APPENDIX B: SITE VISIT REPORTS

ASSESSMENT OF RESEARCH NEEDS FOR COAL UTILIZATION

DOE COAL COMBUSTION AND APPLICATIONS WORKING GROUP
(CCAWG)

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May 1983

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APPENDIX B

SELECTED REPORTS OF SITE VISITS, CONFERENCES AND DISCUSSIONS

This section contains edited copies of site-visit and other reports prepared by CCAWG members. Some of the hand-out materials prepared by DOE contractors and others are included (without explication) to permit readers the construction of a coherent picture of work in progress.

AB-1

CCAWG SITE VISIT AND DISCUSSIONS
AT PETC (March 19, 1982)

CCAWG members J. Beér, A. K. Oppenheim, S. S. Penner, D. Smoot, and I. Wender attended a review meeting dealing with 1982 and 1983 programmatic activities on coal utilization supported by the Department of Energy. J. Birkeland, G. Jordy, R. Roberts, and S. Freedman of DOE Washington also attended the presentations. The topics discussed and the agenda are shown in Attachment I.

Following brief inspections of experimental facilities, the tentative work plan shown in Attachment II was defined for CCAWG.

Attachment I

CCAWG
PETC COMBUSTION PROGRAM REVIEW
FRIDAY, MARCH 19, 1982

PROGRAM CONTROL ROOM

8:00 a.m. - Introductory Remarks - Jorgen W. Birkeland, Combustion & Heat Systems, Division, Office of Coal Utilization and Extraction

8:15 a.m. - PETC Overview - Sun W. Chun, Director

8:30 a.m. - Combustion Project Management Overview - Daniel Bienstock, Manager, Combustion Project Management Division

8:45 a.m. - Advanced Research and Technology Development - James D. Hickerson, Chief, Combustion Phenomena Branch

9:30 a.m. - Alternative Fuels, Roy C. Kurtzrock, Chief, Coal-Oil Mixture Branch

9:50 a.m. - Magnetohydrodynamics - Ralph A. Carabetta, Assistant Manager, Combustion Project Management Division

10:00 a.m. - Break

10:15 a.m. - Introduction to Characterization of Coals - Joseph Cavallaro, Chief, Coal Characterization Branch

10:30 a.m. - Benefits of Clean Coal for Combustion - Richard E. Hucko, Assistant Manager, Coal Preparation Division

10:45 a.m. - Combustion Technology Division Overview - James I. Joubert, Manager, Combustion Technology Division

11:00 a.m. - Combustion Test Facilities - George Bellas, Chief, Liquid Fuel Combustion Branch

11:15 a.m. - Coal Slurry Combustion Tests: Coal-Oil Mixtures, Coal-Water Mixtures, Coal-Alcohol Mixtures - Yuan-Siang Pan, Liquid Fuel Combustion Branch

11:45 a.m. - Lunch

12:15 p.m. - Fuel Rheology and Flow Characteristics - James M. Ekmann, Chief, Engineering and Technical Support Branch

12:45 p.m. - Pneumatic Transport of Coal - Mahendra P. Mathur, Engineering and Techical Support Branch

1:00 p.m. - Flue Gas Clean-up Technology - James I. Joubert, Manager, Combustion Technology Division

1:15 p.m. - Discussions

2:30 p.m. - Tour/Departure

CCAWG

PETC Combustion Program Review

Friday, March 19, 1982

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ATTACHMENT II: CCAWG WORK PLAN

A. Meetings for the Entire Working Group

1. May 27 and 28 in La Jolla, California, on "Preparation, Distribution and Utilization of Coal Slurries."

Preparatory work will be done by one or two members who will participate at the symposia on "Industrial Coal Utilization" (Cincinnati, April 1 and 2) and "Coal Slurries" (Orlando, May 10-12) and prepare status reports for discussions at the La Jolla meeting. The emphasis in this work will be on identification of technical and economic problems that are impeding commercial applications of coal-oil, coal-water, and coal-alcohol mixtures.

2. June 24 and 25 in Princeton, New Jersey on "Utilization of Pulverized Coals."

3. July 8 and 9 at the Morgantown Energy Technology Center on "Fluidized Bed Combustion, Modeling and Environmental Issues." Participants will be invited as appropriate from PETC and TVA.

4. October in the Eastern United States on "Stokers and Fixed Bed Combustors" at an industrial contractor.

5. December in La Jolla on "Long-Range Basic Research and MHD."

Additional work will be scheduled as needed.

B. Industry Members of CCAWG

Six members of CCAWG will be identified from industry as follows: one from EPRI, two from electric utilities, two from equipment manufacturers, and one from a service-type industrial organization. Alternate members from a given organization will be invited as appropriate. The names of nominees will be submitted by the Chairman of CCAWG to DOE for approval. The industry members are expected to become regular participants beginning with the May meeting in La Jolla.

Tentative rosters of names were discussed by the university members of CCAWG at Pittsburgh.

AB-2

CCAWG DISCUSSIONS AT LA JOLLA, (May 27 and 28, 1982)

1. Meeting Summary

CCAWG members S. B. Alpert, J. M. Beér, C. R. Bozzuto, I. Glassman, A. K. Oppenheim, S. S. Penner, L. D. Smoot, R. E. Sommerlad, C. L. Wagoner, I. Wender, and K. Yeager participated at parts or all of the meeting. DOE Headquarters was represented by ex officio CCAWG member J. Birkeland.

The meeting began with a review and evaluation of information derived from the "Fourth International Symposium on Coal Slurries." R. Kurtzrock of PETC presented a report on the "Status of Coal-Liquid Mixture Fuel Development" (see Appendix I), which was followed by a presentation of EPRI programs and plans introduced by K. Yeager and presented by R. Manfred of EPRI (see Appendix II). Next, L. D. Smoot reviewed past and current work on coal-water mixtures (CWM), with emphasis on studies performed at Brigham Young University (for details, see the paper in the Fourth Symposium). J. M. Beér discussed combustion studies at MIT on coal-oil mixtures (COM) and amplified the contribution made by his group at the Fourth Symposium (see Appendix III for details). The formal presentations were concluded with a paper by V. S. Engleman (Science Applications, Inc., La Jolla), which had been presented at the Fourth Symposium and dealt with a "conceptual design and economic analysis for coal/water mixture utilization in an oil-designed utility boiler."

The discussion on the following day involved in-depth program planning for future CCAWG meetings and evaluations of R&D requirements for the commercialization of COM and CWM, as well as assessments of the likely long-term commercial merits of these activities. These topics are discussed in Section 3.

2. Meeting Plans

CCAWG will meet on June 23 and 24 at Combustion Engineering in Windsor, Connecticut, with C. R. Bozzuto serving as host. This meeting will emphasize direct combustion of comminuted coal and will be followed by inspections of experimental facilities located at the host organization. A tentative meeting agenda will include the following presentations: a discussion of critical problems in utility operations using coal by a utility executive, R. Bryers (Foster-Wheeler Development Corp.) on ash formation and fouling, M. Jones (DOE, Grand Forks) on utilization of low-rank coals, K.Yeager et al (EPRI) on coal cleanup and beneficiation and on environmental controls, R. van Dolah (formerly of PETC and LETC and now a private consultant) on explosions and fires.

The subsequent CCAWG meeting will be held at METC on July 15 and 16. The agenda will be arranged by J. Birkeland and will include discussions of fluidized bed combustion, modeling, environmental issues, and other DOE-sponsored activities.

In view of the anticipated participation at the International Combustion Symposium (Haifa, Israel) during August by a number of CCAWG members, no formal meeting has been scheduled for CCAWG during August or September.

A meeting is tentatively scheduled for October 14 and 15 on industrial, non-utility applications of coal. The agenda will be defined by C. L. Wagoner, J. M. Beér, L. D. Smoot, and S. S. Penner and this meeting will be held in Columbus, Ohio, at Battelle or at Babcock and Wilcox in Alliance, Ohio, with C. L. Wagoner serving as host.

Subsequent meetings are tentatively scheduled for Houston, Texas, in conjunction with a conference on coal-handling and utilization equipment (December 9-10) and for La Jolla (January 1983).

3. CCAWG Discussions on the Utilization of Coal-Liquid Mixtures

Assuming that COM or CWM will enter the commercial markets, it is a relatively straightforward task to define R&D requirements for slurries of these types. These recommendations are summarized in Sections 3.1 and 3.2, respectively. Of equal concern are the crucial issues of costs and likely market penetration assuming that technological issues have been well defined and that application strategies are well in hand and allow reasonably reliable cost estimations. These topics are discussed in Section 3.3.

3.1 COAL-OIL MIXTURE COMBUSTION: R&D STATUS AND RESEARCH NEEDS*

Introduction

Sporadic use of coal-oil mixtures in marine boilers (tankers) and in blast furnaces has a history of several decades. In the mid-1960s, the Bethlehem Steel Co. and the National Coal Board-Esso carried out systematic experiments on the reheological properties of COM and demonstrated the technical feasibility of burning coal in the raceways of blast furnaces to replace expensive metallurgical coke partially by COM. The main objective was to use pulverized coal, the oil serving as a transport medium to permit the more convenient hydraulic feed-transportation system to be used in place of a pneumatic system. Combustion studies at the Canadian Bureau of Mines were the first to highlight the necessity of matching coal and oil combustion properties and showed wide ranging variations in carbon combustion efficiency when different types of coal were used. More recently, results of systematic combustion studies carried out at the DOE Pittsburgh Energy Technology Center have been reported in the four international symposia on COM combustion organized annually since 1978. These symposia are the main source of technical information on fuel preparation, rheological properties (stability, viscosity), atomization, and combustion of COM. Following an earlier demonstration experiment in a boiler at a General Motors Company Plant, which showed encouraging results for the use of COM in an industrial steam-raising plant, two major demonstration trials were carried out in utility plants by NEPSCO (80 MW_e) and by FPL (400 MW_e). These showed that long-term operation of utility boilers with COM is feasible after relatively small alterations to plants and requires little derating. These last conclusions are, however,

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*Prepared by J. M. Beér.

site-specific and depend on the original design of the retrofitted boiler.

COM Preparation and Handling

Successful introduction of COM into industrial use requires that the mixture be stable (i.e., the coal particles do not settle out over a period of weeks) and that the rheological properties be favorable (the mixture can be pumped and atomized). It is also desirable to increase the coal content as much as possible and to use particle sizes which do not require excessive grinding energy for their preparation.

The relationships between these variables show that good stability and favorable rheological properties have conflicting requirements. Thus, the stability improves but the viscosity of the mixture increases with increasing coal concentration, finer particle sizes and increasing oil viscosity. Additions of small amounts (up to 5%) of water and about 1% of surfactant can produce an acceptable solution, e.g., 50 wt% coal ground to a fineness usual in power station practice (80% <76 μm).

The mechanism of COM stabilization is poorly understood. The action of the chemical additives is explained by their effects on electrostatic, steric and flocculated networks in the fluid but the relationships between additive properties and COM stability are, at best, semi-empirical. Improved understanding in these areas is desirable.

COM with less than 40% coal concentration and without water behaves as a Newtonian fluid; COM is pseudoplastic for higher coal concentrations. For these latter conditions, the shear stress τ can be expressed as $\tau = k\dot{\gamma}^n$, where $\dot{\gamma}$ is the shear rate (sec^{-1}) and $n < 1$.

Water and additives influence the k and n values; higher k values are associated with improved stability. The smaller the value of n, the lower the viscosity under flow conditions.

Additive selection and optimization of concentrations of water and additives are determined from optimizations involving k and n.

Storage, Pumping, Flow Metering

Stirred storage tanks and special positive displacement pumps and flow-metering devices for handling COM are commercially available. R&D is needed in this area for design optimization of stirred tanks, for increasing availability of pumps, and for further development of the presently available mass-flow metering devices.

Atomization

High atomization quality (i.e., sufficiently fine atomization with a minimum of droplets in excess of 300 μm) is a prime requisite of good COM combustion and reduced slagging tendency in the combustion chamber. In liquid-fuel atomizers, the fluid is forced by high pressure through orifices and thin liquid sheets are formed which, as the result of development of Rayleigh-type instabilities, break down into ligaments that disintegrate into droplets due to surface-tension forces. An exception to this mechanism of liquid break-up occurs in some mechanical atomizers (rotary cups) in which the liquid sheet is formed on the surface of a fast-spinning disk or cup and its break-up is assisted by impinging high-velocity air.

An important engineering problem in COM atomization lies in the high viscosity and abrasive nature of the fuel. High-velocity flows through nozzles are required to produce fine atomization and may cause unacceptable rates of erosion. The use of special materials in atomizing nozzles has been shown to lead to reduced metal wastage and hence increased atomizer life. The alternative solution, i.e., relaxation of atomization quality, is unacceptable since it leads to high solid carbon carry-over. Studies of atomization in COM require a significant R&D effort.

Improved atomizers should be developed through a better understanding of the physical processes involved and through use of special materials for the structural parts exposed to erosion. Parallel with these fundamental studies, a semiempirical approach to design, coupled with experimental testing of nozzles, will be necessary for early development of improved and acceptable atomizer nozzles. Atomizers should be developed which maintain high atomization quality over a period approaching 1000 hours, before the changing of atomizer tips will become economically and operationally acceptable.

Combustion and Pollutant Emissions

The combustion of COM in an industrial type turbulent diffusion flame is dominated in the near field (i.e., close to the burner) by characteristics of the oil flame and by the burn-out of the residual coal char towards to end of the flame (far field). Single COM droplet studies have shown that COM droplets ignite more readily than oil drops, perhaps because of increased absorptivity to thermal radiation caused by the presence of the solid particles. If a bituminous coal is used, its thermal decomposition commences while the particles are still surrounded by the liquid phase. The high molecular weight tars which evolve from the coal are partially extracted by the oil, and the coal particles swell and produce an agglomerate. On the termination of oil combustion, a solid or carbonaceous residue is left, which encloses the partially devolatilized coal char particles. As oxygen reaches the surface, the temperature of the char agglomerate is raised, causing further evolution of coal volatiles and an increase of pressure; the carbon surface becomes spherical and, eventually, this cenosphere ruptures to permit the volatiles to escape through a blow-hole. The char cenosphere burns out in the tail end of the flame where the temperature is high but the oxygen concentration is low due to the prior combustion of oil and the coal volatiles.

Flame stability obtainable with COM fuel is so good that the recirculation of hot combustion products to the burner could be reduced. Some reduction of recirculation is highly desirable. Otherwise, the combination of resulting high temperature close to the burner and the possibility of carbon (from unburned fuel) becoming embedded in the wall deposit can cause serious slagging problems.

The atomization quality has to be high because the sizes of the char cenospheres are close to those of their parent droplets and their burning time follows Nusselt's square law, i.e., the burning time is proportional to the square of the initial particle diameter.

It is expected that the NO_x emission from COM will be somewhat higher than from oil alone, mainly because of the increased fuel nitrogen content of the COM. However, the staged combustion nature of COM, which involves coal-nitrogen evolution in an atmosphere in which the O_2 has been strongly depleted, tends to reduce the NO_x emission. NO_x emission has been shown to respond sensitively to the variation of the overall excess air.

The emission of sulfur will depend on the compounded sulfur contents of coal and oil in the mixture. Sulfur reduction is an important consideration in coal preparation, because sufficiently low sulfur content of the fuel may lead to arrangements with the EPA for permission to operate without flue-gas desulfurization.

The particulate emission from COM combustion will be higher than from oil burners. It is most likely that the EPA will require compliance with present emission standards for retrofitted oil-fired boilers.

The flame emissivity is increased by coal particles and enhanced radiative heat transfer from the flame is expected. This process, however, does not produce increased heat transfer in the combustion chamber because of the insulating effect of the ash-slag deposit on heat-exchanger surfaces. In FPL demonstration experiments, the flue gas volume had to be increased because of higher excess air requirements for complete combustion and this, together with reduced heat transfer in the combustion chamber, resulted in a higher proportion of the enthalpy of the flue gas being carried into the convective superheater section of the boiler. More research is needed on radiative heat transfer in a partially slagged-up combustion chamber to determine the full implications of these factors upon the distribution of the thermal load over the radiative-convective parts of the boiler.

Transformations of Coal Ash

Perhaps the most sensitive area of COM combustion technology is the slagging of the combustion chamber due to the deposits of partially molten ash and the carry-over of molten fly ash particles into the convective heat exchange section of the boiler. Due to the rapid temperature rise after ignition, slagging can be heavy near the burner unless special care is taken to reduce the recirculation of hot combustion products. Large droplets and coal particles may reach the walls and become embedded in the ash deposit, thus causing the fluxing of the molten slag and attack of the slag on the protective oxide film on the heat-exchanger tube surface.

Research is needed to improve our understanding of the transformations that the mineral matter in the coal undergoes in the combustion process and in the wall deposit and also to predict the physico-chemical properties of the fly ash from knowledge of the coal ash composition and of the concentration-temperature history of the ash. Such information would serve not only the designers and operators of boilers and furnaces but could guide the industrial development of coal beneficiation as well.

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3. Y. S. Pan, "Effect of Coal Particle Size Consist on the Performance of a COM-Fired Boiler," Proc. Third International Symposium on Coal-Oil Mixture Combustion, FL, April 1981.

4. A. Brown, "Final Report on the General Motors Corporation Powdered Coal-Oil Mixture (COM) Program," DOE Report FE 2267-2, U.S. Department of Energy, Washington, DC, October 1977.

5. N. H. Cherry and C. C. Stokes, "Use of Dielectric Properties in the Determination of COM Stability," Proc. First International Symposium on COM Combustion, St. Petersburg, FL, April 1979.

6. G. D. Botsaris, Y. M. Glasman and M. Adams-Viola, "Characterization and Structure Studies of Various Types of COM," Proc. Second International Symposium on COM Combustion, Danvers,MA,April 1980; J. M. Eckman and D. Bienstock, "The Role of Cole and Oil Characteristics on the Stability of COM," ibid.

3.2 STATUS AND NEEDS FOR COMBUSTION-RELATED RESEARCH ON COAL-WATER MIXTURES (CWM)*

Introduction

Coal-water mixtures (CWM) represent a relatively new area of combustion application. The major interest in CWM is for replacement of oil in existing utility and industrial boilers. With declining interest in coal-oil mixtures, resulting principally from low economic incentive, interest in CWM has increased, particularly in the U.S., Sweden, Canada, and Japan.

The 4th International Symposium on Coal Slurry Combustion[1] has afforded a good review of the status of CWM technology. Of the 93 papers presented, approximately one-quarter dealt with CWM; of these, about 13 were on slurry formation and handling, 1 on atomization, 6 on combustion, and 3 on systems evaluations. Not all of the authors reported experimental results. For example, only three of the combustion papers (from PETC, ARC and B&W) showed combustion data for pulverized coal-water mixtures.

To date, no major technical problems have been encountered in the use of CWM. However, work in this area is new and it will require about 3 years to establish a sufficient data base to evaluate the potential of CWM critically. This technical area is related to coal-slurry transport, slurry-fed gasification, and combustion of high-moisture coals.

CWM Preparation/Handling

About 11 industrial organizations are developing CWM for possible commercial use. Six have developed methods and equipment (pilot plants) for the production of CWMs in the 75-120 tpd capacity range . The presently available technology suggests that optimal mixtures contain about 70% coal and 30% water. The blended

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*Prepared by L. D. Smoot.

coal particles generally cover a range from small to large sizes. It is customary to use small percentages (1-2%) of additives for the control of viscosity and settling. Claims are made that mixtures are stable for significant periods of time (e.g., one month). Independent research (e.g., Eckmann[3]) is being conducted on rheological properties of CWM.

Identified research needs in this area include the following:

1. Optimization of CWM, including definitions of particle-size distributions for particulate coal loadings, the use of additives, and the resulting mixture stabilities.

