The MIT/Marine Industry Collegium
Opportunity Brief #26

The Engineering and Economics of Coal-Fired Ship Propulsion

A Project of
The Sea Grant College Program
Massachusetts Institute of Technology
MITSG 81-7

The MIT/Marine Industry Collegium

THE ENGINEERING AND ECONOMICS OF COAL-FIRED SHIP PROPULSION

Opportunity Brief #26

Revised Edition

July 1, 1981

Marine Industry Advisory Services

MIT Sea Grant Program

Cambridge, Massachusetts 02139

Report No. 81-7

Index No. 81-607-Nft

PREFACE

This Opportunity Brief and the accompanying Workshop held on May 8, 1981 were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 100 corporations and government agencies who are members of the Collegium.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

The underlying studies at MIT were carried out under the leadership of Professor Chryssostomos Chryssostomidis, but the author remains responsible for the assertions and conclusions presented herein.

John B. Bidwell

July 1, 1981

TABLE OF CONTENTS

1.0 Business Perspective

As recently as 50 years ago, nearly all ocean-going ships were propelled by coal-fired boilers driving steam turbines or reciprocating steam engines. However, coal was phased out as a marine fuel with the advent of cheap oil which offered other advantages. Oil had a higher caloric content than coal, was easier to store, to handle, and to burn; and left little ash compared to coal.

However, in recent years oil costs have risen, oil supplies have been interrupted, and the quality of marine fuel oil has declined. As a consequence coal is once again being seriously considered as a marine fuel. Although coal-fired ships are more costly to build than oil-fired ships, several factors combine to suggest that a transition to coal would be economically sound and desirable. Savings on fuel costs exist now and are expected to grow. The United States has abundant coal reserves and would thus be freed from dependence on outside sources for its marine fuel. Moreover, technological advances in the burning and handling of coal, and in the disposal of ash, indicate that some of coal's inherent problems as a fuel can be dealt with effectively. Initially coal-fired ships are expected to be introduced on trade routes carrying coal itself as a cargo and on other routes between terminals at which coal for bunkering is already available. By the turn of the century a substantial portion of the world's merchant ships may again be coal-fired.

New construction of coal-fired ships has been supported by studies and by placement of construction orders. Recognizing that a transition period will be necessary, studies underway at MIT are currently examining the more difficult case of converting existing ships from oil to coal-fired. The economic attraction of saving on fuel costs must be sufficiently large to compensate for diminished cargo space and increased weight in bunkers and machinery, as well as capital cost of conversion. These studies examine thermodynamic and mechanical problems of carrying out such a conversion. An economic comparison has been embodied in computer programs which have been run with today's prices and with projected prices of the two fuels.

These studies show an economic incentive to convert existing ships to coal-firing, particularly for ships with high fuel costs. The minimum size of ship that spends a large proportion of its time at sea and carries low value cargo, such as bulk carriers and tankers, for which conversion would currently be profitable is 70,000 DWT. For high speed ships, such as containerships, the minimum size for profitable conversion is now under study. Another interesting parameter is operating speed. The studies found that in the current economic environment of excess tanker tonnage, the 70,000 DWT coal-fired tanker conversion loses economic competitiveness at lower speeds.

These MIT studies were presented at a Workshop of the MIT/Marine Industry Collegium led by Professor Chryssostomos Chryssostomidis of the Ocean Engineering Department on May 8th, 1981.

2.0 Coal as a Fuel for Ships

2.1 Recent Studies

Several recent studies have addressed different aspects of using coal as bunker fuel. Examining the role of coal in meeting world energy needs during the next 20 years, the World Coal Study projected international expansion of steam coal production and trade, requiring major expansion of transportation facilities. For maritime transportation, the study concluded "a major building program will be required to provide the new ships involved in realizing the projected expansion of world coal trade ... averaging 50 coal ships or 5 million DWT per year for 20 years ..." The mix of ships required is expected to range from Panamax-size of 65,000 DWT up to ships as large as 250,000 DWT in the 1990's.

A recent report of a committee of the National Research Council's Maritime Transportation Research Board included as its first principal recommendation that "... coal is the primary alternate marine fuel; every effort should be made to implement its use. Applications for fuel use permits and construction subsidies for ocean ships should include a requirement for the evaluation of coal and coal/oil slurry."

