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BOILER MODIFICATION COST SURVEY FOR SULFUR OXIDES CONTROL BY FUEL SUBSTITUTION

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BOILER MODIFICATION COST SURVEY FOR SULFUR OXIDES CONTROL BY FUEL SUBSTITUTION

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FOREWORD

This document presents the results of a survey of the costs of converting conventional, fossil fueled, stationary combustion equipment to the use of selected coal-derived fuels. The report provides updated information on present-day fuel switching activity, continues with the presentation of equipment conversion costs, and concludes with the formulation of cost models derived from the previously collected data.

The latter four authors of this report, personnel of The Coen Co. in Burlingame, California, performed the boiler modification cost assessments.

Aerotherm extends its appreciation for the valuable assistance provided by Mr. R. C. Carr of the Electric Power Research Institute, Palo Alto, California, and Dr. R. M. Jimeson of the Federal Power Commission, Washington, D.C. Special thanks is given to the diligent members of the Aerotherm Technical Publications Department.

This survey was performed for the Engineering Analysis Branch of the Control Systems Laboratory, U.S. Environmental Protection Agency. Dr. Gary J. Foley was the task officer until July 26, 1974. Dr. Charles Chatlynne was the task officer for the remainder of project's duration. The Aerotherm Project Manager was Dr. Larry W. Anderson. Dr. C. B. Moyer and Dr. H. B. Mason acted as advisors for all phases of the study. The study was undertaken during the months of June to September, 1974.

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INTRODUCTION

The creation of the various combustion-generated chemical species generally regarded as air pollutants can be reduced by a variety of means. Some pollutants, such as "thermal" nitric oxide, lend themselves to reduction by modification of the combustion process. Others, notably the oxides of sulfur, are released in quantities directly proportional to the amount of some contaminant contained in the fuel. Pre- or post-combustion controls are the only feasible means of eliminating combustion systems as sources of SO_X. Therefore, the two leading strategies for controlling SO_X emissions from combustion equipment firing sulfur-containing fuels are: (1) burning desulfurized fuel, or (2) removing the SO_X from the flue gas (Reference 1-1).

For high-sulfur coal, the former method can be effected by burning the products from various gasification and liquefaction processes, while several popular scrubbing techniques exist for stack gas SO_X removal. The choice of the most viable control strategy will be based on cost, among other factors. Such monetary considerations are to be analyzed using detailed, consistent cost models developed by the EPA.

EPA has funded research into several stack gas scrubbing techniques, and has detailed information on the costs of such operations for a given size of installation. The costs associated with typical coal gasification and liquefaction processes are also reasonably well in hand (Reference 1-2). There is not, however, a good source of information on the costs associated with converting oil- and coal-fired equipment to use these "synthetic" gases and liquids as fuels. The purpose of this task order is to provide cost information on the conversion from conventional fossil fuels to selected coal-derived gaseous and liquid fuels as a function of equipment type and firing capacity. This study focuses on conventional stationary combustion systems, such as industrial furnaces and utility boilers. The cost figures collected during this study lead to the formulation of generalized equipment conversion cost models, compatible with existing models involving production and transportation of these coal-derived fuels. The results of this task will contribute to EPA's on-going SO_X Control Strategy Analysis.

Specifically, the coal-derived fuels of concern in the context of the present study include Solvent Refined Coal (SRC) and the range of low-Btu (150 Btu/scf) to high-Btu (1000 Btu/scf) content gases. For the gaseous fuels, an attempt is made to treat the range of gases as a continuum, and to incorporate a heating value term in the cost models for gas. Large-scale research and development programs aimed at determining the feasibility of usir these materials as fuels have only recently been initiated. As a result, very little is known about their combustion and handling properties, and certain assumptions were made in this regard in order to make the required equipment modification cost estimates. It will be possible to evaluate these assumptions as more information on these fuels' physical properties becomes available.

The combustion systems of concern include steam-raising boilers in the 10^7 to 1000 x 10^7 Btu/hr range, encompassing all industrial and utility size equipment. This assures inclusion of the smaller SO_x sources, which tend to lack even intermittent controls (i.e., tall stacks) and which may have a significant impact on local air quality.

A future use for these coal-derived fuels for electric power production will be to fire them in combined-cycle plants, rather than solely in converted equipment of conventional designs. Indeed, the ultimate goal of most present-day coal-conversion power system projects is the demonstration on a commercial scale of an economically and environmentally acceptable electric generating plant that links a coal-conversion system with a combined-cycl plant adapted for using these exotic fuels (see References 1-3, 1-4, 1-5). Combined-cycle power plants are not, however, treated in the present study, but it is felt that determining the costs of converting conventional combustion equipment to the use of these fuels will provide support for future system trade-off and cost-effectiveness assessments.

The remainder of the present study is organized in the following manner:

<u>Section 2</u>: Current Fuel Substitution Activity - Conventional to Coal-Derived Fuels

This section attempts to draw together ongoing, practical experiences and state-of-the-art knowledge on the subject of converting the combustion equipment of concern to the use of exotic, coal-derived fuels from more conventional fossil fuels. This investigation was performed in the hope of supplementing the estimates of equipment conversion costs presented later in the study.

Section 3: Characterization of Combustion Equipment

This section presents the justification of the choice of combustion equipment types scrutinized in the study. Brief qualitative descriptions of the equipment are included.

Section 4: Characterization of Substitute Fuels

The study continues with brief discussions of the Solvent Refined Coal process, the notable coal gasification schemes, and their probable importance as fuels of the future. Typical chemical compositions of these fuels are given as well.

Section 5: Selection of Fuel Substitution Options

The manner in which the conversion cost data will be collected is introduced. This consists of a matrix of boiler type versus boiler capacity for a given type of conversion. The cost estimation method involves applying a set of cost data obtained from a similar conversion (i.e., to a lighter fuel oil) to a postulated coal-derived fuel conversion.

Section 6: Documented Boiler Conversion Cost Data

This section contains the estimated equipment conversion cost data for a given boiler type, original fuel and substitute fuel as set forth in the "Equipment Conversion Cost" data sheets. Included also are plots of the cost versus capacity data. Qualitative descriptions of the methodology of each conversion are provided. A discussion of the possible cost models that may be derived from these data is included as well.

Section 7: Conclusions and Recommendations

The significance of the results of the study are summed up, and recommendations for their future application are provided.

The report concludes with the References and the Appendix. The latter section contains the bulk cost data from which the final equipment conversion cost figures were derived. Included also is a tabulation of popular coal gasification processes. The appendix concludes with a table of British to metric conversion factors.

SECTION 2

CURRENT FUEL SUBSTITUTION ACTIVITY: CONVENTIONAL TO COAL-DERIVED FUELS

2.1 INTRODUCTION

Two energy source substitution strategies exist for reducing sulfur oxide emissions from fossil-fueled steam-generation equipment. First, the generating source itself may be replaced, such as switching from a fossil-fueled to hydropower plant. The second option, and by far the more expedient, is substitution of a cleaner fuel. The present study is concerned with a specialized case of the latter method.

Fuel substitution is a common practice in the operation of most large steam raising plants, although its motivation is most often based on fuel availability rather than on air pollution control. Most of these plants were originally designed for dual fuels, and the actual in-plant fuel switching process is usually quite straightforward. As a general rule, however, difficulty in doing so increases when progressing from gaseous or liquid to solid fuels. The material handling problems are worsened, and the possibility of additional combustion erratics arise with reduced fuel heating value.

Among the more promising low-sulfur fossil fuels are the products from coal conversion processes. The current clean fuel shortage has sparked widespread interest in the energy generation potential of these future fuels. At the present time, however, no existing industrial or utility boiler is firing these fuels, due mainly to a general lack of sufficient quantities. In addition, the combustion and handling properties of these fuels are generally unknown. The probability is high, however, that some degree of equipment modification will be necessary before these fuels can be utilized in existing equipment. The purpose of this study is to assess the capital costs of converting a variety of boiler designs and capacities to two types of coal-derived fuels; namely, lower-BTU gas (HHV = 150-700 Btu/scf) and solvent refined coal (SRC). Current activities in this area are reviewed in the following subsections. Although for many years it has been the practice of the industrial boiler sector to use waste gases (i.e., coke oven gas) of low heating values as fuels, such occurrences are too varied to be included in this discussion. The principles involved in using such fuels are, however, an integral part of the cost estimation methodology performing during this study.

2.2 CURRENT ACTIVITIES

For the most part, actions in the area of converting boilers to coal-derived fuels have been limited to studies, models, and position papers by the utility industry. This lack of actual conversion experience stems, for the most part, from a combination of the following three factors:

- Quantities of these exotic fuels are insufficient even for subscale test purposes, much less for full-scale steam generation.
- Pressure to begin such programs was absent until the energy shortage reached a severe level several years ago. This, naturally, retarded the development of the required new technology.
- The lead time required by the utility industry to implement alterations in electrical generation mode is traditionally long.

However, a discussion of germane literature as well as the current posturing by the utility industry is of interest in the context of this study.

Conversions to Lower-BTU Gas

A recent article by Henry and Burbach of Combustion Engineering, Inc., (Reference 2-1) considered the factors involved when attempting to apply low-Btu gas (130 Btu/scf) to an existing tangentially-fired boiler. The authors' major conclusions were:

- The lower heating value of the gas requires that, compared with natural gas, as much as 12 times the amount of fuel gas (by weight) be handled
- This factor may require a larger combustion volume, and either larger fuel piping or higher supply pressures.
- Operation of the on-site low-Btu gas plant may require that the steam generator be brought on line on its backup fuel (i.e., low sulfur oil) and then transferred to the low-Btu gas. This refers to the "dynamic coupling" difficulties that will be discussed later in this section.

No information on the costs associated with the required modifications were included in the paper. The article also related that Combustion Engineering currently has a four-phase contract with the Office of Coal Research to design a 200 MW pilot plant in combination with 5 ton/hr low-BTU gasification plant.

A recent paper by Frendburg (Reference 2-2) verifies much of the information in the paper by Henry and Burbach, and contains some additional elaborations:

- As the heating value of the fuel gas falls below 300 Btu/scf, the fuel pipes or ducts increase in size making it more difficult to route these pipes or ducts.
- The furnace volume of coal-fired utility boilers are inherently larger than those for either oil or gas, and will, therefore, more readily accommodate lower-Btu gas.
- Unit efficiency may decrease when firing lower-Btu gas, due to increasing heat loss to the stack.

Actual application of lower-Btu gas in power plants is seemingly limited at the present time to some program planning on the part of an electrical utility company in Illinois (References 2-3 and 2-4). Through contributions to the Electric Power Research Institute, the electric utility industry is supporting this development project, which is sponsored by Commonwealth Edison Company. The project's strategy will be to use a Lurgi gasifier to equip the 120 MW Powerton Station. It was determined that using low-BTU gas as a fuel supply possessed two major advantages over stack gas scrubbing:

- The low-Btu gas supply can generate a net excess of electric power by passing the product stream through an unfired expander turbine; this contrasts with the scrubber which uses from 5 to 10 percent of the generated power (Author's comment: it should be noted, however, that generation of low-Btu gas entails the loss of approximately 40 percent of the heating value of the feedstock coal. An overall power generation system energy balance will favor the use of raw coal).
- The associated gas purification process of the gasification system effects cleanup by removing hydrogen sulfide (for which technology exists), and treats less than 5 percent of the volume of gas that would be processed in a scrubbing system.

Detailed information on the present status of this project was not available.

Conversions to Solvent Refined Coal

The practical and economical feasibilities of utilizing solvent refined coal in existing fossil-fueled utility boilers have been analyzed in some depth (References 2-5, 2-6, and 2-7). SRC is a relatively clean fuel, being low in moisture, ash, and sulfur, and its heating value is fairly uniform regardless of the feedstock coal (about 16,000 Btu/lb). On the face of it, this means that the refined product can be shipped on a Btu basis for proportionately less than raw coal. This factor suggests the location of refining plants near cheap sources of coal. In addition, the paper studies show significant pollution control cost savings through the use of SRC. However, the assumption is made that it can be substituted for either oil or coal without difficulty. As it is the purpose of the present study to evaluate such conversion costs, the validity of this assumption will be tested. Also, the cost of producing SRC must be factored in when comparing costs with stack gas scrubbing.

As is described in detail in Section 4 of this report, the physical properties of SRC are such that some controvery currently exists as to whether it is more advantageous to burn it as a liquid or solid. The original fuel may become a deciding factor.

There are currently two schools of thought on the subject of the applicability of solid SRC to coal-fired plants. One contends that the material is sufficiently similar to coal that existing storage facilities, pulverizers, and fuel handling and combustion equipment can all be used, with no modifications necessary. The opposing theory states the opposite: that solid SRC will melt unless preheat operation is discontinued and appropriate portions of the fuel preparation and handling equipment are externally cooled (References 2-8 and 2-4). As so little is known about the actual handling and combustion properties of this material, considerations from both cases have to be treated. The first would require essentially no cost, while some finite cost will be associated with the second.

It is generally agreed that firing liquid SRC in either oil- or coal-fired plants will require some degree of adaptation. SRC's viscosity increases dramatically below about 500F, which will necessitate, among other factors, external pipe- and vessel-heating apparatus. The extent and cost of the liquid SRC handling system will depend to some degree on the location of the SRC plant with respect to the steam generator. If the plant is located inconveniently far from the site of use, the SRC can be transported as a solid (molded pellets) to the boiler and subsequently melted. If the SRC plant is adjacent to the boiler, cooling the material to solid form will not be necessary before combustion. In either case, the usual liquid fuel handling equipment (piping, valves, pumps, storage tanks, etc.) will be required in addition to the special fuel warming equipment. Such considerations will be treated at greater length in Section 6 of this report.

Actual experience in converting steam raising boilers to the use of SRC has been, at present, restricted to preliminary program planning by some electric utility/oil company consortia in the Midwest and Southeast. In Ohio, the team of Old Ben Coal Company, Standard Oil of Ohio, and Toledo Edison are gearing up for a pilot program in which SOHIO will supply SRC, made from coal supplied by Old Ben, to an Edison generating station. Conversations with the principals involved netted the following (References 2-9, 2-10, and 2-11):

- SRC will be transported like coal in existing hopper cars.
- Heated pulverizers cannot be used; Toledo Edison's operates at about 130F.
- What effect SRC's lower ash content will have on the plant's existing ash collection method is unknown.
- Amount of possible boiler derating is unknown.
- SRC may not be able to be heated to a liquid state and stored for long periods of time; in any case, the heating must be done under pressure and an inert atmosphere, to avoid repolymerization.
- The major advantage of SRC as a substitute fuel over lower-Btu gas is the lessening of "dynamic-coupling" difficulties; i.e., a utility plant's output can vary by as much as ± 5 percent per minute, while a gasification plant's rapid turndown capabilities are far less. SRC can be stored easily and its input rate can be modulated readily.

A detailed description of the SOHIO/Toledo Edison/Old Ben enterprise has not yet been published or otherwise made available to the general public.

Additional activity in the area of SRC utilization in power plants is currently taking place at Wilsonville, Alabama. A 6 ton/day SRC pilot plant, sponsored jointly by The Southern Company system and the Electric Power Research Institute, was completed at this location in August, 1973. Preliminary plans are being made for applying the SRC obtained from this pilot plant to a Southern Services generating plant (Reference 2-12).

2.3 SUMMARY AND CONCLUSIONS

The motivation for fuel substitution in steam-raising boilers is based on fuel availability and/or pollution control. The continuing shortage of clean substitute fuels will cause reliance on alternate fossil fuels. With the advent of coal-derived fuels, most of which require special handling and combustion procedures, some effort will have to be expended to convert conventional combustion systems to their use. Of the various coal conversion processes, the products from two of them are considered in this study: solvent refined coal and synthesis gas.

Thus far, activities aimed at converting full-scale utility boilers to the use of either of these types of fuels has been limited to studies, position papers, and preliminary program planning by a few electric utility/oil company consortia in the Southeast and Midwest. For the gaseous coal-derived fuels, a Lurgi coal gasifier will be used to supply a 120 MW generating station. Details on the present status of this project were not available.

In another program, solid SRC will be utilized in a coal-fired power plant. It is anticipated by the participants that little or no equipment conversion will be necessary. An additional SRC-related project is underway in the Southeast, where SRC from a 6 tons of coal/day pilot plant will be supplied to an existing generating unit.

A major advantage of solid SRC over lower-Btu gas as a boiler fuel is that, in contrast to the product from an *in situ* gasifier, SRC can be stored when not in demand by the power plant, thus removing the "dynamic coupling" difficulties prevalent in the gasifier/steam plant strategy.

There is as yet no widespread move to employ either gasified coal or SRC in the industrial boiler sector.

The absence of cost data based on actual experiences in converting to these exotic fuels necessitates that such costs be estimated for this study. The estimation procedure, performed by personnel of The Coen Co., was based on a knowledge of the fuel's physical properties as well as an extensive background of boiler conversions to similar fuels. Section 6 of this report discusses the estimation methods and assumptions used in deriving the cost figures.

SECTION 3

CHARACTERIZATION OF COMBUSTION EQUIPMENT

3.1 INTRODUCTION

The previous section of this report reviewed current activities involving the substitution of various coal-derived fuels for conventional fossil fuels in stationary combustion equipment. The majority of such activity currently centers around full-size utility boilers, with less apparent effort being expended in the industrial boiler sector. Both sectors are, however, obvious candidates for the application of fuel switching as a SO_x abatement strategy.

The choice of the combustion equipment types and their capacities ultimately considered in this study was based on two factors:

- Determination of the most prolific stationary SO_x sources. According to the 1970 nationwide emission estimates given in Reference 3-1, fuel combustion in stationary sources accounts for 79 percent of the total controllable SO_x emissions. Of that amount, 73 percent is contributed by steam-electric, 18 percent by industrial, 3 percent by commercial and institutional, and 5 percent by residential sources. It appeared that the greatest benefit would be derived from considering only the first two source categories.
- Possible impact on the ambient air quality in the immediate vicinity of the source. This consideration demanded the inclusion of the smaller SO_x sources.

These criteria acted to establish the framework for the determination of the types and capacities of combustion equipment to be considered in this report; namely, steam-raising boilers in the 10^7 to 1000×10^7 Btu/hr (1-1000 MW) capacity range, which encompasses all industrial and utility size equipment. Including a wide variety of boilers and capacity ranges increases the probability of arriving at a global relationship between equipment conversion capital cost and capacity.

Boilers used for industrial purposes in the capacity range of interest include the following general types:

- Firetube (packaged)
- Watertube (packaged or field-erected)
- Stoker (field-erected)

Utility boiler types, all of which are field-erected, are categorized mainly by fuel firing mode. These include:

- Face-fired
- Tangentially-fired
- Turbo-fired
- Cyclone-fired

The remainder of this section is devoted to brief descriptions of these types of industrial and utility boilers. Throughout the discussion, it should be noted that the term "packaged" refers to a shop-fabricated boiler which is shipped as a complete unit to the point of use. This fact naturally places an upper limit on physical size; the largest packaged boilers can be transported by barge, and most are sized for railroad flat cars. The opposite fabrication method is described by the term "field erected," meaning the boiler is assembled from its component parts at the site of eventual operation.

Additional, more detailed specifications on the design, construction, and operation of these boilers can be obtained from the references cited.

3.2 INDUSTRIAL BOILER TYPES

3.2.1 Firetube Boilers

Firetube boilers (all of which are packaged) are used where steam demands are relatively small, usually for heating systems, industrial process steam, or as portable boilers. In this design, the hot combustion gases are passed through tubes submerged in a water-containing vessel. The principal types of firetube boilers include Horizontal Return Tubular (HRT), Scotch Marine, and "Short Firebox," the capacities of which fall in the 10^7 to 25 x 10^6 Btu/hr range.

These three types of boilers will be lumped together under the firetube boiler category, mainly because of similarities in capacities and firing equipment. HRT boilers are not commonly built for industry at present, being more predominant 15 to 20 years ago. The same is true of the short firebox boiler. The Scotch Marine boiler type refers to firetube boilers in general use today for low pressure (15 to 20 psig) saturated steam applications with steam flow capacities in the 300 to 25,000 lb/hr range. Firetube boilers are fired solely on gaseous or liquid fossil fuels. Typical manufacturers are Cleaver Brooks, Superior, and Bryant (References 3-2, 3-3).

3.2.2 Watertube Boilers

This category includes both field-erected as well as packaged units. Common sizes for the former type fall between 50 x 10^6 and 500 x 10^6 Btu/hr, while 10^7 to 250 x 10^6 is the capacity range for the latter. Larger packaged boilers, above 450 x 10^6 Btu/hr, are currently being designed and supplied, but are not yet common.

As the name implies, watertube boilers are designed to flow water through the heat transfer tubes, instead of combustion products as in the firetube design. Because of the smaller diameter pressurized components and the advantage using tubes gives in accommodating expansion, they are better able to contain the pressure and afford an inherently safer design.

Field-erected boilers are usually balanced draft and therefore require both forced draft and induced draft fans. Field-erected boilers are commonly fired with coal, gas and/or oil. Many such boilers exist today but very few new applications have capacities lower than 200 x 10^6 Btu/hr, except for pulverized or stoker coal-fired units. This is because of the packaged boiler's domination of the oil- and gas-fired boiler market, which is in turn due to their low capital cost in the sizes between 12 x 10^6 and 200 x 10^6 Btu/hr.

Packaged watertube boilers are used for gas and oil firing applications. They are not used for coal firing because they have much smaller furnace volume than are permissible. They are designed to be rail-shipped as a complete, single package with minimum fieldwork. The furnaces are also designed to operate under positive pressure versus the balanced or slightly negative pressure found in coal-fired boilers.

Both types of boilers use similar type firing equipment. The register-type burner is generally used, with burner capacities being between 50 x 10^6 and 120 x 10^6 Btu/hr on a field-erected boiler, and up to 350 x 10^6 Btu/hr on a packaged boiler. Packaged boilers generally have one burner although older units were fitted with multiple burners - usually two. Popular types of industrial watertube boilers, both packaged and field-erected, are manufactured by Combustion Engineering Company, Riley Stoker, and Erie City Company (References 3-2, 3-4, 3-5, 3-6).

3.2.3 Stoker-Fired Boilers

The two major options available for the controlled combustion of coal are suspended firing, in which the fuel is pulverized to a fine dust prior to being combusted in a wall-mounted burner, and bed combustion, which causes oxidation to take place in and above a layer of raw coal. An example of the latter method is found in the traditional hand-fired coal furnace. Mechanical stoker-fired boilers are an improvement over this design.

The general stoker-fired boiler category includes spreader, underfeed, vibrating grate, chain grate, and traveling grate stokers. All terms refer to the method of coal/air introduction and mixing, as well as char and ash removal. Firing capacities generally range from 15×10^6 to 250×10^6 Btu/hr. It is very unusual for a stoker to be designed with less than 20×10^6Btu/hr capacity. Units above 200×10^6 Btu/hr are also rare.

Stokers are often preferred over pulverized-fired units because of their ability to burn a wide variety of coals and other solid fuels, greater operating range, and lower power requirements.

A major impact on the cost of converting mechanical stoker-fired boilers to a substitute, cleaner fuel will be the required modification of the equipment inside the furnace volume. Pulverized coal-fired units of the same capacity incur no such costs. This effect will be noted in Section 6, later in this report.

3.3 UTILITY BOILERS

Most of the nation's combustion-derived electricity is generated in large fossil-fueled central stations, which consist of watertube boilers operating in the supercritical pressure region serving turbine-generators in the million kilowatt range. Firing capacities of individual burners in utility boilers commonly range up to as high as 125×10^6 Btu/hr. One-thousand MW wall-fired units may require as many as sixty separate burners.

Although there are some differences among utility boiler designs in such factors as furnace volume, operating pressure, and configuration of internal heat transfer surface, the principle distinction is firing mode. This includes the type of firing equipment, the fuel handling system, and the placement of the burners on the furnace walls. The major firing modes, of which equipment conversion costs are a function, are briefly described below.

3.3.1 Wall-Fired Boilers

The multiple burners in wall-fired utility boilers are usually mounted in geometrical patterns on the vertical furnace wall, although some designs employ roof-mounted burners. Depending on the manufacturer and firing capacity, the burners in vertical wall-fired boilers may be mounted either on a single wall or on opposite walls. Figure 3-1 shows cross-sections of these tw types of boilers. Vertical-wall burners are usually of the register type, whi "intertube" burners are normally used in roof-mounted applications. In any ca the burners are fired in a fixed direction normal to the wall. This is in con trast with the tangential firing method which allows some degree of burner "til

Individual burner firing rates lie in the 75 x 10^6 to 125 x 10^6 Btu/hr range; the total heat release rate of wall-fired boilers normally falls between 500 x 10^6 and 10,000 x 10^6 Btu/hr, which corresponds to a generating capacity range of 50 to 1000 MW.

The wall-fired boiler design is capable of utilizing all conventional fossil fuels, including natural gas, fuel oil, and pulverized coal. Well-known manufacturers of this type of boiler include The Babcock and Wilcox and Foster Wheeler Companies (Reference 3-7).

3.3.2 Tangentially- and Turbo-Fired Boilers

Tangentially- and turbo-fired boilers are grouped together because the burner equipment is essentially identical for both boiler types; i.e., both use multiple burners, both fire between the boiler tubes, fuel/air mixing takes place within the boiler furnace itself (as opposed to the burner throat of a register type burner), and they employ a common burner capacity range - 75 x 10^6 to 125 x 10^6 Btu/hr.

The boilers are physically quite different. Tangential boilers, as show in Figure 3-2, are fired with groups of 4 burners at the same elevation with ea burner located in a corner of the boiler. Each burner fires along the tangent of a small imaginary circle in the center of the boiler. The resulting spin of the four "flames" creates high turbulence and thorough mixing of fuel and air i the center of the furnace. Additional levels of burners at 6- to 10-foot incre ments provide additional capacity for larger boilers.

