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COAL-IN-OIL: A SUBSTITUTE BOILER FUEL

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by

G. K. Lee* and T. D. Brown*

ABSTRACT

Pilot-scale combustion experiments have demonstrated that mixtures of coal-in-oil can be successfully burned in industrial oil-fired combustion systems. A lignite slurry comprising 33% by weight lignite in No. 2 oil gave combustion efficiencies greater than 90% at excess-air levels above 12%. On the other hand, combustion efficiencies of the order of 50% were measured using a reject bituminous coal having a high content of non-reactive fusinite and semi-fusinite macerals. The degree of burn-out of the coal component was strongly dependent on both the maceral structure of the coal and the aerodynamic patterns in the flame.

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INTRODUCTION

The use of coal-in-oil slurries in steam boilers dates back to the early part of this century(1,2,3). However, there is little quantitative information on the combustion performance of these fuels. Typical of the early reports on the use of "colloidal fuel" is one describing experiments on board the USS GEM(4) where...."stimulated by the inventiveness of war it (colloidal fuel) was so successful that the GEM worked from April to July 1918 solely on this fuel with results satisfactory in every respect." This recommendation is enthusiastic but scrutiny of eye-witness reports shows that the operating time during the test period was accumulated in short bursts of approximately one hour during which time no effective boiler measurements could be made. In addition, the completeness of combustion and the control of stack emissions were not matters of significant concern.

Presently, coal-in-oil fuels are attracting considerable attention because a continuing shortfall of industrial fuel oil is anticipated and it is essential that substitute fuels be available for use in conventional oil-fired equipment. Accordingly, the main objectives of this CCRL* study were:

1. To clarify the major parameters that affect the physico-chemical properties of coal-in-oil suspensions.
2. To evaluate the combustion and pollution characteristics of selected coal-in-oil blends.
3. To assess the suitability of commercially available hardware for handling and burning coal-in-oil fuels.

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FLUID PROPERTIES OF COAL-IN-OIL

Viscosity

The mixtures most commonly used in previous experiments contained 35%-45% by weight of coal. It has been observed that the apparent viscosity of colloidal fuel increases sharply with increased solids concentrations(5). Figure 1 shows that this will be dependent on the size distribution of the coal but for normal pulverized-coal size distributions it appears that a 40% coal concentration is the maximum acceptable level.

Extensive experiments conducted by the Research Council of Alberta(6) showed that up to 72 wt % of <3 mm coal could be added to oil and still give a pumpable fluid. They also noted that particle attrition occurred rapidly in the handling of the suspension to give an equilibrium size distribution. This attrition was thought to occur in the pumps since samples taken diametrically across a pipeline showed a preferential increase in the solids loading within the central core leaving the outer annulus depleted in solids.

The Alberta pipelining experiments demonstrated that slurry viscosities calculated by the Poiseuille equation were all lower than laboratory data obtained with a Brookfield viscometer. The pipeline experiments also showed that colloidal fuels behaved as Newtonian fluids below 50 wt % rather than below 10 wt % as indicated by viscosity studies. This was attributed to the distribution of solids across the pipeline diameter which reduced the effective colloidal viscosity.

Stability

The oleophilic nature of the coal particles affects the long-term stability of coal-in-oil suspension. Particles without surface polar groups reject contact with the oil (poor "wettability") and settle quickly giving a hard sediment that is difficult to re-entrain. Coke and highly-oxidized coals fall into this category. The absence of polar groups can, to some extent, be offset by the addition of small amounts (2% by weight) of polar liquids such as water, tannic acid or varsol to the coal; highly stable suspension can also be obtained with commercial dispersants. The amounts of polar liquids and dispersants required for satisfactory stability can only be determined by experiment.

Lignitic coals are usually easy to blend and stabilize in oil because their cellulosic constitutents are oleophilic.

COAL QUALITY

The two coals used in the combustion trials were a western Canadian lignite known as Bienfait and an eastern Canadian bituminous coal known as Dominion. The lignite, being cellulosic, was highly reactive and easily ignited. However, the bituminous coal was a washery reject that contained over 60% fusinite and semi-fusinite, both of which are inert forms of carbon having poor ignition and burning characteristics. The proximate analyses of these two coals are given in Table 1.

TABLE 1

Proximate Analyses of the Coal Component of the Coal-in-Oil Fuels

Coal Analyses		Bienfait	Dominion
Moisture	%	21	1
Ash	%	8.5	9
Volatile Matter	%	32	25
Fixed Carbon	%	38	64
Sulphur	%	0.5	1
Gross Calorific Value	kJ/kg	19,790	32,590

TABLE 2

Size Distribution of the Coal Component of the Coal-in-Oil Fuels

Screen Fraction (U.S.S.)	Bienfait Lignite wt %	Dominion Bituminous Grind A wt %	Grind B wt %	Grind C wt %
plus 60	0.63	0.59	2.11	2.85
60 to 100	0.54	0.53	11.29	21.27
100 to 140	0.63	0.89	8.35	14.55
140 to 200	1.21	3.81	6.85	11.03
200 to 325	12.04	15.49	11.92	14.78
minus 325	84.95	78.68	59.48	35.52

The gross calorific values of the coal-in-oil fuels were:

Bienfait Coal-in-Oil	37,250	kJ/kg
Dominion Coal-in-Oil	40,740	kJ/kg

COAL-IN-OIL HANDLING

A series of static sedimentation tests were carried out with the three grinds of Dominion Coal in No. 2 oil shown in Table 2. Typical results for 33 wt % of coal-in-oil are shown in Figure 3 where the influence of the larger size particles on the rate of settling is clearly demonstrated. In view of these settling characteristics, coal Grind "C" was eliminated from the combustion experiments and it was decided to provide continuous stirring and circulation of all coal-in-oil blends rather than to utilize a stabilizing agent to minimize fuel separation in the storage tank.

Having determined that the selected coal-in-oil blends were reasonably stable in suspension, a series of pumping tests were initiated to establish criteria for designing a fuel handling system. These tests, which were carried out in a closed-loop piping system equipped with various types of fittings and valves, demonstrated that:

(a) slurries containing over 33 wt % of 80% minus 200 mesh pulverized coal rapidly blocked all flow passages less than 2.5 mm diameter;

(b) diaphragm-type gauges and control valves are essential for trouble-free operation;

(c) vertical pipelines must be accessible at both top and bottom for purging and cleaning;

(d) shutdown should be as rapid as possible to prevent selective separation of the coal component due to low flow velocities.

