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ECUT Energy Data Reference Series: Boilers

A. D. Chockie
D. R. Johnson

September 1984

Prepared for the U.S. Department of Energy
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ECUT ENERGY DATA REFERENCE SERIES: BOILERS

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Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
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ACKNOWLEDGMENTS

This series was a substantial undertaking that even now would not be accomplished were it not for the significant efforts of Dan Johnson. Dan saw the need for the series and had the vision to patiently persevere through all the obstacles in data gathering, report writing, and finally publication. In the later stages of this work, Judy Danko provided critical editorial assistance and encouragement. It was through her efforts that all the volumes of this series were completed and published simultaneously.

D. L. Brenchley
Project Manager

PREFACE

This study was completed for the Division of Energy Conversion and Utilization Technologies (ECUT) in the Department of Energy. The division's mission has three parts:

1. to monitor advances in basic scientific research and evaluate them for their applicability to energy conservation
2. to perform exploratory development on novel or innovative conservation concepts
3. to expand the technology base for advanced conservation technologies.

To aid in achieving this mission the ECUT staff established a planning and systems analysis function to identify and assess the array of opportunities for energy conservation R&D.

This on-going activity provides ECUT staff with the information necessary to decide where to invest limited research dollars to derive the maximum benefit to the public. As part of its systems analysis role for ECUT, PNL published a general energy use data book covering all major end-use sectors (Imhoff, Liberman, and Ashton 1982). In contrast, the current ECUT Energy Data Reference Series is more narrowly targeted; each volume contains detailed capital stock and energy-use data for selected end-use sectors that are likely to be most impacted by existing or proposed ECUT R&D activities.

This volume relates to the ECUT R&D activity on continuous combustion processes. The objectives of this research activity are to further the fundamental understanding of heat and mass transfer and fluid mechanics in continuous combustion systems, and to investigate the influence of fuel-dependent chemical and physical properties on the combustion process. This research would impact most heavily on the U.S. population of industrial and commercial boilers.

Other volumes in the ECUT Energy Data Reference Series include:

Hane, G. J. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Otto Cycle Engines in Transportation. PNL-5191, Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. B., G. J. Hane and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Lightweight Materials for Ground Transportation. PNL-5192, Pacific Northwest Laboratory, Richland, Washington.

Abarcar, R. B., G. J. Hane and D. R. Johnson. ECUT Energy Data Reference Series: High-Temperature Materials for Advanced Heat Engines. PNL-5193, Pacific Northwest Laboratory, Richland, Washington.

Young, J. K. and D. R. Johnson. 1984. ECUT Energy Data Reference Series: Ammonia Synthesis Energy-Use and Capital Stock Information. PNL-5194, Pacific Northwest Laboratory, Richland, Washington.

The bulk of the research for this series was conducted in calendar year 1982. While the data portrayed in these publications have not changed dramatically, certain trends, particularly those that were forecast, may have shifted in the interim between research and publication.

The ECUT Data Reference Series is part of a series of studies in support of the ECUT research planning effort. Other ECUT publications are:

Bomelburg, H. J. 1983. Efficiency Evaluation of Oxygen Enrichment in Energy Conversion Processes. PNL-4917, Pacific Northwest Laboratory, Richland, Washington.

Chockie, A., et al. 1983. "An Overview of Research Requirements for Stationary Combustion Systems." In Proceedings of the 18th Intersociety Energy Conversion Engineering Conference, pp. 2092-2098. American Institute of Chemical Engineers, 345 E. 47 St., New York, New York.

Hane, G. 1983. Efficiency Evaluation of the DISC, DHC, and DI Diesel Engines. PNL-4568, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1983. A Preliminary Overview of Innovative Industrial Materials Processes. PNL-4505, Pacific Northwest Laboratory, Richland, Washington.

Hane, G., et al. 1984. A Review of Studies of Research Opportunities in Energy Conservation. PNL-4571, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities--Executive Summary. PNL-3944 Ex. Sum., Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1981. An Overview of Energy Conservation Research Opportunities. PNL-3944, Pacific Northwest Laboratory, Richland, Washington.

Hopp, W., et al. 1982. Identification of Energy Conservation Research Opportunities: A Review and Synthesis of the Literature. PNL-3966, Pacific Northwest Laboratory, Richland, Washington.

U.S. Department of Energy. 1981. The 1981 ECUT Work Element Appraisal. DOE/CE-0024, U.S. Department of Energy, Washington, D.C.

U.S. Department of Energy. 1983. Energy Conversion and Utilization Technologies Program Report, 1981-1982. U.S. Department of Energy, Washington, D.C.

Vallario, R. W. and D. E. DeBellis. 1984. State of Technology of Direct Contact Heat Exchanging. PNL-5008, Pacific Northwest Laboratory, Richland, Washington.

Vitullo, M., C. Winter and D. R. Johnson. 1984. The Executive Information System. PNL-5190, Pacific Northwest Laboratory, Richland, Washington.

BACKGROUND ON ECUT ENERGY DATA REFERENCE SERIES

The ECUT Energy Data Reference Series defines and assesses in quantitative terms the potential markets for expected ECUT R&D results. Each volume in the series provides data on a particular class of hardware systems that use and convert fuel. The data for each system include inventories of energy capital stocks, specific fuels consumption and product or service activity levels for the years 1980 and 2000, and average thermal efficiencies. Each data set characterizes the capital stock in a sector or subsector of the U.S. economy to which expected results from ECUT R&D projects can be applied. Each reference volume is consistent with the others in the series in format and approach, thus forming a framework for comparing certain aspects of ECUT R&D activities.

The ECUT Energy Data Reference Series serves as a benchmark for energy consumption and for conservation data for technologies addressed by the ECUT Program. The series incorporates the most accurate and up-to-date projections available in the open literature on energy capital stocks and their consumption levels. The series is specifically intended to be one of the many planning tools ECUT management can use to assess what potential impact its research projects will have. The series can also be used to demonstrate the potential impact of research on various stakeholders and constituencies, including industrial interest groups, budget decision makers, and the general public.

METHODOLOGY

The ECUT Energy Data Reference Series synthesizes data from the open literature, including technical reports, results of techno-economic models, industry surveys, and trade journal publications. A specific format was developed around the data items of interest and the intended purpose of the series. Each volume deals with a unique R&D application. Two scenarios are described--a baseline for 1980 and a projection for 2000.

The first line of effort is to extract the most recent data that are already in usable form in the open literature. In the case of competing data from disparate sources, the most reliable data are selected on the basis of the completeness and extensiveness of the research. Where data sources appear to be equally reliable, an averaging method is employed to derive a single data point.

The second line of effort is to derive or extrapolate the needed data from the literature. For instance, if no energy consumption data are reported, production data can be multiplied by energy intensity data to derive consumption data.

Certain assumptions are used in projecting data points to the year 2000. The general rule is that the status quo is maintained throughout the projected future unless otherwise specified in the text. The energy capital stock is assumed to remain at its 1980 state of technology, and no competing technologies are considered to capture market share. This is in keeping with the objective of defining the potential impact of R&D results. In characterizing systems or processes with multiple fuel inputs, the mix of conventional fuels (those commonly used today) is allowed to change as each fuel is impacted by obvious and compelling factors, but no alternative, non-conventional fuels are projected as part of the fuel mix.

For simplicity, electricity is considered to be a fuel. This allows for a discussion of capital stocks that use electricity as an input without going through the machinations of breaking out power generation inputs, transmission losses, etc. These factors are considered to be constant at the national average, and are readily available in the literature.

SCOPE

The scope is defined along two directions: the data items of interest, and the end-use sector applications for ECUT R&D activities. The data items of interest, described below, are essential to a basic perspective on the potential impact of expected ECUT R&D results. Data items that change with time are defined for the year 198D and projected for the year 2000.

DATA ITEMS

The data items considered in this series of reports are unit process hardware systems, efficiency estimates, capital stock information, fuel consumption demand, and product or service activity level.

Unit Process Hardware System

A unit process hardware system (UPHS) is generally defined as the least extensive configuration of components in a conversion or utilization system to which R&D results can be applied, and for which efficiency and fuel consumption estimates can be made. A UPHS is uniquely defined for each sector potentially impacted by ECUT R&D activity.

Efficiency Estimates

A specific definition of efficiency is developed for each application of each R&D activity. In general, the definition is based on the first law of thermodynamics, and is applied to the UPHS of interest. A broad discussion of major efficiency-loss mechanisms is included in each section on efficiency.

Capital Stock Information

Data derived for 1980 and projected for 2000 are based on the number of UPHSs in the economy that would be potential recipients of ECUT R&D results. UPHSs are disaggregated according to the type of fuel they use or convert. Other factors that help characterize the capital stock as a market for ECUT research are included as necessary and/or available.

Fuel Consumption Demand

Fuel consumption demand is developed for 1980 and projected for 2000. The thermal energy value (measured in Btu) of each fuel type consumed or converted by the capital stock of interest is developed for each application of each R&D activity. Electricity is considered to be a fuel. The extent to which use of alternative (non-conventional) fuels will penetrate the end-use sectors of interest by the year 2000 is not predicted. The relative contribution of conventional fuels in use today is, however, allowed to change with the turnover of capital stocks and with trends in consumer preferences. No attempt is made to project the availability of conventional fuels in 2000.

Product or Service Activity Level

Data on the demand for each product or service resulting from the use or conversion of energy by the capital stock of UPHSs are developed for 1980 and projected for 2000.

SUMMARY

This report summarizes information on the population and fuel consumption of water-tube, fire-tube and cast iron boilers. The use of each boiler type in the industrial and commercial sector is examined. Specific information on each boiler type includes (for both 1980 and 2000) the average efficiency of the boiler, the capital stock, the amount of fuel consumed, and the activity level as measured by operational load factor. This information is summarized in Tables S.1 and S.2.

