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Electricity In Lieu of Natural Gas and Oil for Industrial Thermal Energy: A Preliminary Survey

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NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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ABSTRACT

In 1974, industrial processors accounted for nearly 50% of the nation's natural gas consumption and nearly 20% of its consumption of petroleum. This report is a preliminary assessment of the potential capability of the process industries to substitute utility-generated electricity for these scarce fuels. It is tacitly assumed that virtually all public utilities will soon be relying on coal or nuclear fission for primary energy.

It was concluded that the existing technology will permit substitution of electricity for approximately 75% of the natural gas and petroleum now being consumed by industrial processors, which is equivalent to an annual usage of 800 million barrels of oil and 9 trillion cubic feet of gas at 1974 levels.

Process steam generation, used throughout industry and representing 40% of its energy usage, offers the best near-term potential for conversion to electricity. Electric boilers and energy costs for steam are briefly discussed. Electrically driven heat pumps are considered as a possible method to save additional low-grade energy. Electrical reheating at high temperatures in the primary metals sector will be an effective way to conserve gas and oil.

A wholesale shift by industry to electricity to replace gas and oil will produce impacts on the public utilities and, perhaps, those of a more general socioeconomic nature.

The principal bar to large-scale electrical substitution is economics — not technology.

1. INTRODUCTION

This report contains the results of a preliminary study conducted in 1976 and 1977 to evaluate the potential for substituting electricity for energy-consuming industrial processes that now rely on natural gas and petroleum. The goal of electrical substitution, where feasible, is a step toward achieving national energy independence based on ample reserves of coal and fissionable materials. The national need to employ technologies that permit the channeling of natural gas and petroleum into uses for which there are no substitutes has been well recognized but sparsely implemented.

The winter of 1976–1977 has focused attention not only on the reality of the general nationwide shortage of natural gas[1-17] but also, more specifically, on the distressing consequences of supply failures in an industrial energy system that places complete reliance on an unending, uninterrupted flow of natural gas and oil.

The priorities governing allocation of natural gas during critical shortages are well established; industrial users are the first to suffer cutbacks and shutdowns. The industrial sector now requires 20 to 25% of the natural gas and oil for 55 to 60% of its energy. Table 1 presents, briefly, the U.S. energy distribution for 1974 as compiled by the Federal Energy Administration (FEA).[18] Table 2 shows the approximate end-use distribution of energy in the industrial sector of our economy.[19] The FEA data also show that, in 1974, industrial consumption of natural gas and petroleum exceeded the amount used for transportation. Energy usage patterns in the residential and transportation sectors may not be immutable, but they are not susceptible to appreciable alteration in the near future. There are few or no near-term alternatives to natural gas and petroleum as energy sources for the residential and transportation sectors. Without additional supplies of gas and/or oil, the only effective near-term solution that will maintain a continuing supply of energy, at reasonable costs, for these two groups of users is to substitute

Table 1. Total U.S. and industrial energy consumption[a] in 1974

	Source energy					Totals
	Natural gas	Petroleum	Coal	Hydro and nuclear[b]	Distributed electricity[b]	
U.S. totals						
10^{12} kWhr(t)	6.33	9.79	3.92	1.30		21.3
10^{15} Btu	21.5	33.4	13.4	4.4		72.7
Industrial						
10^{12} kWhr(t)	2.96	1.79	1.23	0.01	2.35	8.3
10^{15} Btu	10.1	6.1	4.2	<0.10	8.0	28.4
Percent, source total	47	18	31	∿0	28	
Percent, U.S. total, all sources	14	8	6		11	39

[a]These data derived from *Monthly Energy Review*, Federal Energy Administration, National Energy Information Center, Washington, D.C. (March 1976).

[b]The primary energy required to generate electricity is estimated by assuming an efficiency of 32%.

Table 2. Energy consumed by industry in 1968[a]

End use	10^{15} Btu	10^{12} kWhr	Percent of industry total	Percent of U.S. total
Process steam	10.1	2.96	40.6 } = 69%	16.3 } = 27%
Direct heat	6.9	2.02	27.7	11.17
Electrolytic processes	0.7	0.21	2.8	1.1
Electric drive	4.8	1.41	19.3	7.7
Feedstock	2.2	0.64	8.8	3.5
Other	0.2	0.06	0.8	0.3
Total	24.9	7.30	100.0	40.0

[a]These data were derived from Table 4 of Ref. 19.

other forms of energy for the gas and oil now being used for thermal energy in industrial processes. After a realistic appraisal of the options, it was concluded that the choices are

1. Thermal energy developed with nuclear fuel and supplied as electricity, direct heat, or both.
2. Thermal energy developed by burning coal and supplied as electricity, direct heat, or both.

With a few exceptions, industrial processors have not considered electricity an acceptable substitute for the burning of natural gas and fuel oil as a source of thermal energy. This now somewhat traditional viewpoint was well founded when gas and fuel oil were inexpensive and abundant. Forecasters generally agree that costs will rise and that shortages will continue and become more severe. It has been assumed that either or both of these forecast trends will prevail; therefore, a reexamination of the potential role of electricity in industrial processing systems has been initiated. For the purposes of this study, it has also been assumed that the additional electricity needed for substitution will be most effectively generated with large, efficient, utility-operated central stations. The advantages of central station power to the industrial user are considered to be as follows:

1. Any process capable of accepting electricity as a substitute for gas or petroleum will be entirely insensitive to the choice of primary energy, whether it be coal or fission. Fission-produced electricity is now the exclusive property of the utilities. Regardless of how electrical power is generated, the potential for electrical substitution will not be altered drastically.

2. The capital and operating costs charged to environmental protection will be borne by the utility and, to a degree, shared by all customers; hence, these charges will have reduced impact on the industrial user.

3. In situations where electricity is or will become the preferred choice, a typical central station, large compared to an industrial facility, offers improved overall thermal efficiency and the economy of scale as it affects funding and operating costs.

4. Increasing the industrial usage of electricity may enable a reduction in the cost of producing and delivering electrical power. This will take place if the generating stations are able to operate continuously at load factors that are at or near, but not over, design base loads. A large-scale industrial conversion that increases the usage of utility-produced electricity will also increase the number of central stations. A large network of interconnected power sources is in a much better position to continuously optimize their operation.

2. EXECUTIVE SUMMARY

The results, conclusions, and, in some cases, recommendations contained in this brief summary are amplified with additional details in subsequent sections and appendices of this report.

General Conclusion

Based solely on technological considerations, utility-generated electricity is capable of replacing at least 75% of the natural gas and oil now being used by industrial processors. Economics dominates industry's ability to substitute electricity (or any other fuel) for natural gas and petroleum. A realistic appraisal that quantifies the economic aspects of electrical substitution will substantially reduce, but by no means eliminate, this hypothetical 75% potential.

Electricity Rate Design

The future costs of electricity as compared with the costs of thermal energy developed with fossil fuels are likely to exert more influence than any other factor on the incentives and ability of industry to increase its use of electricity. Traditionally, industrial users of large amounts of electricity have received cost discounts. A variety of alternative rate designs is undergoing intensive study by regulators, legislative bodies, public utilities, industrialists, and public interest groups. The outcome is conjectural.

Conversion Costs

This summary is based on conversations with industrial managers and on recent articles in the technical journals and the news media. References 20–40 are typical.

With but few exceptions, industrial processors have been reluctant to voluntarily commit the large amounts of capital required to substitute coal for natural gas and oil. Concentrated efforts to conserve energy by improving the efficiency of existing processing systems that use gas and oil have been and are under way. These conservation efforts will enter, or already have entered, the region of diminishing returns. They do not address the long-term goal of reducing industrial dependence on natural gas and oil. In recent times, funds available for capital spending have not been abundant. The current trend of capital spending is for projects that offer a high probability of a satisfactory return in the short term. The abundance and future costs of industry's basic energy sources (including electricity) are controversial and uncertain. The future trends of prohibitions and restrictions on energy usage imposed by legislative and regulatory agencies are indeterminate. The result is an economic climate that does not favor a program of intensive, long-term-gain capital spending by industry to restructure its energy systems.

Process Steam Production

From 40 to 50% of industry's energy usage is in the form of process steam now being produced almost entirely with natural gas and petroleum. There are no technological barriers to producing a major fraction of this steam with electrical boilers; the hardware has been well developed and is in use. Steam generation with electricity is discussed in Sect. 9 and in Appendix B.

Primary Metal Production and Fabrication of Finished Products by Secondary Users

Well over 50% of the natural gas consumed by steel mills, foundries, forge shops, and heat treating facilities is replaceable with electricity. Electric melting in foundries and steel mills is increasing; very high power induction heating is capable of supplanting large amounts of gas and oil used in furnaces that require very large amounts of thermal energy and in areas experiencing shortfalls of above-average severity.

Pulp, Paper, and Paperboard

Pulp, paper, and paperboard are very energy-intensive products. Their production requires large amounts of energy at relatively low temperatures; process steam is the principal medium for energy transfer. Modern pulp mills derive over 40% of their energy from in-plant-produced waste products. More than 90% of the remainder can be developed using electricity and without requiring extensive new technology. High-voltage electrode boilers are now in use as electrical load molding components in West Coast pulp mills.

The application of high-capacity heat pumps for waste heat recovery deserves additional study.

Glass Production

Glass producers now use large amounts of natural gas and oil for melting and lesser amounts in annealing ovens. Successful and efficient electrical melting furnaces are in continuous operation. A well-known company is installing a completely electric melting line. Annealing ovens operate at lower temperatures, and electrical substitution for this purpose is readily accomplished. This industry can become virtually independent of large supplies of gas and oil.