THE EXPERIMENTAL FURNACE

Furnace Description

The CCRL tunnel furnace used in the experiments described in this paper has been reported in detail elsewhere(7). It is a horizontal, cylindrical furnace consisting of 28 individual calorimetric sections and with a total length of 4.25m and a diameter of 1m. The maximum thermal input is 2000 MJ per hour (0.56 MW). Figure 2 is a schematic illustration of the furnace.

The furnace coolant (Therminol FR 1) is a fire-resistant chlorinated biphenyl which remains stable at atmospheric pressure over a temperature range from 0 to 315°C.

Fuel Supply System

The fuel-handling system, illustrated in Figure 4, was designed to operate at a minimum flow velocity of 45 cm per second with the coal-in-oil mix being circulated around the closed-loop system by a Moyno positive-displacement pump. The pressure drop in the flow line to the burner was approximately 15 cm WC per 100m of line. This compares with values of 3.2 cm WC per 100m reported by Berkowitz(6) and the difference is attributed to the different coal sizes. No major change in this pressure drop was observed during any of the combustion experiments. The capacity of the laboratory storage tank limited the duration of each combustion trial to about 4 hours.

Coal-in-Oil Burner

The burner used in the combustion studies was a low-pressure atomizing type, illustrated in Figure 5. In this system, the primary air is divided by movement of the axially adjustable cone into an inner and an outer air stream. The inner air stream passes around the oil nozzle and aspirates the fuel to produce the primary air-fuel mixture. The oil nozzle is illustrated in Figure 6. The primary air-fuel mixture combines with the outer air stream in the mouth of the fixed cone, Figure 5, where the turbulence generated by the two high-velocity flows breaks up any large liquid fuel droplets that have persisted and generates a homogeneous secondary air-fuel mixture. The mixture ignites within a conical refractory quarl downstream of the burner and the flame front stabilizes within this quarl. Provision was made for the injection of secondary air and/or recirculated combustion products just past the quarl.

The coal-in-oil burner and the refractory quarl were mounted on a refractory-lined combustion chamber, 45 cm diam by 60 cm long, at the front end of the tunnel furnace.

Gas and Particulate Sampling and Analyses

Particulate matter was sampled by a system developed at CCRL. A stainless steel probe was inserted into the gas stream to withdraw a sample at isokinetic conditions, through a cyclone separator and filter combination, for subsequent determinations of the solids burden and the degree of coal burn-out.

Samples were taken from the centre of the flue duct 1m downstream from the particulate sampling point and continuously analyzed for carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), nitric oxide (NO), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2). Sulphur trioxide (SO_3) measurements were taken intermittently at the same location.

COMBUSTION EXPERIMENTS

Burner Aerodynamics

The velocity profiles measured at the exit plane of the burner indicated that the flow had a dominant axial velocity component. The radial velocity components reflect the effect of the oil nozzle which diverts flow from its axial path. The tangential component of velocity was approximately symmetrical about the centre line of the burner and showed the presence of some rotation in the flow pattern. The proximity of the peaks of tangential velocity to the burner axis, which indicated that the tangential momentum was small in relation to the axial momentum, is consistent with the relatively low calculated value of the swirl number, 0.1. This implies that the flames generated by this burner do not have a substantial central recirculation core. Further investigation with a small hammer-head pitot revealed the existence of a small bluff body recirculation vortex in the immediate wake of the oil nozzle. This vortex did not extend more than 3 cm down-stream from the nozzle.

TABLE 3

Summary of Combustion Trials Identified by Coal Component

Coal Component	Bienfait Lignite		Dominion Bituminous					
Coal Grind (see Table 2)			A	A	A	B	B	B
Firing Rate Kg/hr	68.1	68.1	45.4	45.4	59.0	57.3	61.8	61.8
Proportioning of Air Supply								
Primary	0.4	0.35	1	0.7	0.6	0.8	0.7	0.3
Secondary	0.6	0.65	0	0.3	0.1	0.2	0.2	0.3
Recirculated Flue Gas	0	0	0	0	0.3	0	0.1	0.4
Flue Gas Dust Loading mg/Nm^3	103	96	470	377	531	410	510	666

Velocity profiles measured across the mouth of the refractory pre-combustion chamber did not show the existence of any recirculation zone. It was noticed, however, that all the velocity components periodically fluctuated by as much as 50%. This was attributed to the existence of massive eddies in the flow system, which undoubtedly contributed to increased turbulence and micro-mixing of air and fuel within the flame.

Flame Appearance

During the combustion trials the fuel could be switched from coal-in-oil to No. 2 oil without loss of ignition or noticeable change in flame stability. The lignite-in-oil flames were similar in brightness and appearance but slightly longer than the No. 2 oil flame. On the other hand, the flames produced by the bituminous coal reject in oil were characterized by a significant carry over of burning particles or "sparklers" in the post-flame gases.

Degree of Coal Burn-Out

As with any substitute fuel, the industrial utilization of coal-in-oil will be largely dictated by the degree of carbon burn-out that can be achieved within the flames. To assess this parameter two assumptions were made: first that the No. 2 oil component was completely burnt out and second that the gas-borne particles all originated from the coal component. The degree of burn-out was then defined by the following equation:

$$\text{Degree of Burn-Out} = \frac{\text{\% Combustible in Fly Ash}}{\text{\% Fixed Carbon} + \text{\% Volatile Matter in Coal}}$$

Figures 7, 8, 9 and 10 show that the degree of burn-out with lignite varied from 91 to 98% at excess air levels of 22 and 12.5% respectively. These values compare favourably with results obtained with the same lignite in a pulverized-fired pilot-scale research boiler when a burn-out of 99% was achieved(8).

The degree of burn-out with the bituminous coal reject did not exceed 60% and was completely unsatisfactory. However, it is apparent from Figures 7, 8 and 9 that the degree of burn-out can be improved by careful control of a number of parameters, by increases in firing rate, excess air level and secondary air ratio and by decreases in flue gas recirculation volume.