TABLE S.1. Research and Development Applications Summary - Boilers

Data Item	UPHS Average Efficiency % 1980	UPHS Average Efficiency % 2000	# Unit Process Hardware Systems 1980	# Unit Process Hardware Systems 2000	Fuel Consumption Demand (Btu) 1980	Fuel Consumption Demand (Btu) 2000	Product or Service Activity Level (% load factor) 1980	Product or Service Activity Level (% load factor) 2000
WATER-TUBE BOILERS	82.5	85.1	54,212	83,772	6.2×10^{15}	9.6×10^{15}	26.1	26.1
Commercial			13,742	21,235				
Industrial			40,470	62,537				
FIRE-TUBE BOILERS	81.8	83.2	284,249	402,124	2.6×10^{15}	3.6×10^{15}	26.1	26.1
Commercial			104,511	147,850				
Industrial			179,738	254,274				
CAST IRON BOILERS	75.0	80.0	1,503,226	1,762,859	1.7×10^{15}	1.9×10^{15}	26.1	26.1
Commercial			1,202,581	1,410,288				
Industrial			300,645	352,571				

TABLE S.2. Market Data Summary - Boilers

Data Item	Total # Unit Process Hardware Systems 1980	Total Projected # Unit Process Hardware Systems 2000	# UPHS Due to Industry Capacity Expansion (Increased Service Demand) 2000	# UPHS Due to Replacement of Obsolete Units 2000	# UPHS from 1980 Remaining in Service 2000
WATER-TUBE BOILERS	54,212	83,772	29,560	10,933	43,279
Commercial	13,742	21,235	7,493	2,771	10,971
Industrial	40,470	62,537	22,067	8,162	32,308
FIRE-TUBE BOILERS	284,249	402,124	117,875	43,597	240,652
Commercial	104,511	147,850	43,339	16,029	88,482
Industrial	179,738	254,274	74,536	27,568	152,170
CAST IRON BOILERS	1,503,226	1,762,859	259,633	259,633	1,213,593
Commercial	1,202,581	1,410,288	207,707	207,707	994,874
Industrial	300,645	352,571	51,926	51,926	248,719

CONTENTS

FIGURES

TABLES

1.0 INTRODUCTION

Boiler fuel use constitutes a significant portion of the total U.S. energy consumption. Industrial boilers alone account for over 17% of the nation's total energy consumption. To understand the role such boilers play in the changing demand for fuels, it is necessary to examine the range of boilers in operation, their efficiencies and their fuel requirements. The objective of this report is to provide information on the fuel use of industrial and commercial boilers (in 1980 and projected for the year 2000), and on the capital stock characteristics of the U.S. boiler population.

There are two basic classifications of boilers as distinguished by their heat transfer configuration. These are the water-tube and the fire-tube boiler. Water-tube units produce steam by circulating water through numerous tubes around which the hot combustion gases pass. In fire-tube boilers the combustion gases flow through tubes that are immersed in water. A diagram of each boiler configuration is shown in Figures 1.1 and 1.2. A third type, or

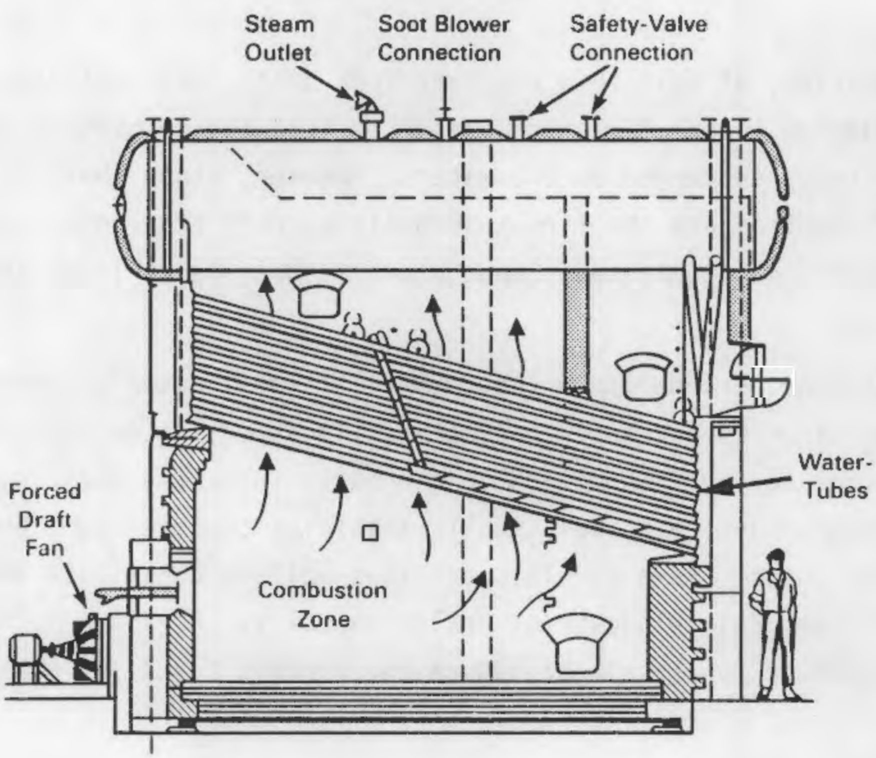

FIGURE 1.1. Longitudinal-Drum Water-Tube Boiler (Babcock and Wilcox 1978)

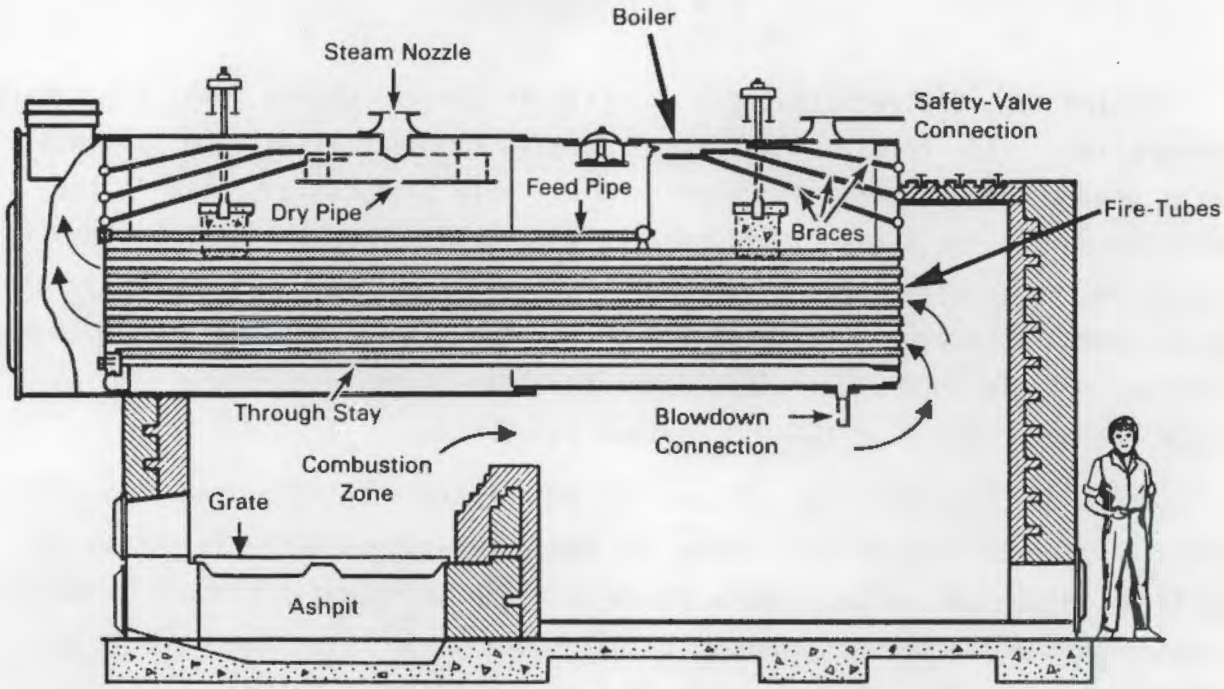

FIGURE 1.2. Horizontal-Return Fire-Tube Boiler (Babcock and Wilcox 1978)

subclassification, of boiler is the cast iron unit. The cast iron boiler is similar in design to the fire-tube boiler in that the combustion gases pass through the tubes submerged in the water. However, since they are not constructed of steel as are the fire-tube boilers, cast iron units are designed to meet different code requirements and generally operate at lower temperatures and pressures.

Cast iron boilers dominate the commercial and industrial boiler sector in total number of units currently installed. Together, water-tube and fire-tube boilers account for only about 18% of the total installed boilers. Cast iron boilers, though, have relatively small capacities compared to either fire-tube or water-tube units. As a result, cast iron boilers contribute only about 20% to the total commercial-industrial boiler capacity. As shown in Table 1.1, water-tube boilers supply almost 60% of the current installed capacity.

TABLE 1.1. 1980 Boiler Population Distribution

Boiler Classification	Installed Units (x 1000)	Total Capacity (10^9 Btu/hr)
Water-tube	54	2,740
Fire-tube	288	1,109
Cast iron	1,586	926
Total	1,928	4,775

There is a significant degree of overlap in relating the capacity of the boilers and their end-use designations. Generally, cast iron units are found in the residential and commercial sectors with some use in industrial plants. Fire-tube boilers are primarily used in commercial and industrial applications. Industrial and utility operations account for the majority of water-tube boiler applications. A plot of these general relationships between boiler size and end-use is presented in Figure 1.3. This report focuses on the commercial and industrial use of the three types of boilers.

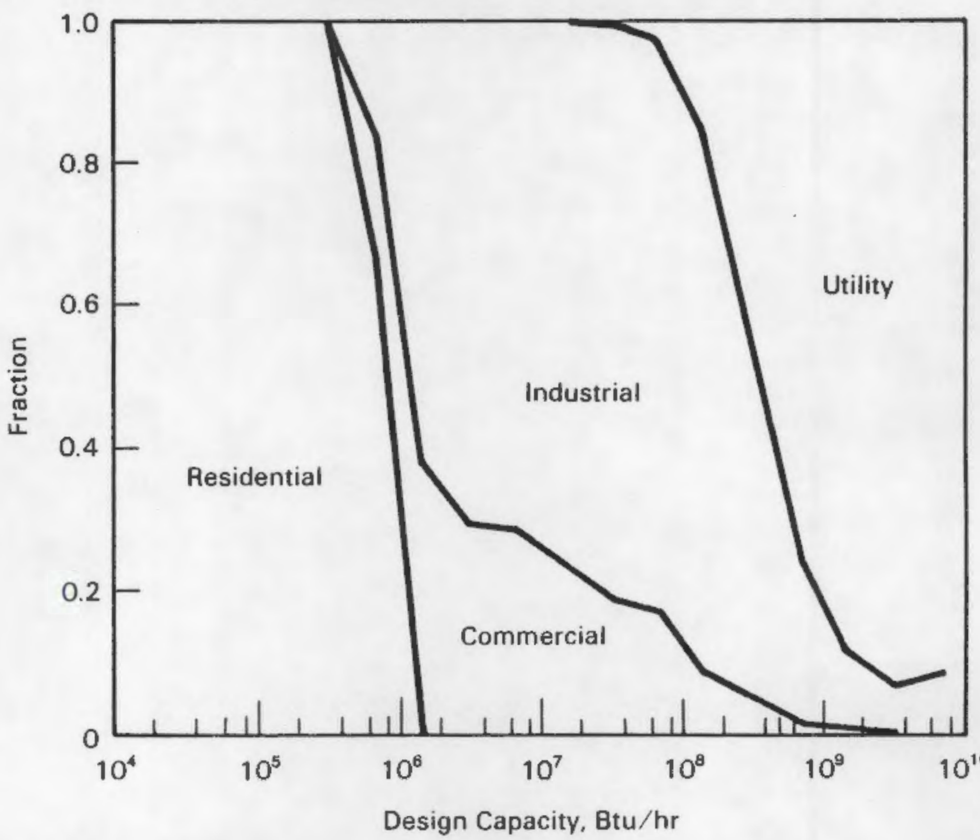

FIGURE 1.3. Relationship of Boiler Use to Design Capacity (KVB 1977)

A number of different fuels are currently used in boilers. The three most common are natural gas, coal and oil. These three make up almost 90% of the fuels currently being burned in boilers. The remaining 10% includes a number of different fuels or energy sources, such as asphalt, kerosene, pumping liquors, liquid petroleum gas, and electricity. Because natural gas, coal and oil are utilized to such a significant degree, past boiler population studies have generally concentrated on these three fuels. In the following sections of this report, the present and anticipated use of oil, natural gas and coal in water-tube, fire-tube and cast iron boilers is assessed.