2. Incorporation of beneficiated coal through fine grinding (micronization) for reductions in ash level. This procedure is being applied to reduce ash levels to 3%.

Work is continuing in the private sector and with EPRI and DOE support.

Atomization and Dispersion

Extensive research has not been performed on atomization rates of water in dispersions of coal in CWM. Only one paper on this subject (from BNL) was presented at the 4th International Symposium and this discussion referred to coal-loading levels well below practically achievable levels. Workers at DOE/PETC have recently initiated sponsored research in this area (Carnegie-Mellon University). The efficiency of coal burnout, fouling, and NO_x pollutant formation are all related to droplet atomization, particle dispersion, and the combustion processes. Atomization studies and the associated CWM nozzle designs have been considered in CWM combustion by workers at PETC and ARC. Commercially available nozzles were frequently used in these early combustion studies.

Key research needs on atomization and dispersion include the following:

1. Determinations of variables such as mass flowrates, pressure levels, and nozzle configurations that control the droplet-size distributions and the droplet and dust-particle dispersions. Relationships must be established between particle-size distributions and droplets formed on injection. The CWMs should cover the ranges of solids loadings, coal sizes and distributions, and additives that are of practical interest.

2. Determination of the relations between nozzle designs, secondary air-flow patterns, and mixing rates in CWM for the purpose of optimizing burner designs.

These studies will have to be closely linked with the combustion studies defined in the next section. Work on optimum nozzle design is in progress at CE and other laboratories, with and without external support.

CWM Combustion

Early investigations of the combustion characteristics of pulverized CWMs were performed at ARC,[2] PETC,[4] and EPRI/B&W.[5] It is apparent from this work that pulverized coal can be burned with high percentages of water. Coal burnout levels up to 98% have been reported and CWMs containing up to 70% of coal have been tested. PETC tests were conducted in 100 hp and 700 hp water tube boilers with up to 63% coal in the CWM. In the smaller unit, carbon conversion up to 85% was achieved while, in the larger unit, carbon conversion up to 96% was obtained with the use of surplus secondary air.

The ARC[2] investigations on CWM involved coal percentages up to 65% in a small laboratory furnace (10^6 BTU/hr). Carbon conversion levels up to 90% were reported. More recent tests[6] have shown combustion efficiencies up to 95% with 70% CWM in the small-scale furnace.

Investigations of CWM combustion are also underway at MIT and BYU. These latter studies will provide details concerning the flame structure. Plans for larger scale testing of CWM in a utility boiler have been outlined by workers at EPRI and at DOE/PETC/CE.

While early results are encouraging, much work remains to be done to provide a suitable data base for quantitative modeling. Important research needs include the following:

1. Measurements of combustion rates, fouling, and pollutant-formation characteristics of practically usable CWMs, including higher coal solids levels, use of beneficiated coals with low ash contents, and effects of additives. Of particular importance are adequate flame stability, control of nozzle erosion, much higher carbon conversions (>99%), and post-combustion controls of ash and NO_x levels.

2. Determination of the optimum burner configurations for CWMs remains to be accomplished.

3. Demonstration of successful, long-term operation of CWMs in large-scale, oil-designed utility boilers, with emphasis on slurry mixture stability, flame stability, fouling and ash control, nozzle erosion, high carbon conversion, boiler derating, and moderation of NO_x levels. This applied task must be performed successfully before commercial applications of CWMs can be considered.

There are many unresolved fundamental research questions that relate to implementation of CWM technology. These include the behavior of dispersions of condensed phases in turbulent media, droplet formation and evaporation in three-phase flows, devolatilization processes of wet coals, turbulence in swirling multiphase flows, and others.

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5. G. A. Farthing, Jr., S. A. Johnson, and S. J. Vecci," Combustion Tests of Coal-Water Slurry," CS-2286, EPRI Final Report, Palo Alto, CA, March 1982.
6. R. S. Scheffee et al., "Further Development and Evaluation of Coal-Water Mixture Technology," in Ref. 1.

3.3 GENERAL REMARKS ON THE ECONOMICS OF INTRODUCING NEW TECHNOLOGIES INTO UTILITY OPERATIONS*

A plot plan of a typical, large, coal-fired power plant is shown in Fig. 1. Space has been allowed for a second unit (right hand side of the page). If this space is subtracted from the total, we can approximate the space requirements for one unit. Rail lines surround the plant and parking lots; security fences, guard shacks, administration buildings, and the like are not shown.

The space required for boiler unit one with precipitators and scrubbers is about 14% of the total space. The waste-treatment facilities shown at this site assume that major ash and sludge disposal is made off-site. If a 20-year ash/sludge disposal area were on-site, it would be at least double the area of the coal pile. In general, when we consider alternative, coal-fired, power generation, we are considering changing the equipment within this 14% enclosure.

The Federal Energy Regulatory Commission (FERC) uses a code of accounts to tally direct costs. These account numbers can be further broken down to provide the level of detail needed by an A/E company to carry out a major project. For government projects (TVA, DOE, DOD, etc.), the FERC code of accounts is generally used. However, each A/E firm may have its own internal account system. This fact causes considerable confusion when discussing costs. For example, the feedwater system can be allocated to the turbine or to the boiler. Boiler manufacturers prefer to allocate the feedwater system to the turbine because it is not in their scope of supply. However, the FERC code of accounts allocates the feedwater system to the boiler plant. Hence, the cost of the boiler plant may mean different things to different people.

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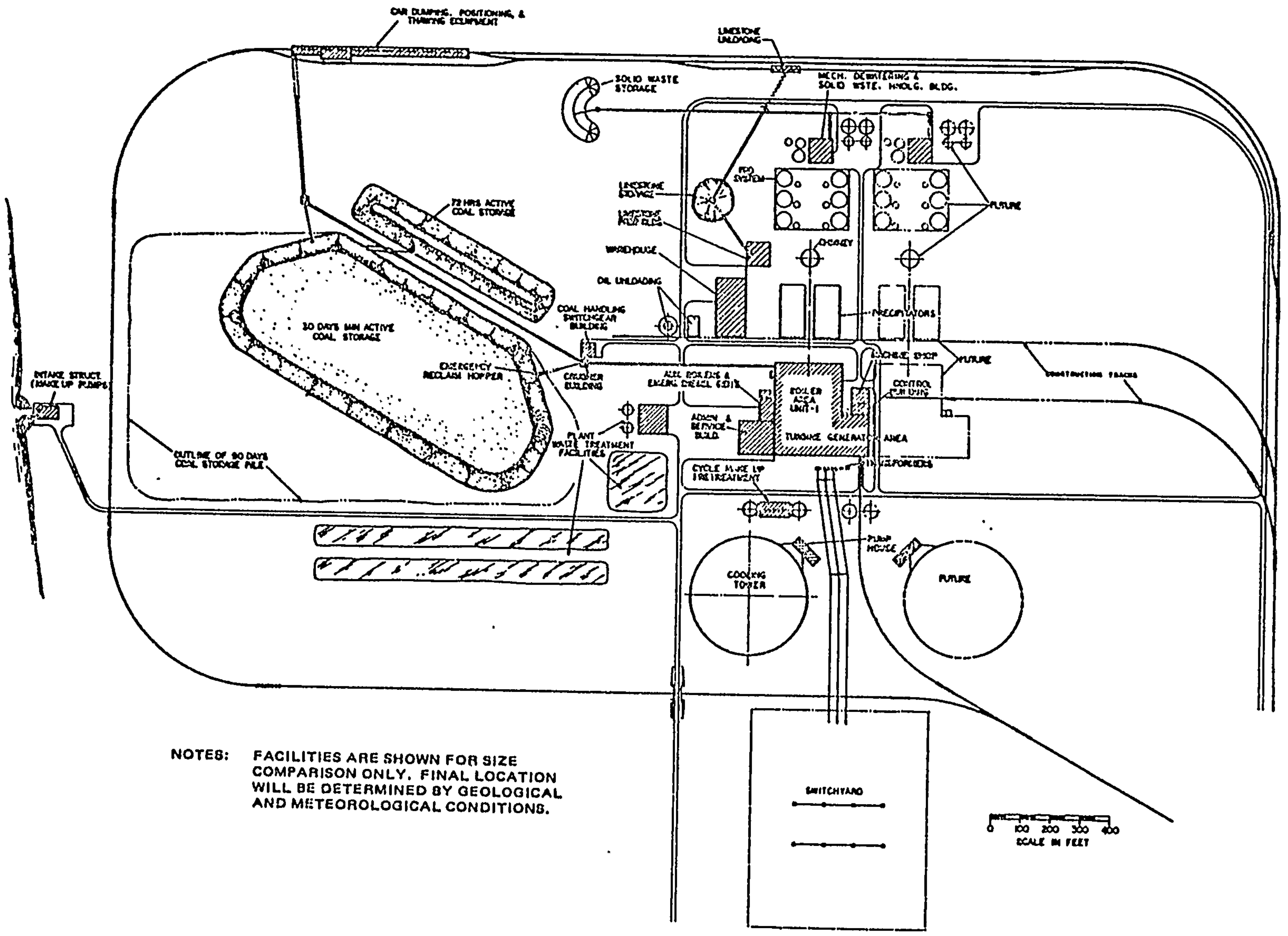
*Prepared by C. R. Bozzuto.



NOTES: FACILITIES ARE SHOWN FOR SIZE COMPARISON ONLY. FINAL LOCATION WILL BE DETERMINED BY GEOLOGICAL AND METEOROLOGICAL CONDITIONS.

Fig. 1 Plot showing a large, coal-fired power plant.

Using the FERC system, the capital costs are broken down in $/kW as follows:

Account No.	Item	Cost	(mid-81, $/kW)
310	Land and Land Rights	3	
311	Structures and Improvements	73	
312	Boiler Island, including Cleanup and Coal Handling:	430	
	- Boiler		100
	- Gas Cleanup		100
	- Coal Handling		100
	- Piping & Steam System		65
	- Mech. Equip., Auxiliaries, Feedwater System, Ash System, Draft System		65
314	Turbogenerator Set	170	
315	Electrical and Switchgear	40	
316	Misc. Station Plant & Equip.	14	
		730	
A/E fees, interest, contingency, etc.		230	
		960	
Working capital		40	
	TOTAL	1000	

These figures are approximate only and final estimates are site-specific. Nonetheless, a review of these figures shows that the majority of the power plant costs will be fixed, as long as coal firing is employed. In going from pulverized coal to fluidized beds to gasified coal to MHD, basically only the boiler and gas-cleanup system are changed. The remaining items are largely fixed and dependent upon the amount of coal fired. Typically, these fixed costs amount to some $800/kW. Clearly, some money must be spent on equipment that replaces the boiler and gas cleanup. Within reason, this figure should be $200/kW (±30%). Thus, all coal-fired plants cost $1000/kW (±6%) in mid-1981 dollars. It is easy to see why utilities are reluctant to build plants with new technology. Capital cost savings are at best very small. Therefore, only operating cost reductions can be hoped for. However, how can one expect to get real operating savings with unproven equipment? Any reduction in capacity factor will basically result in an operating loss. Therefore, it is much more prudent to stick with known technology than risk chasing elusive operating gains based on unproven assumptions.

Nuclear plants cost $1500/kW within 10%. About $100/kW is the cost of the initial fuel load, within 10% accuracy. Assuming that the cost of the first load is included (approximately 2 operating years of fuel), then about $87/ kW could be substracted from the nuclear plant to put it on a 90-day fuel basis. However, since the core is normally maintained with a full load of fuel, it is proper to treat the fuel load as required working capital (just like the 90-day coal pile) and, hence, no subtraction is necessary.

The overall plant economics are then dependent upon a number of assumptions such as the fixed charge rate, fuel cost, capacity factor, heat rate, etc. Some typical assumptions follow:

Fixed Charge Rate -	18.2 - 25.6%, depending on interest rates and tax laws
Fuel Costs (levelized for 30 yrs) -	$3.00 - 4.00/MM Btu for coal, $1.70/MM Btu for nuclear energy, $10.00/MM Btu for oil & gas;
Capacity Factor (levelized) -	70%
Heat Rate -	9,500 Btu/kW-hr for coal, 10,500 Btu/kW-hr for nuclear energy, 9,000 Btu/kW-hr for oil & gas.

On the basis of these figures, the following capital and fuel charges are derived in mills/kW-hr:

	Coal	Nuclear	Oil
Capital Charges	41.75	62.62	25.05
Fuel Costs	28.5 (38.0)	17.85	90.00
O&M	8.0	5.00	5.00
COE	78.25(87.25)	85.47	120.05

It is instructive to examine the preceding costs. They show that, on the average, coal is cheaper than nuclear energy except where coal costs are high (e.g., New England). Oil prices would have to drop by about a factor of two for new oil-fired units to be competitive. Capital represents about half the cost of electricity (COE) in the case of coal. For oil, fuel is about 75% of the COE, which accounts for the high fuel adjustment charges in New England (especially in Massachusetts). It is significant to note that no nuclear units and no large oil- or gas-fired units have been ordered in the U.S. since 1975.

Referring to Fig. 1, coal is delivered by rail to the site where it is dumped, thawed (if necessary), and transported to the coal pile. About 6000 T/day must be delivered for each 500 MW(e) unit; this corresponds to about 60-100 cars per day. Coal from the pile is conveyed to a crushing station to reduce the size to 1-1/2"x0 so that the coal can enter a pulverizer. The coal is then transported to the pulverizers, where it is ground to 70% through 200 mesh and dried. The pulverized coal is conveyed pneumatically by using a mixture of 1 lb of air per lb of coal to the boiler. The mixture is injected through fuel nozzles and mixed with secondary air, which is at a higher preheat temperature. The majority of the coal is burned out in the radiant portion of the boiler. The flue gases then pass over a convective surface, hopefully at a temperature low enough to avoid fouling or corrosion. When the gas is cooled to about 750°F, it is used to preheat air. The flue gas is next cooled to about 300°F. It is finally subjected to particulate removal, which is followed by SO_2 removal. The cleaned flue gas is then routed to the stack. Some flue gas reheat may be necessary to protect fan and stack equipment. Typically, a 175°F stack temperature is sufficient. Ash is collected from ash hoppers at several boiler locations and from the particulate removal system. It can be mixed with sludge from the web scrubber system for stabilization or may be disposed of separately.

Water is taken from the condenser and pumped through various feedwater heaters and a deaerator to the economizer section of the boiler. This procedure preheats the water to a temperature near to but less than the boiling point. The water is then transported to a steam drum, where it is mixed with the water-steam mixture that is circulating within the waterwalls of the boiler. In the steam drum, steam is separated from the water and sent on to the superheater. The water is recirculated to the lower headers of the waterwalls. Because this water absorbs heat, steam is formed, thus creating a steam-water mixture that rises to the steam drum. The superheated steam is sent to the steam turbine, where a part of its enthalpy is recovered. The steam is now at a lower temperature and pressure and is returned to the boiler to be reheated. The reheated steam is returned to the turbine for final conversion to shaft work. Exhaust steam is condensed by cooling water in the condenser. Steam may be extracted from the turbine at various points to heat feedwater. This practice serves to improve cycle efficiency by routing a portion of the working fluid around the condenser. The cooling water is sent to a cooling tower to reject its heat to the atmosphere.

The maximum Carnot efficiency for such a plant, using 1000°F steam and 120°F cooling water, is about 60%. In actual practice, about 38% efficiency is achieved because of stack losses (10-12%), mechanical efficiency of the turbine (88%), electric generator efficiency (97%), auxiliary power requirements (10-12%), and environmental cleanup and other losses (4-8%).

The principal areas of interest to utilities today center on reducing operating costs by improving reliability and availability, reducing auxiliary power requirements, and reducing environmental costs. A significant period of time is required to demonstrate effects on reliability or availability.

A. Comments on Market Penetration*

The preceding discussion represents a good summary of the problems involved with market penetration of improved technologies. Utilities cannot afford to pioneer innovations. New technologies will enter the utility market only after (a) favorable economic assessments have been completed and (b) a large-scale, commercial prototype has been adequately tested, either with federal support or through a joint venture involving an industry consortium (e.g., EPRI). While step (a) has been achieved for CWM but appears doubtful for COM, step (b) remains to be implemented for CWM.

It should be noted that other views and procedures determine market policy in other countries. Thus, in Japan, rates of return are determined from a 25-year perspective for the benefit of the country (not for the benefit of a single industry) and private companies, in cooperation with MITI, pioneer technological assessments (step b). The logical implementation of the indicated U.S. procedures for market penetration has led to non-competitive U.S. steel and automobile production facilities, among others.

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*Prepared by S. S. Penner.

3.4 COAL-AIR MIXTURES[*]

In the retrofitting of oil-burning utility power plants for the use of coal, COM and CWM have found the greatest interest due to what many consider a primary advantage of tank-car delivery of the coal fuel. Such tank-car delivery eliminates the requirement for extensive land use for the storage of raw coal. COM and CWM impose combustion problems and/or loss in plant efficiency that may override the advantage of coal displacement of the oil used. It would appear that the best fluid for transmitting pulverized coal, the same as that used in COM and CWM, would be air and I term this mixture CAM. The finely divided (pulverized) coal could be shipped in the same type of tank cars as those proposed for COM and CWM. A system could easily be developed to transfer the tank-car coal to a simple hopper, which could feed an airstream at a regulated rate. This CAM would then pass through injection nozzles much the same as those used for oil alone. Fundamentally, one would believe CAM should burn extremely well and require practically no modification, other than perhaps injection nozzle design, to an oil-fired power plant. The system poses one major difficulty and that is one of safely transporting and handling finely-divided coal. Great amounts of grain and flour are transported and handled in this country, far more than would be anticipated for CAM. Indeed, grain and flour explosions are known; however, these materials are far more prone to spontaneous or accidental ignition than coal. Nevertheless, the safety aspects of transporting and handling very finely divided coal must be considered. This type of possible coal explosion should be the object of research and reasonable solutions could undoubtedly be found. In fact, such solutions may be simpler to find than the combustion and other problems that COM and CWM pose.

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[*] Prepared by I. Glassman.

A. Comments on the Proposal for Coal-Air Mixtures (CAM)[*]

The following comments refer to CAM. First of all, it must be understood that CAM will not solve the problems of retrofitting oil and gas fired units to coal. These units are inherently not suited to handling solids of any kind. The furnace volumes are too small, the tube spacings too close, and the ash handling equipment non-existent. Therefore, all the problems of downrating and substantial boiler modifications would still be present with CAM. In addition to these problems, there are safety problems which, while solvable, add to the cost of this fuel.

For new plant applications, the suggestion of CAM is workable. Coal has been distributed in the past in containers and continues to be distributed this way in the UK for small applications. However, large powerplants use conventional pulverized coal firing. In order for delivered fuel to be practical for a new utility plant, it must have the following attributes: (1) it must be low in sulfur (i.e., sufficient to meet all regulations), (2) it must be low in ash and moisture, (3) it must have guaranteed delivery so that on-site storage is not required, (4) it must be accompanied with guaranteed ash disposal from the site so that no ash ponds or other disposal facilities are required, and (5) it must be safe. A fuel with these attributes would save the utility the cost of the scrubbers, coal pile, coal handling, ash disposal, and limestone. These savings would allow for a price differential of up to $1.00/MM Btu on fuel costs. Present day coal prices are in the neighborhood of $1.50/MM Btu. Thus, a clean fuel costing $2.50/MM could be competitive. This amounts to producing a clean fuel (such as oil) for about half the price of oil. By way of example, SRC-I would have the above five attributes but costs about

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[*] Prepared by Carl R. Bozzuto.

twice as much as oil. Indeed, oil itself is uneconomical today for new powerplant applications.