Brick Manufacturing

Until recently, brick producers have relied on natural gas for almost 90% of the energy for moisture removal and vitrification of bricks. The prospects for substituting electricity are very poor; it is being demonstrated in production that coal-fired brick kilns are a feasible method that eliminates dependence on natural gas and petroleum.

Hydraulic Cement

In common with the manufacturers of bricks and refractories, cement producers have relied heavily on natural gas and oil. Coal is an acceptable substitute kiln fuel, and conversion is under way. The potential for substituting electricity instead of coal is low.

Food and Related Processes

With but very few exceptions, the energy used by food and related processes is at the low temperatures required for cooking, baking, drying, sterilizing, pasteurizing, etc. Process steam is used extensively. The potential for electrical substitution is excellent, particularly in plants that operate for only a part of the year or that experience wide daily variations in their energy requirements. Very large plants for wet corn milling and sugar production which must operate continuously for long periods of time and at high load factors to be profitable may favor in-house coal-fueled boilers to make steam. Nevertheless, with abundant electrical power, the food industry need not rely on natural gas and petroleum.

Wood and Lumber

The wood and lumber industries develop much of their energy from waste products produced within their processing operations. Their thermal energy is used at low temperatures for such purposes as kiln drying and glue curing. Energy needs not met by waste-product combustion can be filled electrically with electrode boilers, radiant heaters, and radio-frequency heating.

Chemicals and Petroleum

The chemical and petroleum processing groups rank first and third in total industrial energy consumption in the United States. Taken together, they account for 6 to 7% of the total energy used by all consuming sectors in the United States. They have so much in common that it is appropriate, for the purposes of this summary, to consider them together (the word "petrochemicals" is illustrative). Energy usages are noted, briefly, in Appendices K and L. Areas of commonality include the following:

1. Both are heavily dependent on petroleum and natural gas for energy and feedstock.
2. Processing methods, distillation, cracking, and reforming, for example, are often similar.
3. The major fraction of their energy consumption is for process steam and for direct heat at medium [<649°C (1200°F)] and low temperatures.
4. Competition is intense. Both groups are heavily staffed with engineers and scientists in order to maintain and advance their competitive position.

The refiners and chemical processors are theoretically capable of substituting electricity for about three-quarters of their total process energy (not including feedstock), with little or no advanced technology.

Because the large-volume producers of energy-intensive chemicals and the refiners are acutely, often painfully, aware of the growing problems involving energy shortages, they are making concerted efforts to reduce their dependence on natural gas and petroleum for process energy.

A qualified forecast of either the near- or far-term practicable potential for electrical substitution in these processes is well beyond the scope of this report. In view of the producers' and refiners' awareness and engineering capabilities, it is reasonable to assume that electrical substitution will be adopted whenever and wherever it is most logical to do so.

Heat Pumps, Waste Heat, and Energy Storage

Large, industrially sized heat pumps are on the verge of becoming economically acceptable machines to upgrade large-volume flows of low-grade heat to usable temperature levels. Additional engineering development that increases the high-temperature capability is needed.

In a consortium of industries with processes that span a wide range of temperatures, heat pumps plus energy storage systems would enable the recovery of large amounts of heat now being wasted. Appendix C contains additional information.

Economics and Related Factors

The original intent of the survey was to focus on the technical aspects of electrical substitution. The impact on the public utilities of a large-scale, near-term conversion to electricity by industry was not investigated; neither was our national capability to provide the necessary engineering effort and to produce the hardware. Derivative socioeconomic effects may result. These facets of oil and gas conservation and electrical substitution deserve additional close attention.

During recent years, an abundance of articles and news items has appeared in the trade and financial journals on the trends of capital spending.[20-40] Although opinions vary, on balance, many industries appear to be experiencing capital shortages or, when and if capital is available, they seem reluctant to spend it for high-risk, long-term-gain projects. It is concluded that

1. Those industrial managements possessing resources available for capital investment are using these funds to maintain or improve their near-term competitive position. Cost-benefit analyses applied to these ventures can be used with a relatively high degree of confidence.

2. Substantial investments are required to improve energy efficiencies or to shift from gas and oil to energy derived from coal or fission. Future benefits cannot be predicted with confidence. Low confidence is a result of an inability to forecast the long term trends of (a) fuel costs as influenced by regulation and legislation; (b) the costs of environmental protection; (c) interest rates, taxes, and operating costs; (d) scarcity levels of domestic gas and oil; (e) the price increases of both foreign and domestic oil; and (f) the regulated costs charged by utilities for electricity and the rate designs used to determine these costs.

It became equally apparent that economic considerations are controlling the rate at which industry is initiating measures that reduce consumption of gas and oil by conservation or by substitution of alternative energy sources.

3. SURVEY METHOD

The survey was accomplished by (1) selecting specific process industries that require substantial amounts of thermal energy, (2) obtaining a degree of familiarization with the particular processes involved, (3) assessing the impact of current and anticipated energy shortages on the particular industry, and (4) conducting discussions with the managements of the various industries surveyed and with representatives of the public utilities.

4. RECOMMENDATIONS

1. Studies that evaluate the overall costs of making process steam using fossil fuels and electricity should be initiated. Comparative

costs will determine the potential applications of electrical steam generation in the near future. These parametric cost studies, conducted cooperatively with industry and architect-engineers, would take into account:

A. Anticipated, credible energy cost scenarios that include
   1. Costs and supplies of natural gas, fuel oil, coal, and fissile fuels as functions of time and by regions.
   2. Costs of purchased electricity now and in the future. The price of power as it is affected by the various rate designs being proposed should be included as a parameter.

B. Operating costs, present and future, consisting of
   1. Operating labor.
   2. Operating material exclusive of fuel costs that are segregated according to item A above.
   3. Taxes.
   4. Insurance.
   5. Maintenance.

C. Operating costs and energy usage as they are affected by the temporal characteristics of the entire processing system, viz.,
   1. Is steam used continuously and uniformly, or does the need fluctuate?
   2. If the steam plant load does vary, by how much and on what time scale?
   3. What are the probabilities and costs of unscheduled shutdowns or reductions in operating levels?
   4. How efficient is steam usage within the plant?

D. Capital costs of both new and replacement facilities as influenced by
   1. Plant size.
   2. Plant location.
   3. Environmental requirements.
   4. Payback time(s).
   5. Income tax credits.

E. The results of this study should, in part, be summarized by developing and reporting the costs of industrial steam system designs using gas, oil, coal, and electricity and based on a representative spectrum of steam-using processes. Both new plants and retrofits to existing facilities should be included.

F. Ideally, the study will produce an easily understood, easily used methodology that will be available to assist those involved in choosing energy sources for process systems using steam.

2. The potential for electrically powered heat pumps designed for industrial applications should be identified. This involves

   A. Locating and evaluating the potential usefulness of low-grade heat sources in industrial processes.

   B. Locating potential nonindustrial waste heat sources that, with engineering development, are possible thermal energy reservoirs for industrial heat pumps.

   C. Developing proposals for research and development to extend the operating temperature range of industrial heat pumps.

   D. Evaluating the economic benefits, current and anticipated, of heat pumps in a manner similar to that proposed for process steam facilities.

3. The additional applied technology that is required to substitute electrical reheating for the natural gas and oil used in the primary metals sector should be identified. This will lay the foundation for engineering development programs, including demonstration facilities, that are directed to reducing these users' dependence on natural gas and fuel oil.

4. Assessments of the more commonplace uses of electricity to develop processing temperatures less than 538°C (1000°F) should be initiated. Methods and applications should be described, costs quantified, and the results disseminated to users concerned with shortages of gas and petroleum.

5. Conceptual designs of highly electrified processing facilities should be developed. The construction and operation of demonstration plants that proceed from these designs should be considered.

6. The impacts of large-scale conversions by industry from natural gas and petroleum to electrical energy derived from coal and nuclear fission should be identified and, wherever possible, quantified. Attention should be given to
   A. The abilities of capital equipment fabricators to produce the necessary hardware.
   B. The environmental impacts.
   C. The impacts of very large increases in demand for electricity on the public utilities.
   D. The possibility of producing long-term social, economic, and demographic changes across the country.

5. SOCIAL, ECONOMIC, AND DEMOGRAPHIC IMPACTS

A large-scale or wholesale shift by industry to electricity as the source of process energy may produce economic and social changes that extend beyond effects associated with immediate product costs. For the purposes of preliminary assessment, it is sufficient to speculate and suggest possible causes and consequences.

1. Electricity as a source of thermal energy will consume more primary energy in the form of coal or fissionable material than if these energy sources are used directly for heat. How will the increased fuel depletion rates affect our national welfare many years hence?

2. Electricity is produced most efficiently in medium-to-large generating stations and is used most efficiently at or near the generation site. Few, if any, plant processors are capable of using all the energy developed by a large, efficient coal- or fission-based generating station. Does this aspect of electrical substitution increase the future likelihood of a diversity of processors occupying industrial parks or newly developed urban areas centered on large, central-station generating plants? Alternatively, because electricity is so easy to transport and distribute, will a heavily electrified industrial economy tend to produce industrial dispersion? Both scenarios are possible when energy is reliably available, when the cost of energy does not dominate the product's market price, and when all competitors receive equal

treatment. For example, industrial leaders are of one voice in eloquent advocacy of natural gas price deregulation.[41-46] The underlying philosophy equates deregulation to a return of equal abundance for all competitors.

Transporting coal requires energy and costs money. If measured at the generating station terminals, the cost of energy will be reduced if the generating stations are located at or near the coal mines. If energy costs become a more significant fraction of product costs, will processors locate or relocate to areas with large coal supplies? The resultant population shifts will have far-reaching social and economic consequences.