The unsatisfactory burn-out of the bituminous coal reject was due to its maceral structure. Petrographic examinations revealed that this coal contained over 60% fusinite and semi-fusinite. Together with 9% ash and 1% moisture this results in a fuel with about 70% inert matter. These fusinite and semi-fusinite macerals were found to exist in an essentially unreacted state in the fly-ash samples.

Further improvements in burn-out may be possible by either optimization of flame aerodynamics or by selection of a different burner design, but it is unlikely that high-combustion efficiencies with high-fusinite coals are attainable in cold-wall furnaces such as the one used for these experiments.

Future Work

In future coal-in-oil experiments the No. 2 oil will be replaced with No. 6 oil which more closely matches the combustion characteristics of coal. It is anticipated that the degree of burn-out for blends of coal in No. 6 oil will be equal or superior to those reported here because the coal component will be exposed to more oxygen and higher temperatures for a longer time than was the case with No. 2 oil.

Studies are also being planned to elucidate the influence of the higher density of No. 6 oil on the settling and stability characteristics of various coals and the influence of maceral structure on the degree of burn-out.

CONCLUSIONS

1. Experience to date indicates clearly that coal-in-oil slurries are feasible substitutes for fuel oil in industrial boilers.
2. Slurries containing up to 35% by weight of pulverized coal can be prepared, pumped and burned successfully using commercially available equipment.
3. Coal-in-oil flames, being shorter and more intense than pulverized-coal flames, proved less residence time to burn out coal particles. Therefore, petrographic examination of the coal structure is essential to ensure that only high reactivity coals (i.e., those low in fusinite, semi-fusinite and oxidized vitrinite) are selected for blending with oil. This prerequisite is particularly important when dealing with coal tailings and rejects from coal washeries.

ACKNOWLEDGEMENTS

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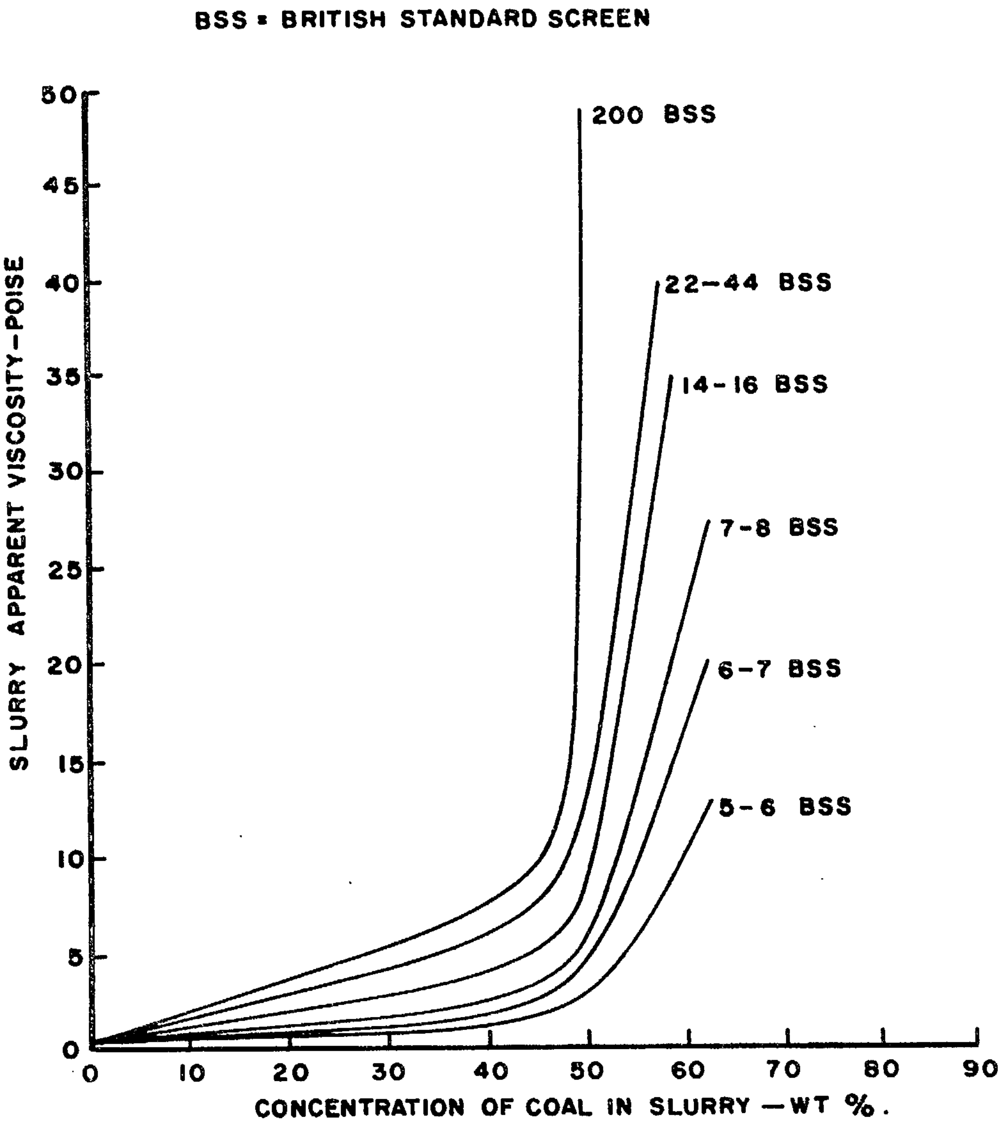

Figure 1. The effect of coal particle size on slurry apparent viscosity at 77°C (after Whittingham and Windsor).

