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A MODEL OF PENETRATION OF COAL BOILERS AND COGENERATION IN THE PAPER INDUSTRY

David B. Reister

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A MODEL OF PENETRATION OF COAL BOILERS AND COGENERATION IN THE PAPER INDUSTRY

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A MODEL OF PENETRATION OF COAL BOILERS
AND COGENERATION IN THE PAPER INDUSTRY

Abstract

A model has been developed to forecast the penetration of coal boilers and cogeneration of electricity in the paper industry. Given the demand for energy services (process steam and electricity) by the paper industry, the Penetration Model forecasts the demand for purchased fuel and electricity. The model splits the demand for energy service between energy carriers (coal, fuel oil/natural gas, bark, and spent liquor) on the basis of the installed capacity of 16 types of boilers (combinations of four types of energy carriers and four types of throttle conditions). Investment in new boilers is allocated by an empirical distribution function among the 16 types of boilers on the basis of life cycle cost.

In the short run (5 years), the Penetration Model has a small price response. The model has a large price response in the long run (30 years). For constant fuel prices, the model forecasts a 19-percent share for coal and a 65-percent share for residual oil in the year 2000. If the real price of oil and gas doubles by the year 2000, the model forecasts a 68-percent share for coal and a 26-percent share for residual oil.

CHAPTER 1

INTRODUCTION

This report describes a model to forecast the penetration of coal boilers and cogeneration of electricity in the paper industry. This project is part of a program in the Energy Conservation Section of the Energy Division of Oak Ridge National Laboratory (ORNL) to develop economic-engineering energy demand models for the residential, commercial, and industrial sectors. The industrial modeling program has developed three models: the Phase I Model, the Penetration Model, and the Oak Ridge Industrial Model (ORIM).

Development of the Phase I Model began in the middle of the 1977 fiscal year and was completed in the 1978 fiscal year. The Phase I Model was described in a previous report (1). Development of the Penetration Model began in the middle of the 1978 fiscal year and was completed in the first half of the 1979 fiscal year. This report was written in February 1979, but the ORNL requirement that all reports use the International System of Units (SI) delayed its publication for two years. (At the request of the sponsors, conventional English units are used throughout this report.) Development of ORIM began in the 1979 fiscal year and was completed in the 1980 fiscal year. ORIM was described in a five-volume report (2).

Since its development, ORIM has gained widespread acceptance as an important tool to analyze the impact of prices and policies on energy demand. After its development, the Penetration Model was delivered to its

sponsors and has not been used very much. However, many of the features of ORIM were first used in the Penetration Model. As an introduction to the Penetration Model, it is interesting to contrast its features with those of ORIM.

Both models are based on the concept of energy service. However, the scope of the Penetration Model is much more narrow than the scope of ORIM. The Penetration Model simulates the provision of one energy service (steam) to one industry (paper). ORIM simulates the provision of four energy services (process steam, process heat, machine drive, and electrical services) to nine industries in ten regions.

Conceptually, energy demand is determined by the equation

$$\text{Energy demand} = \frac{\text{Energy}}{\text{Service}} \cdot \frac{\text{Service}}{\text{Output}} \cdot \text{Output} .$$

We shall call a model that forecasts the ratio of energy and service a fuel share model. We shall call a model that forecasts the ratio of service and output a conservation model. The Phase I Model is a complete model of energy demand in the paper industry; the Phase I Model is a combination of a fuel share model, a conservation model, and a model that forecasts output by the paper industry. The Penetration Model is a fuel share model that is designed to replace the fuel share model in the Phase I Model. ORIM is both a fuel share model and a conservation model; it requires an exogenous forecast of industrial output.

ORIM divides the market for process steam into 24 submarkets based on size, capacity factor, coal feasibility, cogeneration, and fuel; for each variable there are two options. The Penetration Model divides the market into 16 submarkets based on cogeneration and fuel. The submarkets for the Penetration Model are determined by only two factors, but there are four options for each of the two factors; there are four sets of cogeneration options and four types of fuel (spent liquor, bark, coal, and oil/gas). The Penetration Model does not distinguish submarkets on the basis of size and capacity factor; in the ORIM data base, 64 percent of the boilers in the paper industry are large with a high capacity factor, and 36 percent of the boilers are small. Since all of the boilers in the Penetration Model are large with a high capacity factor, the model simulates the biggest market but does not capture a significant portion of the market.

In both the ORIM and the Penetration Model there are two types of purchased-fuel boilers: oil/gas boilers, which can burn either fuel oil or natural gas, and coal boilers. In ORIM all types of fuel can be consumed in either type of boiler. In the Penetration Model all coal boilers burn exclusively coal, and oil/gas boilers never burn coal. If coal is significantly less expensive than fuel oil or natural gas, both models will give similar results. However, if coal is about the same price as natural gas or fuel oil, ORIM will forecast that coal boilers will burn both coal and gas or oil.

Both models simulate investment decisions and keep track of vintages of capital stock. ORIM makes investment decisions every 5 years, while the

Penetration Model makes annual decisions. There are many other features of the two models that are similar; these will be noted in the report.

At the same time that the Penetration Model was being developed, Jackson and Kaserman of Oak Ridge National Laboratory were developing a penetration model for use in the residential and commercial sectors (3). Their model is quite different from the Penetration Model. They assume a 100-percent market share for the new invention and attempt to model the premature retirement decision. We allow for premature retirement but assume that most retirement occurs after 30 years. Our primary focus is allocating investment among the 16 types of boilers. Thus, the two approaches are complementary and focus on two different aspects of the same phenomenon.

To conclude the introduction, we will briefly review historical patterns of energy demand and cogeneration. Historical demand patterns for purchased fuel are shown in Tables 1 and 2. Demand for purchased fuel by the paper industry doubled between 1954 and 1971 and has remained relatively constant since 1971 (Table 1). Similarly, the production of paper doubled between 1954 and 1971, and has remained relatively constant since 1971. The demand for purchased fuel per ton of paper, the fuel ratio, has been relatively constant with a gradual decrease. The average annual decrease in the fuel ratio from 1954 to 1977 was -0.8 percent, while the rate of decrease from 1958 to 1977 was -1.6 percent.

Table 2 shows that in 1954 coal was the dominant purchased fuel; by 1971 fuel oil and natural gas had the dominant role, and the coal share had

TABLE 1. TOTAL PURCHASED FUEL PER TON OF PAPER^a

	Purchased Fuel (10 ¹² Btu)	Paper Production (10 ⁶ Ton)	Fuel Ratio (10 ⁶ Btu/Ton)
1954	568	26.876	21.15
1958	731	30.823	23.70
1962	838	37.543	22.32
1967	936	46.926	19.94
1971	1119	55.092	20.31
1972	1173	59.457	19.73
1975	975	52.359	18.63
1976	1045	60.043	17.40
1977	1068	60.736	17.58

^aBureau of the Census data (1954-1971) are not perfectly comparable with American Paper Institute data (1972-1977).

TABLE 2. PURCHASED FUEL SHARES IN THE PAPER INDUSTRY (%)^a

	Fuel Oil	Natural Gas	Coal
1954	25	21	54
1958	22	30	49
1962	23	32	44
1967	28	39	34
1971	36	44	21
1972	42	39	19
1975	47	36	18
1976	48	31	20
1977	49	30	21

^aBureau of the Census data (1954-1971) are not perfectly comparable with American Paper Institute data (1972-1977).

decreased by more than a factor of two. From 1971 to 1977 the coal share has been constant, the gas share has decreased, and the oil share has increased.

Can we explain these changes in fuel share? One of the primary factors that determines fuel shares is fuel price. Table 3 presents data on average fuel prices for several years. The prices have been corrected for inflation and are expressed in 1971 dollars.

TABLE 3. PRICE OF PURCHASED FUEL IN THE PAPER INDUSTRY
(1971 \$/10⁶ Btu)

	Distillate Oil	Residual Oil	Coal	Natural Gas
1962	0.76	0.54	0.44	0.41
1967	0.53	0.44	0.39	0.37
1971	0.64	0.55	0.48	0.38
1974	1.48	1.37	0.87	0.55
1975	1.53	1.35	1.03	0.74
1976	1.51	1.28	0.91	0.93

Source: Bureau of the Census (4).

For all years, except 1976, the price of natural gas is lower than coal. For all years distillate fuel oil is more expensive than residual fuel oil, which is more expensive than coal.

Fuel price is an important factor, but it is not the best explanation for changes in fuel shares. The best explanation is provided by the cost of energy service. In the data appendix, we will develop estimates of the

total cost of energy service, but we do not have a historical time series as given in Table 3. We can develop qualitative estimates of the cost of energy service.

Natural gas is a clean-burning premium fuel, while coal is a dirty fuel that requires storage space, handling equipment, and environmental protection equipment. Fuel oil is a much cleaner fuel than coal; it requires storage tanks but no special handling equipment. The fuel choice is based on the total cost of energy service, which includes the fuel cost plus the cost of capital and labor. The cost of capital and labor for coal boilers is much higher than the cost for fuel oil boilers, which is slightly higher than the cost for natural gas boilers. From 1945 to 1981 the total cost of energy service from oil and gas boilers has been less than the total cost from coal boilers.

The lower cost for oil/gas boilers has been the primary factor responsible for the loss of market share by coal boilers. From 1971 to 1977 natural gas lost a substantial portion of its market share to fuel oil boilers despite the fact that the price of natural gas service was lower than the price of fuel oil service. How can we explain this counter-intuitive result? Clearly, the loss of market share has been caused by natural gas curtailments and not by market forces.

Table 4 displays historical data on electricity generated by the paper industry and on paper production. The amount of electricity generated per ton of paper has been remarkably constant; there was a slight increase in the early 1960s, followed by a gradual decline.

TABLE 4. COGENERATION IN THE PAPER INDUSTRY

	Generated Electricity (10 ⁹ kWh)	Paper Production (10 ⁶ Ton)	Generation Ratio (kWh/Ton)
1954	12.6870	26.876	472
1958	16.9780	30.823	551
1962	21.1650	37.543	564
1967	23.2114	49.926	495
1971	25.3843	55.092	461
1972	27.5627	59.457	464
1975	24.4326	52.359	467
1976	25.4902	60.043	425
1977	27.3835	60.736	451

Source: Bureau of the Census (4).

To summarize, the historical data shows the following:

1. a gradual decline in purchased fuel per ton of paper;
2. a loss of market share by coal;
3. the market shares for fuel oil and natural gas change rapidly without any impact on the market share for coal; and
4. the amount of electricity generated per ton of paper has been almost constant.

CHAPTER 2

THE PENETRATION MODEL

This chapter begins with a brief review of the Phase I Model for the paper industry (1). Using the framework of the Phase I Model, the inputs and outputs of the Penetration Model are defined. The chapter concludes with a discussion of the features of the Penetration Model.

The structure of the Phase I Model is shown in Figure 1. The four submodels of the model are the Paper Demand Submodel, the Pulp and Paper Process Submodel, the Fuel Share Submodel, and the Energy Conversion Submodel.

Given exogenous information on paper product prices, population, disposable income, and gross national product, the Paper Demand Submodel forecasts the demand for 11 types of paper products.

The Pulp and Paper Process Submodel simulates the production of 11 types of paper products using 45 process vectors. The mix of the 45 process vectors to produce the 11 types of paper products is an exogenous input to the model, rather than the result of cost optimization. The output of the process model is the demand for steam and electricity and the supply of bark and spent liquor. To introduce conservation and other forms of technological change, the output of the process model is multiplied by adjustment factors to produce the final output forecast.

