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By T.T. Fu, PhD., and G.F. Maga

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FLUIDIZED BED BOILER ASSESSMENT FOR NAVY APPLICATIONS

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NAVAL CIVIL ENGINEERING LABORATORY, PORT HUENEME, CALIFORNIA 93043

METRIC CONVERSION FACTORS

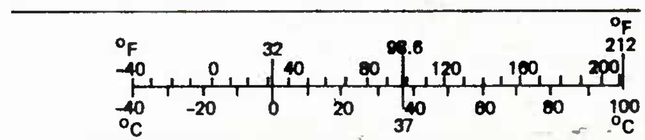
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

The Organization of Petroleum Exporting Countries' (OPEC) oil embargo in 1973 prompted a thorough reevaluation of our country's fuel supplies, fuel pricing policies, energy consumption, and methods for power generation. The United States' vast coal reserves, along with the uncertainties in the price and availability of petroleum oil created pressures for finding new and better ways to use coal.

The Navy shore facilities operate more than 2,000 industrial size boilers. Among the fuels burned by these boilers, petroleum-based fuels (residual oil and distillates) account for 51% of the total heat supply, followed by natural gas at 43%. Coal usage by the Navy is limited to only about 6% of the total heat supplied by fuels. In order to lessen the dependence on petroleum and natural gas, the Navy is being asked by Congress to increase its coal utilization.

The Navy's projected goal of coal utilization is to replace 15% of the conventional fuel (residual oil, distillates, and natural gas) requirements by the end of 1990 and 35% by the end of 2000. Consistent with this goal and the Congress' request, the Naval Facilities Engineering Command has prepared a plan of action to increase the Navy's coal utilization by 600,000 tons per year by 1994. In order to achieve this, it is necessary to assess the available technologies, especially emerging technologies, best suited for Navy applications.

While interest in coal utilization increased in the mid-1970's, many environmental regulations related to air pollution were also placed into effect. Therefore, the combustion of coal must be done with minimal adverse impact to the environment. Among various emerging technologies of coal utilization, fluidized-bed combustion (FBC) appears to be the best alternative for the Navy. FBC offers the advantages of emission control within the combustion chamber, the capability and flexibility of burning various grades of coal and other local fuels, and the mature industrial experience in the design of FBC boilers and the conversion of conventional boilers.

The world wide status of FBC is gaining momentum. In 1983, a total of 53 solid-fuel boilers were sold; six were FBC units. On a capacity basis, these units represent 5.8 million lb/hr or 12% of the total.

As an example, in the first 6 months of 1984, 27 boilers were sold, of which seven were FBCs, representing 26% of the total. On the capacity basis, the increase was even more dramatic: of a total of 5.3 million lb/hr, 2.3 million lb/hr were FBC's, representing 43% of all new capacity.

Many other countries have long been using FBCs to burn their high abundance of low grade coal. They have gained valuable experience and knowledge to successful FBC operation. China for example has over 2,500 units currently in operation.

Two types of FBC boilers currently exist: atmospheric and pressurized. The process for the former takes place at atmospheric pressure, and the latter usually at several atmospheric pressures. Pressurized

FBC is primarily for gas turbine applications, which is largely experimental at this time. Only atmospheric type fluidized-bed combustion will be discussed in this report because of its suitability for Navy applications.

This report is an assessment of the FBC technology and potential for Navy stationary boiler applications.

The fundamentals and working principles of FBC are discussed, along with the evolution of FBC boilers from first generation to the present second generation system, and the features of the different types of FBC boilers. A comparison is then made on the advantages of FBC boilers vice those of conventional boilers in terms of fuel flexibility, operational reliability, environmental acceptability, and economic viability. Next, a compilation of U.S. manufacturers, and the status of commercial and industrial users of FBC boilers are presented. The Navy's experience with the Great Lakes FBC boiler, the background, problems and possible remedies, are then discussed. Finally, the characteristics of Navy boilers, retrofitting considerations, and the proposed approach in retrofitting Navy boilers are examined.

FUNDAMENTALS OF FLUIDIZED-BED COMBUSTION

Fluidized-bed combustion (FBC) denotes a mode of combustion. "Fluidized" refers to the state of dynamic solid-gas equilibrium where the gravitational force on the solid particles is balanced by the forces generated by up-flowing gases and inter-particle reactions. The engineering definition of "bed" is a place where chemical and/or physical reactions take place, and "combustion" is a vigorous form of oxidation reaction that generates heat by oxidizing combustible gases, liquids, and solid substances.

In order to appreciate the characteristics of FBC, it is necessary to understand the packed-bed combustor, a close relative of the fluidized-bed combustor. As shown in Figure 1, a packed-bed combustor is a gaseous fuel burner composed of granular materials that are held and packed together by gravity. Gaseous fuels are burned inside the interstitial space in the packed bed. The packed-bed combustor, serving as a gas burner, would be ideal except it cannot tolerate the solid residues left by combustion. These residues accumulate inside the interstitial space and will eventually plug up the bed. Another problem with the packed-bed combustor is its poor heat dissipation. The packed-bed combustor's temperature escalates. The excessive temperature could exceed the melting temperature of bed materials and fuse the bed.

A fluidized bed, as shown in Figure 1, consists of a stream of gas flowing upward through a bed of solid particles such as ash or sand. At low gas flow rates, the gas permeates through the bed without disturbing the particles (a packed bed). As the gas flow rate increases, the force exerted on the particles becomes greater until eventually the gas stream supports the particles and the bed becomes "fluidized." This causes the particles to separate and the bed to expand. The gas velocity at this point is termed the minimum fluidizing velocity.

As the gas velocity is increased further, bubbles form and rise through the bed. Bubbles passing through the bed cause a highly turbulent mixing of the particles and give the bed the appearance of a boiling fluid. At this point, a bed surface or the boundary separating the bed material and the space above it is visible. This bed is called a "bubbling bed." As the gas velocity is further increased, the smaller particles become entrained in the gas stream and are transported from the bed. If the velocity is increased sufficiently, a condition would be reached where all the particles would be transported from the bed and a distinct bed surface is no longer apparent. A system (at this velocity) with a collection device to separate the gas and return the particles to the bed area is called a "circulating bed." (Fig 2a).

The schematic of an FBC boiler is shown in Figure 2b. To start a cold boiler, the bed is first preheated to around 1,000°F by passing through the combustion products from an auxiliary heater. At this temperature solid fuel could be ignited. Fuel is then introduced either from the base or the top of the bed. Heated fluidizing air is blown through the distributor plate to supply the primary combustion air. Most of the combustion process takes place in the bed where the oxygen is normally deficient (or, in a reducing environment). Combustion is continued in the freeboard space where secondary air is supplied for completing the combustion.

The combustion of fuel with air can produce flame temperatures in excess of 3,000 °F, which can lead to catastrophic material failure. To prevent such problems in bed operations, the temperature must be kept below 2,000 °F. This is achieved usually by using in-bed boiler tubes (a heat sink) in combination with controlling the fuel content in the bed to, for example, less than 5%.

Fluidized bed combustion offers several important advantages. There are two unique features that distinguish this technology from other methods of burning solid fuels. First, the solid particles suspended in a burning "fluid" conduct heat with high efficiency. Direct contact between burning fuel and other particles, and between hot particles and boiler tubes, can yield a rate of heat transfer five to ten times more efficient than the rate of heat transfer achieved through conventional coal-firing boilers. With improved rates of heat transfer, the size of boiler is substantially reduced, the result is a smaller, less expensive boiler. Because of the turbulent mixing and the efficient transfer of heat, temperatures within the fluidized bed is very uniform. Hot spots, which cause metal failures of boiler parts, are minimized. The high thermal inertia and latent heat stored in the bed material allow newly added fuel to ignite quickly and evenly; even wet or low-quality fuels can be burned efficiently. Finally, the improved rates of heat transfer mean that fluidized-beds can operate at lower temperatures and still yield as much heat as conventional boilers. These lower temperatures are below the melting points of most ashes left as residue, and this avoids the slagging and fouling of heat transfer surfaces with melted ash, one of the major problems encountered in solid-fuel fired boilers.

The second advantage of fluidized bed combustion is pollution control. Fluidized bed combustion has the capability of suppressing sulfur dioxide (SO_2) emission at the time of combustion rather than removing it from the flue gas later with "scrubbing" devices. Introduction of limestone in the bed will reduce SO_2 emissions; two reactions occur:

1. The calcining of limestone ($CaCO_3$) to produce calcium oxide (CaO) or lime

$CaCO_3$	+	heat	$\rightarrow$	CaO	+	CO_2
limestone				lime		carbon dioxide

2. The combining of CaO with SO_2 to form calcium sulfate ($CaSO_4$)

CaO	+	SO_2	+	$1/2\ O_2$	$\rightarrow$	$CaSO_4$
lime		sulfur dioxide		oxygen in air		calcium sulfate

Calcium sulfate (gypsum) is an inert material that can easily be disposed of and has many possible byproduct market values (such as, a cement additive). A combustion temperature in the range of 1,500 °F to 1,600 °F provides the greatest sulfur capture, which has been the standard operating temperature range for most fluidized bed boilers. Up to 90% SO_2 removal can be achieved with a calcium to sulfur (Ca:S) ratio of 2.5 being fed to the bed (Ref 1). During combustion, NO_x is formed by the oxidation of atmospheric nitrogen and nitrogen in the fuel. Molecular nitrogen begins to oxidize at about 2,200 °F; hence, FBC, with its low temperature and reducing environment, NO_x formation well below the current standard is possible.

In order to perform fluidized-bed combustion in a prescribed manner, a conventional FBC boiler should have the following seven principal components:

1. Feeder for Fuels and Sulfur Sorbents. The continuous feeding of fuels to the FBC boiler is essential in order to maintain a stable combustion. To maintain low pollutant emission, sulfur sorbents such as limestone are added to the FBC boiler. There are at least four known types of industrial feeders: gravity chute, screw feeder, spreader, and pneumatic feeders.

2. Air Movers. Air movers supply air for combustion and fluidization of the burning fluidized bed and pneumatic transportation of solid matters such as coal, limestone, and ash.

3. Air Distributor. As the name implies, the air distributor insures an even distribution of fluidizing air into the fluidized bed by drilled orifices or by an array of pipes containing flow nozzles. The conventional distributor must support the weight of the bed material when the bed is not fluidized (or slumped).

4. Plenum Chamber. The plenum chamber is located directly underneath the distributor. Fluidizing air enters the distributor by way of the plenum chamber. The plenum chamber serves to minimize air pressure surges, and to contain the spent materials that drifted (weeping) through the distributor.

5. Combustion Chamber. The combustion chamber in a conventional FBC boiler consists of the fluidized bed and the freeboard. The boundary between the fluidized bed and the freeboard is separated by a splashing zone where the gas and some entrained solid particles leave the fluidized bed and enter the freeboard. The bulk of the combustion takes place in the fluidized bed. The entrained combustible particles and volatiles are burned in the freeboard. For circulating fluidized-bed combustor, there is no discernible splashing zone.

6. Solid Withdrawal System. In order to maintain the bed level at the desired height and prevent accumulation of over-sized particles in the bed, the bed material must be removed continuously. There are two types of withdrawal systems: the overflow weir and the bed bottom drain. The latter is used to remove the clinkers, which are the major causes for plugging the gas distributor and the solid withdrawal system.

7. Monitoring Instrument. In order to operate FBC boiler in a satisfactory manner, the bed level, combustion temperature, and the flue gas composition and temperature should be continuously monitored. Pressure drop readings from a manometer can give an indicator of the bed level. The temperature is usually measured by conventional thermocouples. The flue gas composition should be closely monitored for pollutants and combustion efficiency.

EVOLUTION OF FBC BOILERS

The performance of FBC boilers has been explored in many pilot plants over the past decade under the rigors of realistic commercial demands. Most research and development to date has been done on conventional or first-generation design, which will be explained later. Many problems with peripheral equipment and the intrinsic natures of the first generation FBC system have been uncovered. As a result of such experience, a second generation FBC systems have evolved. Several bed design configurations for the second generation FBC system are: the in-bed circulating system, the dual bed, and the circulating bed.