This report consists of three major sections. The first section deals with water-tube boilers. Fire-tube and cast iron boilers are addressed in the second and third sections, respectively. In each section the system efficiency, capital stock, fuel consumption and service activity are examined for both 1980 and 2000.

2.0 WATER-TUBE BOILERS

Water-tube boilers were developed because the fire-tube design could not meet a demand for increased steam capacity and pressure. As attempts to produce increased steam capacity and pressure were made, the shell diameter of the fire-tubes eventually grew to a prohibitive size. Thermal and pressure stresses, in conjunction with hard water scale deposits, resulted in many fire-tube boiler explosions. To overcome these problems, the boiler design was revised so that water was circulated in the tubes and the hot flue gas passed around the outside of the tubes.

2.1 EFFICIENCY ESTIMATES

The efficiency of a boiler is defined as the degree to which the heat put into the system (generally the higher heating value of the fuel) is converted to useful heat output. In the case of boilers, this useful output is the process steam. Determining the system efficiency requires that a system boundary for heat balance purposes be specified. The heat inputs and losses crossing the boundary are involved in the efficiency calculation (see Figure 2.1). Generally, components that require an outside source of heat or energy or that do not return the heat exchanged to the steam generating unit are not included within the system boundary. The items considered in determining the heat balance of major steam generating units include not only the furnace, burners and boiler circulating pump and drum, but also equipment such as superheaters and reheaters, air heaters, economizers and recirculating gas fans (KVB 1977).

The energy input and loss mechanisms for efficiency calculations are categorized in Figure 2.1. The energy input includes the chemical heat in the fuel and heat credits added to the working fluids, air, gas, fuel and other circuits that cross the envelope boundary. Maximum efficiency results when the combustion of the fuel is complete and the energy losses listed in Figure 2.1 are minimized. The usual approach to improving efficiency is to identify the losses, their relative magnitude, and then concentrate initially on those loss mechanisms that have the greatest impact on degrading efficiency.

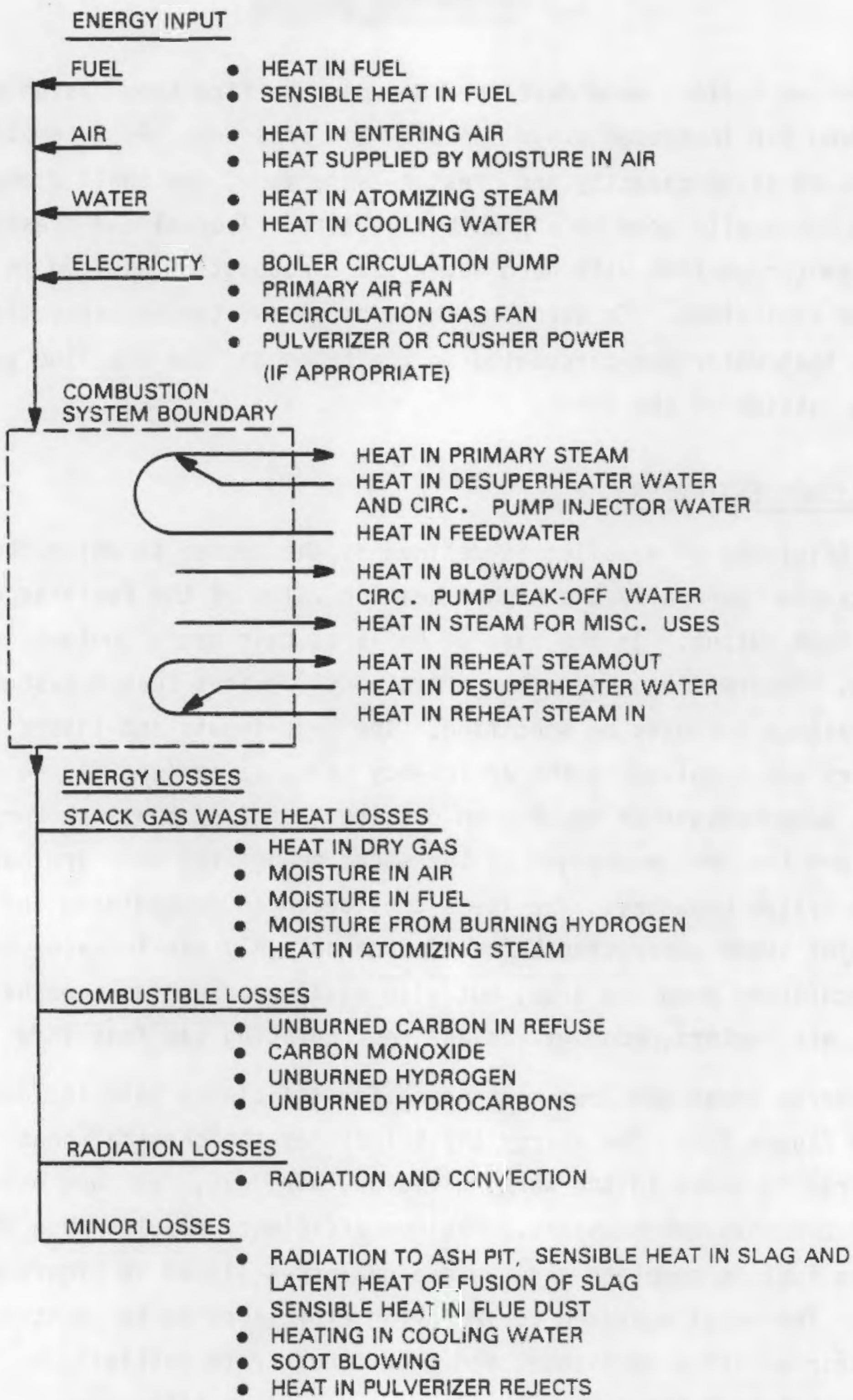

FIGURE 2.1. Heat Balance Factors of Boiler Operation

As can be seen in Figure 2.1, three major energy loss mechanisms are associated with stationary combustion systems: stack gas waste heat losses, combustible losses and radiation losses. Other loss mechanisms, generally classified as minor, include the latent and sensible heat in the slag, the heat in the pulverizer rejects and cooling water, and the sensible heat in the flue dust. These minor losses combined account for only about a 1% to 2% reduction in combustion efficiency. Stack gas losses alone can reduce combustion efficiency by as much as 17% (Table 2.1).

TABLE 2.1. Magnitude of Major Combustion System Efficiency Losses[(a)]

Loss Mechanism	Efficiency Reduction, %	
Stack Gas Losses		9 - 17
• Dry Flue Gas Losses	3 - 8	
• Moisture Losses	4.5 - 11	
Combustible Losses		~0 - 3.6
Radiation Losses		~0 - 13

(a) For major industrial boiler units.

The efficient operation of a boiler is a function of a number of interrelated factors. To mitigate the combustion energy losses these factors must be taken into account. The following is a summary of the major factors (KVB 1978):

- The stack gases constitute the primary source of efficiency loss for base load operations.
- The fuel characteristics control the magnitude of the flue moisture loss (the major component of stack gas losses).
- The magnitude of the dry gas losses (a second major component of stack gas losses) is a function of both the stack gas temperature and excess air levels in the boiler. The stack gas temperature depends on the unit design and fuel characterization.

- Operating efficiency can be improved by reducing excess air levels, which reduce both the quantity and temperature of the stack gases.
- The degree to which excess air (oxygen) can be reduced depends on the amount of combustible materials formed in the stack gases or the extent of unacceptable operating conditions (e.g., slagging or flame impingement).
- With reduced load the radiation losses become a more predominant factor because their absolute magnitude is invariant (Figure 2.2).

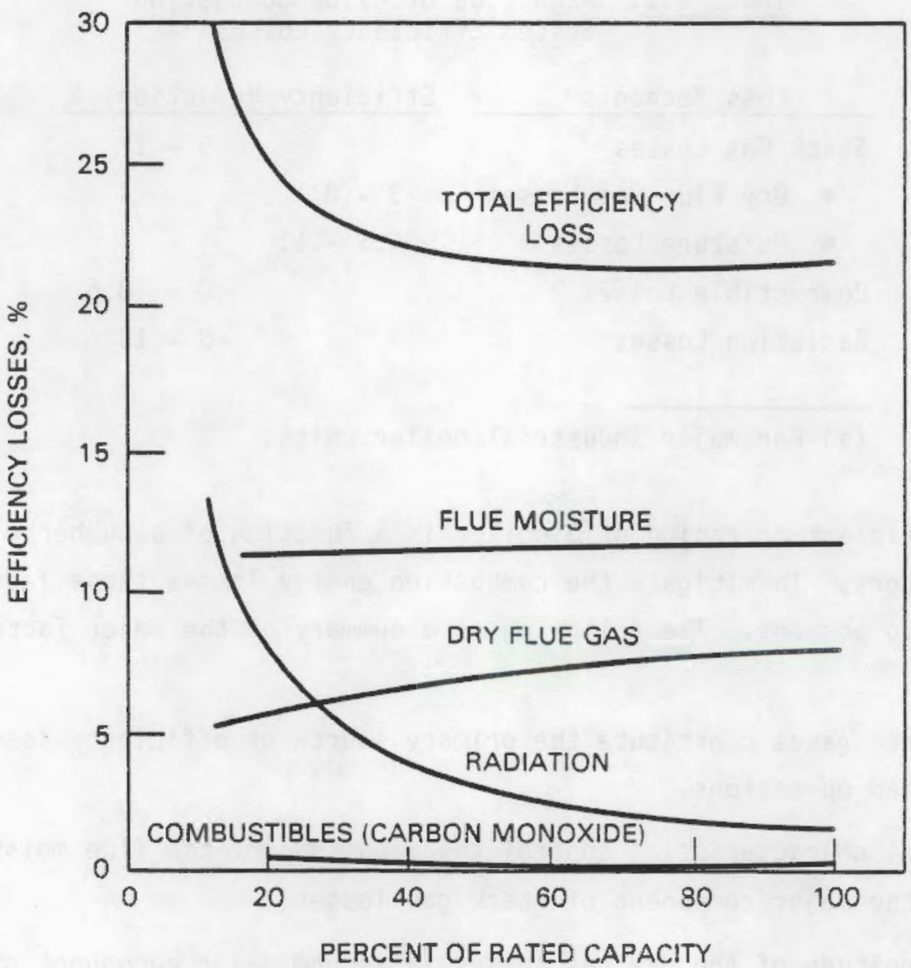

FIGURE 2.2. Effect of Changes in Firing Rates on Boiler Efficiency Loss (KVB 1977)

2.1.1 Stack Gas Losses

Stack gas losses consist primarily of dry flue gas loss and moisture loss. Dry flue gas loss is the sensible heat carried up the stack by the flue gas. Moisture loss is the latent and sensible heat of the water vapor resulting from the combustion of hydrogen in the fuel, the humidity of the combustion air, and the water content of the fuel.