Given fuel prices, the Fuel Share Submodel forecasts the share of the purchased fuel that will be captured by each type of fuel. Given the

Figure 1. The Structure of the Energy Demand Model of the Paper Industry

demand for steam and electricity, the supply of bark and spent liquor, the fuel shares, and exogenous technology assumptions on energy conversion efficiencies and the amount of self-generated electricity per unit of process steam, the energy conversion submodel forecasts the demand for purchased fuel and purchased electricity.

The Penetration Model (Figure 2) replaces the Fuel Share Submodel and the Energy Conversion Submodel. The Penetration Model simulates the provision of energy services (steam and electricity) to the paper industry and requires information on the supply of bark and spent liquor. (In this report, bark includes both bark and hogged fuel as reported by the American Paper Institute.) The primary output of the Penetration Model is the demand for purchased fuel and purchased electricity.

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Figure 2. The Penetration Model

Comparison of Figures 1 and 2 reveals that the Penetration Model has two exogenous inputs that the Phase I Model does not have: factor prices and total boiler investment. In the Phase I Model, the fuel shares were determined by fuel prices. In the Penetration Model, the fuel shares are determined by all of the prices of the factors of production required to produce energy services; these factors include fuel, operations and maintenance, and capital.

The Penetration Model forecasts the penetration rate for the 16 types of boilers shown in Table 5. The boiler options include four types of fuel (spent liquor, bark, coal, and oil/gas) and four throttle conditions (combinations of temperature and pressure of the steam output from the boilers) for a total of 16 types of boilers.

TABLE 5. BOILER OPTIONS IN THE PENETRATION MODEL

COGENERATION OPTIONS				
Throttle conditions	A	B	C	D
Pressure (psia)	200	615	915	1265
Temperature (°F)	450	750	825	900
Fuel				
Spent liquor	1	2	3	4
Bark	5	6	7	8
Coal	9	10	11	12
Oil/gas	13	14	15	16

A fundamental assumption in the Penetration Model is that oil/gas boilers (which burn residual fuel oil, distillate fuel oil, and natural gas) cannot burn coal. A second fundamental assumption is that coal will be less expensive than oil/gas, while coal boilers are more expensive than oil/gas boilers. Thus, the demand for coal is controlled by the stock of coal boilers.

Given the total boiler investment for each year, subdivided into spent liquor boilers, bark boilers, and purchased-fuel boilers, the Penetration Model allocates the investment in new boilers among the 16 types of boilers shown in Table 5.

The Penetration Model can be subdivided into the five modules shown in Figure 3. The input-output (I-O) structure of each of these modules will be discussed in the following paragraphs. The Penetration Model requires a substantial data base. Most of the research effort has been devoted to data base preparation. This task has been divided into the three modules

Figure 3. Structure of the Penetration Model

shown in Figure 3. The input-output structure of these modules will be discussed after the discussion of the Penetration Model modules.

Consider the operation of the Penetration Model in the base year. The stocks of the 16 types of boilers are fixed at the levels estimated by the Boiler Stock Module. Since there is no new investment, no penetration of new technology will take place. Even though no new investment can occur, the first five factors on the left side of Figure 2 can influence the demand for purchased electricity and fuel. If all other exogenous factors were constant and steam demand fell, the demand for purchased fuel would drop, the generation of electricity would drop, and the demand for purchased electricity would increase.

As an introduction to the structure of the model, the impact of a drop in demand for steam will be traced through the various parts of the model. We begin with the Boiler Technology Module. Each of the 16 types of boilers is described by fixed input-output coefficients, which are determined by this module. None of the exogenous variables on the left side of Figure 2 have an impact on these coefficients. The output of each type of boiler is steam and electricity; the inputs are various types of fuel. A drop in the demand for steam must be allocated among the various types of boilers; this allocation occurs in the Operation Module.

In the Operation Module, a drop in the demand for steam does not result in a uniform reduction of steam from all types of boilers; all of the drop in steam is allocated to the boilers that burn purchased fuel. The allocation among the eight types of purchased-fuel boilers is

influenced by changes in operating cost. The operating cost, which is determined in the Cost Module as the product of the boiler I-O coefficients and the factor prices, is not influenced by any of the exogenous variables on the left side of Figure 2, except factor prices. Thus, the operating costs are not changed by a drop in the demand for steam, and the drop would be allocated uniformly to all types of purchased-fuel boilers.

A decrease in the production of steam results in a proportional drop in the demand for purchased fuel and in the generation of electricity. The Energy Balance Module determines the drop in demand for purchased fuel and the increase in demand for purchased electricity. Having completed a brief introduction to the structure of the model, we proceed to a more detailed discussion of each of the modules.

THE OPERATION MODULE

The structure of the Operation Module is shown in Figure 4. Its output is the amount of process steam produced by each type of boiler, which is expressed by the following equation:

$$X_j(k) = h_{jk} \cdot Z_j(k) \quad (1)$$

where $Z_j(k)$ is the total stock of boilers of type j , in year k , measured in 10^6 lb/hr of high-pressure steam; h_{jk} is the capacity factor measured in 1000 hr/year; and $X_j(k)$ is the process steam output measured in 10^9 lb/year. The Operation Module determines the capacity factor based on input of the boiler stock and the following exogenous inputs:

1. total demand for steam,
2. the operating cost of each type of boiler,
3. the nominal capacity factor for each type of boiler,
4. the input-output coefficients for each type of boiler, and
5. the supply of bark and spent liquor.

Figure 4. The Operation Module

The nominal capacity factors are the actual capacity factors for the base year, 1976. The operating cost influences the capacity factor; as the relative price of operating a particular type of boiler increase, its capacity factor decreases. The capacity factors for the spent liquor and bark boilers are adjusted to consume the total supply of bark and spent

liquor. The total steam demand less the process steam supplied by bark and spent liquor boilers is equal to the steam supply from coal and oil/gas boilers. The output from each type of coal and oil/gas boiler is determined by the nominal capacity factors, the operating costs, and the total amount of steam to be supplied by all of the oil/gas and coal boilers.

Mathematically, the forecast capacity factors (h_{jk}) are linked to the nominal capacity factors (H_j) by a distribution function, that is

$$h_{jk} = \eta (O_{jk} / \alpha_j)^{\mu} H_j \quad (2)$$

where η is a normalization factor to match the exogenous supply of bark and spent liquor and the exogenous demand for steam; O_{jk} is the operating cost of boiler type j in the year k ; the coefficients α_j are equal to the operating costs in the base year; and the parameter μ controls the elasticity of the response to changes in operating cost. The results of this paper are based on an elasticity of $\mu = -0.3$; for this elasticity, a 10-percent price increase causes a 3-percent decrease in level of operation.

The operating cost is included in Equation 2 to simulate premature retirement for boilers with high operating costs. Equation 2 is an ad hoc creation without a theoretical basis. In ORIM no attempt was made to simulate premature retirement. No attempt was made in either the Penetration Model or ORIM to use the premature retirement model of Jackson and Kaserman (3).

As an additional method to simulate premature retirement of boilers, the nominal capacity factor for each type of oil/gas boiler is decreased by 5 percent for each year in which the operating cost of the oil/gas boiler is greater than the total cost (capital plus operating cost) for a coal boiler with the same throttle conditions. Thus, output from oil/gas boilers can be decreased by higher operating costs through Equation 2 and also through reduction of the nominal capacity factor.

THE OIL/GAS FUEL SHARE MODULE

Oil/gas boilers can burn fuel oil or natural gas, but they cannot burn coal. Given the steam production from each of the four types of oil/gas boilers, the Energy Balance Module determines the total demand for oil/gas service. Given the demand for oil/gas service and the relative prices of each type of oil/gas, the Oil/Gas Fuel Share Module (shown in Figure 5)

Figure 5. The Energy Balance Module

determines the demand for residual fuel oil, distillate fuel oil, and natural gas.

Existing oil/gas boilers can easily switch from one type of oil/gas to another. Consequently, the Penetration Model can forecast the total demand for oil/gas with greater precision than it can forecast the share for each type of oil/gas. The Oil/Gas Fuel Share Module is basically an output section of the model designed to produce a result that is inherently imprecise.

THE INVESTMENT MODULE

The Investment Module is shown in Figure 6. For each year, the inputs to the module are the total number of new spent liquor boilers, new bark boilers, new purchased-fuel boilers, and the life cycle cost for each boiler option. The output from the module is the amount of new investment in each of the 16 types of boilers. Thus, based on life cycle cost the

Figure 6. The Investment Module

Investment Module chooses between coal boilers and oil/gas boilers and chooses the average throttle conditions for each type of boiler. The throttle conditions determine the amount of electricity produced by cogeneration per pound of process steam.

For convenience, we assume that all boilers in the model have a 30-year lifetime. The model starts with 30 cohorts of each of the 16 types of boilers. (This data base is the output of the Boiler Stock Module.) Each year the investment module adds a new cohort to the boiler stock and retires the 30-year-old cohort of boilers.

The demand for steam, the supply of bark and spent liquor, and the investment in new boilers are independent exogenous inputs to the model. If there is too much investment in boilers, the capacity factors will fall; if there is too little investment, the capacity factors will rise. A user of the Penetration Model may need to run the model several times to achieve proper capacity factors.

The Investment Module uses a simulation algorithm, not an optimization algorithm. If the module used an optimization algorithm, all new purchased-fuel boilers would be the type with the lowest life cycle cost. Historically, the paper industry has purchased a mix of boilers. Even if each manager chooses the boiler with the lowest life cycle cost, the choice will vary from plant to plant due to regional differences in prices and the existing capital stock at the plant.

The Industry Sector Technology Use Model (ISTUM) developed by Energy and Environmental Analysis (5) uses a cost-frequency distribution for each

process option and defines the market share as the fraction of the total market in which the process option will be able to provide energy service more cheaply than any competitor. In ISTUM the market shares are calculated numerically.

Conceptually, the ISTUM approach is appealing. However, numerical integrations are inconvenient. In developing ORIM (2), we showed that if the cost frequency distributions were Weibull distributions, the market shares could be calculated analytically. The result is as follows:

$$Z_{jk} = \lambda \cdot \beta_j \cdot (L_{jk})^\rho \quad (3)$$

where Z_{jk} is the stock of boilers of type j installed in year k ; λ is a normalization factor to match the exogenous total investment in bark, spent liquor, and purchased-fuel boilers; the β_j are coefficients; ρ is a parameter; and L_{jk} is the life cycle cost of boiler type j in year k . Equation 3 has often been used to calculate market shares; it has been used in the SRI-Gulf Model (6) and in the CONAES study (7).

The parameter ρ controls the price response. If ρ is zero, the market shares do not respond to changes in life cycle cost. If ρ is a large negative number, the type of boiler with the lowest life cycle cost will capture most of the market. CONAES used a value of $\rho = -2$. ORIM uses a value of $\rho = -8$. The results in this report are based on the value $\rho = -4$. If $\rho = -4$, a 10-percent increase in relative cost of a boiler option will cause a 32-percent decrease in investment.