Conventional FBC Boiler

The conventional or bubbling bed (the first generation) boiler (shown in Figure 2b) has a bed depth of 2 to 4 feet and fluidizing air velocities of 6 to 8 ft/sec. Uniform fluidizing air flows vertically upward, which yields excellent vertical mixing inside the fluidized bed. Lateral mixing of particles, however, is less desirable. Elutriation of combustibles is high, thus requiring recirculation of particles back to the combustion bed. Fuel and sorbent residence time is relatively short due to a low freeboard design, thereby, reducing the combustion efficiency and efficiency of calcium-sulfur reaction. In-bed tube erosion is also a problem due to the abrasiveness of the bed material.

In-Bed Circulating Boiler

The in-bed circulating, bubbling-bed FBC boiler shown in Figure 2c, is marketed by Deborah Fluidized Combustion Ltd of England. It is configured to create circular motions in the combustion area by either having one chamber wall bent inward and over a portion of the bed in conjunction with sloping distributor plate, or using a concave bed and fuel feeding mechanism to encourage circular bed motion. Lateral or circulating motion increases in-bed residence time, thus achieving increased combustion and sulfur-calcium reaction efficiency. The bubbling-bed operates with bed depth of 2 to 5 feet and fluidizing air velocity of 6 to 8 ft/sec, and is the smallest type of FBC equipment, with boiler capacities ranging from 2,500 to 70,000 lb/hr.

Dual-Bed Boiler

The dual bed FBC (Figure 2d), has two separate beds. The bottom bed where combustion occurs is composed of about 97% inert bed material (e.g., sand) and 3% fuel. The upper bed is composed of finely ground sulfur sorbent and is where desulfurization of flue gases (from the bottom bed) occurs. The temperature in the lower bed is kept around 2,000 °F for most efficient coal combustion, while the upper bed is kept between 1,500 °F and 1,600 °F for efficient sulfur retention reaction. The use of two shallow beds greatly reduces the freeboard height; the largest dual-bed FBC vessel is reported to be only 14 feet high. It is currently marketed by Wormser Engineering Inc.

Circulating Bed Boiler

The circulating bed FBC boiler shown in Figure 2a, uses a high-velocity airstream (15 to 30 ft/sec) to maintain most of the bed material entrained inside the combustion chamber. The exiting material is captured in hot cyclones and recirculated back into the combustion chamber. The entire bed of limestone and fuel is in a constant state of turmoil and may or may not have a distinct bed height. Under this condition, coal particles have a longer time to burn, and fine limestone particles have more surface area available for sulfur retention, which improves the efficiency of both combustion and calcium utilization. There are usually no heat-transfer or steam tubes in the bed that eliminate the erosion of in-bed tubes. Heat tends to be transferred by convection and radiation above the bed rather than by conduction. To increase the residence time, these units are usually taller than classical boilers (50 to 80 feet high). Circulating fluidized bed eliminates many problems associated with overbed or underbed fuel feeding and elutriation of particles. Another advantage of this system is load control. This is achieved by closely regulating the flow of cooled solids through the circulating loop. The equipment ranges in size from 50,000 to 1,000,000 lb/hr.

Table 1 is a summary of the differences between the three primary concepts: bubbling, circulating, and dual-bed FBC boilers.

Present Trend

The second generation designs have addressed many of the problems associated with the first generation. To minimize the problem with particle elutriation, and to increase fuel and sorbent residence time, partial or full recirculation of bed material is now a standard practice. The perils associated with in-bed tube erosion can be minimized by orienting the in-bed tubes in parallel with the bulk flow of the bed material. Another method is by eliminating the in-bed tubes, and separating the combustor and convection sections, as with the circulating bed design. Many commercial second generation systems have been operating with varying degrees of success. These FBC's offer improved combustion efficiency, reliability, performance, and SO_2 removal.

In 1984, FBCs accounted for more than 40% of the total boilers sold, compared to only 12% the previous year. This increased sale of FBC boilers shows the confidence the industries have in this new alternative method of burning coal.

One major drawback of the circulating fluidized bed is its tall structure. Current research attempts have been to reduce the height without sacrificing many of its advantages.

ADVANTAGES OF FBC BOILERS

The criteria that an industrial boiler user applies to select a boiler are: fuel flexibility, operational reliability, environmental acceptability, and economical viability. These subjects are discussed here showing the advantages of the FBC concept over conventional systems.

Fuel Flexibility

The ability to burn a wide variety of fuels and to maintain an uninterrupted operation of the boiler is highly valued by the plant operator.

FBC boilers have a bed of solid matter that have large thermal inertia enabling it to burn coals and many other fuels with high moisture content. Industrial FBC boilers have successfully burned black liquor (effluents from pulp and paper digestor) with water content as high as 60%. Coal slurries with water content greater than 40% could be burned in an FBC boiler without adverse effects to combustion efficiency or environmental emissions. This is a clear demonstration of the boilers' insensitivity to moisture in the fuel.

FBC boilers have also demonstrated their insensitivity to high ash and high sulfur fuels. Coal and oil shales with up to 70% solid inerts and less than 1,800 Btu/lb heating value have been successfully burned in FBC boilers. Inexpensive high sulfur fuels can be burned without the need of the expensive back-end desulfurization equipment. In fact, most FBC boilers can practically burn all combustible material. Examples of these are:

Pelletized wood waste	Natural gas
Pelletized paper waste	No. 2 fuel oil
Shredded rubber	No. 6 fuel oil
Industrial waste oils	Peat

Anthracite culm	Fluid coke
Bituminous coals	Oil shale
Petroleum coke	Wood chips
Alcohol mash waste	Fruit pits
Paper mill sludge	Rice hulls
Sewage sludge	Sawdust
Municipal refuse	Carpet wastes
Coal washing wastes	Biomass wastes
Various vegetable composts	Coal-water mixture
Sulfur laden waste gases	

The high thermal inertia of the bed material guarantees substained burning of practically any combustible materials.

Operational Reliability

When an industrial boiler has an unscheduled shutdown the production capacity suffers. A boiler's operational reliability depends on many factors: the auxiliary equipment that pretreats the fuel (e.g., crushing, screening, feeding); the boiler feed water treatment unit that prepares the water to meet boiler requirements; and the systems that handle combustion flue gas and refuse.

FBC boilers has demonstrated a high degree of operational reliability. This is probably contrary to what one might have heard. Most of the causes for the reported low operational reliability can be traced to the pneumatic conveying system for solid-injection, stream splitting, and coal feeding. In FBC applications, where pneumatic feeding system is not used, a high degree of operational reliability of the whole system has been reported. FBC boilers have a lower and more uniform operating temperature than conventional boilers, also they have no moving parts that need continuous and frequent maintenance.

Environmental Acceptability

Environmental acceptability is one of the crucial criteria for selecting boilers. The current environmental promulgations indicate that sulfur and nitrogen oxides emissions are, indeed, the primary concern of the general public. The emissions from coal-burning boilers are being closely scrutinized. It is only a matter of time before the coal boilers will be subjected to more stringent pollutant emission control regulations.

Fluidized bed combustion is capable of suppressing sulfur dioxide at the time of combustion rather than removing it from flue gases later with expensive and sometimes difficult-to-operate, post-combustive ("scrubbing") devices. Many plant operators do not have the technical expertise necessary to operate an SO_2 scrubbing system. Experience with good coals and limestones in fluidized bed boilers indicate that about 90% sulfur retention is required to meet the current emissions standard of 1.2 lb SO_2/MBtu heat input without the use of scrubbers.

As discussed earlier, by virtue of its low combustion temperature, the FBC boiler exhibits attractive sulfur retention characteristics and low nitrogen oxides emission. From the data now available, it appears that fluidized bed combustion can meet the nitrogen oxides emission limits of 0.6 lb/MBtu, which currently prevail.

Economic Viability

Economic viability is the key to all the selection criteria. Stoker-fired boilers require double-screened coal. Fines cannot be burned in the stoker because they can block the air passage in the mass burning fuel bed. Furthermore, the stoker has a limited fuel flexibility for low-grade coals and poor pollutants emission control. The pulverized coal fired (PCF) boiler has a wider fuel flexibility than the stoker-fired boiler, but the inability to burn high sulfur coal limits the PCF boiler to burning the high-cost, compliance coal. The high cost of fuel preparation prior to combustion also increases the operating cost. The unique feature of FBC to burn inexpensive, low-grade, and high sulfur coals indicate that there is indeed a favorable cost differential in using FBC.

In recent years, engineering experience of FBC retrofitting have accumulated with the rapid growth of the FBC technology. Information on the economical aspects of boiler retrofitting has not been well documented, however. Based on the limited data available, some estimates were made to demonstrate the economic viability of the FBC option. The results are summarized in Table 2, which compares the effective annual costs for four types of boilers operating in 1987 and 1992.

The assumptions used in this table include escalation rates from NAVFAC P-442, fuel costs, financial rates, and operating costs (Ref 2). The comparisons are based on 50,000 lb/hr steam output at an annual capacity factor of 75% and start up year of 1987. The payback periods for FBC and stoker-fired boilers are 2.0 and 2.2 years, respectively, compared to the existing gas-fired boilers. The cost estimates for each boiler are presented in relative magnitudes using the costs for the new FBC boiler as 1.0. The fuel cost differential is seen in this table. Substantial cost saving is achieved by burning coals. The effective annual cost in 1987 for existing oil- or gas-fired boilers is about twice that of new FBC unit and it amounts to about three times as much in 1992.

Due to fluctuating fuel prices, a comparison was made between the effective annual cost of oil and FBC coal-fired boilers as a function of fuel cost differential (Fig 3). It is shown that the effective annual cost of an oil-fired boiler is significantly greater as the fuel cost differential increases. The lower the capacity factor indicates a higher fuel cost differential.

Summary

In summary, FBC boilers are far superior in comparison with stoker-fired and PCF boilers with respect to fuel flexibility, operational reliability, environmental acceptability, and economical viability. FBC boilers are not sensitive to moisture content, size and size distribution, volatile matter content, and ash content of the fuel. The FBC boiler's operating temperature is below the minimum ash fusion temperature thus, no slagging occurs in boiler tubes. Sulfur compounds removal equipment downstream is not required because coal is burned in intimate contact with the sulfur sorbent, which can chemically capture virtually all sulfur during combustion. Low operating temperature limits the formation of NO_x pollutants. FBC boilers have high operational reliability because of its few moving parts and low-uniform, operating temperature. Substantial cost saving is achieved because FBC boilers can utilize low-cost, low-grade coals, and a scrubber system is not needed for SO_2 removal.

MANUFACTURERS OF FBC BOILERS

In the late 1970's, while FBC technology for utility applications faced competition from other emerging technologies (e.g., synthetic fuel), manufacturers' efforts for commercial boilers were limited. The market for FBC utility power plants was small and depended strongly on the successful demonstration of viability and cost advantage of FBC boilers over the other alternatives. Today, FBC technology has been proven, existing industrial installations have been operating successfully, and business has improved to the point where FBC manufacturers are confident about the future of the fluid-bed concept. Technical feasibility of FBC is no longer just a possibility but a certainty.

Most major boiler manufacturers have shown their confidence in FBC by either intensifying, developing, or acquiring the technology over the last few years. Many manufacturers are offering industrial size, guaranteed systems for a wide variety of applications. There are now over 2,500 units currently in operation in China, 275 in Western Europe and North America, and at least 80 more are either under construction or proposed for construction. Orders for FBC boilers in the United States are rapidly increasing in recent years. All major U.S. boiler manufacturers are now offering FBC boilers. Their names together with the boiler capacities and number of installations are listed in Table 3. Manufacturers can custom build a new boiler, or retrofit an old boiler for a given design and application. Sample diagrams of units offered by some U.S. boiler manufacturers, from first generation to second generation FBC boilers, are shown in Figure 4 (a thru h).

Utility companies are becoming more involved with FBC. Atmospheric fluidized-bed combustion (AFBC) technology for steam and electric generation got a big boost last year when three electric utilities: Colorado-Ute Electric Assn. Inc., Northern States Power Co., and Tennessee Valley Authority (TVA) and their partners committed more than $330 million to build three demonstration plants, ranging in size from 100 to 160 MW.