The magnitude of the stack gas losses depends on the gas composition, (which is a function of the quantity of excess air), the fuel, and the stack temperature. Most boilers have large dry flue gas losses because they operate at high excess air levels and high stack gas or exit temperatures. In many cases, boilers are operated at very high excess air levels to ensure complete combustion and safe operation. The degree to which fuel impacts stack gas losses can be noted in Table 2.2. The third factor influencing stack gas losses is the stack temperature, or exit gas temperature. The amount of boiler convective surface or stack gas heat recovery equipment determines the temperature at which the gas exits the stack. The minimum exit temperature in units without heat recovery equipment is fixed by the boiler operating pressure. As the operating pressure increases, though, it becomes more economically desirable to add heat recovery equipment.

2.1.2 Combustible Losses

Incomplete combustion in poorly maintained or operated boilers results in losses because combustion material is carried up with the flue gas and unburned fuel is trapped in the refuse ash. Material being lost in the flue gas

TABLE 2.2. Fuel Impact on Stack Gas Losses (KVB 1978)

Fuel	Firing Type	Fuel H (%WT)	Fuel H_2O (%WT	Fuel S (%WT)	Min. Stack Temp (°F)	Min. Excess O_2 Level (%)	Min. Dry Gas Losses	Min. Moist Losses	Min. Stack Gas Losses
Natural Gas		23.3	--	--	220	1	2.9	10.1	13.0%
#2 Oil		11.9	--	0.5	330	2	5.1	6.4	11.5%
#6 Oil		10.8	--	1.5	390	3	6.6	6.2	12.8%
Bituminous Coal	Pulverized	5.0	4.5	2.8	290	4	4.8	4.5	9.3%
	Stoker	5.0	4.5	2.8	290	6	5.5	4.5	10.0%
Subbituminous Coal	Pulverized	4.1	21.5	0.8	230	4	2.6	6.8	9.5%
	Stoker	4.1	21.5	0.8	230	6	3.0	6.8	9.8%

includes carbon monoxide, hydrogen, carbon carryover, hydrocarbons, and unburned fuel. High excess air levels tend to minimize these losses. However, if the boiler is poorly maintained, is an old poorly designed unit, or is burning an uncommon fuel of inconsistent quality, high excess air levels will not significantly reduce the problem. A certain degree of combustible loss is inherent in the designed operation of many units. The losses range from zero for pulverized coal cyclone combustion units to 3.6% for dumping grate spreader stock units.

2.1.3 Radiation Losses

Heat losses through the insulation on the boiler jacket are termed radiation losses. This includes the heat radiated to the boiler room and the heat picked up by the ambient air in contact with the boiler surface. Radiation losses typically reduce boiler efficiency by at least 3%. The absolute magnitude of the loss is fairly constant at different boiler firing rates and therefore becomes an increasingly higher percentage of the total heat loss at lower firing rates; Figure 2.2 shows the variation with differing firing rates.

2.1.4 Water-Tube Efficiency Estimates

KVB, Inc., and other organizations (KVB 1977) conducted an extensive measurement study of the efficiencies of 140 industrial boilers. Their objective was to determine the actual operating efficiencies of different boiler categories. In addition, to establish whether the actual boiler efficiency data measured in the field test programs were representative, typical operating efficiencies were calculated for over 9,400 industrial boilers included in the National Energy Data Systems (NEDS) data base. The calculations were made using excess air level measurements from the field tests and stack gas temperatures in the NEDS data.

The measured and calculated efficiencies are compared in Table 2.3. As can be seen, there is good agreement in the categories with a large number of field test data entries. For those categories having limited test data, it was felt that the calculated data would be more representative. Since the calculated efficiency figures are based on a much larger data base, these values have been employed as the current water-tube boiler operating efficiency levels

TABLE 2.3. Water-Tube Boiler Operating Efficiencies (KVB 1977)

Fuel	10-16		16-100		100-250		250-500	
	Measured	Calculated	Measured	Calculated	Measured	Calculated	Measured	Calculated
Natural Gas	78.0[a]	79.9	79.5	79.9	81.2	80.9	82.8[a]	81.8
Oil	81.5[a]	83.7	82.8	83.7	83.4[a]	84.6	82.7[a]	85.3
Coal-Stoker	--	81.0	76.6	81.2	82.2	81.8	--	82.5
Coal-Pulverized	--	83.2	--	83.3	86.6[a]	86.1	85.3[a]	86.3

(a) Small boiler population tested.

for base load conditions (80% of rated capacity). Examples of the range of typical measured operating efficiencies for water-tube boilers are presented in Figures 2.3, 2.4 and 2.5. For all gas-fired water-tube units the average calculated efficiency is approximately 80.5%. For oil- and coal-fired boilers the average figure is 84.3% and 82.6%, respectively.

KVB also investigated the maximum attainable efficiency for each boiler category. This was based on the use of adequate auxiliary equipment to achieve the minimum practical operating excess air levels and stack gas temperatures--all without consideration of costs.

The results of this study effort are shown in Table 2.4. The smaller units have a lower maximum attainable efficiency level primarily due to a larger percentage radiation loss. (Improvements to boiler insulation were not taken into account in this study). The ranking of efficiency levels tracks the

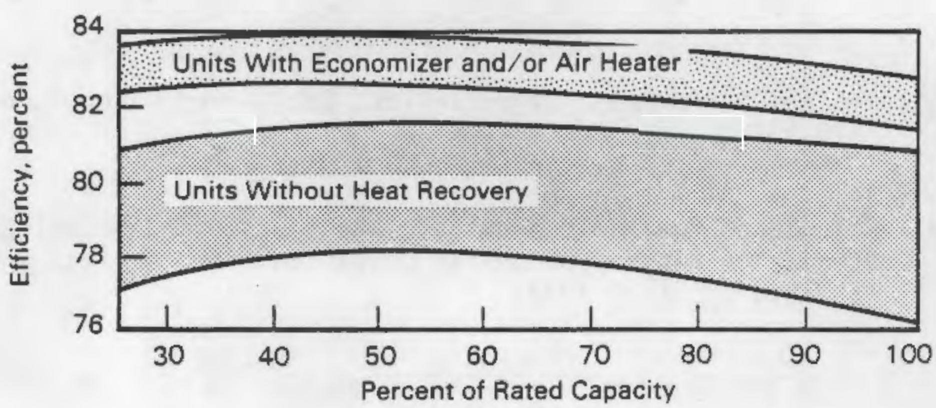

FIGURE 2.3. Typical Performance of Gas-Fired Water-Tube Boiler (KVB 1977)

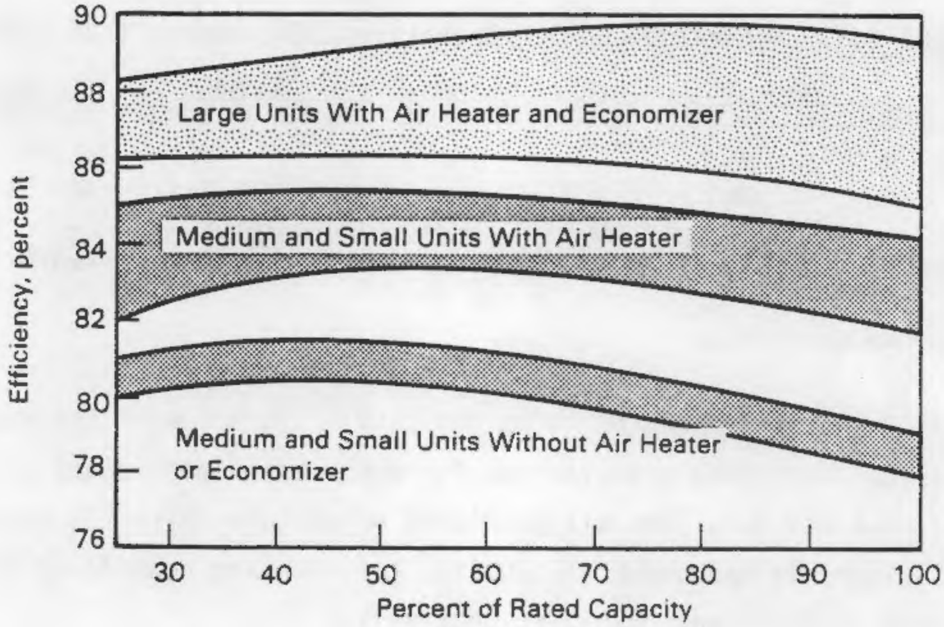

FIGURE 2.4. Typical Performance of Oil-Fired Water-Tube Boiler (KVB 1977)