Investment decisions are influenced by factors in addition to life cycle cost. The coefficients (β_j) are used to capture the effect of these additional factors. If all of the coefficients are equal to 1.0 (as they are in ORIM), investment decisions are made on the basis of life cycle cost alone. If all of the coefficients were equal to 1.0 in the Penetration Model, the model would forecast too large a penetration rate for coal-boilers and high cogeneration boilers. The coefficients used in the Penetration Model are shown in Table 6. The values of the coefficients were chosen to preserve the pre-embargo pattern of investment at pre-embargo prices. The coefficients were chosen to match the pre-embargo pattern qualitatively rather than quantitatively; Figures 15, 17, 19, and 21 in the next section show how the forecast pattern matches the historical pattern. For spent liquor, bark, and oil/gas boilers, the coefficients penalize high cogeneration boilers. For coal boilers the coefficients penalize boilers that have no cogeneration. For example, if the life cycle costs were the same for coal and oil/gas boilers, when both have no cogeneration (Type A),

TABLE 6. COEFFICIENTS FOR THE INVESTMENT DISTRIBUTION FUNCTION

Throttle Conditions	Energy Carrier			
	Spent Liquor	Bark	Coal	Oil/Gas
A	2.0	2.0	0.5	2.0
B	0.5	0.5	1.0	1.0
C	0.5	0.5	1.0	1.0
D	0.1	0.1	1.0	0.5

the market share for the oil/gas boilers will be four times as large as the share for coal boilers.

THE COST MODULE

The Cost Module is shown in Figure 7. The inputs to the Cost Module are the factor prices and the boiler I-O coefficients. The outputs from the Cost Module are the operating cost, the capital cost, and the life cycle cost for each type of boiler.

Figure 7. The Cost Module

The operating cost (O_{jk}) and the capital cost (K_{jk}) are given by

$$O_{jk} = \sum_{i=1}^6 P_{ik} a_{ij} \quad (4)$$

$$K_{jk} = P_{7k} a_{7j} \quad (5)$$

where P_{ik} is the price of factor i in year k , and a_{ij} is the input of factor i to boiler type j . The seven types of factor inputs are shown in Table 7.

TABLE 7. FACTORS OF PRODUCTION FOR THE BOILER OPTIONS

i	Factor	Units
1	Spent liquor service	10^{12} Btu
2	Bark service	10^{12} Btu
3	Coal service	10^{12} Btu
4	Oil/gas service	10^{12} Btu
5	Electricity	10^9 kWh
6	Materials and labor	10^6 1976 \$
7	Capital	10^6 1976 \$

The life cycle cost is defined by

$$I_{jk} = \frac{\sum_{m=0}^{29} \frac{C_{jk+m} F_m}{(1+\gamma)^m}}{\sum_{m=0}^{29} \frac{F_m}{(1+\gamma)^m}} \quad (6)$$

where C_{jk} is the total cost of boiler type j in the year k ($C_{jk} = O_{jk} + K_{jk}$); F_m is the load factor for each type of boiler in year m ; and γ is the discount rate. Each of the 16 types of boilers has a nominal capacity factor that is used to calculate the capital cost. The load factor in Equation 6 is used to express the temporal variation in the use of each type of boiler. The results in this report are for $F_m = 1$. Thus, we have assumed that there was no temporal variation in boiler utilization.

The Penetration Model begins with a base year (1976) and will forecast energy demand for a 30-year period (1976-2005). Each year the model calculates the life cycle cost for each type of boiler, and the life cycle cost requires factor prices for 30 years in the future; that is, the boilers installed in 2004 will operate in 2005 and will run until 2034. Thus, the model requires prices for fuel, electricity, materials, labor, and capital from 1976 to 2034.

THE BOILER TECHNOLOGY MODULE

The Boiler Technology Module is shown in Figure 8. The Boiler Technology Module is the first of the three modules used to prepare the data base. The inputs to the module are technological options (back-pressure turbine versus a condensing turbine, temperature and pressure of steam from the boiler, the number of feedwater heaters, and the

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Figure 8. The Boiler Technology Module

amount of condensate that returns from the process), and the outputs are the energy service I-O coefficients for each type of boiler.

Calculations were performed using the detailed version of the module, which we shall call the Major Boiler Model, shown in Figure 9. The Major Boiler Model was developed by A. R. Major of the J. E. Sirrine Company (8).

Figure 9. The Major Boiler Model

The Major Boiler Model is a flexible representation of the energy service sector of a papermill. The model can use a spent liquor recovery

boiler or a fuel boiler. The model can allow zero, one, or two feedwater heaters for the fuel boiler. (Feedwater heaters are not desirable for a recovery boiler.) The turbine options in the model are a condensing cycle or back-pressure turbine. The model supplies process steam at two different pressures and the amount of condensate returned from the process steam is a significant variable.

To use the Major Boiler Model to estimate the energy service I-O coefficients for the 16 types of boilers, we have selected typical values for the parameters in the model. Since a data base does not exist, the parameters were chosen after discussions with experienced engineers.

Although the Major Boiler Model is a flexible representation of the energy service sector of a papermill, other technological options exist. For example, in a recent paper, R. H. Williams of Princeton University discusses options for industrial cogeneration (29). His emphasis is on maximum production of electricity per pound of process steam and selling the surplus electricity. The structure of the Penetration Model is flexible enough to study the surplus electricity issue, but we have not chosen to develop the data base required to study this issue.

The seven factors of production for the boiler options are listed in Table 7, above. The first five factors are the amount of fuel service to produce a billion pounds of process steam and the amount of electricity produced. The amount of fuel service is the energy delivered to the water to produce high-pressure steam. For a fixed output of process steam, as the throttle conditions are increased, the generator produces more elec-

tricity and the demand for fuel service increases. The Major Boiler Model has two types of boilers--a recovery boiler and a combination boiler. The recovery boiler burns spent liquor, and the combination boiler can burn bark, coal, fuel oil, or natural gas. Since the combination boiler has feedwater heaters, it requires less energy service than the recovery boiler to produce the same output of process steam and electricity. We have used the Major Boiler Model to estimate the demand for energy service by either the recovery boiler or the combination boiler for each of the four sets of throttle conditions. The details are in the data appendix.

The Major Boiler Model produces estimates of the demand for fuel service and the production of electricity for each of 16 boiler options. The other two factors of production in Table 7 are materials and labor and capital; estimates of the I-O coefficients for these factors are developed in the data appendix.

The fuel boiler in the Major Boiler Model is a combination boiler that can burn bark and fuel. We have chosen to model combination boilers as two separate boilers--a bark boiler and a purchased-fuel boiler.

A back-pressure turbine has a fixed ratio between electricity and process steam. To allow flexibility, a papermill can purchase electricity or install a condensing turbine. A choice between these options requires careful cost analysis and depends on the rate structure of the electric utility. The heat rate for a condensing turbine in the Major Boiler Model is about 13,800 Btu/kWh. A typical utility heat rate is about 10,500 Btu/kWh. If there are 10-percent distribution losses, the delivered heat

rate is about 11,700 Btu/kWh. Thus, a condensing turbine does not save energy. The grid should allow the utility to have a higher load factor for its capital stock than the load factor for the capital stock at the papermill. (Williams proposes that the utilities own the capital that produces energy service at papermills. Although his proposal would encourage choices based on marginal costs, radical institutional changes are hard to implement.) Thus, we conjecture that the marginal cost of backup electricity from a condensing turbine should be higher than the marginal cost of utility electricity. (Utility rate structures are not based on marginal costs, and cost analysis may justify a condensing turbine at certain locations.) In the model we assume that all boiler options use back-pressure turbines.

THE BOILER STOCK MODULE

The Boiler Stock Module is shown in Figure 10. Using data from the American Paper Institute (API) (10), the American Boiler Manufacturers Association (ABMA) (11), and the Major Fuel Burning Installation Survey (MFBI) (13), the Boiler Stock Module estimates the total stock of each type

Figure 10. The Boiler Stock Module

of boiler in the base year (1976), the nominal capacity factor for each type of boiler in the base year, and the stock of boilers by type for the 30 years preceding the base year. Details on the methods and results of the module will be given in the data appendix.

THE CAPITAL PRICE MODULE

The Capital Price Module is shown in Figure 11. Given income tax policy, property tax policy, the interest rate on bonds, and payments to stockholders, the capital price module determines the appropriate capital price (rate of return on capital). The methodology for determining the capital price has been discussed in the paper by Phung (14). The Capital Price Module is not a formal computer program but is a side calculation performed by a user of the model. Our estimate of the appropriate capital price for the paper industry is 22 percent per year in constant dollars.

Figure 11. The Capital Price Module

ANALYSIS OF POLICY ALTERNATIVES

This section concludes with a brief discussion of how the Penetration Model can aid the analysis of policy alternatives. The policy alternatives include changes in income tax policy, a Btu tax or government orders that all new boilers consume coal, and new technology.

Changes in income tax policy, such as depreciation allowances or tax credits, directly affect the price of capital, which is one of the factor prices (see Table 2).

A Btu tax on oil/gas would encourage investment in coal boilers and increase the premature retirement of oil/gas boilers. Government orders that a certain class of new boilers burn coal can be simulated by using a Btu tax to increase the share of coal boilers to hit the appropriate target.

Research and development (R&D) policy can produce new process options. Given the I-O coefficients for a new technology, the model can forecast the penetration of the new technology and estimate the energy savings for the new technology. Thus, the Penetration Model can provide an estimate of the benefits from energy R&D.

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CHAPTER 3

RESULTS OF THE PENETRATION MODEL

The previous chapter presented the model. A natural sequence would be to present the data base in this section and the results in the next section. To make this report interesting to a general audience, the details of the Boiler Stock Module and the results of the Boiler Technology Module are presented in a data appendix. (The details of the Boiler Technology Module are too complex for a general audience and too elementary for power engineers and will not be presented. The detailed equations of conservation of energy and mass can be written directly from Figure 9.) The results of the Penetration Model will be presented using 14 figures. To preserve the continuity of the text, Figures 15-25 are at the end of this chapter.

The results of the Penetration Model are presented for three scenarios: High Price, Medium Price, and Low Price. The model requires prices from the base year (1976) to 2034 for the seven factors shown in Table 5. For the three scenarios all of the factor prices are constant, except the price of oil/gas service, which is shown in Figure 12. The price shown in Figure 12 is a price index with an initial value of 1.0 in 1976. (In physical units, the base year price for oil/gas service is \$2 per million Btu.) In the High Price scenario the oil/gas price index increases to 4.0 by 2000 and remains at that value thereafter. In the Medium Price scenario the price index increases steadily to 2.0 in 2000 and 3.0 in 2034. In the Low Price scenario the price index remains at 1.0 from 1976 to 2034.

Figure 12. The Price Index for Oil/Gas Service for Three Scenarios

The demand for oil/gas service and for coal service for the three scenarios is shown in Figures 13 and 14. The demand for oil/gas service doubles by 2005 in the Low Price scenario, while the demand for coal service is almost constant. In the Medium Price scenario the demand for oil/gas service decreases slowly, while the demand for coal service increases strongly, doubling by 1990 and increasing by a factor of six by 2005. In the High Price scenario the demand for oil/gas service decreases by more than a factor of ten in 30 years, while the demand for coal service increases by a factor of nine.

To summarize, at current prices fuel oil and natural gas will remain the dominant boiler fuels. If the oil/gas price doubles by 2000, coal

Figure 13. Demand for Oil/Gas Service

Figure 14. Demand for Coal Service

boilers will penetrate and will provide more process steam than oil/gas boilers by 1996. If the oil/gas price quadruples by 2000, coal boilers will penetrate rapidly and will provide more process steam than oil/gas boilers by 1986.