Regardless of demographic pattern, it is recognized that the very large long-term expansion in electricity production required for wholesale industrial electrification will generate consequences not capable of evaluation using hard technology and typical engineering-economic analyses. For example, Rock Springs and Wright, Wyoming, have developed almost overnight from train stops to boom towns[47,48] as a consequence of intense coal mining in the vast coal beds in this region. Arizona, experiencing industrialization and a 20% population growth by migration during the period 1970–1976, has developed acute water shortages.[47] In Germany, thousands of persons are being relocated to make way for lignite strip mining.[49] Large-scale industrial conversion to electricity may affect land and water usage, transportation loads, employment, and tax burdens and may produce geographical population shifts.

The impacts of large-scale, near-term, industry-wide conversions from primary energy derived from natural gas and petroleum to primary energy derived from coal[50,51] and nuclear fission are, to an extent, being identified and quanitifed. Attention should be given to

a. The abilties of capital equipment fabricators to produce the hardware required to convert and their response to a temporary, near-term need for greatly expanded productive capacity.
b. Evaluation of the effect of concentration of future capital outlays for the sole purpose of restructuring industrial energy usage and the consequences of diverting funds from other needs.

c. The environmental impacts brought on by the increased tonnages of coal that will be mined, hauled, stored, and burned[52,53] if nuclear energy production is not expanded to meet the needs of industry.[54]

d. Determining whether or not we possess a sufficiency of qualified technical personnel to get the job done.[55]

3. The impact on the public utility systems, if called upon to meet a very large increase in electricity demand, is not debatable.[56-60] In some areas the utilities are now strained to meet peak demands for power. There is mounting evidence that the utilities will be overloaded in the not-too-distant future. If, based on 1974 figures, industry were to replace 75% of its natural gas and petroleum usage with utility-generated electricity, the utilities would experience a 60% increase in demand if the usage efficiencies of electricity equaled those of oil and gas. With respect to the sum total of all heat-using processes (steam production, for example), electricity cannot be applied as efficiently as gas and oil, and thus the demand increment would exceed 60%. The reflected impact on coal supply capabilities (if no nuclear capability is involved) will amount to trebling the 1974 tonnages delivered to the utility sector.

The necessary capital expenditures can be measured only in billions. Alternatively, if electricity becomes attractive or necessary as the principal source of process energy, will industrial users form power generating consortiums designed exclusively to produce processing heat and power for the members and to do so at the lowest cost? These captive power stations presumably would be free from governmental rate regulation and, in many cases, would incorporate the industrial park concept but without providing power to the citizenry. A possible by-product will be a reduction of load factors of existing public utilities with a consequent loss of efficiency.

6. ELECTRICAL SUBSTITUTION FOR THE LOW- AND INTERMEDIATE-TEMPERATURE HEAT REQUIRED BY INDUSTRIAL PROCESSORS

Assuming an ample supply of utility-generated electricity, the industrial processes using energy at low and intermediate temperatures

[<538°C (1000°F)] are logical, front-running candidates for substitution of electricity to reduce our consumption of natural gas and fuel oil. The principal reasons are as follows:

1. More than 50% of the U.S. industrial energy is expended at these low temperatures.[61-64]

2. The components and methods required to effect conversions that produce low-temperature energy with electricity have been designed and developed. Typical industrial applications of electricity that require little or no additional technology include resistance heating in electrical ovens for baking and drying and in electrode boilers to make hot water and process steam, radio-frequency heating for baking and glue drying, and radiant heat for paint and enamel drying.

3. Process steam (Table 2 and Refs. 61–63) is the single largest means of transferring and applying industrial energy. Coal-fired process steam generators have been uneconomical in plants using less than 250,000 lb of steam per hour when natural gas or fuel oil has been available.[65] A large number and variety of processing facilities use less than this amount of steam per hour. The other alternative to natural gas and fuel oil is electricity. If economic pressures dictate a large-scale reduction in U.S. natural gas and oil consumption, process steam generation, accomplished electrically, will effect a reduction of about 25% of the U.S. consumption of natural gas and will substantially increase the supply of petroleum for uses outside industry. Electrical generation of process steam is discussed in greater detail in Sect. 9 and Appendix B.

The following industries use large amounts of low-temperature energy: food and related products, pulp and paper, wood and wood products, and petroleum and chemicals. All these applications are capable of becoming virtually independent of natural gas and oil for energy if electricity is an available substitute. A host of processes using lesser amounts of energy as heat are in a similar situation.

7. SUBSTITUTION OF ELECTRICTY IN HIGH-TEMPERATURE PROCESSING

Not all higher-temperature [>538°C (1000°F)] energy-using processes are capable of adopting electricity as an acceptable substitute for fossil fuel. Several energy-intensive, high-temperature processes were surveyed in a preliminary way. The results, qualitatively, as they bear on electrical substitution, follow.

Primary Metals and Foundries

1. Melting of metals by steel producers and foundries is being done with electricity. Open-hearth furnaces are being phased out, and it is likely that all melting of pig iron and scrap will soon be done with electricity.

2. Reheating by primary steel producers, over a wide range of temperatures, uses very large amounts of oil and natural gas. The broad technology for electrical reheating has been developed and is in limited use.[66-70] Reduction of this technology to practice for acceptable use in continuous, high-production-rate steel making will require extensive development of a wide range of very high power components and equipment.[71] Electricity for reheating steel is technologically capable of replacing as much as 80% of the natural gas used by large integrated steel plants.[72] Since iron and steel production accounts for approximately 5% of industry's total gas usage and takes place in areas experiencing shortfalls and curtailments, the potential benefit of electrical substitution is significant.

3. Heat treating to produce specified physical and electrical properties in finished or semifinished metal products is now frequently being accomplished with electricity, but gas furnaces are in extensive use. From the standpoint of existing technology, a very large percentage of the natural gas used in these applications is replaceable with electricity. Relatively small amounts of hydrocarbon gases will be required to maintain correct furnace atmospheres.

4. Iron ore reduction, accomplished in blast furnaces, requires coke as the fuel. Low-Btu blast furnace gas and waste heat are used to

produce steam[73] for electricity, for turbine-driven blowers, for heating pickling vats, for cleaning, and for similar miscellaneous uses.

5. The production of copper and aluminum requires appreciable energy for electrolytic refining. Electric melting of copper is entirely practicable. Kellogg[74] reports energy efficiencies, referenced to the base fuel, of 43% for gas-fired shaft furnaces and 24% for arc furnaces. Agarwal and Sinek conclude: ". . . Consequently, total capital is the main criterion when deciding between such process options as, for example, electric versus fuel-fired smelting of calcined copper concentrates . . ."[75]

Viewed solely from the standpoint of technology, very large percentages of the natural gas and oil used in the primary metals industries are replaceable with electricity. Additional discussion of electrical substitution in primary steel production is in Appendix D.

Glass Production

Glass manufacturing is very energy intensive. Gas and oil are the predominant fuels used for melting — the principal energy sink. Electrical melting has been reduced to practice,[76] and electric melters are commercially available. Annealing, at intermediate temperatures in the 399 to 538°C (750 to 1000°F) region, presents no major problems that impede conversion to electricity.

The capital costs of removing existing facilities, replacing them with electrically powered furnaces, and doing so with acceptable payback are a major deterrent.[77] Appendix F provides additional information.

Bricks and Refractories

Construction brick plants have been largely dependent on natural gas or oil as fuel. It is now being demonstrated by a large producer that coal is an acceptable substitute.[78] Unless technology shows the way to speed up the chemical changes (induced by high temperatures) which produce vitrification of clays, there is little incentive for electrical substitution. Appendix G contains additional discussion.

There is little reason to believe that the patterns of energy usage in manufacturing tile and refractories are markedly different.

Portland Cement

Conversion to direct usage of coal is in progress. The possibility that electrical substitution will be effective is remote.

Waste heat from high-temperature processes is a potential source of prime energy for lower-temperature processes. Heat pumps and energy storage will be effective tools if further developed for industrial applications. Systems analyses that forecast and evaluate the energy performance obtained with multi-industry consortiums are required to quantify their potential.

8. MODIFICATION OF ESTABLISHED PROCESSING FACILITIES FOR ENERGY SUBSTITUTION AND CONSERVATION

A large number of the energy-using processing plants in the United States were built when the availability of fuel oil and natural gas was considered unlimited and their costs were low. In many cases the efficient use of energy was not a primary consideration among process designers and plant operators. The environmental constraints on energy usage were moderate. Plant designs and layouts, locations, and property acquisitions did not include planning a capacity for future conversion from fuel oil or natural gas to alternative energy sources such as coal or electricity. To varying degrees, industrial processors have become aware of the inefficiencies within their operations. It is not always possible to translate this awareness to corrective actions in the form of conservation or substitution. A process manager, examining the pros and cons of retrofit in existing plants to conserve or to substitute, will address these questions among many others:

1. Is space available to add the components required to conserve or substitute? If not, what will be the cost of acquisition?

2. If electrical substitution appears to be a feasible solution within the processing plant, will the electrical distribution system

sustain the additional load? Are the voltages now available suitable for the equipment required by substitution? If not, what will it cost to provide additional distribution lines, transformers, and switchgear? Who bears the cost of these items — the processor or the utility?

3. Does the public utility serving this region have sufficient reserve capacity to accept the increased demand brought about by substitution?

4. What are the costs involved in the plant shutdown that may be required to install the necessary equipment?

5. A choice between electricity and coal as a substitute for gas or oil involves not only the capital cost difference, often in favor of electricity (see Sect. 9), but, in addition, the processor may be a victim of urbanization. Factories and mills, once isolated from residential areas, are now frequently surrounded by well-populated housing areas. Environmental problems are more severe; zoning boards, planning commissions, and public pressures from local residents become prominent elements in decisions. The choices may narrow to three, viz:

a. Move and rebuild.

b. Shut down completely.

c. Use electricity because it is clean, occupies little or no additional space, creates no local pollution, requires no unsightly coal yards, and creates no additional traffic problems.