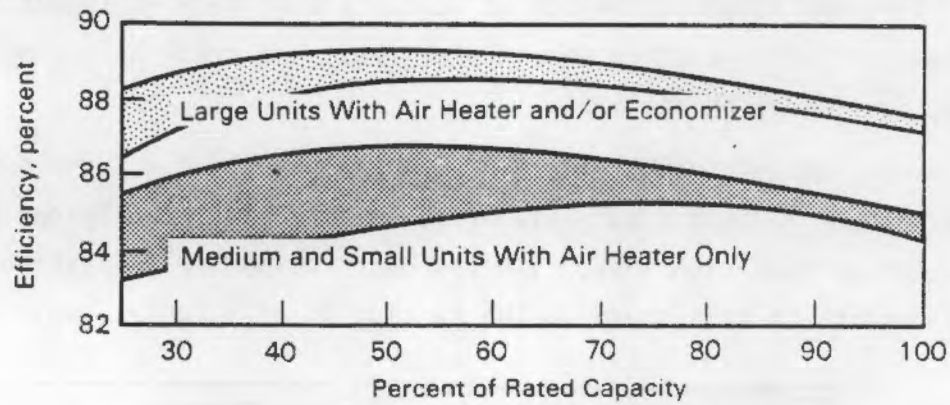

FIGURE 2.5. Typical Performance of Pulverized Coal-Fired Water-Tube Boiler (KVB 1977)

TABLE 2.4. Calculated Maximum Economically Achievable and Technically Attainable Water-Tube Boiler Operating Efficiencies (10^6 Btu/hr) (KVB 1977)

	10-16		16-100		100-250		250-500	
Fuel	Max Econ	Max Attain	Max Econ	Max Attain	Max Econ	Max Attain	Max Econ	Max Attain
Natural Gas	80.1	85.6	81.7	86.2	84.0	86.5	85.2	86.6
Oil	84.1	88.8	86.7	89.4	88.3	89.7	88.7	89.8
Coal-Stoker	81.0	86.4	83.9	87.0	85.5	87.3	85.8	87.4
Coal-Pulverized	83.3	89.5	86.8	90.1	88.8	90.4	89.1	90.5

hydrogen content levels of the fuel and the resulting stack gas moisture losses. The higher combustible losses of stoker coal units resulted in a considerably smaller efficiency figure than for pulverized units.

The maximum economically achievable efficiency levels determined by KVB are also included in Table 2.4. The figures take into account the realistic cost considerations of payback or return on investment in selecting efficiency improvement equipment. These estimates were based on cost data supplied by the manufacturers of the appropriate auxiliary equipment. The figures in Table 2.4 represent the cost-effective application of stack gas heat recovery equipment. Variations in fuel cost, company economic situation and other factors can have a significant impact on the actual level of economically achievable efficiency for specific boilers. For the purpose of this report, it is assumed that, on the average, the following operating efficiency levels will be achieved by the year 2000: 82.8% for gas-fired, 87.0% for oil-fired, and 85.5% for coal-fired units.

2.2 CAPITAL STOCK INFORMATION

2.2.1 Capital Stock Information - 1980

Water-tube boilers constitute a major portion of the total capacity of boilers currently in place in the U.S. Almost 60% of the total capacity is due to water-tube boilers alone (PEDCo 1979). Water-tube boilers in the 25 x 10^6 to 250 x 10^6 Btu/hr range account for some 36% of total boiler capacity. As is shown in Figure 2.6 and Table 2.5, almost 85% of the water-tube boiler capacity is installed in industrial operations. The remaining 15% capacity, situated in the commercial sector, corresponds to 25% of the installed water-tube units. Figure 2.6 shows the relationship of water-tube boiler capacity in the commercial and industrial sectors for various design capacity ranges (from 0.4 to 1500 x 10^6 Btu/hr units).

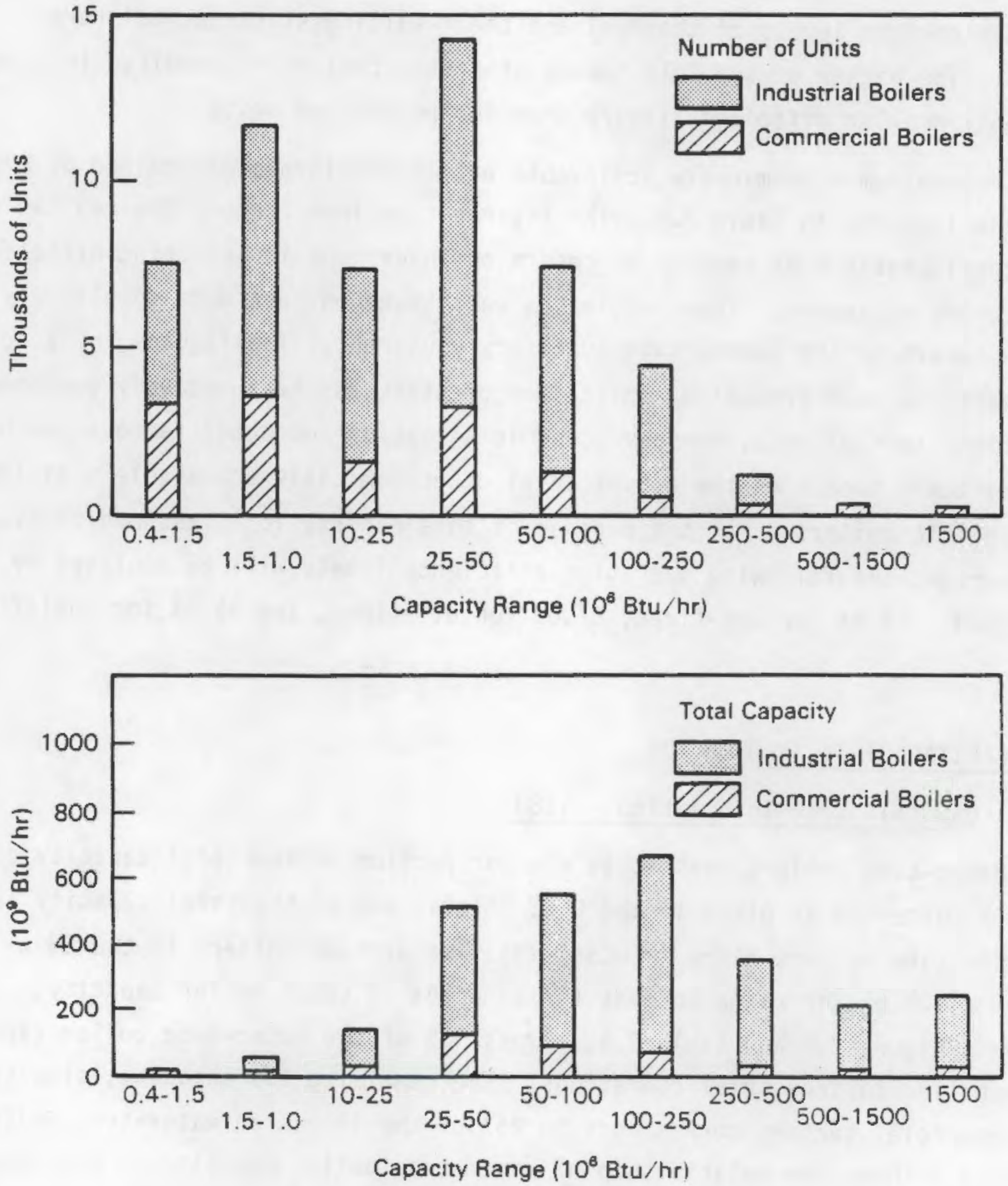

FIGURE 2.6. Water-Tube Boiler Population Distribution: Number of Units and Capacity - 1980

As can be noted, most of the water-tube boilers are industrial rather than commercial boilers. In fact, water-tube boilers make up only about 27% of the boilers installed in the commercial sector, the balance coming from fire-tube and cast iron units.

TABLE 2.5. Distribution of Commercial and Industrial Water-Tube Boilers - 1980[a]

Capacity Range (10^6 Btu/hr)	Commercial Number	Commercial Total Capacity (10^9 Btu/hr)	Industrial Number	Industrial Total Capacity (10^9 Btu/hr)	Total Number	Total Capacity (10^9 Btu/hr)
0.4-1.5	3,474	4.0	4,122	4.9	7,596	8.9
1.5-10	3,552	16.4	8,188	37.3	11,740	53.7
10-25	1,689	27.7	5,626	93.1	7,315	120.8
25-50	3,141	115.2	11,060	407.4	14,201	522.6
50-100	1,288	95.1	6,056	445	7,344	540.1
100-250	465	72.8	4,116	605.8	4,581	678.6
250-500	112	37.0	981	322.8	1,093	359.8
500-1500	17	13.2	255	192.2	272	205.5
1500	4	18.5	66	230.7	70	249.2
	13,742	399.9	40,470	2,339.2	54,212	2,739.2

(a) Based on 1977 survey (PEDCo 1979) and estimated average 2.4% annual growth rate 1975-1980.

2.2.2 Capital Stock Information - 2000

Between 1966 and 1975 the number of water-tube boilers grew at an annual rate of 3.2%. From 1975 to 1980 this rate slowed to 2.4%. Based on the current state of the economy it is unlikely that boiler additions will reach even this late-1970s level during the 1980s. It is therefore assumed that the water-tube boiler population will increase by about an average of 2% per year during the 1980s and by 2.4% for the following 10 years.

During the 1970s several studies developed predictions of future growth in the number and total capacity of boilers. The Institute of Gas Technology (IGT) completed an examination of the five most energy-intensive industries in the U.S. in 1974. From their work it was concluded that industry would have a composite annual energy growth rate of 3.3% for the period from 1975 to 1985 (Fejer and Larson 1974). In 1979 PEDCo Environmental, Inc. reviewed the IGT work and stated that this growth rate in energy use could be expected to continue from 1985 to the year 2000. PEDCo assumed that the capacity of industrial and commercial boilers would grow at the same rate as the demand for energy. This 3.3% per year increase in capacity was based on the assumption that the relationship between boiler capacities and total energy consumed remains constant and that the growth rate for commercial boilers parallels that of industrial boilers (PEDCo 1979). But, based on an analysis of the Bureau of Census data for the late 1970s, it appears more reasonable to assume a 2% growth rate for the 1980s and 2.4% growth for the 1990s. Therefore, these lower figures have been used to develop the water-tube boiler estimates for the year 2000. This growth rate incorporates the boiler manufacturers' assumption that 27% of the new capacity additions for water-tube boilers replace existing older units.

The predictions presented in Figure 2.7 and Table 2.6 are rough indications of the possible future of boiler capacity. A more accurate and reliable prediction would require a much more detailed assessment of such influencing factors as the state of the national economy, the technological advances in energy conversion and in energy resources available for boiler use, the changing fuel use patterns, and energy and environmental regulatory requirements.