Figures 13 and 14 present the results of the Penetration Model. To understand the results, Figures 15 through 22 present details on the installed capacity of four of the eight types of purchased-fuel boilers. Figures 15, 17, 19, and 21 show the market share of each type of boiler by year of installation from 1946 to 2004. Figures 16, 18, 20, and 22 show the total capacity of each type of boiler from 1976 to 2005.

Figure 15 displays the market share for coal boilers of type A. (The 16 boiler options are defined in Table 5. Type A boilers produce no electricity.) In 1946, the market share was 6.5 percent; by 1976 the market share was nearly zero. Thus, type A coal boilers have lost their market share in the last 30 years. The Penetration Model forecasts three market share scenarios for the period 1976 to 2004; in the Low Price scenario the market share is about 1 percent; in the Medium Price scenario the market share increases from 2 percent to 3 percent; in the High Price scenario the market share increases from 3 percent to 4 percent. Even for the High Price scenario, the forecast market share is less than the historical market share in 1946.

Figure 16 displays the total boiler capacity for coal boilers of type A, measured in units of millions of pounds per hour. (Figure 15 displays market shares for annual boiler sales. Figure 16 displays market shares for total stocks of boilers. Since Figure 16 is a 30-year summation, it does not have any discontinuities in the base year as in Figure 15.) In the Low Price scenario retirements of old boilers are greater than additions of new boilers until 1993, and the total capacity decreases. After 1993, the total capacity increases, and it is slightly greater than the initial capacity by 2005. In the Medium Price scenario the total capacity increases by a factor of four by 2005. In the High Price scenario the total capacity increases by a factor of five by 2005.

The market share for coal boilers of type D is shown in Figure 17. The market share increased to more than 8 percent in 1952 before decreasing

to less than 2 percent by 1975. The Penetration Model forecasts three market share scenarios: the market share is about 3 percent for the Low Price scenario; the market share increases from 6 percent in 1976 to 11 percent in 2004 for the Medium Price scenario; the market share increases from 11 percent in 1976 to 14 percent in 2004 for the High Price scenario.

Figure 18 displays the total boiler capacity for coal boilers of type D. In the Low Price scenario the total capacity increases steadily but slowly from 10 to 17 million pounds per hour. In the Medium Price scenario the total capacity increases by a factor of six by 2005. In the High Price scenario the total capacity increases by a factor of nine by 2005.

The market share for oil/gas boilers of type A is shown in Figure 19. The peak market share was 29 percent in 1966; the 1975 market share was 28 percent. In 1975, oil/gas boilers of type A have the largest market share of all of the 16 types of boilers. The Penetration Model forecasts lower market shares for oil/gas boilers of type A for all three scenarios. In the Low Price scenario the market share decreases from 15 percent in 1976 to 14 percent in 2004. In the Medium Price scenario the market share decreases from 13 percent in 1976 to 6 percent in 2004. In the High Price scenario the market share decreases from 8 percent in 1976 to 2 percent in 2004.

Figure 20 displays the total capacity of oil/gas boilers of type A. The total capacity increases from 60 to 93 million pounds per hour in the Low Price scenario. The capacity increases to 73 in 1989 before decreasing to 56 in 2005 in the Medium Price scenario. The total capacity increases

to 63 in 1983 before decreasing to 20 in 2005 in the High Price scenario. Although the forecast market share in the High Price scenario is always lower than the historical share, a smaller fraction of a larger market causes the new capacity to be larger than the retired capacity for the period 1976 to 1983.

In the Low and Medium Price scenarios saturated (type A) oil/gas boilers have a larger market share and a larger total capacity than saturated coal boilers throughout the 30-year forecast period. In the High Price scenario saturated oil/gas boilers have a larger market share than coal until 1984 and a larger total capacity until 1996.

The market share for oil/gas boilers of type C is shown in Figure 21. The market share decreased from 24 percent in 1946 to 7 percent in 1975. In the Low Price scenario the model forecasts a 10-percent market share. In the Medium Price scenario the model forecasts a decrease from a 7-percent share in 1976 to a 3-percent share in 2004. In the High Price scenario the forecast market share decreases from 4 percent in 1976 to 1 percent in 2004.

Figure 22 displays the total capacity of oil/gas boilers of type C. In the Low Price scenario the capacity increases by a factor of two. In the Medium Price scenario the capacity is constant. In the High Price scenario the capacity decreases by a factor of three.

The model forecasts the penetration rate for cogeneration as well as for coal boilers. Figures 23, 24, and 25 present the cogeneration forecast for the three scenarios. The three scenarios were designed to illustrate

penetration of coal boilers rather than cogeneration. The primary variable that influences the penetration of cogeneration is the price of electricity. Substantial changes in the cogeneration penetration rate can be achieved by large changes in electricity price.

The demand for purchased electricity is shown in Figure 23. The demand increases by about a factor of four for all three scenarios. The difference between the demand in the High Price scenario and the demand in the Low Price scenario is about 10 percent. The cogeneration of electricity is shown in Figure 24. The production of electricity as a by-product of steam production increases by about a factor of three in all three scenarios. The difference between cogeneration in the High Price scenario and in the Low Price scenario is about 17 percent. (The difference in cogeneration is equal in magnitude to the difference in purchased electricity. Since the amount of purchased electricity is greater than the amount of generated electricity, the percentage difference is smaller for purchased electricity.)

Figure 25 displays the average power ratio as forecast by the model. The power ratio is the ratio of by-product electricity and process steam measured in kWh per 1000 pounds of process steam. As shown in the data appendix, the power ratio ranges from zero for a type A boiler to 62 for a type D boiler. In the Low Price scenario the power ratio is 27 in 1976 and decreases to 26 in 1987, before increasing to 28 in 2005. The decrease is caused by the retirement of coal boilers with high throttle conditions. In the High Price scenario the power ratio increases from 27 in 1976 to 33 in

2005. From 1972 to 1977 the power ratio increased rapidly; linear extrapolation of the recent rapid growth would result in a power ratio of 48 in 2005. An increase in the price of electricity would cause the model to forecast a higher power ratio.

Comparison of Figures 23 and 24 reveals a paradox: the power ratio increases, resulting in an increased generation of electricity per unit of process steam; at the same time, the demand for purchased electricity increases more rapidly than the generation of electricity. In 1976 the demand for purchased electricity is equal to the production of electricity. In the Low Price scenario in 2005, the demand for purchased electricity is 66 percent higher than the production of electricity. In the High Price scenario in 2005, the demand for purchased electricity is 25 percent higher than the production of electricity. The explanation of the paradox is the exogenous assumption that the demand for electricity will increase more rapidly than the demand for process steam. Thus, conservation of process steam encourages greater purchases of electricity.

Figure 15. Capacity by Year of Installation of Type A Coal Boilers

Figure 16. Total Capacity of Type A Coal Boilers

Figure 17. Capacity by Year of Installation of Type D Coal Boilers

Figure 18. Total Capacity of Type D Coal Boilers

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Figure 19. Capacity by Year of Installation of Type A Oil/Gas Boilers

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Figure 20. Total Capacity of Type A Oil/Gas Boilers

Figure 21. Capacity by Year of Installation of Type C Oil/Gas Boilers

Figure 22. Total Capacity of Type C Oil/Gas Boilers

Figure 23. Purchased Electricity

Figure 24. Generated Electricity

Figure 25. Power Ratio

CHAPTER 4

CONCLUSIONS

The Penetration Model is an important milestone on the road to improved energy-demand models for the industrial sector. It is not the end of the road because the model is designed to be part of a comprehensive model for the paper industry, and the paper industry is only one of many industrial sectors. The model is based on many assumptions and approximations. The approximations could be improved if better data were available. The art of model development is to find a close approximation to reality by using the existing data base.

The conceptual framework of the model provides a solid foundation. The conceptual framework links the demand for energy carriers to the demand for energy services that are linked to the demand for paper products. To be more specific, paper is produced from inputs of wood, chemicals, energy services, capital, labor, and materials. By-products of paper production are bark and spent liquor. Energy services (process steam and electricity) are produced from inputs of energy carriers (purchased fuel and purchased electricity), bark, spent liquor, capital, labor, and materials. The demand for energy services is driven by the demand for paper products, and the demand for energy service drives the demand for energy carriers.

Conservation can be defined as the link between demand for paper products and demand for energy services; that is, the demand for energy service is equal to the product of demand for paper products and conservation.

Fuel shares can be defined as the link between demand for energy services

and demand for energy carriers; that is, the demand for energy carriers is equal to the product of fuel shares and the demand for energy services. With these definitions the Penetration Model is a fuel shares model that requires exogenous information on conservation and the demand for paper products.

Energy carriers are consumed in boilers to produce high-pressure steam, which is expanded in a turbine to produce electricity and process steam. The stock of boilers determines the demand for coal and oil/gas. The Penetration Model tracks the movement in new boilers and the retirement of old boilers for 16 types of boilers (combinations of four types of carriers and four types of throttle conditions). Investment in new boilers is allocated among the 16 types of boilers on the basis of life cycle cost by using a distribution function.

The distribution function is a significant innovation that we are using for the first time in the Penetration Model. The distribution function is a bridge from the micro level to the macro level. At the micro level each firm chooses the optimal technology for its conditions. Due to differences in local conditions, the macro result of local optimization is an incredible diversity in technology. The paper industry is composed of about 800 papermills with about 2,000 boilers. Considering the capacity, throttle conditions, and age for the boilers, each of the 2,000 boilers is unique; no two boilers have the same age, capacity, and throttle conditions.

Development of a macro model that yields the same result as the sum of the micro optimizations is a difficult problem. An unconstrained optimiza-

tion problem will yield a single "best" solution. A constrained optimization problem can yield a mixture of solutions, but introduces the complication of forecasting the constraints. Similarly, if the macro result is the sum of several local optimization problems, a forecast of the local conditions is required. The distribution function is an empirical simulation device that will yield a mixture of results for a single set of average prices.

The credibility of the Penetration Model could be improved by increasing the number of boiler options; an increase in options could offer regional detail, size detail, more information on capability to burn alternate fuels, and detail on throttle conditions. The credibility of the model could be improved by a systematic attempt to estimate the distribution function. However, both increasing the boiler options and estimating the distribution function require a greatly improved data base. An improved data base would consist of a comprehensive census of all boilers; census data would include capacity data by region, size, fuel and throttle conditions, and year of installation, as well as capital cost and annual operating cost.

Although the Penetration Model cannot yield a precise forecast, the model is the result of a compromise to achieve the maximum detail that can be supported by the existing data base. Given the demand for energy services, the model splits the demand between coal and oil/gas boilers. The basis for the split is the difficulty of retrofitting an existing oil/gas boiler to burn coal. Since a natural gas boiler can be easily retrofitted

to burn fuel oil, the model does not attempt to differentiate between boilers that consume natural gas, distillate fuel oil, and residual fuel oil. One of the strongest conclusions of our model development effort is the impossibility of an accurate forecast of fuel shares for oil/gas boilers. The model splits demand between coal and oil/gas boilers on the basis of capacity and allocates investment to new boilers on the basis of a distribution function. Although the distribution function is the weakest feature of the model, the data base is too weak to develop a more reliable substitute for the distribution function.