As each of the restrictions imposed by the five attributes is eased, the utility plant costs go up and the full cost differential becomes less. If we were to assume that pulverized coal is delivered without treatment or guarantees, the system would be uneconomical because the utility still must buy 90-day storage, SO_2 scrubbers, handling equipment, ash-disposal ponds, limestone, sludge disposal, and safety equipment. In addition, the distributor must buy equipment and make a profit. Therefore, such a system would not be economical and I would see no point in recommending any research on it.

Appendix I

STATUS OF COAL-LIQUID MIXTURE FUEL DEVELOPMENT

by R. Kurtzrock (PETC)

GENERAL

- CANADIAN GOVERNMENT HAS IDENTIFIED COAL-LIQUID MIXTURE TECHNOLOGY DEVELOPMENT AS A PRIORITY FOR FUNDING UNDER THEIR NATIONAL ENERGY PROGRAM (NEP).
- JAPAN AND SWEDEN HAVE TAKEN A SIMILAR POSITION WITHOUT SPECIFIC STATEMENTS.
- U.S. POSITION IS SOMEWHAT NEBULOUS BASED ON BUDGET REQUESTS FOR FY 1983.

STATUS OF COAL-LIQUID MIXTURE FUEL DEVELOPMENT

COAL-OIL MIXTURES (COM)

- COM IS AN ALMOST COMMERCIAL FUEL (SWEDEN). DEMONSTRATIONS IN A NUMBER OF COUNTRIES.
- LONG TERM EFFECTS ON BOILERS ARE STILL UNKNOWN.
- COUNTRIES IMPORTING BOTH OIL AND COAL (JAPAN) CAN REDUCE THEIR OIL DEPENDENCE BY USING COM.
- COM WILL PROBABLY NOT SEE ANY SIGNIFICANT APPLICATION IN THE U.S. UTILITY INDUSTRY.
    - BREAK EVEN POINT FOR COM WITH FLORIDA POWER & LIGHT CO. IS $31/BBL; CURRENT PRICE OF FUEL OIL IS $26/BBL.
- INDUSTRIAL APPLICATION OF COM IS NOT PREDICTABLE; BLAST FURNACES WILL BE ONE OF THE FIRST USERS.
- CANADA WILL NOT USE A FUEL MIXTURE CONTAINING FUEL-OIL IN UTILITY BOILERS, HOWEVER IT APPEARS LIKELY COM WILL BE USED IN INDUSTRIAL BOILERS.
- MOST COST ESTIMATES BY SUPPLIERS OF COM INDICATE A FUEL COST SAVING OF APPROXIMATELY 10% OVER THAT OF NO. 6 FUEL OIL.

STATUS OF COAL-LIQUID MIXTURE FUEL DEVELOPMENT
(continued)

COAL-WATER MIXTURES (CWM)

- "COAL OUTLOOK" (MAY 17TH) SAYS A MID-COURSE SHIFT FROM COM TO CWM IS TAKING PLACE.
- AN ADEQUATE DATA BASE SHOULD BE AVAILABLE IN 3 YEARS OR LESS.
- SIX SLURRY DEVELOPERS HAVE PILOT PRODUCTION FACILITIES OPERATING OR WILL BE OPERATING SOON. PRODUCTION CAPACITIES RANGE FROM 25 TONS/DAY TO 120 TONS/DAY.
- ASH EFFECTS ARE THE KEY TO SUCCESSFUL APPLICATION OF CWM.
  - SLAGGED DEPOSITS IN COMBUSTION ZONE.
  - EXTENSION OF COMBUSTION ZONE BY BURN-OUT TIME.
  - CONVECTION PASS EROSION AND/OR FOULING.
- BENEFICIATED COAL.
- ULTRA FINE GRINDING OF COAL.

CURRENT DOE ACTIVITIES IN CWM DEVELOPMENT

- ENGINEERING ASPECTS
  - COMBUSTION & FUEL CHARACTERIZATION (COMBUSTION ENGINEERING)
  - EQUIPMENT SELECTION & PERFORMANCE (TRW, INC.)
- FUNDAMENTAL R&D

COMBUSTION AND FUEL CHARACTERIZATION

Scope of Work

- Selection of Candidate Fuels
  - —Selection of Candidate Coals
  - —Acquisition of Beneficiated Coals
  - —Selection of Candidate CWM's
- Bench Scale Characterization and Screening Tests
  - —Bench Scale Properties
  - —Secondary Fracturing of CWM Particles
- CWM Preparation and Test Slurry Supply
  - —Coal Acquisition
  - —Beneficiation of Test Coals
  - —CWM Preparation
  - —Storage
- Combustion Evaluation/Atomization and Burner Testing
  - —Commercial Burner Selection
  - —Initial Burner Evaluation
  - —Secondary Burner Evaluation
  - —CWM Combustion Characterization
- Ash Deposition/Performance Testing
  - —Facility Requirements
  - —Facility Shakedown and Baseline Oil Testing
  - —CWM Performance Testing

(Continued)

COMBUSTION AND FUEL CHARACTERIZATION

- Commercial Application and Performance Prediction
    - Selection of Typical Oil-Designed Units for Evaluation
    - Boiler Performance Evaluation Firing Oil
    - Performance Evaluation Firing Several CWM's
    - Identify Required Modifications
    - Economic Trade-Off Studies

PLANT EQUIPMENT SELECTION AND PERFORMANCE

Scope of Work

- Facility Modifications
  - Preliminary Design
  - Final Design
  - Equipment Selection
  - Instrumentation
  - Equipment Installation and Test Loop Checkout
- Slurry Selection and Supply
  - Selection of Slurry for Hydraulics/Screening Tests
  - Slurry Selection for Long-Term Testing
  - Slurry Supply
- Test Operations and Data Collection
  - Screening Test Plan
  - Screening Test Operations
  - Long-Duration Test Operations
  - Equipment, Component, and Piping Evaluation
  - Slurry Degradation Evaluation
  - Erosion/Corrosion Evaluation
  - Hydraulic System Tests
  - Data Collection and Reduction
- Data Analysis and Reporting
  - Slurry Degradation Analysis
  - Hydraulics Analysis
  - System/Component Evaluation
  - Corrosion/Erosion Evaluation
  - Full-Scale, CWM-Fired Boiler Applications Assessment

FUNDAMENTAL R&D

SLURRY RHEOLOGY

CARNEGIE-MELLON UNIVERSITY

RHEOLOGY OF COAL-WATER MIXTURES

- MEASURE RHEOLOGY, STABILITY, ELECTRO KINETIC BEHAVIOR
- "PURE" SLURRIES, INORGANIC AND ORGANIC ADDITIVES

SLURRY HANDLING

PETC

TRANSPORT CHARACTERISTICS OF COAL-LIQUID MIXTURES

- PRESSURE DROP MEASUREMENT AND CORRELATION
- LABORATORY MEASUREMENTS
- INSTRUMENT EVALUATION

ATOMIZATION

CARNEGIE-MELLON UNIVERSITY

ATOMIZATION OF COAL-WATER MIXTURES

- PRESSURE, TWO-FLUID, ROTATING CUP ATOMIZER
- MECHANISMS OF DROPLET FORMATION
- DROPLET SIZE AND VELOCITY MEASUREMENTS

COMBUSTION/CHAR BURNOUT

JOHNS HOPKINS
APPLIED PHYSICS
LABORATORY

COMBUSTION OF COAL-WATER MIXTURE DROPLETS

- MONODISPERSE DROPLET ARRAY
- EFFECTS OF PARTICLE SIZE, DROPLET SIZE, TEMPERATURE, HEAT FLUX
- PHOTOGRAPHIC OBSERVATIONS

BRIGHAM YOUNG
UNIVERSITY

COMBUSTION CHARACTERISTICS OF COAL-BASED FUELS

- PYROLYSIS CHARS AND COAL-WATER MIXTURES
- DETAILED COMBUSTOR MAPPING
- RESULTS EMPLOYED FOR MODEL IMPROVEMENT

JET PROPULSION
LABORATORY

"CATALYTIC" COAL COMBUSTION

- EXTENSION OF GRAPHITE COMBUSTION TECHNOLOGY
- CALCIUM, POTASSIUM, LITHIUM, ACETATES
- TREATMENT METHODS
- COMBUSTION TESTS FOR BURNING RATES AND EMISSIONS

PYROLYSIS/DEVOLATILIZATION

ADVANCED FUEL
RESEARCH

DEVOLATILIZATION AND PYROLYSIS OF COAL BASED FUELS

- COAL-WATER MIXTURES AND HIGHLY CLEANED COALS
- FLOW REACTOR
- IN-SITU APPLICATION OF FTIR
- EMPHASIS ON PYROLYSIS CHEMISTRY
- APPLY DATA TO UPGRADE EXISTING MODEL

POLLUTANT FORMATION/REDUCTION

ENERGY &
ENVIRONMENTAL
ENGINEERING

SULFUR CAPTURE IN COAL-WATER MIXTURES

- Ca FIXATION TECHNIQUES
- COMBUSTION EXPERIMENTS
- MODEL SULFUR CAPTURE

AB-2

Appendix II

by R. Manfred (EPRI)

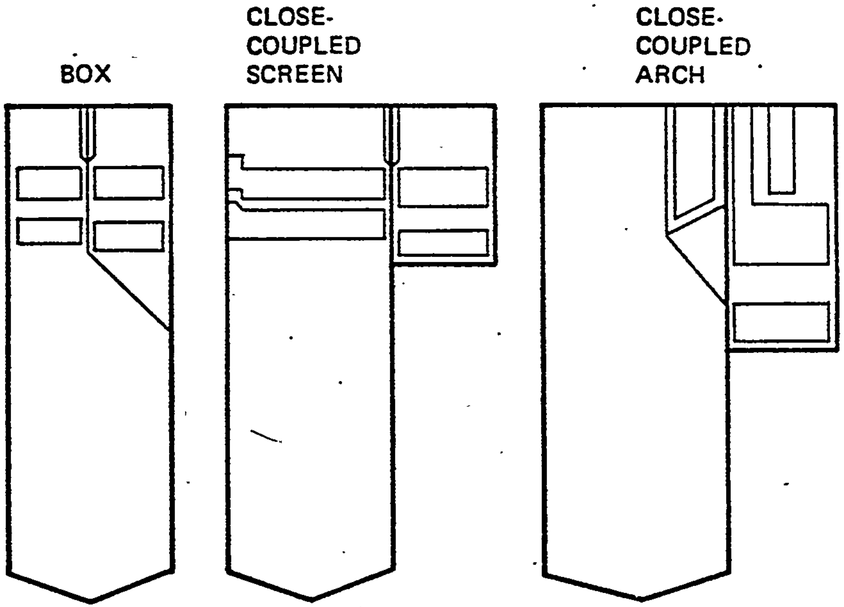


Figure 2-1 STUDY BOILER CONFIGURATIONS

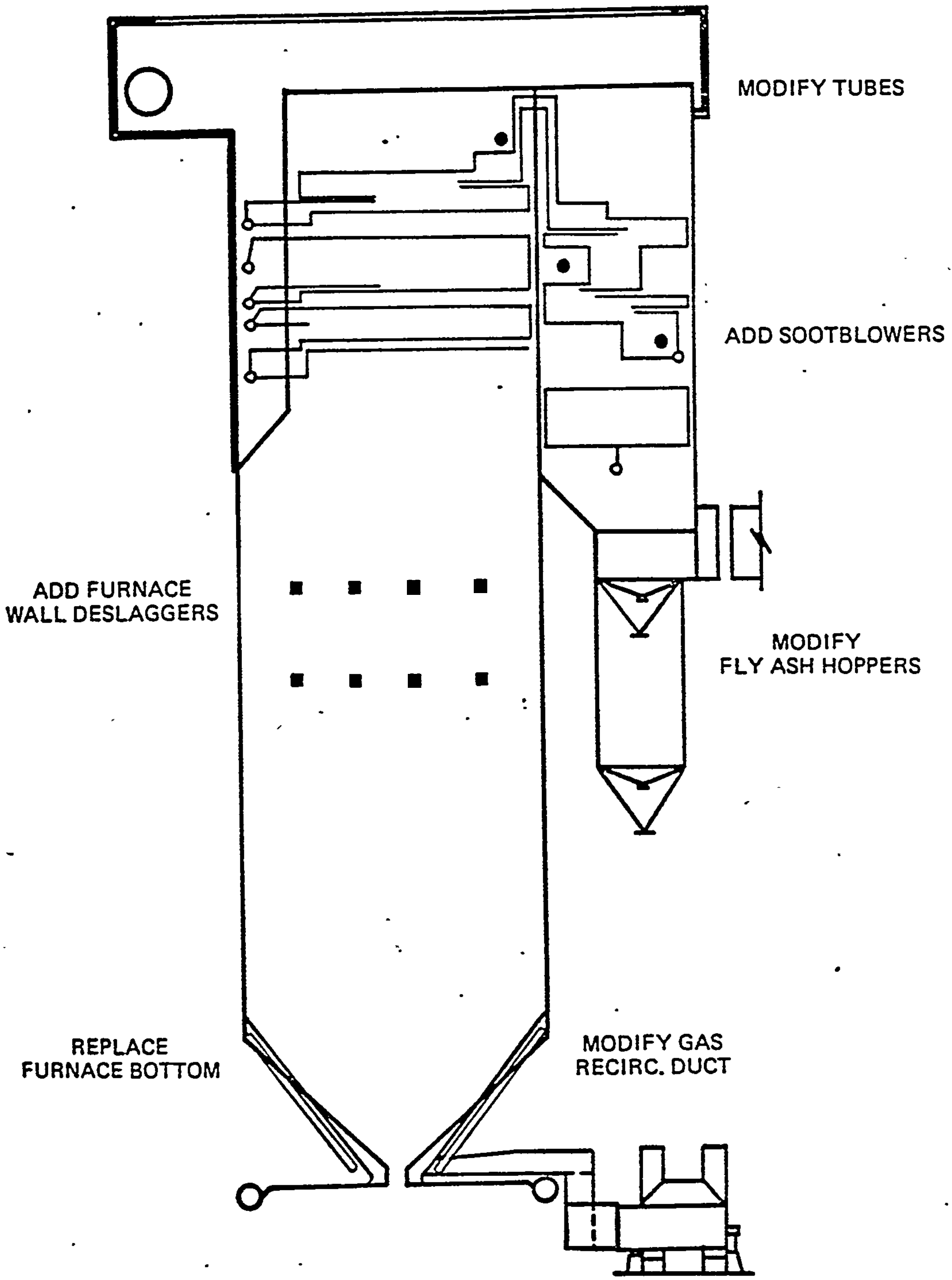


Figure 2-5 SCHEMATIC OF MODIFIED OIL-DESIGNED CCS BOILER UNIT

Table 2-1

BOILER LOAD DERATING FIRING 50/50 COM

Study Boiler Configuration	Nameplate Capacity on Fuel Oil, MWe	Percent Load Derating(1)	
		Kittaning COM	Pocahontas COM
Close-Coupled Arch (CCA-1)	850	27	50
Close-Coupled Arch (CCA-2)	820	20	51
Close-Coupled Screen (CCS)	565	36	56
Box (Box-1)	410	56	66
Box (Box-2)	382	58	64
Conventional Pulverized Coal Capable (C/PCC)	392	0	0

(1) Based on the predicted reduction in the maximum rate of steam generation when firing fuel oil.

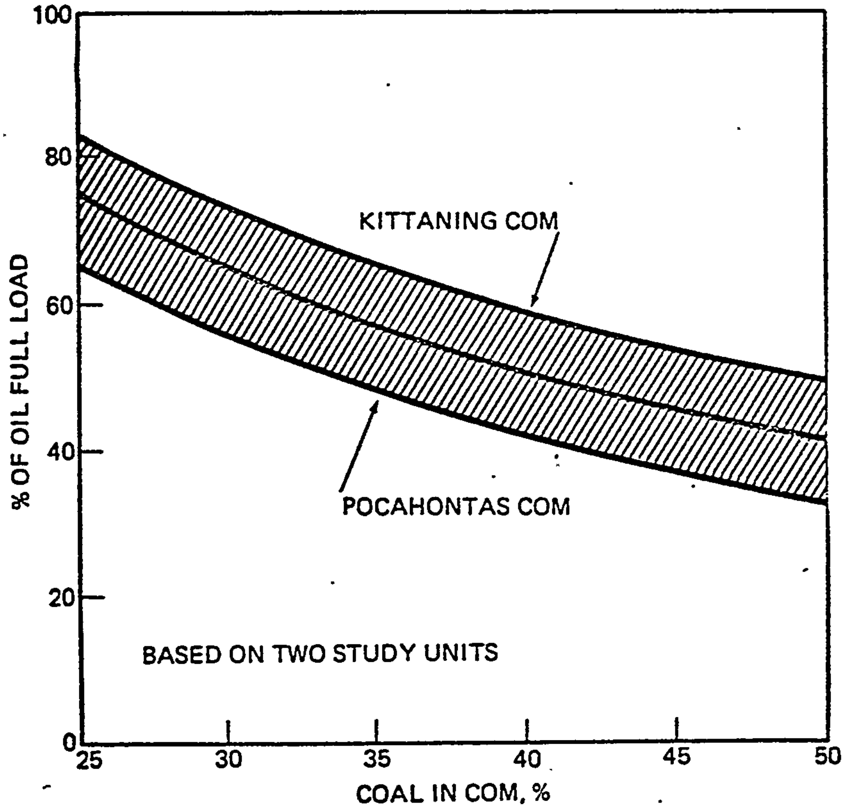


Figure 2-4 BOILER LOAD CAPABILITY FOR FIRING COM
(Box Boilers Designed for Oil)

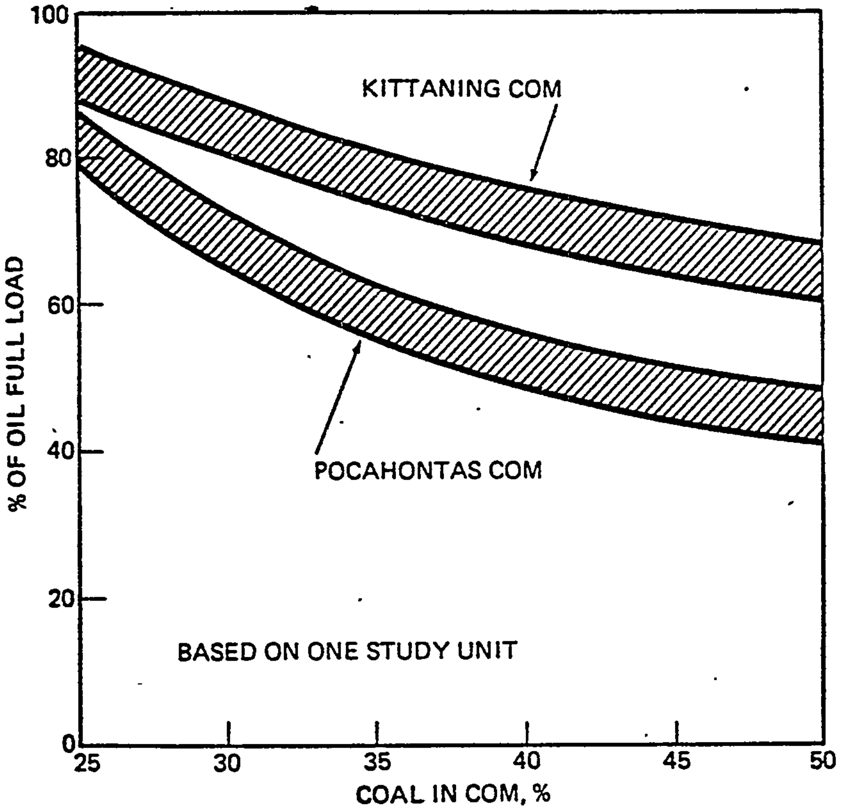


Figure 2-3 BOILER LOAD CAPABILITY FOR FIRING COM (Close–coupled Screen Boilers Designed for Oil)