If these conditions exist, a strong case for electrical substitution results.

These are problems that are associated primarily with existing processing facilities. New, "greenfield" plants may be sited and designed to bypass many problems associated with retrofitting.

Plant managers are becoming increasingly aware that reliance on continuing, low-cost supplies of natural gas and fuel oil is a hazardous policy. They are aware because (1) they possess vision and accurate perceptions of unalterable future trends; (2) in many cases, their gas supply is now subject to curtailment and interruption; or (3) gas and oil prices have suddenly increased.

Plant operators and the money managers are acutely aware of the costs and operating complexities required to meet environmental standards. This facet of plant design and operation is given close attention when new plant designs or alterations to existing systems are considered. Heat produced with electricity is inherently clean. The capital and operating costs required to obtain and maintain acceptably clean heat with fossil fuels are not negligible; with coal they may be prohibitive.

9. COSTS OF AND PROSPECTS FOR THE DIRECT ELECTRICAL GENERATION OF PROCESS STEAM

Energy Cost

The production of chemicals, primary metals, petroleum products, pulp and paper, wood products and building materials, food and kindred products, manufactured products, and textiles requires process steam. We have noted that 40 to 50% of industry's energy needs are for steam production. The technology for electrical steam generation (Appendix B) is well established. Since steam generation with electricity offers the largest potential for electrical substitution by a large margin, it is appropriate to examine the economic pros and cons of using utility-generated electricity instead of burning the conventional fossil fuels. Engineering managements faced with replacing or expanding existing facilities or building new facilities for making process steam will take into consideration the following energy scenarios.

1. Oil, natural gas, and coal will continue to be available. The prices of these fuels will escalate at rates that are greater than the escalation rate of purchased electricity or equal to the escalation rate of purchased electricity.
2. Oil and gas, regardless of price, will become scarce, and industrial allocations will be restricted or curtailed on a seasonal basis. This condition now exists in several localities.[1-19,79-101]
3. The shortages of gas and fuel oil will become so acute that industry will voluntarily choose between burning coal or purchasing electricity.

4. With but few exceptions, local, state, and federal regulatory authorities will not permit industrial processors to burn natural gas or petroleum. In a limited way, such prohibitions are taking place.[102-107]
5. Regardless of forecast trends of costs and supplies of fossil fuels, the local utility is now unable to supply additional demands for a continuous supply of electrical power. This situation now prevails in some localities.[14,50,51,56-60]
6. The continuing evolution of electrical rate designs will either favor or discourage the industrial use of large amounts of utility-generated electricity.

With reference to item 6 above, the design of regulated utility rates has become a subject for active controversy among all elements of society and a matter of great concern to industry and the utilities.[108-113] Uhler[114] is directing a very comprehensive* rate design study[115] being undertaken jointly by the Electric Power Research Institute (EPRI) and the Edison Electric Institute. The Electricity Consumers Resource Council (ELCON) has been formed to amplify and publicize[116-118] the rate design policies advocated by a group of industrial companies that use large amounts of electricity. Consumer groups are also active. The literature on the subject of rate-making is large in volume[119] and growing. No final outcome has been reached; the issue is cloudy and no conclusions are drawn or predictions made in this report.

It is not within the purpose or scope of this report to quantify, in forecasts, energy supplies and the future costs to industry for raw energy. The consensus is that low-cost natural gas and oil are becoming scarce and that, ultimately, natural gas and fuel oil prices will rise at substantial yearly percentage rates.

Coal costs will also rise. Mine mouth costs may follow the same trend as those of gas and oil. Interstate rail and truck rates are rising and currently experiencing a degree of deregulation.† If the trend continues,

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*This program is being documented continuously in a series of reports (numbering more than 40); as of Oct. 26, 1978, more than 60 had been issued.

†"White House Moves Quickly Toward Railroad Deregulation," news article, The Knoxville News-Sentinel, Jan. 14, 1979.

the usual economic indicators used to forecast costs during the near future may not apply. Articles in the financial journals indicate that deregulation will produce very appreciable increases in transportation rates.

If the effects of availability (as evidenced by interruptible contracts and curtailments) are neglected, natural gas is less expensive per Btu available for steam generation than electricity. Figures 1 and 2 show break-even and equivalent costs of fossil fuels and electricity for steam generation. A note of caution — these break-even comparisons do not take into account the energy losses associated with startups and shutdowns, load changes, and blowdowns. From Fig. 2, if fuel costs to generate steam are the only variable of consequence and if electricity costs $0.02/kWhr, the current and equivalent costs shown in Table 3 result.

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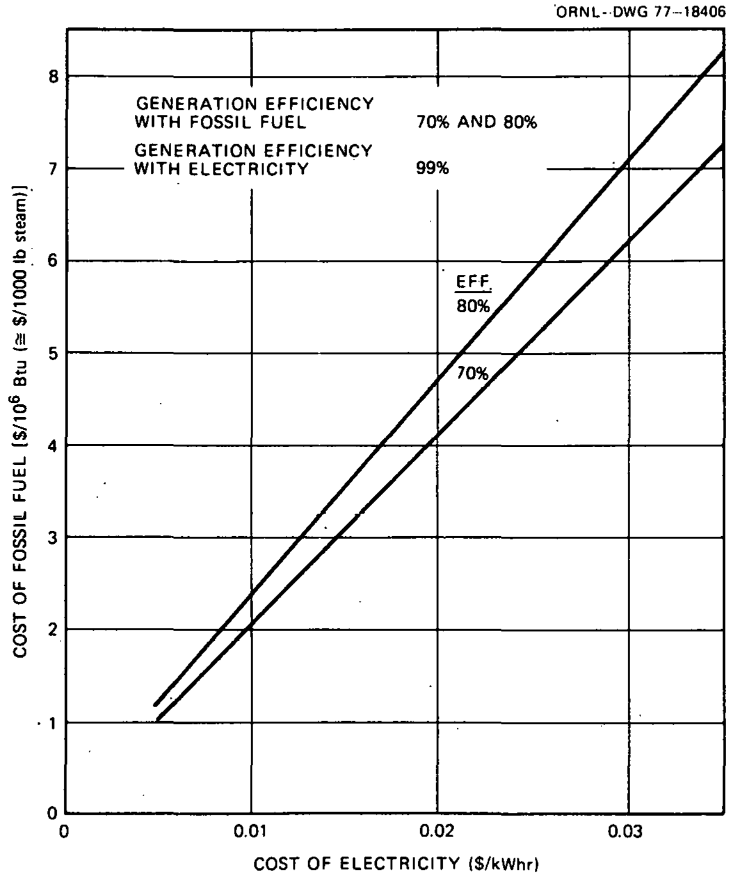

Fig. 1. Break-even costs of fossil fuel electricity for process steam generation. Generation efficiency with fossil fuel — 70 and 80%. Generation efficiency with electricity — 99%.

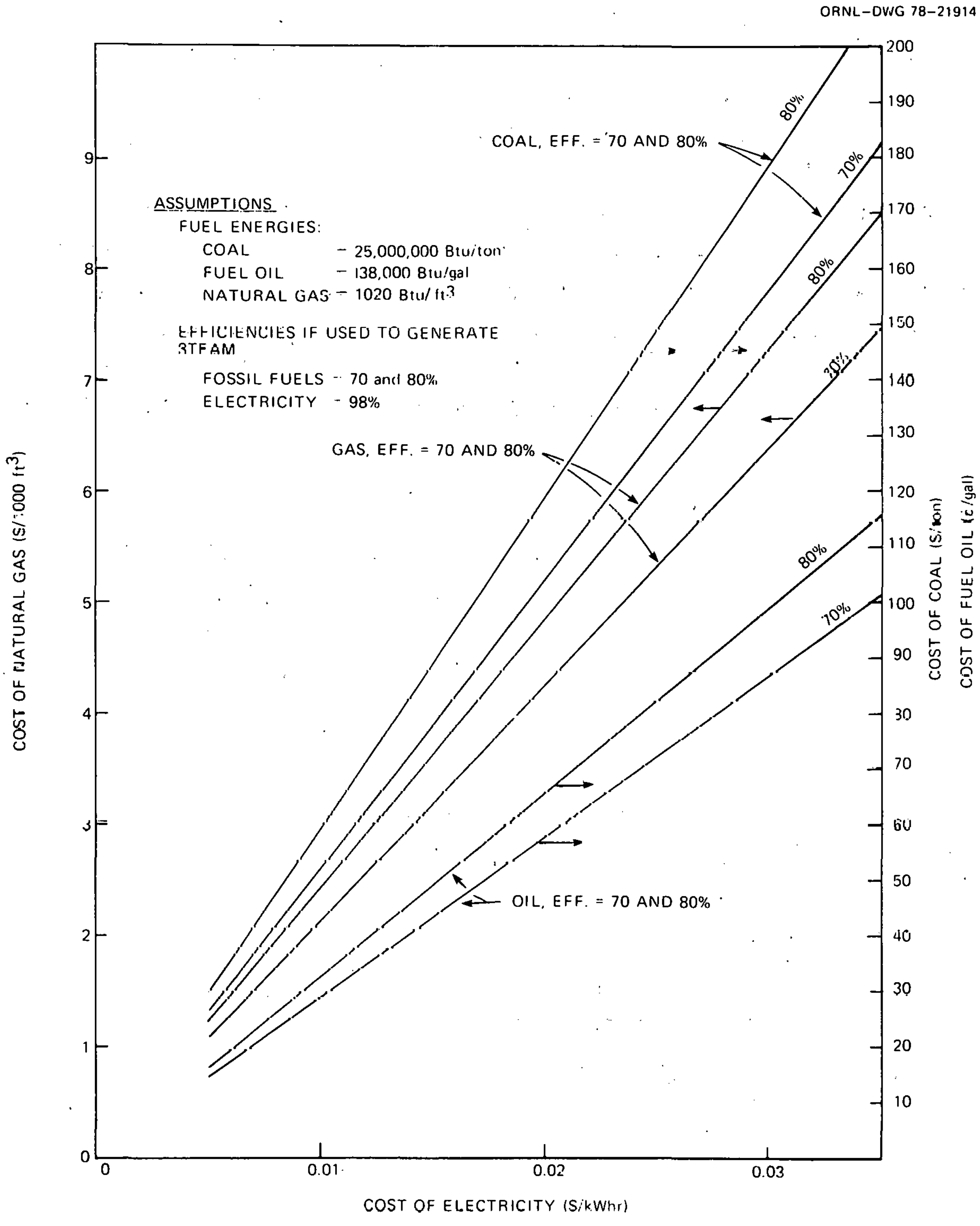

Fig. 2. Estimated equivalent costs of fossil fuels and electricity when used to generate process steam.