DATA APPENDIX

This appendix consists of 16 tables that are the data base for the Penetration Model. Table A-1 contains estimates of demand for fuel and electricity by the papermill industry for 1972, 1975, 1976, and 1977. (The papermill industry consists of SIC sectors 261, 262, 263, and 266. The paper products industry consists of SIC sectors 264 and 265.) The source of the data is the American Paper Institute (10). The data in Table A-1 provides the control totals for the Penetration Model.

"Other purchased energy" is primarily crude oil and will be combined with residual fuel oil. "Energy sold" is steam and electricity; we assume it is 70 percent electricity and 30 percent steam. "Other energy" is purchased solid waste (e.g., sawdust) and will be combined with bark and hogged fuel.

Table A-2 presents estimates of demand for purchased fuel and electricity by the paper industry for several years. The data source is the Bureau of the Census (4).

Table A-3 compares the API data to the Census data for 1975 and 1976. The coverage of the Census data is the paper industry, while the API covers the papermill industry. The Census does not cover all establishments; however, for the paper industry the "fuels not specified by kind" is about 1 percent of the total. Thus, the Census claims to have measured 99 percent of the energy consumption in the paper industry.

According to the Census, the papermill industry consumes about 93 percent of the total purchased fuel used by the paper industry. (The paper

TABLE A-1. ESTIMATED FUEL AND ELECTRICITY DEMAND BY THE PAPERMILL INDUSTRY

A. 1977

Type	Unit	Demand 10^6 units	Energy 10^{12} Btu	Conversion Factor 10^6 Btu/unit
Purchased electricity	MWh	34.7852	118.2697	3.400
Steam generated electricity	MWh	33.4904	113.8674	3.400
Purchased steam	10^3 Lb.	16.9287	20.4042	1.2053
Coal	Ton	8.9858	222.8478	24.80
Residual fuel oil	Barrel	80.3815	506.4035	6.300
Distillate fuel oil	Barrel	2.9183	17.2180	5.900
Liquid propane gas	Barrel	0.3257	1.2583	3.864
Natural gas	10^3 Cubic feet	311.8718	318.1092	1.0200
Other purchased energy	10^6 Btu	1.7964	1.7964	1.0
Energy sold	10^6 Btu	-18.3603	-18.3603	1.0
Hogged fuel	Ton	10.3742	86.1059	8.300
Bark	Ton	10.6029	94.3658	8.900
Spent liquor	Ton	64.8000	797.0400	12.300
Hydroelectric power	MWh	2.8405	9.6577	3.400
Other energy	10^6 Btu	5.7753	5.7753	1.0
Total	10^6 Btu	2180.8915	2180.8915	1.0

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Source: American Paper Institute (10).

TABLE A-1. ESTIMATED FUEL AND ELECTRICITY DEMAND BY THE PAPERMILL INDUSTRY (continued)

B. 1976

Type	Unit	Demand 10^6 units	Energy 10^{12} Btu	Conversion Factor 10^6 Btu/unit
Purchased electricity	MWh	32.4624	110.3714	3.400
Steam generated electricity	MWh	31.6060	107.4604	3.400
Purchased steam	10^3 Lb.	15.2154	17.9741	1.1813
Coal	Ton	8.6600	212.3061	24.52
Residual fuel oil	Barrel	76.9443	482.9576	6.277
Distillate fuel oil	Barrel	2.9843	17.6727	5.922
Liquid propane gas	Barrel	0.4355	1.6767	3.850
Natural gas	10^3 Cubic feet	320.6481	327.6034	1.0217
Other purchased energy	10^6 Btu	2.5327	2.5327	1.0
Energy sold	10^6 Btu	-18.6922	-18.6922	1.0
Hogged fuel	Ton	9.1795	75.5789	8.233
Bark	Ton	10.5470	94.9920	9.007
Spent liquor	Ton	60.9949	754.3373	12.367
Hydroelectric power	MWh	2.8305	9.5554	3.376
Other energy	10^6 Btu	6.2459	6.2459	1.0
Total	10^6 Btu	2095.1120	2095.1120	1.0

Source: American Paper Institute (10).

TABLE A-1. ESTIMATED FUEL AND ELECTRICITY DEMAND BY THE PAPERMILL INDUSTRY (continued)

C. 1975

Type	Unit	Demand 10^6 units	Energy 10^{12} Btu	Conversion Factor 10^6 Btu/unit
Purchased electricity	MWh	26.9483	91.6232	3.400
Steam generated electricity	MWh	28.1402	95.6767	3.400
Purchased steam	10^3 Lb.	13.6080	16.1339	1.1858
Coal	Ton	7.1901	174.0491	24.21
Residual fuel oil	Barrel	69.7029	437.8522	6.282
Distillate fuel oil	Barrel	2.2808	13.5271	5.931
Liquid propane gas	Barrel	0.3382	1.2926	3.822
Natural gas	10^3 Cubic feet	340.8979	347.6343	1.0198
Other purchased energy	10^6 Btu	1.0190	1.0190	1.0
Energy sold	10^6 Btu	-17.1518	-17.1518	1.0
Hogged fuel	Ton	6.9710	56.0839	8.045
Bark	Ton	9.1382	82.8187	9.063
Spent liquor	Ton	54.4156	675.7884	12.419
Hydroelectric power	MWh	2.6863	9.1324	3.400
Other energy	10^6 Btu	6.0554	6.0554	1.0
Total	10^6 Btu	1895.8604	1895.8604	1.0

Source: American Paper Institute (10).

TABLE A-1. ESTIMATED FUEL AND ELECTRICITY DEMAND BY THE PAPERMILL INDUSTRY (continued)

D. 1972

Type	Unit	Demand 10^6 units	Energy 10^{12} Btu	Conversion Factor 10^6 Btu/unit
Purchased electricity	MWh	27.1458	92.4286	3.405
Steam generated electricity	MWh	29.8167	101.3768	3.400
Purchased steam	10^3 Lb.	18.6673	21.7636	1.1659
Coal	Ton	8.9507	221.9912	24.80
Residual fuel oil	Barrel	73.9754	466.5298	6.307
Distillate fuel oil	Barrel	3.4033	20.2744	5.957
Liquid propane gas	Barrel	0.5791	2.2815	3.940
Natural gas	10^3 Cubic feet	453.4451	461.9209	1.0187
Other purchased energy	10^6 Btu	0.2073	0.2073	1.0
Energy sold	10^6 Btu	-14.1430	-14.1430	1.0
Hogged fuel	Ton	5.5078	44.7943	8.133
Bark	Ton	11.1398	102.6422	9.214
Spent liquor	Ton	59.1811	748.3543	12.645
Hydroelectric power	MWh	2.5731	8.7509	3.401
Other energy	10^6 Btu	3.4489	3.4489	1.0
Total	10^6 Btu	2181.2449	2181.2449	1.0

Source: American Paper Institute (10).

TABLE A-2. ESTIMATED FUEL AND ELECTRICITY DEMAND BY THE PAPER INDUSTRY

Year	Distillate Oil (10 ⁶ barrels)	Residual Oil (10 ⁶ barrels)	Coal (10 ⁶ tons)	Natural Gas (10 ³ cubic feet)	Purchased Electricity (MWh)	Generated Electricity (MWh)
1954	-	22.4720	12.5720	116.6	10.8520	12.6870
1958	-	25.2850	14.4650	212.2	12.5380	16.9780
1962	2.5780	28.5270	15.1450	265.1	17.0520	21.1650
1967	10.6053	31.2941	12.9163	351.2	25.8578	23.2114
1971	18.0891	46.4995	9.4390	477.0	34.9994	25.3843
1974	17.6436	56.5554	8.4308	422.8	40.8702	27.3832
1975	10.6815	70.7726	7.4163	357.9	39.1204	24.4326
1976	10.6815	70.7726	8.4425	357.9	43.4588	25.4874

Source: Bureau of the Census (4).

TABLE A-3. DEMAND FOR PURCHASED FUEL BY THE PAPER INDUSTRY: COMPARISON OF DATA FROM
THE BUREAU OF THE CENSUS AND THE AMERICAN PAPER INSTITUTE

	1975			1976		
	API	Census	Ratio (%)	API	Census	Ratio (%)
Distillate oil	2.2808	13.3814	17	2.9843	10.6815	28
Residual oil	69.7029	58.4199	119	76.9443	70.7726	109
Fuel oil	71.9837	71.8013	100	79.9286	81.4541	98
Coal	7.1901	7.4163	97	8.6600	8.4425	103
Natural gas	340.8979	369.6	92	320.6481	357.9	90
Purchased electricity	26.9483	39.1204	69	32.4624	43.4588	75
Generated electricity	30.8265	24.4326	91	34.4365	25.4874	135
Total electricity	57.7748	63.5530	91	66.8989	68.9462	97

product industry consumes 7 percent of the total.) Disclosure problems prevent precise detailed comparison of all types of fuel, but using the Census data, the papermill industry consumes 86 percent of the distillate fuel oil, 97 percent of the residual fuel oil, 96 percent of the total fuel oil, 99 percent of the coal, and 89 percent of the natural gas.

Consider Table A-3; there appears to be a definition problem for distillate and residual fuel oil. (The definitions appear to have changed several times recently at the Census Bureau.) The API has less distillate and more residual than the Census. There is better agreement on total fuel oil. Based on Census data, we expect the fuel oil ratio to be 96 percent in 1976; the ratio in Table A-3 is 98 percent, which is in good agreement. We expect the coal ratio to be 99 percent, and we find 103 percent. We expect the natural gas ratio to be 89 percent, and we find 90 percent. Thus, except for the two types of fuel oil, the purchased fuel data are in good agreement.

Using the Census data, the papermill industry consumes 81 percent of the total purchased electricity and produces 100 percent of the total generated electricity. In Table A-3 the papermill industry purchases 75 percent of the electricity and generates 135 percent of the electricity. The Census total is "generated less sold," while the API total is generated; if we correct for electricity sales of 3.8337×10^9 kWh (see Table A-15), the papermill industry generates 120 percent of the electricity. Thus, there appears to be a 20-percent difference between API and Census estimates on generated electricity.

We have chosen the API data as the source for benchmark energy demand totals. Based on the data in Table A-1, Table A-4 provides an estimate of total consumption of fuel by the papermill industry and an estimate of production of energy service in boilers. In 1972, for example, 221.9912×10^{12} Btu of coal were consumed in boilers. At an efficiency of 79 percent the coal provided 175.3730×10^{12} Btu of energy service.

Some fuel is consumed in lime kilns and other types of furnaces to provide process heat. In Table A-4, we assume that 10 percent of the purchased fuel provides process heat and that the source of process heat is fuel oil. Thus, the energy service in Table A-4 is an estimate of the total energy service provided by boilers.

Tables A-5, A-6, A-7, A-8, and A-9 are based on information from the Major Fuel Burning Installation (MFBI) data base (13). The MFBI data base is the result of a 1975 questionnaire that was sent by the Federal Energy Administration to all industries that have an MFBI. (An MFBI is a boiler or furnace with a design firing rate of more than 100×10^6 Btu/hour.) A discussion of the strengths and weaknesses of the MFBI data base is given by Samuels and Johnson (15).

Table A-5 presents data on fuel consumption and estimates of coverage factors and capacity factors from the MFBI data base. Boiler type is determined by the primary boiler fuel. Coal boilers burn primarily coal but also burn a small amount of oil and gas. Coal is consumed by coal boilers, oil boilers, gas boilers, and other (bark and spent liquor) boilers. (In the model coal boilers burn coal, and oil/gas boilers do not burn coal. Thus, the real world is more complex than the model.)

