	NO_X, ppm Corr. to 3% O_2	% Carbon Conversion Efficiency (gas anal.)	% Carbon Conversion Efficiency (part anal.)
SD63C	42	100	5.9	12.6	90	390	621	97.5	98.3
	88	50	9.2	10.0	50	435	596	99.5	99.3
SD52A	32	100	4.5	13.9	90	361	469	99.6	98.8
	39	50	5.7	12.9	85	332	436	98.6	99.2
	46	33	6.3	12.4	48	329	700	99.0	99.7
CG53C	39	100	6.3	12.3	83	461	491	93.6	98.9
	40	50	6.1	12.4	27	448	600	95.7	99.8
	50	33	7.1	11.8	35	447	447	96.9	99.7
UF62C	40	100	6.9	11.7	42	544	566	88.5	98.1
	61	50	8.2	10.8	27	520	485	92.7	--
	100	33	10.2	9.4	27	492	512	98.3	--
SD71F	42	100	6.7	12.1	38	341	688	93.8	99.5
	59	50	7.7	11.2	26	332	562	96.5	99.7
	95	33	9.8	9.4	40	313	394	96.5	--

Efficiency data presented in Table 4 is based on flue gas constituent analysis as well as carbon analysis of collected flyash. If one were to look only at carbon conversion efficiency determined by analysis of particulate collected isokinetically (EPA Method 5) from the furnace flue duct, one could conclude that all five fuels were capable of achieving carbon conversions in excess of 98% at all tested loads. However, optimum carbon conversion efficiencies for the five fuels were found to vary over a much wider range (88.5% - 99.6%) when efficiencies were calculated from flue gas constituents. The numerical discrepancies between the two efficiency determination methods appear to be due to the particulate sampling techniques. It was noted throughout the test program that several of the fuels had a tendency to generate fairly large "agglomerates". Photographic evidence of this is presented later in this report. Specifically, fuel UF62C experienced significant agglomeration under combustion conditions. This phenomena has been noted by a number of CWF researchers (10,11). It is theorized that these "agglomerates" may derive from fuel "ligaments" which issue from the nozzle and remain essentially intact in the high temperature furnace environment, rather than breaking down into small, readily combusted, spherical droplets as has been demonstrated during isothermal atomization testing.

While the specific agglomerate formation mechanisms were not identified, it is clear from these tests that a significant population of agglomerates generated by several fuels were not entrained in the combustion gas stream, but rather fell partially combusted to the furnace floor. Flue particulate samples collected for the fuels having agglomerating tendencies did not accurately represent the high carbon percentage material which fell to the furnace floor. For this reason, it is assumed that the carbon conversion efficiency data generated via flue gas analysis represent fuel performance more accurately than do the efficiency data derived from collected flue particulate samples. With the above analysis in mind, carbon conversion performance trends presented in this paper will be based on carbon conversion efficiencies derived from flue gas analysis.

Figure 21 summarizes carbon conversion efficiency data obtained at 100% load as a function of excess air for the five fuels. In general, carbon conversion efficiency improved from all five CWF's with increased excess air. A similar observation was made in the previous comparative burner test program. It is evident in reviewing Figure 21 that the five fuels can be clearly ranked in terms of achievable levels of carbon conversion efficiency. The highest carbon conversions were achieved with fuel SD52A, followed in relative order by fuels SD63C, CG53C, SD71F, and UF62C. The fundamental reasons for the above fuel ranking, after conducting a detailed review of the laboratory fuel characterization data and the atomization characterization study, are not clearly evident.

Most CWF investigators agree that fine fuel atomization is a precursor to good carbon conversion efficiency. The isothermal atomization data indicated that atomization quality for fuels SD52A, SD63C, CG53C, and SD71F was similar. This result does not correlate with the wide range of carbon conversion efficiencies observed for these fuels. Additionally, fuel UF62C generated the finest sprays, on average, during atomization testing; yet this fuel on average generated the lowest levels of carbon conversion.