Table 3. Equivalent costs of fossil fuels to electricity at $0.02/kWhr

Energy source	Approximate price range, 1976–1977	Electricity equivalent price (Fig. 2)
Electricity, $/kWhr	0.02	
Natural gas, $/1000, ft^3	1.00–2.00	4.25–4.85
Fuel oil, $/gal	0.30–0.40	0.58–0.66
Coal, $/ton	15.00–40.00	105.00–120.00

It is evident that electricity is not now an attractive alternative based simply on the price of energy delivered at the steam plant. In the absence of severe curtailments or regulatory prohibitions forbidding the use of gas and oil for industrial uses, electrical steam generation will succeed only if the capital recovery and operating costs are attractive and if price escalations favor coal and nuclear-generated electricity in the future.

Figure 3 shows the relative cost growths of oil, gas, and electricity if it is assumed that, initially, gas costs one-half and oil costs two-thirds as much as electricity to attain a given result (1 lb of steam) and that their escalation rates are 10%/year for gas and oil and 5%/year for electricity. Cost equality will be reached in about 5 years with oil and in 15 years with gas.

The future costs and availability of the source energies used to make steam are but one component of a complete analysis that forecasts steam costs. Overall costs are the decision-forcing elements. In a comparison of electrically powered steam generators with conventional fossil-fueled boilers, these additional cost elements must be considered: investment, maintenance, operational personnel, reliability, public acceptance, and social impact.

Capital Investment

A somewhat brief survey of prevailing installed costs of steam generating facilities produced these broad general conclusions:

1. Delivered costs of high-voltage electrode steam and hot water boilers and gas- or oil-fired package boilers are competitive, as shown in Fig. 4. If considerations of fuel availability are neglected, the

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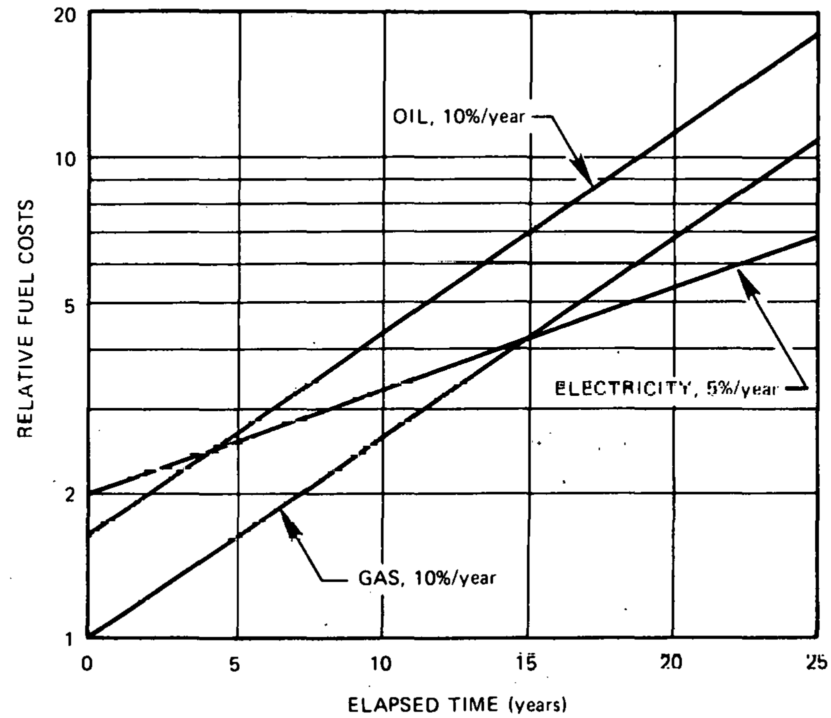

Fig. 3. Relative costs of gas and oil escalating at 10% per year and of electricity at 5% per year.

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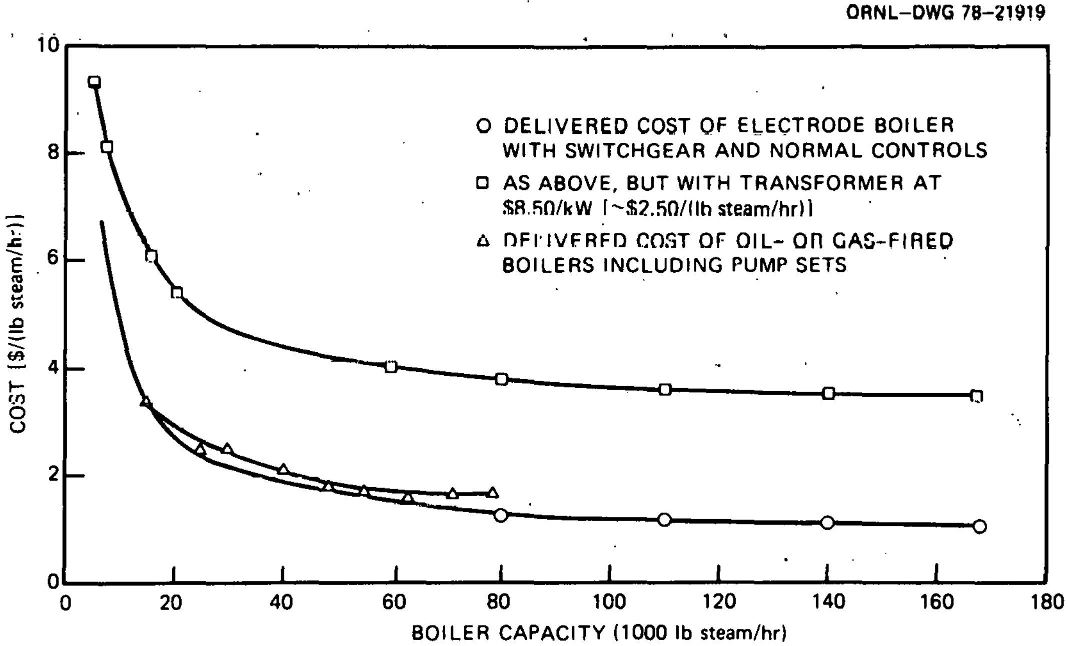

Fig. 4. Costs of oil, gas, and electrode package boilers.

total capital required will be determined by costs charged to land used, buildings and foundations, fuel storage and piping, transformers, switchgear, power lines, engineering, administration, and management. Typically, the cost of turnkey facilities in the range of 100,000 to 200,000 lb of steam per hour will range from $6.00 to $20.00 per lb of steam per hour for both types of boilers. If electrical power of suitable voltage and capacity is immediately available and onsite, the electrode boiler may have a first cost advantage.

2. Installed costs of coal-fired boilers in industrial sizes will be much higher than those for gas, oil, or electrically heated boilers by factors of 2 to 5 or more. The large increase is for the additional monies spent for field erection, coal and ash handling equipment, stacks and environmental protection, space occupied, interest charges during a longer installation time, and additional engineering, management, and overhead costs.

Because the conditions and circumstances that determine the capital required for a particular installation will be peculiar to the installation, it is not possible to cite precise costs or even to bracket them narrowly. Some of the general considerations involving retrofits for modernization or energy substitution in existing industrial plants have been outlined in Sect. 8. Table 4 is a comparative outline of the cost elements that may require evaluation in making an energy choice to generate steam.