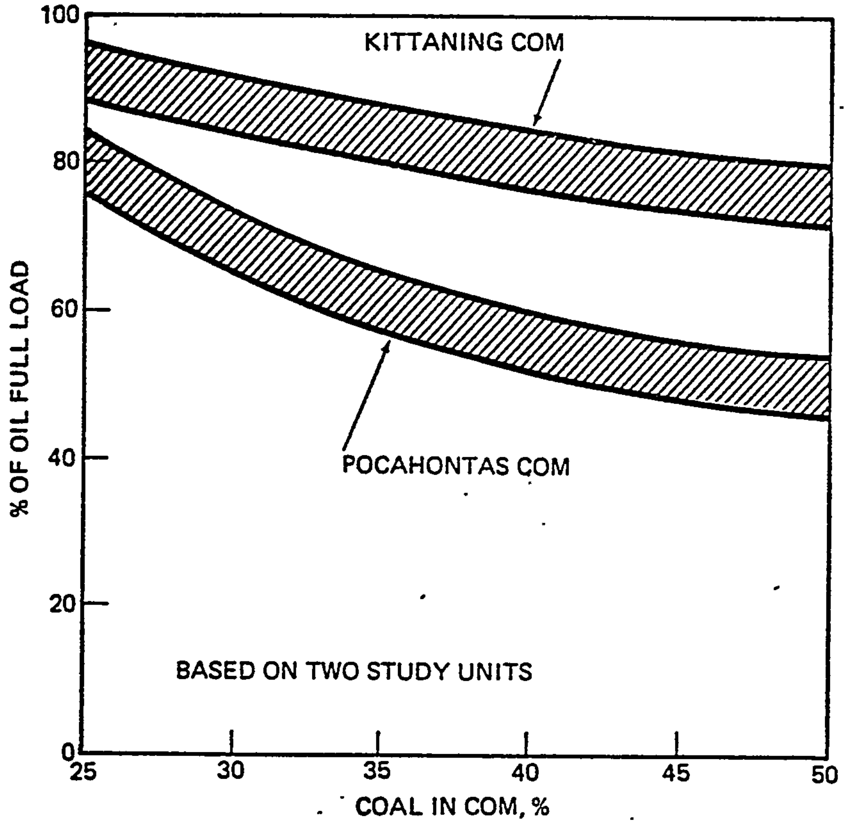


Figure 2-2 BOILER LOAD CAPABILITY FOR FIRING COM
(Close–coupled Arch Boilers Designed for Oil)