Based on these results, it would appear that an isothermal measurement of atomization quality cannot be considered the dominant predictor of CWF combustion characteristics when applied to <u>differing CWF formulations</u>. However, previous investigations have confirmed that isothermal spray quality measurements made on a <u>single CWF formulation</u> can be extremely helpful in predicting the

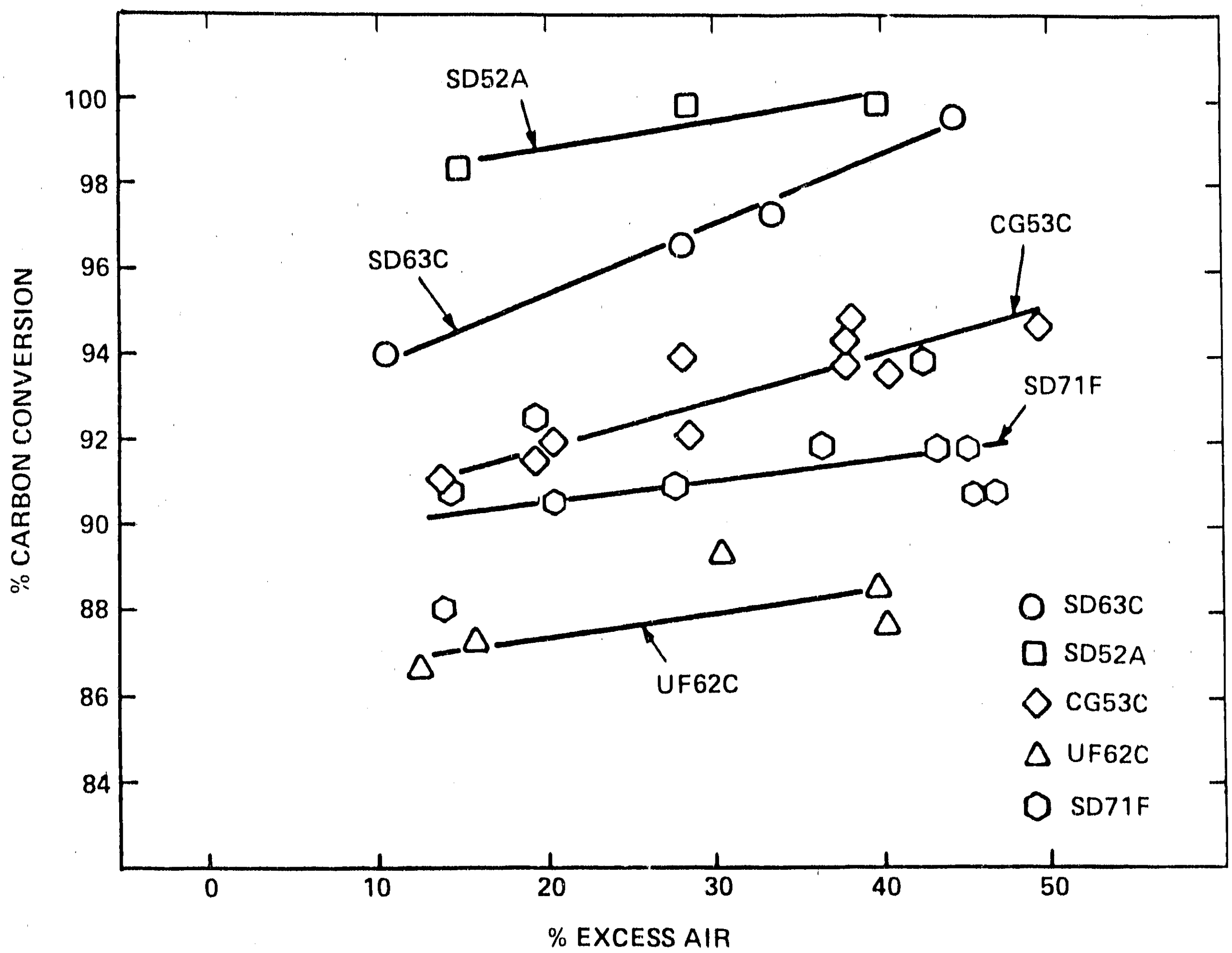

FIGURE 21: EFFECT OF EXCESS AIR AT 100% LOAD ON CARBON CONVERSION

combustion performance of CWF. This was true in this study as well. Figure 22 presents carbon conversion efficiencies at 100% load as a function of spray droplet mass median diameter for three of the five CWFs. As previously shown (Figure 19), atomizer A/F ratio has a dominant influence on spray quality (droplet mass median diameter). These results show that for fuels SD63C, CG53C and UF62C, carbon utilization is a strong function of mass median diameter. As MMD was increased, carbon conversion was found to decrease. This observation is consistent with the previous conclusion that isothermal spray quality measurements made on a single CWF formulation can effectively predict CWF combustion performance trends as a function of droplet size distributions.

A number of scanning electron micrographs (SEM's) were taken of collected particulate from the combustion study in an attempt to clarify the inconsistencies noted between each CWF's isothermal atomization performance and combustion performance. Four representative photographs are shown in Figure 23 for fuel UF62C. The photos show evidence of elongated char particles which are interspersed amongst fine flyash particles. The shape of these char particles seems to support the previously mentioned theory that a certain population of long CWF strands or "ligaments" did not completely atomize in the hot furnace. Rather these ligaments, which contain a number of coal particles, tended to dry and burn as agglomerates. Cold flow atomization data would not predict this phenomenon since it was conducted at a distance (far field) which ensured spherical droplet formation.

Burner flame stability was documented photographically for all five of the fuels tested. The luminous flames produced by all fuels, with the exception of UF62C, were highly stable and attached to the

