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# A Unique Combustion System for Oil to Coal Conversions

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# A UNIQUE COMBUSTION SYSTEM FOR OIL-TO-COAL CONVERSIONS

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## ABSTRACT

Until recently, conversion to coal meant one of the contemporary methods of firing: traveling grate stokers or pulverized coal. An emerging coal utilization technology is now being looked at for direct conversion—the slagging combustor.

This paper describes the general data base which facilitates proper evaluation of conversion considerations of existing oil- and gas- firing units to coal firing. It also discusses design considerations of the furnaces, heat recovery equipment, and firing equipment such as the slagging combustor. The advantages of retrofit capability, outage time, ash removal, and maintenance of prior fuel capability are reviewed.

It is important to reject a major portion of the coal ash in the combustor in order to prevent serious boiler fouling problems and consequent derating of the boiler.

This paper presents a unique combustor design which employs a gas flow pattern that drives toroidal vortices which entrains the ash particles and deposits them as slag on the combustor walls.

## INTRODUCTION

Recent events in the Persian Gulf have brought back memories of ten years ago to America and many foreign countries. There were long lines for gas, fuel costs rose sharply, and talk of energy independence was everywhere. The combustion of coal as an alternate fuel to oil and natural gas in steam generating units was proposed by the government and industry alike.

One of the driving forces in the mid-to-late-70s for conversion to coal was the rapidly rising cost of oil and the apparent small reserves of natural gas. As oil prices steadied out and deregulation provided new sources of natural gas, the requirements for oil to coal conversions waned.

There is still a need for energy independence here in the United States. To accomplish this, coal must take the leading role in supplying energy needs. Nearly 90% of the proven reserves within this country come from coal of one rank or another. It can be seen in Table I that the net petroleum consumption in the industrial sector was approximately one-third of the total inputs in 1975. The projections for future imports are based on the dwindling domestic petroleum output and the ever-increasing gap between demand and recovery from domestic resources. Since 1965, consumption of coal in the industrial sector has steadily declined, indicating that oil and natural gas are being relied on more heavily than previously[1].

While America is becoming more and more energy independent, if the supply of oil is cut off from the Middle East, then many of our allies who are still dependent on oil for the bulk of their energy needs will be looking to the United States for help, thereby drawing on our fuels availability.

## CONVERSION CONSIDERATIONS

Before delving into the problem areas associated with the steam generator itself, other concerns have to be resolved. A conversion to coal requires that a plant site have adequate facilities for transportation, handling, and storage. In addition, there must be adequate space and facilities provided for pulverizing the coal as well as collecting and disposing of the ash which is formed[2].

CONSUMPTION PATTERN IN INDUSTRIAL SECTOR

| Year of Consumption | Total Annual Consumption | Total Units in Quads | Petroleum Contribution (Percent) | Natural Gas Contribution (Percent) | Coal Contribution (Percent) | Total Annual Imports in Quads |
|---|---|---|---|---|---|---|
| 1950 | 35.2 | 11.9 | 18.5 | 31.1 | 50.4 | |
| 1955 | 39.7 | 13.9 | 26.6 | 30.2 | 43.2 | |
| 1960 | 45.6 | 14.4 | 23.6 | 45.1 | 31.3 | 3.3 |
| 1965 | 53.3 | 17.1 | 24.0 | 40.9 | 35.1 | 5.6 |
| 1970 | 58.1 | 19.8 | 25.3 | 49.5 | 24.2 | 6.7 |
| 1975 | 70.5 | 20.3 | 25.6 | 47.3 | 27.1 | 15.5 |
| 1980 | 81.9 | 31.6 | 23.4 | 45.4 | 31.2 | 16.5 |
| 2000 | 114* | 46.7* | 11.0** | 20.5** | 68.5** | 15.5** |

*Approximate estimates.
**Proposed targets based on current technology for coal production.