Turbo-fired furnaces, as illustrated in Figure 3-3, provide a similar turbulent mixing of fuel and air in the furnace, but in this case, the burners are mounted in opposing walls of a "bottle neck" type furnace. The walls are tilted towards each other such that opposing burners fire down at a 30° angle towards the center of the lower part of the boiler. The burner sizes mentioned

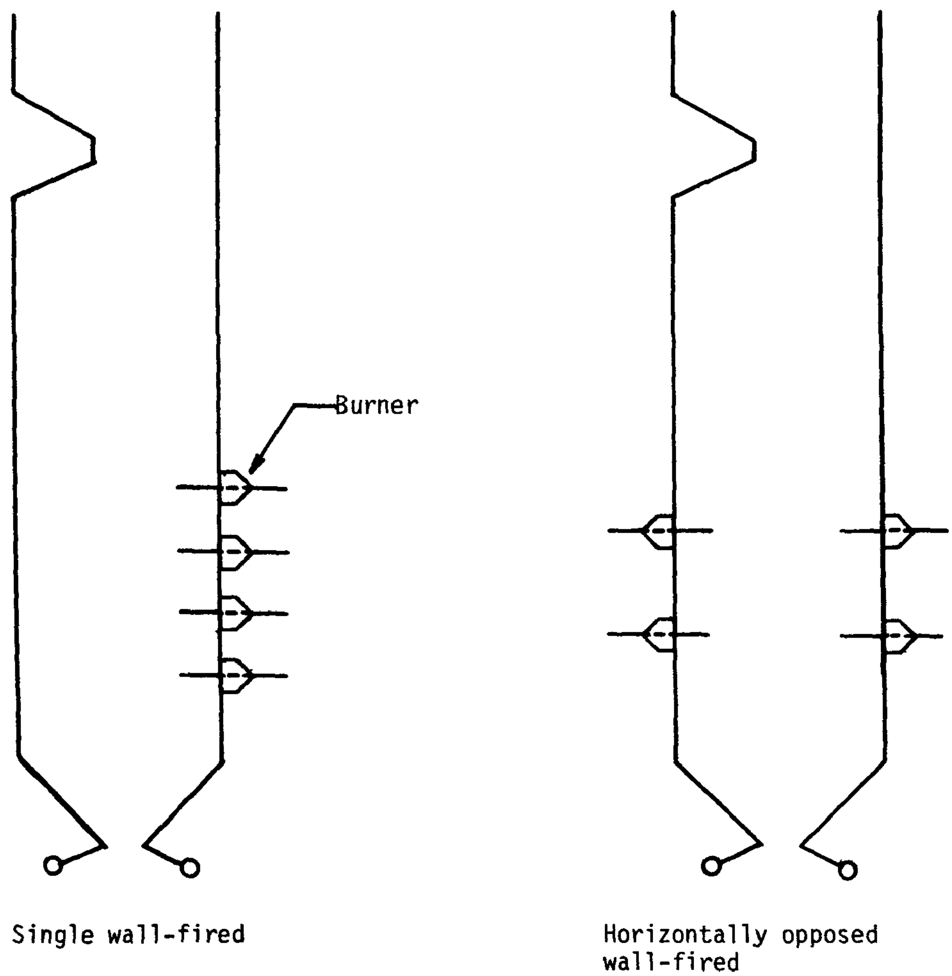


Figure 3-1. Vertical wall-fired utility boiler shapes and burner configurations

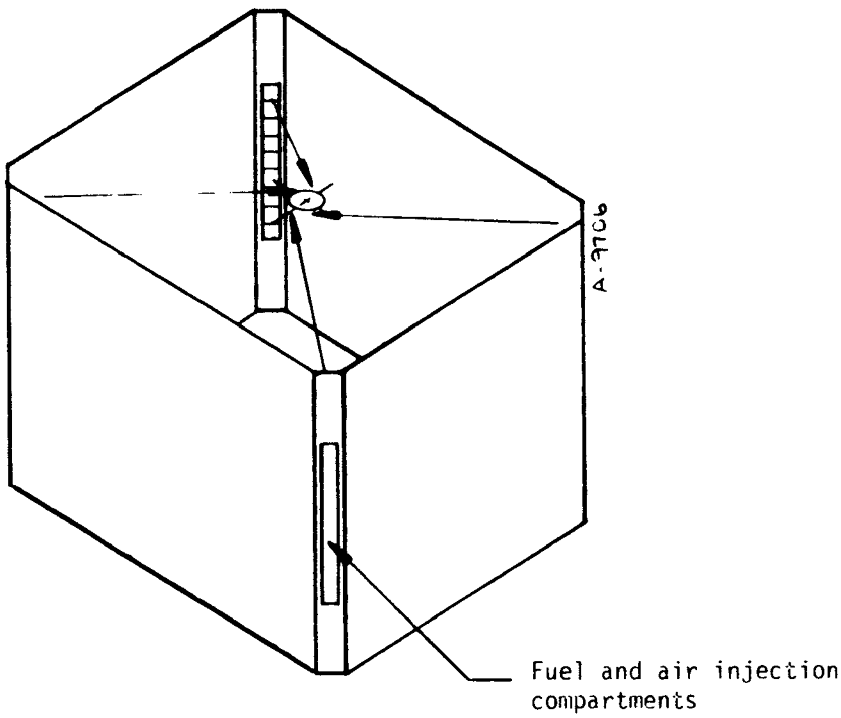


Figure 3-2. Tangentially-fired utility boiler shape and firing pattern

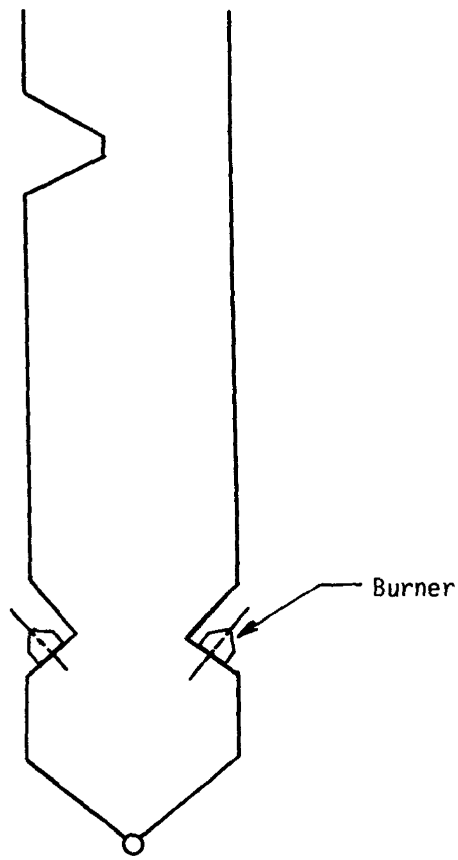


Figure 3-3. Riley Turbo® furnace shape and burner configuration

above are the same as those commonly found in tangentially-fired boilers. Therefore, higher boiler capacities are attained by increasing the boiler widt and the number of burners.

Turbo-fired boilers are manufactured by Riley Stoker, while most of the tangentially-fired utility boilers are constructed by Combustion Engineering, Incorporated (Reference 3-8).

3.3.3 Cyclone-Fired Boilers

A cyclone boiler is composed of the combination of a watertube boiler and a separate "cyclone" furnace (or series of furnaces) that are themselves water-cooled. Cyclone furnace firing arrangements are depicted in Figure 3-4. This type of furnace is capable of handling coals with high slag viscosities (250 poise at 2600F or lower). The air-conveyed coal and secondary air are injected into the furnace such that a highly swirling "cyclone" flame results. The high heat release of the furnace results in the high gas temperatures that are necessary for the formation of liquid slag. Slag taps permit continuous removal of the molten slag. Typical single furnaces are designed for firing capacities between 100×10^6 and 400×10^6 Btu/hr, with multiple cyclone furnaces being employed for loads above 400×10^6 Btu/hr. Cyclone furnaces are designed primarily for coal-firing, with gas or oil available only for standby operation. For gas operation, the fuel is injected horizontally with the secondary air.

Most cyclone-type boilers are constructed by The Babcock and Wilcox Company or its subsidiaries (Reference 3-7).

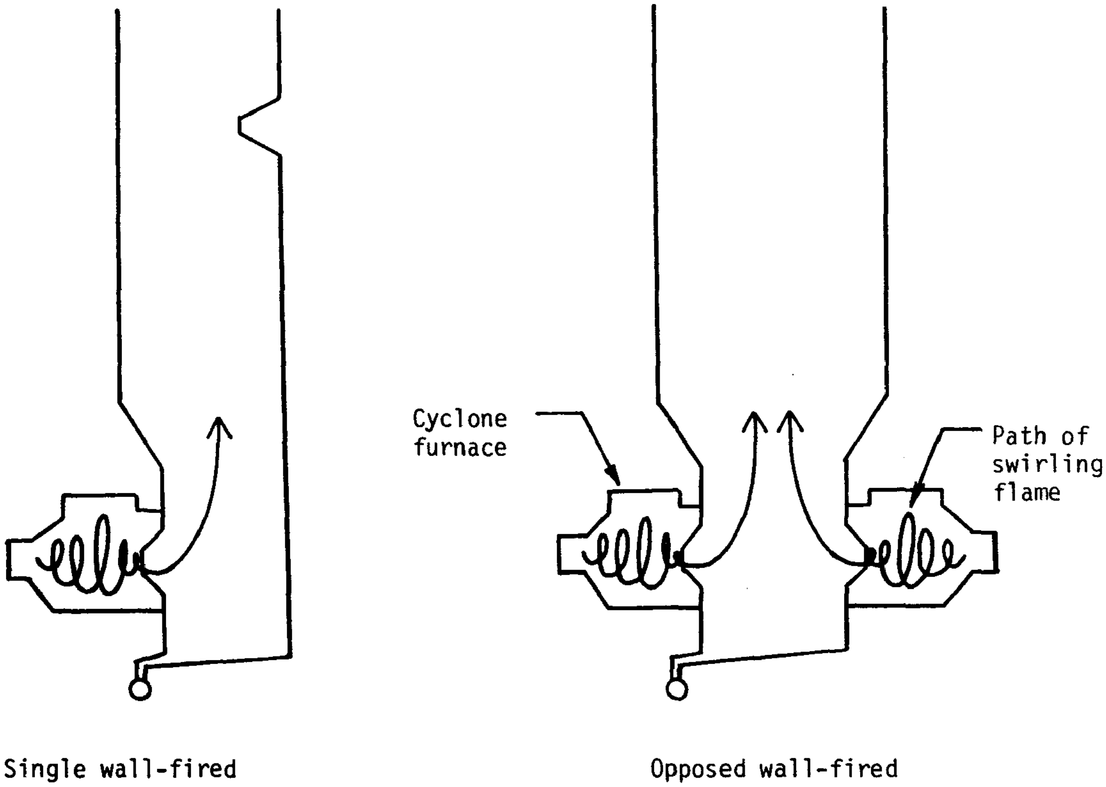


Figure 3-4. Cyclone furnace firing arrangements

SECTION 4

CHARACTERIZATION OF SUBSTITUTE FUELS

4.1 INTRODUCTION

The preceding section provided brief descriptions of the types of SO_x emitting combustion systems for which the costs of switching from conventional fossil fuels to various coal-derived fuels were estimated in this study. The present section attempts to characterize these exotic fuels.

Four distinct coal conversion routes are possible. These include: pyrolysis, hydrogenation, solvation, and production of synthesis gas. The amount, type and quality of the products from each of these methods depend upon the coal properties and process conditions (Reference 4-1).

In pyrolysis, the coal is heated in an inert atmosphere to break it down into solids, liquids, and gases, the amounts of which are proportional to the heating rate.

In hydrogenation reactions, coal and hydrogen are reacted together directly. In the presence of a catalyst at 850F and at elevated pressures, a liquid product is made. If a catalyst is not present, the coal reacts directly with hydrogen at higher temperatures (about 1600F) and pressures (150-300 psi) to form methane.

During solvation, the coal is dissolved and, with the addition of hydrogen at modest pressure, can be filtered and converted into an essentially ash-free and low sulfur solid or liquid.

Synthesis gas is produced by reacting coal with an oxidizing agent and steam. The resulting low heating value gas can then be used to make a high-Btu gas by a methanation step which reacts the purified gas over a nickel catalyst.

The present study concerns itself with the conversion of steam-raising boilers firing conventional fossil fuels to the use of selected products from solvation and synthesis gas coal conversion methods; namely, solvent refined coal (SRC) and lower-Btu gas. Brief summaries of these processes and their products are presented in the following subsections.

4.2 LOW- AND MEDIUM-BTU GAS

The basic process for converting solid coal to a fuel gas comprising principally nitrogen, carbon monoxide, hydrogen, and a certain amount of methane is well understood. In fact, the "town gas" commonly used, especially in Europe, before the general availability of natural gas was produced with earlier versions of present-day equipment. In general, these gases are produced when an insufficient quantity of oxidizer is supplied to the coal at a high temperature, thus preventing the reaction from going to completion to form carbon dioxide and water.

Most gasification processes have in common four basic sequentially-occurring reactions. The principal heat-producing reaction is oxidation, which results when oxygen reacts with fuel to form water and carbon dioxide:

$$C + O_2 \rightarrow CO_2$$

$$H_2 + 1/2\ O_2 \rightarrow H_2O$$

Next comes the gasification reaction, which is the most endothermic. This reaction occurs when unburned carbon from the fuel reacts with steam and carbon dioxide to form hydrogen and carbon monoxide:

$$C + \left\{ \begin{matrix} H_2O \\ CO_2 \end{matrix} \right\} \rightarrow CO + \left\{ \begin{matrix} H_2 \\ CO \end{matrix} \right.$$

The third reaction, hydrogasification, is mildly exothermic and takes place when hydrogen reacts with fuel carbon to give methane:

$$C + 2H_2 \rightarrow CH_4$$

Finally, and sometimes concurrently with the preceding reactions, devolatilization occurs when the fuel is subjected to heating:

$$\text{Coal} + \text{Heat} \rightarrow C + CH_4 + HC$$

Among the myriad types of gasification processes either operating or contemplated, these four basic reactions can occur simultaneously in a reactor, or each may take place in a particular region of the reactor, or each may be confined to a separate vessel. Most of these processes are designed so that the heat required by the highly endothermic gasification reaction is supplied by the heat released from the other three reactions. Adjusting the amount of oxidizer lent to the process controls this heat balance. Raw gas leaving the gasifier consists mainly of methane, hydrogen, nitrogen, carbon oxides, and sulfur compounds. The sulfur compounds and other impurities are removed downstream.

The basic gasification process described to this point delivers a product gas whose heating value abides primarily in the carbon monoxide and hydrogen resulting from the gasification step. This product is usually termed "lower-Btu gas." This definition is employed because there are two fuel-gas heating values of potential interest below the SNG level of 900 to 1000 Btu/scf. The first of these is the range of 300 to 700 Btu/scf, which is referred to as medium-Btu gas. The other is the range of 150 to 250 Btu/scf, which is referred to as low-Btu gas.

Two basic motives exist for converting coal to gas, depending on the ultimate application (Reference 4-2):

- If pipeline quality, high-Btu gas is desired, the product gas must go through an additional methanation step. This is an expensive process, whereby additional hydrogen is produced and chemically reacted with carbon monoxide to form methane. Current SNG costs are in the range of $1.05 - $1.50/$10^6$ Btu.
- If the purpose of gasifying coal is solely to remove ash and sulfur so that the fuel gas is nonpolluting when burned, the heating value need only be high enough to maintain a stable flame, with a minimum deleterious effect on plant efficiency. Medium- and low-Btu gases are well suited for this purpose. In most processes, oxygen injected into the gasification step will produce the former gas ("oxygen-blown"), while air injection will produce low-Btu gas ("air-blown"). Medium-Btu gasification saves 10 to 15 percent in coal feed rate, 30 to 35 percent of plant investment, and 25 to 35 cents/10^6 Btu relative to SNG. Producing low-Btu gas provides an additional savings of 5 to 10 cents/Btu over gases of intermediate Btu heat content.

The attractiveness of lower-Btu gas as a boiler fuel is quite apparent. Studies have shown that the most feasible location for lower-Btu gasification plants is at the point of use, while the product from SNG plants can be economically transported by pipeline over long distances (References 4-3, 4-4, 4-5, 4-21). It is therefore easy to visualize lower-Btu gasification plants constructed next to a new or existing combustion system, whether the product is destined for the steam-electric utility or industrial boiler sector.

Combustion systems firing conventional fossil fuels, however, will require some degree of equipment modification before these new gaseous fuels can be burned. Assessing the costs of such conversions was the objective of the present study.

For the purposes of the study, certain simplifying assumptions are made about the combustion characteristics of these gases. Table 4-1 shows the chemical compositions of selected lower-Btu gasified coal fuels. These gases are representative of the products of all gasification processes, detailed descriptions of which are given in Appendices A and B. The heating value of the gases range from 170 Btu/scf for the air-blown Lurgi to 780 Btu/scf for the Hydrane process. For the most part, heating value is directly proportional to volume percent of methane.

It will be assumed that the combustion characteristics of these and all lower-Btu gases will depend on heating value alone and be decoupled from specific chemical composition. This will allow the range of gas types to be treated as a continuum. In this way, the equipment conversion costs of substituting for these gases can be related to heating value. Section 6 will describe in more detail the method used for incorporating a heating value term in the conversion cost equations for the gaseous substitute fuels.

4.3 SOLVENT REFINED COAL

In Section 4.2, the feasibility of using coal-derived gases of lower heating values (<1000 Btu/scf) as low sulfur boiler fuels was discussed. Similar advantage can be gained by using the products from coal conversion processes that generate clean fuels that are liquids or solids at room temperature. Examples of the former type are the products from the Bergius - I.G. Farben, Fischer-Tropsch, COED, H-Coal, and Flash Pyrolysis processes. Ample descriptions of these treatment methods, which are essentially pyrolysis or hydrogenation processes, appear in References 4-14, 4-15, and 4-1. Clean solid fuels from solvation processes are exemplified by solvent refined coal (SRC). Cost estimations for converting stationary combustion equipment to the use of this fuel were established in the present study.

Solvent refined coal (SRC) is a name given to a reconstituted coal which has been dissolved, filtered, and separated from its solvent. It is moisture-free, low in sulfur and ash, and can apparently be handled in the liquid as

TABLE 4-1

COMPOSITIONS OF SELECTED LOW- AND MEDIUM-BTU GASIFIED COAL FUELS

("-" denotes negligible quantity and "m" denotes missing data)

Item	Koppers-Totzek (4-6)	Koppers-Totzek (4-6)	Koppers-Totzek (4-6)	Synthane (4-7)	BCR, Inc. (4-8)	IGT (4-9)	Oxygen Lurgi (4-10)	Hydrane (4-11)	Wellman-Galusha (4-12)	Commercial Lurgi (4-10)	Texaco (4-13)
Coal Type	Western	Illinois	Eastern	Pgh. Seam	W. Ky.	Lignite	Sub. Bit.	Pgh. Seam	m	m	m
Product Gas, Volume %											
CO	58.68	55.38	55.9	16.8	44.0	19.5	17.1	4.2	27.0	14.1	27.5
CO_2	7.04	7.04	7.18	28.8	14.0	24.6	31.4	1.3	2.1	12.5	1.0
H_2	32.86	34.62	35.39	27.8	24.4	24.5	40.2	21.4	14.4	20.9	25.3
N_2	1.12	1.01	1.14	0.8	0.6	0.6	-	1.0	47.25	40.0	37.2
H_2S	0.28	1.83	0.35	0.5	1.4	0.4	0.3	3.3	0.05	0.1	0.009
COS	0.02	0.12	0.04	-	-	-	-	-	-	-	-
CH_4	-	-	-	24.5	15.6	28.2	10.2	68.5	2.6	5.8	0.5
C_mH_n	m	m	-	0.8	-	2.1	0.4	m	-	-	-
H_2O	-	-	-	-	-	m	-	-	6.6	6.6	8.5
S(gm/10^6Btu)	-	-	-	-	-	-	-	-	117	221	-
HHV(Btu/scf)	295	290	294	406	380	467	400	780	160.4	172.7	175.8

well as the solid state. In the latter form, it is brittle and easily grindable. The process of pulverization can, however, heat the material sufficiently to cause undesirable agglomeration. Its major advantage is that its heating value remains at 16,000 Btu/lb regardless of the quality of the coal feedstock.

The SRC process has been under development for a number of years. Pittsburg & Midway Coal Mining Company, under the sponsorship of the Office of Coal Research, demonstrated the technical feasibility of the process on a pilot scale in 1964. In 1972, construction was begun on two additional SRC pilot plants. The 6 ton/day Wilsonville, Alabama, facility has been completed and is currently producing small amounts of material for experimental purposes. The project is sponsored by the Electric Power Research Institute and Southern Services. A larger plant, 50 ton/day, is located at Tacoma, Washington, and will be completed in late 1974. In both facilities, emphasis is placed on developing a utility fuel of a quality that will meet environmental standards when burned (Reference 4-3).

The solvent refined coal process is shown schematically in Figure 4-1. SRC is produced by first dissolving coal under pressure in a recycled solvent containing a small quantity of hydrogen. The coal solution is then filtered to remove virtually all of the mineral matter including the pyritic sulfur. Small quantities of hydrocarbon gases and lighter liquids are distilled off. The main product from the process is a heavy organic material which has a melting point of about 350F and, depending on the composition of the feedstock coal, contains less than 0.1 percent ash and less than 0.8 percent sulfur. The yield of solvent refined coal and other liquid products is approximately 90 percent of the original coal (References 4-16, 4-17).

The compositions of typical samples of SRC are presented in Table 4-3, while the analysis of the coal from which they were derived is shown in Table 4-2. These analyses are associated with projects performed by the Bureau of Mines (Reference 4-18), Combustion Engineering, Inc. (Reference 4-19), and The Babcock and Wilcox Company (Reference 4-20), in an effort to determine the combustion characteristics of SRC, samples of which were supplied by the Office of Coal Research. The investigators came to the following general conclusions:

- Based on both the proximate and ultimate analyses, the solid phase material appeared similar to a high volatile bituminous coal except for the reduced sulfur and ash content.
- Thermogravimetric analyses indicate ignition characteristics similar to a high volatile bituminous coal, but for burnout it appears to more closely resemble a semianthracite.

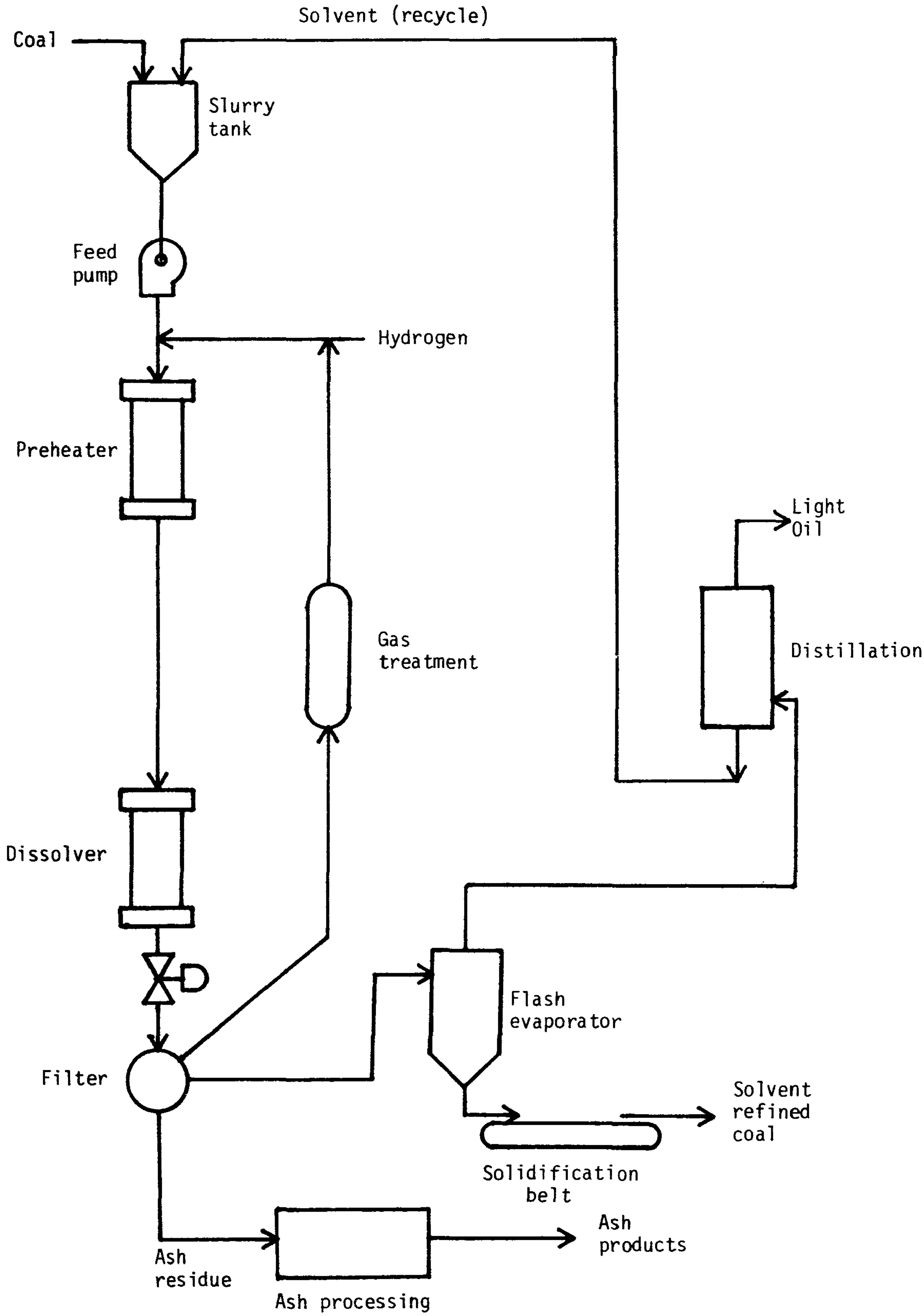


Figure 4-1. Solvent Refined Coal Process (Reference 4-16)

TABLE 4-2

ANALYSIS OF KENTUCKY NO. 11 COAL, AS RECEIVED
(References 4-18, 4-19)

Proximate Analysis, Mass %	
Total	5.2
Volatile Matter	40.2
Fixed Carbon	48.1
Ash	6.2
Ultimate Analysis, Mass %	
Hydrogen	5.5
Carbon	70.9
Nitrogen	1.9
Oxygen	12.0
Sulfur	3.5
Ash	6.2
Heating Value, Btu/lb	12,770
Hardgrove Grindability	61

TABLE 4-3

ANALYSIS OF SOLVENT REFINED COAL
("m" denotes missing data)

Proximate Analysis, Mass %	Ref. 4-18	Ref. 4-19	Ref. 4-20
Total Moisture	0.0	0.0	0.0
Volatile Matter	57.6	59.2	57.7
Fixed Carbon	42.3	40.6	40.9
Ash	0.1	0.15	0.36
Sulfur	m	m	1.1
Ultimate Analysis, Mass %			
Moisture	0.0	0.0	0.0
Hydrogen	5.5	5.3	5.2
Carbon	88.2	86.9	88.4
Nitrogen	1.5	1.4	1.44
Sulfur	1.1	1.4	1.1
Oxygen	3.6	4.8	3.5
Ash	0.1	0.15	0.36
High Heating Value, Btu/lb	15,680	15,559	15,730
Hardgrove Grindability	m	m	164
Melting Temperature, F	m	300	m
Pumping Temperature, F	m	m	500
Atomization Temperature, F	m	m	665

- The grindability index (about 160) indicated that the solid SRC can be pulverized with less power than nonprocessed coal (e.g., grindability for the Kentucky No. 11 coal was 61).
- In pulverized form, firing tests indicated that the material tended to agglomerate in the fuel lines when the primary (coal conveying) air was preheated.
- In the liquid phase, firing tests indicated that the material was similar to No. 6 fuel oil in handling and combustion characteristics. The preheating requirements are greater, however. For good pumpability (viscosity <30 cp) it must be heated above 635F. Because of the expulsion of volatile matter at temperatures above 350F, heating should be carried out under pressure in a closed system.
- When firing in the liquid phase, all fuel handling equipment in contact with the SRC must be heated to above 350F. In addition, steam-atomizing, heavy oil guns are recommended to eliminate the need for heating the gun components with an external heat source.