TABLE A-4. CONSUMPTION OF FUEL AND PRODUCTION OF ENERGY SERVICE BY BOILERS
IN THE PAPERMILL INDUSTRY

<u>Fuel Consumption (10^{12} Btu)</u>	<u>Efficiency</u>	<u>1972</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>
Coal ^a		221.9912	174.0491	212.3061	222.8478
Fuel oil ^b		489.2930	453.6909	504.8397	526.6762
Natural gas ^a		461.9209	347.6343	327.6034	318.1092
Purchased fuel		1173.2051	975.3743	1044.7492	1067.6332
Process heat oil ^c		117.3205	97.5374	104.4749	106.7633
Boiler oil ^c		371.9725	356.1535	400.3648	419.9129
Bark ^d		150.8854	144.9580	176.8168	186.2470
Spent liquor ^a		748.3543	675.7884	754.3373	797.0400
Total boiler fuel		1955.1243	1698.5833	1871.4284	1944.1569
<u>Energy Service (10^{12} Btu)</u>					
Coal	79	175.3730	137.4988	167.7218	176.0498
Boiler oil	83	308.7372	295.6074	332.3028	348.5277
Natural gas	79	364.9175	274.6311	258.8067	251.3063
Oil/gas		673.6547	570.2385	591.1095	599.8340
Bark	68	102.6021	98.5714	120.2354	126.6479
Spent liquor	60	449.0126	405.4730	452.6024	478.2240
Total		1400.6424	1211.7817	1331.6691	1380.7557

^aTable A-1 is the source of all of the data.

^bFuel oil is the sum of residual fuel oil, distillate fuel oil, liquid propane gas, and other purchased energy.

^cProcess heat is 10 percent of purchased fuel. Boiler oil is the difference between fuel oil and process heat oil.

^dBark is the sum of hogged fuel, bark, and other energy.

TABLE A-5. CONSUMPTION OF FUEL, COVERAGE FACTOR, AND CAPACITY FACTORS
FROM THE MAJOR FUEL BURNING INSTALLATION (MFBI) DATA BASE

1973 Fuel Consumption (10^{12} Btu) by Boiler Type				
	Coal	Oil	Gas	Total
Coal	124.794	3.622	1.488	129.904
Oil	7.440	194.034	22.953	224.427
Gas	1.248	33.147	167.407	201.802
Other	5.964	55.366	29.787	91.117
Total	139.446	186.169	221.635	647.250
1974 Fuel Consumption (10^{12} Btu) by Boiler Type				
Coal	120.820	3.567	1.494	125.881
Oil	8.002	193.602	14.364	215.968
Gas	1.452	32.152	168.181	201.785
Other	6.080	53.879	26.929	86.888
Total	136.354	283.200	210.968	630.522
1974 Capacity Hours by Boiler Type				
	Fuel Consumption (10^{12} Btu)	Boiler Capacity (10^9 Btu/hr)	Full Capacity Hours	Capacity Factor (%)
Coal	125.881	21.168	5947	68
Oil	215.968	41.740	5174	59
Gas	201.785	39.382	5124	58
Total	543.634	102.290	5315	61
Other	86.888	62.861	1382	16
1974 Coverage Factor by Fuel Type				Coverage Factor (%)
	MFBI Consumption (10^{12} Btu)	Census Consumption (10^{12} Btu)		
Coal	136.354	204.110	67	
Oil	283.200	348.672 ^a	81	
Gas	210.968	434.216	49	
Total	630.522	986.998	64	

^aFuel oil consumed in boilers. 109.666×10^{12} Btu of fuel oil have been allocated to process heat consumption (see Table A-4).

Source: MFBI data base (13).

TABLE A-6. CONSUMPTION OF FUEL IN 1974 AND FULL CAPACITY HOURS

		Throttle Conditions ^a				
		Unit	A	B	C	D
Coal boilers						
Coal	10 ⁹ Btu		9280	15440	30484	47504
Oil	10 ⁹ Btu		88	0	1082	2043
Gas	10 ⁹ Btu		0	0	758	64
Total	10 ⁹ Btu		9368	15440	32324	49611
Capacity	10 ⁶ Btu/hr		2090	3203	3963	8715
Hours	Hr		4482	4820	8156	5693
Factor	%		51	55	93	65
Oil boilers						
Coal	10 ⁹ Btu		416	3426	546	130
Oil	10 ⁹ Btu		38395	37942	77880	30873
Gas	10 ⁹ Btu		481	2545	7747	3591
Total	10 ⁹ Btu		39292	43913	86173	34594
Capacity	10 ⁶ Btu/hr		7406	9186	15530	7541
Hours	Hr		5305	4780	5549	4587
Factor	%		61	55	63	52
Gas boilers						
Coal	10 ⁹ Btu		596	0	24	832
Oil	10 ⁹ Btu		10610	7837	7603	3813
Gas	10 ⁹ Btu		57756	42304	38464	25617
Total	10 ⁹ Btu		68962	49841	46091	30262
Capacity	10 ⁶ Btu/hr		15710	7718	9693	5337
Hours	Hr		4390	6458	4755	5670
Factor	%		50	74	54	65
Other boilers						
Coal	10 ⁹ Btu		0	360	5720	0
Oil	10 ⁹ Btu		6536	14223	24480	4299
Gas	10 ⁹ Btu		3730	2133	11627	8043
Total	10 ⁹ Btu		10266	16716	41827	12342
Capacity	10 ⁶ Btu/hr		8340	8806	28220	15472
Hours	Hr		1231	1898	1482	798
Factor	%		14	22	17	9

^aThrottle conditions defined by the percentage of the boiler output that is devoted to electricity generation: A, 0; B, 1-10; C, 11-20; and D, 21-35.

Source: MFBI data base (13).

TABLE A-7. CAPACITY FOR COAL BOILERS BY YEAR OF INSTALLATION
AND THROTTLE CONDITIONS

	MFBI Data (10^6 Btu/hr)				Smoothed MFBI Data (10^6 Btu/hr)			
	A	B	C	D	A	B	C	D
1947	103	103	243	322	43	80	114	168
1948	200	130	330	259	44	81	116	185
1949	107		193	160	45	80	116	204
1950		103			45	79	114	224
1951				160	45	78	111	245
1952					45	77	107	266
1953	106				44	77	104	288
1954		188	165	756	43	77	101	308
1955					43	79	98	326
1956				1144	43	82	96	341
1957	169		375		43	86	95	352
1958		110	238	578	42	90	94	358
1959		256		846	42	94	93	358
1960		110			41	99	93	354
1961		165			40	102	93	345
1962	330	125			37	106	93	332
1963			250	1077	34	109	94	315
1964					31	111	94	295
1965				790	27	114	94	273
1966		378		295	22	115	92	251
1967			379		18	116	90	228
1968		118	370		14	116	87	207
1969					11	116	83	188
1970		275			8	115	79	172
1971		275			6	113	74	159
1972				480	4	111	70	150
1973					2	109	66	144
1974					2	107	63	140
1975					1	105	61	138
1976					1	103	60	137

Source: MFBI data base (13).

TABLE A-8. CAPACITY FOR FUEL OIL AND NATURAL GAS BOILERS

	MFBI Data (10^6 Btu/hr)				Smoothed MFBI Data (10^6 Btu/hr)			
	A	B	C	D	A	B	C	D
1947		200	1212	520	118	378	702	194
1948		1099	1518	200	130	396	739	215
1949	147	325	1801	135	146	411	767	237
1950	107	514	351	362	166	421	784	258
1951		396	991	103	192	427	790	278
1952	100		423	764	223	430	786	297
1953	187	338	915	205	261	432	773	315
1954	180	760	898		307	433	754	332
1955	180	370	523		361	436	732	349
1956	483	1000	578		424	442	709	365
1957	358		702	905	497	452	687	381
1958	347		496	1496	579	468	670	398
1959	584	180	340	100	671	488	658	416
1960	383		1112		769	513	652	437
1961	613	433			871	539	653	459
1962	145	799	632	210	973	566	662	485
1963	719	867	342		1072	589	676	511
1964	1846	890	160	459	1161	607	694	539
1965	2455	592	950	1360	1238	618	714	565
1966	786	958	989	388	1299	620	733	589
1967	2766	1513	769	1058	1344	615	750	609
1968	1096	293	603	335	1372	603	763	623
1969	1699	175	973	1426	1386	587	771	633
1970	1265	596	2082	421	1390	569	773	637
1971	684	179			1387	551	770	638
1972	771	149	1198	1281	1380	536	764	636
1973	740	442		178	1372	524	755	633
1974	1471	491	167	196	1363	515	745	629
1975					1352	508	734	623
1976					1338	501	721	616

Source: MFBI data base (13).

TABLE A-9. CAPACITY FOR OTHER (BARK AND SPENT LIQUOR) BOILERS

	MFBI Data (10^6 Btu/hr)				Smoothed MFBI Data (10^6 Btu/hr)			
	A	B	C	D	A	B	C	D
1947		101	446	489	22	87	354	201
1948		532	498	169	25	97	411	222
1949		130	556	760	30	106	468	241
1950			705	192	36	115	526	258
1951			1149		44	124	584	273
1952				748	53	132	641	286
1953			494		65	142	697	298
1954	340	397	557		78	153	752	309
1955		150	263		94	166	806	320
1956		236	765	586	113	181	859	332
1957			1701		134	199	911	344
1958		123	1205	1084	159	219	962	359
1959	268		1881	560	187	243	1012	377
1960		276		317	218	269	1060	399
1961	379		707		253	298	1107	426
1962	190	600	318		290	328	1152	459
1963	324	686	782		330	361	1194	498
1964	158	338	2361		373	394	1232	542
1965	750	108	670	480	416	428	1264	590
1966		464	2095	1210	458	461	1290	641
1967	200	297	2600	1954	499	491	1309	693
1968	750		655	408	538	519	1323	744
1969	631	997	520		572	543	1331	791
1970	538		1453		601	561	1335	834
1971	1603	2249	731	675	623	572	1337	870
1972	210	865	1340	2229	639	577	1337	899
1973	701		971	1777	647	577	1334	919
1974	505	108	1820	108	649	570	1329	930
1975					644	559	1319	932
1976					634	544	1302	924

Source: MFBI data base (13).

In 1974 the average capacity factor for the purchased-fuel boilers was 61 percent, and the range was 58 percent to 68 percent. The capacity factor for the other boilers is low (16 percent) because the MFBI data base does not include consumption of other fuel (bark and spent liquor).

Comparing data from the MFBI and the Census, the 1974 coverage factor is 64 percent, with a range from 49 percent to 81 percent. We expect coal boilers to be large and gas boilers to be small, with oil in between. Thus, the low coverage factor for gas is reasonable. However, we would expect a higher coverage factor for coal than for oil. The oil total has been reduced by 109.666×10^{12} Btu to correct for process heat. If we use the original fuel oil consumption, the coverage factor for fuel oil becomes 62 percent. Since the lower coverage factor for oil is more reasonable, perhaps our assumption that oil is the process heat fuel is incorrect. However, if we decrease the boiler consumption of natural gas and increase the consumption of fuel oil, the average coverage factor will be unchanged, and the only change in our estimate for boiler energy service in Table A-4 will be caused by the differences in efficiency (79 percent for natural gas and 83 percent for fuel oil.)