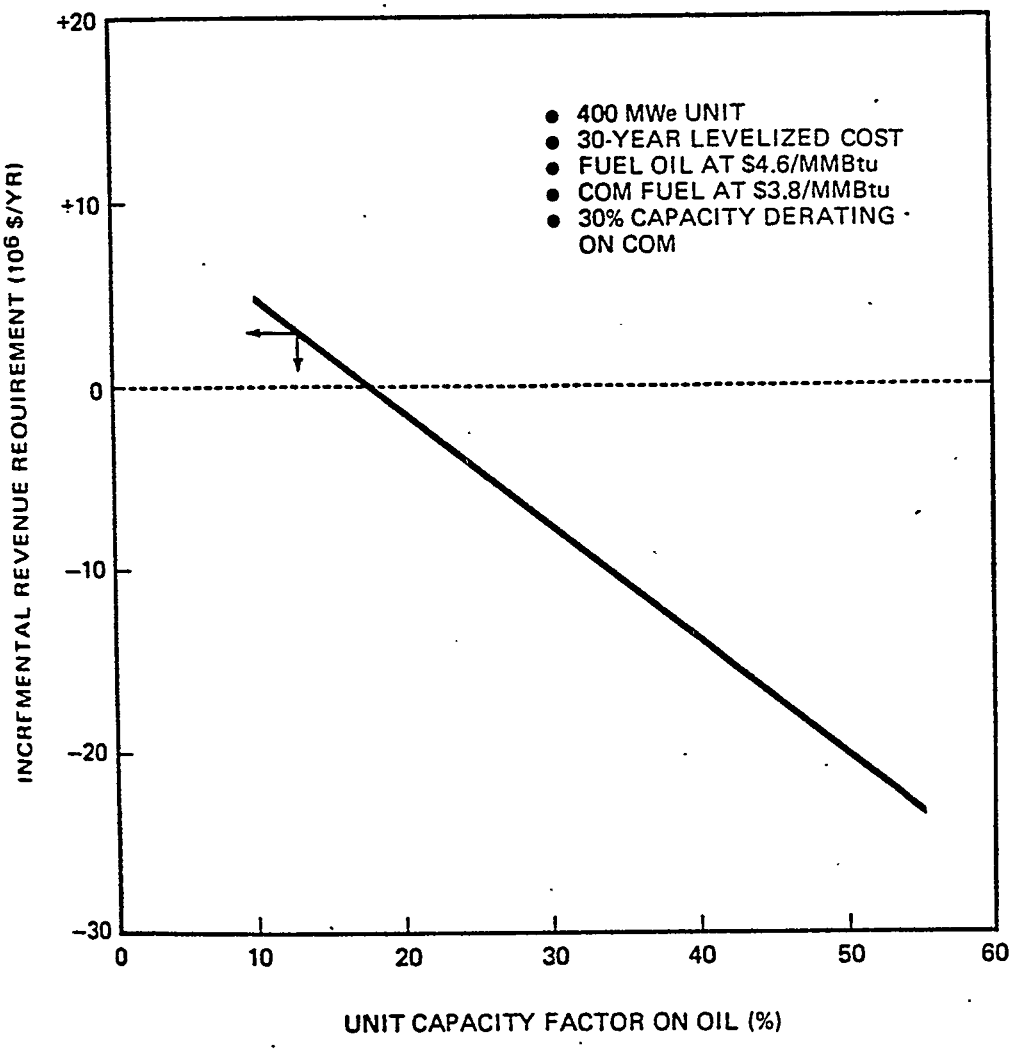


Figure 2-12 SENSITIVITY TO CAPACITY FACTOR

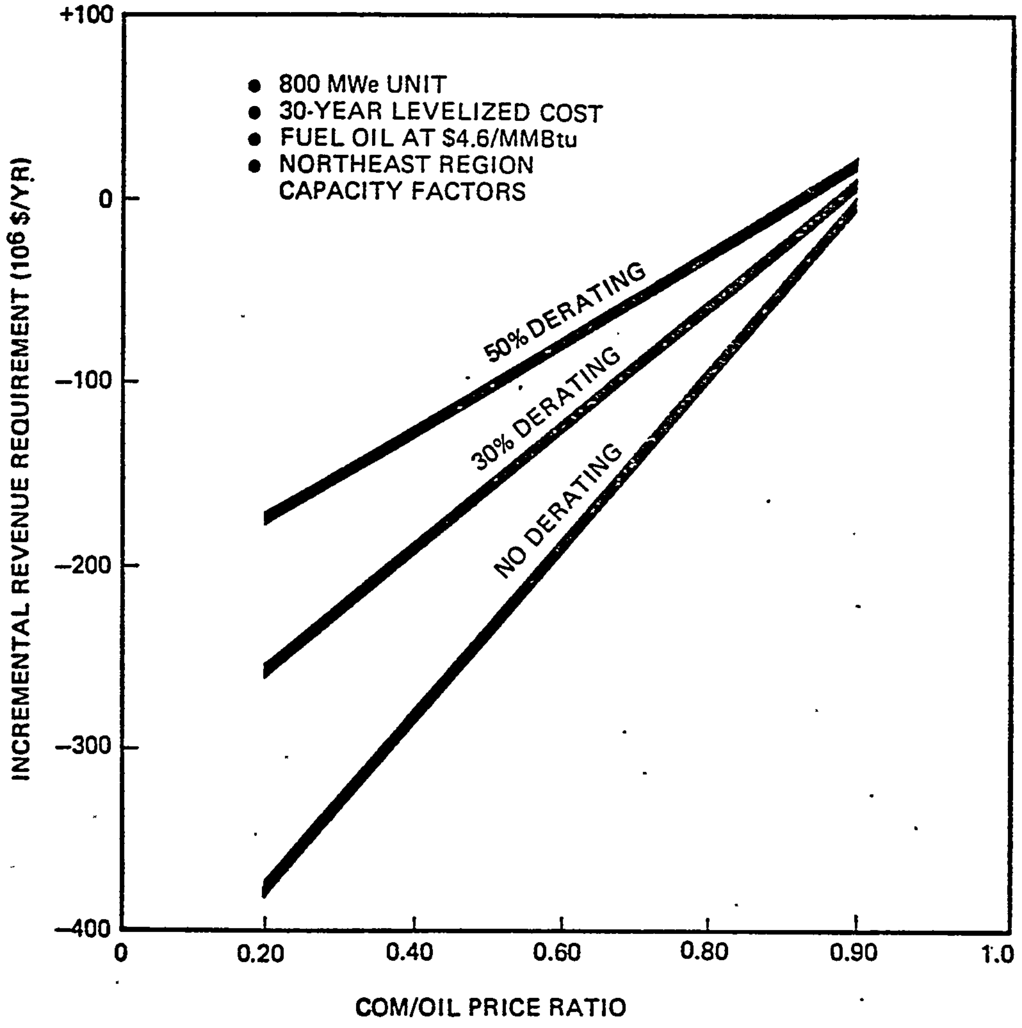


Figure 2-13 SENSITIVITY TO COM/OIL PRICE RATIO

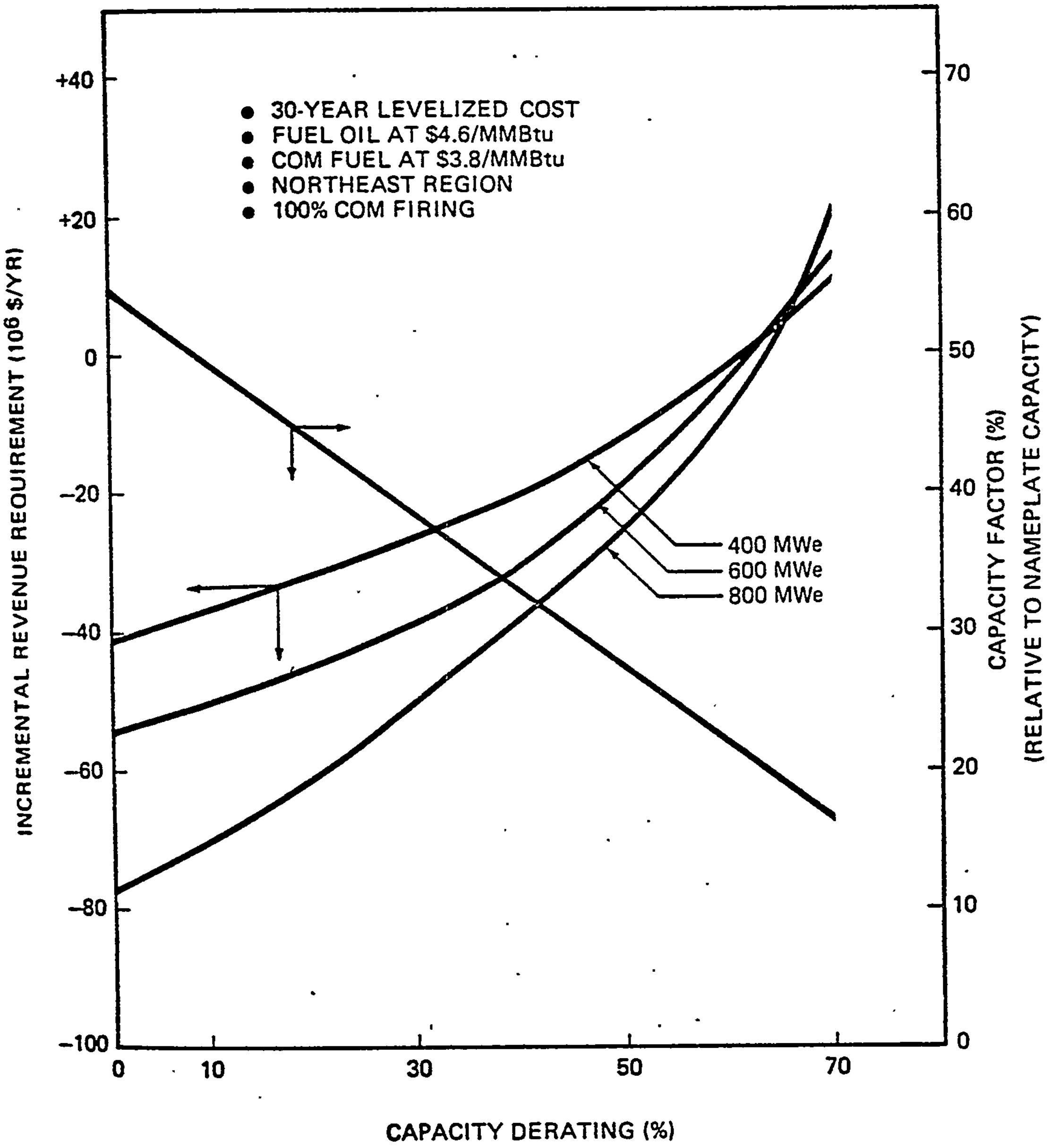


Figure 2-11 SENSITIVITY TO DERATING

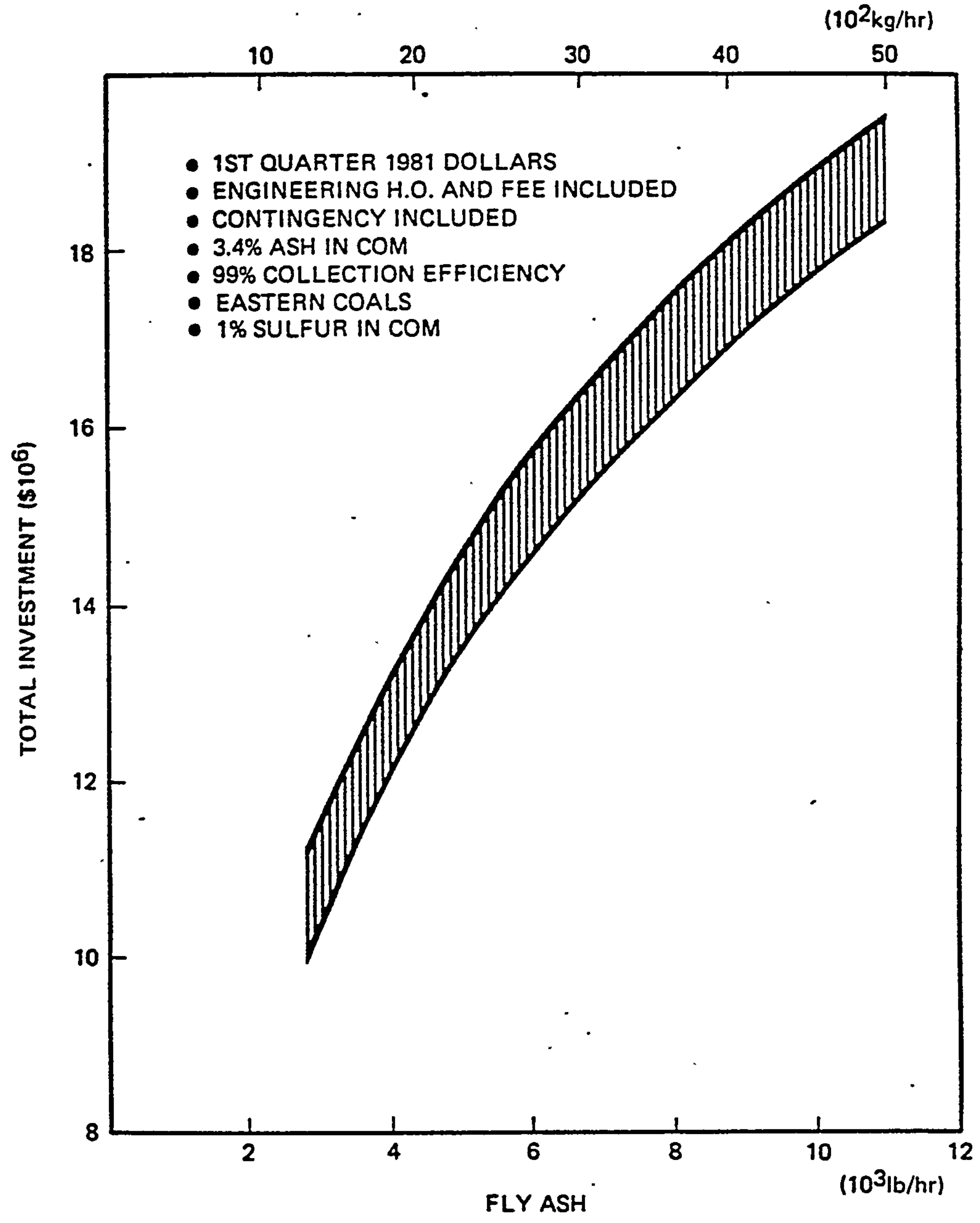


Figure 2-8 GENERALIZED ELECTROSTATIC PRECIPITATOR COSTS

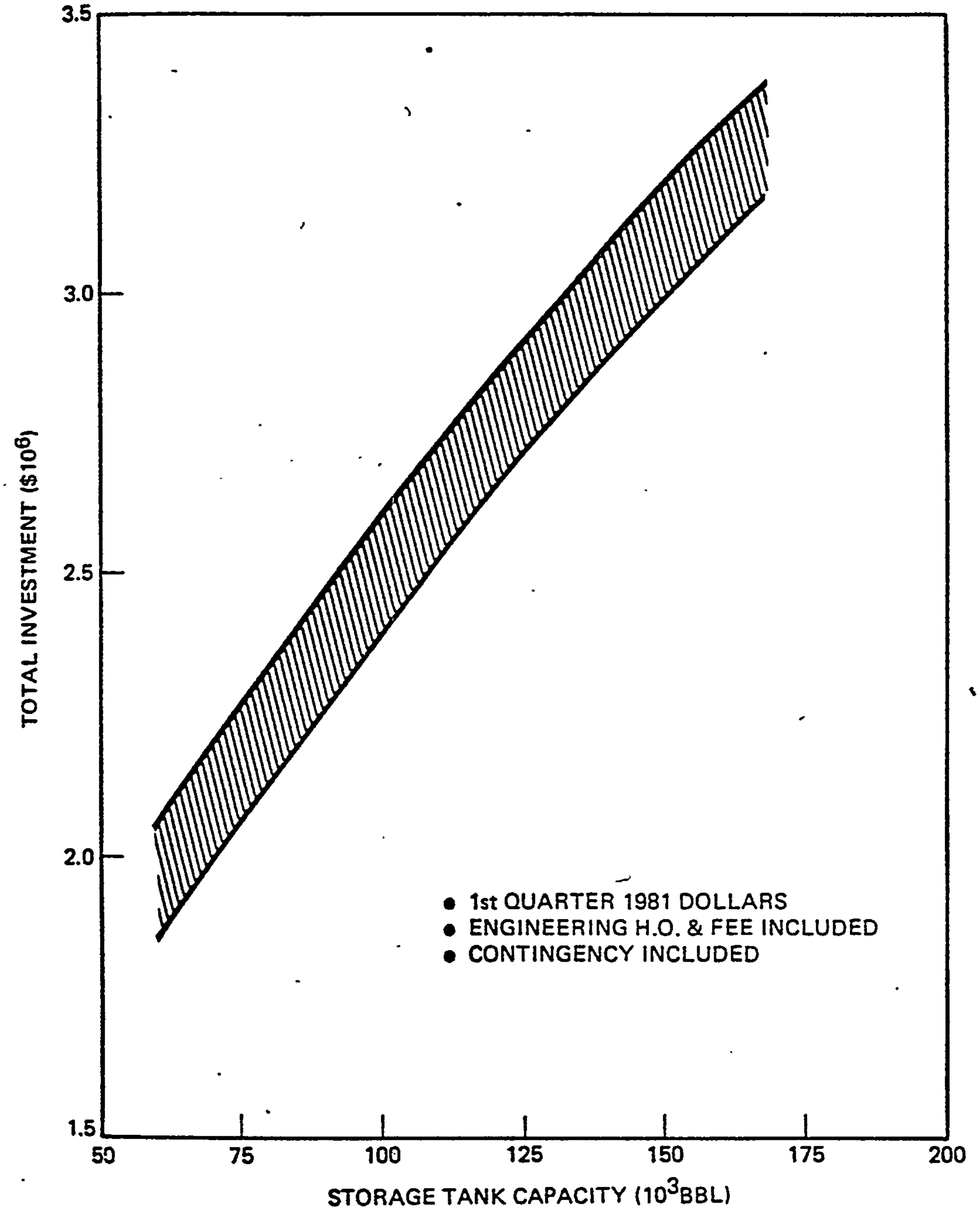


Figure 2-9 GENERALIZED COM STORAGE COSTS

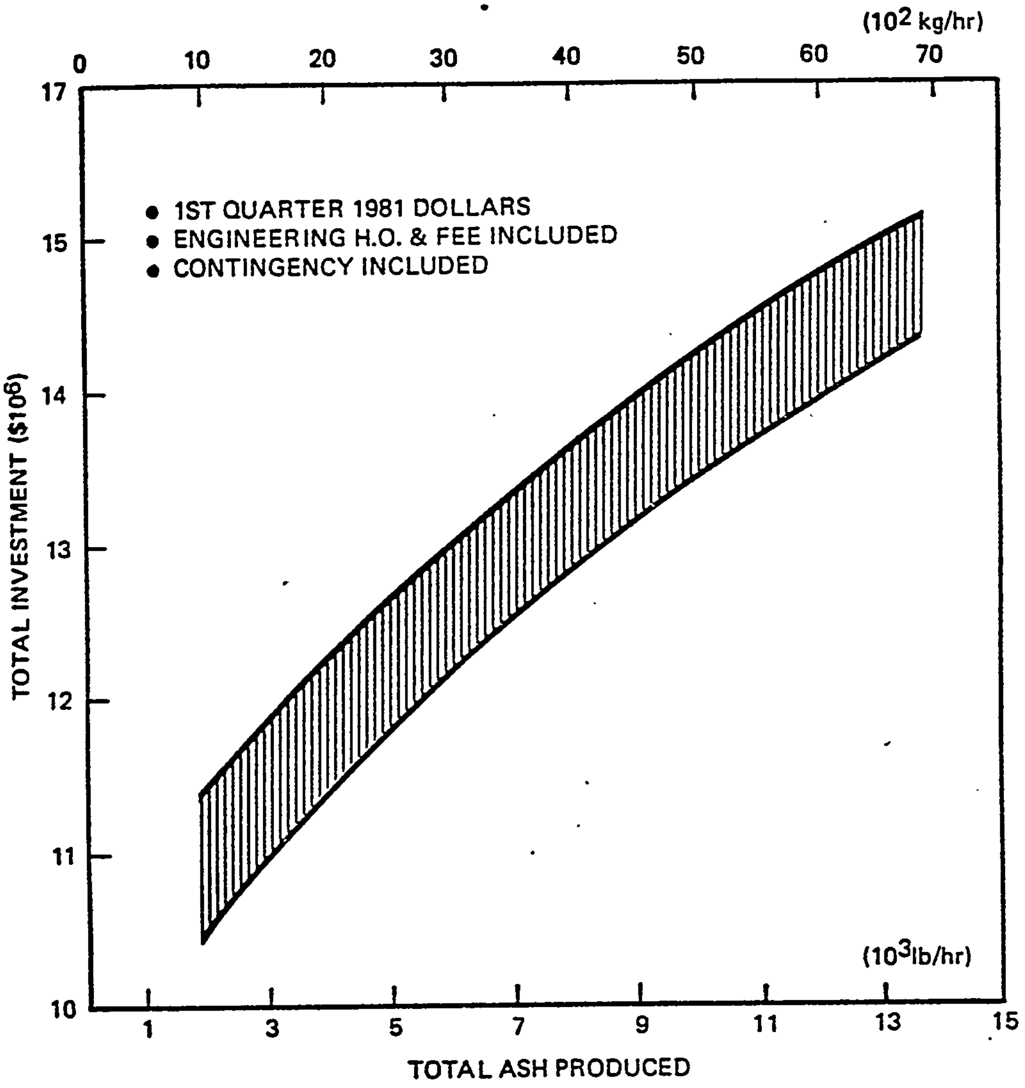


Figure 2-7 GENERALIZED ASH HANDLING COSTS

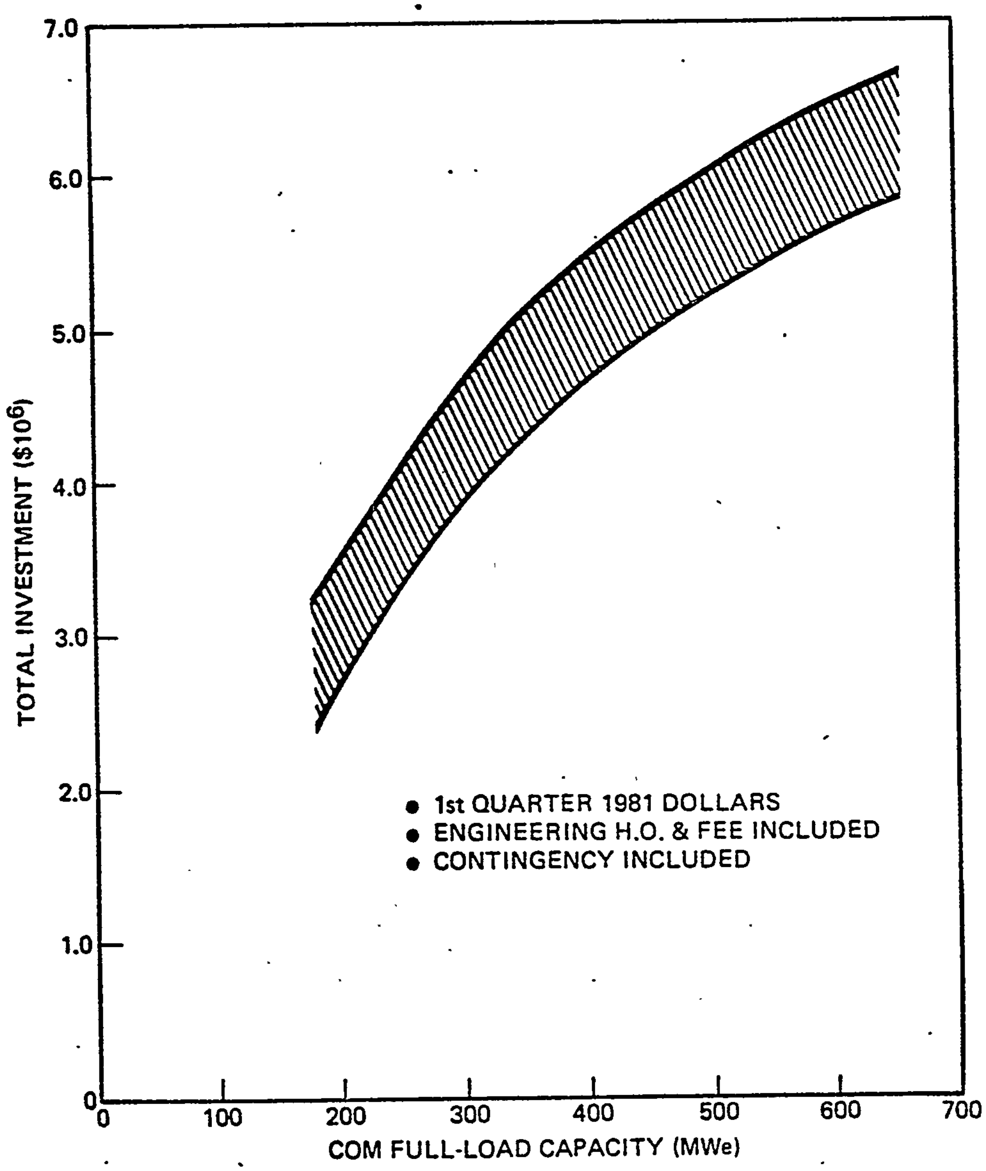


Figure 2-10 GENERALIZED COM HANDLING COSTS

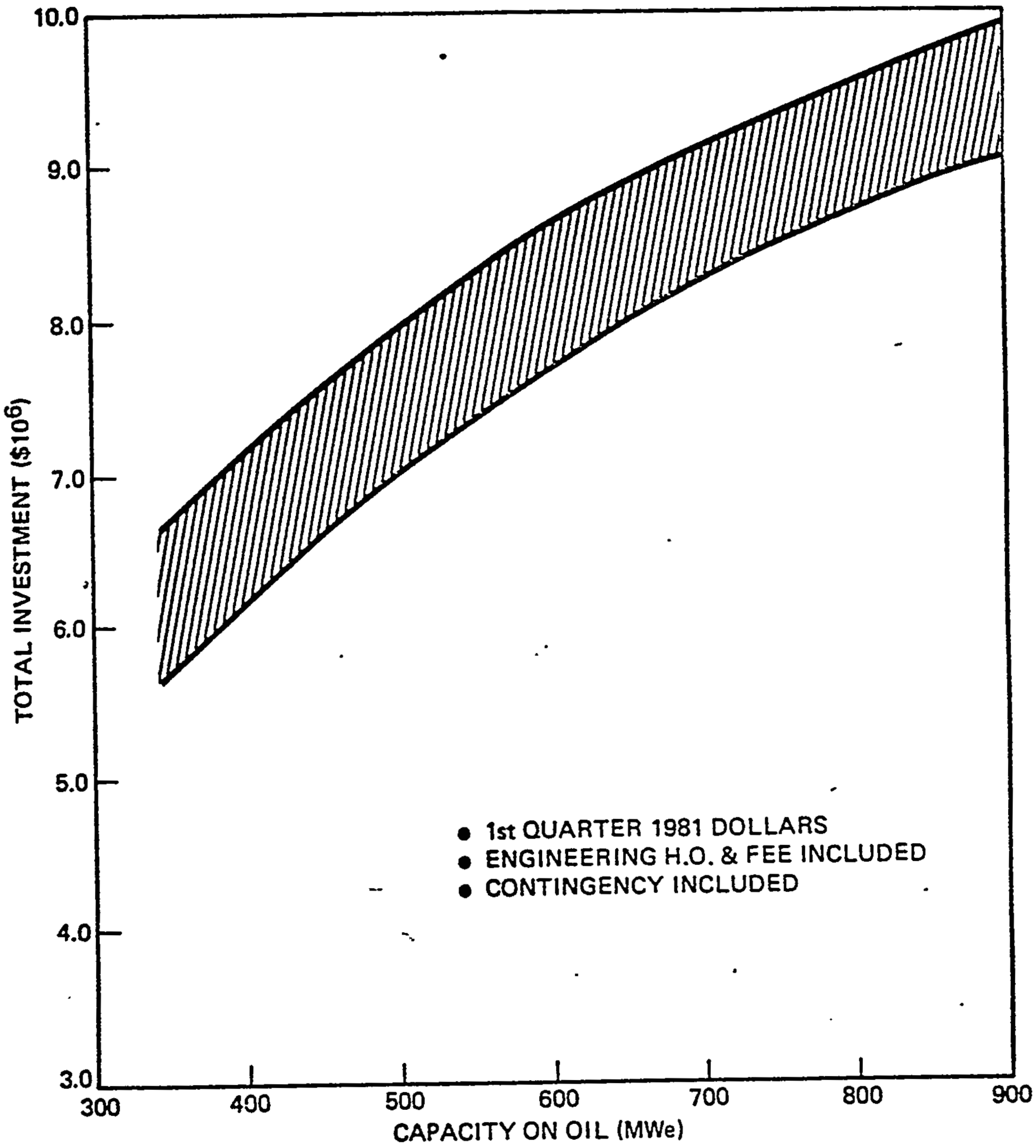
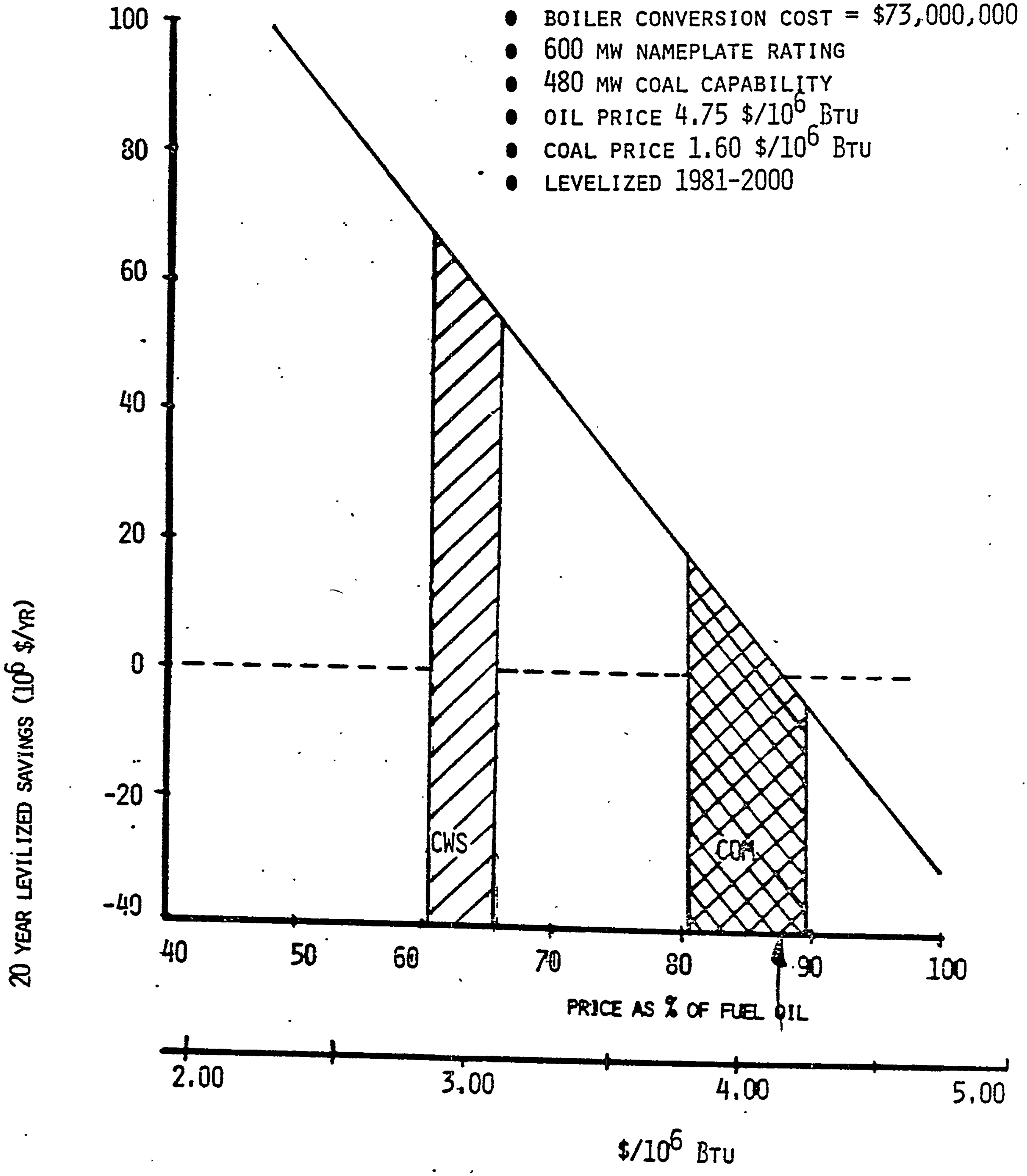


Figure 2-6 GENERALIZED BOILER MODIFICATION COSTS

COM/ALTERNATE FUEL COST INCENTIVES



BENEFITS

- LOWER COST THAN OIL

  ESTIMATED DELIVERED COSTS ($/MBTU)

OIL	4.7
COAL-OIL MIXTURE	4.0
COAL-WATER SLURRY	~ 3.0
COAL	1.6

- USES EXISTING OIL HANDLING/STORAGE SYSTEMS (PLANT MODIFICATIONS ESTIMATED TO BE IN RANGE FROM $80 TO $150/KW)
- DOMESTIC FUEL SUPPLY
- USES EXISTING RAIL TRANSPORTATION AND UNLOADING FACILITIES FOR BRINGING COAL TO CENTRAL PRODUCTION PLANT. LESS EXPENSIVE BARGES THEN TRANSPORT CWS TO UTILITY.
- TECHNOLOGY HAS INTERFACE POTENTIAL (PIPELINING, GASIFICATION, COAL CLEANING).

WHERE IS THE UTILITY APPLICATION FOR CWS?