As implied by these conclusions, there remains some question as to the most advantageous phase in which to handle and burn the SRC. If applied in the solid form to conventional pulverized coal-fired combustion equipment, the retrofit procedure may be straightforward and inexpensive if most of the original equipment can be used and if the fuel handling equipment need not be externally cooled. When heated, by all indications, this material can be fired as an oil. In both cases, however, unforeseen retrofit difficulties may arise. More light will be cast on the situation when the results of additional EPRI-funded combustion tests, currently being performed by Combustion Engineering and Babcock & Wilcox, become available early in 1975.

As was related in Section 2 of the present study, no actual conversions of conventional steam-raising boilers of any capacity to the use of solvent refined coal have yet taken place. This is partially due to a general lack of sufficient quantities of this fuel at the present time. For the purposes of this study, the conversion cost estimation methods described in Section 5 will necessarily be based on past conversion experience involving similar substitute fuels.

4.4 SUMMARY AND CONCLUSIONS

Of the four basic coal conversion routes, pyrolysis, hydrogenation, solvation, and synthesis gas formation, representative products from the latter two processes have been considered in this study.

Solvent refined coal, in its solid state, is brittle and readily grindable into a fine powder. It is low in ash and sulfur, moisture free, and can be melted and handled as a fluid. Its heating value is about 16,000 Btu/lb, regardless (theoretically) of the type of feedstock coal. If its application as a boiler fuel is proven feasible, the major advantages afforded by SRC are:

- Use of plentiful high-sulfur coal reserves would be permitted
- The uniformity of the SRC product would permit power plants to use one "off-the-shelf" boiler design

The production of synthesis gas from coal has a lengthy history, and the technology is currently being revived. Most coal gasification processes have in common four basic reaction steps, ultimately producing a gas of heating value below that of natural gas (150-700 Btu/scf). To produce synthetic natural gas (SNG), the products from most of the gasification processes can be exposed to additional methanation steps. Economics demand that lower-Btu gasification plants be located on the site of use, while it is feasible to pipe SNG over long distances. As lower-Btu gas is less expensive than SNG to produce, is sulfur and ash free, and by all indications is able to produce a stable, trouble-free flame, it shows promise as a boiler fuel.

In order to use either lower-Btu gas or SRC in existing stationary boilers, it will be necessary to convert the combustion equipment from the use of conventional fossil fuels. As this has yet to occur on a large scale for any of these exotic fuels, the conversion costs appearing in this report are necessarily estimations, based on past conversion experience to similar substitute fuels.

SECTION 5

SELECTION OF FUEL SUBSTITUTION OPTIONS

Section 3 of this report described the types of combustion equipment that will be considered as candidates for conversion to cleaner fuels. These consist of all major types of industrial and utility boilers, encompassing a boiler capacity range from 10^7 Btu/hr to 1000 x 10^7 Btu/hr. For an estimated 35% thermal efficiency, these heat release rates correspond to an electric generating capacity range of 1 to 1000 MW. Section 4 of this report discussed the various types of clean fuels considered as subsitutes for conventional, high sulfur fossil fuels. These included solvent refined coal, low-Btu gas, medium-Btu gas, and natural gas. The first three are of interest in that they are the products of promising coal-conversion processes. The costs of equipment conversions to natural gas, an operation for which ample experience has already been gained, will act as a reference point for the conversions to the other fuels.

The information contained in Sections 3 and 4 helped to define the logical fuel substitution options available for a given type of boiler firing a given type of original fuel. These options are compiled in Table 5-1. The major points to be gained from this table are the following:

- The initial assumption is that all boiler types are capable of being converted to all of the substituted fuels.
- This number is reduced by the exclusion of certain illogical conversions, based on the following reasons:
  - Nonexistence of coal-fired firetube and packaged watertube boilers
  - Exorbitant cost associated with converting oil-fired combustion equipment to solid SRC (only conversions from solids to liquids or gases, and from liquids to gases are judged practical)
  - Nonexistence of oil-fired stoker and cyclone furnaces

TABLE 5-1

FUEL SUBSTITUTION OPTIONS

Original Fuel	Boiler Category	Applicable Substitute Fuels	Comments
Coal	Industrial Types:		
	• Firetube	None	No coal-fired boilers of this type
	• Packaged watertube	None	Essentially no coal-fired boilers of this type
	• Field-erected watertube	LBG, MBG, NG LSRC, SSRC	
	• Stoker	LBG, MBG, NG LSRC, SSRC	Equipment conversion will necessitate modification of equipment internal to the boiler; solid SRC cannot be burned like coal (on the grates) due to its low melting point.
	Utility Types:		
	• Cyclone-fired	LBG, MBG, NG LSRC, SSRC	
	• Tangentially-fired	LBG, MBG, NG, LSRC, SSRC	
	• Wall-fired	LBG, MBG, NG LSRC, SSRC	
	• Turbo-fired	LBG, MBG, NG LSRC, SSRC	
Oil	Industrial Types:		
	• Firetube	LBG, MBG, NG LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil
	• Packaged watertube	LBG, MBG, NG LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil

Notation: LBG = low-Btu gas
MBG = medium-Btu gas
NG = natural gas
LSRC = liquid SRC
SSRC = solid SRC

TABLE 5-1 (Concluded)

Original Fuel	Boiler Category	Applicable Substitute Fuels	Comments
	• Field-erected watertube	LBG, MBG, NG, LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil
	• Stoker	None	Stokers are fired solely with solid fuel
	Utility Types:		
	• Cyclone-fired	None	Essentially no oil-fired cyclone furnaces; designed mainly for coal
	• Tangentially-fired	LBG, MBG, NG LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil
	• Wall-fired	LBG, MBG, NG LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil
	• Turbo-fired	LBG, MBG, NG, LSRC	Solid SRC is considered an illogical substitute fuel for boilers originally firing oil

Notation: LBG = low-Btu gas
MBG = medium-Btu gas
NG = natural gas
LSRC = liquid SRC
SSRC = solid SRC

These options were instrumental in the determination of the required equipment conversion cost data, as indicated by the space enclosed within the bold lines in Figures 5-1 and 5-2. These figures are the forms of the master data sheets that were ultimately used to tabulate the cost figures. The two extreme left-hand columns contain the delineation of industrial and utility boiler types, an indication of whether the boiler is packaged or field-erected, and its normal capacity range in units of 10^6 Btu/hr. The columns between the double vertical lines serve to space out the increments in boiler capacity range. The letters in the rows contained in the extreme right-hand column indentify the cost category entered in the row; "E" denotes equipment cost, "I" denotes installation expense, and "T" is the sum of E and I, or, total capital investment.

Five sheets of the form of Figure 5-1 will contain the costs for converting the appropriate boilers from coal to the use of the five substitute fuels. Similarly, Figure 5-2 indicates that four data sheets will be completed for conversions of oil to the four applicable substitute fuels.

The equipment conversion cost estimations and associated documentation are contained in the following section of this report.

ORIGINAL FUEL: [X] COAL
[ ] OIL

SUBSTITUTE FUEL: [X] LOW-BTU GAS (170 BTU/SCF)
[X] MEDIUM-BTU GAS (400 BTU/SCF)
[X] NATURAL GAS (1000 BTU/SCF)
[X] LIQUID SRC (16,000 BTU/LB)
[X] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

← Industrial Size → ; ← Utility Size →

	BOILER CATEGORY	SUB-CATEGORY P = PACKAGED E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { }	26-50 { }	51-100 { }	101-150 { }	151-250 { }	251-500 { }	501-2000 { }	2001-5000 { }	5000-10000+ { }	CONVERSION COST: E = EQUIPMENT I = INSTALLATION T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)											E
													I
													T
	STOKER	P or F (10-250)											E
													I
													T
Utility Types	CYCLONE	F (100-10000+)											E
													I
													T
	TANGENTIALLY-FIRED	F (100-10000+)											E
													I
													T
	WALL-FIRED	F (500-10000+)											E
													I
													T
	TURBO-FIRED	F (100-10000+)											E
													I
													T

Figure 5-1. Conversion Cost Data Sheet for Coal-Fired Boilers

Figure 5-1. Conversion Cost Data Sheet for Coal-Fired Boilers

ORIGINAL FUEL: ☐ COAL ☒ OIL

SUBSTITUTE FUEL:
- ☒ LOW-BTU GAS (170 BTU/SCF)
- ☒ MEDIUM-BTU GAS (400 BTU/SCF)
- ☒ NATURAL GAS (1000 BTU/SCF)
- ☒ LIQUID SRC (16,000 BTU/LB)
- ☐ SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 151-250; Utility Size: 251-500 through 5000-10000+

	BOILER CATEGORY	SUB-CATEGORY P = PACKAGED E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { }	26-50 { }	51-100 { }	101-150 { }	151-250 { }	251-500 { }	501-2000 { }	2001-5000 { }	5000-10000+ { }	CONVERSION COST: E = EQUIPMENT I = INSTALLATION T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)											E
													I
													T
	STOKER	P or F (10-250)											E
													I
													T
Utility Types	CYCLONE	F (100-10000+)											E
													I
													T
	TANGENTIALLY-FIRED	F (100-10000+)											E
													I
													T
	WALL-FIRED	F (500-10000+)											E
													I
													T
	TURBO-FIRED	F (100-10000+)											E
													I
													T

Figure 5-2. Conversion Cost Data Sheet for Oil-Fired Boilers

SECTION 6

DOCUMENTED BOILER CONVERSION COST DATA

6.1 INTRODUCTION

The preceding section served to define the available fuel substitution options for a given type of boiler. The techniques used to compile the cost data were introduced as well. This section begins with a brief discussion of the major considerations associated with the various types of boiler conversion procedures, continues with the actual cost figures presented in both tabular and graphical form, and concludes with a presentation of the proposed cost models that can be derived from the cost data.

6.2 BOILER MODIFICATION CONSIDERATIONS

This subsection is organized into four portions:

- The general equipment modification considerations prevailing for all of the boiler types
- Some specific points pertaining to certain unique boiler types
- A general discussion of the proposed substitute fuel handling systems
- Descriptions of the firing equipment required for the gaseous and liquid substitute fuels.

6.2.1 General Equipment Modification Considerations Applicable to All Boiler Types

The following are general considerations applicable to all boilers of the indicated type:

- The conversion to the new fuel was planned and implemented in such a manner as not to effect boiler efficiency.
- Existing burner registers can be reused; for coal-fired boilers, the coal nozzles are removed to such a position as to allow adequate working space for installation of new burners.

- The burners selected for gas firing are termed "center-fired" gas guns. Each burner assembly includes a burner gun, guide pipe, shield, flame stabilizing device, flex hose, hand valve, and mounting adapter plate.
- Burners for liquid SRC firing are steam atomizing oil burners of the internal mixing type. (Refer to Table 6-1 for the determination of the number of burners required for the individual boiler capacities chosen for the cost estimations.)
- For converting coal-fired boilers to any of the substitute fuels, a burner management system will be required. The type recommended by the NFPA Supervisory Manual was used. The system includes a logic cabinet, safety interlocks, and all interconnecting piping and wiring. Reference 6-1 supplies additional information on this system. For oil-fired equipment, the existing burner management system can be used, but with new limit and safety interlock settings.
- Existing combustion controls can be reused. Each conversion requires a new fuel flow transmitter, fuel flow rate control valve, and miscellaneous relays and valves to be interfaced with the existing panel.
- It was assumed that no modifications to the boilers' wall-mounted heat transfer surfaces, superheaters, or economizers were required. Indeed, one industrial-size boiler manufacturer stated that their boilers' interior designs for the coal-derived fuels would not differ appreciably from designs presently used for more conventional fossil fuels.
- Existing forced draft and induced draft fans can be reused for the new fuels.
- The assumed gas and liquid SRC supply pressures at the burners are given in Table 6-2. In an existing plant, of course, the supply pressures must be chosen on the basis of practical line size and physical space considerations.

6.2.2 Special Equipment Modification Considerations for Unique Boiler Types

The following are some additional fuel substitution program considerations for five unique categories of boilers.

TABLE 6-1

BOILER TYPES, CAPACITIES, AND ASSOCIATED BURNER QUANTITIES FOR GAS- AND LIQUID SRC-FIRING

Boiler Category	Capacity (10^6Btu/hr)	Burner Quantity	Capacity (10^6Btu/hr)	Burner Quantity	Capacity (10^6Btu/hr)	Burner Quantity
Fire Tube	12	1	20	1	35	1
Watertube (field-erect.)	75	1	150	2	350	4
Watertube (packaged)	25	1	75	1	150	2
Stoker	25	1	75	1	150	2
Cyclone	250	2	1,000	8	7500	60
Tangentially-fired	250	2	1,000	8	7500	60
Wall-fired	1,000	8	3,500	28	7500	60
Turbo-fired	250	2	1,000	8	7500	60

TABLE 6-2

BURNER SUPPLY PRESSURES FOR GASEOUS AND LIQUID SUBSTITUTE FUELS

Substitute Fuel Type	Burner Supply Pressure (psig)
Low-Btu gas	35 - 40
Medium-Btu gas	30
Natural gas	15
Liquid SRC	125

6.2.2.1 Firetube Boilers

It was assumed that an industrial-type flame safeguard system exists and is reusable. Gas safety interlocks and a fuel selector switch are added. In addition, it was assumed that the existing burner guns are steam- or high pressure air-atomized, and not mechanical atomized.

6.2.2.2 Stoker-Fired Boilers

For the purposes of this study, it was assumed that the mechanical stoker and internal grates would be removed and a new twelve inch-thick refractory floor would be installed. A completely new windbox-burner assembly would be installed in the lower front wall. The actual number of burners needed depends on the furnace capacity.

In some cases, the more economical approach would be to install the refractory directly on the existing grates, and mount the windbox burner in the boiler's sidewall. However, this would require bending of the heat transfer tubes in the vicinity of the burner to afford clearance for the burner throat. The disadvantages of this approach are operator inconvenience, possible water circulation problems due to the unusual tube bends, and minor problems in adjusting the flame shape to retain a uniform temperature profile across the boiler tube bank or superheater (if employed).

As a general rule, the retrofitted burner can be supplied with an integral fan rather than attempting to reuse the existing combustion air fan. This is because the fan cost is offset by the labor, materials, and engineering required for the installation of a duct from the existing fan to the new burner.

For solid SRC, the only practical conversion strategy would be to install a suspended firing system as is described above. Due to its rather low melting temperature (260F), the SRC would be incompatible with the stoker's grates, which are designed for bed-type combustion with concurrent removal of incombustible ash and char.

6.2.2.3 Cyclone-Fired Utility Boilers

For retrofitting this class of boiler to the gaseous or liquid coal-derived fuels, the new burner guns can be installed through the existing coal burner. It was assumed that the average cyclone furnace heat release rate was 250×10^6 Btu/hr. Capacities of larger boilers would be multiples of this figure, and would require a correspondingly larger number of individual cyclone furnaces. It was assumed that on liquid SRC firing above 200×10^6 Btu/hr, two simultaneously-firing oil atomizers will be used, because this heat release quantity is currently the upper limit of a single atomizer as currently designed.

The existing combustion control system can be used, but will require the addition of a fuel flow control valve for each cyclone furnace.

6.2.2.4 Turbo- or Tangentially-Fired Utility Boilers

For oil-fired boilers of these types, retrofit of the gases and liquid SRC will involve the installation of the burners ("gun" design) either in a parallel (tangentially-fired) or an adjacent (turbo-fired) configuration. In coal-fired units, the guns can be substituted in place of the existing coal burner tubes and nozzles.

There may occur a small difference in piping installation costs between the tangentially- and turbo-fired boilers due to running the piping vertically versus horizontally. This variation, however, was considered insignificant in light of the other plumbing costs, such as valve installation.

6.2.3 Fuel Handling Systems

In the determination of piping costs for the gaseous substitute fuels, it was assumed that the amount of piping installed could be grouped into three categories, the length being an arbitrary function of the boiler capacity. Therefore, the piping to the boiler is essentially independent of boiler type. The capacities and respective pipe runs are given in Table 6-3 (A).

The second general assumption made for the gaseous fuel handling systems was that the piping supplied a single boiler. The third and possibly most important assumption was made in regard to the pressures of each type of gas as supplied to the steam plant boundary. This information is given in Table 6-3(B). These pressures were selected because they appeared to be commercially practical, and because the line sizes more closely match existing industrial standards. It is obvious that the variation in the main gas supply pressure could effect the validity of the cost estimates; this is especially true in the case of low-Btu gas.

For solvent refined coal (SRC) in the hot liquid state, complete heating systems are required for both the SRC storage facilities and the burner supply piping system. A liquid heat transfer system using Therminol 77 was selected for these purposes (see Reference 6-2 for Therminol's properties). This heat transfer fluid is heated by firing No. 2 fuel oil in a firetube boiler on the plant premises. The hot Therminol is then used to warm the storage tanks and the day tanks, to supply the suction heaters, and to heat trace all piping and valves. It was assumed that the SRC would be delivered at 450F, all pumping would be done at 1100 centistokes, and that the SRC would arrive at the

TABLE 6-3

GASEOUS FUEL HANDLING SYSTEM PIPING LENGTHS AND SUPPLY PRESSURES

(A) Piping Length, All Gases

Boiler Capacity Range (10^6 Btu/hr)	Piping Length (ft)
10-65	500
75-350	1000
500-7500	2000

(B) Supply Pressure to Plant Boundary

Gaseous Fuel Type	Supply Pressure (psig)
Low-Btu	350
Medium-Btu	130
Natural	50

burner at 66 centistokes (640F). Each system includes the following features:

- An unloading pump set of capacity equal to six times the firing rate
- Insulated bulk storage tank(s) for the liquid SRC and No. 2 fuel oil, with an estimated thirty day storage capacity
- Tank foundations and firewalls
- Tank suction heater(s)
- Therminol heaters and circulation pumps
- No. 2 oil pump sets
- SRC transfer pump set
- Insulated SRC day tank (two day storage capacity)
- Day tank suction heater
- Final pump and heater set
- All necessary interconnecting piping and valves

For solid SRC, the costs of converting coal-fired boilers will reflect the requirement that various portions of the fuel handling system be externally cooled, by either water or air. It was assumed that the existing coal handling and preparation equipment could be used with no major modifications necessary. Air preheat operation would be discontinued and replaced by a system supplying ambient or chilled air for coal conveying purposes. It was also assumed that the coal supply pipe at the burner would be water-cooled.

6.2.4 Firing Equipment For Gases and Liquid SRC

This subsection contains more detailed information on the replacement firing equipment for the gaseous and liquid substitute fuels, including:

- Burner types
- Burner fuel supply valving
- Burner management systems

For conversions of coal-fired combustion systems to the use of solid SRC, it was assumed that the existing firing equipment with the retrofits described previously would be adequate for the purpose. For these boilers, major modification costs will be associated only with the fuel handling system.

6.2.4.1 Burner Types

For gaseous substitute fuel firing, the burner selected was the center-fired gas gun. Table 6-4 shows the gun sizes chosen for the various gases.

To burn liquid SRC, a burner of the multiple venturi design was deemed practical. This is a steam-atomized burner normally used for heavy fuel oil (No. 6) combustion applications. Table 6-5 lists the model numbers and corresponding heat release rates of a typical commercially-available multiple venturi burner. Similarly-designed burners are available from a number of manufacturer

6.2.4.2 Burner Fuel Supply Valving

The following are typical valve requirements for single and multiple burner applications:

Single Burner, Gas-Fired

Pilot gas cock, pilot gas PRV, two pilot safety shut-offs, one pilot gas vent, main gas safety shut-off, supervisory gas plug cock, and main gas fuel flow control valve.

Single Burner, Liquid SRC-Fired

Main oil safety shut-off, main oil check, supervisory oil cock, steam purge, steam check, manual oil shut-off, manual steam shut-off, oil strainer steam drain, steam trap, steam-oil pressure differential control, and main oil flow control valve; pilot valves are the same as for gas.

Multiple Burners, Gas-Fired

The following valves are required at the header: main gas strainer, manual shut-off, main gas PRV, bypass PRV, main safety shut-off, main gas header vent, two manual gas vent valves, main gas reliefs, pilot gas manual shut-off, pilot gas PRV, and one main gas control valve.

The following valves are required at each burner: burner safety shut-off, supervisory shut-off cock, two pilot gas safety shut-offs, and one pilot gas vent valve.

Multiple Burners, Liquid SRC-Fired

The following header valves are required: manual oil shut off, oil strainer, main oil safety shut-off, oil by-pass PRV, oil return check valve, oil recirculating valve, steam manual shut-off, steam strainer, steam trap, steam PRV, steam bleed check, steam-oil differential pressure, oil flow control valve, manual pilot gas valve, and pilot gas PRV.

TABLE 6-4

GUN SIZES FOR GASEOUS SUBSTITUTE FUEL FIRING
(NOMINAL PIPE SIZE, INCHES)

Gaseous Fuel Type \ Burner Firing Rate (10^6 Btu/hr)	25	75	125
Low-Btu gas	4	6	8
Medium-Btu gas	3	4	6
Natural gas	2	3	4

TABLE 6-5

TYPICAL MULTIPLE VENTURI BURNER TYPES
FOR LIQUID SRC FIRING
(MANUFACTURER: THE COEN CO.,REFERENCE 6-3)

Coen Co. Model Number	Maximum Heat Release Rate (10^6 Btu/hr)
1 MV	35
2 MV	75
3 MV	150
3-1/2 MV	350
Dual 3 MV or 3-1/2 MV	> 350

The following valves are required at each individual burner: burner safety shut-off, oil check, supervisory oil cock, steam purge, steam check, steam manual shut-off, two pilot gas safety shut-offs, and one pilot gas vent valve.

6.2.4.3 Burner Management System

Converting from coal to gaseous substitute fuels requires the addition of at least the following safety interlocks: high gas pressure, low gas pressure, forced draft air, purge air, instrument air, fan starter interlocks, damper position switches for the forced and induced draft fans (if used), and steam over-pressure. Converting from coal to liquid SRC requires basically the same except for low oil pressure and temperature limit switches. Atomizing steam pressure and flow switches are also required. For multiple burner applications, such as in utility boilers, header switches are included in addition to the individual burner fuel interlocks.

6.3 BOILER CONVERSION COST DATA AND EVALUATION

6.3.1 Introduction

The previous subsection presented the basic assumptions on which the boiler conversion cost estimations were based. The present subsection contains these cost figures, tabulated on the data sheet first introduced in Section 5 of this report. In order to visualize more clearly the functional relationship between conversion cost and capacity for a given boiler, these data are plotted for each original fuel-to-substitute fuel conversion. A discussion of the data and their concomitant uncertainty factors is given as well.

6.3.2 Boiler Conversion Cost Data

Tables 6-6 through 6-14 are the completed data sheets for all nine possible conversions: coal-fired equipment modified to burn all five coal-derived fuels, and the oil-fired equipment modified to burn four out of the five substitute fuels (excluding solid SRC). It should be remembered that "liquid SRC" refers to the melted solid SRC material. The installation costs are based on 1974 San Francisco Bay Area labor rates. The total capital costs, or required plant investment, indicated on the tables are therefore specific for that metropolitan area. These numbers must be modified by a location factor if the installation costs for another site are desired. This point will be discussed further in subsection 6.3.4. All of these cost figures were reduced from the bulk cost data included in the Appendix of this report. These figures are sums of numbers from individual modification considerations; the last three digits are not significant.