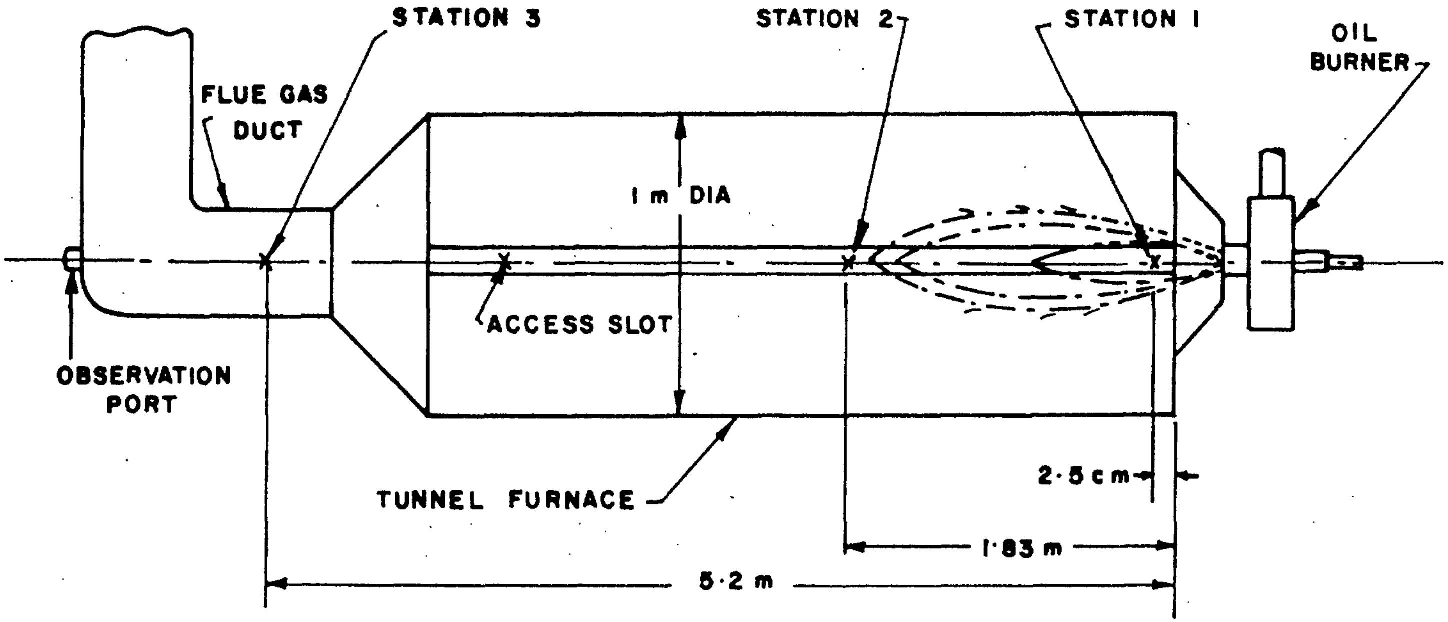

Figure 2. Schematic diagram of the CCRL tunnel furnace.

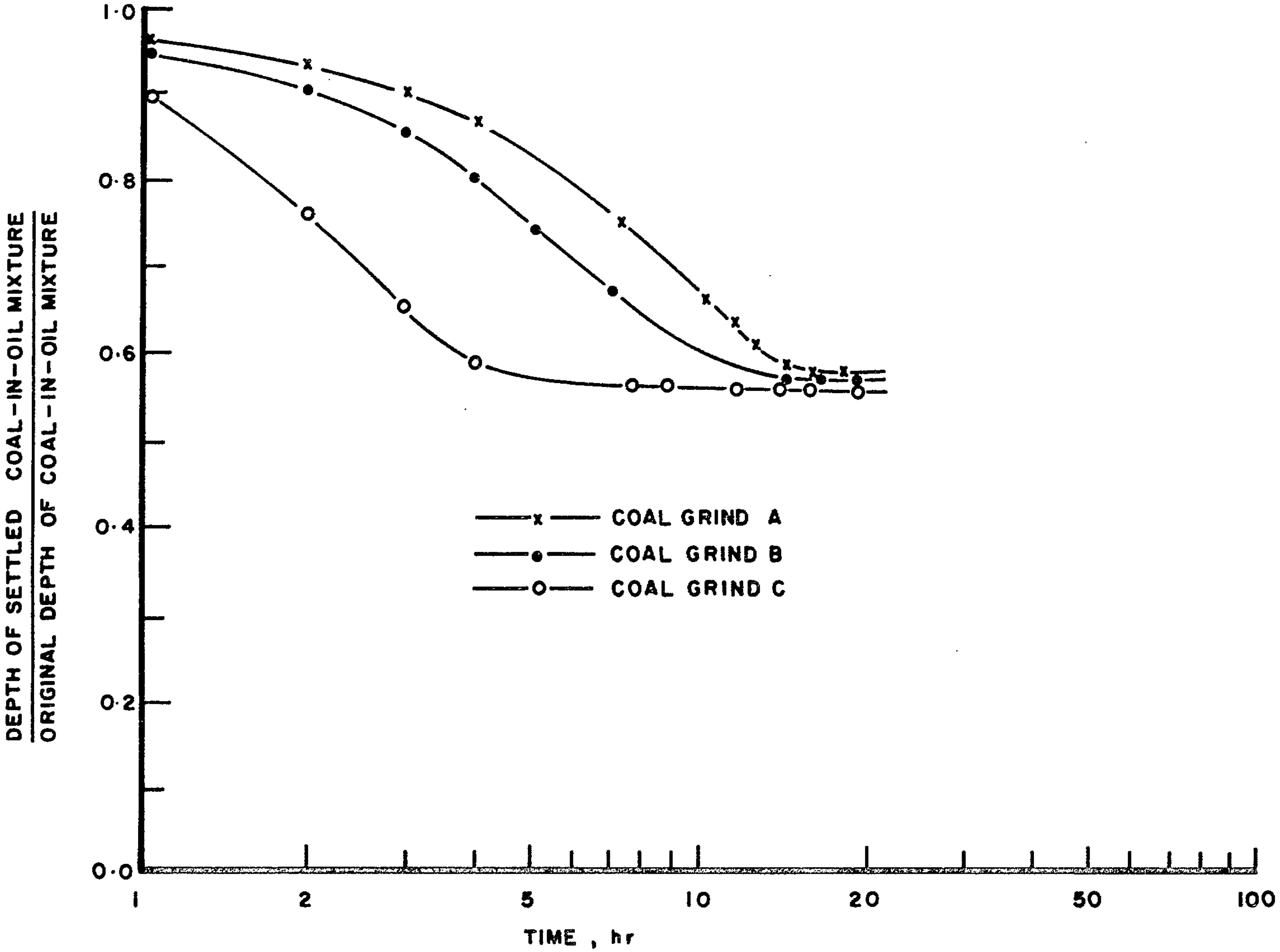

Figure 3. Stability characteristics of the coal-in-oil mixtures.