Colorado-Ute is installing the nation's first utility circulating FBC boiler (by Pyropower), rated at 926,000 lb/hr. It will be the largest FBC boiler in the world when it goes into service in 1986. It is a part of a major life-extension project that will: (1) increase plant capacity, from its present 36MW to 110MW, for an investment of $840/kW, (2) improve net station heat rate by 15%, (3) reduce fuel cost by about 30%, and (4) reduce emissions.

Northern States Power Co.'s Black Dog generating plant, in Minneapolis, is retrofitting an existing pulverized-coal-fired boiler to a bubbling-bed AFBC type (by Foster Wheeler Energy Corp.). The $50M plant will be the largest bubbling-bed boiler in the world (125 MW) when completed in late 1986. Through the conversion efforts the utility company expects to find a technical and cost effective basis for responding to the acid rain issue, and also to demonstrate the plant's ability to achieve a higher unit capability and availability.

Encouraged by progress in the development of the AFBC process over the last few years, TVA, in cooperation with the Electric Power Research Institute (EPRI) and others, is designing a bubbling-bed boiler in Paducah, Kentucky, to produce 160MW. Completion of the $220-million project is expected in 1989.

Perhaps the most surprising aspect of the rapid commercialization of the fluidized-bed boiler, is industry's fascination with circulating fluidized bed (CFB) system. These boilers typically operate at higher combustion efficiencies and at a higher excess air levels than the bubbling-bed FBC. CFBs also have more forgiving fuel-feed systems, requires less limestone for SO_2 capture, and usually are more easily adaptable to staged-combustion techniques for NO_x control. Despite the facts that only two CFBs are now operational in this country (50,000 lb/hr) and their service time is somewhat short, because of their apparent advantages U.S. companies recently ordered several such boilers capable of producing 100,000 lb/hr and at least eight other boilers rated at more than 400,000 lb/hr each (Ref 3).

U.S. interest in the CFB, nurtured primarily by Pyropower, probably was not anticipated by the traditional boiler manufacturers. Babcock & Wilcox, Combustion Engineering, Riley Stoker, and Foster Wheeler, each now offer CFB boilers under license or in cooperation with overseas manufacturers. Keeler/Dorr-Oliver, who sells CFBs of their own design, recently sold six units to plants in Iowa.

The most significant fact to emerge from an analysis of overall boiler sales in 1984 (Ref 4), is that the FBC units accounted for over 40% of the coal-fired capacity purchased. Successful operation of FBCs here, and of commercial units overseas, gave buyers confidence in the relatively new technology.

The vote of confidence by U.S. utilities, traditionally among the most demanding companies when it comes to adopting new technology, means to many industry observers that FBC boilers are truly commercial.

NAVY'S FBC EXPERIENCE - GREAT LAKES BOILER

Background

In June 1976, the U.S. Department of Energy (DOE) and Combustion Engineering entered into a cost-sharing contract to develop a coal-fired FBC boiler demonstration plant. Since then, the Navy and the State of Illinois have also funded the program. The plant was located at the Great Lakes Naval Training Center in Illinois.

The primary objective of this program was to demonstrate the practical application of an industrial coal-fired, AFBC boiler that meets the environmental regulations in burning high sulfur coal. Additional objectives were:

- To advance the state-of-the-art of FBC boiler design to include a natural circulation unit that can be assembled in a shop and shipped by rail.

- To provide a boiler plant that will operate in a manner consistent with present industrial practice and fire coals competitively with other firing systems.

- To obtain engineering data to verify design procedures so that commercial units can be designed in compliance.

- To accumulate substantial operating experience to provide an objective appraisal for industry of the performance, reliability, and economics of FBC boilers.

The program was carried out in two phases. In Phase I, a subscale FBC unit with a bed area of 2 feet by 2 feet was engineered, constructed, and operated to collect performance data and other information necessary to design the Great Lakes demonstration plant. Phase II included the design, construction, operation, and testing of a demonstration FBC plant as shown in Figure 5, with a steam capacity of 50,000 lb/hr at 365 psig and 560 °F. Construction began in April 1979, at the Great Lakes Naval Training Center on the shore of Lake Michigan. The entire power plant at Great Lakes provided a total of 750,000 lb/hr of steam mainly used to heat the base and the nearby Veterans Administration Hospital. The FBC plant supplied an additional 50,000 lb/hr of steam to the Navy's existing facility.

Due to the poor performance and reliability, this boiler was dismantled and disposed of. The purpose of the following discussions is threefold:

1. Show where the fundamental engineering principles were violated in the boiler design.

2. Show that these errors could have been corrected inexpensively based on established engineering know-how.

3. Reestablish the confidence of decision makers in FBC boiler techniques.

Problems and Possible Remedies

The Great Lakes FBC boiler was plagued with many problems since the beginning. In this section, efforts concentrate on identifying problem areas and associated remedial concepts. Routine problems, such as crushing, screening, and drying of coal particles, are not discussed here since they are easily solved by selecting the proper equipment from commercial vendors. The initial operation of the Great Lakes FBC boiler was adversely affected by the low-bed temperature, high elutriation of particles, and low operational reliability of the solid handling system.

Fuel and Sorbent Feeding. The pneumatic feeding system showed problems of deposition and line blockage due to unexpected larger-than-designed particle size and the high moisture content of the fuel. The use of a number of pipe fittings, such as T-junctions, to split the solid feed (coal and limestone) to eight under-bed injection ports presented the boiler operator with a very limited flexibility in choosing the particle size and moisture content. The pneumatic system operated against a substantial back pressure; high back pressure caused the blowback of fine particles during solid feeding that rendered the rotary valve and the eductor inoperative. Furthermore, the injection of a solid-gas mixture into the fluidized bed produced high momentum plumes of air bubbles that caused excessive elutriation. Replacement of the pneumatic system with an alternative feeding system would be necessary to ensure high reliability and reduce particle elutriation.

Screw feeders should have been considered for solid feeding for the Great Lakes FBC boilers. A screw feeder extrudes fuels and sorbents into the fluidized bed by the positive displacement of screw flights. The screw conveyor can have a variable pitch to achieve a pressure seal and thereby deter the backflow of gas and leakage from the boiler. Practitioners in FBC boilers have used screw feeders for almost two decades with high operational reliability. The distinct advantage of screw feeders is that they have the ability to maintain a constant feed rate against a high back pressure. In fact, they have been satisfactorily used to feed coal/sorbent to a pressurized FBC system against pressures up to several atmospheres.

The only drawback of screw feeders is the limited bed area they can serve. Usually a single screw feeder can adequately serve an area of 30 ft^2. Based on the rule of thumb from China's experience and the heat input requirement, the Great Lakes FBC boiler would have required two 4-inch diameter screw feeders.

The screw feeder system can handle a wide range of moisture and coal fines. Mixing dry limestone with undried coals will reduce the total moisture content, and with some modifications, the Great Lakes FBC boiler would have been able to burn undried coal. The pneumatic feeding system caused uncertainty in operating the Great Lakes FBC boiler. Improvements in both performance and operational reliability could have been realized by using a screw feeder. The screw feeder system that should have been used is shown in Figure 6(a).

<u>Fuel Combustion</u>. Due to a low freeboard height (about 6 feet) and air superficial velocity of 7 ft/sec, the flue gas had a short time to burn in the freeboard (less than 1 second residence time). The flue gas exited from the two sides of the boiler top tube bank and flowed down to the lower ports of the convection tube bank and then to the flue gas exits. It simply did not have enough time to achieve complete burnout of carbon and carbon monoxide. This was quite evident from the fact that at low-load operations (partly active bed), which allowed some of the flue gas to have a longer residence time in the freeboard, higher burnout of carbon monoxide was achieved.

There were slag deposits on the boiler ceiling and some of the boiler tubes. These deposits contained about 50% carbon and 50% ash. Experience in combustion shows that if a flame is prematurely quenched by contacting a cold surface, soot and slag form. The deposition problems could have been significantly reduced if the tube surface temperature had been increased by increasing the flue gas residence time.

At full load, the flue gas passed through the convection bank at a high velocity (20 ft/sec) parallel to the tubes. This arrangement was ineffective in heat extraction and adversely affected the steam production capacity.

As shown in Figure 6(b), the existing flue gas exit ports could have been blocked and modified so that the flue gas would have traveled the full length of the boiler. The flue gas would have entered the convection tube bank at the upper rear end, and exited near the the lower front end. This arrangement would have forced the flue gas:

- To follow a cross-flow pattern to increase the contact heat transfer area.

- To reduce its dust loading (particles will fall out when they hit the cross-flow tubes).

- To increase its velocity in the convection bank and fully utilize the contact area to give a higher heat transfer rate.

Blocking the old exit slits and installing new exit ports would not have been an extensive effort. The current flue gas flow pattern leaves much to be desired in freeboard residence time and in heat transfer in the convection tube bank surface. If the modification had been tried, the combustion efficiency and steam production rate would have shown significant improvements.

Flyash Handling. The original feeding system mixed the recovered flyash from the mechanical ash collector and the coal/limestone from the feed hopper. The solid mixture was recycled to the FBC boiler. The presence of flyash in the solid mixture caused the trouble in the rotary valve and the eductor. The excessive blow back of fine particles, combined with high moisture, caused problems of deposition and blockage of the pneumatic system.

Another problem with this reinjection system was the build up of flyash particles in the boiler convection bank and the mechanical dust collector. The glowing flyash was prematurely quenched due to insufficient residence time in the freeboard. It was cooled in the convection tube bank and collected in the ash collector. The flyash was further cooled by mixing with coal and limestone feeds while being transported in the pneumatic system. Before the flyash could reach the required combustion temperature, the particles were blown out of the bed again to continue the additional cycle of recirculation. Eventually, the solid particle loading increased to such an extent that serious erosion of the tube bank and blockage of gas passages resulted.

One known benefit of flyash reinjection is the high calcium utilization. The extensive handling of flyash in the recycle process grinds away the inert sulfate layer and makes a fresh limestone surface. It is best to reinject the flyash into the boiler as soon as it is captured. Undoubtedly, the bottom of the convection tube bank had excessive amounts of flyash accumulated. This flyash would have been at glowing temperatures and would have burned easily once it is injected into the fluidized bed.

Several flyash hoppers should have been built at the bottom of the convection tube bank with a flyash reinjection nozzle (eductor) at the bottom of each ash hopper. To avoid any possible process problems, which may cause an excessive amount of flyash accumulation at the bottom of the convection tube bank, a manually operated flyash discharge device should also have been installed at each flyash hopper.

The modifications are depicted in Figure 6(c). Such modifications, properly implemented, would have facilitated the flyash reinjection operation and shown substantial improvements in combustion efficiency and calcium utilization for sulfur retention.

Heat Transfer Surface. The limestone specified for the demonstration plant was based on the operation of the 2 feet by 2 feet subscale unit (SSU). This limestone was not locally available at Great Lakes. A smaller sized limestone was selected that had different attrition and spalling characteristics from the limestone tested in the SSU.

The present boiler had an excessive in-bed heat transfer surface designed for use with much finer bed material. Instead of reducing the heat transfer surface, the boiler vendor chose to use a large-diameter bed material to reduce the heat transfer coefficient. Even with this measure, the boiler could not reach a combustion temperature in excess of 1,500 °F.

The in-bed heat transfer surface should have been reduced. There were rows of in-bed tube bundles in the fluidized bed as shown in Figure 5(b). The innermost tube rows could have been removed and separated by a firewall, leaving only one horizontal "V" of the outermost row extending into the bed, as shown in Figure 6(d).

Bed Area. The boiler bed area was twice as large as required for the heat load. What was lacking in the freeboard height could have been made up by the distributor's length. The required bed area could be estimated from a simple calculation for the distributor. The conventional design requires about 1.5 ft^2 bed (distributor) area for each 1,000 lb/hr of steam output. The present unit was designed to provide a steam production rate of 50,000 lb/hr. Therefore, the required bed area was in the range of 75 ft^2, instead of the current distributor area of 140 ft^2.