Associated with each of these tables are the corresponding data plots, Figures 6-1 through 6-9. Table 6-15 presents the uncertainty factors for the conversion costs. These confidence limits are indicated on the plots by the vertical bars on each point. Some error bars, however, are not included since they would have been of insignificant length when drawn on the log-log graph.

Figure 6-10 is the composite of all the data. Superimposed on these points are straight lines showing cost as a function of capacity for all boiler types. The overall significance of the conversion cost data is discussed in the following subsection.

6.3.3 Cost Data Evaluation

Within the scatter of the data plotted in Figures 6-1 to 6-9 there is a correspondence between conversion cost and capacity for individual boiler types. In addition, a general correspondence between conversion cost and capacity exists for all boiler types for a given original fuel to substitute fuel conversion. The data appear to be described by power law functional relationships. The following are some additional significant items that require amplification

- For the gaseous substitute fuels, boiler conversion costs increase in proportion to a decrease in heating value of the fuel (Figures 6-1 through 6-3, 6-6 through 6-8). The greatest cost differential exists for 750 MW equipment, for which a 45% cost variance exists.
- In some of the plots, the data points for stoker-fired equipment lie above the correspondence defined by the remaining points (Figures 6-1 through 6-3). This reflects the additional cost incurred as a result of the required internal modifications, a procedure unique to this type of boiler.
- The data points for oil-fired, firetube boilers (Figures 6-6 through 6-9) indicate a slightly different trend than that defined by the remaining points. This reflects certain fixed costs, such as piping common to all types of boilers, which become more noticeable as the boiler's physical size and capacity decrease.
- For all of the original fuel-to-substitute fuel conversions, the costs required to modify the utility boilers differ among the various types of boilers only slightly. This is at variance with the notion conceived previous to compiling the data that conversion cost would be a strong function of utility boiler type. The costs associated with the individual conversion considerations for each type of boiler are contained in the Appendix of this report.

TABLE 6-6
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: [X] COAL [ ] OIL

SUBSTITUTE FUEL: [X] LOW-BTU GAS (170 BTU/SCF) [ ] MEDIUM-BTU GAS (400 BTU/SCF) [ ] NATURAL GAS (1000 BTU/SCF) [ ] LIQUID SRC (16,000 BTU/LB) [ ] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 151-250 through 5000-10000+

CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)

	BOILER CATEGORY	SUB-CATEGORY (P = PACKAGED, E = FIELD-ERECTED) (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 {25}	26-50 { }	51-100 {75}	101-150 {150}	151-250 {250}	251-500 {350}	501-2000 {1000}	2001-5000 {3500}	5000-10000+ {7500}	CONVERSION COST
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)				22870	49085		83040				E
						18130	43970		68270				I
						41000	93055		151310				T
	STOKER	P or F (10-250)		26250		26800	75435						E
				34780		58470	101430						I
				61030		95270	176865						T
Utility Types	CYCLONE	F (100-10000+)						59985		204205		1068350	E
								69460		241890		811690	I
								129445		446095		1880040	T
	TANGENTIALLY-FIRED	F (100-10000+)						59985		206205		1073850	E
								69380		241990		798230	I
								129365		448195		1872080	T
	WALL-FIRED	F (500-10000+)								206375	526655	1073850	E
										241630	411350	798030	I
										448005	938005	1871880	T
	TURBO-FIRED	F (100-10000+)						59985		206205		1073850	E
								69380		241990		798230	I
								129365		448195		1872080	T

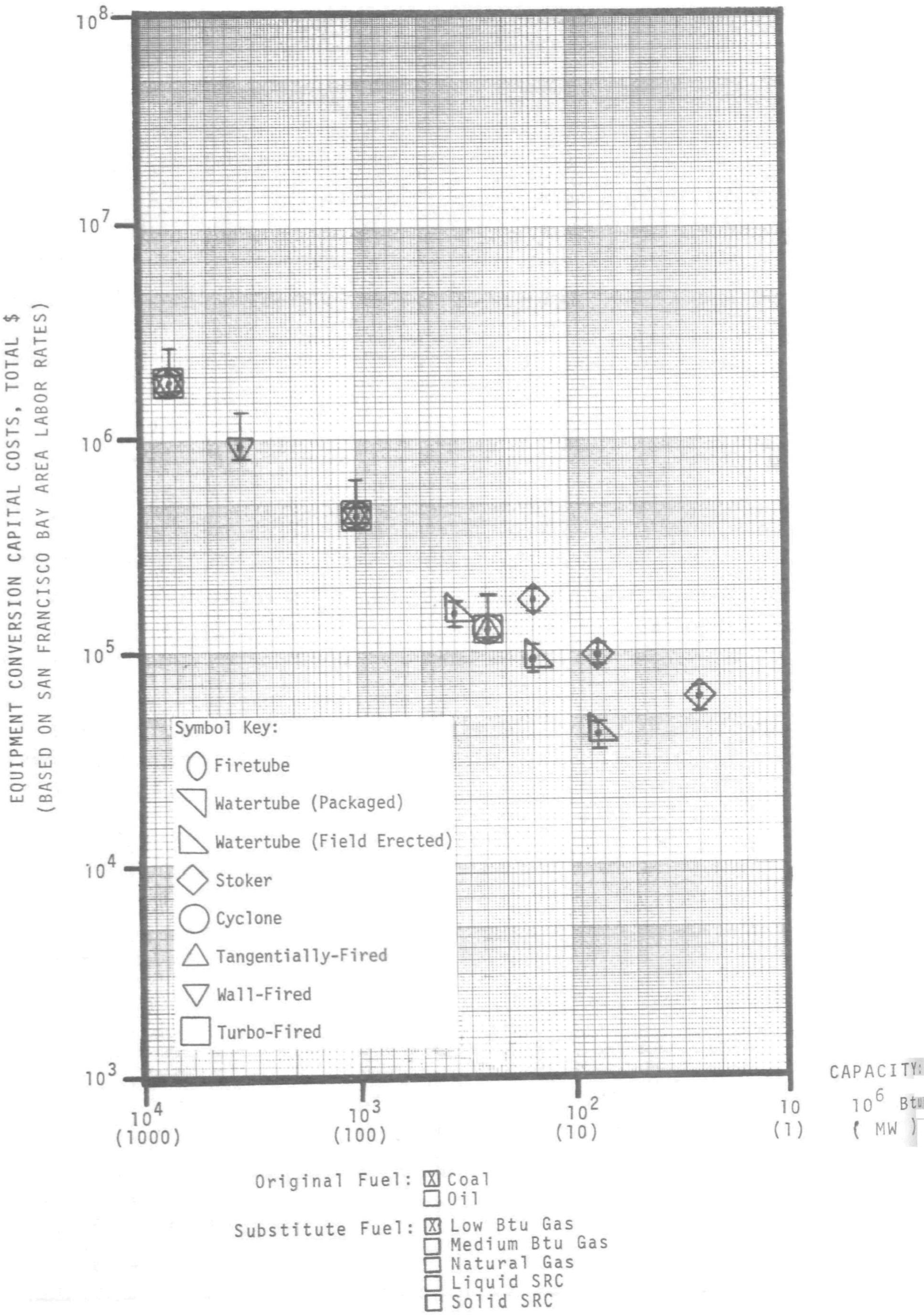


Figure 6-1. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-7
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: [X] COAL [ ] OIL

SUBSTITUTE FUEL: [ ] LOW-BTU GAS (170 BTU/SCF) [X] MEDIUM-BTU GAS (400 BTU/SCF) [ ] NATURAL GAS (1000 BTU/SCF) [ ] LIQUID SRC (16,000 BTU/LB) [ ] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 251-500 through 5000-10000+

Industrial Types: Firetube, Watertube, Stoker. Utility Types: Cyclone, Tangentially-Fired, Wall-Fired, Turbo-Fired.

BOILER CATEGORY	SUB-CATEGORY P = PACKAGED E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { 25 }	26-50 { }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST: E = EQUIPMENT I = INSTALLATION T = TOTAL (FOR GIVEN F)
FIRETUBE	P (10-50)											E
												I
												T
WATERTUBE	P (10-250)											E
												I
												T
	F (50-500)				18850	44710		69415				E
					16960	42685		67230				I
					35810	87395		136645				T
STOKER	P or F (10-250)		23240		32500	69060						E
			34180		57460	100580						I
			57420		89960	169640						T
CYCLONE	F (100-10000+)						54660		163875		858245	E
							64280		213870		610640	I
							118940		377745		1468885	T
TANGENTIALLY-FIRED	F (100-10000+)						54760		163475		842725	E
							64830		214500		561940	I
							119590		377975		1404665	T
WALL-FIRED	F (500-10000+)								163675	436660	842725	E
									214500	369010	561940	I
									378175	805670	1404665	T
TURBO-FIRED	F (100-10000+)						54760		163475		842725	E
							64830		214500		561940	I
							119590		377975		1404665	T

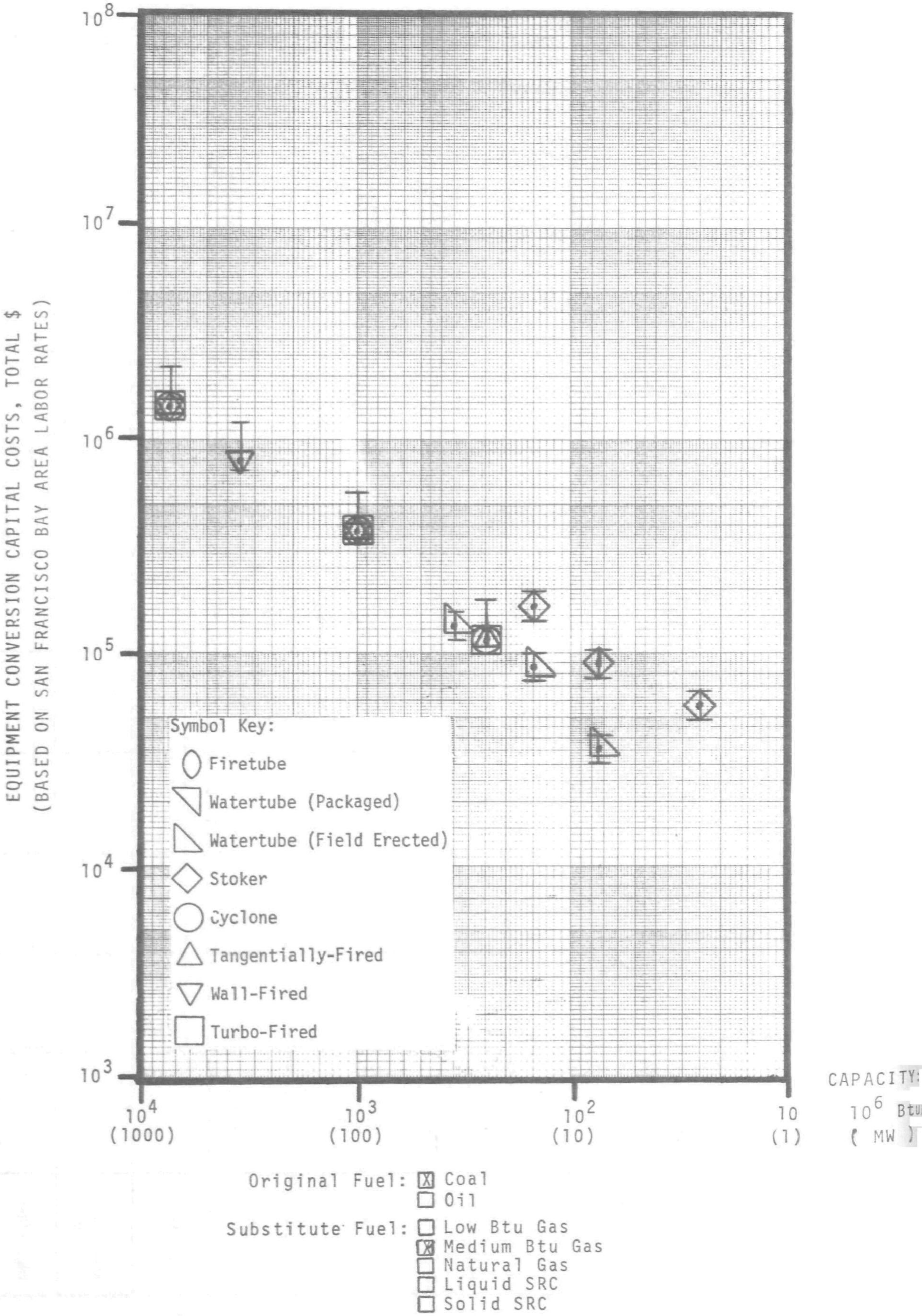


Figure 6-2. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-8
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: [X] COAL [ ] OIL

SUBSTITUTE FUEL: [ ] LOW-BTU GAS (170 BTU/SCF) [ ] MEDIUM-BTU GAS (400 BTU/SCF) [X] NATURAL GAS (1000 BTU/SCF) [ ] LIQUID SRC (16,000 BTU/LB) [ ] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR (Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 251-500 through 5000-10000+

CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)

	BOILER CATEGORY	SUB-CATEGORY (P = PACKAGED, E = FIELD-ERECTED) (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { 25 }	26-50 { }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)				15570	34025		52795				E
						16430	42175		65930				I
						32000	76200		118725				T
	STOKER	P or F (10-250)		22045		30370	56875						E
				33860		57070	99430						I
				55905		87440	158105						T
Utility Types	CYCLONE	F (100-10000+)						41165		143665		733525	E
								59590		209870		562470	I
								100755		353535		1295995	T
	TANGENTIALLY-FIRED	F (100-10000+)						40915		143855		813285	E
								58640		207430		558030	I
								99555		351285		1371315	T
	WALL-FIRED	F (500-10000+)								104055	364890	813285	E
										207730	315390	558030	I
										311785	680280	1371315	T
	TURBO-FIRED	F (100-10000+)						40915		143755		813285	E
								58640		207430		558030	I
								99555		351185		1371315	T

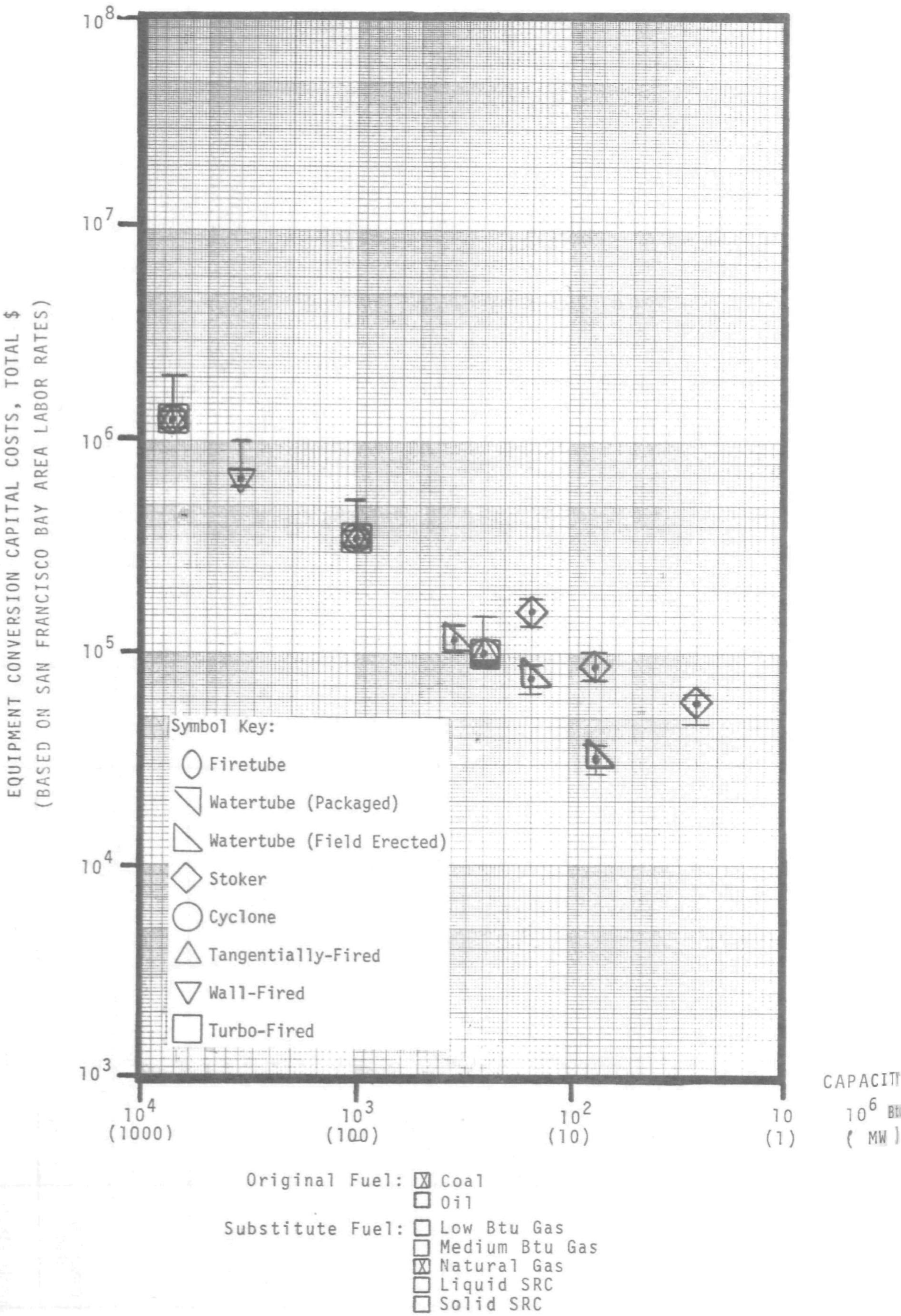


Figure 6-3. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-9
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: [X] COAL
[ ] OIL

SUBSTITUTE FUEL: [ ] LOW-BTU GAS (170 BTU/SCF)
[ ] MEDIUM-BTU GAS (400 BTU/SCF)
[ ] NATURAL GAS (1000 BTU/SCF)
[X] LIQUID SRC (16,000 BTU/LB)
[ ] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 251-500 through 5000-10000+

Types	BOILER CATEGORY	SUB-CATEGORY (P = PACKAGED, E = FIELD-ERECTED) (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { 25 }	26-50 { }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)				299425	386630		750120				E
						414350	599255		1473650				I
						713775	985885		2223770				T
	STOKER	P or F (10-250)		160930		310375	407880						E
				247870		438880	636755						I
				408800		749255	1044636						T
Utility Types	CYCLONE	F (100-10000+)						499905		1668000		14723020	E
								881430		3526700		23691480	I
								1381353		5194700		38414500	T
	TANGENTIALLY-FIRED	F (100-10000+)						496505		1722480		15107200	E
								884540		3716030		24065480	I
								1381045		5438510		39172680	T
	WALL-FIRED	F (500-10000+)								1716320	5762020	15128200	E
										3716030	11131680	24284380	I
										5432350	16893700	39412580	T
	TURBO-FIRED	F (100-10000+)						496505		1668000		14723020	E
								884540		3526700		23691480	I
								1381045		5194700		38414500	T

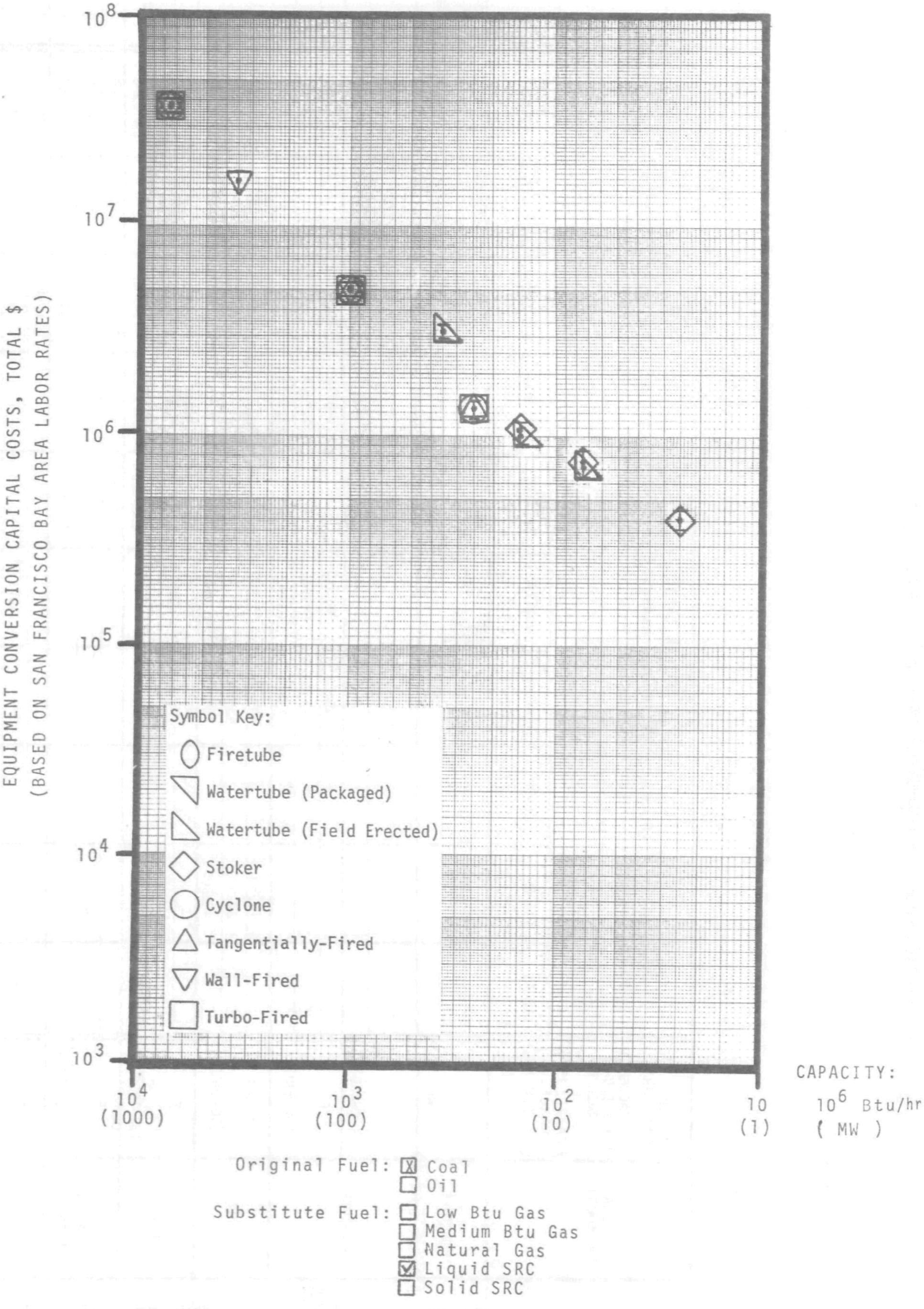


Figure 6-4. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-10
EQUIPMENT CONVERSION CAPITAL COSTS ($)

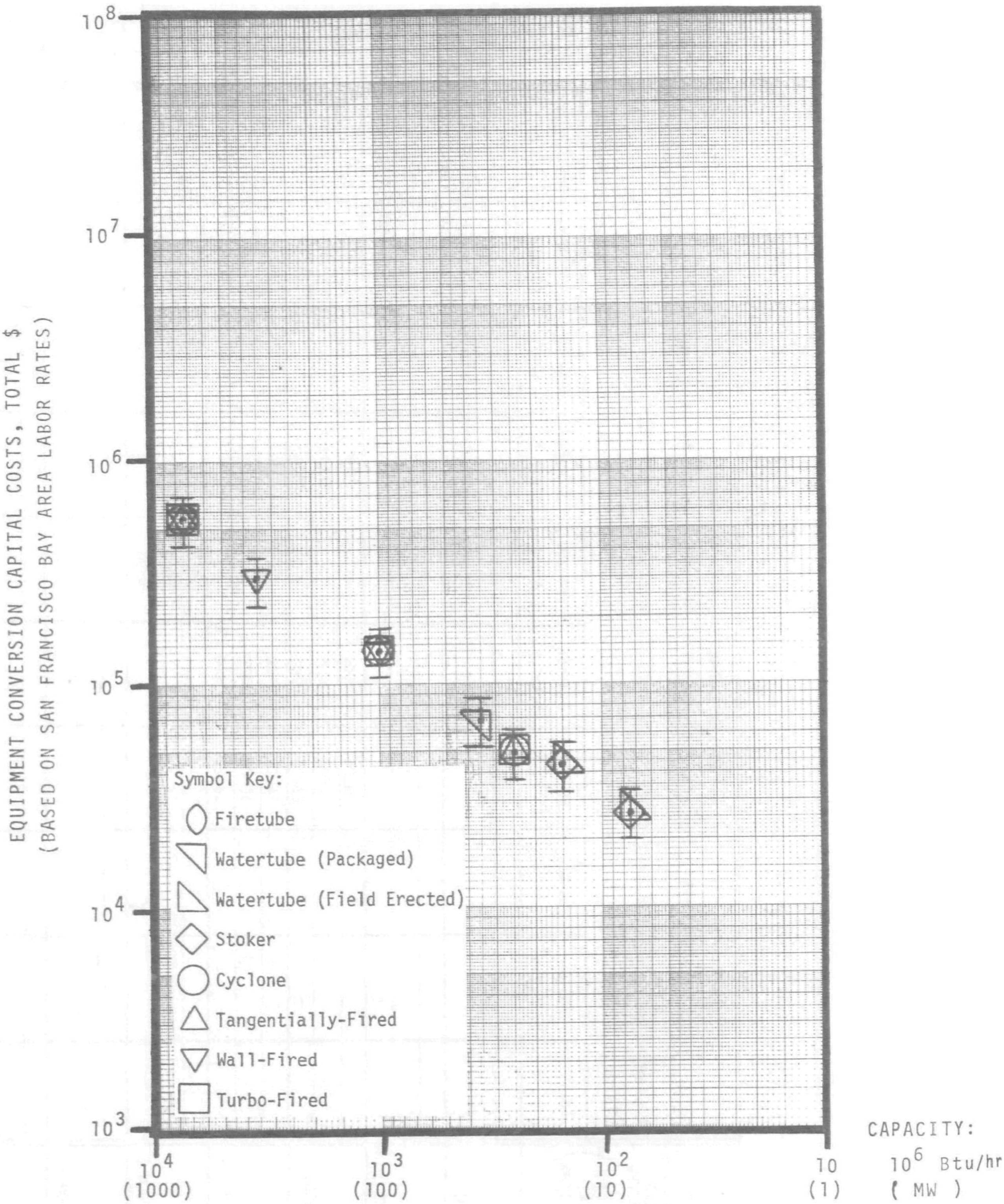
ORIGINAL FUEL: [X] COAL
[ ] OIL

SUBSTITUTE FUEL:
[ ] LOW-BTU GAS (170 BTU/SCF)
[ ] MEDIUM-BTU GAS (400 BTU/SCF)
[ ] NATURAL GAS (1000 BTU/SCF)
[ ] LIQUID SRC (16,000 BTU/LB)
[X] SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