Heil and Leatham[120] recently compared the capital and operating costs of an electric and a coal-fired industrial facility nameplate rated at 300,000 lb of steam per hour and apparently intended to generate about 200,000 lb per hour. Their results are presented in Table 5. Some comments are in order. Electric boilers are capable of a very high degree of automation,[121-123] and the labor charge (for five men) indicated in the table may be excessive if additional capital is spent for the necessary instrumentation and control equipment. In general, other information[121] (not quantitative) indicates that maintenance costs for electrode boilers are very small, frequently limited to electrode gasket replacements on a routine, preventive schedule. Intuitively, it is

Table 4. Steam generators — a comparison of equipment and characteristics

Item	Oil- and gas-fired package boilers	Coal-fired boilers	Electric boilers
1. System components			
a. Boiler	Water tube or fire tube; depends on size and manufacturer	Water tube or fire tube	Single pressure vessel with internals
b. Insulation and refractories	Yes	Yes	Not required to operate; may be desirable around pressure vessel
c. Draft equipment			
1. Fan(s)	Required	Required	Not required
2. Ducts and stack	Required	Required	Not required
d. Equipment for environmental protection			
1. Particulate removal	Not required for gas. May or may not be required for oil	Required; dust collectors and electrostatic precipitators	Not required
2. SO_x and NO_x removal[a]	Depends on sulfur content of fuel and applicable regulations	Required	Not required
e. Fuel handling equipment	Fuel oil pumps for oil-fired units or dual fuel boilers Oil storage tanks and/or auxiliary tanks for gas storage if supplemental standby fuel is required	Coal yard, coal hopper(s), conveyor, bulldozer(s), car thawing shed Crusher, pulverizer(s) or stoker(s) Access roads, rail spurs	Transformer(s) if existing electrical service voltage is not suitable. Supplemental fuel for standby not a possible option.
f. Water treating equipment	Yes	Yes	Yes, to maintain proper electrical conductivity
g. Air preheaters and economizers	Optional and desirable	Optional and desirable	No air is used. If waste heat transfer to feedwater is feasible, yes.
h. Superheaters	If desirable, yes	If desirable, yes	No, limited to saturated steam
i. Equipment for soot removal from boiler surfaces	Required	Required	Not required
j. Ash and waste equipment	Not required	Required; SO_x removal may increase waste problem	Not required
k. Transformer(s)	Not required	Not required	Depends on available voltage at plant site
2. Dimensions	Per unit of boiler capacity, are intermediate between coal-fired and electrical systems. Typical package boiler requires more floor space but, neglecting the stack, less ceiling height than an electrode boiler.	The complete facility, which includes the space required for the boiler and peripheral equipment, coal storage and handling, ash handling and disposal, will occupy several times the space required for oil, gas, or electrical steam systems. Coal boilers require more volume for combustion.	Requires least total space and least floor space. The boiler proper may need more headroom than the equivalent gas- or oil-fueled package boiler.

Table 4 (continued)

Item	Oil- and gas-fired package boilers	Coal-fired boilers	Electric boilers
3. Operational characteristics			
a. Startup time from cold condition	Rule of thumb practice limits heat-up rate to ∿55°C (∿100°F/hr)		Relatively short; can be made less than 1/2 hr depending on methods used to preheat and pressurize the water in the boiler.
b. Response to load changes	Fast	Slower than oil, gas, or electricity	Very fast, in the order of a few seconds. Response not limited by thermal stresses produced by changes in energy input. Often limited by the response time of other system components, e.g., valves.
c. Load range	Wide, efficiency decreases at low outputs	Not as wide as gas and oil. Particulate emission may be a problem at low loads.	Very wide, operable at 5% rated load with little change in efficiency.
d. Efficiency Note: Efficiencies do not take into account the losses due to blowdowns, startup, and load changes.	Over 80% if operated carefully and continuously at uniform load, 75% to 80% of maximum rating. One manufacturer claims an 87.5%[b] maximum for oil-fired units. Efficiency falls to ∿70% at 25% load.	Similar to gas and oil	From 99 to 96% at loads from 100 to 25% respectively and referenced to kWhr input. Efficiency referenced to the energy content of the base fuel (oil, gas, coal, or fission) is approximately 82%.
e. Controllability	Easily controlled; remote operation possible. Start from cold condition usually manual.	Usually require personnel in attendance	Easily controlled and is highly susceptible to fully automated, unattended, remote control during normal operation.
4. Safety	Loss of water may damage the boiler. Gas and fuel oil are potentially explosive. Usual overpressure protection is mandatory. Noise level of fans and blowers may constitute a problem.	Loss of water may damage the system. Coal dust and gas or oil used as a supplemental fuel or for startup are potentially explosive. Depending on the type of coal, spontaneous combustion may be a problem in connection with coal storage. Usual overpressure protection is mandatory. Noise level of fans and blowers may constitute a problem.	Fails to safe condition on loss of water; usual overpressure protection is mandatory. Electrical hazards will be those associated with high- and intermediate-voltage electrical systems such as substations. No fans or blowers are required.

[a] SO_x removal not required with fluidized-bed coal boilers.

[b] Ref. 75.

Table 5. Cost comparison (in 1977 dollars) of coal-fired and electric boilers[a,b]

Comparative capital costs of coal-fired vs electric boiler plant[c]

Item	Coal	Electric
Steam generators and auxiliaries	3,100	590
Building and sitework	1,839	566
Coal and ash handling	1,645	
Water treatment	420	420
Piping and mechanical auxiliaries	666	574
Electrical	348	1,548
General conditions	235	235
Subtotal	8,253	3,933
Insurances, taxes, overhead, profit, etc.	4,847	3,002
Total construction contracts	13,100	6,935
Administration and professional	1,310	695
Total capital required	14,410	7,630

Comparative annual operating and owning costs of coal-fired vs electric boilers

Item	Coal	Electric
Number of personnel	13	7
Operating labor costs	335,500	129,000
Maintenance and materials	57,800	67,100
Service and supplies	10,600	10,300
Fuel and energy	3,245,400	5,311,300
Total operating costs	3,245,400	5,517,700
Capital investment	14,410,100	7,517,700
Insurance and property taxes (6%)	864,600	457,800
Capital recovery (20 years @ 9%)	1,579,300	836,200
Annual fixed charges	2,443,900	1,294,000
Total annual cost (excluding income taxes)	6,103,100	6,811,700

[a] *Source:* Ref. 120. (Published courtesy of T. J. Heil et al., Gilbert/Commonwealth, Jackson, Michigan.)

[b] The coal-fired plant includes electrostatic precipitators but does not include sulfur oxides removal.

[c] Rated at 300,000 lb of steam per hour.

reasonable to assume that the maintenance on the boiler and the machinery required to operate a coal-fired system would be substantially higher. Heil and Leatham's comparison and that of Tyrrell[123] in Table 6 do show that the annual owning and operating costs are not far apart. If fossil fuel costs escalate faster than those of electricity, these will soon be equal. If the coal-fired system (Table 5), includes sulfur oxide removal, the cost analysis may favor electricity.[124] Table 7 illustrates the wide range of costs for steam generation as these are influenced by the energy source and by the degree to which the estimate represents a complete, "grass roots" facility.

Table 6. Comparison of municipal[a] heating costs (in dollars) with gas/oil, electricity, and electricity plus heat storage[b,c]

Expenditure	Gas/oil	All-electric	All-electric with storage
Capital cost	2,891,000	2,693,000	2,871,000
Annual operating cost	604,000	679,000	616,000
Annual owning and operating cost in 1973	991,000	1,040,000	1,000,000
Annual owning and operating cost in 1983	1,927,000	2,126,000	1,876,000

[a]City of Hamilton, Ontario.

[b]Table abstracted from Ref. 123.

[c]Costs assume that (1) wages escalate at 10% and (2) gas costs escalate faster than electricity (equal in about 1982).

Maintenance

Intuitively, it is easy to assume that the amount and cost of maintaining a system will be in proportion to its complexity. Steam generators listed in the order of ascending complexity are (1) electrode boilers, (2) gas- and/or oil-fired package boilers, and (3) coal-fired boilers. Experience has confirmed this assumption. Users of electric boilers report[121,122] that maintenance consists principally of routine inspections, with some replacement of insulators and insulator seals.

Table 7. Typical recent cost estimates for industrial steam facilities

Item No.[a]	Plant size	Energy source	Expense: Capital ($)	Expense: Operating ($/1000 lb)	Remarks
1a	2 boilers, 100,000 lb/hr each, 125 psi	High-sulfur coal	11,800,000 (59.00/lb-hr)	2.06[b]	These estimates for a "grass roots" facility. The capital costs are in 1975 dollars and include 20% for contingencies.
1b	As in 1a	Low-sulfur coal	8,900,000 (44.50/lb-hr)	1.21[b]	
1c	As in 1a	Low-sulfur coal	3,200,000 (16.00/lb-hr)	0.77[b]	
2a	1 package boiler rated at 160,000 lb/hr, 190 psi	Low-sulfur coal	1,350,000 (8.44/lb-hr)		Costs, in 1976 dollars, are for a complete "grass roots" facility.[c]
2b	1 boiler rated at 160,000 lb/hr, 190 psi	Coal	11,000,000 (68.75/lb-hr)		As in 2a. Estimate does not include SO_x removal. Contingencies approximately 10%.
3	1 boiler rated at 200,000 lb/hr, 220 psi	Low-sulfur coal	12,520,000 (62.60/lb-hr)	2.34	Cost, in 1977 dollars, for a complete, "grass roots" facility that meets all environmental standards. Contingencies are ~20%. Cost includes a 60,000 lb/hr standby boiler, oil fired. (a) Coal is compliance grade with estimated delivered cost of $40.00/ton. (b) Does not include capital charges and depreciation.[d]
4a	1 boiler, rated at 125,000 lb/hr	Oil	950,000 (7.60/lb-hr)		Boiler only, purchased and installed, in 1977 dollars.[e]
4b	As in 4a	Coal	3,600,000 (28.80/lb-hr)		As in 4a
4c	As in 4a	Electricity	1,000,000 (8.00/lb-hr)		As in 4a

[a] See col. 1 of Table 4 for a description of the items in this column.

[b] Operating costs do not include fuel or capital charges (Ref. 125).

[c] Ref. 126.

[d] Ref. 127.

[e] Ref. 128.

Because electrode boilers contain no refractory insulation, because metals are not exposed to flames and metal temperatures seldom if ever exceed steam temperatures, and because the internal components are rugged and simple, these boilers tend to be relatively trouble free.

Package oil- or gas-fired boilers pose no major maintenance problems, but the overall costs of routine inspection and parts repair and replacement are expected to be higher than for an electrode boiler. A coal-fired system with the array of necessary peripherals — stokers, bulldozers, crushers, conveyors, precipitators, SO_x and NO_x removal equipment, and ash handling — may require a substantial amount of attention by maintenance personnel. The costs thereof cannot be ignored.

Operating Personnel

The number of persons routinely required to maintain steam production in an industrial installation is least for electrode and gas- or oil-fired boilers; operating personnel may become a significant cost element in a coal-burning steam plant. Gas- and oil-fired and electrode boilers are capable of being instrumented and, once started, operated from remote control stations. In general, occasional attention by a roving operator with other in-plant duties is sufficient.