The existing large bed area could have been fully utilized to achieve a long horizontal freeboard residence time of the flue gas by installing a firewall to divide the fluidized bed into a main bed operated at a higher fluidization velocity and auxiliary bed operated at a much lower fluidization velocity. The auxiliary bed would have served as a flyash carbon burn-up cell and the firewall would have served also as a radiation reflector to help maintain a uniform bed temperature.

The firewall construction is depicted in Figure 6(e). It would have been made of castable fire clay and sit across the in-bed superheater tube bundles. Two large windows made of firebrick would have been installed on the firewalls to provide a minor diversion of flue gas flow to settle some entrained dust particles into the carbon burnout bed. The fluidizing air from the rear end of the main bed and the burnout bed would have served as the secondary air to enhance combustion efficiency and pollutants emission control. It is expected that substantial improvements in the boiler's performance would have been achieved.

Summary

The Great Lakes FBC boiler was an unfortunate experience for the Navy for promoting coal utilization. This boiler was not specifically designed for fluidized-bed combustion. Rather, it was converted from an old version, type "A" oil-fired boiler. Attempts to confine the fluidized bed into the A-shape frame severely restricted the freeboard height. The heat transfer was poor and the flue gas freeboard residence time was insufficient. Poor combustion efficiency was one of the results. Salvage of this boiler by the traditional FBC configuration was not feasible because of the low freeboard height dictated by the A-shape boiler construction.

Fortunately, this boiler was built with a bed area twice as big as necessary. The performance of this FBC configuration could have been improved by redirecting the solid bed material and the flue gas flow into a horizontal fashion for longer residence time. The combustion efficiency and pollutant emissions control could have been further enhanced by using a simple flyash reinjection system, installing a firewall, and reducing the in-bed heat transfer surface.

This study identifies only low-risk and short-term measures that could have realized maximum benefits with limited effort and expenditure. Five major tasks are identified as retrofit possibilities for this type of FBC configuration.

1. Improve the operational reliability of the solid feeding system by replacing the present pneumatic system with screw feeders.

2. Increase residence time and heat recovery by redirecting the flue gas flow in the fluidized bed and convection tube bank.

3. Enhance carbon burnout and calcium utilization by adding a simplified flyash reinjection system with minimum detour and complexity.

4. Improve bed temperature and level control, and reduce solid particle elutriation by installing a firewall inside the FBC boiler.

5. Increase combustion efficiency and bed temperature by reducing the in-bed heat transfer surface area.

With these modifications, the boiler performance could have been improved to the level of design specifications.

FBC FOR NAVY BOILER APPLICATIONS

The rationale behind retrofitting other selected Navy boilers to FBC operation is to provide an expeditious approach to achieve the Navy's goals in coal utilization. The U.S. has an abundance of coal deposits and vast limestone quarries all over the continent. Navy base facilities are usually located in the vicinity of main sea lanes and waterways that can serve as main arteries for coal and limestone transportation.

Many of the Navy boilers may be amenable for retrofitting (or conversion) to FBC operation. The retrofitting of conventional boilers, especially stoker-fired boilers, is not a new technology. It has been fully demonstrated in many parts of the world. In China, for example, more than 1,000 FBC boilers currently in service are retrofits (Ref 5). Most of the retrofitted FBC boilers enjoy improved performance. Because of the high heat transfer capability in FBC operation, the steam capacity for a properly retrofitted boiler can increase up to 50% without sacrificing the original steam conditions.

Navy Stationary Boilers

According to a recent study (Ref 6), the Naval shore facilities has 2,012 water-tube and fire-tube boilers in 275 facilities with a total capacity of 29×10^9 Btu/hr ($\sim 29 \times 10^6$ lb/hr). Large boilers with capacities greater than 50×10^6 Btu/hr account for 7% of the total number of boilers, but 60% of the total capacity, whereas small boilers with capacities less than 5×10^6 Btu/hr account for 64% of the total number, but only 10% of the total capacity. The capacity factor, which measures the extent the boiler is used, is defined as the ratio of the actual annual fuel consumption and the maximum boiler capacity that is required for full, continuous operation. The capacity factors range from 25% to 31% for the larger boilers and only about 20% for the small boilers. A summary of distribution of boiler sizes in all the Naval shore facilities, together with annual fuel consumption and average capacity factor is shown in Table 4.

Among the newer (<20 years old) large gas- and oil-fired boilers (Table 5), it is estimated that one-third are capable of burning coal. They are potential candidates for retrofitting to FBC boilers because they have a longer remaining useful life and many design features amenable for coal burning. This is significant compared with all the Navy's large boilers currently firing coal.

Retrofitting Considerations

Retrofitting considerations depends on the age, size, configuration, and accessories of the boiler. For instance, boilers that are not structurally sound or that have extensive internal corrosion are not suitable. The selection of candidates for FBC boiler retrofitting should be based on the following considerations:

Boiler Size. Operational uncertainty of retrofitted boiler performance generally increases with boiler size. Large-sized boilers, capacities over 400×10^6 Btu/hr, possess a large bed area that requires a large number of fuel feeders. The added complexity of the feeding system design, such as stream splitting and blowback of air-solid mixture, may reduce the system operational reliability. They usually have complicated networks of steam-water circuits and in-bed tube banks. Unless it is properly compartmentalized, the steam-water circuit can be a highly involved endeavor in retrofitting large-scale boilers.

Boiler Age. The boiler age determines the remaining useful economic life. From an economic standpoint, the investment in retrofitting must be adequately covered by the savings from fuel cost differential and the costs of operating and maintenance for the remaining years of boiler life. Generally speaking, boilers 20 years and older are not considered economically suitable for FBC retrofitting.

Boiler Configuration. Depending on the furnace bottom-to-grade clearance and the steam-water circulation design, some boilers are more suitable for retrofitting than others. Low-pressure, low-superheat units are best suited for FBC retrofitting because the simple circulation system requires less work to rearrange generating, superheating, and reheating surfaces. In general, the boiler configuration should be examined on an individual basis by a knowledgeable expert to determine the feasibility of retrofitting. It is impractical to set rigid rules for boiler configuration considerations.

Boiler Components. Air heaters, supporting structures, particulate control devices, and draft fans are boiler components that need to be considered before retrofitting a boiler. Air heaters on existing units are usually the rotary regenerative type, and air leakage may be a problem, especially with the higher air pressure in the FBC operation. The existing supporting structures may need reinforcement to support the added weight. Fabric filters (bag house) are commonly used for stack gas cleaning. For proper bed fluidization, high forced-draft fan pressures may be necessary. This can be done by replacing the existing fan with a higher pressure fan or by adding booster fans.

Available Space. An FBC boiler needs space for the air plenum, fabric filters, and bottom-ash handling system. Usually, for a coal-fired boiler, the ash hopper and the flyash system can be removed to provide this space. Some modifications and rearrangement may be necessary. An FBC boiler also needs additional space for coal and limestone storage. A good rule of thumb is to assume that limestone takes up 25 to 30% of the space needed for coal storage.

CONCLUSIONS

FBC is an ideal option for the Navy to implement its coal utilization program in the most efficient, reliable, economical, and environmentally sound manner. The problems encountered by some of the FBC boilers in the U.S. can all be traced back to the misconception of the FBC processes and correctable design errors. FBC boiler applications are successful in foreign countries and are capturing a larger percentage of new boiler sales each year both in the U.S. and abroad. All major U.S. boiler manufacturers now build FBC boilers.

RECOMMENDATIONS

It is recommended that the Navy evaluate FBC as a coal utilization option by the following approaches:

1. Conduct preliminary studies to:

    a. Compile experience in FBC technology and boiler conversions.

    b. Develop concepts for erosion prevention.

c. Develop concepts to improve existing FBC technologies.

d. Conduct test and evaluation relevant to FBC applications.

2. Develop Test and Evaluation Master Plan (TEMP) for boiler retrofitting to:

   a. Identify the Navy's coal convertible boilers.

   b. Retrofit a lead boiler to demonstrate its feasibility and obtain long term operating experience.

   c. Develop guidelines for boiler retrofitting.

   d. Retrofit other coal convertible boilers.

3. Develop guidelines and identify requirements for the Navy to replace old boilers with FBC units.

4. Disseminate Users Data Package (UDP) on FBC retrofitting technology.

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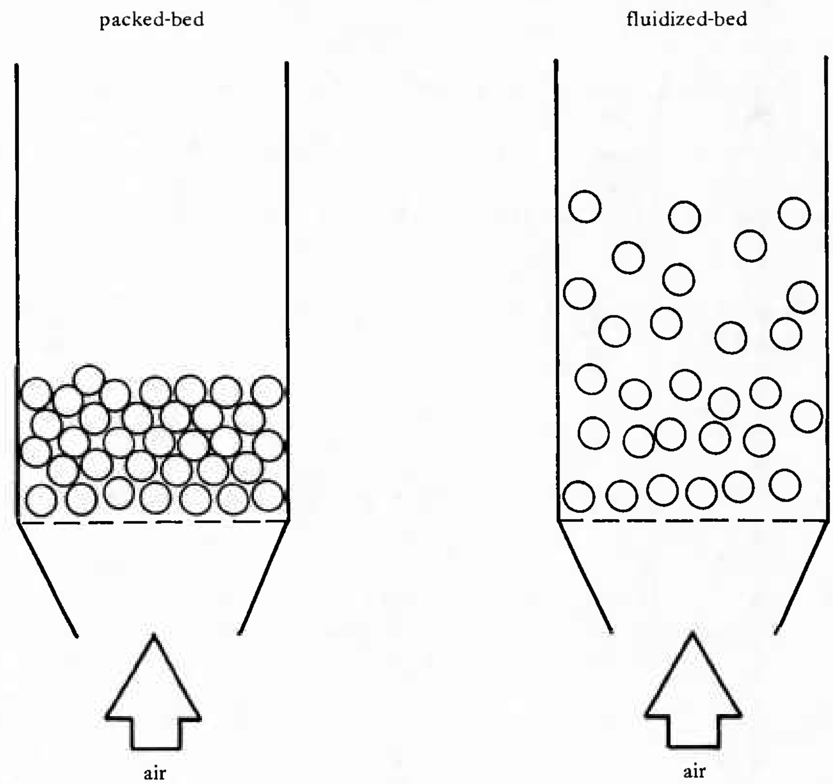
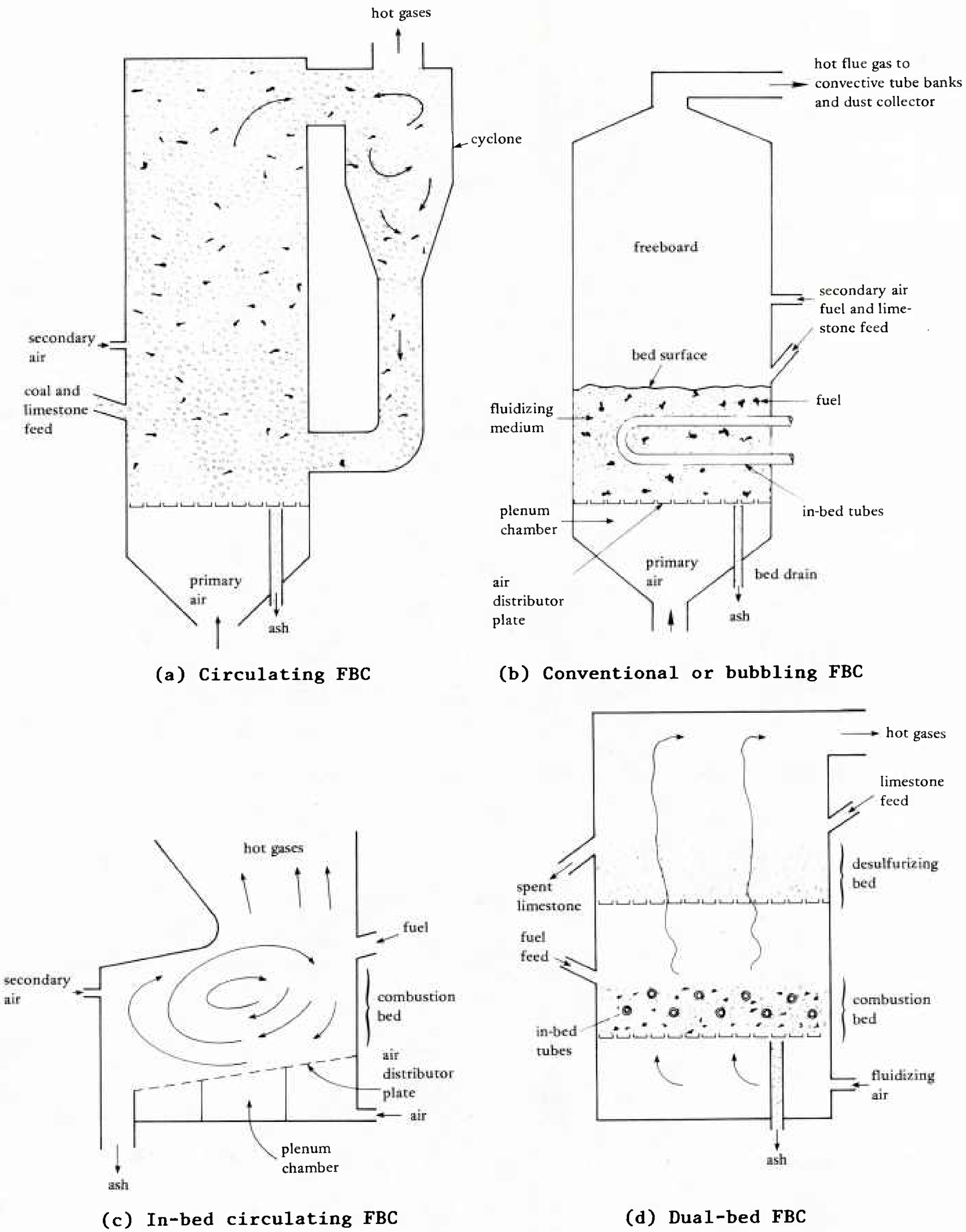