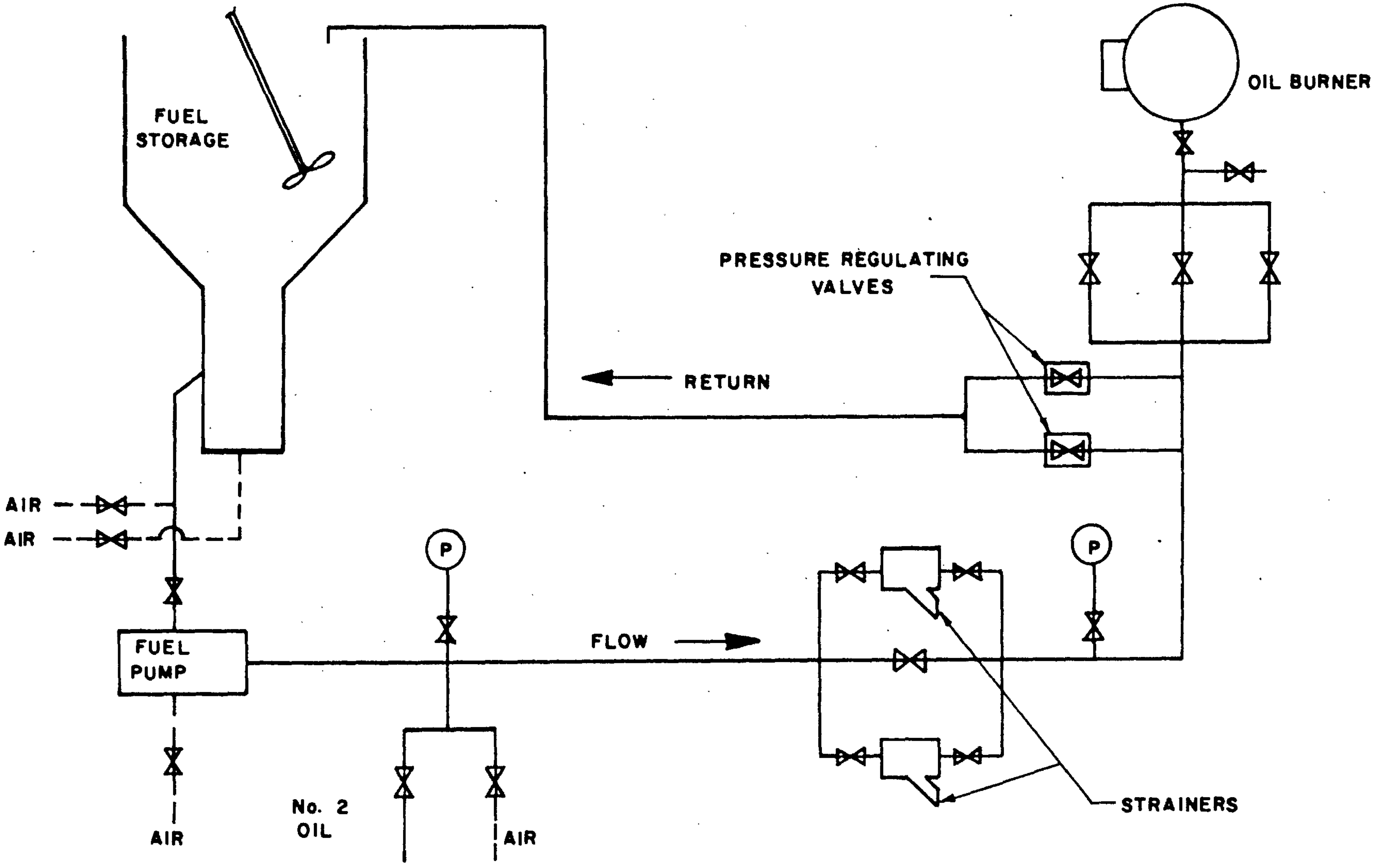

Figure 4. Schematic diagram of the coal-in-oil fuel storage and handling system.