Y-ARD Ltd. of Glasgow performed a comparative evaluation of a coal-fired and a diesel oil powered vessel for the British Ship and Marine Technology Requirements Board. The vessel chosen was a Panamax bulk carrier on postulated coal-trading routes. A fluidized-bed combustion system was assumed for the coal-powered ship, because this type of equipment is expected to be available as a superior coal-firing option within a few years. The study examined the case of new ship construction for the two types of power and concluded that with current comparative fuel costs, the break-even point has recently shifted in favor of coal.

2.2 Characteristics of Coal

Coal was formed after millions of years of heat, pressure and lack of oxygen resulting from sediments laid down over layers of dead organic material. It is classified as one of several grades of anthracite or bituminous according to the degree of metamorphism achieved during its creation.

The calorific content of coal tends to increase as the proportion of fixed carbon rises and the proportion of moisture falls. Excessive moisture increases the weight of coal and causes higher shipping costs, permits freezing with consequent handling difficulties, and is converted to steam during combustion with absorbtion of energy. Wet coal must be dried prior to combustion.

Soft coal has a high proportion of volatile matter and requires a relatively large volume furnace. Its fine particles burn faster than those of hard coal, which has a low proportion of volatiles and burns with a shorter flame length.

Ash, the inorganic residue from burning coal, is composed principally of oxides of silicon, aluminum, iron, calcium, magnesium, titanium, sodium, potassium and sulfur. It may be economically viable to save coal ash for later treatment and recovery of valuable minerals.

Coal is almost always treated or processed before sale to or use by the customer. This processing can reduce moisture, mineral matter and sulfur content and improve calorific content and uniformity of size. Bituminous and anthracite coals each have somewhat different standard schemes of gradation by size.

Bulk density of coal varies with specific gravity, size distribution, moisture content and amount of settling.

Coal comprises over 60% of the world's total resources of fossil fuels _in situ_ measured by energy content. By the same measure it also accounts for over 60% of the world's economically recoverable reserves of fossil fuels. The United States holds over 30% of world recoverable reserves of coal.

Table 1 describes the size of the international coal trade in 1978. Future trends in the form of net exports of thermal coal from 1976 to 2000 are shown in Table 2. Typical costs in 1980 for steam coal for bunkering are shown in Table 3. (All three tables were taken from Reference 1.)

2.3 Pollution from Using Coal

Air pollution may occur as liquid mist, as gaseous fume or as solid particulate matter. The air pollution from a coal-fired boiler varies depending upon the characteristics of the coal and the design of the boiler and associated equipment. There is no single representative level of emission from coal-firing. The best predictor of pollution to be expected from a given boiler is measurement of emissions from a similar type of boiler burning a similar grade of fuel. Otherwise it is customary to use pollution factors published by the EPA for the type of coal expected to be burned. Air pollution control regulations are usually expressed in terms of mass of pollutant emitted per unit rate of heat input to the boiler. Thus both the concentration of pollutant in the fuel and the heating value of the fuel are important.

Visible emissions result from scattering of light by finely divided particles. Usually black smoke comes from unburned carbon, brown and dark grey smoke are emitted from unburned hydrocarbons, and white is often from liquid aerosols including water vapor. Visible emissions are controlled by furnace design and by operating to promote complete combustion.

Particulate emissions come from the ash content of the coal, which may be as high as 10%. At full power, a 5000 SHP coal-fired ship could produce particulate emission on the order of 25 kg/hr (55 lb/hr). Except for electrostatic precipitators, the efficiency of other collection devices usually increases with the size of the particles. Other collection devices for removing particulates from a gas stream include inertial separators, mechanical filters, wet washers and combinations of these. Electrostatic precipitators also remove liquid aerosol pollutants. From the characteristics of the coal and boiler to be used, the rate of emission and size distribution of expected particulates can be estimated. Then by knowing the maximum permitted emission levels, the percentage required to be removed can be determined. This information can then be matched to the available devices to select an appropriate one for the expected task.

Gaseous pollutants from combustion of coal are primarily the oxides of sulfur and nitrogen. Since the former react with water to form sulfurous and sulfuric acid, the sulfur content and its control are of considerable concern. The boiler may burn low sulfur coal, or the oxides of sulfur may be removed chemically during combustion, or they may be removed from the flue gas after combustion. Low sulfur coal occurs naturally or it may be produced by mechanical and/or chemical processing of high sulfur coal. A means of sulfur removal by burning coal charged with crushed limestone in fluidized bed or stoker furnaces is being developed and holds early promise for high efficiency. Over 100 processes have been proposed for flue gas desulfurization, and some may be adaptable to shipboard use. However, they would probably be used only when the vessel is in the vicinity of land and would be by-passed at sea.