Figure 1. Comparison between packed bed and fluidized bed.



(a) Circulating FBC

(b) Conventional or bubbling FBC

(c) In-bed circulating FBC

(d) Dual-bed FBC

Figure 2. Schematic of various types of fluidized bed combustors.

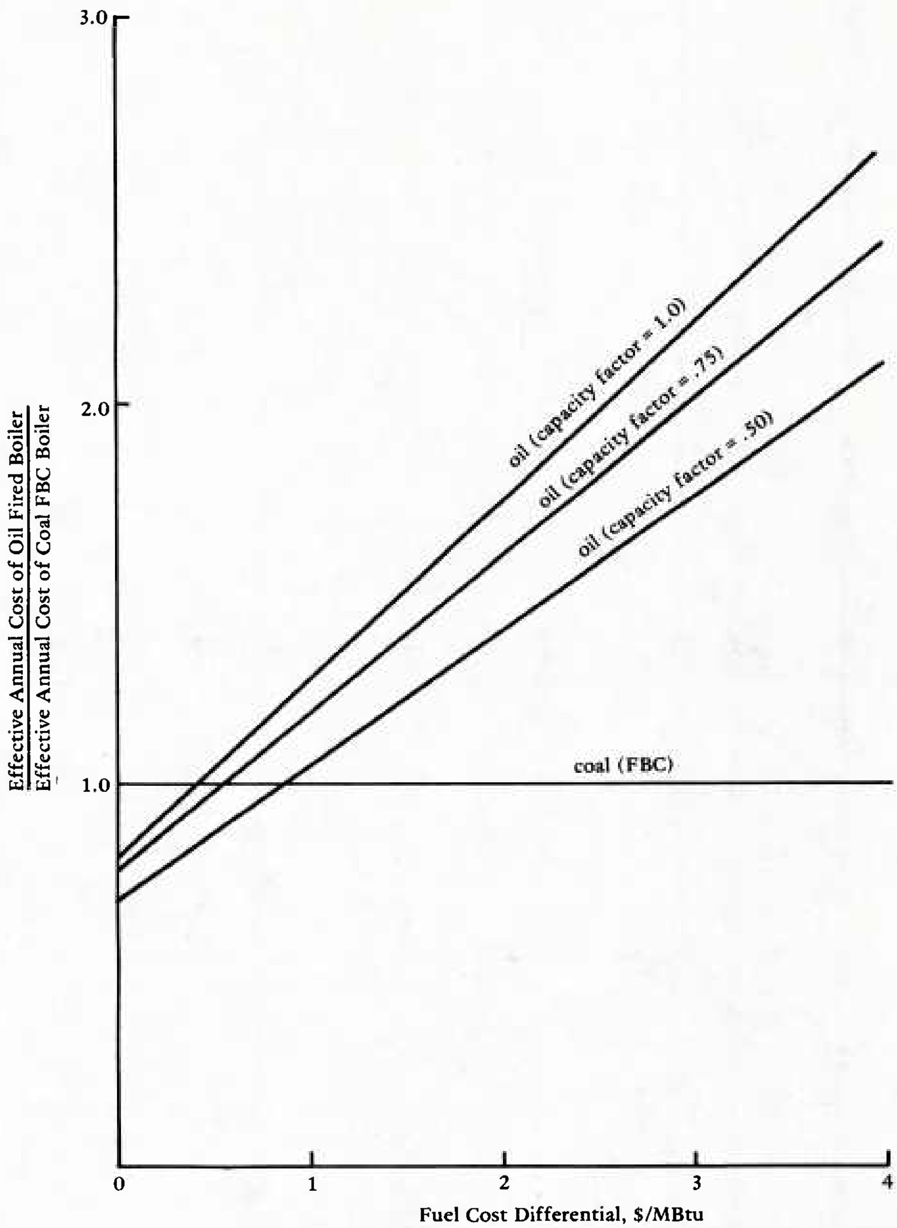
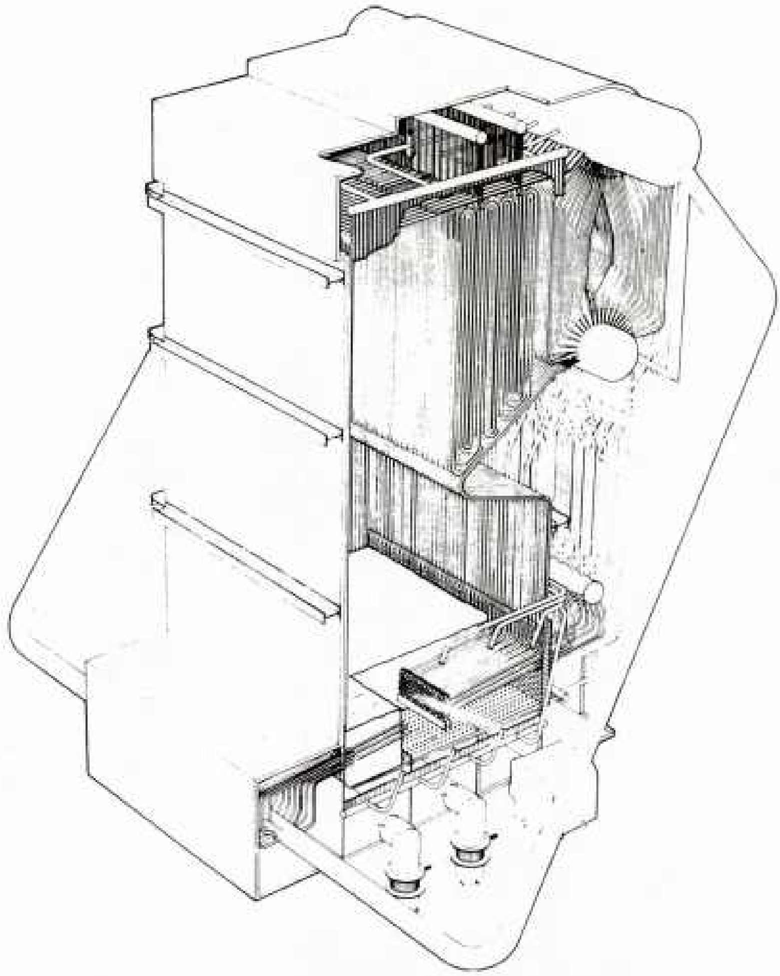
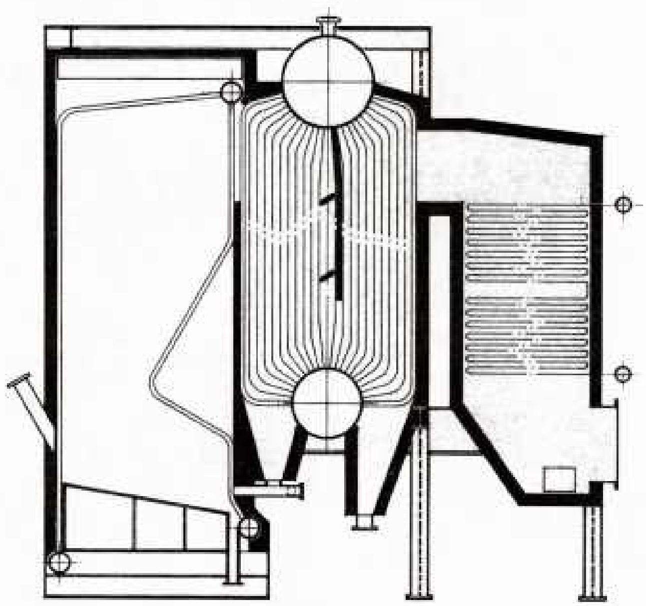


Figure 3. Relative cost between oil- and FBC coal-fired boilers.

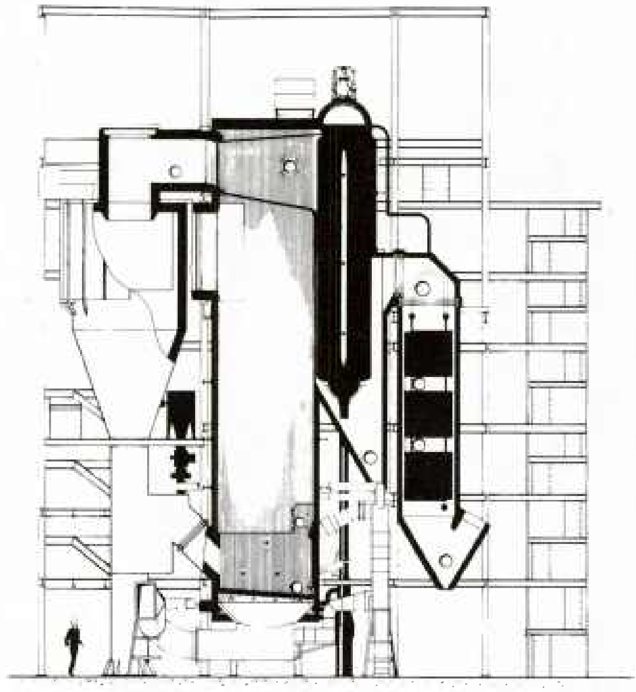


(a) In-bed circulating or bubbling bed boiler by Babcock & Wilcox

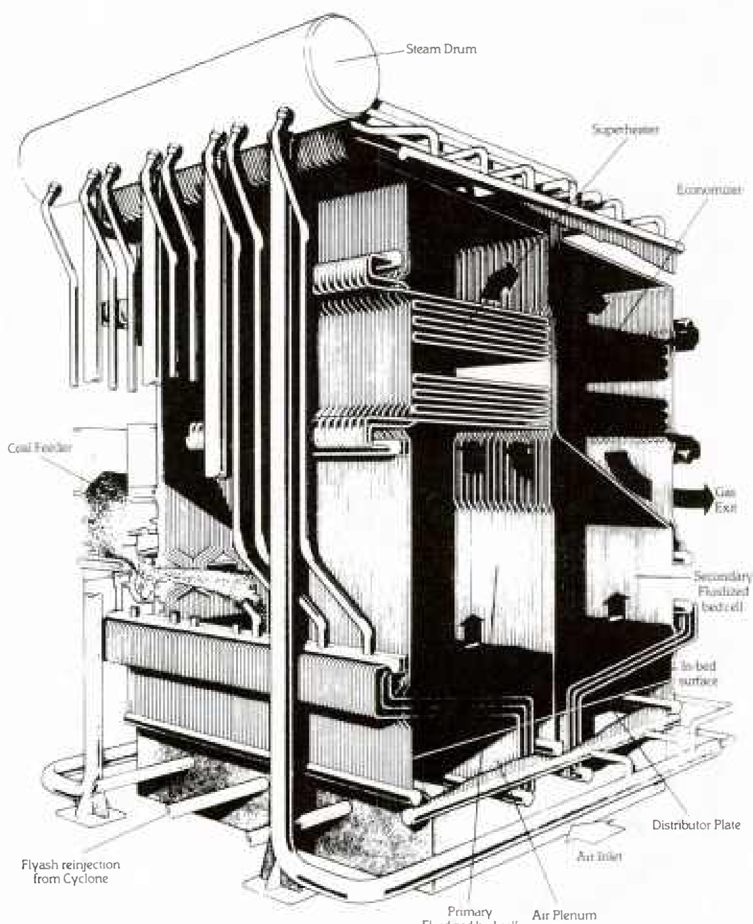


(b) In-bed circulating boiler by International Boiler Works Co.