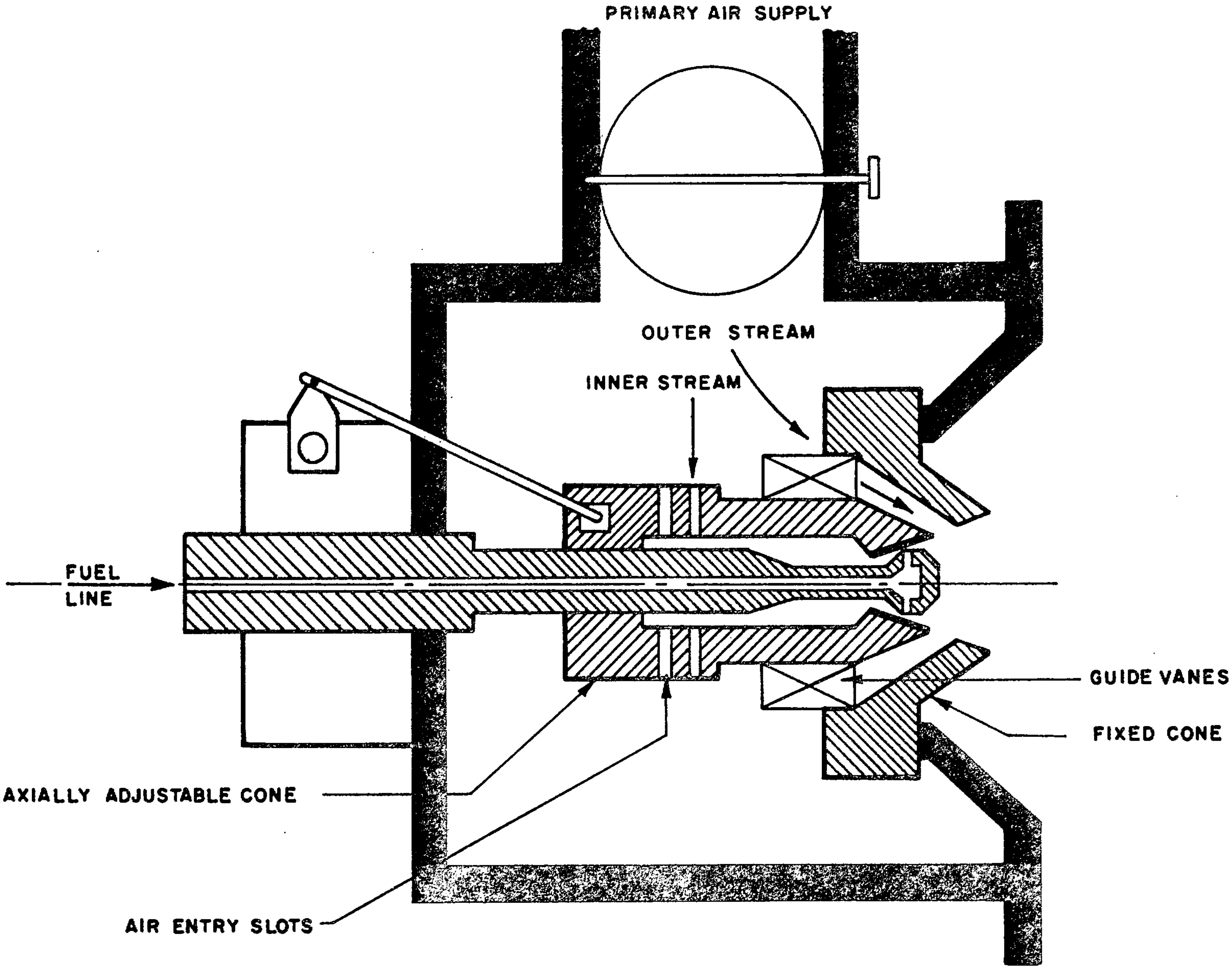

Figure 5. Schematic diagram of the coal-in-oil burner.

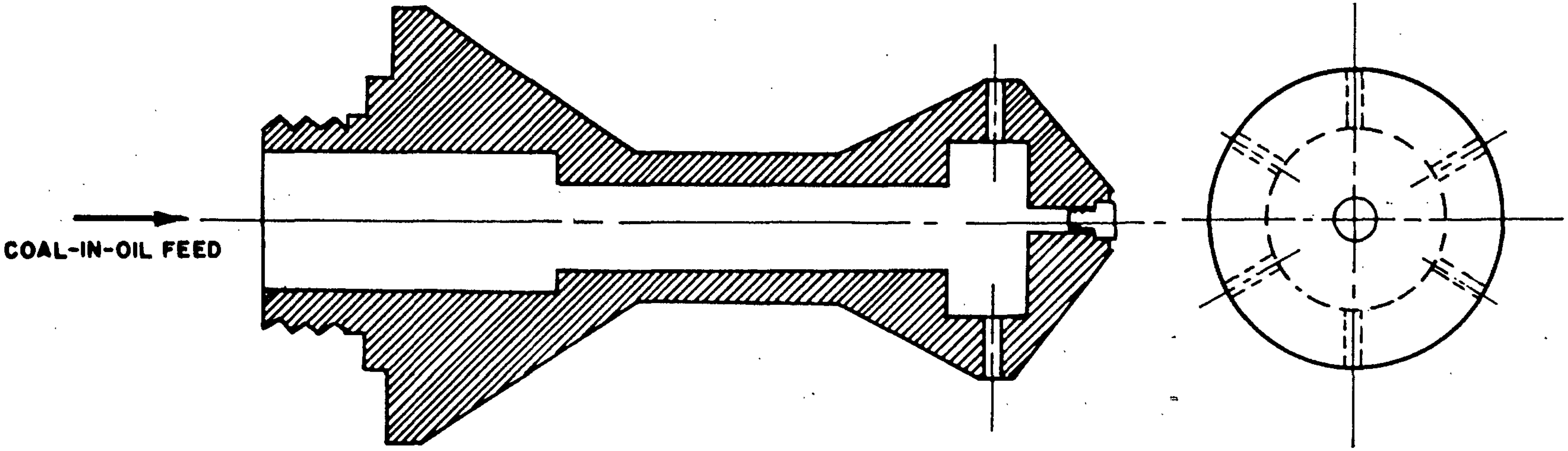

Figure 6. Schematic diagram of the coal-in-oil nozzle.