*Table I Energy Utilization for United States, 1950-2000*

SUMMARY OF INDUSTRIAL BOILER SIZE AND TYPE INVENTORY

| | | 1967 Boiler Population | | Sales, 1967-1974 | | Retired, 1967-1974 | | 1975 Boiler Population | |
|---|---|---|---|---|---|---|---|---|---|
| Capacity $10^6$ Btu/hr | Furnace Design | No. of Units | Total Capacity $10^6$ Btu/hr | No. of Units | Total Capacity $10^6$ Btu/hr | No. of Units | Total Capacity $10^6$ Btu/hr | No. of Units | Total Capacity $10^6$ Btu/hr |
| 10-16 | Watertube | 7,300 | 91 | 375 | 5.2 | 176 | 2.4 | 7,499 | 93.8 |
| 16-100 | Watertube | 27,060 | 833 | 4,934 | 236.3 | 2,319 | 109.0 | 26,675 | 960.3 |
| 100-250 | Watertube | 4,015 | 658 | 1,157 | 180.3 | 845 | 131.6 | 4,327 | 706.7 |
| 250-500 | Watertube | 942 | 259 | 168 | 61.6 | 56 | 20.0 | 1,054 | 300.6 |
| 10-16 | Firetube | 9,970 | 126 | 6,615 | 85.1 | 1,190 | 15.3 | 15,215 | 195.8 |
| 16-30 | Firetube | 3,160 | 66 | 2,138 | 44.7 | 385 | 8.0 | 4,913 | 102.7 |
| | Totals | 52,267 | 2,033 | 15,387 | 613.2 | 4,971 | 286.8 | 62.683 | 2,359.9 |

Source: KVB, Inc., Industrial Boiler User's Manual, p. 204

*Table II Summary of Industrial Boiler Size and Type Inventory*

In general, industrial boiler sizes vary from 10 million Btu/hr heat input to 500 million Btu/hr. Table II shows a summary of the industrial boiler size and type of inventory. Many of the almost 63,000 units which were operating in 1975 were originally installed for coal firing but, between 1960 and 1975, were converted to oil firing. Many of them were designed for oil or gas firing initially. It is not known exactly how many of these units would be a potential candidate for conversion but certainly many of them would qualify. However, before any of these units can be converted, and removed from oil or gas firing, the companies must satisfy both state and Federal governments that the unit is suitable for coal firing, facilities are available for handling the coal and for the transportation of it, and long range commitments are available from the suppliers. It goes without saying, that the units would have to meet air emission control regulations when firing coal.

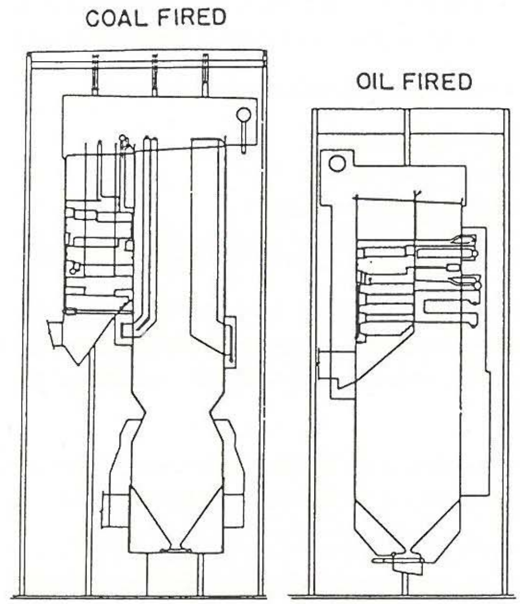



*Figure 1 Steam Generators*

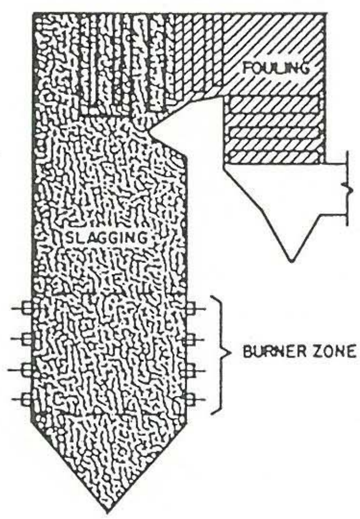



*Figure 2 Slagging and Fouling Areas — Pulverized Coal-Fired Boiler*

There are three distinct areas which must be considered in any unit conversion:

- Furnaces
- Heat recovery equipment
- Auxiliaries

Two modern steam generating units are shown in Figure 1, one designed for oil firing and the other for coal. The difference in size is apparent with coal requiring the larger amounts of area and volume for completing combustion. These size differences show up in design parameters such as heat releases but other considerations which are not readily apparent are flue gas velocity limitations and slagging and fouling tendencies.