Figure 4. Examples of existing fluidized-bed combustor boilers.

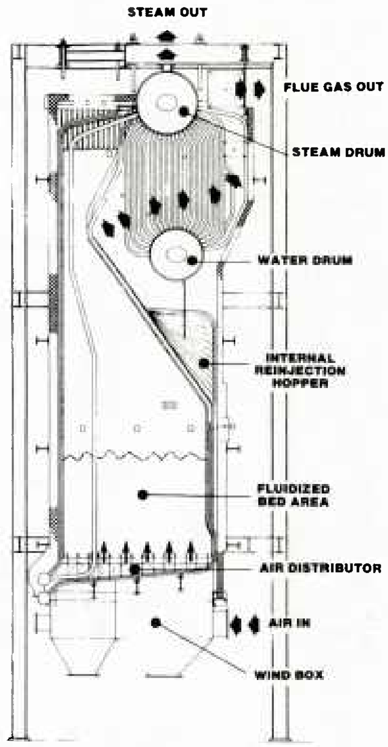


(c) Circulating FBC system by Pyropower

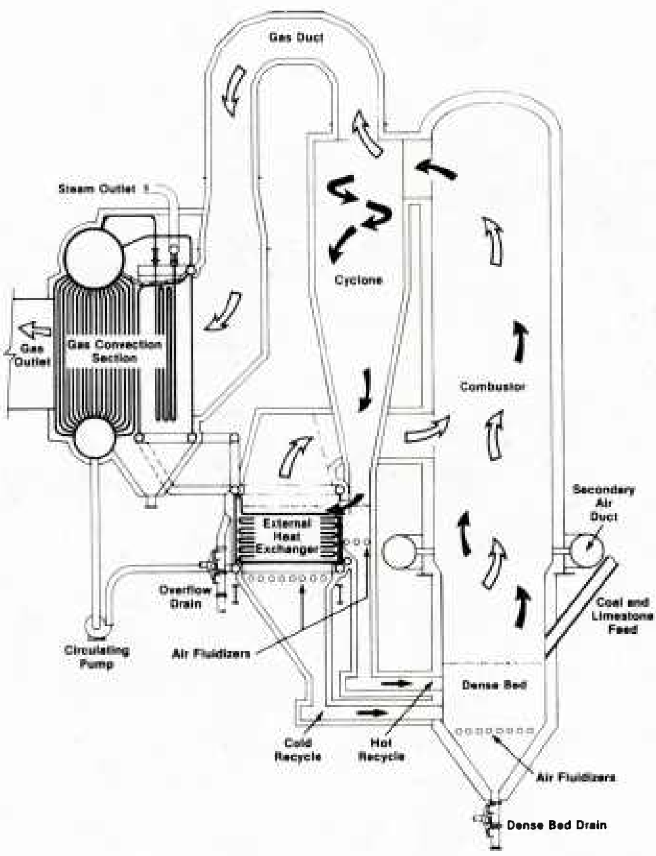


(d) Conventional FBC boiler by Foster Wheeler Corp.

Figure 4. Continued.

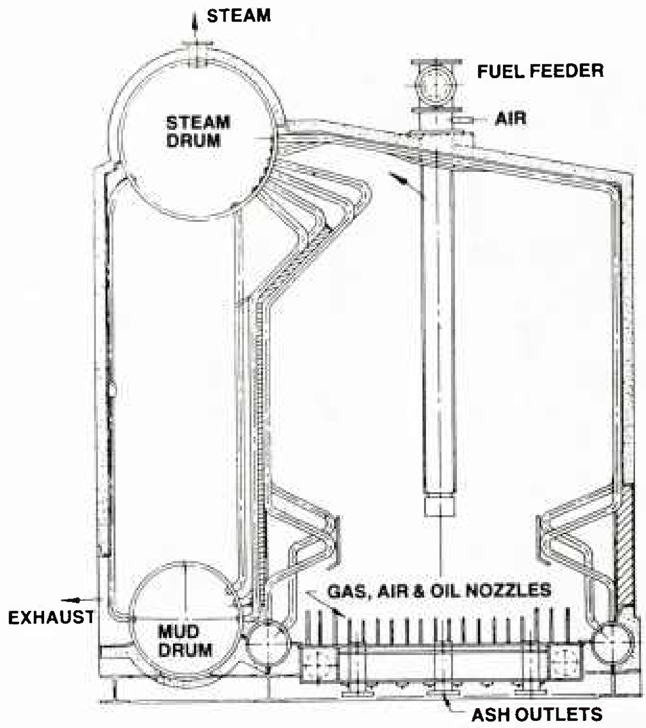


(e) In-bed circulating bubbling bed by Keeler/Dorr-Oliver

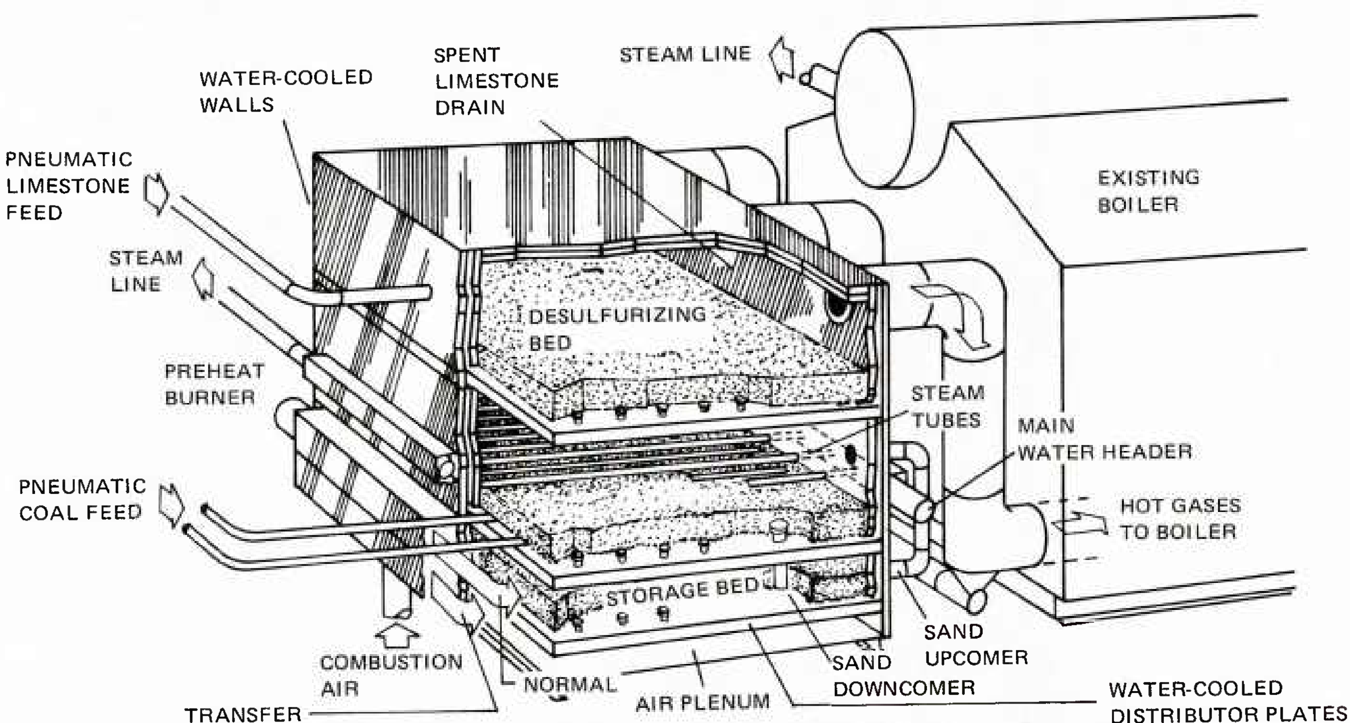


(f) Circulating FBC boiler by Riley Stoker Corp.

Figure 4. Continued.

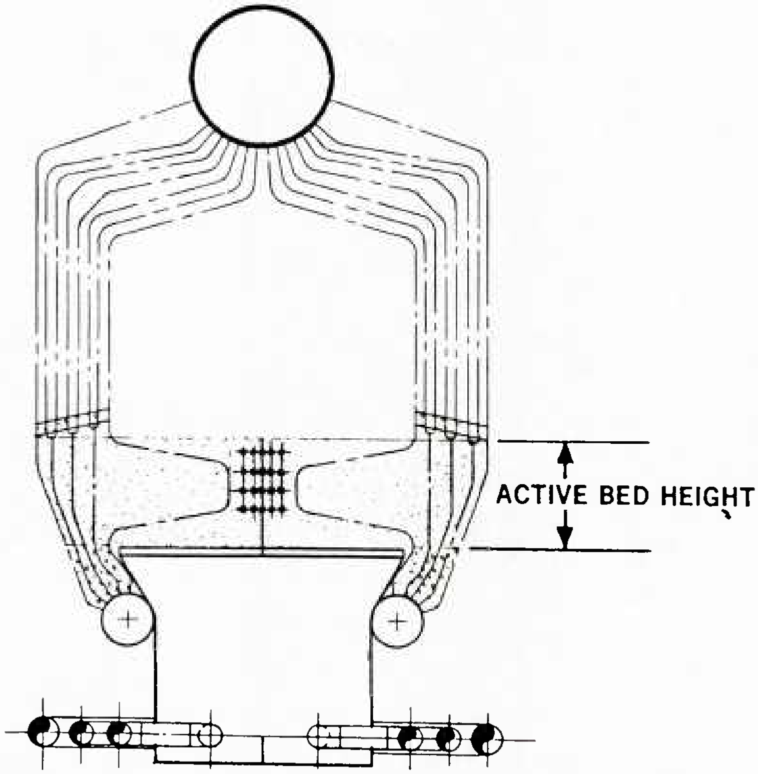


(g) In-bed FBC boiler by Stone Johnson Corp.

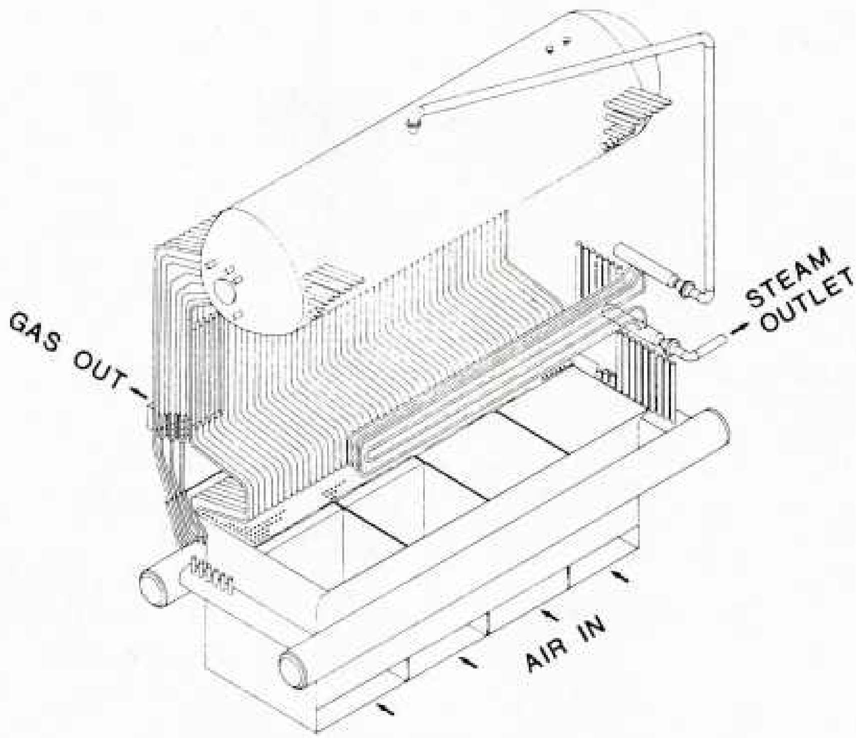


(h) Dual-bed boiler by Wormser Engineering, Inc.