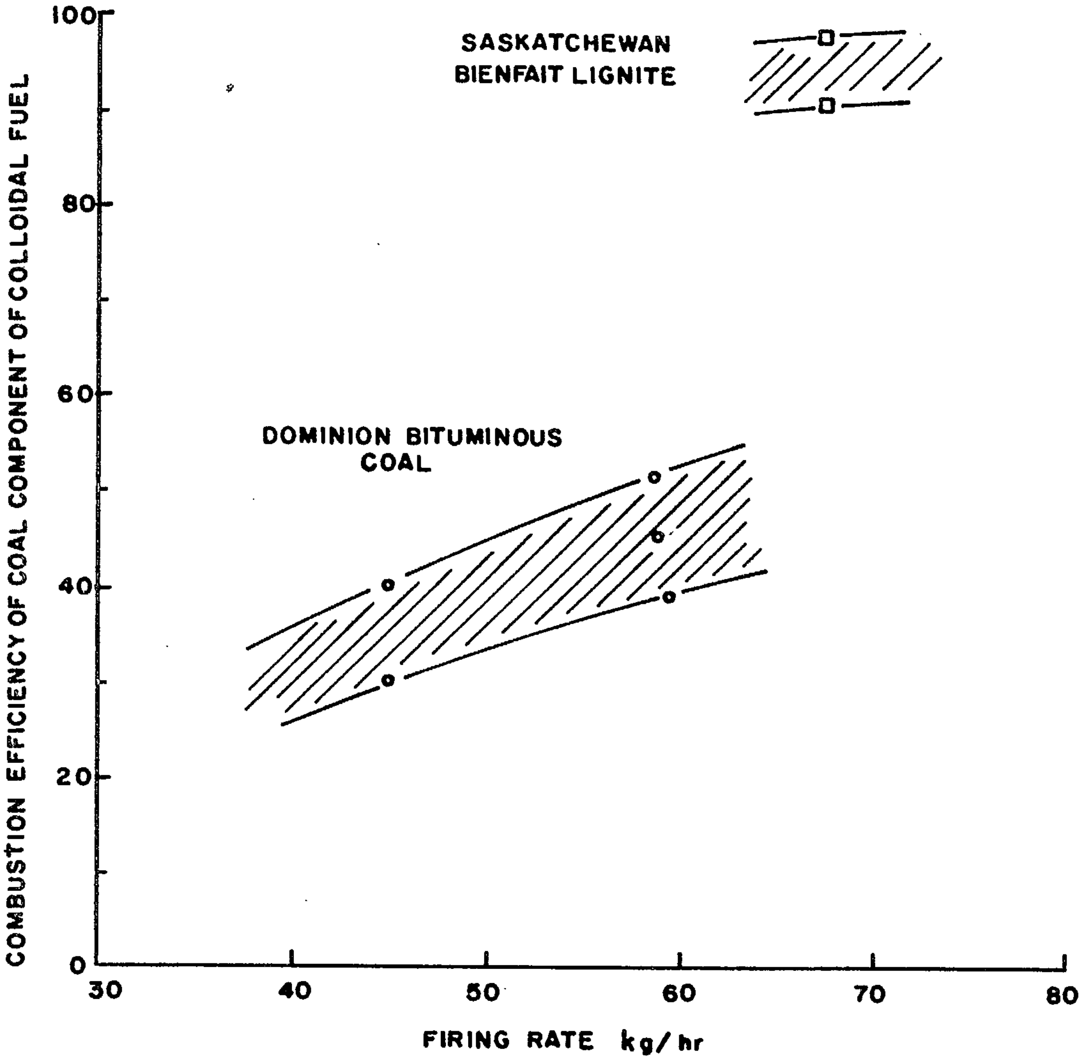

Figure 7. The effect of firing rate on the combustion efficiency of the coal component of the colloidal fuel.

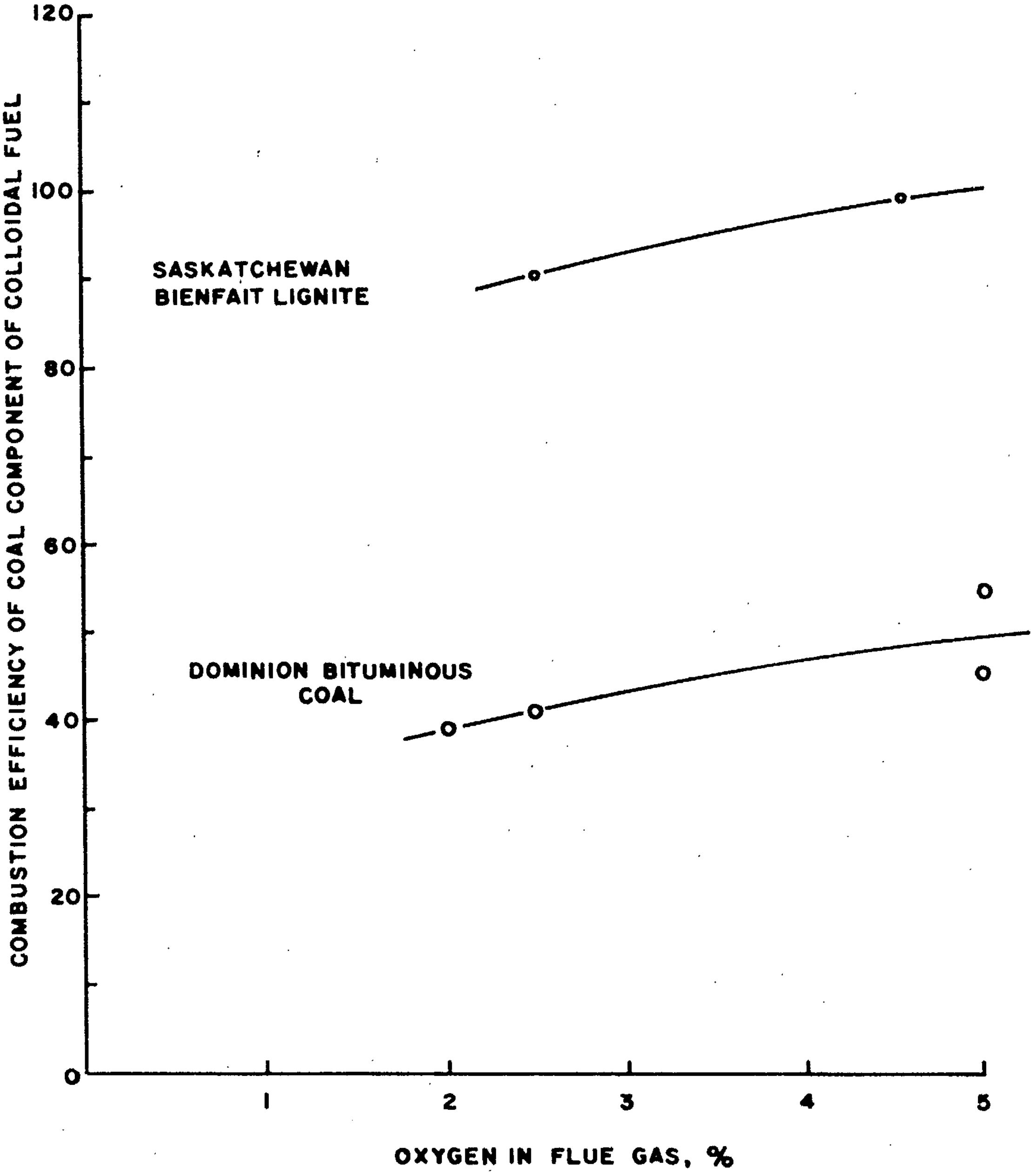

Figure 8. The effect of excess-air level on the combustion efficiency of the coal component of the colloidal fuel.