Heat releases are parameters used by boiler designers to provide sufficient heat recovery surface to generate the proper amount of steam required, to completely burn the fuel to ash, to insure that furnace exit gas temperatures are sufficiently below the ash fusion temperature of the coal to prevent fouling, and to determine that furnace heat absorption is sufficient to prevent a slagging condition on the furnace walls.

Normal ranges of heat releases for coal-fired units are as follows:

- Area heat release: 60,000 to 75,000 Btu/hr/ft$^2$
- Volumetric heat release: 10,000 to 15,000 Btu/hr/ft$^3$
- Plan area heat release: 1.25 to 2.0 million Btu/hr/ft$^2$

Lower rank coals tend to require lower heat releases to prevent excessive slagging.

Slagging and fouling tendencies of the fuels must be predicted accurately by the boiler designer whether we are looking at new construction or a retrofit conversion (see Figure 2). There is a large amount of work on the part of the boiler manufacturers and the coal suppliers to achieve accurate prediction methods based on fuel analyses or empirical data.

Further on in this paper we will see that an external combustor, which eliminates the major percentage of ash in the fuel, aids in reducing or eliminating the amount of derating which might be necessary in an ordinary oil-to-coal conversion.

Just as slagging tendency affects furnace design, fouling tendency influences convection pass design. Flue gas velocities with pulverized coal fuels are limited to approximately one-half of those used for oil-or natural gas-fired boilers because of the erosive property of fly ash entrained in the flue gases. In Figure 3, a curve is drawn to determine the clear space required between tubes as a function of flue gas temperature and fouling tendencies.

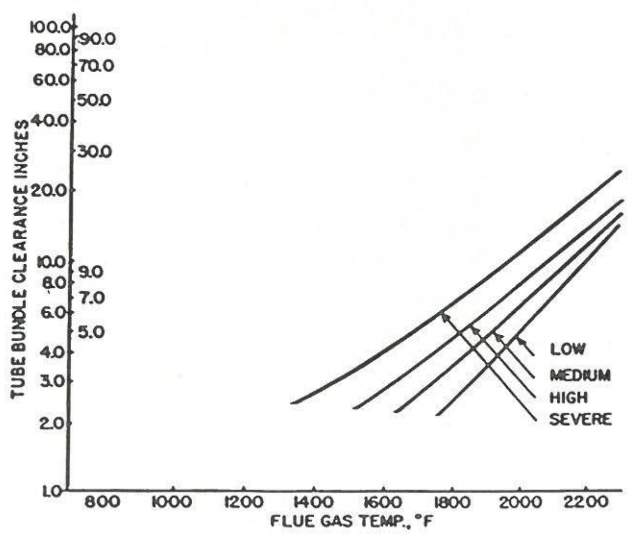



*Figure 3 Tube Bundle Clearance for Various Fouling Tendency Coals*

Increasing the clear space between tubes reduces the probability of a serious fouling problem by increasing the time required for ash to build up and bridge from tube to tube across the gas stream path. This allows the sootblowers to keep the gas lanes open with normal blowing cycles. Larger clear spacing also reduces gas velocity and thus erosion tendencies. Often, oil and gas fired units are equipped with finned surface economizers. These would have to be replaced by bare tube surface or finned surface designed for coal firing. Excessive fouling can usually be prevented by increasing soot blowing equipment operating pressures, adding additional soot blowing capability, or minor tube bundle redesign.