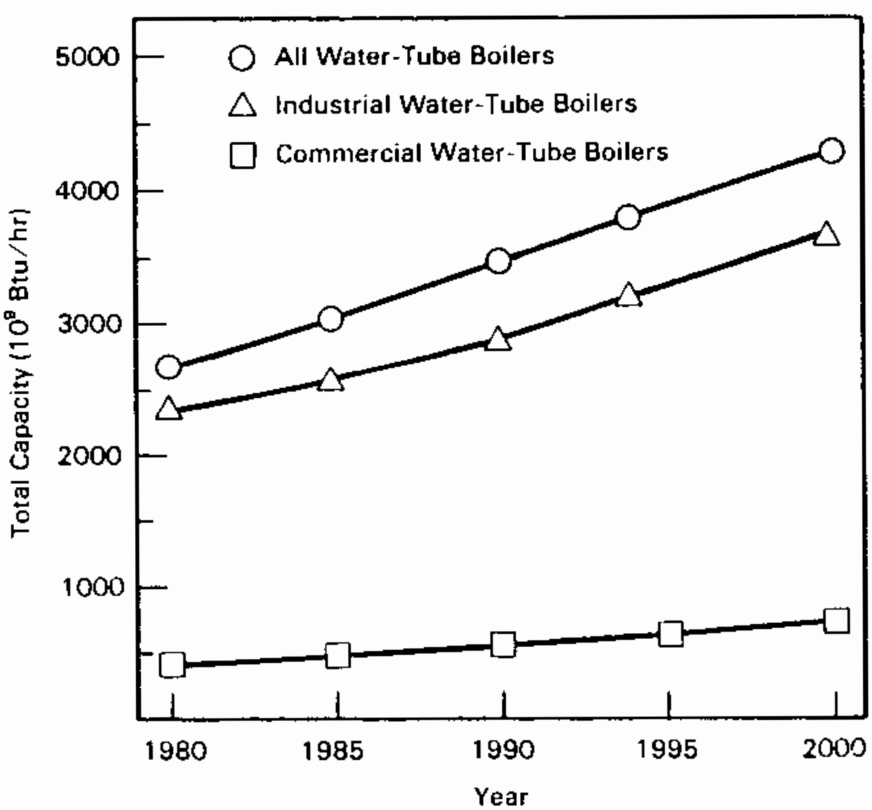

FIGURE 2.7. Projected Increase in Water-Tube Boiler Capacity

TABLE 2.6. Projected Increase in Water-Tube Boiler Capacity: 1980 to 2000 (10^9 Btu/hr)[a]

Year	Commercial	Industrial	Total
1980	399.9	2339.2	2739.1
1985	441.5	2582.7	3024.2
1990	487.5	2851.5	3339.0
1995	548.9	3210.5	3759.4
2000	618.0	3614.7	4232.7

(a) Assumes an annual growth rate of 2% for 1980-1990 and 2.4% for 1990-2000.

Such an analysis is outside the scope of this study. Because of the uncertainties associated with these and other influencing factors, boiler manufacturers are generally unwilling or unable to predict growth trends, particularly long-term growth trends, in the boiler population.

Based on the assumed growth rate, the water-tube boiler population would be expected to increase by about 29,000 units by the year 2000. If the rate of new orders in the commercial sector parallels that of the industrial sector, then by the year 2000 there will be some 7,000 new commercial and 22,000 new industrial water-tube boilers.

2.3 FUEL CONSUMPTION DEMAND

The difficulty in identifying boiler fuel consumption is evident in the extensive discussions in various fuel use studies on the limitations of the data. The major difficulty is in attempting to disaggregate the national fuel use figures. Several research organizations have tried to identify the amount of fuel used by the different end-use sectors--residential, commercial, industrial and utility--but the data are not sufficient for the calculation of fuel consumption by boiler size. Further work is needed both to refine the national fuel-use data base and to assess the consumption by boiler size, type, specific use sector and, possibly, geographical area.

2.3.1 Fuel Consumption Demand - 1980

An estimated 11 quads (11×10^{15} Btu) of fuel was consumed in 1980 in all industrial and commercial boilers (PEDCo 1979). A breakdown of the fuel type by boiler category is shown in Table 2.7. As can be noted, natural gas constitutes 92% of all the fuel used. These figures generally agree with those found in other recent studies. The Gas Research Institute has a natural gas usage for "other industries" of 6.78×10^{15} Btu in 1980 (GRI 1982), coal consumption was estimated to be 1.4×10^{15} Btu, residual oil consumption was 1.5×10^{15} Btu, and distillate oil consumption was 1.62×10^{15} Btu. GRI estimated total "other" industrial fuel use to be 11.3×10^{15} Btu.

TABLE 2.7. Estimated 1980 Fuel Use for All Industrial and Commercial Boilers (10^{12} Btu)[a]

	Industrial	Commercial	Total
Coal	1048.5	134.4	1182.9
Residual Oil	844.7	1047.5	1892.2
Distillate Oil	286.7	926.2	1212.9
Natural Gas	4358.1	2493.7	6851.8

(a) Based on 1977 estimates (PEDCo 1979) and a 2.4% average annual growth rate.

The amount of fuel used in water-tube boilers is estimated to account for approximately 60% of the total (6.2×10^{15} Btu). This is based on the population characteristics, load factor and fuel distribution use of water-tube boilers.

2.3.2 Fuel Consumption Demand - 2000

With an annual increase of 2% in water-tube boiler capacity in the 1980s and 2.4% in the 1990s, it is estimated that by the year 2000 these boilers could be consuming 9.6×10^{15} Btu of fuel. This is assuming that there is no improvement in the operating efficiency. If the maximum attainable efficiency improvements are achieved (an average 5.3% improvement), then water-tube boilers could require approximately 9.1×10^{15} Btu of fuel by the year 2000.

2.4 SERVICE ACTIVITY LEVEL

The load factor, or percent of time that a boiler actually operates, is an important factor in the quantity of fuel consumed annually. Several previous studies have attempted to calculate the load factors for various boiler types based on boiler capacity and fuel consumption. Because of differing assumptions and the limitations of the data, the load factor estimates tended to be quite different.

A breakdown of load factors by type of fuel burned in industrial and commercial boilers prepared by PEDCo produced a weighted average of 26.1% (PEDCo 1979). The results of this effort are shown in Table 2.8.

TABLE 2.8. Estimated Load Factors for All Industrial and Commercial Boilers (in percent) (PEDCo 1979)

	Industrial	Commercial
Coal	18.0	7.2
Residual Oil	10.6	29.2
Distillate Oil	13.5	46.9
Natural Gas	31.3	45.9

A previous boiler study in 1971 calculated an average load factor of 35% (Ehrenfeld 1971). In 1974, Battelle-Columbus (Putman 1974) used the EPA National Emissions Data System to estimate much higher average load factors than PEOCo. Some of the limitations in the Battelle study data included capacity and consumption figures for some boilers that produced a load factor of greater than 1.0. Also, certain areas of the country were not included in the data base.

PEDCo stated that their figures may be low because they have assumed a capacity replacement rate from new sales of 27% for water-tube and fire-tube boilers and 50% for cast iron boilers. In addition, fuel switching was not taken into account. Therefore, the installation of a new boiler burning a different fuel was calculated as a reduction against the new boiler fuel category rather than against the fuel category that was really affected.

An explanation given for the low load factors is the possibility of a substantial number of boilers on stand-by. But additional work is necessary to obtain a better understanding of the stand-by levels and the replacement and retirement rates in order to produce better estimates of capacity and load factors.

Based on available information the load factor for 1980 is estimated to be 26.1% for all categories of boilers--water-tube, fire-tube and cast iron. This load factor is expected to hold for boilers in the year 2000 also.

3.0 FIRE-TUBE BOILERS

3.1 EFFICIENCY ESTIMATES

As previously noted, all boiler types have three major heat loss mechanisms: stack gas losses, combustible losses and radiation losses. Other, less significant, losses include sensible and latent heat in the slag and the sensible heat in the flue dust. The magnitude of the efficiency losses is a function of unit design, fuel properties, and operating and maintenance practices.

A survey of fire-tube boilers by KVB identified an average measured efficiency of about 80% for natural-gas-fired units and 86% for oil-fired boilers (KVB 1977). There was generally good agreement between these measured values and calculated values (see Table 3.1).

A tune-up operation designed to minimize excess air has the potential to improve boiler efficiency by 0.2% to 0.5%.

The addition of auxiliary equipment (such as stack gas heat recovery units on boiler systems) with sufficient potential to justify the additional costs was also examined. Maximum economically achievable efficiencies were calculated to be a 3% improvement over the calculated "as-found" base.

The maximum attainable efficiencies were calculated assuming all required auxiliary equipment was installed to achieve minimum operating excess air levels and stack gas temperatures. A maximum possible efficiency improvement of almost 7% above the "as-found" state was identified.

For purposes of this report, the average fire-tube efficiency in 1980 is assumed to match the calculated values more closely than the measured values in Table 3.1. This assumption is made because the calculated values represent a much larger data base. Thus, the resulting 1980 efficiency estimates for fire-tube boilers are 79.9% for gas-fired and 83.7% for oil-fired. The efficiency estimates for the year 2000 are assumed to match the maximum economically attainable levels of 80.9% for gas-fired and 85.4% for oil-fired.

TABLE 3.1. Fire-Tube Boiler Efficiency Improvement (in percent) (KVB 1977)

Efficiency Category	Boiler Category (10^6 Btu/hr) 10 - 16 Gas	10 - 16 Oil	16 - 100 Gas	16 - 100 Oil
Measured	81.0[a]	86.3[a]	79.5	85.8[a]
Calculated	79.9	83.7	79.9	83.7
Tuned-up	80.1	84.1	80.2	84.2
Maximum Economically Attainable	80.1	84.1	81.7	86.7
Maximum Attainable	85.6	88.8	86.2	89.4

(a) Indicates small boiler population tested.

3.2 CAPITAL STOCK INFORMATION

3.2.1 Capital Stock Information - 1980

In 1980 there were approximately 295,000 fire-tube boilers in operation with total capacity of slightly over 1,100 x 10^9 Btu/hr. As can be seen in Figure 3.1 and Table 3.2, most of these boilers were in the size range of 0.4 to 1.5 x 10^6 Btu/hr.

The number of commercial fire-tube boilers decreases significantly as one goes up the capacity range scale. Over 95% of the commercial fire-tube boilers have a capacity of less than 10 x 10^6 Btu/hr. Most of the industrial fire-tube boilers are also concentrated in the 0.4 to 10 x 10^6 Btu/hr categories. Industrial units account for approximately three-fourths of the total fire-tube boiler capacity.