Federal laws on air and water pollution are enacted by Congress and administered by the EPA, which publishes regulations establishing standards to be met and having the force of law. The function of the EPA is to assist the states, which together with local government have primary responsibility for prevention and control of pollution at its source, at least for stationary sources. The EPA has published standards for mobile sources, including motor vehicle and aircraft engines, but not for ship engines. No standards for air or water emissions from ships other than oil and sewage have been published at the federal level.

The standards are set in terms of maximum concentrations of atmospheric pollutants allowed in one area. A single ship is unlikely to exceed these in a local area. The problem is in areas where concentrations exceed the criteria. Most state codes treat such "non-attainment areas" as special cases and provide that more stringent limits may be enforced. These may permit local authority to apply controls to ships source by source through application for emission permits, even though ships are not otherwise regulated by the state. Several major seaports are non-attainment areas. Those states which treat air emissions from ships at all, treat them differently from one another. Consequently, it is probably impracticable to try to meet requirements of all jurisdictions in one design level which would be too strict. Economic competitiveness probably dictates meeting only the requirements of the jurisdiction in which the ship will trade.

Most techniques for cleaning boiler flue gas produce solid wastes such as fly ash, or liquid wastes which require disposal. Together with bottom ash from the coal-fired boiler and liquid waste from boiler blowdown, their disposal over the side is subject to water pollution regulations. These appear to permit the discharge of ash and scrubber effluent beyond the "three mile limit" of U.S. territorial waters. However, under some circumstances the discharge may be constrained by regulations that limit "dumping" as opposed to routine operational discharge. Within the three mile limit state and federal codes are amibiguous in many respects that might impact on coal-fired vessels. For the longer term it is unlikely that coal-fired ships will remain relatively unregulated as to water pollution, other than for discharge of oil and sewage.

2.4 Coal Bunkering Stations

An infrastructure of coal bunkering facilities will have to be constructed, beginning with stations on coal trading routes and eventually extending to incorporate world-wide charter market routes. There is a chicken-and-egg element to this expansion. For many reasons, the most important of which are that ships have grown in size and port calls must be as short as possible, it is not possible to return to the style of bunkering of 50 years ago. One problem will be whether ports will have only a few types of coal to service ships on specific runs or a variety of coals, feed rates and berths for all ships. If fluidized bed combustors are successfully introduced it may ease the problem of coal varieties. Bunkering feed rates may vary from 500 to 1200 or even 2500 tons per hour.

There are four principal means for accomplishing bunkering, including existing bulk cargo handling equipment, specialized terminals, self loading ships, and floating colliers or barges.

Most bulk cargo equipment can handle coal bunkering in ports around the world. However, ports may not be able to accomodate the extra tonnage throughout, and berths for ships may not be suitably arranged for bunkering.

Specialized terminals would consist of four sections integrated to provide efficient and varied solid fuel bunkering service. The sections would include coal reception, storage, dispatch and blending.

Self loading equipment could be adapted for bunkering, permitting the ship to trade at ports with coal further afield than just those with bunkering facilties. This equipment would reduce payload and is thus more suited for larger ships.

Special colliers or barges might be used if ports could not stockpile coal or could not install bunkering equipment dockside. An advantage would be that ships of a size that could not be taken into port could still be bunkered outside.

3.0 Classification Societies

Rules governing all aspects of construction of coal-fired ships from coal bunker hoppers to engine room have already been published by the classification societies.

Lloyd's Register of Shipping assumes automatic coal handling and some form of grate for firing, but will examine other firing methods including pulverized coal and fluidized bed. Arrangements for collection and disposal of bottom ash and fly ash are covered, as is boiler protection and ventilation systems.

American Bureau of Shipping also expects to see boilers fired by stoker and grate but will examine other methods. Pulverized coal boilers are not to use the bin system for coal distribution. Coal transfer burning and ash removal systems must function satisfactorily for specified angles of list, roll and pitch. Boiler protection and ventilation systems are specified.

In addition, Det Norske Veritas advises that coal fuel be used on a "first in - first out" basis. They also specify the use of two boilers unless it can be demonstrated that a single boiler meets specific criteria as to critical reliability.

4.0 Burning and Handling Coal Aboard Ship

4.1 Combustion

Three methods are available for combustion of coal to generate steam. Each of these methods - - stoker fired, pulverized coal fired and fluidized bed combustion - - is in a different stage of development. Fluidized bed is the most suitable size for shipboard use, but pitch and roll design requirements are under study. Pulverized coal firing is well developed for large units but is not cost effective scaled down for marine use. Several types of stoker firing are well tested and are suitable for marine use.