← Industrial Size → (10-15 through 251-500) ← Utility Size → (251-500 through 5000-10000+)

Types	BOILER CATEGORY	SUB-CATEGORY (P = PACKAGED, E = FIELD-ERECTED) (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { }	16-25 { }	26-50 { }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)											E
													I
													T
	WATERTUBE	P (10-250)											E
													I
													T
		F (50-500)				16825	28000		43400				E
						10000	15800		26400				I
						26825	43800		69800				T
	STOKER	P or F (10-250)				16825	28000						E
						10000	15800						I
						26825	43800						T
Utility Types	CYCLONE	F (100-10000+)						31000		86740		345000	E
								18800		56000		215000	I
								49800		142740		560000	T
	TANGENTIALLY-FIRED	F (100-10000+)						31000		86740		345000	E
								18800		56000		215000	I
								49800		142740		560000	T
	WALL-FIRED	F (500-10000+)								86740	186000	345000	E
										56000	114000	215000	I
										142740	300000	560000	T
	TURBO-FIRED	F (100-10000+)						31000		86740		345000	E
								18800		56000		215000	I
								49800		142740		560000	T



Original Fuel: ☒ Coal
☐ Oil

Substitute Fuel: ☐ Low Btu Gas
☐ Medium Btu Gas
☐ Natural Gas
☐ Liquid SRC
☒ Solid SRC

Figure 6-5. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-11
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: ☐ COAL ☒ OIL

SUBSTITUTE FUEL: ☒ LOW-BTU GAS (170 BTU/SCF) ☐ MEDIUM-BTU GAS (400 BTU/SCF) ☐ NATURAL GAS (1000 BTU/SCF) ☐ LIQUID SRC (16,000 BTU/LB) ☐ SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR (Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 151-250; Utility Size: 251-500 through 5000-10000+

Industrial Types: Firetube, Watertube, Stoker; Utility Types: Cyclone, Tangentially-Fired, Wall-Fired, Turbo-Fired

BOILER CATEGORY	SUB-CATEGORY F = PACKAGED E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { 12 }	16-25 { 20 }	26-50 { 35 }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST: E = EQUIPMENT I = INSTALLATION T = TOTAL (FOR GIVEN F)
FIRETUBE	P (10-50)	11425	13175	14975								E
		7575	8275	8825								I
		19000	21450	23600								T
WATERTUBE	P (10-250)		14000		17750	41035						E
			8300		16910	42330						I
			22300		34660	83365						T
	F (50-500)				16850	39035		68290				E
					16910	42330		65055				I
					33760	81365		133345				T
STOKER	P or F (10-250)											E
												I
												T
CYCLONE	F (100-10000+)											E
												I
												T
TANGENTIALLY-FIRED	F (100-10000+)						47120		167005		789570	E
							65765		226490		685945	I
							112885		393495		1475515	T
WALL-FIRED	F (500-10000+,								169175	389070	789570	E
									226130	358015	685745	I
									395305	747085	1475315	T
TURBO-FIRED	F (100-10000+)						47120		167005		789570	E
							65765		226490		685945	I
							112885		393495		1475515	T

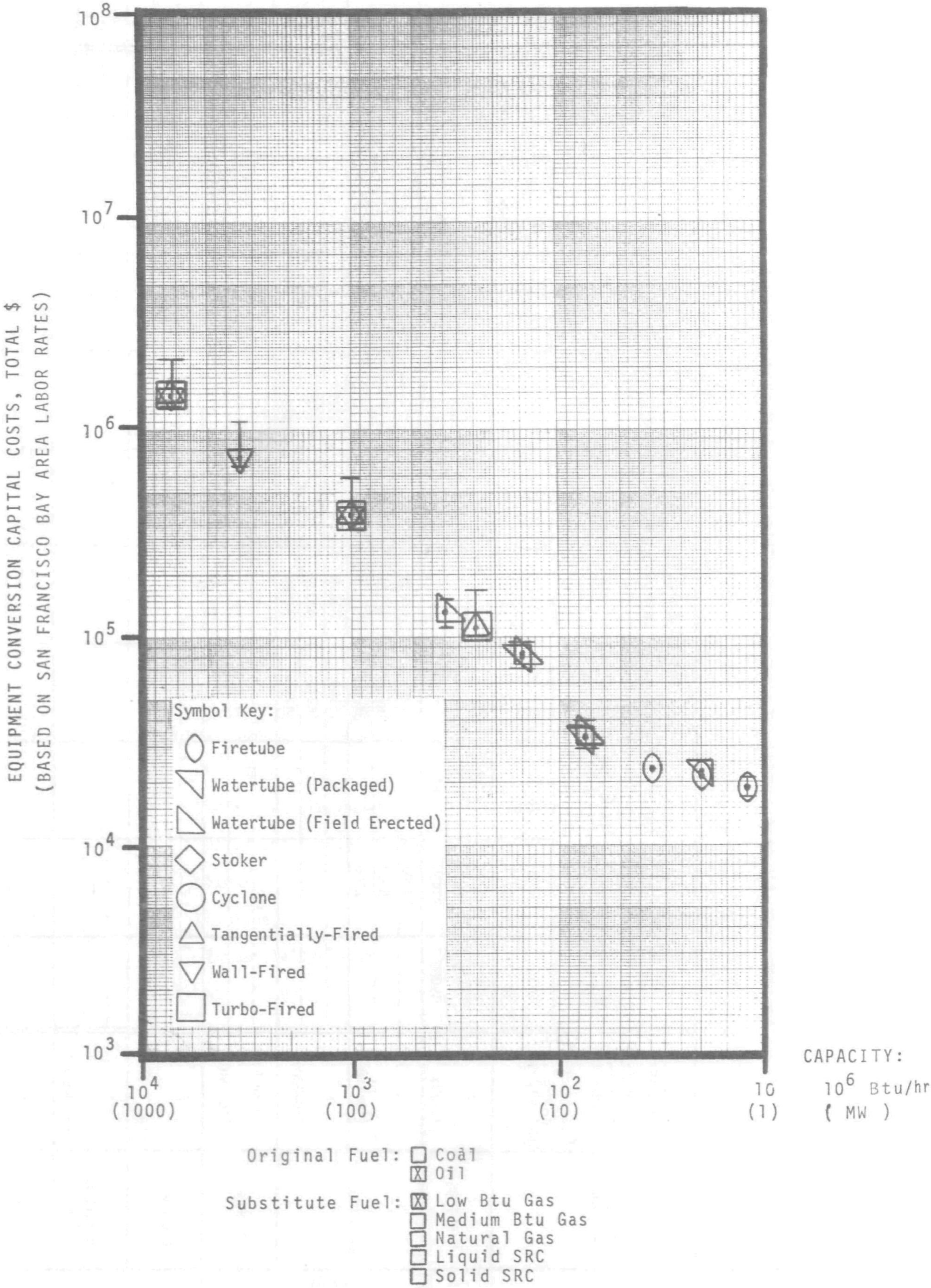


Figure 6-6. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-12
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: ☐ COAL ☒ OIL

SUBSTITUTE FUEL: ☐ LOW-BTU GAS (170 BTU/SCF) ☒ MEDIUM-BTU GAS (400 BTU/SCF) ☐ NATURAL GAS (1000 BTU/SCF) ☐ LIQUID SRC (16,000 BTU/LB) ☐ SOLID SRC (16,000 BTU/LB)

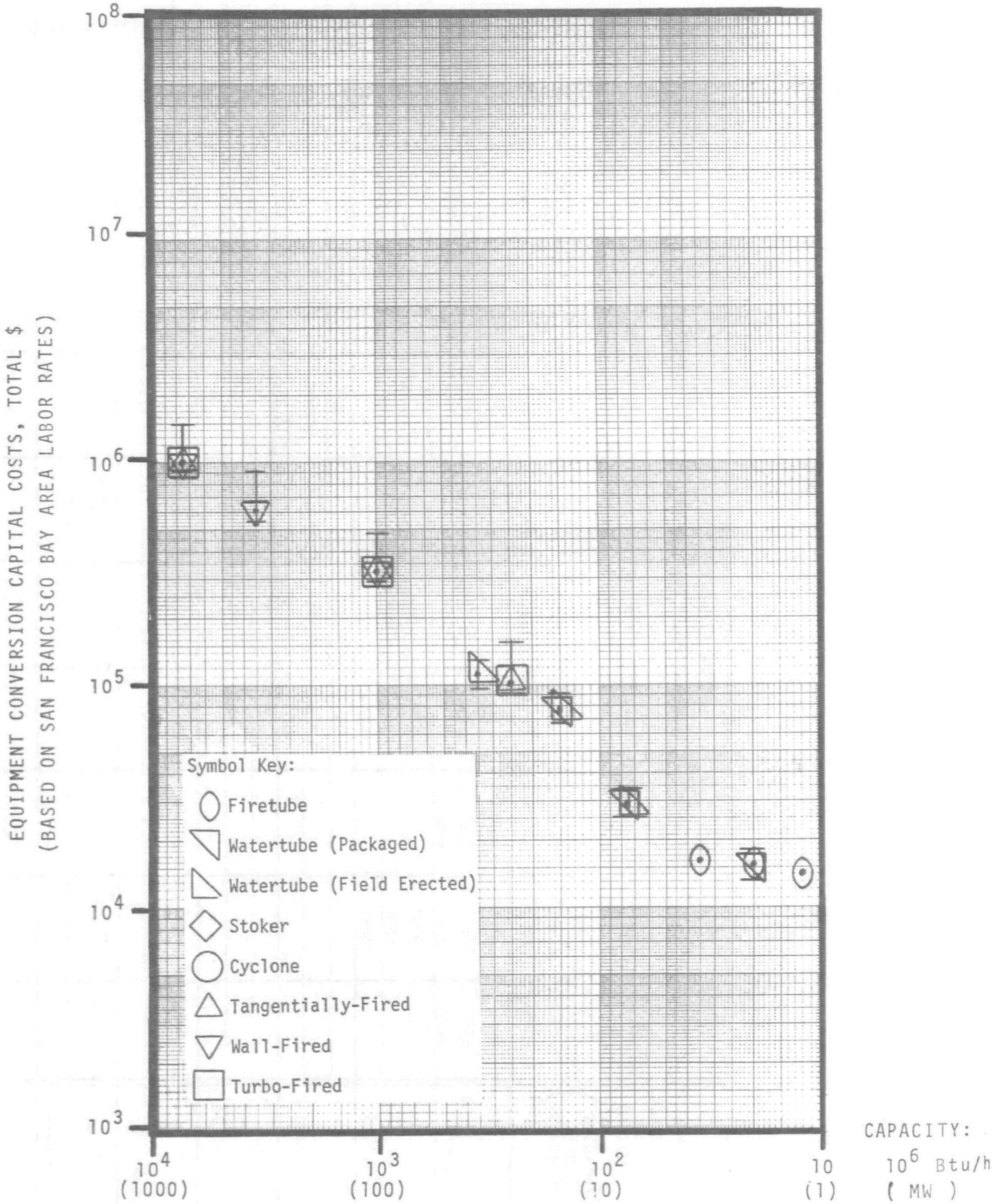
BOILER CAPACITY, 10^6 BTU/HR (Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 251-500 through 5000-10000+

SUB-CATEGORY: P = PACKAGED, E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)

CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)

Type	BOILER CATEGORY	SUB-CATEGORY (CAPACITY RANGE)	10-15 {12}	16-25 {20}	26-50 {35}	51-100 {75}	101-150 {150}	151-250 {250}	251-500 {350}	501-2000 {1000}	2001-5000 {3500}	5000-10000+ {7500}	CONVERSION COST
Industrial Types	FIRETUBE	P (10-50)	7425	8725	9875								E
			6475	6625	6725								I
			13900	15350	16000								T
	WATERTUBE	P (10-250)		9000		14080	37860						E
				6650		15675	41095						I
				15650		29755	78955						T
		F (50-500)				13280	35360		54265				E
						15675	41095		58950				I
						28955	76455		113215				T
	STOKER	P or F (10-250)											E
													I
													T
Utility Types	CYCLONE	F (100-10000+)											E
													I
													T
	TANGENTIALLY-FIRED	F (100-10000+)						41895		124275		555445	E
								61215		199000		449655	I
								103110		323275		1005100	T
	WALL-FIRED	F (500-10000+)								124470	293075	588443	E
										199000	315675	449655	I
										323470	608750	1008098	T
	TURBO-FIRED	F (100-10000+)						41895		124275		558445	E
								61215		199000		449655	I
								103110		323275		1008100	T



Original Fuel: ☐ Coal
☒ Oil

Substitute Fuel: ☐ Low Btu Gas
☒ Medium Btu Gas
☐ Natural Gas
☐ Liquid SRC
☐ Solid SRC

Figure 6-7. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-13
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: ☐ COAL ☒ OIL

SUBSTITUTE FUEL: ☐ LOW-BTU GAS (170 BTU/SCF) ☐ MEDIUM-BTU GAS (400 BTU/SCF) ☒ NATURAL GAS (1000 BTU/SCF) ☐ LIQUID SRC (16,000 BTU/LB) ☐ SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR
(Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 501-2000; Utility Size: 251-500 through 5000-10000+

Type	BOILER CATEGORY	SUB-CATEGORY (P = PACKAGED, E = FIELD-ERECTED) (CAPACITY RANGE: 10^6 BTU/HR)	10-15 { 12 }	16-25 { 20 }	26-50 { 35 }	51-100 { 75 }	101-150 { 150 }	151-250 { 250 }	251-500 { 350 }	501-2000 { 1000 }	2001-5000 { 3500 }	5000-10000+ { 7500 }	CONVERSION COST: E = EQUIPMENT, I = INSTALLATION, T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)	6075	7125	8525								E
			6350	6450	6575								I
			12425	13575	15100								T
	WATERTUBE	P (10-250)		8000		10320	24775						E
				6500		15150	40370						I
				14500		25470	65145						T
		F (50-500)				9720	23175		37445				E
						15150	40370		57290				I
						24870	63545		94735				T
	STOKER	P or F (10-250)											E
													I
													T
Utility Types	CYCLONE	F (100-10000+)											E
													I
													T
	TANGENTIALLY-FIRED	F (100-10000+)						28050		104655		529000	E
								55025		191930		445745	I
								83075		296585		974745	T
	WALL-FIRED	F (500-10000+)								104855	227305	529005	E
										192230	262055	445745	I
										297085	489360	974750	T
	TURBO-FIRED	F (100-10000+)						28050		10465		529000	E
								55025		191930		445745	I
								83075		296585		974745	T

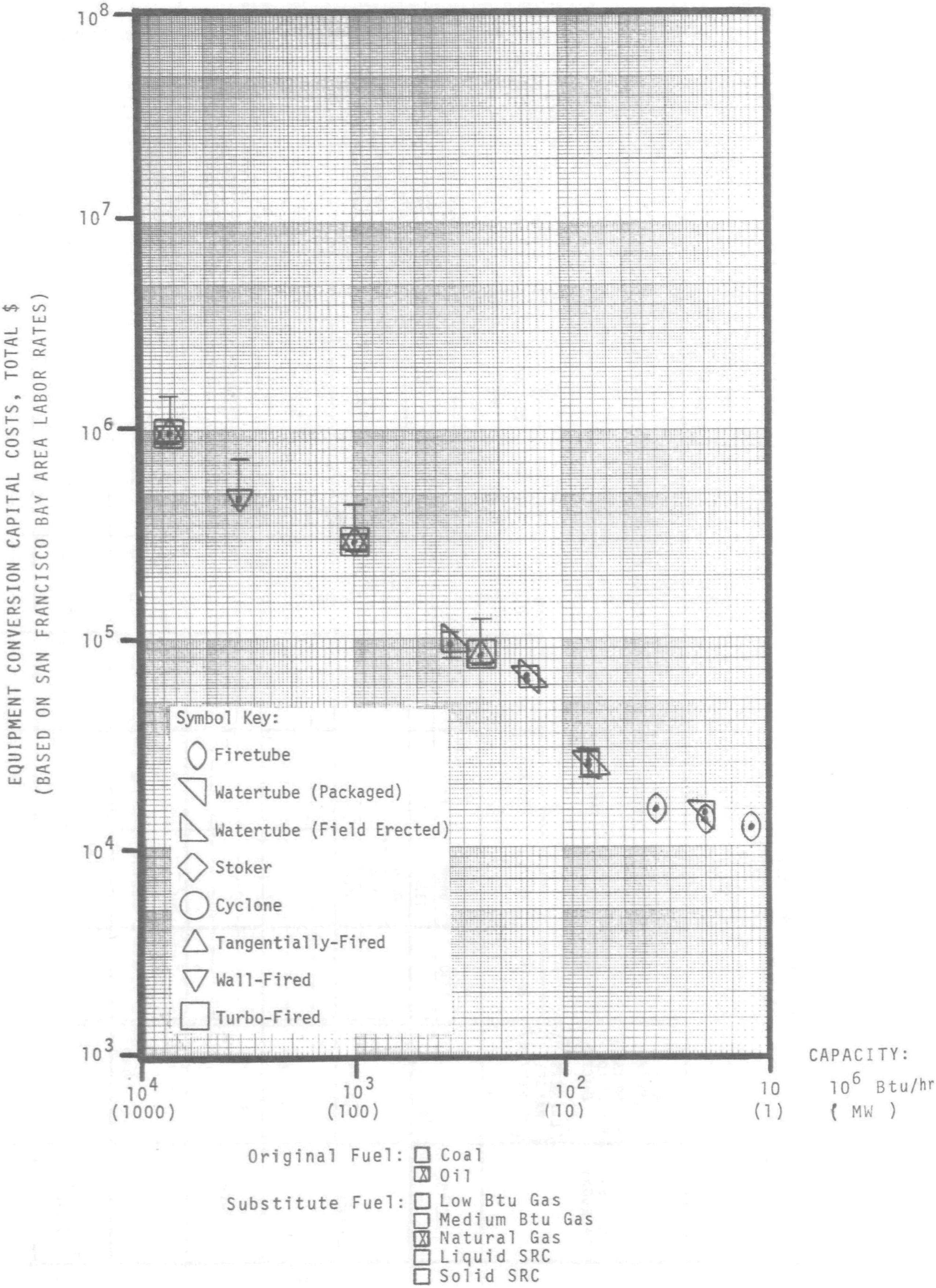


Figure 6-8. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-14
EQUIPMENT CONVERSION CAPITAL COSTS ($)

ORIGINAL FUEL: ☐ COAL ☒ OIL

SUBSTITUTE FUEL: ☐ LOW-BTU GAS (170 BTU/SCF) ☐ MEDIUM-BTU GAS (400 BTU/SCF) ☐ NATURAL GAS (1000 BTU/SCF) ☒ LIQUID SRC (16,000 BTU/LB) ☐ SOLID SRC (16,000 BTU/LB)

BOILER CAPACITY, 10^6 BTU/HR (Note: { } denotes capacity for which costs beneath apply)

Industrial Size: 10-15 through 251-500; Utility Size: 251-500 through 5000-10000+

	BOILER CATEGORY	SUB-CATEGORY P = PACKAGED E = FIELD-ERECTED (CAPACITY RANGE: 10^6 BTU/HR)	10-15 {12}	16-25 {20}	26-50 {35}	51-100 {75}	101-150 {150}	151-250 {250}	251-500 {350}	501-2000 {1000}	2001-5000 {3500}	5000-10000+ {7500}	CONVERSION COST: E = EQUIPMENT I = INSTALLATION T = TOTAL (FOR GIVEN F)
Industrial Types	FIRETUBE	P (10-50)	123000	134000	145000								E
			175000	212000	231000								I
			298000	346000	376000								T
	WATERTUBE	P (10-250)		140000		298075	383655						E
				220000		412440	597195						I
				360000		710515	980850						T
		F (50-500)				296075	379655		735620				E
						412940	597195		1489270				I
						709015	976850		2204890				T
	STOKER	P or F (10-250)											E
													I
													T
Utility Types	CYCLONE	F (100-10000+)											E
													I
													T
	TANGENTIALLY-FIRED	F (100-10000+)						484905		1679730		14981950	E
								880500		3694020		25500250	I
								1365405		5373750		40482200	T
	WALL-FIRED	F (500-10000+)								1680230	5627520	14849950	E
										3700720	11074680	24175995	I
										5380950	16702200	39025945	T
	TURBO-FIRED	F (100-10000+)						484905		1679730		14981950	E
								880500		3694020		25500250	I
								1365405		5373750		40482200	T

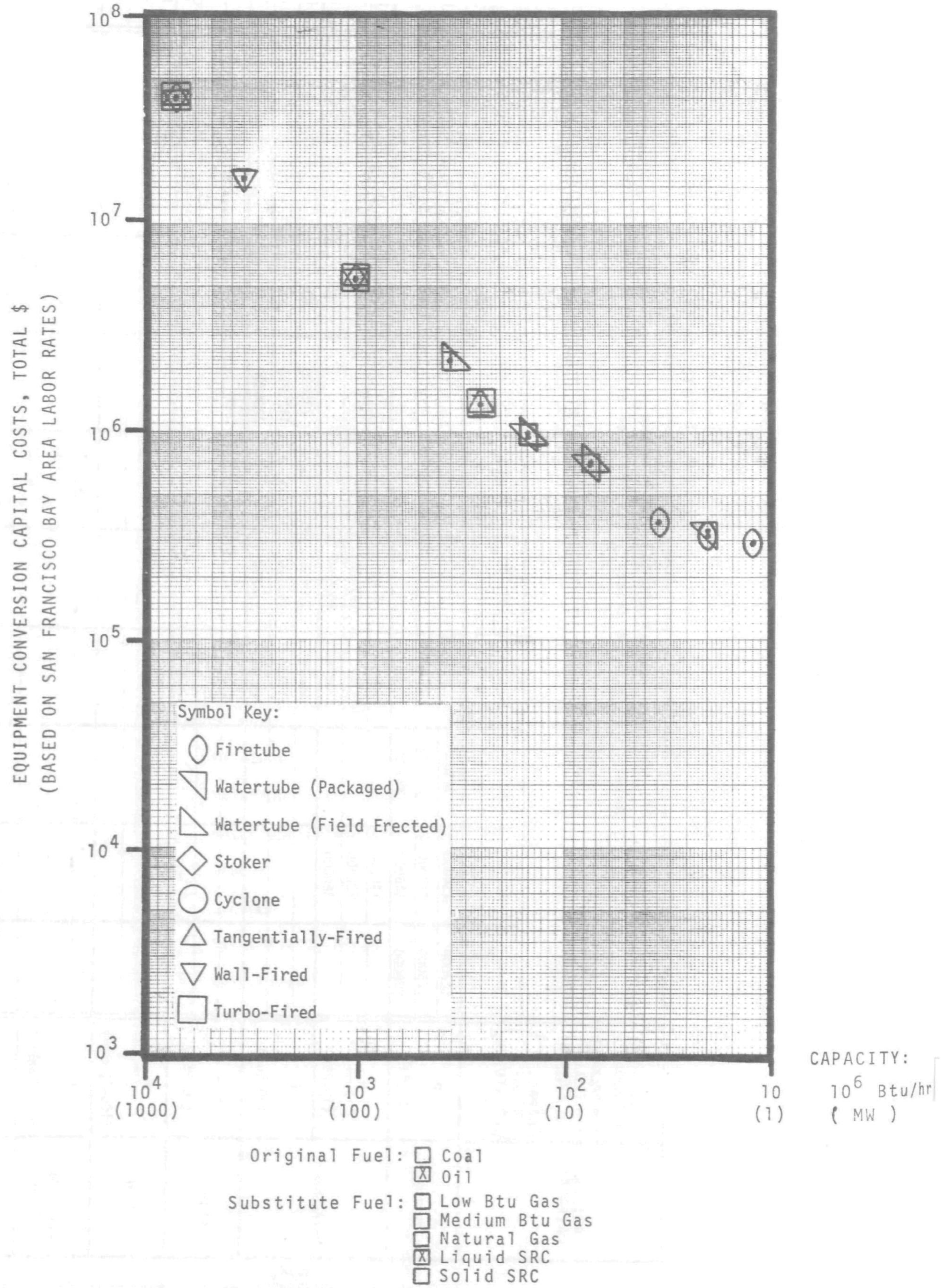


Figure 6-9. Combustion Equipment Conversion Capital Costs (Total $) vs. Boiler Capacity