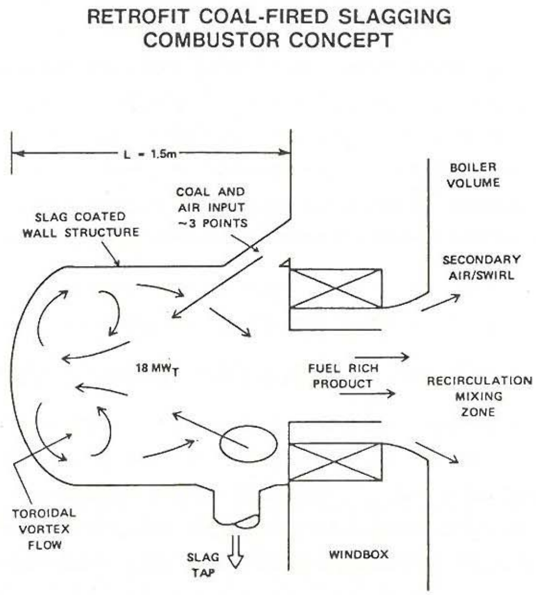



*Figure 4 Retrofit Coal-Fired Slagging Combustor Concept*

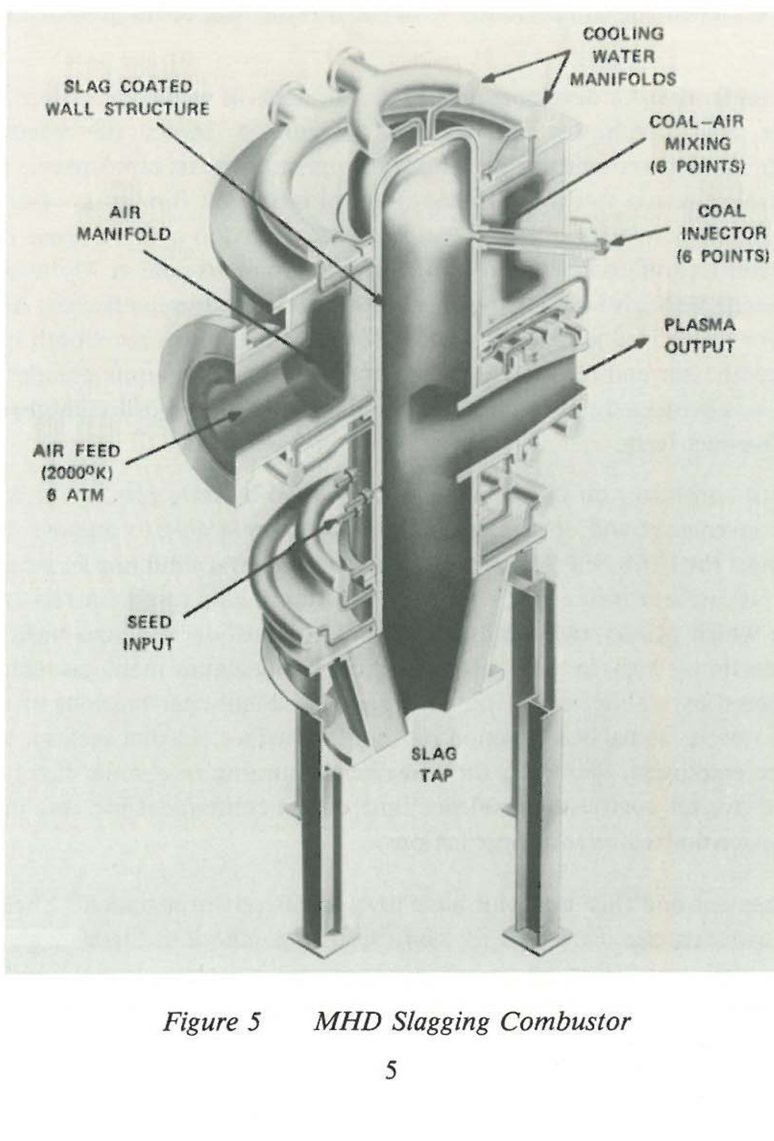



*Figure 5 MHD Slagging Combustor*

Just as important as the furnace and the heat recovery equipment areas in an oil-to-coal conversion are the existing auxiliaries. We have already discussed the need for additional soot blowers and for fuel handling and pulverizing equipment. In any conversion, forced draft and induced draft fans and drives may have to be modified to handle the larger air and flue gas quantities which are inherent in an oil-to-coal conversion. In addition, air heater surface may require changes to provide sufficient volumes and temperatures for coal drying and to prevent fouling of its surfaces. Precipitators and/or scrubbers will be required to meet particulate and $SO_2$ emission regulations. Additional digital and analog control systems will be needed to adequately monitor the operation of the steam generator and the auxiliary equipment.