The atmospheric fluidized bed combustor provides a compact, high performance steam generator with good pollution control capabilities. Its advantages include a very high rate of heat transfer and its ability to utilize coal of varying quality. In a fluidized bed the fuel is mixed with hot inert particles which provide a stable environment, enabling combustion of poor quality, high ash coals. The inert material is formed from the ash which must periodically be removed to maintain correct bed depth. Introducing limestone to the bed achieves desulfurization of the coal in the furnace itself, while the even temperature distribution within the bed allows combustion at low temperatures and reduces emission of nitrogen oxides.

One problem with fluidized bed combustion is that thermal inertia of the mass of inert fluid in the bed runs counter to the need for quick engine response to bridge orders. Another problem being overcome by design development is the behavior of the bed in rolling and pitching at sea.

The principal advantage of pulverized coal firing is its greater power output than stoker firing of a boiler. It has several disadvantages, including the need to pulverize the coal. The damp atmosphere at sea would make pulverizing, handling and storing the coal difficult. Pulverizing on demand at firing time is the likely solution. A large furnace volume is needed to ensure the retention time necessary for complete combustion. Finally, the dust collectors to capture the high volume of fly ash produced will probably be prohibitively expensive if environmental restrictions are applied to ships.

There are four principal types of stoker firing, depending upon size of boiler and type of coal used. These include spreader stoker, underfeed stoker, water cooled vibrating grate stoker, and chain grate and travelling grate stoker. Stoker firing in general is well developed and some types are adaptable to shipboard use, but pollution control is difficult, and there is often poor efficiency due to carbon loss.

With the spreader stoker mechanism used in ships in the past, coal is thrown into the furnace above the bed. As it falls the fines are burned in suspension and the larger pieces burn on the bed or grate. The proper distribution of particle sizes is important for pollution control and other reasons, but difficult to maintain. However, this type responds well to change in load and can utilize coals of varying quality.

There are two types of underfeed stoker. Gravity feed with rear ash discharge is not recommended for marine purposes for a variety of reasons. However, horizontal feed with side ash discharge could be used. In this type ash removal is especially simple.

The water cooled vibrating grate stoker is simple, with relatively low maintenance, capable of using different coals and exceptionally good combustion. However, it would probably perform inadequately in a rolling and pitching ship.

The chain grate and travelling grate stoker have been used in ships in the past. They can maintain low smoke emissions over a large operating range, have relatively low maintenance costs, and burn almost any coal. However, their efficiency is relatively low.

All in all, the spreader stoker is probably the best suited for marine use of all the stoker types of coal-fired combustors. This type is illustrated in Figure 1 (taken from Reference 1).

4.2 Storing and Transferring Coal

With present handling methods coal cannot be stored in double bottom tanks. Consequently storage bunkers must be placed forward of the engine room, at the expense of cargo space, and near the bow to allow trim adjustment in combination with the after bunkers. Coal would be transferred from these to day hoppers ready for use. Based on current practice in handling dry, dense particulate materials in shore-based industries, remotely controlled totally enclosed pneumatic transfer is proposed for coal transfer aboard ship. Such systems are in satisfactory use for coal transport on shore. They are simple, economical, and clean in operation. Potential operating problems include variations in particle size and moisture content, possible presence of foreign matter, and degradation of particle size during transfer. Bunker tanks, boiler hoppers, coal transferring pipelines, cyclone separators, air blowers and valves in the proposed system are shown schematically in Figure 2 (taken from Reference 5). The present design provides for easy access to the entire transfer system.

Classification society rules require that coal storage, transfer, preparation, burning and ash removal systems be arranged so that failure of any single element, or a bunker fire, will still permit 50% of steam production needed for propulsion, safety of the ship and preservation of the cargo. Generally this requires duplicate systems throughout except for the boiler, provided it is equipped to satisfy the single failure principle. The system illustrated meets all requirements by opening or closing relevant gate valves. In addition, safety valves and fire extinguishers capable of automatic operation would be included.

4.3 Storing and Handling Ash

The ash content of coal ranges from 3% to 30%, with most bituminous coal used for power in the U.S. ranging from 6% to 20%. A variable ash content must be assumed in boiler design to accomodate or avoid ash deposit on furnace walls, floors and convection banks.