TABLE 6-15

CONVERSION COST UNCERTAINTY FACTORS

Original Fuel	Substitute Fuel	Boiler Category	Uncertainty	Basis
Coal	Low-, medium-Btu gas and natural gas	Stoker and watertube (F)	±15%	Uncertainty in required number of burners for the furnace and length of fuel piping
Coal and Oil	Low-, medium-Btu gas and natural gas	Cyclone, tangentially-fired, wall-fired, and turbo-fired	+50% -10%	Upper limit due to uncertainty in required number of burners for furnace and length of fuel piping; lower limit based mostly on possible decrease in required piping lengths (also, probability is low that the original number of burners will be reduced upon conversion to a different fuel)
Coal and Oil	Liquid SRC	All boilers	±10%	The uncertainty in the cost of the fuel handling system dominates all other factors
Coal	Solid SRC	All boilers	±25%	Due to uncertainty in: amount of required cooling water, ductwork required to bypass preheater, piping to bring water from source to boiler front, cost of materials for stainless steel nozzle, plus general lack of knowledge of solid SRC's handling and combustion properties
Oil	Low-, medium-Btu gas and natural gas	Firetube	±10%	Uncertainty in piping installation costs
Oil	Low-, medium-Btu gas and natural gas	Watertube (P)	±15%	Uncertainty in required number of burners for the furnace and length of fuel piping

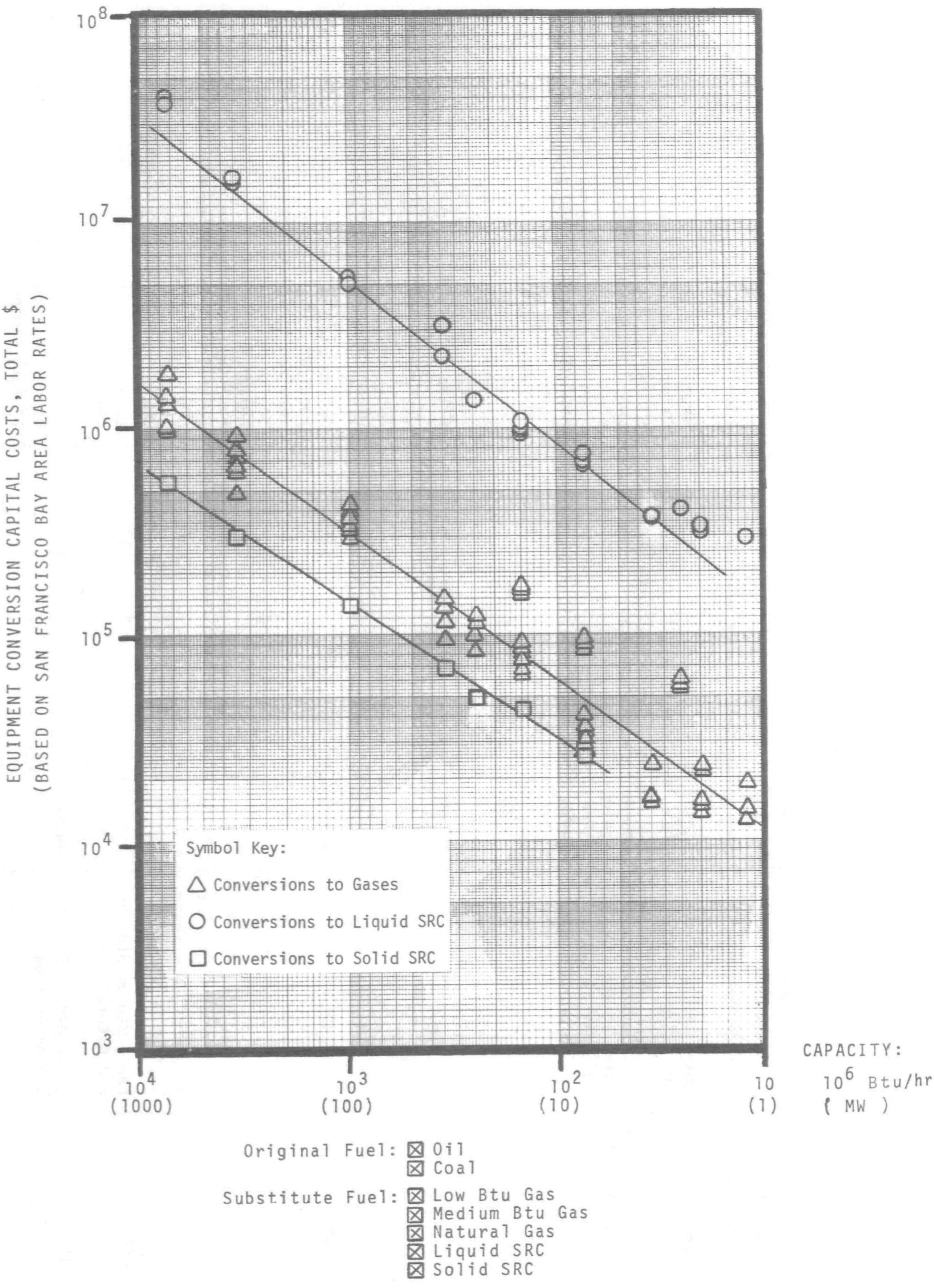


Figure 6-10. Composite of All Conversion Cost Data vs. Capacity

- The differences in conversion costs for the field-erected and packaged watertube boilers are slight. An incrementally higher engineering cost for the latter type accounts for this difference.

Figure 6-10 is the composite of all cost data previously shown in Figures 6-1 through 6-9. Three lines, again appearing to conform to power law functional relationships, have been fared in to illustrate the correspondence between cost and capacity for all boiler types for the three major fuel switching strategies. These are:

- Conversion to Liquid SRC
  Enabling all coal- or oil-fired boiler types to use liquid SRC is clearly the most expensive fuel substitution option. This cost is dominated by the elaborate fuel handling system that is required.

- Conversion to solid SRC
  This appears to be the least expensive strategy for abating SO_x emissions by way of fuel switching. It does, of course, apply only to boilers that were originally burning coal. The low cost reflects the savings realized through the reuse of existing fuel handling and firing equipment.

- Conversion to the Coal-Derived Gases and Natural Gas
  These costs fall between those for liquid and solid SRC. The option for conversion to gas is open for all boiler types firing either original fuel. Due to the data scatter, the straight line in Figure 6-10 representing the costs for this operation is only one of many that could have been drawn in. It serves, however, to identify the overall trend. A more accurate placement of the line can be obtained by performing a regression analysis.

6.3.4 Use of Cost Data for Other Locations

As was mentioned previously, the installation costs associated with each type of conversion were based on San Francisco Bay Area labor rates. Therefore, the total plant investment as shown on the data sheets is specific for that metropolitan area. To determine installation costs for other areas, it will be necessary to modify the Bay Area figures by some labor rate factor.

M. W. Kellogg Co. presented location factors for the major U.S. cities in Reference 6-4. These are repeated in Table 6-16. Adjacent to each of these numbers is a corresponding factor as normalized to the Bay Area figure (1.45). With these factors, the installation cost estimates contained in this report can be used to calculate total equipment conversion capital costs for other major cities.

TABLE 6-16

LOCATION FACTORS FOR MAJOR U.S. CITIES

Location	M. W. Kellogg Location Factor (Reference 6-4)	Location Factor Normalized to San Francisco
Atlanta	1.10	0.76
Baltimore	1.41	0.97
Birmingham	1.16	0.80
Boston	1.23	0.85
Chicago	1.52	1.05
Cincinnati	1.53	1.06
Cleveland	1.86	1.28
Dallas	1.07	0.74
Denver	1.03	0.71
Detroit	1.73	1.19
Kansas City	1.37	0.95
Los Angeles	1.44	0.99
Minneapolis	1.54	1.06
New Orleans	1.16	0.80
New York	2.08	1.43
Philadelphia	1.82	1.25
Pittsburgh	1.52	1.05
St. Louis	2.01	1.39
San Francisco	1.45	1.00
Seattle	1.21	0.83
Houston	1.00	0.69

6.3.5 Proposed Cost Models

Interpolation and regression will allow the formulation of the functional relationships suggested by the correspondences between cost and capacity for each type of fuel-to-fuel conversion for each boiler category, as shown in Figures 6-1 through 6-9. Therefore, the most specific cost models would take the following forms:

SRC:

$$\text{Equipment Cost} = (K_e)\ (\text{Capacity})^{n_e}$$

$$\text{Installation Cost} = (F)(K_i)\ (\text{Capacity})^{n_i}$$

Gas:

$$\text{Equipment Cost} = (K_e)\ (\text{Capacity})^{n_e}(\text{HHV})^{p_e}$$

$$\text{Installation Cost} = (F)(K_i)\ (\text{Capacity})^{n_i}(\text{HHV})^{p_i}$$

where

HHV = high heating value for substitute fuel gas (Btu/scf)

F = location factor

and n's, p's and K's are calculated by the regression analysis.

Due to the lack of more than three data points for each boiler type, and the overall scatter of the data, the creation of these elaborate cost models may not be justified. More simplistic cost models can be obtained from the composite of all the data, illustrated previously in Figure 6-10. Thus, the general form of these functions would be the same for the three principal fuel substitution options for all boiler types:

$$\text{Equipment Cost} = (K_e)(\text{Capacity})^{n_e}$$

$$\text{Installation Cost} = (F)(K_i)(\text{Capacity})^{n_i}$$

The total plant investment is the sum of the equipment and installation costs.

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

The following are this study's major conclusions:

- On the basis of the estimated equipment modification cost data, there appear to be three basic fuel switching options for the abatement of oxides of sulfur emissions from industrial and utility boilers. These include conversions to melted solvent refined coal, solid solvent refined coal, and the gaseous fuels of any heating value.
- Based on the engineering assumptions made during the cost estimation procedure, conversions to hot liquid SRC seem to be the most expensive of the investigated alternatives. The fuel handling system cost is the major portion of the total plant investment. This strategy is open to applicable boiler types firing either oil or coal.
- Converting coal-fired boilers to the use of solid SRC is the least expensive alternative. Considerable cost savings result from the reuse of the existing fuel handling and firing sytems. Modifying oil-fired boilers to enable the use of solid SRC is considered impractical. The costs of such an operation would exceed the costs for converting to liquid SRC.
- Between the costs for converting to SRC in either phase lie those for converting to the gaseous fuels. These costs are generally inversely proportional to the heating value of the substituted gas. This fuel switching option is available for all boiler types firing either oil or coal originally. The sulfur oxide reduction benefit is greater for the gaseous fuels since, unlike SRC, they contain no sulfur.
- There appears to be a correspondence between conversion cost and capacity for the three basic fuel switching options; a power law functional relationship probably best describes this correspondence.

The following are the principal recommendations made in light of the results of this study:

- A regression analysis should be performed for each of the correspondences between conversion cost and boiler capacity for each of the three major fuel substitution options. This procedure will result in the formulation of generalized equipment conversion cost models.
- The results of the ongoing experimental and practical activities in handling and burning solvent refined coal and the lower-Btu gases should be used to periodically update the cost estimations contained in this report.
- The cost estimation methodology used in this study should be employed to evaluate the costs of converting boilers to other coal-derived fuels, especially the products from the more promising coal liquefaction processes.

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APPENDIX A

PROCESSES FOR LOW AND INTERMEDIATE BTU FUEL GAS

(From Reference 4-21 except where noted)

PROCESSES FOR LOW AND INTERMEDIATE BTU FUEL GAS

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Applied Technology Corp.	Coal is continuously gasified by air (without steam) in a molten-iron bath. Reaction with limestone takes out sulfur.	Tested in pre-pilot reactor equivalent to 10 bl/min of coal. Aiming for funding for bigger unit.
Applied Technology Corp. (Patgas)	Similar to company's Atgas process (see Appendix B) but without shift conversion or methanation.	Gas intended for, e.g., iron and steel industry
Babcock & Wilcox Co.	Coal is entrained in air for feeding to gasifier, which uses no steam. Char is recycled.	Tested in experimental unit.
Bituminous Coal Research, Inc.	Gasification in multiple fluidized beds yields a gas stream free of liquids. Btu content of gas depends on whether air or oxygen is fed.	Construction of 100-lb/h unit to begin at Monroeville, PA, this year.
Columbia University	Coal's carbon reacts with steam in electric arc at about 10,000°C. Depending on reaction and subsequent quench conditions, process can be used to make low- or high-Btu gas.	As of May 1973, had been tested on batch basis at about 30 kw. Sponsored by Consolidated Natural Gas Co.
Combustion Engineering, Inc.	Pulverized coal is entrained in air and steam for feeding to gasifier.	Preliminary tests completed; await funding for 5-ton/h unit.
Davy Powergas, Inc. (Winkler)	Fluidized-bed gasification accommodates wide range of particle sizes. Some installations use oxygen instead of air, to obtain higher-Btu gas.	Developed in Germany; widely commercial in Europe and Asia; no contracts in U.S. yet.

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Garrett Research & Development Co. (GRD Coal Gasification Process)	Gasifier output of pipline-gas process described in Appendix B is also offered (after cleanup) for industrial fuel, at about 600°F 650 Btu/ft^3F).	See Appendix B.
General Electric Co. (Gegas)	Employs a moving fixed bed of coal and ash in gasifier. Under study are: feeding of coal fines by mixing with tar and then extruding; use of solid diluents to increase mass-flow through gasifier; use of liquid membrane for H_2S removal.	Tested at 50-lb/h rate. Seeking partners for erecting a demonstration unit at a utility plant.
Hydrocarbon Research, Inc.	Conical fludized-bed gasifier. High superficial velocity permits bed to operate at above ash softening point (e.g., 2200°F to 2300°F).	Concept developed by Arthur Squires, of City University of New York. HRI proposes a 10-ton/d unit.
Institute of Gas Technology (U-Gas)	Mild air-oxidation pretreats coal to avoid caking and produces a portion of the gas product. Fluidized-bed gasifier includes conical internals; ash is agglomerated within the cones.	Design study underway for pilot plant (10 to 35 tons/h).
M. W. Kellogg Co.	Gasification step similar to that in firm's pipeline-gas process (see Appendix B); but it employs air instead of oxygen, and no steam.	Investigating formation of concortium for demonstration project at a utility plant.
Koppers Co. (Koppers-Totzek)	Oxygen employed instead of air. Gasification occurs at very high temperatures around 3000°F, yielding an effluent free of tars and similar condensables. Raw gas is about 300 Btu/ft^3.	Sixteen commercial plants in Europe and Afica, making ammonia-synthesis gas. U.S. inquiries also involve fuel gas and pipeline gas.

Developed of Offered by (and Process Name if any)	Process Comments	Status and Remarks
Lurgi Gesellschaft für Wärmeund Chemotechnik mbH.	Gasifier at about 300 psi receives coal through a lock hopper. Revolving grate at bottom removes ash and allows air and steam to enter. Oxygen replaces air to manufacture town gas (or a precursor for pipeline gas; see Appendix B).	Process has been widely used outside U.S. to make town gas, synthesis gas and fuel gas.
North American Rockwell, Corp.	Coal is contacted with air (but no steam) in molten Na_2CO_3, at about 1800°F and 5 to 10 atm. Sulfur and ash removed externally, from a recirculating bleed stream of the salt.	Has been tested (at 1 atm) in 200-lb/h unit. A 5-ton/h pilot plant with Northeast Utilities Service Co. is planned for Norwalk, Conn.
Riley Co.	Low-pressure gasification; fixed bed of coal. Btu content of gas depends on whether air or oxygen is fed.	Fuel-gas manufacturers are offered an updated version of Morgan Construction Co. gasifiers.
U.S. Bureau of Mines	Gasification reactor's stirrer moves horizontally and vertically, providing uniform gasification conditions with caking or noncaking of any size.	Successfully tested at Morgantown, W. VA, in 12-ton/d unit having a 3-ft-dia reactor.
Wellman-Galusha (Reference 4-12)	Atmospheric, fixed-bed process; similar to Lurgi	Unknown
Westinghous Electric, Corp.	Gasifier has fluidized bed of recirculated char. Insensitive to coal's size distribution, caking properties and sulfur content.	A 1200-lb/h pilot plant due onstream at Waltz Mill, PA Commercial unit to be built at a Terre Haute, Ind., utility plant by 1978.
Westinghouse Electric Corp.	Gasifier at around 1850°F produces gas to energize solid-electrolyte fuel cells immersed in gasifier bed itself. Water vapor and carbon dioxide from fuel cell react with coal during gasification.	Concept studied between 1962 and 1970 and found to be attractive; but no active project underway now.
Woodall-Duckham Ltd. (IGI Two-stage Coal-Gasification Process)	Gasifier, operating a 1 atm, is divided into compartments by vertical walls, to aid distribution of rising gas through descending bed of coal.	Developed by Italy's II Gas Integrale in 1940's. Being offered anew by Woodall-Duckham.

APPENDIX B

PROCESSES FOR HIGH BTU PIPELINE GAS (SNG)

(From Reference 4-21)

Processes Developed With Their Own Technology for Methanation

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Bituminous Coal Research, Inc. (Bi-Gas)	Gasifier, at 1000 to 1500 psi, has two stages. Char is gasified with oxygen and steam in lower stage; the gas rises, picking up and entraining incoming coal; this stream goes to upper stage, which makes char and enriches the gas. Methanator has fluidized catalyst bed, with imbedded heat-transfer surfaces.	Gasification tested in 100-lb/h continuous unit; methanation likewise sucessfully tested. A 5-ton/h pilot plant for overall process being built at Homer City, PA.
Columbia University	Coal's carbon reacts with steam in electric arc at about 10,000°C. Proper reaction and quench conditions enable production of SNG without additional methanation step.	As of May 1973, had been tested on batch basis at about 30 kw.
Institue of Gas Technology (Hygas)	After pretreatment by air oxidation or by dilution with char, coal is oil-slurried and fed to top of 1000 - 1500 psi two-stage hydrogasifier, while mixture of steam and hydrogen (generated externally, from leaving hydrogasification) enters at the bottom. Heat in gasifier is supplied by carbon-hydrogen reaction. Methanator downstream uses multiple packed-catalyst-bed reactors.	Three-ton/h pilot plant compleated at Chicago in 1971 has operated on lignite, with hydrogen produced from char electrothermally. Now, IGT will run caking bituminous coal, and produce hydrogen via oxygen-combustion as source of heat.
Lurgi Gesellschaft für Wärme- und Chemotechnik mbH. (Lurgi Pressure Gasification)	In pipeline-gas projects, gasifier with lock hopper and grate (see Appendix A) employs oxygen for gasification, producing a raw gas of about 400 Btu/ft^3. A heterogeneous nickel catalyst is used in the downstream methanation step.	Gasification well established (see Appendix A). Methanation being groomed in demonstration plants. First SNG-from-coal plants in U.S. will use Lurgi technology.

Processes Developed With Their Own Technology for Methanation (Concluded)

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Stone & Webster Engineering Corp. (Solution/Gasification)	Coal is slurried in a solvent; then a two-step treatment with hydrogen solubilizes the coal and produces pipeline-quality gas without an explicit methanation step. Process does not entail oxygen or steam.	Tested on bench scale. Under new joint venture with General Atomic, nuclear reactors will provide heat for hydrogen generation. Demonstration plant planned.
U.S. Bureau of Mines (Synthane)	Coal is pretreated with steam and oxygen in fluidized-bed reactor that is integral part of gasification system. The system operates at high pressures (e.g., 1000 psi). Of methane contained in final gas, 60 percent is made during gasification step. Two variants of downstream methanation with Raney nickel catalyst are under study.	Tested in continuous unit rated at 10 to 20 lb/h. A 75-ton/d pilot plant due completed at Bruceton, PA, in August 1974.

Processes That Will be Combined with "Outside" Methanation Technology

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Applied Technology Corp.	Coal is injected into 2500°F molten-iron bath; reaction with steam and oxygen produces sulfur-free gas for shift conversion and methanation. Sulfur removed as slag by limestone addition.	Gasification step has been tested in 2-ft-dia. reactor, equivalent to 10 lb/min of coal. Company seeks funds to build 15-ton/h unit.
Babcock & Wilcox Co.	Entrained-coal gasifier; char recycled. Methane content of gasifier output can be regulated by selecting pressure and temperature.	Technology commercial in 1950's for making synthesis gas. Now soliciting cutomers for fuel production (including SNG) as well.
Babcock & Wilcox Co.	Gasifier employs sulfur dioxide instead of oxygen for blowing.	Conceptual. Seeking Funds for testing.

Processes That Will be Combined with "Outside" Methanation Technology (Continued)

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
Cogas Development Co. (Cogas)	Multistage pyrolysis of coal yields gas, oil and char. More gas comes from reacting char with steam, at under 100 psi. Heat for gasification supplied by burning some char in air, in a combustor external to the gasifier. No oxygen needed.	Pyrolysis step demonstrated in COED-Process work of FMC Corp., one of the partners in Cogas Development Co. Two pilot plants will test char-gasification step.
Consolidation Coal Co. (CO_2 Acceptor)	Lignite is gasified with steam in presence of hot, calcined dolomite. This reacts exothermally with the gasification-generated carbon dioxide, removing it while providing heat for gasification. Dolomite regenerated by heating.	Runs have been made in a 30-ton/d pilot plant completed in South Dakota in 1972.
Davy Powergas, Inc. (Winkler)	Oxygen-feeding version of process outlined in Appendix A serves as gasification step to precede shift conversion, purification, and methanation.	Developed in Germany; widely commercial in Europe and Asia; no U.S. contracts yet.
Exxon Corp.	Air burns char outside of gasifier, to provide heat for gasification reactions involving steam. System does not require oxygen.	Tested in 1/2-ton/d unit at Baytown, Tex. Design of proposed 500-ton/d plant nearly completed.
Garrett Research & Development Co. (GRD Coal Gasification Process)	A low-pressure (30 to 50 psi) step pyrolyzes coal quickly in the presence of some steam and recycled gas. The pyrolyzer also receives partially burned char (produced externally by air combustion), which supplies the needed heat.	Tested in a 50-lb/h unit (a highly similar liquefaction process has been tested in a 300-lb unit). Now seeking support for a 250-ton/d pilot plant.

Processes That Will be Combined with "Outside" Methanation Technology (Concluded)

Developed or Offered by (and Process Name if any)	Process Comments	Status and Remarks
M. W. Kellogg Co.	Coal is contacted with oxygen and steam in a molten-sodium-carbonate bath at about 1700°F. and 1200 psi. The salt serves as catalyst and heat-transfer agent; all operations involving salt take place in the one vessel. Raw gas from gasification is tar-free. Of methane in the final gas, 55 percent to 60 percent is made during this gasification step.	Process development, underway for several years, has included studies in a 5-1/4-in-dia. reactor. Next step will employ a 30-in reactor. Funding sought for building a large continuous pilot plant.
Koppers Co. (Koppers-Totzek)	Effluent from gasification described in Appendix A is suitable for shift conversion, and methanation.	Sixteen commercial plants in Europe and Africa, making ammonia-syntesis gas.
Union Carbide/Battelle/Chemico	Two fluidized-bed systems, a combustor and a gasifier, are linked by an agglomerated-ash circuit that transfers heat. Gasifier, at 1800°f and 250-350 psi, is fed coal and steam; the combustor is fed char and air. No oxygen required.	Components of process tested during 1960's by Union Carbide and Battelle. Chemico completing design, for Battelle, for 25-ton/d pilot unit.
U.S. Bureau of Mines (Hydrane)	In a first, "dilute" stage, coal particles are heated through their plastic-transition temperature range in a stream of hydrogen and methane from fluidized-bed second stage. Devolatilized coal, meanwhile, falls into second stage, where it contacts hydrogen gernerated externally from char, steam and oxygen. Gas leaving dilute stage, at 2000 psi, is 75 percent or more methane.	The two stages have been tested separately at Bruceton, PA. A pilot unit to demonstrate them together has just been built but is not likely to start up during this fiscal year.