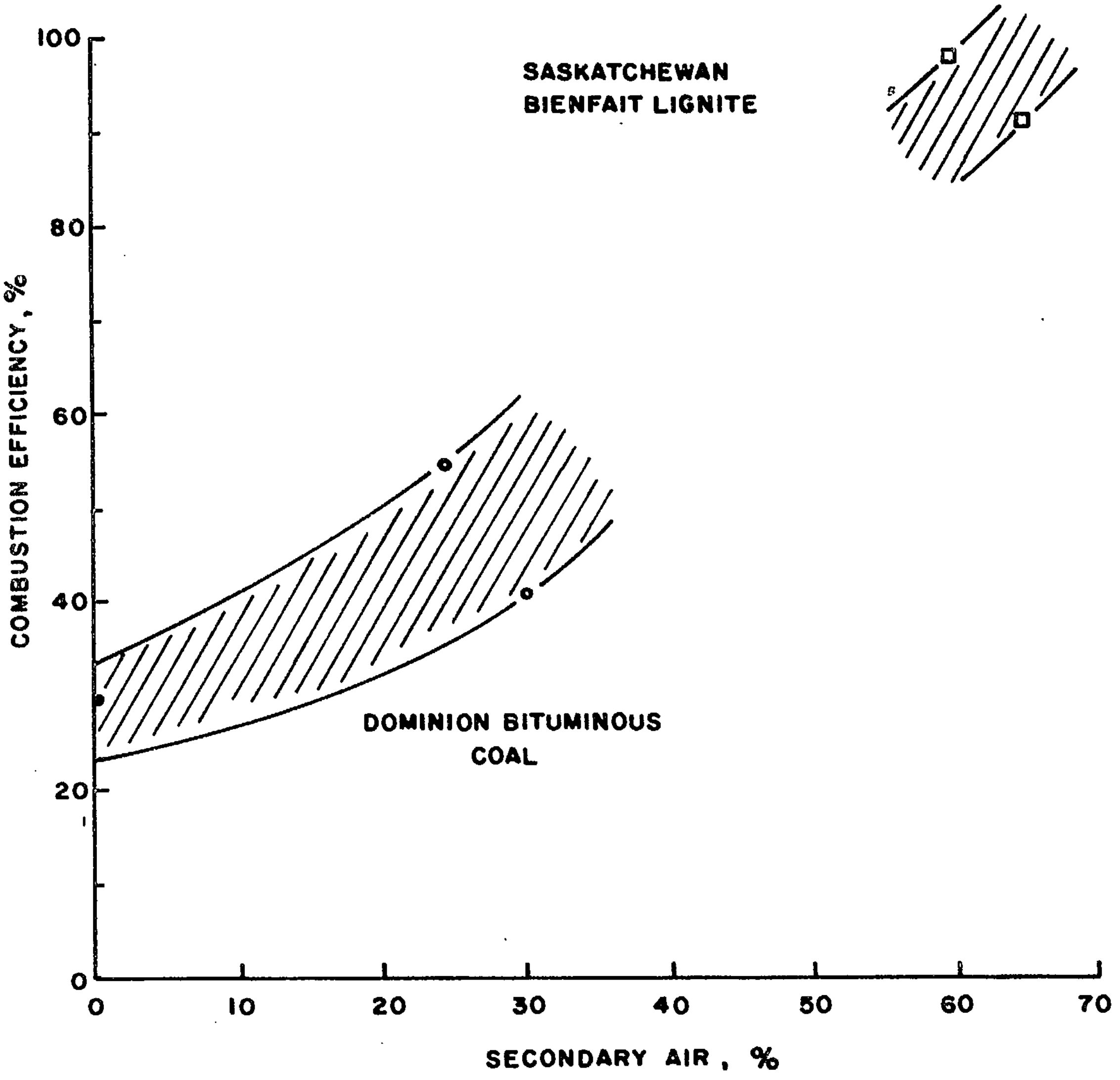

Figure 9. The effect of secondary air proportion on the combustion efficiency of the coal component of the colloidal fuel.

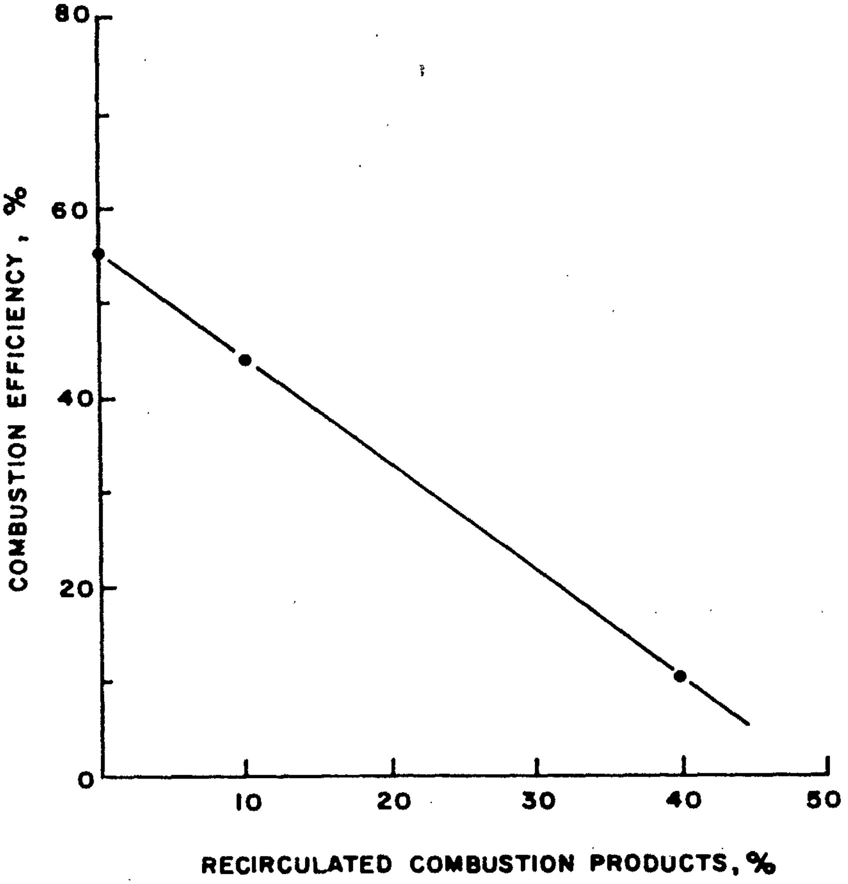

Figure 10. The effect of recirculated flue gas on the combustion efficiency of the coal component of the colloidal fuel (coal Grind B).