MARKET # 1 Oil-Design Boilers

- Atlantic Seaboard, Gulf Coast, Mississippi River Regions
- At least 60% of 55 GW are Candidates
  - 10^+ years of service life left
  - Configurations or locations where conversion to coal is impractical

SECOND MARKET A Few Coal-Design Boilers

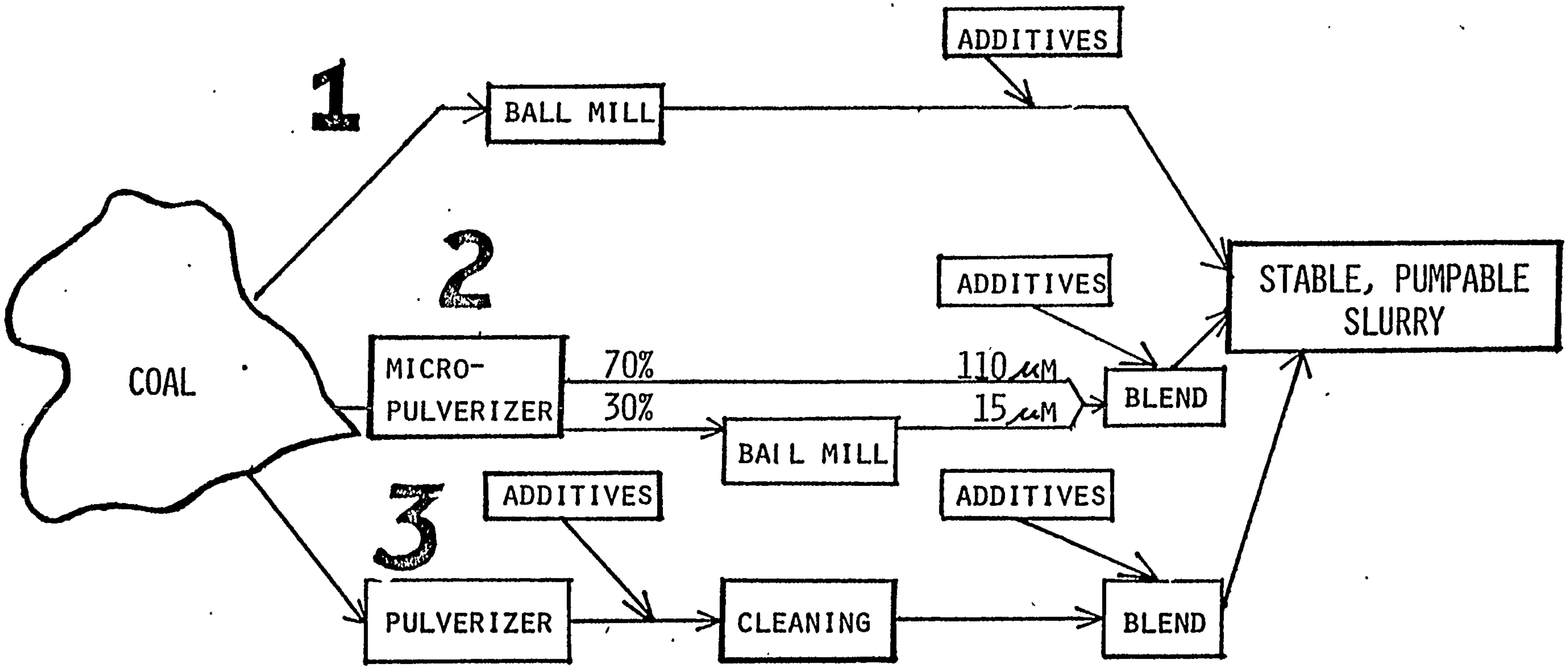
- Plants with Space or Handling Problems
- Estimated 30% of 15 GW are Candidates

UNLIKELY MARKET New Plants

PROBLEMS

- COMBUSTION STABILITY IN LARGE-SCALE TO BE DEMONSTRATED
- EROSION-RESISTANT BURNERS/NEED DEVELOPMENT AND DEMONSTRATION
- SUB-SYSTEMS STATE-OF-ART MUST BE DEMONSTRATED
- 4% BOILER EFFICIENCY LOSS DUE TO WATER
- DERATING
- INSTALLATION OF EMISSION CONTROL SYSTEM
- SLURRY PRODUCT MUST BE DEFINED AND VENDORS MUST BUILD PLANT ($200 MILLION)

THREE WAYS TO MAKE CWS

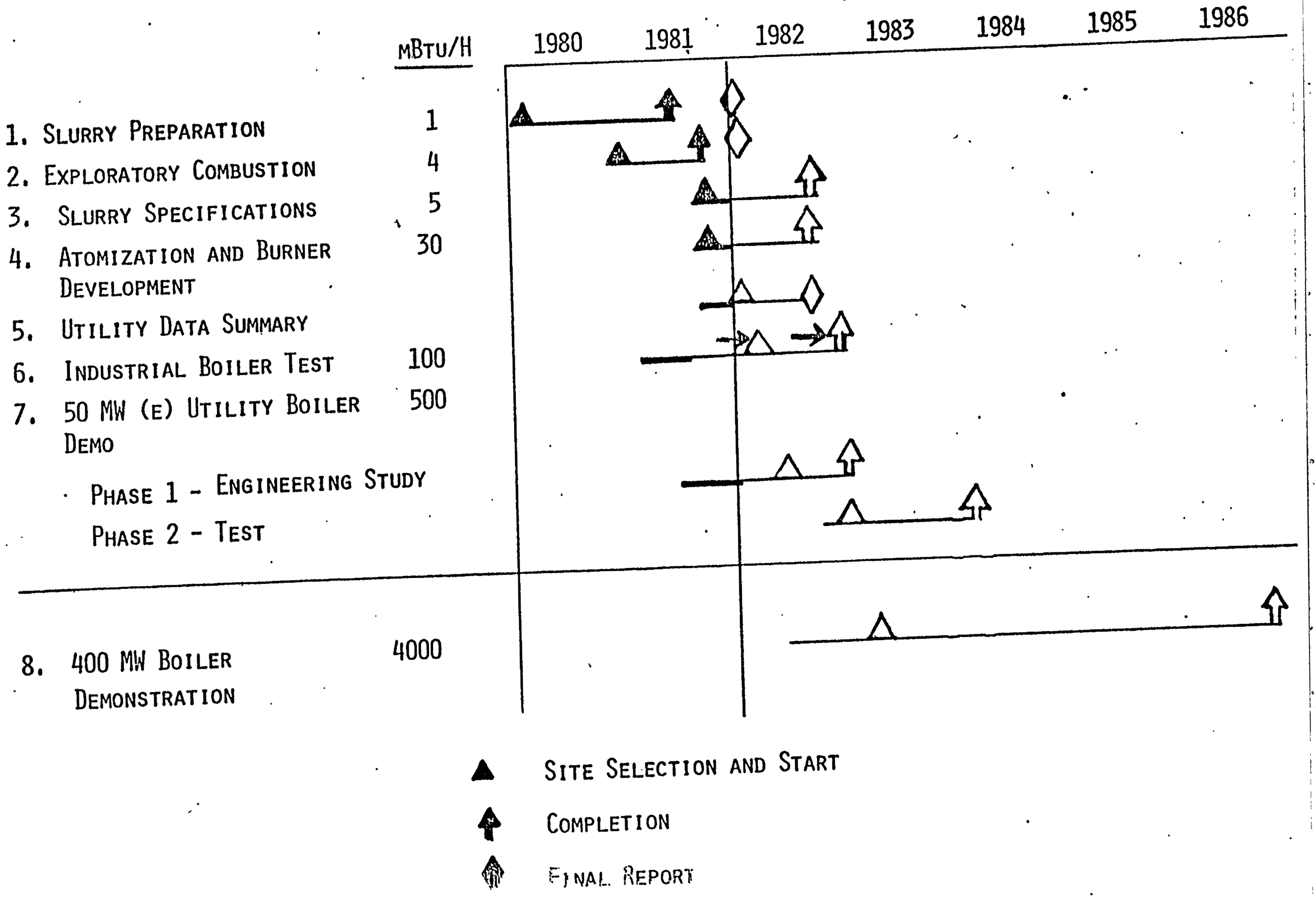


STATUS OF SLURRY SUPPLIERS (JAN. '82)

	LAB	PILOT PLANT (1-10 TPH)	PRODUCTION PLANT
GULF + WESTERN *	X	ON STREAM	1.0 MT/YR ('83) SWEDEN
OCCIDENTAL RESEARCH *	X	JUNE '82	-
SLURRYTECH (AND OTHERS)	X	ON STREAM	0.5 MT/YR ('83) ANNOUNCED
ATLANTIC RESEARCH CORP.	X	ON STREAM	0.03 MT/YR ('82) ANNOUNCED
AB CARBOGEL *	X	(1 TPH AND 10 TPH) ON STREAM	0.01 MT/YR ('82) NOVA SCOTIA 0.3 - 0.6 MT/YR ('82-'83) SWEDEN
ASHLAND OIL	X	EARLY '82	-
GULF OIL *	X		
ARCO *	X		
SHELL *	X		
BRITISH PERTOLEUM	X		
COALIQUID	X		
ERGON	X		

* PROCESS INCLUDES COAL CLEANING

COAL-WATER SLURRY PROJECT PLAN



AB-2

Appendix III

COMBUSTION, HEAT TRANSFER, ASH DEPOSITION AND POLLUTANT EMISSION CHARACTERISTICS OF COAL-OIL MIXTURES

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Abstract

A detailed combustion characterization study is under way at the MIT Combustion Research Facility (CRF) on industrial type turbulent diffusion flames. The objectives of the study are to characterize COM flames with respect to gaseous and particulates emissions, heat transfer, COM and slagging/solids deposition, and to determine flame input and operating conditions which favorably influence these flame characteristics. Results from the first experiments carried out in this ongoing research program are reported.

The CRF is a 1.2 x 1.2m cross section, 10m long variable heat sink combustion tunnel equipped with a variable swirl burner of up to 3 MW thermal, multi-fuel firing capability, and is used for detailed study of industrial type turbulent diffusion flames.

The major flame input and operating variables investigated to date consist of atomizer type: an International Combustion Ltd. design for COM fuels and a modified Y-jet; fuel type: 40% and 50% COM fuels of differing coal and oil constituents; excess air level: ∿ 15% and ∿ 5% in the flue; and without or with swirl in the combustion air flow. The thermal input in these experiments was maintained at 1 MW.

Measurements carried out include gas temperatures, velocities, gaseous and solids species concentrations, at several points in the flame and also incident radiation from the flame to the furnace wall along its length. Scanning electron micrographs were taken of char and ash cenospheres for a number of the in-flame solids.

Taking place concurrent with the CRF experiments are modeling efforts on COM flame radiative heat transfer and fuel burnout. Some preliminary results from the radiation modeling are reported.

Introduction and Research Objectives

Coal-oil mixtures (COM) are seen as an attractive alternative fuel for the power industry from the point of view of decreasing dependence upon foreign oil, of stretching existing domestic petroleum supplies, of taking advantage of the nations immense coal reserves, of abating rising fuel costs, and of potentially requiring a minimum expenditure in time and capital for implementation in existing facilities. Potential problems that can accompany the retrofit of oil-fired utility boilers to utilize COM include: (1) an increased slagging tendency brought about by the relatively large ash content of the coal, by possible synergistic effects of oil ash constituents and those of coal ash, and by differences in the heterogeneous combustion process in COM flames; (2) increased emissions of combustibles and NO_x due primarily to the coal in the fuel; and (3) possible changes in the heat flux distribution caused by differences in flame temperature profiles and emissivities.

A research effort is under way at the 3 MW thermal MIT Combustion Research Facility (CRF) under the sponsorship of a number of utility and oil companies, aimed towards obtaining information on the effects of flame input and operating parameters upon the combustion, heat transfer, pollutant emission and ash deposition characteristics of COM flames. It is considered that these important flame characteristics can be favorably affected or controlled by suitable choice of flame input conditions, with the result of making the use of COM in existing utility boilers practical. Major input parameters that can be used to favorably influence COM flame characteristics include atomizer design, air-fuel mixing (degree of swirl of the combustion air, axial momentum of the jet flame) excess air level, and combustion air preheat. This paper presents results from some of the first COM combustion trials carried out in this ongoing research program.

Parallel with the experimental research being carried out at MIT, modeling efforts are being made in the areas of COM fuel burnout and radiative heat transfer. The overall objectives of these efforts is to develop a predictive capability for COM flames as well as for those of other fuels so as to facilitate the retrofit and new design of combustion devices, particularly utility boilers, with a minimum amount or need of experimentation. Preliminary results of radiative heat transfer modeling for the MIT-CRF are reported within.

Experimental Apparatus

The experimental program involved the use of the MIT Combustion Research Facility (Figure 1) which was designed especially to permit detailed experimental investigations of large turbulent diffusion flames. The CRF is a 1.2 x 1.2 m cross-section, 10 m long combustion tunnel equipped with a single burner of up to 3 MW thermal multi-fuel firing capability. The combustion tunnel comprises a number of individual 30 cm wide sections all of which are water cooled with some sections having a refractory lining on the fireside while the rest have bare-metal fireside walls. The sections are interchangeable, an arrangement which permits a variable heat sink for control of heat extraction along the length of the flame (Figure 1).

The burner used in these experiments is equipped with a variable swirl generator (moveable block type International Flame Research Foundation burner); the combustion air enters in the form of a swirling annular jet, the annulus being formed around the 60 mm diameter fuel spray gun. At the burner exit a 35° half angle water cooled quarl assists in the formation of a toroidal recirculation zone in the central region of the jet.

Combustion of the fuel is completed in the portion of the furnace labeled 'experimental section' in Figure 1. In the present COM combustion studies, the experimental section is approximately 4.5 m long and is composed of refractory lined sections only. It is considered that the use of refractory lined walls is necessary for the reduction of the heat loss from the flame so as to simulate the thermal environment characteristics of large boiler combustion chambers. The firing rate in these experiments is approximately 1 MW, giving a total average residence time in the experimental section of ∿ 3.8 seconds.

The COM fuel delivery system (Figure 2) consists of a 275 gallon, heated (120F) and stirred 'day' tank for holding the COM test fuel, a Moyno pump designed for handling of highly viscous materials, and a fuel line capable of heating the COM in two steps to maximum firing temperature of 140-150C (280-300F). The day tank allows operation for about 10 hours before requiring refilling from 55 gallon COM storage drums.

Measurements

Measurements were carried out wihin the flame along the axial centerline, in the flue and along the furnace walls. They consist of time average determinations of gas temperatures, gas velocities, and gaseous and solids species concentrations (O_2, CO_2, CO, NO_x, soot, coke, flyash). Incident radiation at the furnace walls, furnace wall temperatures, and furnace wall heat absorption were also measured. Additional measurements are planned; these include flame emissivity profiles by the modified Schmidt method, ash deposition rates, and ash deposit collection and analysis along the furnace walls and within the flames.

Water cooled probes are used in the measurements; some of these were developed by the International Flame Research Foundation[1,2] (IFRF) at Ijmuiden, Holland, and others at MIT[3]. They include gas and solids sampling probes, suction pyrometer for temperature measurement, multidirectional impact tube for velocity, ellipsoidal-cavity radiation probe for radiative heat flux, narrow-angle radiometer for flame emissivity, conductivity plug type heat flux meter for ash deposition rates, and in-flame and furnace-wall steam, air or water-cooled ash deposit collection probes.

Experimental Run Conditions, Input Variables

Flame input and operating conditions for the experimental runs reported here are given in Table 1.

Experiments were carried out without and with swirl in the combustion air. When swirl was used, the degree of rotation was moderate (S=0.53)*, the fuel nozzles consisted of a scaled down version similar

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*The swirl number, S, is a nondimensional ratio of the angular to linear momentum of the flow and is an indicator of mixing and recirculation in the flame. At S=0.53 an internal recirculation pattern is just beginning to form within the flame.

to one tested by the Florida Power and Light Company, manufactured by International Combustion, Ltd. (Figure 3), and a modified Y-jet originally intended for oil in which the number of exit holes was reduced from 6 to 3, and their size enlarged from 0.053 inches in diameter to 0.084 inches (Figure 4). Excess air level was held at 15% and ∿ 5% in these first experiments.

Three fuels have been employed in the tests. These come from two sources, the first being the Florida Power and Light Company (a 50% COM) and the second the Columbia Chase Corporation (40% COM). The fuels are somewhat different in composition as shown by the analyses in Table 2.

The water and asphaltenes content of these fuels may have a strong effect upon their burnout characteristics. The coal ash initial deformation and fluid temperatures are an indication of the slagging tendency.

Experimental Results

Visual Inspection of the COM Flames

All of the COM flames investigated to date were visibly longer than No. 6 fuel oil and SRC-II* flames of earlier studies having similar input conditions. Typically, flame of the No. 6 and SRC-II fuels at a 1 MW firing rate and low swirl (S=0.53) were 2 to 3 meters long, whereas the COM flames (S=0.53) were seen to extend the entire length (4.5 m) of the furnace experimental section. This increase in visible flame length can be attributed to the longer burnout time of the coal in the COM fuel and to the presence of relatively large amounts of fly ash which continue to radiate even after the combustion of the fuel is essentially complete.

Visual comparison of COM flames of the International Combustion, Ltd. (ICL) and Y-jet nozzles show that the ICL nozzle produces a superior flame from the point of view of stability and cleanliness of combustion. The ICL nozzle gave better atomization. When viewed from the back end of the furnace (facing the burner) flames of the Y-jet nozzle showed distinct areas of brightness corresponding to the lobes of fuel issuing from the 3 holes of the nozzle. Flamelets and puffs of soot and smoke were minimal in flames of the ICL nozzle when compared to those of the Y-jet. Also, the higher operating pressure of the ICL nozzle (see Table 1) made the flames less susceptible to instabilities caused by slight fluctuations in the fuel pressure (on the order of 1/2 psi).

A visual comparison of weakly swirling flames (S=0.53) and flames of essentially zero swirl (S=0) shows that as would be expected, the introduction of swirl improves the combustion of the fuel and the stability of the flame. Large frequency fluctuations, fluctuations in flame brightness, of flamelets and of puffs of soot and smoke observed

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*A liquid distillate fuel oil produced by the Solvent Refined Coal II process developed by a subsidiary of the Gulf Oil Corporation under contract to the U. S. Department of Energy.

in the zero swirl flame were reduced by swirling air flow.

Axial particulates concentration profiles presented later confirm these visual comparisons drawn between flames of the two nozzle types and of the two swirl degrees.

Visual inspection of the furnace walls following experimental runs on the Florida Power and Light fuel (FPL) and that of the Columbia Chase Corporation (CCC) indicate an increased slagging tendency on the part of the latter. Examination of the initial deformation temperature of the coals of these two fuels (Table 2) explains this result; that of the CCC fuel is considerably lower than of the FPL COM.

Axial Temperature Profiles

Axial temperature profiles of various COM flames, and of No. 6 fuel oil and SRC-II heavy distillate flames are shown in Figure 5. Axial centerline temperatures for most of the 15% excess air COM flames peak in the range of 1350C - 1400C and decrease to a value of ∿ 1200C at the furnace exit. The low excess air COM flame represented in Figure 5 exhibits temperatures that are approximately 100°C higher than those of the 15% excess air COM flames. The temperature profiles of the COM, No. 6 fuel oil and SRC-II distillate flames of comparable swirl (S=0.53) and excess air level (10-15%) are quite similar, the differences in temperature values at a particular axial position being attributable to scatter in the temperature measurement or slight variations in fuel input, as easily as to differences in fuel type.

The temperature peaks of the zero swirl COM flames shown in Figure 5 are seen to be shifted further downstream of the burner nozzle when compared with those of the weakly swirling flames (S=0.53). This behavior is expected; introduction of swirl alters the pressure distribution within the flame, thus causing the flame to become shorter and moving the area of most intense combustion in towards the nozzle.

The axial temperature profile of the zero swirl, modified Y-jet COM flame shown in Figure 5 displays a temperature peak that is shifted further downstream of the fuel nozzle than that of the zero swirl, ICL nozzle COM flame. The temperatures of the Y-jet flame are also somewhat higher than those of the ICL flame. At present there are insufficient data to determine with certainty whether these differences in the two profiles are attributable to the atomizer, fuel types, or to errors in the measurement. It should be noted that the two profiles were taken with different suction pyrometers. These probes can yield temperatures under identical flame conditions that vary as much as 5% from one another.

Axial Velocity Profiles

Axial velocity profiles as measured with the multi-directional impact tube are presented in Figure 6 for various COM flames. The gas velocity distributions within the flames are of particular interest from the point of view of COM combustion modeling studies, which are presently being undertaken at MIT.

The profiles shown in Figure 6 are similar to those of No. 6 fuel oil and SRC-II distillate flames of comparable input conditions. Note that the peak axial velocity of the weakly swirling COM flame (S=.53) represented in Figure 6 is somewhat lower than those of the zero swirl COM flames shown in the figure. This is to be expected: swirling flames tend to exhibit lower velocities along the axial centerline than non-swirling due to the adverse pressure gradient that is set up within the flame. Towards the tail end of the flames the pressure differentials across the pressure taps in the head of pitot probe become so small in value that they begin to approach the lower detectable limits of the pressure transducers installed at the facility. When the gas velocities fall below 3 meters per second the accuracy of the measurement begins to fall off and data points begin exhibit more scatter.

Combustion Chamber Heat Balance

As mentioned earlier, the experimental furnace is composed of a number of individually water-cooled refractory lined and/or bare metal sections. The cooling water flow rate and temperature rise is measured for each section; this allows the determination of the distribution of the furnace wall heat loss along the furnace length. The exit gas heat loss (chimney loss) can be calculated based upon knowledge of the exit gas temperature, and the fuel and air flow rates, the assumption being made that the combustion of the fuel is complete.

A typical heat balance for the experimental combustion chamber is given in Table 3. Since 94% of inside surfaces are refractory lined the (wall temperatures at a 1 MW firing rate typically reaching 1050-1300C), a major proportion of the heat released by the flames is re-radiated to the combustion gases leaving combustion number. Heat absorption through the furnace surfaces accounts for approximately a third of the thermal input which is somewhat lower than that in boiler furnaces.