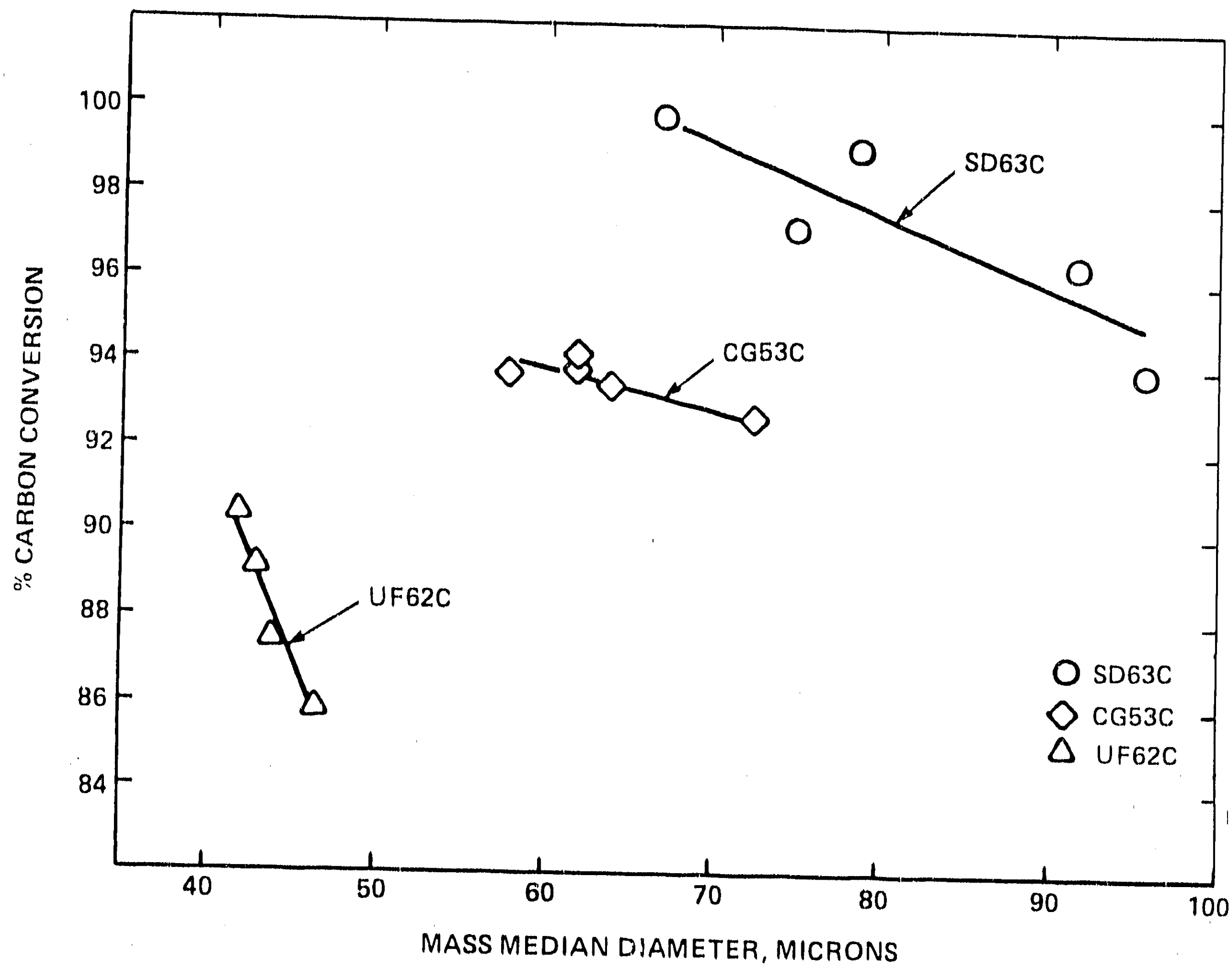

FIGURE 22: EFFECT OF SPRAY DROPLET DIAMETER ON CARBON CONVERSION

a) 100% LOAD
100X

b) 100 LOAD
100X

c) 100% LOAD
90X

d) 100% LOAD
50X

FIGURE 23: SCANNING ELECTRON MICROGRAPHS OF FLY ASH FROM UF6.2C CWF

burner quarl. Good flame stability was achieved during initial testing of UF62C. However, as testing progressed flame stability degraded. The source of the degradation was likely variability in the solids loading for fuel UF62C. Progressive coal settling was noted in the fuel supply tank during the later portions of the combustion test program.

An interesting flame stability observation was made during the evaluation of SD52A. Flame stability was poor for SD52A when the burner's atomizer was operated at atomizing air/fuel mass flow ratios of 0.19 to 0.21 at 100% load. The other four fuels in the program operated successfully at A/F ratios in the 0.19 to 0.21 range. A dramatic improvement in flame stability was achieved when the A/F ratio was reduced to 0.16 for fuel SD52A. An explanation for this anomalous behavior may be found from an analysis of the isothermal atomization data. The percentage of spray droplets exceeding 300 microns tended to increase with fuel SD52A when the atomizer A/F ratio exceeded 0.18. At an A/F ratio of 0.22, the percentage of droplets exceeding 300 microns was in excess of 1%. It is possible that ignition stability would suffer as a result of the increased population of large droplets generated when fuel SD52A was atomized at A/F ratio's in excess of 0.18.

The formation of NO_x during combustion is commonly classified in terms of the nitrogen source for the reaction. "Thermal NO_x" refers to NO_x that is formed at high temperatures from nitrogen and oxygen present in the combustion air. NO_x formed in this way has been shown to be function of temperature, N_2 and O_2 concentrations, and the time of exposure of N_2 to O_2 at high temperatures. Temperatures in excess of approximately 2800 degrees Fahrenheit are generally required for this process (12).

"Fuel NO_x" refers to NO_x formed from organically bound fuel nitrogen. Although the mechanisms of "fuel NO_x" formation are generally not yet fully understood, it is known that its formation is insensitive to flame temperature. Since significant quantities of nitrogen (0.1 to 2 percent by weight) can be found in coals, fuel NO_x is a major contributor to the total NO_x formed. Previous studies have indicated that up to 80% of the total NO_x can be fuel related. The main factor affecting the conversion of fuel bound nitrogen to NO_x is oxygen availability.

Extensive furnace temperature mapping data, obtained with a suction pyrometer, indicate that at no time during combustion testing of the five CWF's did flame temperatures exceed the 2800°F necessary for thermal NO_x formation. This indicates that the NO_x emissions measured for all of the fuels were primarily fuel related.