3.2.2 Capital Stock Information - 2000

The total capacity and number of fire-tube units is anticipated to increase by about 1.5% per year between 1980 and 1990 and by 2% from 1990 until the year 2000. These growth rate assumptions are based on an analysis of the historical sales of fire-tube boilers from 1966 to 1980 (PEDCo 1977, U.S. Bureau of Census 1983). Between 1966 and 1975, fire-tube boiler sales increased at about 2.4% per year. During the late 1970s, these sales decreased

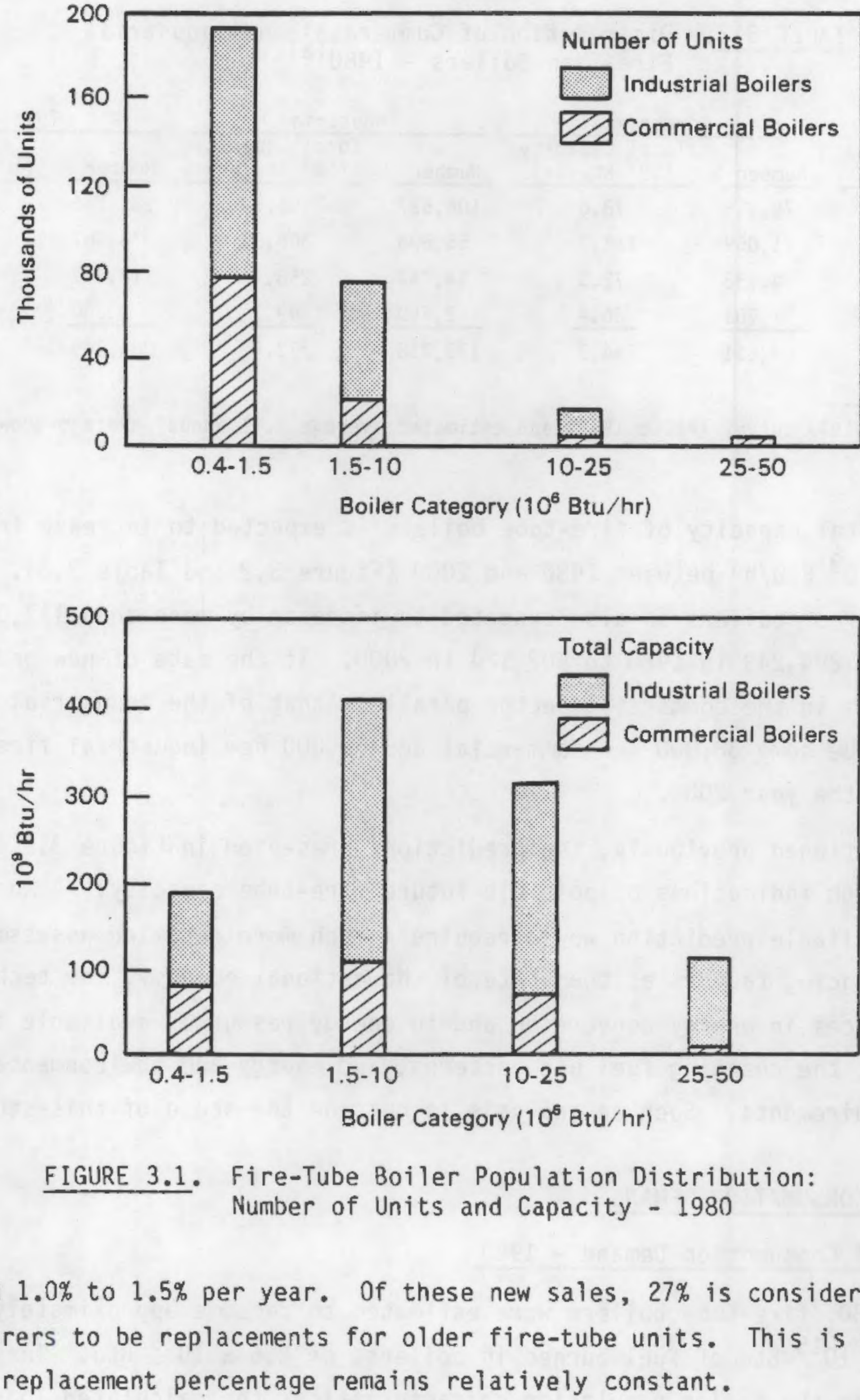

FIGURE 3.1. Fire-Tube Boiler Population Distribution: Number of Units and Capacity - 1980

to around 1.0% to 1.5% per year. Of these new sales, 27% is considered by the manufacturers to be replacements for older fire-tube units. This is assuming that the replacement percentage remains relatively constant.

TABLE 3.2. Distribution of Commercial and Industrial Fire-Tube Boilers - 1980[a]

Capacity Range (10^6 Btu/hr)	Commercial Number	Commercial Total Capacity (10^9 Btu/hr)	Industrial Number	Industrial Total Capacity (10^9 Btu/hr)	Total Number	Total Capacity (10^9 Btu/hr)
0.4-1.5	78,618	78.6	106,527	106.5	185,145	185.1
1.5-10	21,059	117.0	55,808	308.8	76,867	425.8
10-24	4,133	72.3	14,744	258.4	18,877	330.7
25-50	701	26.4	2,659	99.7	3,360	126.1
Total	104,511	294.3	179,738	773.4	284,249	1,067.7

(a) Based on 1977 survey (PEDCo 1979) and estimated average 2.4% annual average growth rate 1975-1980.

The total capacity of fire-tube boilers is expected to increase from 1068 to 1510 x 10^9 Btu/hr between 1980 and 2000 (Figure 3.2 and Table 3.3). The total number of boilers is also expected to increase by more than 117,000 units--from 284,249 in 1980 to 402,124 in 2000. If the rate of new orders and replacements in the commercial sector parallels that of the industrial sector, there will be some 38,000 new commercial and 65,000 new industrial fire-tube boilers by the year 2000.

As mentioned previously, the predictions presented in Figure 3.2 and Table 3.3 are rough indications of possible future fire-tube capacity. A more accurate and reliable prediction would require a much more detailed assessment of such influencing factors as the state of the national economy, the technological advances in energy conversion and in energy resources available for boiler use, the changing fuel use patterns, and energy and environmental regulatory requirements. Such an analysis is outside the scope of this study.

3.3 FUEL CONSUMPTION DEMAND

3.3.1 Fuel Consumption Demand - 1980

In 1980, fire-tube boilers were estimated to consume approximately 25% of the 10.4 x 10^{15} Btu of fuel burned in boilers, or 2.6 x 10^{15} Btu. This figure was based on the boiler population characteristics, the calculated load factors and the distribution of fuel in fire-tube boilers.

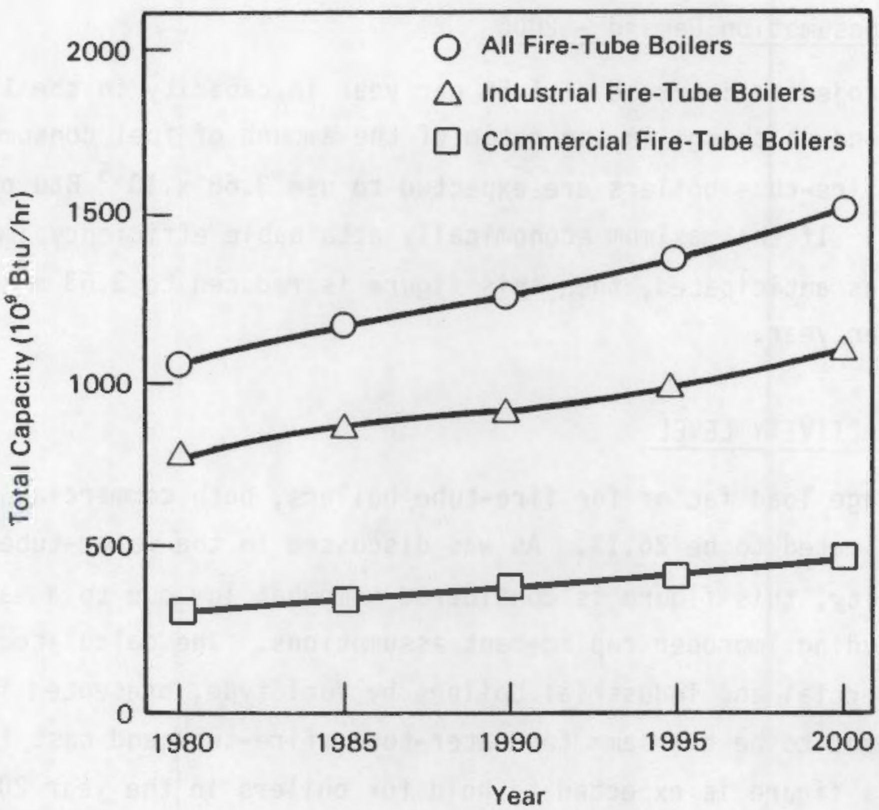

FIGURE 3.2. Projected Increase in Fire-Tube Boiler Capacity

TABLE 3.3. Projected Increase in Fire-Tube Boiler Capacity: 1980 to 2000 (10^9 Btu/hr)[(a)]

Year	Commercial	Industrial	Total
1980	294.3	773.4	1067.7
1985	317.0	833.2	1150.2
1990	341.6	897.6	1239.2
1995	377.1	991.0	1368.1
2000	416.3	1094.1	1510.4

(a) Assumes an annual growth rate of 1.5% 1980-1990 and 2.0% 1990-2000.

3.3.2 Fuel Consumption Demand - 2000

With a projected increase of 1.5% per year in capacity in the 1980s and 2% in the 1990s and no change in the ratio of the amount of fuel consumed per unit of capacity, fire-tube boilers are expected to use 3.68 x 10^{15} Btu of fuel by the year 2000. If the maximum economically attainable efficiency improvements are realized as anticipated, then this figure is reduced to 3.63 x 10^{15} Btu of fuel burned per year.

3.4 SERVICE ACTIVITY LEVEL

The average load factor for fire-tube boilers, both commercial and industrial, is estimated to be 26.1%. As was discussed in the water-tube section on service activity, this figure is considered somewhat low due to a variety of factors, including improper replacement assumptions. The calculated load factors for commercial and industrial boilers by fuel type, presented in Table 2.8, are assumed to be the same for water-tube, fire-tube and cast iron boilers. This figure is expected to hold for boilers in the year 2000 also.

4.0 CAST IRON BOILERS

4.1 EFFICIENCY ESTIMATES

As noted in the introductory section, cast iron boilers are similar to fire-tube boilers except that they are constructed of cast iron rather than steel. They also operate at lower pressures and temperatures. Because of this, their operating efficiencies are generally lower than those of fire-tube units. The average efficiency of cast iron units is estimated to be between 75% and 80% (KVB 1977). This may actually be somewhat high due to the potentially large number of small units that are improperly operated and poorly maintained.