The proposed ash handling system removes ash from a hopper at the bottom of the furnace and transfers it to storage hoppers if the vessel is in areas where discharge is not permitted, or discharges it over the side at sea. Storage hoppers should permit discharge either to the sea or to a barge. As with coal handling, ash transfer will be automatic and pneumatic. Classification society rules relate to capacities, explosion and fire hazards, corrosion and wear protection, and require a clinker grinder or crusher to be installed. As with the coal-transfer system, the single failure principle is specified. The proposed system is shown schematically in Figure 3 (taken from Reference 5).

5.0 Conversion of Existing Ships

Orders for newly constructed coal-fired ships have already been placed for 75,000 DWT vessels and the evidence for placement of more new construction is growing. However, the need for a transition period of several years strongly suggests examining the conversion of existing oil-fired ships to coal-fired. In particular supertankers and other large vessels need to be examined as candidates for conversion.

The main effects of using coal instead of oil include increased weight of the engine and associated machinery, an increase in bunker fuel weight and in the volume of bunker space required, concomittant effects on trim and stability, increase in capital costs and changes in operating costs. In a conversion situation the changes in operating costs include decrease in cargo revenue as a result of lessened cargo deadweight and cargo volume, as well as the basic objective - lowered fuel costs.

The naval architectural aspects of weight and balance, trim and stability, sheer force and bending moment calculations have been incorporated into a set of computer programs operated interactively at MIT. These permit analysis of a conversion proposal.

The economic feasibility aspects of a conversion have also been built into another set of computer programs. All elements of cost and revenue are analyzed for an unconverted oil-fired ship of a type selected for study and for the same ship converted to coal. The ultimate outputs of interest, for current and several possible future prices of oil and of coal, are net present value of profits after tax versus speed of ship for converted and unconverted ships of the same type. The type initially studied at MIT is a Machias class tanker of 75,500 DWT designed by Bath Iron Works.

The details and results of these studies of both the naval architectural and the economic feasibility aspects of conversion, as well as some of the engineering design aspects of power plant, coal transfer and ash transfer systems, were presented at the May 8th Workshop of the MIT/Marine Industry Collegium.

Table 1

INTERNATIONAL COAL TRADE, 1978

(million t)

COUNTRY	EXPORTS	IMPORTS	NET EXPORTS (IMPORTS)
Poland	40	1	39
Australia	39	--	39
United States	37	3	34
U.S.S.R	26	9	17
West Germany	19	7	12
South Africa	15	--	15
Canada	14	14	--
Czechoslovakia	4	6	(2)
United Kingdom	2	2	--
Japan	--	52	(52)
France	1	24	(23)
Italy	--	12	(12)
Belgium/Luxembourg	--	8	(8)
Bulgaria	--	6	(6)
Denmark	--	6	(6)
East Germany	--	6	(6)
Netherlands	--	5	(5)
Finland	--	5	(3)
Brazil	--	3	(3)
Spain	--	3	(3)
Romania	--	2	(2)
Austria	--	2	(2)
Yugoslavia	--	2	(2)
Others	2	21	(19)

Table 2

NET EXPORTS OF THERMAL COAL, 1976 - 2000
(million t.c.e.)

COUNTRY	1976	1985	1990	2000
POLAND (to non-Communist world)	14	15	15	20
UNITED STATES	10	13	19	59
SOUTH AFRICA	6	34	60	90
U.S.S.R. (to non-Communist world)	4	5	7	15
AUSTRALIA	3	14	36	120
CHINA (to non-Communist world)	--	3	4	6
DEVELOPING COUNTRIES	--	5	17	36
UNITED KINGDOM	--	1	--	--

Table 3

TYPICAL COSTS OF STEAM COAL FOR EXPORT/BUNKERING 1980

(US$/t)