Radiative Heat Flux

Radiation measurements were carried out on COM and No. 6 fuel oil flames to determine the axial distribution of radiative flux incident to the furnace wall. Incident radiative flux was measured along the length of the furnace with an ellipsoidal radiometer having a solid view angle of 2π steradians positioned flush with the inside surface of the furnace wall. The probe was calibrated in two blackbody furnaces, and is subject to a clibration error of about 5%.

Figure 7 is a comparison of the axial distribution of radiative flux of a No. 6 fuel oil flame and three 50% Florida Power and Light COM flames. The relevant input conditions of these flames are given in the figure. Note that the radiative heat fluxes at a particular axial position of the various flames differ from one another by no more than 15%, and that the No. 6 fuel oil radiative profile is bracketed by those of the COM flames. The most important conclusion that can be drawn from this figure is that the change in fuel type from a No. 6 fuel oil to a 50% COM does not greatly affect the radiative flux from the flame in this furnace.

It may be that expected increases in flame emissivity caused by high particulate concentrations in COM flames are compensated for by lower peak flame temperatures that tend to be characteristic of the heterogeneous combustion processes taking place in this type of flame. The resulting radiative flux emanating from the COM flame, thus in this fashion may turn out to be comparable to that of a No. 6 fuel oil.

A comparison of the axial positions at which the maximum radiative heat flux occurs for the different flames represented in Figure 7 is also of interest. The exact shape of the radiative flux profile of the weakly swirling (S=0.53) ICL nozzle COM flame in Figure 7 is uncertain at distances from the nozzle falling between 0.2 and 1.0 meters because the ellipsoidal cavity of the probe was being fouled by ash from flame during the measurements, despite nitrogen purging. Keeping this uncertainty in mind the peak in radiation from this weakly swirling COM flame occurs at about the same position as, or a little further from the burner than that of the No. 6 fuel oil flame which is of comparable swirl. Because COM combustion is delayed somewhat by the presence of the coal particles, a shift in position of the peak away form the burner is expected.

As would be expected, the radiation peak in the case of the zero swirl ICL nozzle COM flame occurs at a position further downstream of the burner than that of the weakly swirling (S=0.53) ICL nozzle COM flame. A lack of swirl results in a longer, more slowly burning flame. This longer flame leads to the radiation plateau in the profile shown in Figure 7. The radiative heat flux measurements for the zero swirl, ICL nozzle, 15% excess air FPL COM flame were compared with preliminary results of radiative heat transfer computer modeling. As shown in Figure 8, radiative fluxes predicted by the computer model are within 11% of the measured values throughout the furnace.

The computer model being used is based on the zone method of furnace analysis originally proposed by Hottel and Cohen[4] in which the furnace is divided into many volume and surface zones. The properties of each zone are considered uniform and constant, and the radiative exchange areas between the zones are determined based on measured concentrations of absorbing species in each zone. Given fluid flow and combustion patterns, a system of nonlinear energy balance equations can be set up and solved for the unknown temperature of each zone, allowing the radiative heat flux distribution to be predicted.

Johnson was successful in developing a computer program that employed this zone method to predict radiative flux from a fuel oil flame[5]. Wall and co-workers extensively modified this program, primarily by incorporating the Monte Carlo method to determine direct exchange areas[6]. This probabilistic method, in which a zone's energy emission is divided into several thousand "particles" that are tracked as they are reflected and absorbed throughout the furnace, allows considerable flexibility in choosing zone size and shape. The zone shapes can be made physically more realistic, thus allowing a smaller number of zones to be used in the model while retaining the same degree of accuracy. For example, the zones containing the flame itself can be shaped as truncated cones which more accurately represent the flame's shape.

This program has been modified for use at the MIT-CRF, and has been used successfully to model synthetic fuel flames. Further modifications are being made to allow COM and other ash-bearing flames to be modeled. The current zoning system consists of 11 volume zones and 10 surface zones in a parallelepiped as shown in Figure 8. Because the zone method requires the absorbing gas and soot concentrations of each volume zone as inputs, measurements are required in any flame being modeled. Although only the axial distributions of these concentrations are known for COM flames in the MIT-CRF, radial distributions can be approximated to allow preliminary computer modeling. Figure 9 is a comparison of the axial radiative heat flux distributions of the zero swirl, ICL nozzle, FPL COM flame and as predicted for those conditions by the Monte Carlo zone method computer program. The predicted and average measured values are less than 11% apart in each of the 5 axial surface zones. Johnson was able to predict radiative fluxes within 10% of measured fluxes; it is believed that these numbers may be further improved as refinements in the input data and radiation model are made.

The major improvement required for COM radiative flux modeling is in the treatment of radiation from fly ash. At present, all particulates in the COM flame are combined and assigned the absorption coefficients that Johnson determined for soot alone. The validity of treating ash as soot has not been demonstrated, so further work is needed to determine suitable absorption coefficients for ash. For high fly ash concentrations, scattering of radiation by the particles will become important, so its effect-must also be investigated and modeled.

Other improvements being made include re-evaluating the gas absorption coefficients used by Johnson, since the partial pressure of water to that of carbon dioxide in the combustion products of this COM flame is 0.7 compared to 1.0 for the fuel oil flames Johnson investigated. Also, further detailed experiments on COM flames will remove the uncertainty in predictions due to some approximated input data used in the present calculations. Finally, the possibility of improving the accuracy of radiative flux prediction by doubling the number of zones is also being investigated.

Implementing the improvements mentioned above will determine the accuracy of applying the zone method to COM flames, but the results obtained thus far show that the feasibility of extending the method to ash-bearing flames is quite good.

Axial Gas Composition Profiles

Measurements of O_2, CO_2, CO and NO_x concentrations along the flame axis were carried out for a number of COM flames and are shown in Figures 10 to 14. Similar profiles for an SRC-II flame are presented in Figure 15.

A comparison of the O_2 and CO_2 profiles of the COM flames with the SRC-II distillate clearly demonstrates the delayed nature of the combustion process for COM. In the case of the SRC-II all-liquid fuel the O_2 and CO_2 profiles are relatively flat indicating that combustion is completed very near the burner. In the case of COM, the O_2 and CO_2 concentrations begin to reach equilibrium only very close to the exit of the combustion chamber, this being indicative of slower fuel burnout rates, particularly of the coal in the fuel.

A comparison of the CO profiles of long (S=0) and short (S=0.53) flames of the 50% FPL COM using the ICL nozzle (Figures 10 and 11) shows the effect of swirl, an indicator of the degree of turbulent mixing of air and fuel, upon the rate of combustion of the fuel. The CO is seen to burn out in the case of the shorter (S=.53) flame 1 meter from the nozzle and in the case of the longer (S=0) at 2 meters. It is interesting to note that the concentration of CO for both flames is essentially the same at the furnace exit, being on the order of 0 to 50 ppm. Axial total particulates concentration profiles discussed in the next section exhibit similar behavior.

The axial NO_x concentration profile for the weakly swirling (S=0.53), 50% FPL COM flame shown in Figure 13 is flatter than those of the zero swirl flames represented this figure and in Figure 14, indicating that the NO_x is formed a little more rapidly at this swirl condition. These profiles, like those of the CO, are illustrative of the more rapid fuel/air mixing and subsequent reaction processes that accompany the introduction and increase of swirl in a flame.

The gas composition profiles of the flames of the 50% FPL fuel and of the 40% CCC Figures 10 and 12, respectively, at a zero swirl condition exhibit trends that are fairly similar. The CO is seen to burn out at approximately the same position along the furnace axis.

Decreasing the excess air level from 15% to 5% resulted in modest increases in CO emissions. COM flames at 15% excess air exhibited CO emissions usually close to 0 ppm with occasional rises to 50 ppm. The 5% excess air flame studied in detail (Flame 5, in Table 1) yielded CO emission levels that were within 100 ppm. At near stoichiometric conditions (< 0.2% O_2 in the flue) the CO concentration usually remained within 500 ppm. The relatively modest increase in CO emission, particularly in changing from a 15% excess air level to a 5% level, may be attributed in part to the relatively high temperatures in the combustion chamber at this excess air condition, even towards the exit, which were in the neighborhood of 1300C, and also to the excellent fuel/air mixing that can be achieved within this experimental combustor.

Axial Particulates Concentration Profiles

Axial total particulates concentration profiles for several COM flames are shown in Figure 16. The input conditions for each flame are also indicated in the figure.

The effect of swirl is seen in Figure 16 to be most noticeable in the early portions of the flames, at distances of less than 2 meters from the burner. At these distances, solids concentrations in the weakly swirling (S=0.53), ICL nozzle, 50% Florida Power and Light (FPL) COM flame are considerably lower than the zero swirl (S=0) flame of the same nozzle and fuel type. This can be probably attributed to the improved fuel/air mixing that accompanies the swirl. It is interesting to note that from the point of view of solids emissions these two flames are practically identical; the solids concentrations are seen in Figure 16 to decay to nearly the same value.

The effect of nozzle type upon COM flame solids concentration profiles may also be seen in Figure 16. Early in the zero swirl (S=0.0), 50% Florida Power and Light COM flames (at distances less than 1.5 meters from the nozzle) the Y-jet gives slightly lower particulate levels than the ICL nozzle. Considering that the 3-hole Y-jet gives a very distinct hollow cone, 3-lobed spray pattern this result is quite understandable. Upon examining the particulates concentrations towards the end of the flames represented in Figure 16, it appears that the ICL nozzle gives a slightly lower emission than the Y-jet. This is in keeping with the visual observations on these flames discussed earlier, and is supportive of the conclusion that the ICL nozzle gives better atomization than the modified Y-jet, which in turn results in improved fuel burnout.

The solids emission levels of the COM flames of the two fuel types but which are otherwise similar, are quite close in value. At positions near the nozzle (< 2 m) solids concentrations in the 40% CCC flame are slightly lower than the 50% FPL flame, this presumably being attributable to the lower coal content of the fuel.

An example of the effect of excess air level upon COM flame particulates emission is given in Table 4. In the case of this zero swirl, Y-jet nozzle, 40% CCC COM flame, solids concentrations are seen to increase by 25% when going from a 15% excess air to a near stoichiometric condition. This is probably due to the increase in combustibles emission.

At the time of the preparation of this paper all of the solid samples that are represented in Figure 16 and Table 4 are being analyzed for their combustibles content.

Ash Deposition Studies

A number of samples have been collected of ash and slag that have accumulated on the furnace walls and upon the ∿ 3/4 inch diameter stainless steel flue gas sampling tube which extends into the center of the exit of the furnace experimental section. Tables 5 and 6 present mineral and fusion temperature analyses carried out by a commercial laboratory on a few of the deposits from flames of the 50% Florida Power and Light COM. The deposits were accumulated over more than one set of flame conditions.

Mineral analyses using atomic absorption techniques were carried out upon the inside and outside layer of an ash deposit formed on the flue gas sampling tube. A thickness of approximately 1/8 - 1/4 inches was scraped off for each layer. This deposit was lightly packed in nature and could be broken up into fine particles in the hand. The deposit was collected over a period of about 10 hours over flame conditions varying in swirl (S=0.0-0.053) and in excess air level (1-4% O_2) and was approximately 3-4 inches thick. The temperature of the gases passing by and being drawn into the sampling tube was approximately 1000 C (± 100 C).

As evident from Table 5 the mineral analyses of the deposits are similar to that of the coal ash. The relative concentrations of sulfur and alkalies in the inner and outer layer are noted with interest since they appear to follow a trend contrary to that typically reported in the literature [7]. It should be mentioned, that the period of time over which the deposit was exposed to the flame was probably of insufficient duration for the diffusion processes of the alkali metal and sulfur species through the porous deposit to be manifested. Relative concentrations of various species in deposit layers formed from COM flames can be followed more closely in later experiments using deposition probes, which will allow the conditions under which the deposits are formed to be monitored and controlled more closely.

Fusion temperature analyses were carried out upon slag chipped off of the furnace wall at a distance of approximately 2 meters from the burner and upon an ash deposit on the flue gas sampling tube. The results are reported in Table 6. The initial deformation temperature (∿ 1340C) and fluid temperature (∿ 1440C) of these samples is slightly lower than that of the coal ash (∿ 1430C and ∿ 1540C, respectively). Peak flame temperatures measured along the axis were typically ∿ 1400-1500C as shown in the profiles in Figure 5.

Detailed Particulates Characterization Studies

The history of coal particles within COM flames, their burnout and accompanying transformation of inherent mineral matter, are of particular interest, since such information may bring to light factors and/or conditions in the flames which enhance and/or retard their propensity towards combustibles emission and ash deposition. In the current studies diagnostic tools for characterization of particulates and deposits are being explored and developed.

A number of in-flame solids samples of one of the COM flames investigated to date were examined under a scanning election microscope at MIT (Materials Science Laboratory) and some of the photographs that were taken are shown in Figures 17 through 23. The major input conditions for this flame are as follows: thermal input: 1 MW, swirl No.: 0.53, excess air level: 15%, fuel type: 50% Florida Power and Light COM, and air preheat: nil. A general history of coal particle transformations within a COM flame as believed to be represented by Figures 17-23, may be described briefly as follows.

In the first stage coal particles or agglomerations thereof, are heated and undergo plastic deformations. The trapped coal volatiles, gases and water vapor blow the particle into a 'ballon' (Figure 17). As a result of further pyrolysis and cracking the particle surface carbonizes; a hollow coke particle or cenosphere is formed, and blow holes develop through which gases escape (Figures 18 and 19). As the coal char burns away some of the finer particles of mineral residues are separated at the burning surface and disperse as carbon is converted to CO (Figures 20 and 21. Others if touching tend to coalesce, this process being aided by the negative contact angle between silicate glass and the carbon surface. The non-wetting of the carbon by the molten silicates results in the production of a large number of glassy spheres and cenospheres from each coal particle (Figure 22 and 23).

Summary of Experimental Observations

1. The axial temperature profiles of COM, No. 6 fuel oil and SRC-II distillate flames of comparable swirl (S=0.53), and excess air level (10-15%) are similar in shape and close in value, peaks occuring at ∿ 1400C and exit temperatures being ∿ 1200C.

2. The axial centerline temperature peaks of the zero swirl COM flames are shifted downstream of those of the weakly swirling (S=0.53) flames. This is an effect that would be expected to accompany the introduction of swirl.

3. Axial velocity profiles of COM, No. 6 fuel oil and SRC-II distillate flames of comparable swirl and excess air level are similar in form and value. Swirling flames (S=0.53) exhibited peak velocities on the centerline (∿ 7.5 m/s) that were lower than those of zero swirl flames (∿ 12 m/S), as was expected.

4. Axial radiative heat flux profiles of No. 6 fuel oil and COM flames of comparable input conditions are similar in form and value, exhibiting a relative insensitivity towards fuel type. The radiative heat flux in these flames peak in the neighborhood of 350-370 kW/m^2 and towards the tail end are on the order of 250-275 kW/m^2.

5. The radiative heat flux peak of zero swirl COM flames appears to be slightly shifted downstream of that of flames having swirl. This is an expected trend; as swirl is increased the flame is shortened and the region of most intense combustion moves in towards the nozzle.

6. A comparison of the axial O_2 and CO_2 concentration profiles of COM flames with those of a flame of an all-liquid fuel, in this case SRC-II, demonstrates the somewhat delayed nature of the COM combustion process. The concentrations of O_2 and CO_2 reach their equilibrium values earlier along the SRC-II flame axis than along that of the COM flames.

7. The sharp decay in CO concentration that accompanys its burnout, along the axis of zero swirl COM flames takes place at a position further downstream of that of swirling COM (S=0.53 flames). However the CO concentration decays to nearly identical values of 0-50 ppm for both flame types at the combustor exit.

8. Axial total particulate concentration profiles of COM flames investigated to date decay to values on the order of 0.8 g/Nm^3 at the combustor exit. Exit particulate concentrations of No. 6 fuel oil and SRC-II flames are on the order of 0.01 to 0.05 g/Nm^3.

9. The introduction of swirl (from S=0 to S=0.53) in COM flames noticeably affects the solids concentration along the flame axis at positions close to the nozzle (< 1.5 m). However the total solids concentration decays to nearly identical values at the combustor exit.

10. The solids emission levels of a zero swirl COM flame were observed to increase by approximately 25% when changing from 15 excess air to near stoichiometric combustion conditions.

11. COM flames at a 15% excess air level exhibited CO emissions on the order of 50 ppm. Decreasing the excess air level to 5% resulted in modest increases in CO emissions, which ranged up to 100 ppm. COM flames at or very near to stoichiometric combustion conditions (< 0.1 - 0.2 O_2 in the flue) yielded CO emissions that were usually less than 500 ppm, except for occasional puffs in excess of this value.

12. Ash deposits collected over varying input and operating conditions of the Florida Power Light COM yielded mineral analyses that were similar to that of the coal ash.

13. The relative concentrations of alkalies and sulfur on the inside and outside layer of an ash deposit from flames of the 50% Florida Power and Light COM exhibited a trend contrary to that typically reported in the literature. However, the deposit was collected over a time that may have been too short for migration of these species to be evidenced.

14. Fusion temperature analyses of ash and slag from flames of the Florida Power and Light COM show initial deformation and fluid temperatures under reducing conditions that are 80-100C lower than that of the coal ash. This is possibly indicative of the formation of eutectics resulting from the interaction of mineral constitutents in the ash of the coal and the oil.

15. Photographs taken with a scanning electron microscope of axial centerline solids samples of a Florida Power and Light COM flame show the presence of cenospheres of diameters typically 50-100 μm which are believed to be formed from the coal in the fuel. Glassy spheres and cenospheres of pure mineral matter typically of diameters of 2-10 μm ere also observed.