APPENDIX C

BULK CONVERSION COST DATA

		Q = 12×10⁶ Equip.		Q = 12×10⁶ Install.	20×10⁶ Equip.		20×10⁶ Install.	35×10⁶ Equip.		35×10⁶ Inst.
Burner & Windbox - E										
1.	Burner Ass'y	$2000.00	4	100.00	8' 2600.00	6	150.00	8' 2600.00	6	150.00
	Adaptor Plate	500.00	8	200.00	500.00	12	300.00	500.00		300.00
	Gas Electric Pilot	400.00	1	25.00	400.00		25.00	400.00	1	25.00
Burner Management - M										
	Limits: H.G.P. - F	120	2	50.00	120.00		50.00	120.00		50.00
	L.G.P. - F	120.00	2	50.00	120		50.00	120.00		50.00
Burner Fuel Piping - M										
1	Pilot Train - FA	250.00		—	—		—	—		—
1	Main Gas - FA	5000.00		1000.00	6000.00		1500.00	7500.00		2000.00
1	Supply Piping	610.00		4100.00	610.00		4100.00	610.00		4100.00
Instrument · Comb. Contr.										
2	Press. Gages - F	75.00		INCL	25.00		INCL	75.00		—
	Control Valve - Damper	—	4	100.00						
Fans - No change		—		—	—		—	—		—
Furnace - Boiler Mod		100	4	100.00	200.00	5	200.00	200.00		200.00
		$9175.00		$5725.00	$10,625.00		$6375.00	$12,125.00		6875.00
Misc. Services										
	Engr	2250.00		—	2550.00		—	2850.00		—
	Start-up	—		1250.00	—		1250.00	—		1250.00
	Install. Superv.	—		600.00	—		650.00	—		700.00
		$11425.00		$7575.00	13175.00		8275.00	14975.00		8825.00

BOILER CATEGORY: FIRE TUBE — SHT 2 of 15

ORIG. FUEL: OIL — SUBSTITUTE FUEL: MBG — 8-12-79

	1	2	3	4	5	6
	12 MKB		20 MKB		35 MKB	
BURNER & WINDBOX	EQUIP	I	E	I	E	I
1 BURNER ASS'Y	1250.00	100.00	1500.00	150.00	1750.00	200.00
1 ADAPTOR PLATE	500.00	200.00	500.00	250.00	500.00	300.00
1 GAS ELECTRIC PILOT	300.00	25.00	300.00	25.00	300.00	25.00
BURNER MANAGEMENT						
1 LIMITS: HGP.	120.00	50.00	120.00	50.00	120.00	50.00
1 LGP.	120.00	50.00	120.00	50.00	120.00	50.00
BURNER FUEL PIPING						
1 PILOT TRAIN	250.00	—	250.00	—	250.00	—
1 MAIN GAS TRAIN	2500.00	INCL	3250.00	INCL	4000	INCL
1 SUPPLY PIPING	610.00	4100.00	610.00	4100.00	610.00	4100.00
INSTRUMENT - COMB. CONTR						
2 PRESS GAGES - F	75.00	INCL	75.00	INCL	75.00	INCL
CONTROL VLV. DRIVE	—	100.00	—	100.00	—	100.00
FAN NO CHANGE	—	—	—	—	—	—
FURNACE - BOILER MOD	100.00	100.00	200.00	200.00	200.00	200.00
	5825.00	4725.00	6925.00	4925.00	7925.00	5025.00
MISC SERVICES						
ENGR	1600.00	—	1800.00	—	1950.00	—
START-UP	—	1250.00	—	1250.00	—	1250.00
SUPER	—	500.00	—	500.00	—	500.00
	7425.00	6475.00	8725.00	6625.00	9875.00	6725.00

BOILER CATEGORY: FIRETUBE

ORIG. FUEL: OIL SUBSTITUTE FUEL: NAT. GAS

8-13-79

4806 - Buff 5806 - Blue 8806 - Green

			1	2	3	4	5	6
			12 MKB		20 MKB		35 MKB	
BURNER & WINDBOX			E	I	E	I	E	I
	1	BURNER ASS'Y	1000.00	100.00	1200.00	150.00	1400.00	200.00
	1	ADAPTOR PLATE	400.00	200.00	400.00	250.00	400.00	300.00
	1	GAS ELECTRIC	300.00	25.00	300.00	25.00	300.00	25.00
BURNER MANAGEMENT								
		LIMITS HGP.	120.00	50.00	120.00	50.00	120.00	50.00
		LGP.	120.00	50.00	120.00	50.00	120.00	50.00
BURNER PIPING								
		PILOT TRAIN	250.00	INCL	250.00	INCL	250.00	INCL
		MAIN GAS TRAIN	1800	INCL	2500.00	INCL	3500.00	INCL
		SUPPLY PIPING	610.00	4100.00	610.00	4100.00	610.00	4100.00
INSTRUMENT-COMB. CNTR.								
	2	PRESS. GAGES - F	75.00	INCL	75.00	INCL	75.00	INCL
		CONTROL WIN. DAMPER	—	100.00	—	100.00	—	100.00
FAN - NO CHANGE			—	—	—	—	—	—
FURNACE - BOILER MOD			—	—	—	—	—	—
			4675.00	4625.00	5575.00	4725.00	4775.00	4825.00
MISC SERVICES								
		ENGR	1400.00 ~~1375.00~~	—	1550.00	—	1750.00	—
		START-UP	—	1250.00	—	1250.00	—	1250.00
		SUPVR	—	475.00	—	475.00	—	500.00
		TOTAL	6075.00	6350.00	7125.00	6450.00	8525.00	6575.00

	12 MKB E	12 MKB I	20 MKB E	20 MKB I	35 MKB E	35 MKB I
Burner & Windbox						
1 Burner Assy	900.00	40.00	900.00	40.00	1100.00	160.00
1 Adapter Plate-Screen	350.00 6	160.00	350.00	160.00	500.00	160.00
1 Gas Electric Pilot	100.00	20.00	100.00	20.00	100.00	20.00
1 Spare Gun	250.00	—	250.00	—	300.00	—
Burner Management						
1 H.Q.P.	200.00	80.00	200.00	80.00	200.00	80.00
1 L.O.T.	50.00	80.00	50.00	80.00	50.00	80.00
Burner Fuel Piping						
1 Pilot Train	100.00	80.00	100.00	80.00	100.00	80.00
1 Main ~~Gas~~ Oil Train	1000.00	160.00	1000.00	160.00	1200.00	200.00
1 Supply Piping	92,670.00	149,362.00	98,600.00	183,440.00	108,734.00	199,341.00
1 Stm Train	350.00	120.00	350.00	120.00	400.00	160.00
Instrument-Comb. Contr.						
2 Press-Gage	600.00	80.00	600.00	80.00	600.00	80.00
Control Val. Dmpr.	—	—	—		—	—
Fan - No Change						
Furnace-Boiler Mod Mi	1250.00	20.00	1250.00	[illegible]	1250.00	750.00
	~~[illegible]~~	~~[illegible]~~	103750	184200.00	114572	200962.00
	97,820.00	150,258.00				
	98000.00	150,000.00	104,000.00	184,000.00	115,000	201,000.00
Misc Services						
Engr	25,000.00		30,000.00		30,000.00	
Start-up		10,000.00		10,000.00		10,000.00
Super.		15,000		18,000.00		20,000.00
	$123,000.00	$175,000.00	$134,000.00	$212,000.00	$145,000.00	$231,000.00

COSTS FOR CONVERTING ALL BOILER TYPES FROM COAL TO SOLID SRC ($)

CAPACITY (10^6 Btu/hr)	75	150	250	350	1000	3500	7500
NO. OF BURNERS	1	2	2	4	8	28	60
COOLING WATER TUBES	3500	6000	6000	10000	20000	50000	90000
COOLING WATER HDR	0	500	500	1000	2000	5000	9000
COOLING WATER TANK AND HEAT EXCHANGER	2500	3500	3500	5000	10000	25000	45000
COOLING WATER PUMP	750	1000	1000	1500	2500	5000	8000
CONNECTING PIPES & VALVES	1750	2500	2500	3500	6000	15000	25000
AIR PREHEATER BYPASS	3325	10000	16000	20800	58240	122000	260000
ENGINEERING	6000	8000	8000	10000	15000	20000	30000
INSTALLATION	7500	10000	10000	15000	25000	50000	80000
SUPERVISION	1000	1500	1500	2000	3000	5000	8000
START-UP SERVICE	500	800	800	1000	2000	3000	5000
TOTAL EQUIPMENT COST	16825	28000	31000	43400	86740	186000	345000
TOTAL INTALLATION COST	10000	15800	18800	26400	56000	114000	215000
TOTAL PLANT INVESTMENT	26825	43800	49800	69800	142740	300000	560000

BOILER CATEGORY: CYCLONE

ORIGINAL FUEL: COAL

SUBSTITUTE:

	Low BTU Gas 51-(250)-500 E	51-(250)-500 I	501-(1000)-5000 E	501-(1000)-5000 I	5001-(7500)-10,000 E	5001-(7500)-10,000 I
EXCL. BURNER MODIFICATION						
Burners	4600.00	400.00	18,000.00	1200.00	136,800.00	7200.00
Forming Plates	1100.00	800.00	5250.00	1920.00	17,500.00	14,400.00
Igniter Pilots	550.00	320.00	2250.00	760.00	15,000.00	5760.00
Misc Mat	500.00	600.00	5500.00	480.00	14,[illegible]	2600.00
Σ1-4	6750.00	1920.00	31,250.00	4860.00	183,[illegible]	25,320.00
BURNER MANAGEMENT						
Logic: New	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00
Limits: HGP, LGP, FD, PA, IA, FP, FPP, IO	750.00	720.00	1200.00	720.00	1200.00	720.00
	8250.00	1920.00	31,200.00	12,720.00	245,200.00	100,720.00
BURNER FUEL PIPING						
Pilot Gas Train	560.00	960.00	4560.00	4200.00	24,250.00	22,000.00
Main Gas	17,250.00	14,000.00	54,570.00	45,000.00	313,600.00	289,000.00
Supply Piping	5500.00	37,350.00	23,000.00	124,260.00	66,750.00	235,350.00
	23,310.00	52,310.00	82,130.00	173,460.00	404,600.00	546,350.00
COMBUSTION CONTROLS	5800.00	2100.00	6150.00	2600.00	11,700.00	4800.00
INSTRUMENTATION	1425.00	850.00	6925.00	3200.00	12,125.00	4000.00
FANS						
FD	—	—	—	—	—	—
ID	3500.00	230.00	7050.00	350.00	31,725.00	2500.00
	3500.00	230	7050.00	350.00	31,725.00	2500.00
EQUIPMENT REMOVAL	—	1000.00	—	8400.00	—	18,000.00
FURNACE BOILER MODIFICATION	—	—	—	—	—	—
ENGINEERING	11,800.00	—	49,500.00	—	160,000.00	—
ERECTION SUPERVISION	—	2000.00	—	22,000.00	—	74,[illegible]
START-UP SERVICE	—	2000.00	—	15,[illegible]	—	35,[illegible]
Σ 5, 9, 14, 16, 18, 22, 24, 26, 28, 30, 32	57,965.00	63,460.00	209,205.00	2[illegible]6,850.00	1,068,850.00	811,690.00

	Med BTU Gas 51-(250)-500 E	51-(250)-500 I	501-(1000)-5000 E	501-(1000)-5000 I	5001-(7500)-10,000 E	5001-(7500)-10,000 I
EXCL. BURNER MODIFICATION						
Burners	2800.00	360.00	15,500.00	1080.00	102,000.00	6480.00
Forming Plates	800.00	1720.00	2800.00	1730.00	14,000.00	12,960.00
Igniter Pilots	500.00	790.00	2800.00	660.00	15,000.00	5200.00
Misc Mat	900.00	180.00	[illegible]	480	10,[illegible]	3240.00
Σ1-4	[illegible]	1560.00	[illegible]	3920.00	142,400.00	31,800.00
BURNER MANAGEMENT						
Logic: New	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00
Limits: HGP, LGP, FD, PA, IA, FP, FPP, IO	750.00	720.00	1200.00	720.00	1200.00	720.00
	8250.00	1920.00	51,200.00	12,720.00	245,200.00	100,720.00
BURNER FUEL PIPING						
Pilot Gas Train	560.00	960.00	4560.00	4200.00	24,250.00	22,000.00
Main Gas	15,525.00	10,000.00	30,140.00	20,000.00	197,175.00	189,000.00
Supply Piping	5500.00	37,350.00	23,000.00	124,260.00	61,[illegible]	[illegible]
	21,585.00	48,310.00	57,700.00	148,460.00	282,025.00	342,000.00
COMBUSTION CONTROLS	5100.00	5640.00	5800.00	2720.00	10,850.00	4120.00
INSTRUMENTATION	1425.00	850.00	6925.00	3200.00	12,126.00	6000.00
FANS						
FD	—	—	—	—	—	—
ID	3500.00	230.00	7050.00	350.00	31,725.00	2100.00
	3500.00	230.00	7050.00	850.00	51,125.00	2100.00
EQUIPMENT REMOVAL	—	1000.00	—	8400.00	—	15,000.00
FURNACE BOILER MODIFICATION	—	—	—	—	—	—
ENGINEERING	10,800.00	—	34,000.00	—	133,500	—
ERECTION SUPERVISION	—	580.00	—	19,600.00		56,[illegible]
START-UP SERVICE	—	2500.00	—	15,000.00	—	50,000.00
Σ 5, 9, 14, 16, 18, 22, 24, 26, 28, 30, 32	54,660.00	64,280.00	163,875.00	212,870.00	8[illegible]	610,[illegible]

	Nat Gas 51-(250)-500 E	51-(250)-500 I	501-(1000)-5000 E	501-(1000)-5000 I	5001-(7500)-10,000 E	5001-(7500)-10,000 I
EXCL. BURNER MODIFICATION						
Burners	1800.00	300.00	7000.00	900.00	74,000.00	5400.00
Forming Plates	150.00	600.00	3500.00	1440.00	14,000.00	10,800.00
Igniter Pilots	500.00	640.00	2200.00	576.00	15,000.00	4320.00
Misc Mat	[illegible]	150.00	[illegible]	480.00	8,[illegible]	2700.00
Σ1-4	2850.00	1290.00	17,150.00	3[illegible]70.00	112,500.00	20,500.00
BURNER MANAGEMENT						
Logic: New	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00
Limits: HGP, LGP, FD, PA, IA, FP, FPP, IO	650.00	720.00	1200.00	720.00	1200.00	720.00
	8150.00	1920.00	51,200.00	12,720.00	245,200.00	100,720.00
BURNER FUEL PIPING						
Pilot Gas Train	560.00	960.00	4560.00	4200.00	24,250.00	22,000.00
Main Gas	7850.00	5000.00	23,780.00	17,500.00	133,600.00	90,000.00
Supply Piping	5500.00	37,350.00	23,000.00	124,260.00	61,600.00	220,000.00
	13,850.00	43,310.00	51,340.00	145,960.00	219,450.00	332,000.00
COMBUSTION CONTROLS	4850.00	1940.00	5580.00	2220.00	14,400.00	4180.00
INSTRUMENTATION	1425.00	850.00	6425.00	3200.00	12,125.00	6000.00
FANS						
FD	—	—	—	—	—	—
ID	—	—	—	—	—	—
	—	—	—	—	—	—
EQUIPMENT REMOVAL	—	1000.00	—	8400.00	—	18,000.00
FURNACE BOILER MODIFICATION	—	—	—	—	—	—
ENGINEERING	7200.00	—	32,000.00	—	118,200.00	—
ERECTION SUPERVISION	—	5250.00	—	19,100.00	—	51,150.00
START-UP SERVICE	—	2000.00	—	15,000.00	—	30,[illegible]
Σ 5, 9, 14, 16, 18, 22, 24, 26, 28, 30, 32	41,165.00	59,570.00	143,6[illegible]	209,870.00	7[illegible]3,5[illegible]	572,[illegible]

Boiler Category: Wallfired

Original Fuel Category

Substitute Fuel	Low BTU Gas 501-(1000)-2000 E	I	2001-(3500)-5000 E	I	5001-(7500)-15,000 E	I	Med. BTU Gas 501-(1000)-2000 E	I	2001-(3500)-5000 E	I	5001-(7500)-10,000 E	I	Natural Gas 501-(1000)-2000 E	I	2001-(3500)-5000 E	I	5001-(7500)-10,000 E	I
Burner, Hoses, & Shields (A.F.)	21000	1800	73000	4200	157500	8910	14800	1800	4800	4000	106500	7000	13440	1800	37690	3500	77000	6000
Windbox Mod & Burner Additions	4000	1,700	6000	3200	8000	4000	2000	1000	8,000	1250	4000	2000	2000	1000	2000	1250	4000	2000
Pilots	3600	800	9100	5000	15000	5760	2000	1000	6300	3000	12000	4600	2000	1000	6300	3000	12000	4500
Misc Mat & Cost	5000	[illegible]	10,000	[illegible]	15,000	[illegible]	3000	1250	[illegible]	2000	10,000	4000	[illegible]	1250	[illegible]	[illegible]	10,000	4000
	32,600	4900	98,000	13,800	195,500	22160	21800	4650	65000	14,250	132,500	17600	17,640	4250	56,590	9750	105,500	16,500
Burner Management																		
Logic Cabinet, ...	30,000	12,000	116,000	46400	244000	100,000	30,000	12,000	116,000	46400	244,000	100,000	30,000	12,000	116,000	46,400	249,000	100,000
Limits ...	1200	720	1200	720	1200	720	1200	720	1200	720	1200	720	1200	720	1200	720	1200	720
	31200	12,720	117200	47120	245200	100720	31200	12,720	117,200	47120	245200	100720	31200	12,720	117,200	47120	245200	100720
Burner Fuel Piping																		
Pilot Gas Train	4560	4200	12,440	11,600	24250	22,200	4560	4200	12440	11,600	24250	22000	4560	4200	12,440	11,600	24,250	22,000
Main Gas Train	54570	45,000	145555	120,000	313600	280,500	30140	20,000	106,310	72,000	197,175	120,000	25750	17500	62,510	42000	133,000	90,000
Supply Piping	22000	124,260	46,200	171,900	[illegible]	238,350	22,900	[illegible]	36,800	151,800	61,600	220,000	22000	124260	46200	171,900	61,600	220,000
	82,150	193,460	204,195	303,500	404600	540,500	57700	148,460	155,550	235400	283025	362000	51,340	146960	121,150	187700	219,450	332,000
Combustion Controls																		
Fuel ... <2000; 800>	6025	2100	8800	5520	11,700	4800	5800	2320	8550	3420	10450	4120	5500	2200	8500	5320	10,200	4080
Instrumentation; For oil ... <1225; 725>	6425	3200	9100	1100	12,125	6000	4475	3200	3900	1000	12,125	6000	6425	3200	3400	1000	12,125	6000
Fans I.D.	7050	350	6460	420	31,725	2800	7050	360	8460	420	31,725	2800	—	—	—	—	—	—
Equipment Removal	—	5400	—	14400	—	18000	—	8400	—	14400	—	18000	—	8400	—	14,400	—	18000
Furnace or Boiler Modification	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Engineering	47720	—	85000	—	170,000	—	54300	—	72000	—		—	31950	—	61500	—	126510	—
Erection Supervision	—	22000	—	37400	—	72500	—	19500	—	35600	—		—	18860	—	28700	—	50730
Start-up Service	—	15000	—	22500	—	36000	—	15,000	—	22500	—	30,000	—	15,000	—	22,500	—	30,000
Σ 5,9,14,16,18,20,22,24,26,28,30	406,375	264,330	526655	411350	1073855	790030	168475	214500	436,160	369010	647725	561940	194055	207130	364510	315,[illegible]	813,285	558030
Deduct for ... Fired	39,200	15,500	137,585	52,935	284,285	112,285	21,100	15,500	172,585	[illegible]	284,280	112,285	37,200	15,500	137,585	52,935	284,280	112,286
	167,175	226,130	389,070	358,415	789,570	685745	124415	199,000	293,075	315,675	358,445	449,655	104,855	192,230	227,005	262,055	528,005	445,744

C-8

Boiler Category: Stoker & Cyclone

	Emulsion Oil: Stoker 10-(25)-50 E	I	Dir. Fuel: Coal 51-(75)-100 E	I	Sub. Fuel: Liq. SRC 101-(150)-200 E	I	Boiler Cat.: Cyclone 5/-(250)-500 E	I	Dir. Fuel: Coal 501-(1000)-5000 E	I	Sub. Fuel: Liq. SRC 5001-(7500)-10,000 E	I
Windbox (or adapters)	1) 500	725	1) 2250	1080	1) 4000	2000	1) 4450	5000	16,000	10,000	52,000	40,000
Register	1200	320	2500	1180	5000	440	—		—		—	—
Burner Gun(s) & spare (1-per boiler)	550	160	1000	760	1750	280	3250	4900	16,000	8000	75,000	16,000
Pilots	100	80	100	80	800	160	750	400	2800	1200	19,500	7500
Throat Tile	150	680	200	240	800	1120	—	—	—	—	—	—
Insulated W.B	—	—	—	—	1600	—	—	—	—	—	—	—
Misc. Mat'l/Cost	500	—	400	—	750	—	750	—	10,000	8000	20,000	5200
Stl Sockets & SS tips	250	40	300	40	500	80	1500	120	2500	800	15,000	6000
Stl Hoses	100	40	150	40	300	80	800	120	800	800	6000	6000
Hand Valves (2 per burner)	150	40	150	60	300	80	700	120	800	800	6000	6000
Σ1-10	4250	1880	7050	2260	15,150	4240	10,400	4240	37,000	18,600	193,500	86,500
Burner Management	3025	2960	3025	2960	8150	3840	8750	3840	81,680	12,500	245,680	100,000
Burner Fuel Piping												
Fuel Valve (Burner Front) Piping	3100	1600	4025	2000	11,150	5000	12,866	6000	41,570	20,000	228,670	105,000
Fuel Supply Piping	108,780	199,300	222,000	[illegible]	[illegible]	511,475	[illegible]	773,000	1,110,457	3,275,[illegible]	16,479,170	21,710,[illegible]
	111,500	200,950	226,375	355,880	277,780	521,475	248,500	779,500	1,152,020	3,295,[illegible]	16,1[illegible]	21,811,[illegible]
Combustion Controls	2000	800	2000	800	2900	1200	5650	1460	6200	2520	11,000	4400
Instrumentation	825	880	825	650	1800	1600	1300	1600	2680	2800	15,680	1800
Fans: NC No Change	2000	400	3000	900	5000	1500	—	—	—	—	—	—
Equipment Removal / Foundations Mod	—	10,500	—	20,000	—	30,000	—	—	—	—	—	—
Engineering	37,000	—	62,100	—	95,000	—	125,000		470,000		3,400,000	—
Erection Supervision	—	22,500	—	39,100		57,900	—	80,130	—	160,000	—	1,700,000
Start-up Service	—	7500	—	12,000		15,000	—	15,000	—	42,500	—	67,500
	166,930	247,870	310,375	[illegible]	407,980	636,755	499,405	[illegible]	1,668,000	3,526,100	14,123,020	23,414,[illegible]

Boiler Category: Tangentially or Turbo Fired

	Orig Fuel: Coal 101-(250)-500 E	I	Subst Fuel: Liquid SRC 501-(1000)-5000 E	I	5001-(7500)-10,000 E	I	Orig Fuel: Oil 101-(250)-500 E	I	Sub Fuel: Liq SRC 501-(1000)-5000 E	I	5001-(7500)-10,000+ E	I
Base Boiler	3650.00	480.00	[illegible]	1600.00	60,000.00	10,500.00	3650.00	480.00	10,000.00	1600.00	60,000.00	10,500.00
Furnace & Windbox Modifications	750.00	400.00	5000.00	5000.00	36,000.00	10,000.00	750.00	400.00	5000.00	5,000.00	2,500.00	10,000.00
Ign. Pilots	500.00	400.00	2500.00	1200.00	15,000.00	7500.00	500.00	400.00	2500.00	1200.00	4,500.00	7500.00
Steel Support Mods	1000.00	120.00	4000.00	460.00	30,000.00	4800.00	1000.00	120.00	4000.00	460.00	30,000.00	4800.00
[illegible]	300.00	120.00	1200.00	480.00	9000.00	4800.00	300.00	120.00	1200.00	480.00	9000.00	4800.00
[illegible]	300.00	120.00	1200.00	480.00	9000.00	4800.00	300.00	120.00	1200.00	480.00	9000.00	4800.00
Misc Mat & Equip Handling	600.00	600.00	5000.00	[illegible]	10,000.00	10,000.00	600.00	600.00	[illegible]	[illegible]	8750.00	8750.00
	6500.00	2240.00	16,500.00	14,640.00	172,000.00	51,400.00	6500.00	2240.00	28,550.00	12,490.00	170,750	51,150.00
Burner Management	8755.00	2,840.00	31,500.00	12,500.00	241,600.00	100,000.00	1250.00	2400.00	1680.00	2600.00	1680.00	2600.00
Burner Fuel Piping												
Fuel Valve & Burner Front Piping	12,865.00	6000.00	41,570.00	[illegible]	225,675.00	105,000.00	—	Same	as	Coal		
Fuel Supply Piping	330,980.00	73,000.00	[illegible]	[illegible]	10,861,700.00	21,711,051.00						
	340,605.00	[illegible]	1,162,022.00	[illegible]	11,102,805.00	21,814,051.00	340,605	779,000.00	1,152,220.00	3295270.00	11,102,840.00	21,814,051.00
Combustion Controls	5650.00	1460.00	6300.00	2520.00	11,800.00	4400.00	5650.00	1460.00	6300.00	2520.00	11,800.00	4400.00
Instrumentation	1300.00	1600.00	2680.00	2800.00	15,680.00	18,000.00	1300.00	1600.00	2680.00	2800.00	15,600.00	18,000.00
Fans	—	—	—	—	—	—	—	—	—	—	—	—
Equipment Removal	—	1000.00	—	6600.00	—	18,000.00	—	—	—	—	—	—
Engineering	126,500.00	—	500,000.00	—	3,500,000.00	—	121,600.00	—	468,000.00	—	3,680,000.00	—
Erection Supervision	—	8,600.00	—	337,600.00	—	2,188,000.00	—	50,000.00	—	345,800.00	—	2,315,000.00
Start-up Service	—	15,000.00	—	45,000.00	—	67,500.00	—	15,000.00	—	42,500.00	—	67,500.00
	496,505.00	834,540.00	1,723,450.00	3,716,030.00	15,107,200.00	24,065,490	484,005.00	880,000.00	1,671,730.00	3,694,020.00	14,991,952.00	25,580,250.00