Package boilers may or may not need the continuous attention of an operator. The operating manpower costs are a function of plant size and process load needs. In any set of circumstances, these costs will be equal to or greater than those for an electric boiler.

Coal-fired steam systems must be attended continuously by onsite personnel. Coal must be unloaded, conveyed, and perhaps crushed and pulverized before being fed to the boiler. Ash and waste disposal must be taken care of and the entire system managed. In a medium- or large-sized, three-shift industrial steam plant designed for on-line reliability, an average of four persons per shift is not extravagant.[127]

Reliability

Reliability, treated here as a separate subject, cannot be divorced completely from considerations involving the amount of capital and operating costs. The degree of plant reliability required is judgmental and takes into account failure probabilities, the costs of a plant shutdown in terms of lost production, and restart costs. If the consequences of steam plant shutdown are costly, it may develop that it is worthwhile to install spares of the critical components or a complete facility and provide standby alternative fuel sources, thereby escalating capital expenditures. The larger processing operations, typified by ammonia plants, steel mills, pulp and paper mills, sugar refineries, and corn processing, cannot afford sporadic operation resulting from power losses or equipment failures. The retention of permanent maintenance personnel to keep the system running increases operating costs. Managers and engineers considering steam system designs will address the following questions among others:

1. What is the economic loss produced by a steam plant shutdown and how is the loss affected by the length of the shutdown?
2. Will energy delivery, as gas, oil, or electricity, be assured? If one source fails, is there a reasonable alternative? Note that unless a processor is almost completely independent of utility-produced power, an electrical power system blackout will produce plant shutdown. The decision-makers will have to take into account interruptible contracts for natural gas, rail delivery of coal, and the past performance of the local power system.
3. What are the failure probabilities of the individual components comprising gas, oil, coal, and electric steam systems? What are the compound failure probabilities of the different systems?

Public Acceptance

The time when industrial plant operators could ignore the public's response to industry actions is long past. If an industry's projected energy choice alters the environment or the comfort of those in adjacent areas, there will be cost repercussions in the form of construction delays, legal fees, public relations work, and possible design changes, all of which are expensive. This aspect of energy usage has been discussed in Sect. 5, Social, Economic, and Demographic Impacts.

Prospects for Direct Electrical Generation of Process Steam

In a large number and variety of industries using large quantities of process steam, the widely accepted, traditional approach has been to include an in-house gas- or oil-fired steam plant. A fraction (usually less than half) of the energy so developed is sometimes used to provide shaft power by means of high backpressure or bled turbines. Turbine efficiency in these circumstances is not as important as in a plant designed solely to produce electricity. Whether or not a particular processor generates all or part of his electrical power with an in-house steam plant, the preponderant energy sources for saturated process steam have become natural gas and fuel oil.

The preceding paragraphs have dealt, in a general way, with the cost elements associated with process steam generation. It is a premise that the ideal conditions that resulted in the wholesale adoption, by industry, of natural gas and oil no longer exist; therefore, it has become unrealistic for industry to summarily reject electricity for process steam generation on the sole basis of energy efficiency. It becomes food for thought when (see Appendix B) electrode boilers with rates up to 50,000 kVA, equivalent to steam rates up to 77,000 kg/hr (= 170,000 lb/hr), are available and growing in use here and in Europe.

In regard to the energy content of the electricity at their terminals, electrical boilers are very efficient devices — up to 99% and, in all but very small units, never less than 95%. In reference to the energy contained in the base fuel (coal, oil, gas, or fission), they are obviously not as energy efficient as the more conventional steam generators. It has been pointed out that industrial choices are, of necessity, based primarily on economic efficiency and long-term fuel abundance — not solely on energy efficiency.

Some current applications of electrode boilers are

1. For load leveling in a base load public utility power plant that produces both electric power and heating steam, stored energy in the form of pressurized water is flashed into heating steam during peak demand periods. The cities of Toronto and Hamilton, Ontario, now

use electric boilers with heat storage for heating municipal buildings in their city centers.[121,122] Off-peak power is used.

2. Pulp and paperboard producers are using electrode boilers for load molding.[129-131]
3. Several colleges and a variety of large and small industries have installed electrode boilers for space heating.[132-136]
4. Utilities use electrical boilers for startup steam[137] and for nuclear waste processing in large central generating stations.
5. A public utility in Iowa that also supplies heating steam to the business district in Sioux City, Iowa, has recently substituted electrode boilers located at or near the point of steam use for a high-thermal-loss network of steam lines from the central station.[137]

Electrical substitution to generate industrial process steam should be considered when one or more of these conditions exists or is anticipated:

1. The price of oil and gas is expected to escalate rapidly in the not-too-distant future and at a rate faster than for purchased electricity.
2. The only other choice open is to burn coal.
3. Coupled with item 2 above, the only coal available at an acceptable price is high-sulfur, noncompliance coal.
4. Labor and capital costs favor a high degree of automation.
5. Energy costs are a small fraction of product final cost.
6. Plant shutdowns are very costly, and electricity is the most reliable source of a continuous supply of energy.
7. The plant site offers no better alternative for reasons such as zoning, traffic, or available space.
8. The product is the result of batch or semicontinuous processing. Steam usage is very nonuniform and discontinuous. Meat processors, dairies, and other food producers are in this category.
9. In contract to item 8 above, the process tends to operate at uniformly high levels but does so seasonally. Beet sugar plants fit this description.

10. Electricity rates and rate designs are favorable, viz.:
    a. Rates are generally low, as in the Pacific Northwest.
    b. Bulk rates to large consumers are favorable.
    c. The utility offers discounts for off-peak electricity, and the process is susceptible to load management and is capable of using energy developed and stored during off-peak periods.

The preceding list includes a variety of uncertain and intangible factors. No attempt is being made to quantify the near-term prospects for electrical steam generation. The technological potential for producing all saturated process steam with electricity is at hand. See Appendix B for a description and discussion of electric steam generators.

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Appendix A

ENERGY CONSUMPTION AND DISTRIBUTION IN THE UNITED STATES AND BY INDUSTRY

Data on energy use and distribution (Table A-1 and Figs. A-1 to A-7) are included to provide an overall view of U.S. and industrial energy usage and to indicate the current dependency of industrial processes on gas and petroleum. Additional data on particular industries are, in some cases, included in the appendices that deal with specific processes.

Table A-1. Distribution,[a] by fuel source and use sector, of the energy comsumed in the United States in 1974; 10^{12} kWhr and (10^{15} Btu)

Use sector	Primary energy source				Distributed electricity[b]	Total	U.S. total (%)
	Natural gas	Petroleum	Coal	Nuclear and hydro			
Residential and commercial	2.18 (7.4) 28.4%	1.96 (6.7) 25.6%	0.09 (0.3) 1.2%	0.09	3.43 (11.7) 44.8%	7.66 (26.1)	35.9
Industrial	2.96 (10.1) 35.5%	1.79 (6.1) 21.5%	1.23 (4.2) 14.8%	0.01 (0.1)	2.35 (8.0) 28.2%	8.35 (28.4)	39.1
Transportation	0.19 (0.6) 3.5%	5.09 (17.4) 95.4%	0.005 (0.01)		0.06 (0.02) 1.1%	5.34 (18.2)	25.0
Electric utilities	1.00 (3.4) 17.1%	0.94 (3.2) 16.1%	2.59 (8.9) 44.7%	1.29 (4.4) 22.1%	(19.9)		
Totals by source	6.33 (21.5) 29.6%	9.79 (33.4) 45.9%	3.92 (13.4) 18.4%	1.30 (4.4) 6.1%			
U.S. total						21.3 (72.7)	

[a]These data are derived from *Monthly Energy Review*, Federal Energy Administration, National Energy Information Center, Washington, D.C. (March 1976).

[b]The primary energy required to generate electricity is estimated by assuming an efficiency of 32%; the net distributed electrical energy in 1974 was 1.86 × 10^{12} kWhr.

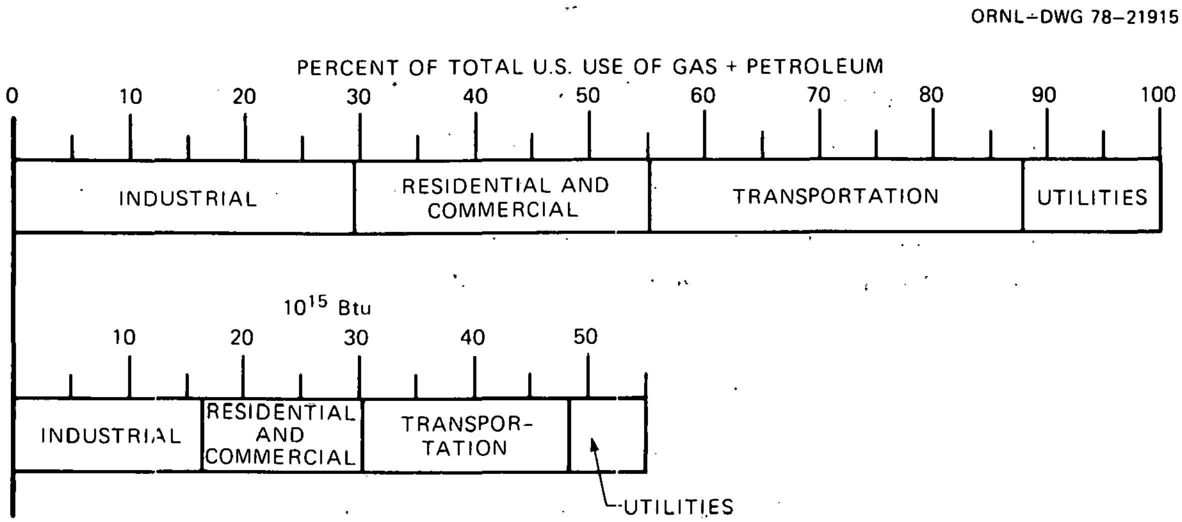

Fig. A-1. Total consumption of natural gas and petroleum in the United States in 1974 (Ref. 18).