Table 5 summarizes the range of NO_x emissions measured for each CWF. Note that no attempts were made in this test program to minimize NO_x levels; test guidelines focused on flame stability and carbon conversion efficiency. Application of commonly known NO_x control technologies such as "staged combustion" would likely reduce the levels of NO_x observed here.

Sulfur dioxide emissions, in general, are not a function of burner/ furnace operating conditions.The amount of SO_2 generated during the combustion process is directly proportional to the amount of sulfur present in the fuel. Since essentially all (90% or more) of the sulfur present in the fuel is converted to SO_2 and SO_3, any increase or decrease in fuel sulfur should result in a corresponding increase or decrease in SO_x emissions.

TABLE 5

NO_x Emissions

Fuel	% by weight Nitrogen Content (moisture free)	lbs $NO_x/10^6$ Btu Fired (range for all firing rates)
SD63C	1.5	0.54 - 1.13
CG53C	1.7	0.64 - 1.06
UF62C	1.5	0.67 - 0.95
SD71F	1.5	0.68 - 1.06
SD52C	1.8	0.54 - 0.97

XI. SUMMARY OF TASK 4 RESULTS

Multiple Burner Test Program

The subject test program successfully quantified the performance characteristics of four generically different CWF burner designs with respect to a predetermined set of Preliminary Performance Objectives (PPOs). A single reference CWF formulation was used throughout testing; this allowed the investigators to draw conclusions about the relative performance of one burner design to another.

Tests were conducted first on each burner's fuel atomizer. These tests defined spray droplet size distribution and general droplet ballistics characteristics. All tests were conducted in a non-combustion environment using non-intrusive optical instrumentation.

Comparative combustion tests on the atomizer/burner register systems followed. These tests were conducted in a facility designed to simulate a boiler environment which represented a typical oil to CWF retrofit situation.

All of the burner systems in the program were capable of firing the reference CWF formulation. Each burner configuration tended to exhibit unique performance characteristics which can be attributed to fundamental differences in each burner's atomization properties and/or near-field thermal/aerodynamic characteristics. Table 6 summarizes the relative performance of each burner system design with respect to the Preliminary Performance Objectives. It is clear upon examination of Table 6 that in many cases the burners evaluated met or exceeded PPO levels of performance.

TABLE 6

BURNER PERFORMANCE SUMMARY

P.P.O. Target	HSWF Burner	REF Burner	REF/REG Burner	TAN Burner
Atomizer assist fluid consumption: less than 0.25 lbs/lb of fuel (A/F) at 100% of full load	0.19 - 0.22	0.53 - 0.55	0.19 - 0.29	0.19 - 0.22
Average atomized CWF droplet mass median diameter (MMD): less than 200 microns at 100% of full load	60	115	130 - 140	60
No atomizer pluggage/ erosion during 8 hour test	None noted	None noted	Conventional atomizer materials eroded	None noted
Ignition requirements: less than 20% of full load heat input for 30 minutes	10% for 10 minutes	20% for 15 minutes	10% for 15 minutes	15% for 10 minutes
Combustion air preheat requirement: less than 500°F	300°F - 600°F	500°F - 600°F	500°F - 600°F	250°F - 600°F
Less than 40% excess combustion air required at full load firing rate	27%-44%	23% - 30%	27% - 48%	19% - 36%

TABLE 6 cont'd

BURNER PERFORMANCE SUMMARY

P.P.O. Target	HSWF Burner	REF Burner	REF/REG Burner	TAN Burner
Windbox air pressure: less than 16 inches Water Column	8	16 - 17	17 - 19	5
Confirmed scanner signal over turndown range	Visible light intensity/ frequency scanner acceptable	Conventional IR scanner acceptable	Conventional IR scanner acceptable	Visible light intensity/ frequency scanner acceptable
No excessive burner coking during 8 hr. test	None noted	Limited deposition at 100% and 50% load: considerable deposition at 25% load	None noted	None noted
Carbon conversion efficiency: greater than 98% at full load	97%	86%	98%	99+%
Turndown without support fuel: greater than 4:1	2.5 to 1	4 to 1	1.3 to 1	2 to 1