BOILER CATEGORY: WALLFIRED

	Orig Fuel: Coal 501-(1000)-2000 E	I	Sub Fuel: Liq SRC 2001-(3500)-5000 E	I	5001-(7500)-10,000 E	I	Orig Fuel: Oil 501-(1000)-2000 E	I	Sub Fuel: Liq SRC 2001-(3500)-5000 E	I	5001-(7500)-10,000 E	I
Base Burner	10,000.00	1600.00	30,000.00	5040.00	60,000.00	16,800.00	10,000.00	1600.00	30,000.00	5040.00	60,000.00	10,080.00
Adapter Plate & Windbox Modifications	5000.00	5000.00	16,000.00	7000.00	38,000.00	15,000.00	5000.00	5000.00	16,000.00	7000.00	35,000.00	10,000.00
Ign Pilots	2800.00	1200.00	9100.00	4400.00	18,000.00	7000.00	2800.00	1200.00	9100.00	4400.00	18,000.00	7000.00
Steel Sockets & Tips	4000.00	680.00	14,000.00	2100.00	30,000.00	4800.00	4000.00	480.00	14,000.00	2100.00	30,000.00	4800.00
S. Stl Hose	1200.00	450.00	4200.00	2400.00	9000.00	4800.00	1200.00	480.00	4200.00	2400.00	9000.00	4800.00
Hand Valves - Stl.	1400.00	480.00	4200.00	2400.00	9000.00	4800.00	1400.00	[illegible]	4200.00	2400.00	9000.00	4800.00
Misc Mat & Contingency	5000.00	—	7000	—	10,000.00	—	3750.00	—	6000.00	—	8750.00	—
Misc Handling	—	5000.00	—	2100.00	—	10,000.00	—	2250.00	—	4000.00	—	5720.00
E1-B	29,800.00	14,240.00	85,800.00	21,340.00	169,000	57,400.00	26,550.00	12,990.00	84,300.00	29,800.00	167,750.00	51,375.00
Burner Management	3680.00	12,500.00	11,680.00	48,680.00	295,680.00	100,800.00	1680.00	2640.00	1680.00	2640.00	1680.00	2640.00
Burner Fuel Piping												
Burner Valve & Burner Fuel Piping	4510.00	10,000.00	110,600.00	56,000.00	223,670.00	105,000.00	41,570.00	20,000.00	110,600.00	56,000.00	223,670.00	105,000.00
Fuel Supply Piping	1,110,450.00	2,275,270.00	3,891,080.00	9,905,340.00	10,879,170.00	21,711,840.00	1,110,450.00	3,275,270.00	3,887,857.00	9,905,340.00	10,879,170.00	21,711,840.00
	1,156,122.00	2,312,270.00	4,019,460.00	9,961,340.00	11,103,840.00	21,812,050.00	1,154,920.00	3,295,270.00	4,002,960.00	9,961,340.00	11,103,840.00	21,816,280.00
Combustion Controls	6800.00	2520.00	8200.00	3600.00	11,000.00	4400.00	6300.00	2520.00	8200.00	3600.00	11,000.00	4400.00
Instrumentation	2660.00	2800.00	7680.00	8260.00	15,660.00	18,000.00	2680.00	2800.00	7680.00	8260.00	15,660.00	18,000.00
Fans	—	—	—	—	—	—	—		—	—	—	—
Equipment Removal	—	8400.00	—	12,000.00	—	18,000.00	—	8400.00	—	12,000.00	—	18,000.00
Engineering	493,800.00	—	1,532,000.00	—	3,503,200.00	—	491,000.00	—	1,508,000.00	—	3,559,000.00	—
Erection Supervision	—	337,800.00	—	1,012,000.00	—	2,258,000.00	—	326,400.00	—	1,007,000.00	—	2,148,000
Start-up Service	—	42,500.00	—	65,000.00	—	67,500.00	—	42,500.00	—	54,000.00	—	67,500.00
	1,714,220.00	2,724,230.00	5,763,220.00	11,131,680.00	15,128,300.00	24,284,380.00	1,684,230.00	3,700,720.00	5,627,520.00	11,029,680.00	14,909,020.00	24,175,910.00

C-11

Boiler Category: Tangentially Fired & Turbo Fired

Ind. Fuel: Coal or Oil

Substitute Fuel	Low BTU Gas 101-(250)-500 E	I	501-(1000)-5000 E	I	5001-(7500)-10,000+ E	I	Med. BTU Gas 101-(250)-500 E	I	501-(1000)-5000 E	I	5000-(7500)-10,000 E	I	Natural Gas 101-(250)-500 E	I	501-(1000)-5000 E	I	5001-(7500)-10,000 E	I
Base CF Guns Hdrs, Shield Etc.	4200.00	400.00	21,000.00	1200.00	157,000.00	6600.00	2200.00	300.00	14,200.00	1300.00	106,500.00	7000.00	1600.00	300.00	10,640.00	1600.00	79,800.00	6200.00
Burner Plates or Windbox Modifications	1100.00	800.00	4000.00	1120.00	8,000.00	4000.00	800.00	720.00	2000.00	1500.00	9,000.00	4000.00	700.00	400.00	2000.00	1000.00	4000.00	2000.00
Pilots	650.00	320.00	2600.00	760.00	18000.00	5760.00	500.00	290.00	1800	1000.00	12,000.00	4500.00	500.00	240.00	1000.00	700.00	13,500.00	4500.00
Misc Mat	500.00	200.00	5000.00	490.00	15,000.00	5000.00	400.00	600.00	3000.00	1250.00	10,000.00	9000.00	[illegible]	150.00	3000.00	1350.00	10,000.00	4000.00
Σ 1-4	6250.00	1720.00	32,600.00	4360.00	198,500.00	23,260.00	3900.00	1550.00	21,000.00	4550	132,500.00	17,500.00	3400.00	1250.00	17,410.00	3950.00	106,800.00	16,500.00
Burner Management																		
-oil: New for Coal, Existing for oil (7500, 30,000, 244,000)	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00	7500.00	1200.00	30,000.00	12,000.00	244,000.00	100,000.00
Limits: HGP, SP, FD, PA, IA, FP, FD, 125 (850, 1000, 1000)	850.00	720.00	1200.00	720.00	1200.00	720.00	850.00	720.00	1200.00	720.00	1200.00	720.00	850.00	720.00	1200.00	720.00	1200.00	720.00
	8350.00	1920.00	31,200.00	12,720.00	245,200.00	100,720.00	8350.00	1920.00	31,200.00	12,720.00	245,200.00	100,720.00	8350.00	1920.00	31,200.00	12,720.00	245,200.00	100,720.00
Burner Fuel Piping																		
Pilot Gas Train	560.00	960.00	4560.00	4200.00	24,250.00	22,000.00	560.00	960.00	4560.00	4200.00	24,250.00	22,000.00	560.00	900.00	4560.00	4200.00	24,250.00	22,000.00
Main Gas Train	17,250.00	14,000.00	54,670.00	45,000.00	315,600.00	280,000.00	15,525.00	10,000.00	30,140.00	20,000.00	197,175.00	120,000.00	7880.00	5000.00	23,780.00	17,500.00	138,600.00	90,000.00
Supply Piping	5500.00	37,500.00	25,000.00	124,260.00	[illegible]	238,350.00	5500.00	37,850.00	23,000.00	124,260.00	61,500.00	120,000.00	5500.00	37,500.00	23,000.00	124,260.00	61,600.00	220,000.00
	23,310.00	52,310.00	62,130.00	173,460.00	404,600.00	540,350.00	21,585.00	48,810.00	57,700.00	148,460.00	253,025.00	262,000.00	13,590.00	43,310.00	51,840.00	145,960.00	219,450.00	332,000.00
Combustion Controls																		
Trim (for retrofit) Req'd: Existing (2200 & 800)	5350.00	2100.00	6065.00	2400.00	11,700.00	4800.00	5100.00	2240.00	5800.00	2320.00	10,450.00	4120.00	4950.00	1990.00	5500.00	2220.00	10,200.00	4080.00
Instrumentation																		
Flame Monitoring (1425, 775)	1425.00	880.00	6925.00	3200.00	12,125.00	6000.00	1425.00	880.00	6425.00	3200.00	12,126.00	6120.00	1425.00	880.00	6925.00	3200.00	12,125.00	6000.00
Fans																		
F.D.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I.D.	3500.00	230.00	7650.00	550.00	31,725.00	2500.00	3500.00	230.00	7650.00	350.00	31,725.00	2500.00	—	—	—	—	—	—
	3500.00	230.00	7652.00	550.00	31,725.00	2500.00	3500.00	220.00	7650.00	350.00	31,725.00	2500.00						
Equipment Removal	—	1000.00	—	8400.00	—	18,000.00	—	1000.00	—	8400.00	—	16,800.00	—	1020.00	—	6200.00	—	18,000.00
Furnace or Boiler Mod	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Engineering	11,800.00	—	40,153.00	—	170,000.00	—	10,900.00	—	36,300.00	—	127,700.00	—	9000.00	—	31,750.00	—	120,510	—
Erection Supervision	—	6500.00	—	22,000.00	—	72,000.00	—	5900.00	—	19,500.00	—	51,000.00	—	5300.00	—	18,000.00	—	50,130
Start-up Service	—	5000.00	—	15,000.00	—	30,000.00	—	5000.00	—	10,000.00	—	31,000.00	—	3,000.00	—	15,000.00	—	20,000.00
Σ 5, 9, 14, 16, 19, 22, 25, 27, 29, 31, 33	59,985.00	69,360.00	206,215.00	241,[illegible]	1,032,[illegible]	798,250.00	54,760.00	64,830.00	143,425.00	214,500.00	862,125.00	561,[illegible]	40,015.00	58,600.00	148,805.00	207,490.00	812,285.00	555,030
For oil fired	<12,865.00>	<3,[illegible]>	<39,[illegible]>	<[illegible]>	<[illegible]>	<112,305.00>	<12,955.00>	<3615.00>	<[illegible]>	<15,000.00>	<[illegible]>	<[illegible]>	<12,[illegible]>	<[illegible]>	<[illegible]>	<[illegible]>	<[illegible]>	<112,[illegible]>
	47,120.00	65,[illegible]	167,065.00	[illegible]	189,570.00	685,945.00	41,805.00	61,215.00	124,275.00	199,500.00	559,[illegible]	449,555.00	28,050.00	52,625.00	104,655.00	[illegible]	529,000.00	445,745

BOILER CATEGORY: WATERTUBE (F)

	ORIG. FUEL: COAL 51-(75)-100		SUB. FUEL: LIQ SRC 101-(150)-250		251-(350)-500		ORIG. FUEL: COAL 51-(75)-100		SUB. FUEL: SOLID SRC 101-(150)-250		251-(350)-500		ORIG FUEL: OIL 51-(75)-100		SUB FUEL: LIQ SRC 101-(150)-250		251-(350)-500	
	E	I	E	I	E	I	E	I	E	I	E	I	E	I	E	I	E	I
BURNER GUN (INCL SPARE) + SMV	(1) 1700.00	800.00	(3) 2050.00	480.00	(2) [illegible]	[illegible]							[illegible] as Coal to Liquid SRC					
ADAPTOR PLATES	400.00	160.00	750.00	400.00	1500.00	400.00												
ATOMS	300.00	80.00	500.00	400.00	1000.00	700.00												
STEEL SOCKETS, TIPS ETC	500.00	40.00	1000.00	120.00	800.00	240.00												
STEEL HOSES	150.00	40.00	300.00	120.00	600.00	240.00												
2 STEEL MAIN VALVES	150.00	45.00	[illegible]	120.00	[illegible]	240.00												
Σ1-6	3200.00	1160.00	5900.00	1640.00	11,400.00	2660.00							3200.00	1160.00	5700.00	1640.00	11400.00	2660.00
BURNER MANAGEMENT	3725.00	2960.00	8750.00	2640.00	12,150.00	6840.00							1625.00	2160.00	1250.00	2240.00	1250.00	2240.00
BURNER FUEL PIPING																		
BURNER VALVES & BURNER FRONT PIPING	4075.00	2000.00	11150.00	5000.00	21,300.00	10,000.00							4075.00	2000.00	11,150.00	5000.00	21,300.00	10,000.00
FUEL SYSTEM	222300.00	356550.00	[illegible]	516975.00	495270.00	1295,920.00							222800.00	353850.00	268400.00	511975.00	495270.00	1295920.00
	226,275.00	358880.00	279160.00	521,475.00	516,570.00	1,305,920.00							224575.00	355850.00	279780.00	521475.00	516570.00	1305920.00
COMBUSTION CONTROLS	2000.00	800.00	2900.00	1200.00	3200.00	1280.00							750.00	400.00	2550.00	1100.00	2900.00	1200.00
INSTRUMENTATION	825	880.00	1300.00	1600.00	3200.00	2150.00							725.00	800.00	1175.00	1450.00	3000.00	3750.00
ENGINEERING	64,000.00	—	90,000.00	—	202,000.00	—							64020.00	—	89000.00		200500.00	
ERECTION SUPERVISION	—	37670.00	—	45000.00	—	134,000.00							—	37540.00	—	54290.00	—	153500.00
START-UP	—	12,000.00	—	15000.00	—	20,000.00							—	12,000.00	—	12,000.00	—	22,000.00
	291,425.00	414,300.00	384,630.00	599255.00	750,120.00	1497650.00							291075.00	412,940.00	379,355.00	577195.00	730,420.00	1,465,270.00
For watertube, packaged boilers (oil fired) add extra engineering cost, obtain [redacted]													298015.00 [redacted]	412940.00	383655.00	597155.00		

BOILER CATEGORY: WATERTUBE (F)

ORIGINAL FUEL OIL

	Low BTU Gas 51-(75)-100 E	I	101-(150)-250 E	I	251-(375)-500 E	I	Med. BTU Gas 51-(75)-100 E	I	101-(150)-250 E	I	251-(380)-500 E	I	Nat. Gas 51-(75)-100 E	I	101-(150)-250 E	I	251-(350)-500 E	I
WINDBOX & BURNER																		
Base Suits w/Hdw, Scanner etc.	(1) 2000	160	(2) 2400	320	(3) 7500	480	1250	120	2200	240	8600	360	1600	120	1800	240	5000	360
[illegible]	500	400	800	720	1800	1200	500	400	600	800	1750	960	400	400	700	800	1500	760
Pilots, Ign. Tr. etc.	400	160	450	520	1400	480	300	160	500	240	1000	400	300	160	530	540	1000	400
Misc. Mat. & Cont.	250	100	500	200	1000	400	200	100	400	200	800	400	100	100	250	200	400	400
Σ1-4	3150	900	5150	1560	11,700	2560	2250	780	3700	1480	[illegible]	2120	1800	780	3250	1860	5900	2120
BURNER MANAGEMENT																		
Logic: Existing and fuel selector switch	100	160	100	160	100	160	100	160	100	160	100	160	100	160	100	160	100	160
Limits: 11GELLGP	200	320	200	320	200	320	200	320	200	320	200	320	200	320	200	320	200	320
	300	480	300	480	300	480	500	480	300	480	300	480	300	480	300	480	300	480
BURNER FUEL PIPING																		
Pilot Gas	110	480	560	960	1290	2240	110	480	560	960	1190	2240	110	480	560	960	840	2240
Main Gas	3150	1600	16450	4000	30,075	7200	2500	1120	14625	4200	22850	7200	1220	880	5190	3000	9580	6000
Supply Piping	2740	8757	3300	24750	5500	37350	1940	8550	3300	24750	5500	37350	1940	8550	3300	24750	5500	37350
Header Piping	—	—	500	2000	750	5000	—	—	400	1500	600	2500	—	—	400	1500	600	2500
	6000	10830	20,810	31,710	37,625	51,790	4550	10,150	18,885	30,735	30,140	44,290	3270	9910	9450	30,210	16,520	48,090
COMBUSTION CONTROLS	2700	1080	2850	1140	3350	1340	1900	760	2650	1060	3100	1240	1300	520	2350	940	2850	1140
INSTRUMENTATION	1100	880	1425	1040	3275	1300	1100	880	1425	1040	3275	1300	1100	880	1425	1040	3275	1360
FANS & DUCTWORK																		
FD	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
ID	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
EQUIPMENT REMOVAL	—	200	—	800	—	1400	—	200	—	800	—	1600	—	200	—	800	—	1600
FURNACE MOD.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
ENGINEERING	3600	—	8500	—	12,100	—	3200	—	8200	—	10,300	—	2500	—	6400	—	8800	—
ERECTION SUPERVISION	—	1540	—	3850	—	5925	—	1425	—	3150	—	5360	—	1250	—	3670	—	5730
START-UP SERVICE	—	1000	—	1750	—	2000	—	1000	—	1750	—	2500	—	1000	—	1750	—	2500
	16850	16910	39025	42330	64,[illegible]	65,050	13280	15,675	35,360	41,095	54265	58,950	9720	15150	23,175	40270	37445	57290
For Watertube (P), add extra engineering, obtain	17750	16910	41055	42330			14060	15675	37860	41095			10320	15150	24775	40270		

Boiler Category: Stoker

Original Fuel: Coal

Substitute Fuel	Low BTU Gas 10-(25)-50 E	I	51-(75)-100 E	I	101-(150)-250 E	I	Med BTU Gas 10-(25)-50 E	I	51-(75)-100 E	I	101-(150)-250 E	I	Nat Gas 10-(25)-50 E	I	51-(75)-100 E	I	101-(150)-250 E	I
Windbox Burner	1750	480	2500	600	(2) 4500	720	(1) 1500	480	(1) 2250	600	(2) 4250	720	(1) 1500	480	(1) 2250	600	(1) 4250	720
Register(s)	1050	640	2250	800	5500	1500	1250	500	5500	700	5000	1250	(1) 1250	960	2600	500	(2) 5000	1000
SS. Gas Ring (w/ Gun for Low BTU Gas)	1850	160	1800	160	3600	960	600	160	1500	480	3000	880	600	160	1600	480	2200	880
Fire-Lite Pilot (300,000 BTU)	400	80	400	80	667	120	100	80	100	80	300	120	100	80	100	80	300	120
Throat Tiles	600	480	750	750	1500	600	150	500	200	800	600	1400	150	600	200	1000	400	1800
Install WB	—	—	—	—	1750	—	—	—	—	—	1600	—	—	—	—	—	1600	—
Misc Matl & Const.	400	200	750	800	1000	500	250	100	250	[illegible]	550	800	—	—	—	—	250	100
	5250	2000	8450	3080	18500	4920	4150	1820	6800	2810	15050	4570	3600	1720	6250	2660	13860	4620
Burner Management																		
Logic - New	4500	800	4500	800	9000	1200	4500	800	4500	800	7500	1200	4500	800	4500	800	7500	1200
Lights HGP & LGP, FOR, ...	750	640	750	640	850	720	750	640	750	640	850	720	750	640	750	640	850	720
	5250	1440	5250	1440	9850	1920	5250	1440	5250	1440	8350	1920	5250	1440	5250	1440	8350	1920
Boiler Fuel Piping																		
Pilot Gas	110	480	110	480	560	960	110	480	110	480	560	960	110	480	110	480	560	960
Main Gas	2430	1200	3130	1600	16450	4000	1220	880	2500	1120	14625	4000	975	760	1220	780	5190	3000
Supply Piping	610	4100	2440	8750	5300	24750	610	4100	1940	8550	3300	24750	610	4100	1940	8650	3300	24750
Remove Piping	—	—	—	—	500	2500	—	—	—	—	400	1500	—	—	—	—	400	1500
	3150	5780	6400	10830	20812	31710	1940	5460	4550	10150	18885	31210	1695	5340	3270	9910	9450	30210
Combustion Controls	2700	1080	2700	1080	2850	1140	2700	1080	2700	1080	2850	1140	2700	1080	2700	1080	2850	1140
Instrumentation	1100	880	1100	880	1405	1040	1100	880	1100	880	1425	1040	1100	880	1100	880	1405	1040
Fans & Ductwork																		
FD	2000	400	3000	900	5000	1500	2000	400	3000	900	5000	1500	2000	400	3000	900	5000	1500
ID	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2000	400	3000	900	5000	1500	2000	400	3000	900	5000	1500	2000	400	3000	900	5000	1500
Equipment Removal																		
Grates	—	5000	—	10000	—	15400	—	5000	—	11000	—	15000	—	5000	—	10000	—	15000
Surface Boiler Mod	—	5000	—	10000	—	15000	—	5000	—	10000	—	15000	—	5000	—	10000	—	15000
Engineering	6400	—	9600	—	18500	—	6100	—	9100	—	17500	—	5100	—	9600	—	16000	—
Erection Supervision	—	3200	—	5200	—	7200	—	3100	—	5200	—	9200	—	5000	—	5200	—	7200
Start-up Service	—	10000	—	15000	—	20000	—	10000	—	15000	—	20000	—	10000	—	15000	—	20000
Σ 8,12,18,21,23,27,29,31,33,35,37	26250	34780	36600	56476	75436	101430	23240	34180	32500	56400	64066	100680	22245	33840	30370	57070	56575	99450

Boiler Category: Watertube

Original Fuel: Coal

Substitute Fuel / Capacity	LBG 51-(75)-100 E	LBG 51-(75)-100 I	LBG 101-(150)-250 E	LBG 101-(150)-250 I	LBG 251-(350)-500 E	LBG 251-(350)-500 I	MBG 51-(75)-100 E	MBG 51-(75)-100 I	MBG 101-(150)-250 E	MBG 101-(150)-250 I	MBG 251-(350)-500 E	MBG 251-(350)-500 I	Natural Gas 51-(75)-100 E	Natural Gas 51-(75)-100 I	Natural Gas 101-(150)-250 E	Natural Gas 101-(150)-250 I	Natural Gas 251-(350)-500 E	Natural Gas 251-(350)-500 I
Burners & Controls																		
Burner Gun Hose & Shield	(1) 2500	160	(2) 3200	320	(4) 7500	480	(1) 1550	120	(2) 2200	240	(4) 3600	360	(1) 1000	120	(2) 1800	240	(4) 3000	360
Diffuser Plate	600	480	900	720	2000	1200	500	900	800	800	1750	960	400	900	750	800	1500	960
Pilots (Hi-energy Ignition)	400	160	650	320	1400	480	500	160	500	240	1000	400	300	160	500	240	1500	400
Misc. Mat.	550	100	500	200	1000	400	200	100	400	200	[illegible]	400	100	100	200	200	600	400
Σ 1-4	3550	900	5250	1560	11,900	2560	2250	1280	3900	1480	7350	2120	1800	780	3250	1480	6100	2120
Burner Management: New																		
Logic System	4500	800	7500	1280	12500	2000	4500		7500		12500		4500		7500		12500	
Limits: LGP	100	80	200	160	200	160	100		200		200							
FDA	100	80	100	80	100	80	100		100		100							
Purge Air	100	80	100	80	100	80	100		100		100							
Inst. Air	100	80	150	80	100	80	100		100									
Furn. Press	25	80	125	80	125	80	125		125									
FD & ID Damper Posi 2275	150	160	150	160	150	160	150		150									
Misc.	75	50	75	60	75	20	75		75									
Σ 7-14	5550	1440	8350	1920	13350	2720	5050	1440	8350	1920	13350	2720	5250	1440	8350	1920	13350	2720
Burner Fuel Piping																		
Pilot Gas	110	480	560	960	1250	2240	110	480	560	960	1190	2240	110	480	560	560	840	2240
Main Gas	5150	1600	16460	4000	30,075	7200	2500	1120	14625	4000	22850	7200	670	560	5170	5000	9580	6000
Supply Piping	2745	2752	3800	24750	5500	37,350	1710	8550	3301	24375	5500	37,350	1940	8550	3300	24150	5500	37350
Bridge (Header Piping)	—	—	800	2000	750	3000	—	—	400	1500	600	2500	—	—	400	1500	600	2500
	6000	15,850	20810	81710	37,565	49,790	4550	10,150	18,665	30,735	30,140	44,290	2720	9910	9450	80210	16,520	48,490
Integrated Controls	2700	1080	2550	1140	3850	1340	1900	760	2650	1060	3400	1240	1300	520	2350	740	2850	1140
Instrumentation	1100	880	1425	1040	3275	1360	1100	880	1425	1040	3275	1360	1100	880	1425	1040	3275	1360
Fans:																		
F.D.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
I.D.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Equipment Removal	—	500	—	1000	—	2000	—	500	—	1000	—	2000	—	500	—	1000	—	2000
Furnace, Boiler Mod.	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Engineering	9770	—	10,400	—	13600	—	3800	—	9500	—	12400	—	3800	—	9200	—	10700	—
Erection Supervision	—	1500	—	3850	—	6000	—	1450	—	3700	—	6000	—	1400	—	5855	—	6000
Start-up Service	—	1000	—	1750	—	2500	—	1000	—	1750	—	2500	—	1000	—	1750	—	2500
Σ 5,15,22,24,29,30,33,35,37,39	22,870	18130	49095	45970	83540	68270	18850	16960	61,960	42,685	69,415	67,230	15570	16430	24025	42,175	52795	65750

APPENDIX D

METRIC SYSTEM CONVERSION FACTORS

Although EPA's policy is to use the metric system in all of its documentation, certain non-metric units are used in this report for convenience. Readers more familiar with the metric system may use the following to convert to that system:

Non-Metric Unit	Multiplied By	Yields Metric Unit
in	2.540	cm
ft	0.3048	m
ft^2	9.3×10^{-2}	m^2
ft^3	28.317	liter
gal.	3.785	liter
lb.	0.454	kg
ton	907.185	kg
centistoke	10^{-6}	m^2/sec
°F	5/9(°F-32)	°C
Btu	1.055×10^3	joule
Btu/ft^3	37.256	joule/liter

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-650/2-74-123	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Boiler Modification Cost Survey for Sulfur Oxides Control by Fuel Substitution		5. REPORT DATE November 1974 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R. J. Schreiber, A. W. Davis, J. M. Delacy, Y. H. Chang, and H. N. Lockwood		8. PERFORMING ORGANIZATION REPORT NO. 74-113
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aerotherm/Acurex Corporation 485 Clyde Avenue Mountain View, CA 94042		10. PROGRAM ELEMENT NO. 1AB013; ROAP 21ADE-010 11. CONTRACT/GRANT NO. 68-02-1318, Task 9
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development NERC-RTP, Control Systems Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; through 10/74 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT
The report gives results of a study to identify capital costs associated with converting industrial and utility boilers from conventional high-sulfur fossil fuels to low-sulfur products from selected coal conversion processes. The boilers of concern include all industrial and utility size equipment in the 10 to the 7th power to 10 to the 10th power Btu/hr capacity range. The substitute fuels include solvent refined coal (SRC) in the solid and hot liquid (melted) phases as well as lower-Btu gas. The cost assessment methods used in the study showed that conversion to liquid SRC is the most expensive alternative. Converting coal-fired boilers to solid SRC is the least expensive alternative for these types of boilers. Between the costs of converting to SRC in either phase lie those costs for converting to the gaseous fuels. A significant result of the study is that the costs of all conversion strategies increase exponentially with boiler capacity: cost appears to be a weak function of boiler design.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution	Coal	Air Pollution Control	13B
Boilers		Stationary Sources	13A
Engineering Costs		Boiler Modification	14A
Capitalized Costs		Fuel Substitution	
Sulfur Oxides		Coal Conversion	07B
Fossil Fuels		Low-Btu Gas	21D, 08G

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