While some of these design criteria and physical equipment changes may still be necessary, the concept of an external slagging combustor provides many benefits in an oil-to-coal conversion.

## SLAGGING COMBUSTOR TECHNOLOGY

The coal retrofit conceptual approach under development by us[3] is based on replacement of each oil gun-burner assembly by a compact external coal combustor, with the general layout of Figure 4. This operates as a high intensity, slag rejecting combustor, under fuel rich stoichiometry to control $NO_X$ generation. The combustion product exhausts into the boiler heat exchanger column where heat transfer and secondary air addition complete fuel oxidation while controlling thermal $NO_X$ production. Limestone injection into the primary combustor or within the heat exchanger volume may be practical for $SO_X$ control.

Small physical scale, for practical retrofit sizing, is obtained by use of a jet-driven combustion flow field with very high recirculation and excellent high intensity mixing[4]. Mineral rejection occurs as droplet or particle deposits on the combustor wall structure, driven by the high radial accelration of the combustor flow field. The wall structure is designed for compatibility with the flowing slag coating, which serves as the primary thermal insulator.

This approach derives from prior development work in the areas of coal combustion[5],[6] slag management[7],[8] and combined cycle coal combustor technology[4],[9]. Figure 5 shows the geometry of a slagging magnetohydrodynamics (MHD) combustor developed for operation at six atmospheres pressure and 4500°F, with 70 percent mineral rejection to the wall. Slag removal is as melt flow to a water quench system. The combination of high intensity mixing and high temperature resulted in a heat release rate of approximately 130 MW per cubic meter (2 million Btu/ft$^3$ hr atm), firing bituminous coal at 70 percent through 200 mesh grind. Comparable results were also obtained using a Montana sub-bituminous coal. An extensive predictive modeling capability for pulverized fuel combustion rate and stability was used both in development of the MHD topping cycle combustor and for scaling and combustion stability mapping under boiler retrofit conditions. Based on this, it is projected that a nominal 60 million Btu/hr retrofit combustor will be about four feet in diameter by five feet long.

Figure 6 shows some constaints on operating regime imposed by $NO_X$ production and molten slag flow. In terms of retrofit convenience and operating efficiency, it is preferable to operate the retrofit combustor at low heat loss. To meet the EPA NSPS $NO_X$ limit, this imposes an overall burner stoichiometry not greater than 0.85 to 0.95 (at 10 percent heat loss to the wall structure). This results in relatively high combustion product temperature which allows rapid pulverized coal combustion via high yield devolatilization and heterogeneous char reactions. Also, in that region of the operating regime map, gas temperature is well above the lower bound imposed by stable flow of the resulting slag. Final char burnout of the large particle size fraction is expected to occur as particle reaction on the slag surface. In that respect, a stoichiometric ratio as low as 0.6 could be employed. However, the slower char burning rate under highly reducing conditions would force increased overall combustor residence time, and a consequent increase in package size, which is not desirable for space-limited retrofit applications.

Slag coating development and flow behavior have been extensively investigated[7],[8] based on a water-cooled metal wall structure with ceramic inclusions for controlled slag adhesion. Figure 7 shows a set of sequence photographs of slag coating evolution on an initially bare wall structure. Initial bonding is to the exposed ceramic with subsequent flow of melt streamers bridging the metal, and steady state development of a uniform