Although large in absolute numbers, cast iron boilers represent only a small portion of the total capacity of boilers. As a result, even though efficiency improvements similar to fire-tube boilers may be expected if the units are operated and maintained properly, the reduction in fuel requirements may be small with respect to water-tube and fire-tube units.

For the purposes of this report, it is assumed that, on the average, the operating efficiency levels for cast iron boilers in 1980 was 75%. By 2000 this is expected to increase to 80% with tune-up, design, and operational improvements.

4.2 CAPITAL STOCK INFORMATION

4.2.1 Capital Stock Information - 1980

The majority of cast iron boilers are less than 0.4 x 10^6 Btu/hr in capacity. Of the approximately 1.5 million cast iron units in existence in 1980, 1 million were less than 0.4 x 10^6 Btu/hr. In fact all industrial and commercial boilers below this capacity are cast iron. Above this size and through 10 x 10^6 Btu/hr, cast iron and fire-tube boilers overlap considerably. There are no cast iron units larger than 10 x 10^6 Btu/hr.

A breakdown of the cast iron boilers in the commercial and industrial sectors is presented in Figure 4.1 and Table 4.1. The majority of the cast iron units are commercial boilers. Almost 80% of the total stock and 80% of the capacity of cast iron units are located in commercial operations.

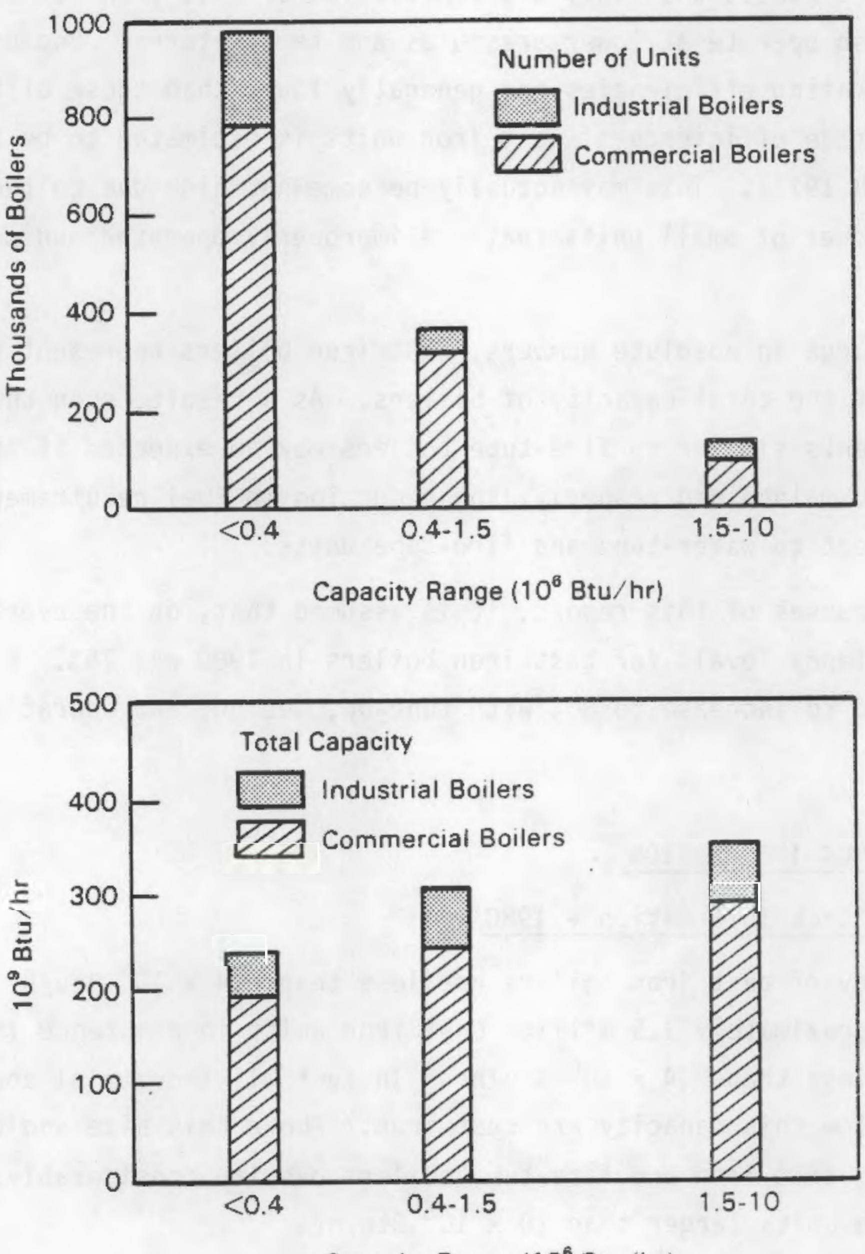

FIGURE 4.1. Cast Iron Boiler Population Distribution: Number of Units and Capacity - 1980

TABLE 4.1. Distribution of Commercial and Industrial Cast Iron Boilers - 1980[a]

Capacity Range (10^6 Btu/hr)	Commercial Number	Commercial Total Capacity (10^9 Btu/hr)	Industrial Number	Industrial Total Capacity (10^9 Btu/hr)	Total Number	Total Capacity (10^9 Btu/hr)
< 0.4	790,850	192.2	197,712	48.1	988,562	240.3
0.4-1.5	311,273	246.9	77,819	61.8	389,092	308.7
1.5-10	100,458	290.8	25,114	72.8	125,572	363.6
Total	1,202,581	729.9	300,645	182.7	1,503,226	912.6

(a) Based on 1977 survey (PEDCo 1979) and estimated average 0.6% growth rate from 1975-1980.

4.2.2 Capital Stock Information - 2000

The growth rate of cast iron boilers for the period 1966 and 1975 has been calculated to be about 1.7% per year (PEDCo 1979). Between 1975 and 1980 the growth rate in cast iron sales was estimated to be approximately 1.2% per year. Based on discussions with manufacturers, previous investigators have concluded that 50% of the cast iron boiler sales is for replacement purposes. Therefore, the actual number of units in the late 1970s increased at only about 0.6% per year. This rate is assumed to hold through the 1980s and to increase slightly, to 1.0% per year, in the 1990s.

As shown in Figure 4.2 and Table 4.2, total capacity for cast iron boilers between 1980 and 2000 is projected to increase by 158 x 10^9 Btu/hr. During this time the total number of cast iron boilers is anticipated to increase by 250,000 units.

4.3 FUEL CONSUMPTION DEMAND

As previously discussed, several research organizations have attempted to identify the amount of fuel used by the different end use. But the data are not sufficient for the calculation of fuel consumption by boiler size. Further work is needed both to refine the national fuel use data base and to assess the consumption by boiler size, type, specific use sector and geographical area.

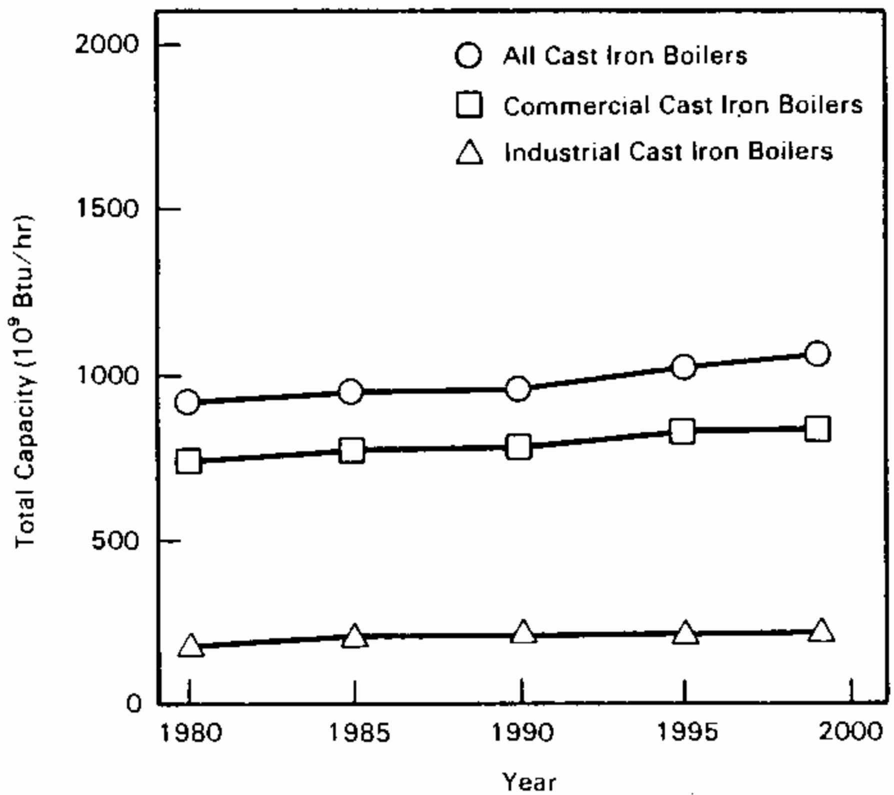

FIGURE 4.2. Projected Increase in Cast Iron Boiler Capacity

TABLE 4.2. Projected Increase in Cast Iron Boiler Capacity: 1980-2000 (10^9 Btu/hr)[a]

Year	Commercial	Industrial	Total
1980	729.9	182.7	912.6
1985	752.1	188.3	940.4
1990	774.9	194.0	968.9
1995	814.4	203.9	1018.3
2000	856.0	214.3	1070.3

(a) Assumes an annual growth rate of 0.6% 1980-1990 and 1.0% 1990-2000.

4.3.1 Fuel Consumption Demand - 1980

Boilers consumed approximately 11 quads of fuel in 1980. Cast iron units are estimated to have burned 15% of total (1.7×10^{15} Btu). A breakdown of the total consumption by all industrial and commercial boilers was presented in Table 2.7.

4.3.2 Fuel Consumption Demand - 2000

With an annual increase of 0.6% in cast iron boiler capacity in the 1980s and 1.0% in the 1990s, it is estimated that by the year 2000 these boilers could consume 1.96×10^{15} Btu of fuel. This is assuming no improvement in operating efficiency between 1980 and 2000. If, as assumed, the average efficiency improves approximately 5% (from 75% to 80%), then fuel consumption could be reduced to about 1.86×10^{15} Btu in cast iron boilers.

4.4 SERVICE ACTIVITY LEVEL

A breakdown of load factors by type of fuel burned in industrial and commercial boilers presented in Table 2.8 showed an average weighted value of 26.1% Additional work is necessary to document replacement, retirement and stand-by issues so that better load factor estimates can be generated. As discussed previously in the water-tube and fire-tube sections, based on the available information, the average load factor for all boiler types in 1980 was estimated to be 26.1%. This value is expected to remain constant through the year 2000.

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