Figure 4. Continued.

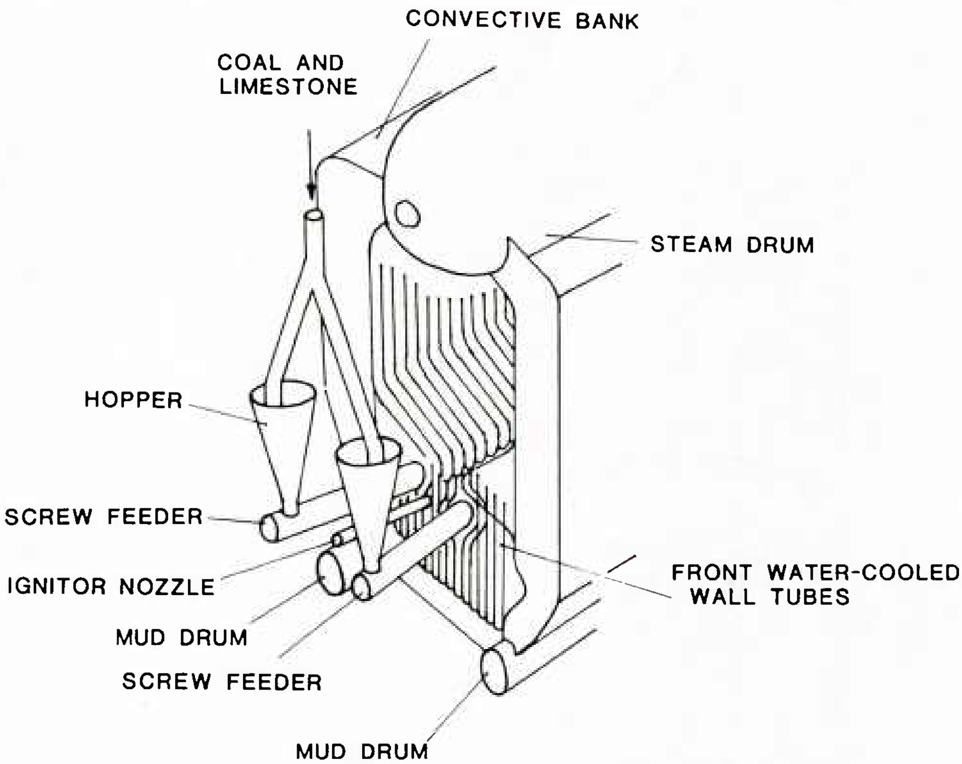


(a) Front cross-sectional view showing gas flow and bed height

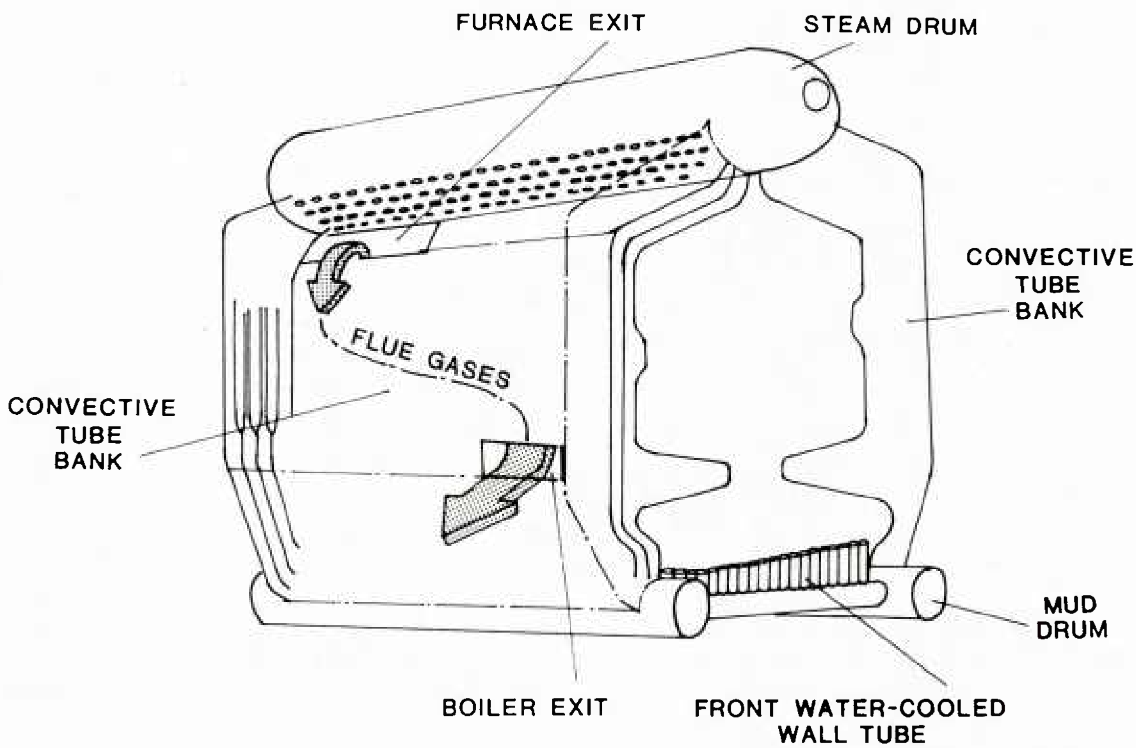


(b) General arrangement of the FBC boiler

Figure 5. General layout of the Great Lakes FBC boiler (by Combustion Engineering.

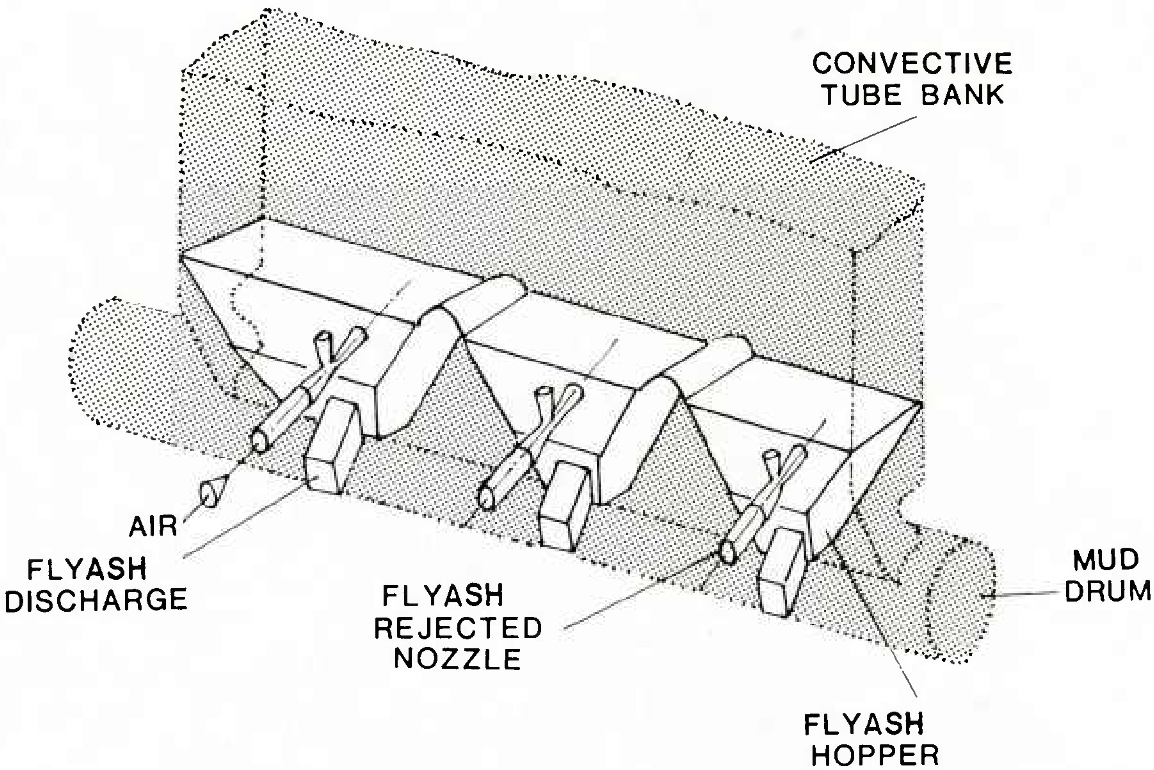


(a) Screw feeder system

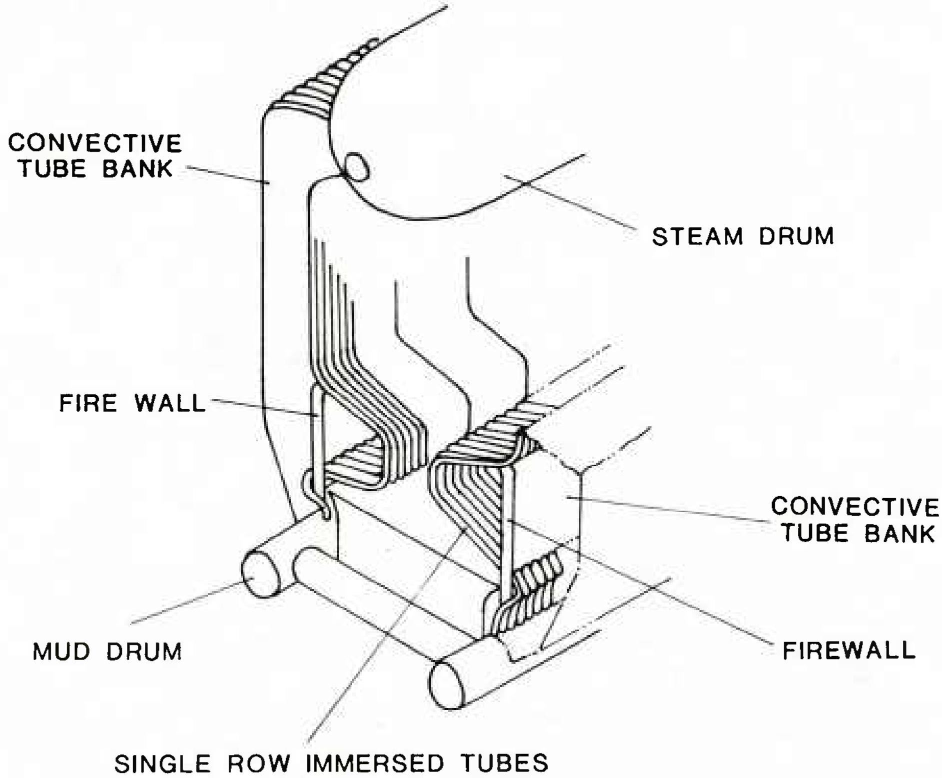


(b) Redirection of flue gas flow path to increase residence time and heat extraction

Figure 6. Possible modifications to rehabilitate the Great Lakes FBC boiler.