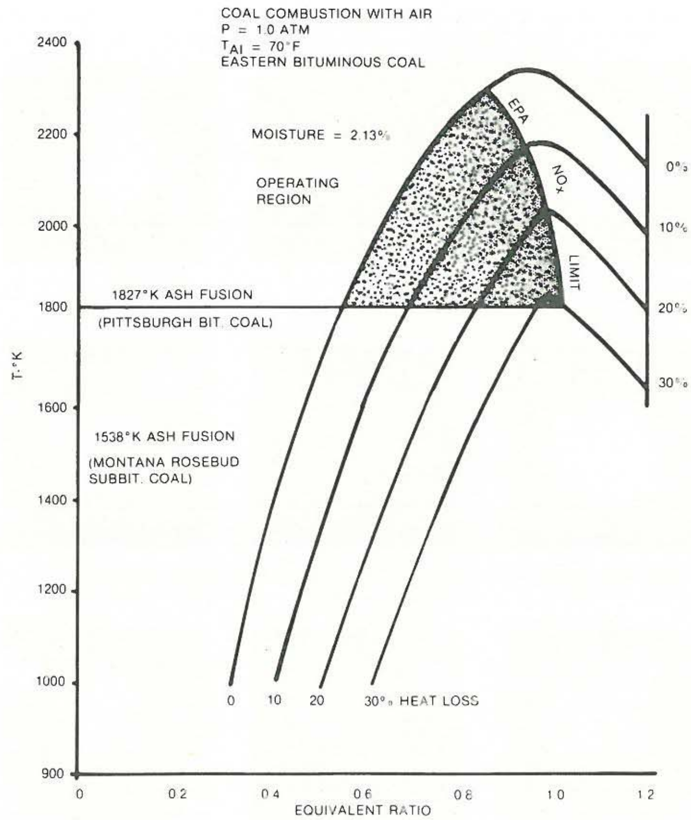



*Figure 6 Effect of Burner Heat Loss on Allowable Ratio and $NO_x$ Control and Slag Flow*

flowing coating on a time scale of some tens of minutes. Figure 8 shows some of the engineering constraints on wall structure design for stable steady state operation of a metal wall with a protective slag thermal barrier. This approach has been employed in long duration MHD topping cycle components, with well over 1,000 hours of individual component operation and several thousand hours of time accrued[10]. It has also been demonstrated in an entrained flow gasifier[11] and coal combustors[4,8]. Figure 9 shows the uniform slag coating developed on the steel wall of a coal combustor under steady state conditions.

Performance of a retrofit coal combustor is determined as a balance among several conflicting desirable features, as outlined in Table III. As suggested above, minimum combustor size results from combusting fine coal with near stoichiometric air, with intense mixing driven by high pressure drop. High slag rejection also drives air pressure drop but requires larger particle size. Low heat loss suggests low product temperature and small size, which are qualitatively incompatible. Finally, low emission of $NO_x$ implies low temperature and excess fuel operation which conflicts with the requirement for minimum unit size.

As shown in Figure 10, a useful regime of operation is available in which slagging operation with low-$NO_x$ and high fuel combustion rate are possible. Experimental results indicate that a combustor residence time of 50 ms or less is required to approach 100 percent fuel utilization under these conditions. This results in an acceptable combustor size envelope for many industrial and utility retrofit applications (1 million Btu/$ft^3$ hr) while firing a nominal 70 percent through 200 mesh coal with an overall pressure drop of about twenty inches $H_2O$. Depending on specific application constraints, a more compact unit or higher slag rejection could be obtained by choice of different fuel properties and system pressure drop.

## RETROFIT CAPABILITY

The slagging combustor will become a component of the much larger industrial boiler system. The combustor must meet boiler heat transfer requirements with respect to gas circulation, radiation, and water use.