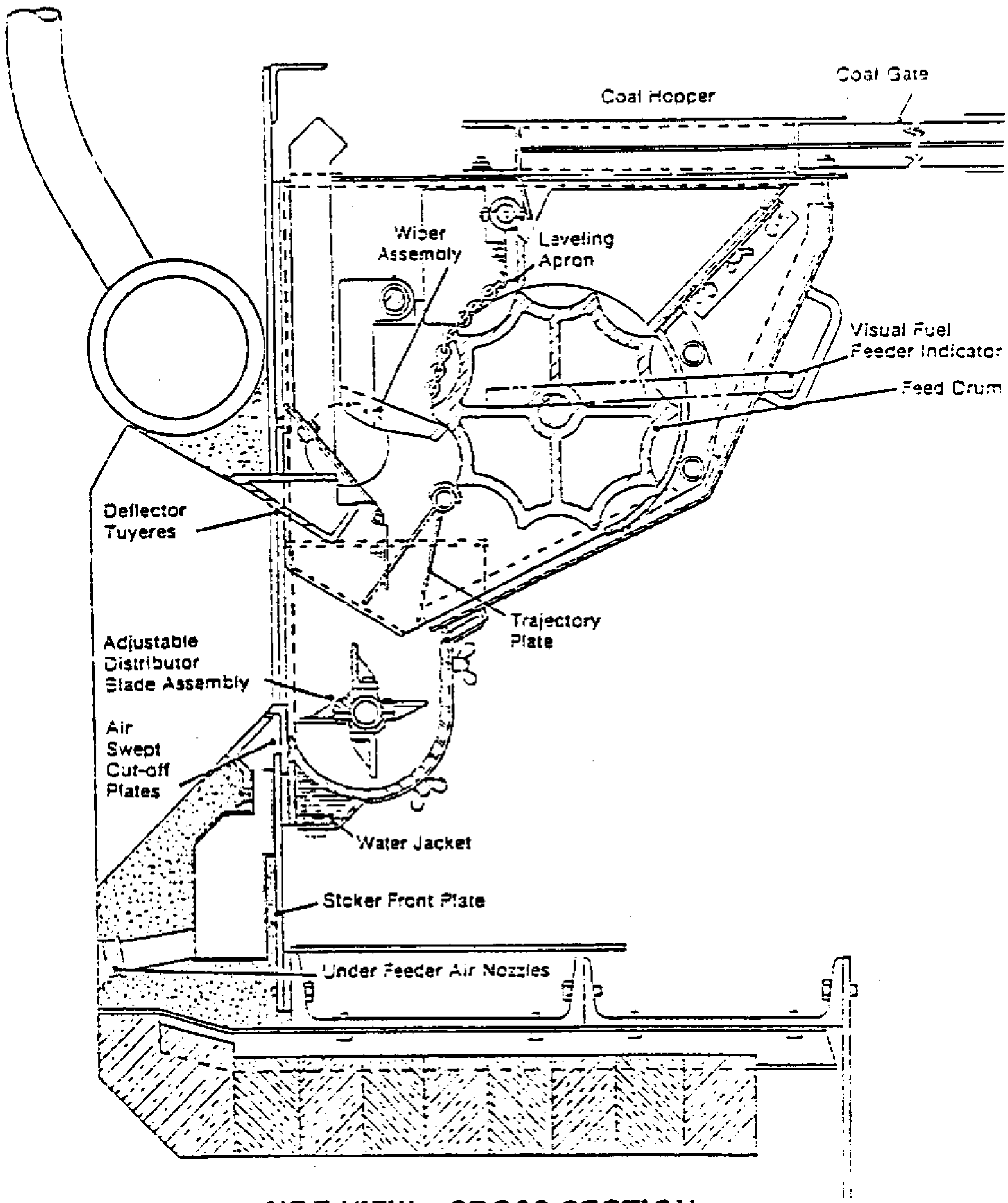
	South Africa (u/g)	Australia (u/g)	U.S.A. (o/c)	U.K. (u/g & o/c)	West Germany (u/g)
Cost at Mine, f.o.b.	11.61	21.98	29.21	55.19	92.18
Transport to port	8.75	8.35	13.70		
Port charges	2.50	3.08	2.16		
TOTAL COST, f.o.b.	22.86	33.41	45.07		