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TABLE I
RUN CONDITIONS FOR COM FLAMES INVESTIGATED AT THE MIT CRF

FLAME NO. (DATE)	1 (10/15/81)	2 (11/4/81)	3 (11/4/81)
Thermal Input MW (lb/min)	∿ 1	∿ 1	∿ 1
Fuel Type	50% FPL	50% FPL	50% FPL
Nozzle Type	ICL	ICL	Y-Jet
Swirl No., S	0.53	0.0	0.0
Velocity of Jet at Burner Exit ft/s (m/s)	115 (35)	115 (35)	115 (35)
% O_2 in Flue (Excess Air)	2.82 ± .2 (∿ 15)	2.82 ± .2 (∿ 15)	2.82 ± .2 (∿ 15)
Comb. Air Inlet Temp. F (C)	80±20(27)	80±20(27)	80±20(27)
Air Flow Rate lb/min (SCFM @ 60°F, 1 atm)	52±2(680)	52±2(680)	52±2(680)
COM 'Day' Tank Temp. F (C)	160(71)	140(60)	125(52)
Com Firing Temp. F (C)	245(119)	245(119)	180(83)
COM Firing Press, psig	200	195	46
Atomizing Fluid Pressure, psig	110	110	60
Measurements Taken:	Axial Profiles: CO_2, O_2, CO, NO_x, Temp., Particulates, Radiative Flux, and Flue Gas Analysis	Axial Profiles: CO_2, O_2, CO, NO_x, Temp., Particulates, Radiative Flux, and Flue Gas Analysis	Axial Profiles: Particulates only, and Flue Gas Analysis

TABLE I
(Continued)

FLAME NO. (DATE)	4	4a	4b	5
Thermal Input MW (lb/min)	∿1	∿1	∿1	∿1
Fuel Type	40% CCC(A)	40% CCC(A)	40%CCC(A)	40%CCC(B)
Nozzle Type	Y-Jet	Y-Jet	Y-Jet	ICL
Swirl No., S	0.0	0.0	0.0	0.53
Velocity of Jet at Burner Exit ft/s (m/s)	∿110(34)	91(27.7)	100(30.4)	96(29.2)
% O_2 in Flue (Excess Air)	2.8±.3	0.5±.1(∿2%)	1.1±.2(∿5%)	0.9±.2(∿5%)
Comb. Air Inlet Temp., F (C)	60±20(16)	60±20(16)	60±20(16)	50±20(10)
Air Flow Rate, lb/min (SCFM @ 60°F, 1 atm)	52±2(680)	43±1(560)	47±1(615)	46±1(600)
COM 'Day' Tank Temp., F(C)	118(48)	118(48)	118(48)	130(55)
COM Firing Temp., F (C)	210(99)	210(99)	210(99)	250(120)
COM Firing Press, psig	∿50	∿50	∿50	∿175
Atomizing Fluid Pressure, psig	100	100	100	100
Measurements Taken	Axial Profiles of CO_2, O_2, CO, NO_x, Temp., Particulates, and Flue Gas Analysis	Flue Gas/Solids Sampling and Analysis	Flue Gas/Solids Sampling and Analysis	Axial Profiles of CO_2, O_2, CO NO_x, Temp., Particulates, Radiative Flux and Flue Gas Analysis

TABLE 2
ANALYSES OF COM FUELS AND OF THEIR COAL AND OIL COMPONENTS

FUEL SOURCE: FLORIDA POWER AND LIGHT CO. (FPL)

	OIL	COAL	MIXTURE 10/2/81	MIXTURE 10/15/81	MIXTURE 11/4/81
% Coal in Mixture			49.3	51.4	47.4
Coal Particle Size			∿80% through 200 mesh		
Ultimate Analysis					
Carbon		82.21	85.16	84.99	83.44
Hydrogen		3.82	9.23	9.03	9.20
Nitrogen		1.15	0.75	0.69	0.64
Sulfur	1.8-2.3	0.71	1.94	1.78	1.81
Oxygen		2.32	1.73	3.76	3.85
Ash	0.04	6.87	1.48	1.72	1.67
Water		2.75	0.36	0.44	0.48
Asphaltenes	5.0				
Vanadium (PPM)	200				
Sp. grav. 60F			0.996		1.05
API grav, 60F	13				
HHV BTU/lb	18,410		16,706	16,356	16,610

FUEL SOURCE: COLUMBIA CHASE CORPORATION (CCC)

	CCC (A)			CCC(B)		
	OIL	COAL	MIXTURE	OIL	COAL	MIXTURE
% Coal in Mixture			40			40
% Water in Mixture			3			3
% Oil in Mixture			57			57
Coal Particle Size	∿80% through 200 mesh			100% through 100 mesh		
Ultimate Analysis						
Carbon	85.15	75.3		84.41		
Hydrogen	10.72	5.1		11.15		
Nitrogen	0.37	1.50		0.39		
Sulfur	1.98	2.10		2.00		
Oxygen	1.71	6.8		1.98		
Ash	0.07	7.2		0.07		
Water	0.07	2.0		0.8		
Asphaltenes	8.0			9.0		
Vanadium (PPM)	252			340		
Sodium (PPM)	68			59		
API grav. (60F)	12.4			14.8		
HHV Btu/lb	18417	12887		18563	13688	
Proximate Analysis						
Volatile Matter		39.21			40.11	
Fixed Carbon		47.77			52.34	
Ash		13.02			7.55	

TABLE 2
(Continued)

FUEL	FPL	CCC(A)	CCC(B)
COAL ASH FUSION TEMPERATURES (F)			
Initial Deformation	2600	2230	2200
Fluid Temperature	2800		
COAL ASH ANALYSES			
Silica	50.72	49.3	
Alumina	30.78	23.20	
Titanium Oxide	1.40	1.20	
Ferric Oxide	8.58	20.3	
Calcium Oxide	1.29	2.10	
Sodium Oxide	0.45	0.70	
Potassium Oxide	2.96	1.10	
Sulfur Trioxide	1.10	0.90	

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(1) Analytical data on these fuels are still being collected at the time of writing of this paper.

(2) The data presented above has come from Florida Power and Light Company, New England Power Service Company and Galbraith Laboratories, Inc.

TABLE 3
CRF HEAT BALANCE (KW)

THERMAL INPUT	REFRACTORY LINED SURFACES (23.56 m^2)	WATER-COOLED BURNER QUARL (0.76 m^2)	STEEL SURFACES VIEWING DOORS (0.19 m^2)	AIR-COOLED ACCESS DOORS (0.27 m^2)
996	240	70	25	27

FURNACE EXIT RADIATIVE LOSS (0.21 m^2)	CHIMNEY LOSS	UNDETERMINED
63	580	9

TABLE 4
SOLIDS EMISSIONS AT DIFFERENT EXCESS AIR LEVELS
(S=0.0, Y-jet, 40% CCC (A) COM)

Excess Air	Solids Emission g/Nm^3
0-2%	1.15
5%	1.06
15%	0.923

TABLE 5

MINERAL ANALYSES OF ASH DEPOSITS OF 50% FLORIDA POWER AND LIGHT COM FLAMES

Mineral Analysis Percent	Ash in Coal	COM ASH[2] Deposit Inside Layer (1/8-1/4")	COM ASH[2] Deposit Outside Layer (1/8-1/4")
Silica	50.72	49.39	49.00
Ferric Oxide	8.58	7.48	7.11
Alumina	30.78	29.02	28.46
Titania	1.4	1.49	1.48
Lime	1.29	3.03	3.26
Magnesia	1.12	1.47	1.63
Sulfur Trioxide	1.10	0.10	0.67
Potassium Oxide	2.96	1.52	1.53
Potassium Pentoxide	0.45	---	---
Sodium Oxide	0.45	0.49	1.09
Phos. Pentoxide	---	0.02	0.01
Sulfur Forms **Percent**			
Pyritic		0.02	0.01
Sulfate		<0.01	0.03
Organic		0.03	0.14
Total		0.05	0.18

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1. Data provided by Florida Power and Light.

2. Analyses carried out by Galbraith Laboratories.

TABLE 6

FUSION TEMPERATURE ANALYSES OF SLAG AND ASH DEPOSITS

(Fuel Type: 50% Florida Power and Light COM)

	Reducing Atmosphere		
	Ash in[1] Coal	Slag Deposit[2] 2m from burner	Ash Deposit[2] 4.5m from burner
Initial Deformation	2600F(1427C)	2480F(1360C)	2440F(1338C)
Fusion (Softening) H/W		2540F(1393C)	2520F(1382C)
Fusion (Softening) 1/2 H/W		2560F(1405C)	2550F(1399C)
Fluid Temperature	2800F(1538C)	2620 (1438C)	2620F(1438C)

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1. Data provided by Florida Power and Light Co.
2. Analyses carried out by Galbraith Laboratories Inc.

Beer

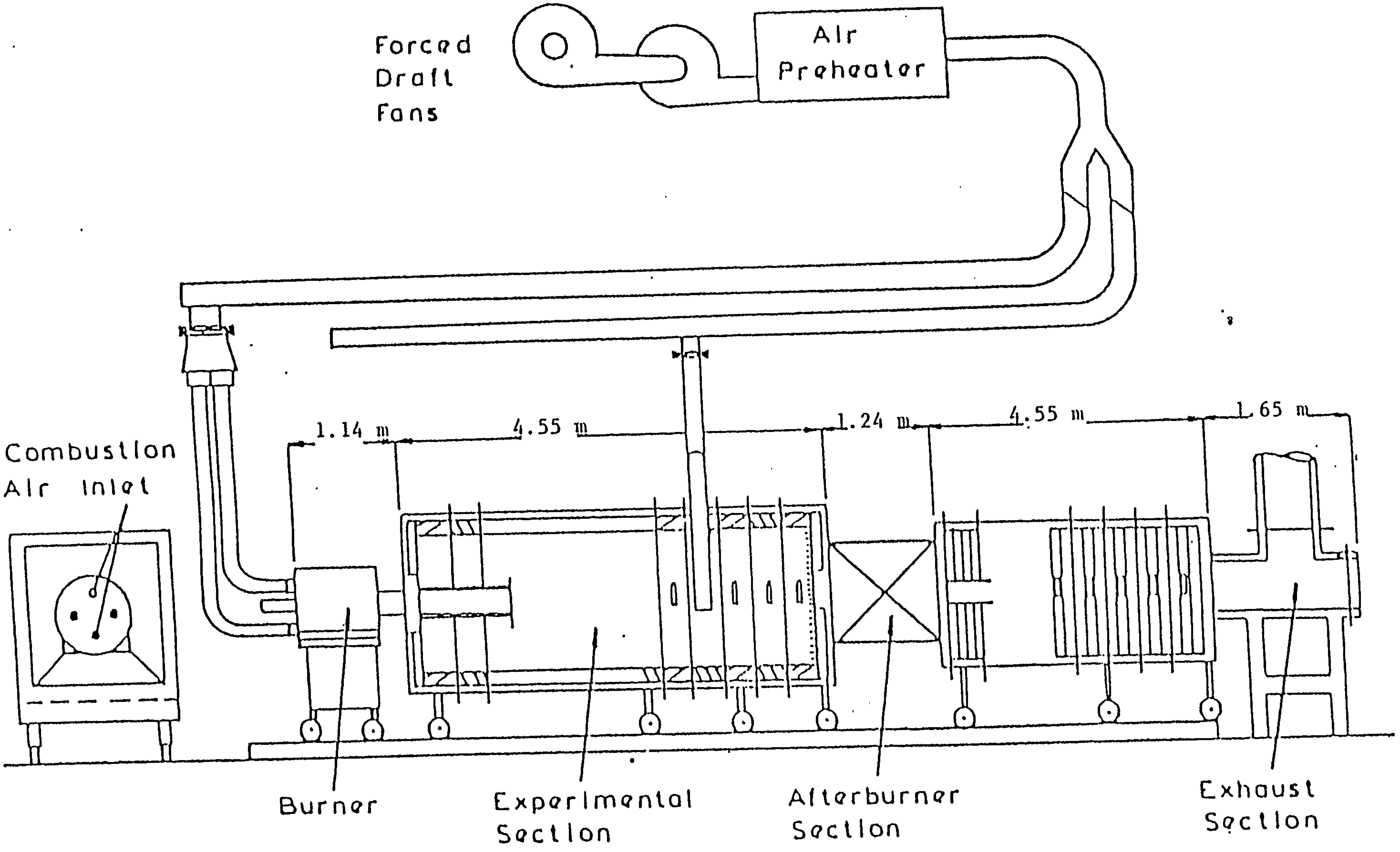


FIGURE 1. DIAGRAM OF THE MIT COMBUSTION RESEARCH FACILITY

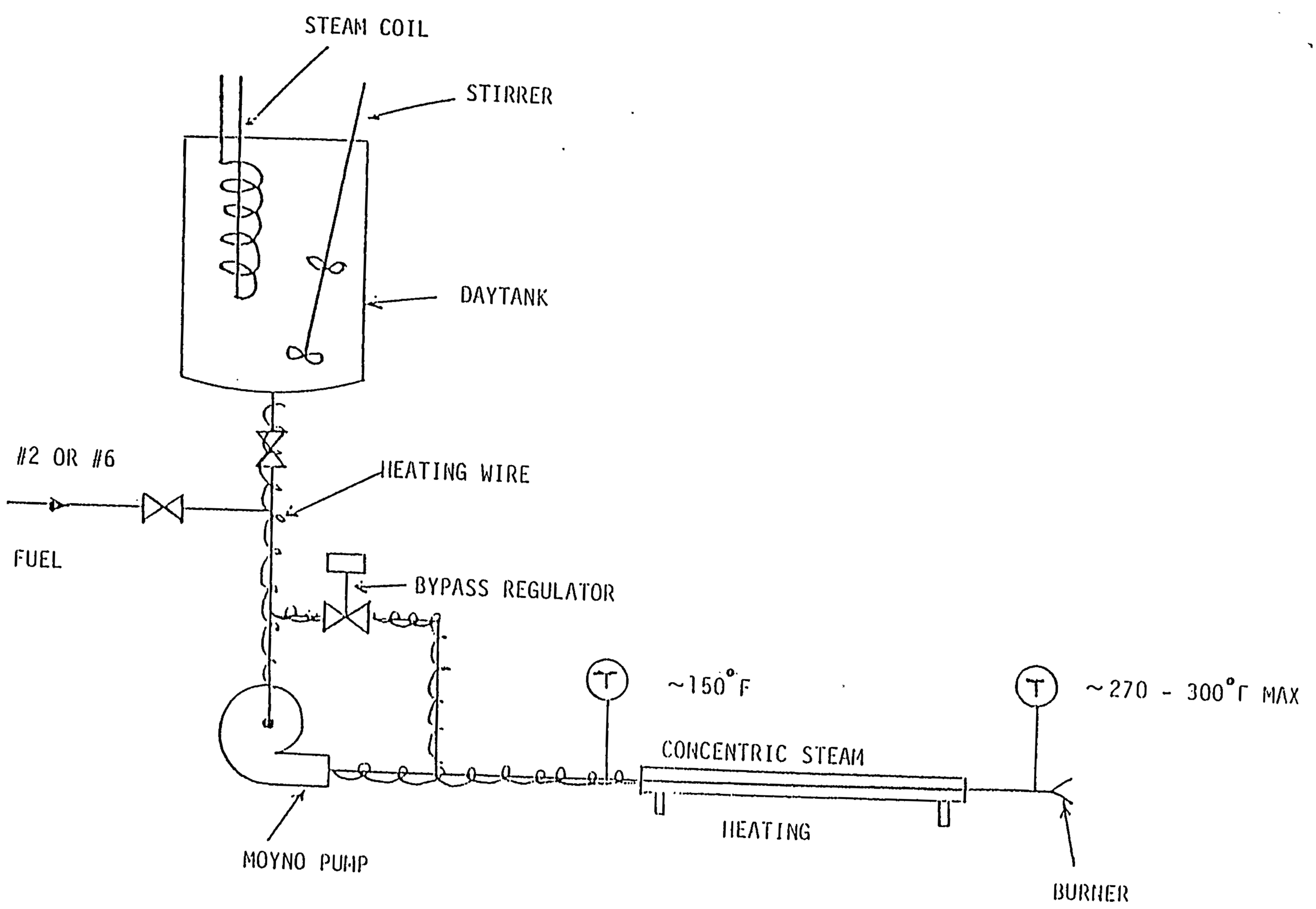


FIGURE 2. THE MIT - CRF COM FUEL DELIVERY SYSTEM

Beer

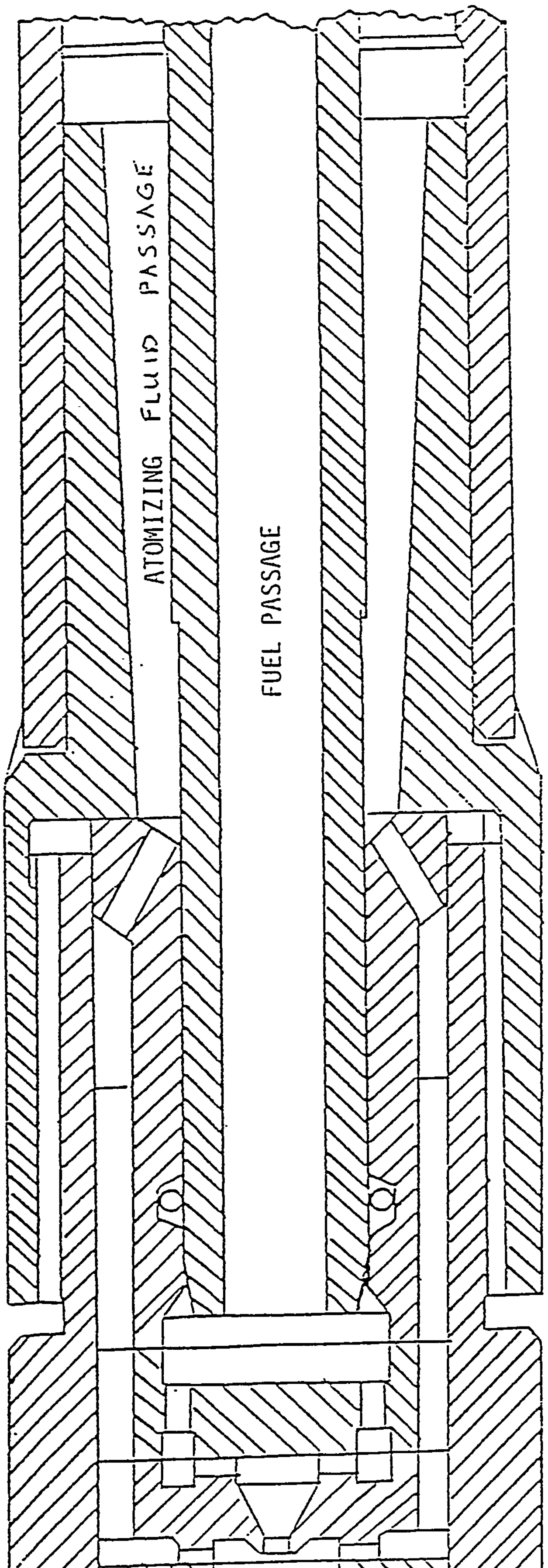
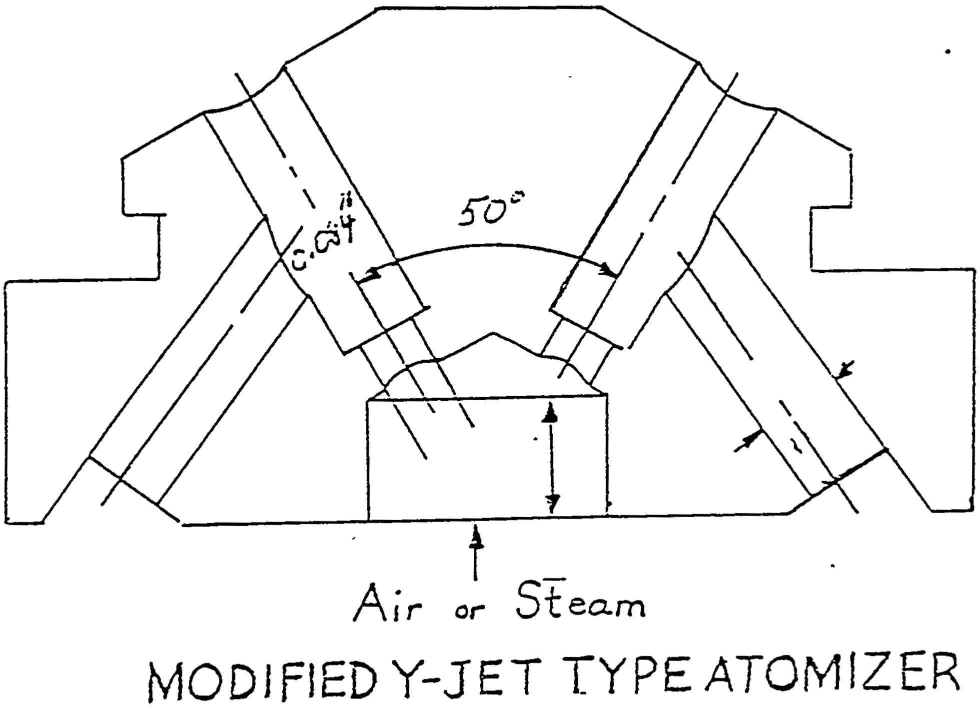


FIGURE 3. ATOMIZER FOR COAL OIL MIXTURES, ~ 1 MW (NEI ICL COMBUSTION SYSTEMS)



.FIGURE 4. MODIFIED Y-JET TYPE ATOMIZER