Table A-6 presents data on fuel consumption and capacity factors for four types of throttle conditions. (For the MFBI data, throttle conditions are defined by the percentage of the boiler output that it devoted to electricity generation.) The data does not appear to have a consistent pattern. Some of the data may be in error; for example, the capacity factor for coal-C is too high, and the capacity factor for natural gas-B may be too high.

Tables A-7, A-8, and A-9 present capacity data for coal, oil/gas, and other boilers by year of installation and by type of throttle conditions. The data are presented as direct MFBI data and as smoothed MFBI data. The impact of smoothing the MFBI data is shown in Figure A-1. The MFBI data varies from large positive numbers to zero from one year to the next. The MFBI data was smoothed by replacing each data point by a normal distribution with a standard deviation of 5 years and an area equal to the magnitude of the data point. The boiler capacity in each year is obtained by adding the contributions from all of the distribution functions. The smoothed MFBI data is an input for the Penetration Model.

Figure A-1. Smooth MFBI Data for Type D Coal Boilers

Table A-10 presents data on capacity by fuel type and throttle conditions for boilers ordered from 1965 to 1977. The data source is the American Boiler Manufacturers Association (ABMA)(11). The data coverage includes MFBI boilers and small boilers.

Table A-11 presents a comparison of the MFBI data and ABMA data. The MFBI data is in units of millions of Btu per hour, while the original ABMA data is in units of millions of pounds of steam per hour. To convert from pounds to Btu, we have used the conversion factors shown in part E of Table A-11. The conversion factors were derived using the Major Boiler Model. The conversion factors increase with throttle conditions, since more electricity is produced, and increase with decreasing fuel conversion efficiency. Recall that oil has the highest efficiency (83 percent), while spent liquor has the lowest efficiency (60 percent).

Throttle conditions have different definitions for the two sets of data. The throttle conditions are given for the ABMA data. The throttle conditions for the MFBI data are based on the fraction of the boiler output devoted to electricity. An ABMA boiler with low throttle conditions (type A) and a condensor could have high electricity production.

Compare parts A and C of Table A-11: the total fuel demand for oil/gas boilers reported by ABMA is lower than the total for MFBI, but the ABMA has more type A boilers than the MFBI. The MFBI has only large boilers, while the ABMA has all boilers ordered in a 13-year period. The oil/gas type A boilers that are smaller than MFBI size would appear in the ABMA data but not in the MFBI data. The total fuel demand by coal boilers in

TABLE A-10. CAPACITY BY FUEL TYPE AND THROTTLE CONDITIONS FOR BOILERS ORDERED FROM 1965 TO 1977

A. Capacity by Fuel Type (10^6 lb/hr)

Throttle Conditions	Fuel Type				Total
	Oil/Gas	Coal	Spent Liquor	Bark	
A	27.29	1.43	23.01	11.38	63.11
B	10.14	1.72	15.47	1.37	28.70
C	11.52	3.12	16.83	5.63	37.10
D	2.34	3.19	1.62	0.30	7.45
Total	51.29	9.46	56.93	18.68	136.36

B. Definitions of Normal Throttle Conditions

Type	Pressure (psig)	Temperature (°F)	Enthalpy Categories
A	185	450	1-8
B	600	750	9
C	900	825	10
D	1250	900	11

Source: ABMA data (11).

TABLE A-11. COMPARISON OF MFBI AND ABMA ESTIMATES OF CAPACITY
BY FUEL TYPE AND THROTTLE CONDITIONS

Throttle Conditions	Fuel Type			Total
	Oil/Gas	Coal	Other	
A. MFBI (10 ⁶ Btu/hr)				
A	23116	2090	8340	33546
B	16904	3203	8806	28913
C	25223	3963	28220	57406
D	12878	8715	15472	37065
Total	78121	17971	60838	156930
B. MFBI (%)				
A	15	1	5	21
B	11	2	6	18
C	16	3	18	37
D	8	6	10	24
Total	50	11	39	100
C. ABMA (10 ⁶ Btu/hr)				
A	30806	1651	53546	86003
B	13151	2294	31517	46962
C	25385	4278	41771	61434
D	3286	4498	3731	11515
Total	62628	12721	130565	205914
D. ABMA (%)				
A	15	1	26	42
B	6	1	15	23
C	7	2	20	30
D	2	2	2	6
Total	30	6	63	100
E. ABMA conversion factors (Btu/lb of steam)				
	Oil	Gas/Coal	Bark	Spent Liquor
A	1098.7	1154.4	1341.1	1663.8
B	1269.2	1333.5	1549.2	1900.1
C	1304.9	1371.0	1592.8	1949.1
D	1342.0	1409.9	1638.0	1999.9
F. Boiler fuel shares (%)				
	Oil/Gas	Coal	Other	
1972	43	11	46	
1975	41	10	48	
1976	39	11	50	
1977	38	11	51	

the ABMA data is smaller than the demand in the MFBI data for all types of boilers. For other boilers the ABMA reports more than twice the capacity of the MFBI, and there are six times as many type A boilers in the ABMA data.

Compare parts B, D, and F of Table A-11: for the MFBI, 50 percent of the capacity is oil/gas; for the ABMA, 30 percent of the capacity is oil/gas; the actual fuel share for oil/gas decreased from 43 percent to 38 percent in the period from 1972 to 1977. Similarly for "other" boilers the MFBI is lower than the fuel shares and the ABMA is higher than the fuel shares.

The oil/gas boiler data from both the MFBI and ABMA appears to be reasonable. Other boilers are primarily spent liquor boilers, and spent liquor boilers tend to be large (the average size is 340,000 lb/hr). Thus, spent liquor boilers are MFBI's and should be part of the MFBI data base. If the oil/gas data is approximately correct, there are too few "other" boilers in the MFBI data and too many in the ABMA data. Other boilers have a shorter lifetime than oil/gas or coal boilers, and the fuel consumption in other boilers has been increasing. Thus, the ABMA data seems reasonable, but the MFBI data appears to have too few other boilers.

We assume that the MFBI data (Tables A-7, A-8, and A-9) gives the correct age distribution for the stock of boilers and that the ABMA data (Table A-10) gives the correct throttle condition distribution for the boiler stock. To match the control totals for energy service and generated electricity (provided by Tables A-1 and A-4), we need to choose a typical

representative from each of the 16 classes of boilers and use the Major Boiler Model to calculate I-O coefficients. The nominal throttle conditions are given in Table A-10, and the boiler I-O coefficients are given in Table A-12. Using the boiler I-O coefficients in Table A-12, the estimates of capacity and process steam production are given in Tables A-13 and A-14.

Table A-12 presents the results of the Major Boiler Model for a recovery boiler and a combination (bark, coal, oil/gas) boiler for four types of throttle conditions. Both the spent liquor and combination boilers provide the same amount of process steam (953,000 lb/hr) for all four types of throttle conditions. The combination boiler has one feedwater heater and requires more high-pressure steam from the boiler per unit of process steam than the spent liquor boiler, but as a consequence the combination boiler produces more electricity and requires less energy service than the spent liquor boiler. Thus, the combination boiler with one feedwater heater is more efficient than a spent liquor boiler without a feedwater heater.

The saturated boilers (type A) do not produce electricity. The superheated boilers produce electricity, and the amount increases with an increase in throttle conditions. The superheated systems produce electricity very efficiently. Compared to the saturated boilers, the differential heat rates for the superheated systems range from 3,464 to 3,448 Btu of energy service per kWh of electricity. The energy service efficiencies range from 98.53 percent to 98.99 percent. (We assume a turbine efficiency of 98.5 percent. The differential energy service efficiencies are higher than the turbine efficiencies because higher throttle conditions improve system performance.)

TABLE A-12. RESULTS OF THE MAJOR BOILER MODEL FOR A RECOVERY BOILER
AND A COMBINATION BOILER

			Throttle Conditions			
Symbol	Units		A	B	C	D
Spent Liquor Recovery Boiler						
Boiler steam output	M	10 ³ lb/hr	1000	987	992	992
Boiler energy service input	U	10 ⁶ Btu/hr	999	1125	1160	1191
Process steam demand	Q	10 ³ lb/hr	953	953	953	953
Electric power output	P	MW	0	36.5	46.7	55.7
Steam ratio	M/Q	lb/lb	1.049	1.035	1.041	1.041
Power ratio	P/Q	kWh/10 ³ lb	0	38.3	49.0	58.5
Energy ratio	U/Q	Btu/lb	1048	1180	1217	1249
Heat rate	ΔU/ΔP	Btu/kWh	--	3464	3457	3448
Bark, Coal, Oil/Gas Boiler						
Boiler steam output	M	10 ³ lb/hr	1072	1054	1060	1060
Boiler energy service input	U	10 ⁶ Btu/hr	978	1110	1148	1181
Process steam demand	Q	10 ³ lb/hr	953	953	953	953
Electric power output	P	MW	0	38.2	49.2	58.8
Steam ratio	M/Q	lb/lb	1.125	1.106	1.112	1.113
Power ratio	P/Q	kWh/10 ³ lb	0	40.1	51.6	61.7
Energy ratio	U/Q	Btu/lb	1026	1165	1204	1239
Heat rate	ΔU/ΔP	Btu/kWh	--	3463	3460	3455

TABLE A-13. BASE YEAR (1976) ACCOUNTS BY FUEL TYPE
AND THROTTLE CONDITIONS

	Spent Liquor	Bark	Coal	Oil/Gas	Total
Capacity (10^6 lb/hr)					
A	31.7	14.3	4.5	60.7	111.2
B	21.3	1.7	5.4	22.5	51.0
C	23.2	7.1	9.8	25.6	65.7
D	2.2	0.4	10.0	5.2	17.8
Total	78.6	23.5	29.7	114.0	245.8
Process steam (10^9 lb/yr)					
A	156.1	65.7	20.6	278.2	520.5
B	110.0	8.3	26.1	108.9	253.2
C	119.1	34.0	47.1	122.9	323.0
D	11.5	1.8	48.1	25.0	86.3
Total	396.6	109.8	141.8	534.9	1183.1
Nominal capacity factor (hr/yr)					
A	4915	4586	4586	4586	4680
B	5155	4826	4826	4826	4964
C	5128	4799	4799	4799	4915
D	5126	4797	4797	4797	4838
Total	5049	4671	4771	4691	4813
Generated electricity (10^9 kWh/yr)					
A	0	0	0	0	0
B	4.21	0.33	1.05	4.37	9.96
C	5.83	1.75	2.43	6.34	16.36
D	0.67	0.11	2.97	1.54	5.29
Total	10.72	2.20	6.44	12.25	31.61
Demand for energy service (10^{12} Btu/yr)					
A	163.5	67.4	21.1	285.4	537.4
B	129.9	9.7	30.4	126.7	296.7
C	144.9	40.9	56.6	148.0	390.6
D	14.3	2.2	59.6	30.9	107.0
Total	452.6	120.2	167.7	591.1	1331.7

TABLE A-14. TOTAL CAPACITY, TOTAL PRODUCTION OF PROCESS STEAM, AND
FULL CAPACITY HOURS FOR 1972, 1975, 1976, AND 1977

CAPACITY, PROCESS STEAM, AND HOURS

	Total Capacity (10 ⁶ lb/hr)	Total Process Steam (10 ⁹ lb/yr)	Power Ratio (kWh/1000 lb)	Average (hr/yr)	Saturated (hr/yr)	Superheated (hr/yr)
1972	261.2	1256.3	23.7	5256	5937	4700
1975	224.2	1078.8	26.1	5256	5254	5258
1976	245.8	1183.1	26.7	5256	5159	5337
1977	254.2	1224.1	27.4	5256	5004	5464

TOTAL CAPACITY BY FUEL TYPE FOR 1972, 1975, 1976, AND 1977 (10⁶ lb/hr)

	Spent Liquor	Bark	Coal	Oil/Gas	Total	Percent			
						Spent Liquor	Bark	Coal	Oil/Gas
1972	79.7	19.4	34.0	128.5	261.6	30	7	13	49
1975	70.6	19.2	24.6	109.9	224.2	31	9	11	49
1976	78.6	23.5	29.7	114.0	245.8	32	10	12	46
1977	82.6	24.9	30.7	116.0	254.2	33	10	12	46

TOTAL CAPACITY BY THROTTLE CONDITIONS FOR 1972, 1975, 1976, AND 1977 (10⁶ lb/hr)

	A	B	C	D	Total	A	B	C	D
1972	117.5	54.7	69.5	19.9	261.6	45	21	27	8
1975	102.4	46.8	59.4	15.6	224.2	46	21	27	7
1976	111.2	51.0	65.7	17.8	245.8	45	21	27	7
1977	114.9	52.8	68.1	18.4	254.2	45	21	27	7

Given the energy service heat rate, the fuel heat rate is computed using the combustion efficiency of fuel. For example, suppose coal is burned with an efficiency of 79 percent in a type C boiler with an energy service heat rate of 3,460 Btu/kWh. The energy service efficiency of 98.64 percent multiplied by the coal combustion efficiency of 79 percent yields a system efficiency of 77.93 percent and a heat rate of 4,380 Btu/kWh, which is much better than the 11,000 Btu/kWh heat rate for delivered utility electricity.