u/g — UNDERGROUND

o/c — OPENCAST

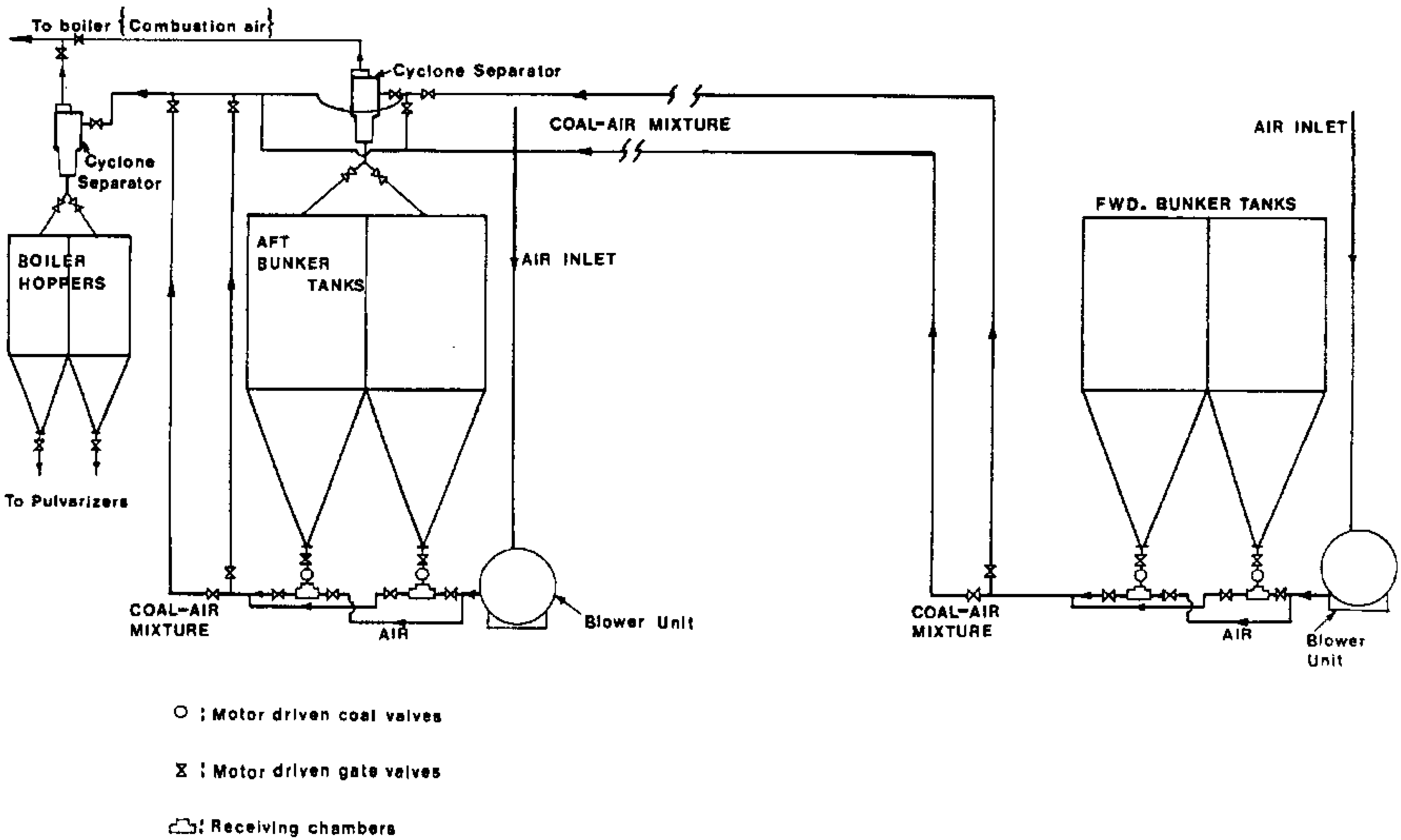
Figure 1

Riley Model F Spreader Feeder



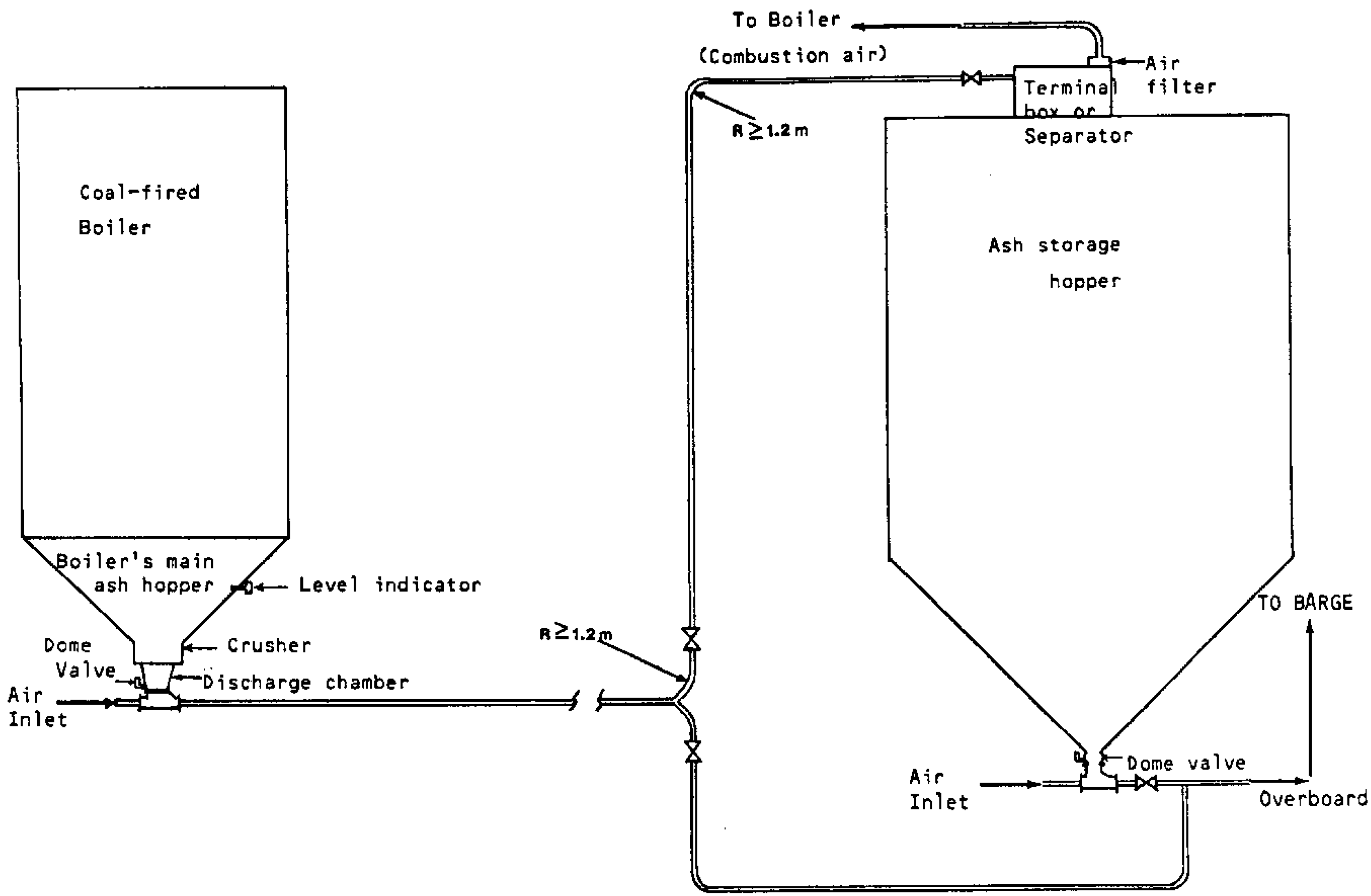
SIDE VIEW - CROSS SECTION

Figure 2



Schematic arrangement of coal storage and handling system

Figure 3



Diagrammatic view of ash handling system.

6.0 References

1. Pateras, G. D., "From Oil to Coal: A Feasibility Study on the Conversion of Ship Power Plants," M.S. thesis in Naval Architecture and Marine Engineering, MIT, January 1981.

2. Beeton, A. M., "Impact of Energy Crisis on Maritime Industry," prepared for discussion at Council of Sea Grant Directors' Meeting, September 24-26, 1980, Washington, D.C.

3. Y-ARD Report No. 2587/80, Y2161, "Coal as a Fuel for Merchant Ships," Y-ARD Limited, Glasgow, December 1980.

4. Wilson, C. L., "Coal - Bridge to the Future, Report of the World Coal Study," Ballinger, Cambridge, Massachusetts, 1980.

5. Drossos, I. P., "The Conversion of Ships to Coal-Fired Power Plants," Ocean Engineering thesis in Naval Construction and Engineering, MIT, June 1981.

6. Stockton, W. H. II, "Considerations for Applying Air Pollutant Emission Regulations to Coal-Fired Marine Boilers," M.S. thesis in Naval Architecture and Marine Engineering, MIT, June 1981.

7.0 Appendix

MIT/Marine Industry Collegium

Workshop #26

THE ENGINEERING AND ECONOMICS OF COAL-FIRED SHIP PROPULSION

May 8th, 1981

MIT, Sea Grant Conference Room,
3rd Floor, Building E38, (292 Main Street, Cambridge)

8.30	Coffee and Registration
9.15	Welcome Norman Doelling, Manager, Marine Industry Advisory Service MIT Sea Grant College Program
9.30	The Economic Feasibility Model Professor Chryssostomos Chryssostomidis MIT Department of Ocean Engineering
10.30	Coffee Break
11.00	Coal Properties and Transfer
12.00	Lunch
1.00	Conversion of Existing Ships
2.00	Results of Case Studies
2.45	Discussion, followed by demonstration of computer models in Room 5-218 for interested attendees