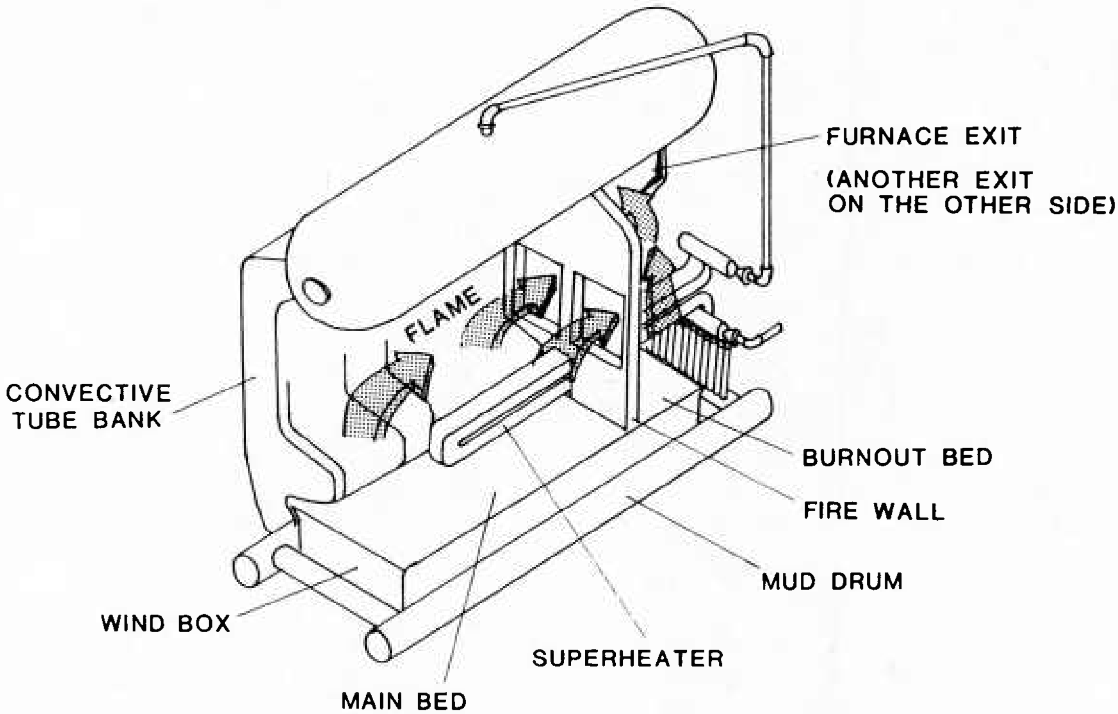


(c) Installation of a flyash recycle system to improve combustion efficiency and pollutions control (Shown one side of boiler only)



(d) Reduction of in-bed heat transfer surface

Figure 6. Continued.



(e) Construction of a separating firewall to control the bed level and improve the combustion and pollution control

Figure 6. Continued.

Table 1. Comparison Between the Bubbling Fluidized Bed, Circulating Bed, and Dual-Bed Boiler

Criterion	Bubbling Fluidized-Bed	Circulating Fluidized-Bed	Dual-Bed
Heat exchange surface	Immersed in bed Erosion problems in close packing of tubes	Only tube walls in fluidized bed combustor, with further decoupled heat exchange in an external solids heat exchanger	Immersed in combustion bed and additional heat exchange on exit of flue gas
Gas/solids	Restricted to bed, 1-6 feet	The whole reactor is filled with dispersed solids - bed height 6-30 feet	Restricted to combustion bed, 1 foot
Turn down capability ratio	5:1	3:1	30:1
Load following	Relatively slow	Faster than conventional FBC	Faster than conventional FBC
Bed material	Relatively course	Fine	Relatively course
Combustion efficiency	Problems with entrained char are encountered	Virtually complete (97%)	95-98%
Coal crushing	Coarse, drying coal may be avoided	Finer particle size, however coarser than pulverized coal combustion; drying coal may be necessary	Run-of-mine coal
Excess air (%)	20-40	10	20
Emission characteristics:			
a. Ca:S mole ratio for 90% removal of SO_2 with limestone addition	3 and higher	1.5-2 (longer contact time, smaller particles)	3

(continued)

Table 1. Continued

Criterion	Bubbling Fluidized-Bed	Circulating Fluidized-Bed	Dual-Bed
b. NO_x, ppm	300-400	100-200	100-200
Coal feed	Complicated, large number of feed points (one per 1-2 m^2) Alternatively, overbed feeders have higher carbon losses in fines	Simple, two feed points per unit	Underbed pneumatic coal feed
Specific thermal load per unit cross section	1-3 MW/m^2	3-8 MW/m^2 and higher	No information
Temperature uniformity	Freeboard combustion possible due to fines and volatiles	Uniform temperature in reactor and cyclone system due to high solids recirculation rate.	Separate temperatures for each bed for more efficient combustion and sulfur capture

Reference: TERA Corp. report for DOE of 14 Jan 1982.

Table 2. Estimated Relative Costs of Four Types of Boilers With 50,000 lb/hr Steam Output Operating in 1987 and 1992.

Item	Relative Annual Capital and Operating Costs							
	Existing Oil-Fired Boiler		Existing Gas-Fired Boiler		New Stoker Fired Boiler[a]		New FBC Boiler[b]	
	1987	1992	1987	1992	1987	1992	1987	1992
Fuel Cost	2.9	3.5	2.6	3.2	1.1	1.2	1.0 ($1048K)	1.0 ($1612K)
O&M, Labor	0.9	0.9	0.8	0.8	1.0	1.0	1.0 ($210K)	1.0 ($294K)
Ash Disposal	-	-	-	-	0.6	0.6	1.0 ($70K)	1.0 ($92K)
Debt Service on Loan	-	-	-	-	1.0	1.0	1.0 ($212K)	1.0 ($212K)
Effective Annual Cost	2.1	2.7	1.9	2.5	1.1	1.1	1.0 ($1540K)	1.0 ($2210K)

[a]Approximate payback period is 2.2 yr.

[b]Approximate payback period is 2.0 yr.

<u>Assumptions (all 1985 figures)</u>:
Capital cost: $50 per pound of steam escalated at 7%; total cost $2,750K midpoint of 1987, financing at 75% debt (25 years at 7% discount rate). Capacity factor 75%.

$1.24/MBtu high sulfur coal for FBC; $1.88/MBtu compliance coal for Stoker; $0.21/MBtu limestone; coal and limestone, O&M labor, and ash disposal, 7% escalation rate; $4.19/MBtu natural gas, 14% escalation rate; $4.97/MBtu No. 6 oil, 13% escalation rate. O&M: 2.5% of capital cost; labor: $20K/man-year, 2 man/shift, 3 shifts.

Table 3. FBC Boilers by U.S. Manufacturers

Manufacturer	No. of Installations			Type	Capacity (1,000 lb/hr)	Operating Pressure (psig)	Operating Temperature (°F)	Fuel[a]
	U.S.	Foreign	Under Construction					
Babcock & Wilcox	2	-	2	Bb, Circ	50 to 1,500	125 to 2,400	Sat to 2,400	2
Combustion Eng. Power System	7	10	1	Bb, Circ	50 to 1,600	100 to 1,800	330 to 950	1
Combustion Power Co.	8	-	6	Bb	15 to 250	40 to 1,850	250 to 1,100	3
Dedert Corp.	6	3	1	Bb	5 to 100	10 to 900	Sat to 825	4
Energy Products of Idaho	36	12	2	Bb	10 to 250	15 to 1,500	250 to 950	5
Fluidyne Engineering Corp.	1	-	-	Bb	7 to 50	15 to 650	up to 750	6
Foster Wheeler Corp.	12	19	1	Bb, Circ	35 to 600	150 to 2,400	Sat to 1,050	7
International Boiler Works	6	10	1	Bb	5 to 75	30 to 800	Sat to 750	8
Keeler/Dorr-Oliver	3	1	6	Bb, Circ	up to 500	up to 1,500	up to 1,000	8
Power Recovery System	2	-	-	Bb	10 to 100	up to 650	up to 950	1

(continued)

Table 3. Continued

Manufacturers	No. of Installations			Type	Capacity (1,000 lb/hr)	Operating Pressure (psig)	Operating Temperature (°F)	Fuel[a]
	U.S.	Foreign	Under Construction					
Pyropower Corp.	2	18	9	Circ	50 to 1,000	up to 2,500	Sat to 1,005	9
Riley Stoker	1	-	1	Bb, Circ	more than 40	150 to 2,600	up to 1,005	2
Stone Johnston Corp.	23	5	-	Bb	2.5 to 70	up to 700	Sat to 750	1
Struthers Wells Corp.	2	2	-	Circ	75 to 500	250 to 2,650	Sat to 950	1
Wormser Engineering Corp.	1	1	3	Bb, Dual-bed	20 to 200	up to 2,600	up to 1,000	1
York-Shipley Inc.	17	1	-	Bb, Circ	2 to 80	15 to 600	250 to 750	1
Total	129	82	32					

Symbols   Bb - Bubbling bed
Circ - Circulating bed
Sat - Saturated

[a]Fuel(s) designed to burn separately or in combination are:
(1) Coal, woodwaste, biomass, liquid wastes or sludges, coal-washing waste
(2) Coal, lignites, oil shale, coal water, slurry, petroleum coke
(3) Shredded tires, municipal wastes, natural gas, fly carbon, sludges, wood fines, lignites
(4) Wood chips, rice hulls, municipal solid waste, asphalt shingle waste, high sulfure coal
(5) Paunch, manure, coal, wood chips, cotton hulls/waste
(6) Anthracite culm, coal
(7) Bituminous coal, wood, coffee grounds, peat, wood chips, gas
(8) Coal, wood, waste oils, tires
(9) Petroleum coke, heavy oils, high ash coals

Table 4. Boiler Size Distribution and Fuel Use in Naval Shore Facilities' Boilers

Description	Boiler Capacity, MBtu/Hr							
	<5	5-10	10^+-25	25^+-50	50^+-100	100^+-Over	Total	
Boiler - Number	1,279	308	174	100	87	64	2,012	
- % Total	64	15	9	5	4	3		
Combined Capacity - M Btu/hr	3,011	2,132	2,938	3,465	8,274	9,399	29,219	
- % Total	10	7	10	12	28	32		
Annual Fuel Consumptions (1984):								% of Total Fuel, Btu
Distillate Fuel Oil - 10^3 Gal	15,934	10,707	8,613	7,939	5,067	12,925	61,185	
- (10^{12} Btu)	(2.207)	(1.483)	(1.193)	(1.10)	(0.702)	(1.790)	(8.476)	13
- % Total	26	18	14	13	8	21		
Residuals Fuel Oil - 10^3 Gal	935	9,143	17,632	20,301	61,391	117,778	227,181	
- (10^{12} Btu)	(0.141)	(1.38)	(2.65)	(3.06)	(9.24)	(17.72)	(34.191)	52
- % Total	0.4	4	8	9	27	52		
Natural Gas - 10^6 ft^3	1,901	1,225	1,756	3,500	7,203	4,368	19,953	
- (10^{12} Btu)	(1.996)	(1.286)	(1.843)	(3.675)	(7.563)	(4.586)	(20.949)	32
- % Total	10	6	9	18	36	22		
Coal - Tons	108	0	0	0	23,967	59,875	83,959	
- (10^{12} Btu)	(0.003)	0	0	0	(0.676)	(1.688)	(2.367)	4
- % Total	0	0	0	0	29	71		
Average Capacity Factor, %	16	22	22	26	25	31	26	

Note: Heating Value of Fuel used in the above calculation:
Distillate Fuel Oil = 138,500 Btu/gal
Residual Fuel Oil = 150,500 Btu/gal
Natural Gas = 1,050 Btu/ft^3
Bituminous Coal = 14,100 Btu/lb = 28.2 x 10^6 Btu/ton

Table 5. Age Distribution of Navy Stationary Boilers Larger Than or Equal to 25,000 lb/hr

Design Fuel	Age, Years				
	0-10	10^{+}-20	20^{+}-30	30^{+}-Over	Total
Oil:					
Number of boilers	28	37	41	189	295
Total capacity, 10^6 Btu/hr	1,874	3,424	4,282	13,965	23,546
Gas:					
Number of boilers	7	17	12	87	123
Total capacity, 10^6 Btu/hr	254	1,819	1,106	4,650	7,829
Coal:					
Number of boilers	5	1	2	17	25
Total capacity, 10^6 Btu/hr	444	165	330	1,742	2,681
Total:					
Number of boilers	40	55	55	293	443
Total capacity, 10^6 Btu/hr	2,572	5,408	5,718	20,357	34,055

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