Table A-13 presents the base year energy accounts. For the base year the amount of process steam produced by each process, $X_j(t)$, is the product of the capacity for each process, $Z_j(t)$, and the nominal capacity factor, $H_j(t)$:

$$X_j(t) = H_j(t) \cdot Z_j(t); \quad j = 1, 16 \quad . \quad (A-1)$$

Capacity is measured in pounds of steam from the boiler, which is greater than the amount of process steam. Thus, the nominal capacity factor is equal to the quotient of the number of full capacity hours of boiler operation, $H_j^f(t)$, and the steam ratio, η_j ; that is,

$$H_j(t) = H_j^f(t) / \eta_j; \quad j = 1, 16 \quad . \quad (A-2)$$

The values of the steam ratio in Table A-12 range from 1.035 for a type B recovery boiler to 1.125 for a type A combination boiler.

The total demand for factor i by all boilers, $Y_i(t)$, is determined by summing over all boilers the product of the output of process steam and the I-0 coefficient, a_{ij} ; that is,

$$Y_i(t) = \sum_j a_{ij} X_j(t); \quad i = 1, 7 \quad . \quad (A-3)$$

The first five factors are (1) spent liquor service, (2) bark service, (3) coal service, (4) oil/gas service, and (5) electricity. For the base year (1976), the total amounts of the first five factors are given in Tables A-1 and A-4. The I-0 coefficients and steam ratios are given in Table A-12. The unknowns are the number of full capacity hours for each process and the capacity for each process. There are 32 unknowns to be determined by five conditions. To solve the system, 27 additional conditions are required.

Estimates of full capacity hours from the MFBI data base are presented in Tables A-5 and A-6. For purchased fuel boilers the average capacity factor was 61 percent in 1974. Although the data in Table A-6 could provide a basis for estimating full capacity hours, we decided the data was too unreliable. We assume the average capacity factor for the base year was 60 percent, that is, 5,256 full capacity hours per year. We assume that the superheated boilers (types B, C, and D) have the same capacity factor and allow it to differ from the capacity factor for saturated boilers (type A). Thus, the 16 possible values for the number of full capacity hours are reduced to two, and the average value is constrained,

resulting in one degree of freedom to determine the number of full capacity hours for each process.

Our estimate of the capacity for each process could be based on the MFBI data base or on the ABMA data base. We have chosen the ABMA data base because the data seem more reliable and the coverage is more complete. We use the ABMA data in Table A-10 to determine the mix of throttle conditions for each fuel type but vary the magnitude to match the control total for each type of energy service given in Table A-4.

Compare part A of Tables A-10 and A-13. The total capacity increases from 136 to 246, less than a factor of two. Coal capacity almost triples, while oil/gas capacity doubles; capacity of spent liquor and bark boilers increases by about 35 percent.

To summarize, the ABMA data determines the mix of throttle conditions. The magnitude of the capacity by type of energy service is determined by the control totals on demand for energy service. The relative number of full capacity hours for saturated and superheated boilers is determined by the control total on generation of electricity.

Table A-13 presents the detailed energy accounts for the base year. For each process the table presents an estimate of capacity, process steam production, nominal capacity factor, generation of electricity, and demand for energy service.

Table A-14 presents a summary of the energy accounts for 1972, 1975, 1976, and 1977. The estimate of total capacity drops sharply from 1972 to 1975. Since actual capacity did not drop, our assumption of a 60-percent

capacity factor is incorrect. It probably should be higher than 60 percent in 1972 and lower in 1975. Since a change in the average capacity factor changes the scale, but not the distribution of capacity and does not change any of the details of the process steam estimate, we shall retain a 60-percent capacity factor but warn the reader not to compare capacity estimates from different years.

The estimates of total process steam are the most important output of the calculation. They are a significant improvement over the estimates in the Phase I report (1).

Using the estimate of total process steam, we can define an average power ratio by dividing the total production of electricity in Table A-1 by the total production of process steam. The average power ratio increases from 23.7 kWh per 1000 pounds of process steam in 1972 to 27.4 in 1977.

A change in the relative number of full capacity hours for saturated boilers and superheated boilers changes the average power ratio in the model. To match the power ratio of 26.1 in 1975 requires equal capacity factors for both saturated and superheated boilers. To match the power ratio of 23.7 in 1972 requires a higher capacity factor for saturated boilers. To match the power ratio of 27.4 in 1977 requires a higher capacity factor for superheated boilers.

From 1972 to 1977 the fraction of the capacity that consumes spent liquor and bark increased, while the fraction that consumes oil/gas decreased. The fraction of capacity in each type of throttle condition has remained almost constant.

Using data from Table A-1 and the process steam estimates in Table A-14, we can develop the annual electricity and steam balance estimates shown in Table A-15. Based on discussions with API, we assume that energy sold is 70 percent electricity and 30 percent process steam.

The I-0 coefficients for the boiler options are shown in Table A-16. The source of the energy I-0 coefficients is Table A-12. The sources of the materials, labor, and capital I-0 coefficients are discussed in the notes for the table. Despite the fact that the fuel costs for coal boilers are less than the fuel costs for oil/gas boilers, both the operating costs and the total costs are greater for coal boilers than for oil/gas boilers. In all cases higher throttle conditions result in lower operating costs and lower total cost.

TABLE A-15. ANNUAL ELECTRICITY AND STEAM BALANCE
FOR THE PAPERMILL INDUSTRY

	1972	1975	1976	1977
<hr/>				
Electricity (10^9 kWh/yr)				
Generated ^a	29.8167	28.1402	31.6060	33.4904
Purchased ^a	27.1458	26.9483	32.4624	34.7852
Sold ^b	-2.9007	-3.5178	-3.8337	-3.7657
Hydro ^a	2.5731	2.6863	2.8305	2.8405
Demand	56.6349	54.2570	63.0652	67.3504
Steam (10^9 lb/yr)				
Generated ^c	1256.3226	1078.7568	1183.0643	1224.0970
Purchased ^a	18.6673	13.6080	15.2154	16.9287
Sold ^b	-3.5358	-4.2880	-4.6731	-4.5901
Demand	1271.4541	1088.0768	1193.6066	1236.4356

^aSource: Table A-1.

^bSource: Table A-1. Assumptions: Energy sold is 70 percent electricity and 30 percent steam, 1200 Btu/lb of steam, 3413 Btu/kWh.

^cSource: Table A-14.

TABLE A-16. INPUT-OUTPUT COEFFICIENTS FOR THE BOILER OPTIONS WHERE OUTPUT IS 10^9 POUNDS OF PROCESS STEAM

Throttle Conditions	Spent ^a Liquor Service (10^{12} Btu)	Bark Service (10^{12} Btu)	Coal Service (10^{12} Btu)	Oil/Gas Service (10^{12} Btu)	Electricity (10^9 kWh)	Materials Labor (10^6 1976 \$)	Capital Service (10^6 1976 \$)	Capital Stock (10^6 1976 \$)	Operating Cost (10^6 1976 \$)	Total Cost (10^6 1976 \$)
Price (10^6 1976 \$/unit)	1.00	1.00	1.50	2.00	17.90	1.00	1.00			
1 A	1.048					0.610	1.253	28	1.658	2.911
2 B	1.180				-0.0383	0.582	1.536	36	1.077	2.613
3 C	1.217				-0.0490	0.585	1.544	36	0.925	2.469
4 D	1.249				-0.0585	0.585	1.545	36	0.788	2.333
5 A		1.026				0.654	2.063	43	1.680	3.743
6 B		1.165			-0.0401	0.622	2.325	51	1.068	3.393
7 C		1.204			-0.0516	0.625	2.338	51	0.906	3.244
8 D		1.239			-0.0617	0.625	2.339	51	0.760	3.099
9 A			1.026			1.199	2.686	56	2.738	5.424
10 B			1.165		-0.0401	1.140	2.918	64	2.169	5.087
11 C			1.204		-0.0516	1.146	2.888	63	2.029	4.917
12 D			1.239		-0.0617	1.146	2.843	62	1.900	4.743
13 A				1.026		0.327	1.343	28	2.379	3.722
14 B				1.165	-0.0401	0.311	1.641	36	1.922	3.563
15 C				1.204	-0.0516	0.313	1.650	36	1.798	3.448
16 D				1.239	-0.0617	0.313	1.651	36	1.686	3.337

^aBased on Major Boiler Model, Table A-12. Price of coal, oil, gas, and electricity from the Annual Survey of Manufactures (4). Energy conservation efficiencies and price of bark and spent liquor are Oak Ridge National Laboratory estimates.

^bBased on data from EEA (5). The annual operating cost for coal and oil/gas boilers with a capacity of 100,000 lb/hr are 550,000 1976 \$ and 150,000 1976 \$, respectively. Our estimate for a similar spent liquor or bark boiler is 300,000 1976 \$. Using data from Table A-13, a spent liquor boiler with a capacity of 100,000 lb/hr produces 0.492 billion pounds of process steam per year. Thus, the operating cost for the boiler is $300,000 \div 0.492 = 610,000$ 1976 \$ per 10^9 pounds of process steam. Similar calculations yield the other estimates for the operating (materials and labor) cost.

^cCapital cost estimates for boilers and generators from (16) and (17). The price of capital is 22%/yr. The cost per billion pounds of process steam is determined by the data in Table A-13. For example, a spent liquor boiler with a capacity of 100,000 pounds of steam per hour produces 0.492 billion pounds of process steam per year. The capital cost is 2.8 million dollars. At 22%/yr the annual capital charge is 0.616 million dollars or 1.253 million dollars per billion pounds of process steam.

^dThe operating cost is the sum over all factors except capital of price times the I-O coefficients.

^eTotal cost is the sum of operating cost and the cost of capital.

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P.O. Box 117
Oak Ridge, Tennessee 37830