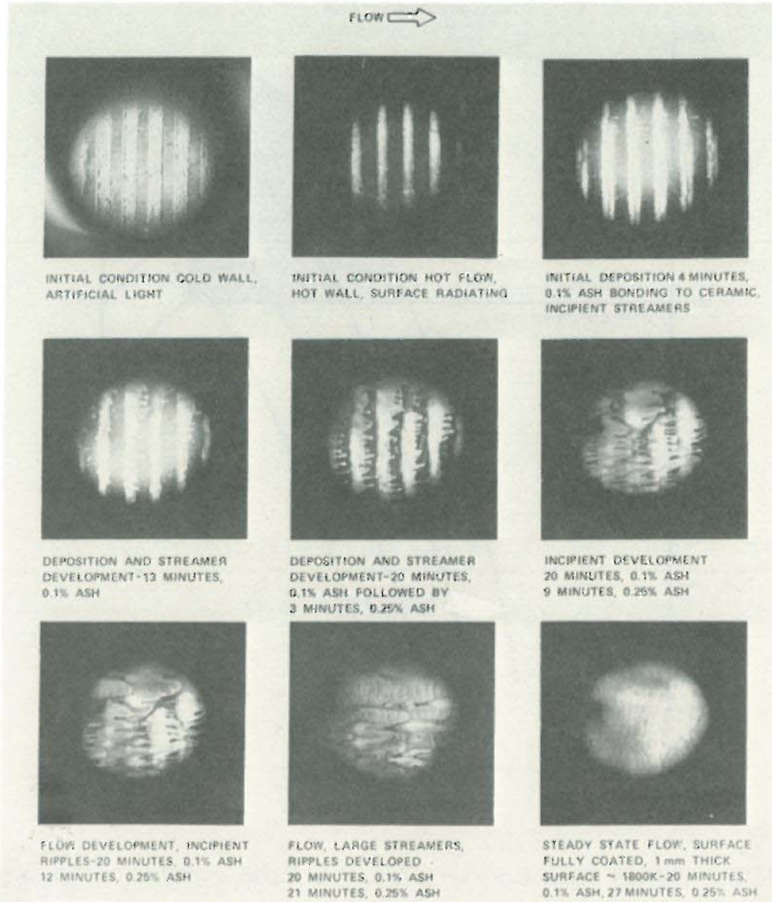
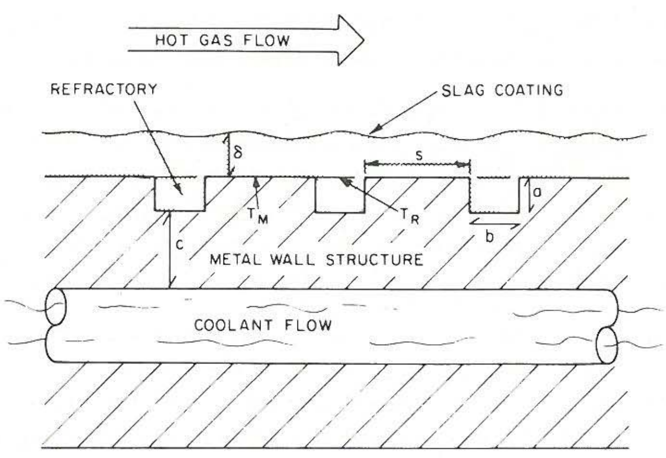



*Figure 7 Slag Layer Development Sequence Photographs*




- THERMAL CONSTRAINTS

  $T_M$ > DEW POINT: OR > HYDRATE DECOMP. TEMP.

  $T_R$ < FUSION TEMP. OF EUTECTICS

*Figure 8 Operating Regime Constraints*

The overall "retrofit" conversion system utilizes a specially designed coal combustor, mounted external to the boiler and operated in a manner to reject the major portion of the coal ash as slag prior to entering the boiler. Analysis has shown that this design will be more compact and have higher ash rejection rates and lower heat losses than cyclone designs that have been used in utility applications.

The mechanical interface with the boiler, the boiler room, the coal supply, and ash disposal systems must be defined. The slag tap will be part of the external combustor. To keep it open, attention must be given during design to the local heat balance on the slag flowing through the tap. Both tap geometry and strategies for avoiding blockage have been explored. Operational experience with coal combustors has provided a practical basis for the necessary technology development. Fuel is a power plant's largest single operating cost, therefore, efficient fuel utilization is important. The slagging combustor provides a stabilized primary combustion zone which provides sufficient residence time and heat transfer for pyrolizing and igniting the incoming fuel. The option is available for increasing the ash particle diameter and particle rejection efficiency by burning a coarser coal grind. An advantage of the slagging combustor is that the unit maintains its prior fuel capability after conversion. It is not necessary to burn coal solely after retrofit.

As with other fuels, coal combustion may emit undesirable pollutants such as $NO_X$ and $SO_X$ into the atmosphere. $NO_X$ emissions can be limited by maintaining substoichiometric (fuel rich) combustion conditions in the slagging combustor which represents the first combustion stage. The second stage of combustion (the final oxidation) occurs in the boiler furnace. This stage will be used to control the gas time/temperature history for low-$NO_X$ emission levels.

Sulfur in the fuel will be converted to $SO_2$ during combustion. However, $SO_2$ emissions can be substantially lowered by injection of sorbents into the furnace. Under the overall reducing conditions of the slagging combustor and the highly reducing environment of the char reaction on the slagging wall, high levels of sulfur capture are obtained.

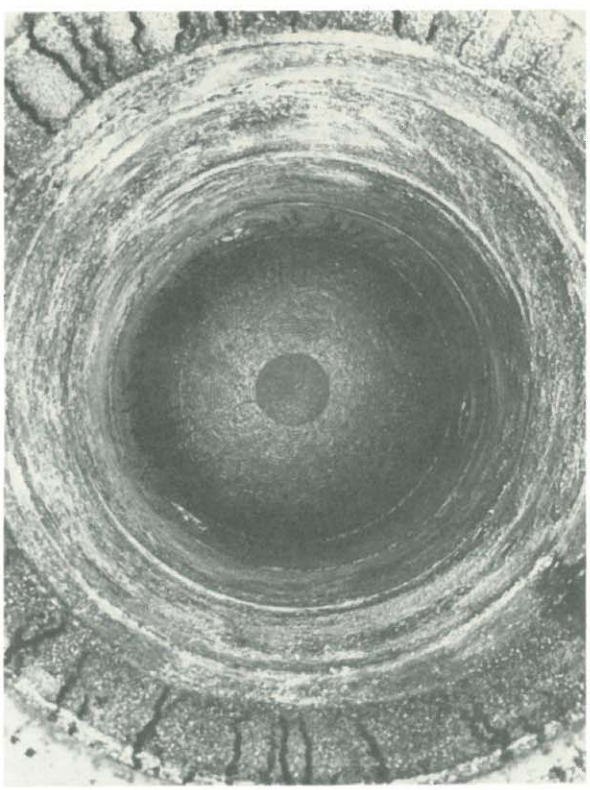


*Figure 9 Slag Coating*

RETROFIT COMBUSTOR - TECHNOLOGY ISSUES

| Device Requirement | Key Parameter | Controlling Factors |
|---|---|---|
| Compact | Residence Time | Coal particle size<br>Stoichiometry<br>Temperature<br>Fluid mixing |
| High slag rejection | Inertia/drag | Coal particle size<br>Air pressure drop<br>Geometry |
| Low heat loss | Wetted wall area<br>Specific heat flux | Size/configuration<br>Temperature<br>Wall chemistry |
| Low emissions | Gas chemistry | Temperature<br>Stoichiometry<br>Coal Composition<br>Additives? |

*Table III Retrofit Combustor — Technology Issues*

## CONCLUSIONS

The slagging combustor concept presents many advantages to oil-fired unit conversion to coal firing. These include:

- Retrofit capability
- Outage time
- Ash removal
- Prior fuel capability

The slagging combustor is designed to fit within the space taken by existing fuel burning equipment. It is not anticipated that pressure part changes would be required. Some changes will be required in the circulation system and space would be needed for slag removal. However, these are not considered to be overpowering.

Ash removal can be readily accomplished since the ash is in a molten state. The design of the combustor is such that good turndown, easy start-up and shut-down, and rapid load following can be maintained. There may be a market for the ash because of its quenched state from a molten condition.

The retrofit to coal firing does not necessarily mean that the unit could not revert back to its present fuel capability. If oil or natural gas are available, they could be used as back-up or main fuel utilizing the same combustor in the event coal was not available.

While the concept of the slagging combustor is intriguing, there are still some areas of development which are necessary. Many of these will be addressed in a program for the Department of Energy which has recently been initiated. Areas of investigation include operating pressures, air preheat temperatures, burning characteristics, and furnace performance. Boiler compatibility is affected primarily by slag rejection. This is the key issue of this program. The benefits of a successful program are substantial and industry will be following this program closely.

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