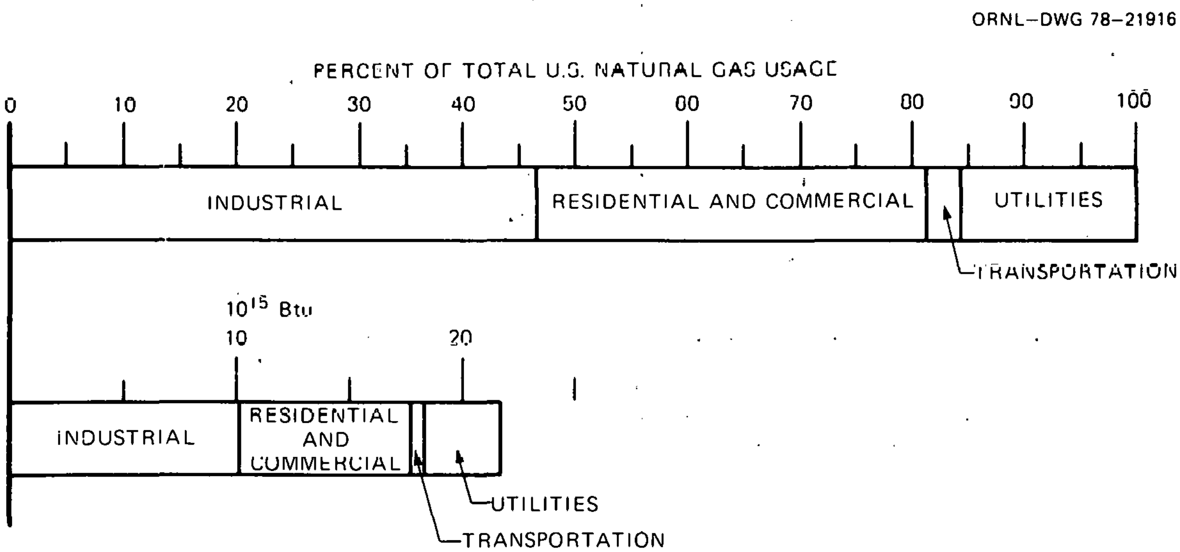

Fig. A-2. Distribution of the natural gas consumed in the United States in 1974 (Ref. 18).

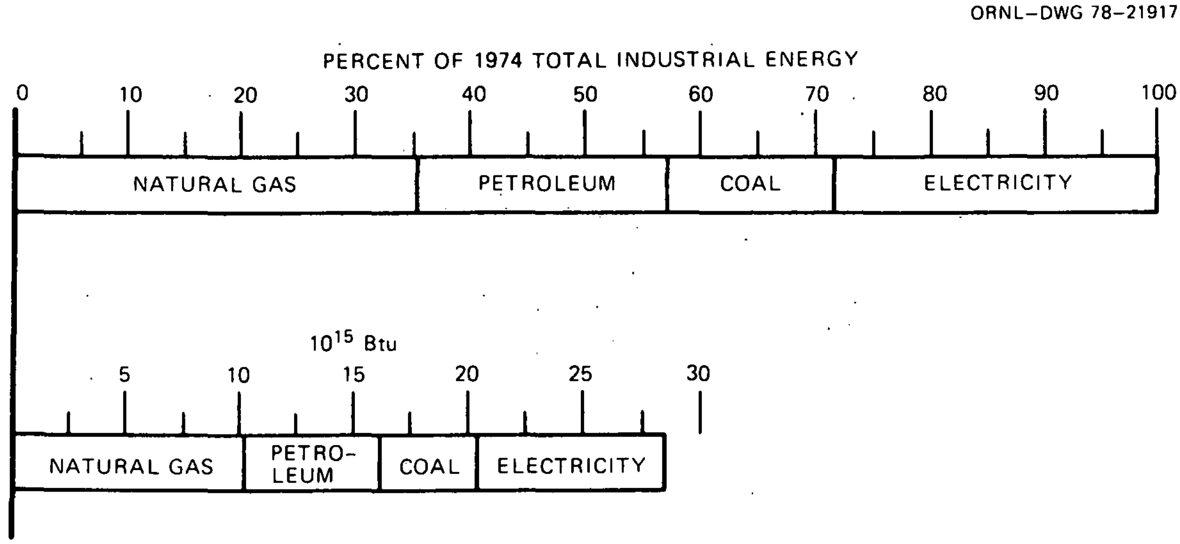

Fig. A-3. Distribution, by source, of the industrial energy used in the United States in 1974.

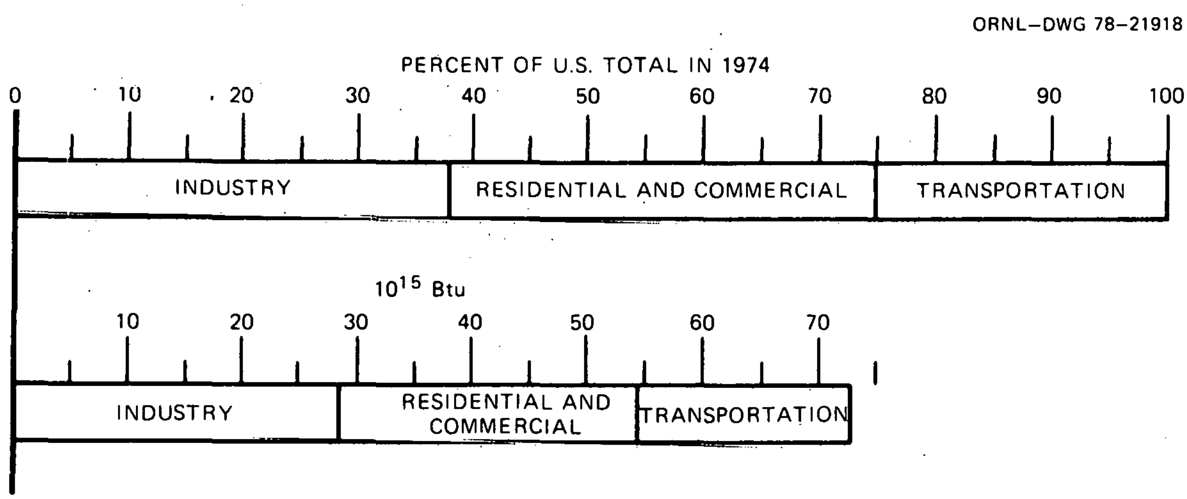

Fig. A-4. Distribution of energy used in 1974 in the United States by end-use sectors (industrial, residential and commercial, and transportation) (Ref. 18).

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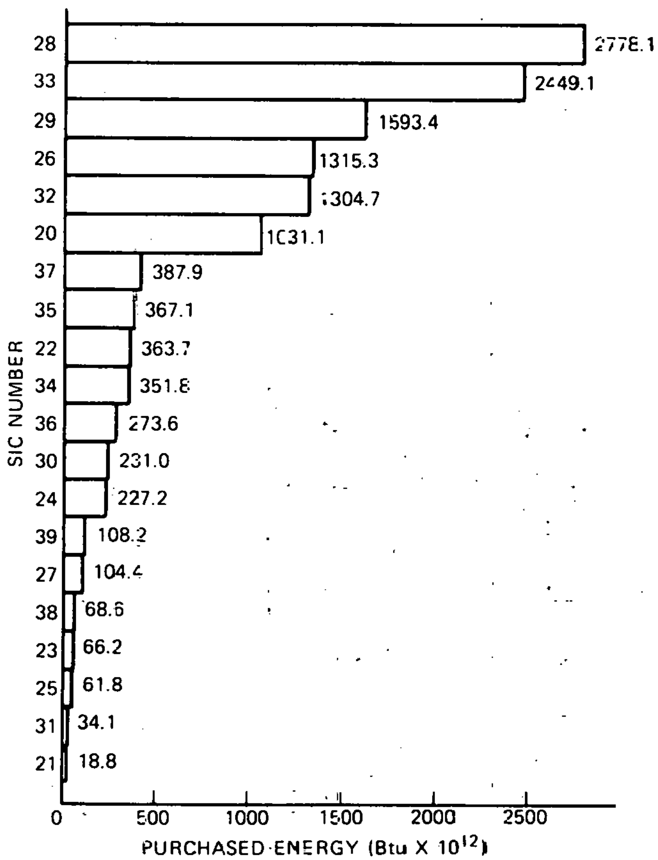

PERCENT OF INDUSTRIAL TOTAL	CUMULATIVE PERCENT
21.2	21.2
18.6	39.8
12.1	51.9
10.0	61.9
9.9	71.8
7.9	79.7
21.3	100.0

SIC NO.	NAME	RANK
28	CHEMICALS AND ALLIED PRODUCTS	1
33	PRIMARY METAL INDUSTRIES	2
29	PETROLEUM AND COAL PRODUCTS	3
26	PAPER AND ALLIED PRODUCTS	4
32	STONE, CLAY, AND GLASS PRODUCTS	5
20	FOOD AND KINDRED PRODUCTS	6
37	TRANSPORTATION EQUIPMENT	7
35	MACHINERY, EXCEPT ELECTRICAL	8
22	TEXTILE MILL PRODUCTS	9
34	FABRICATED METAL PRODUCTS	10
36	ELECTRICAL EQUIPMENT AND SUPPLIES	11
30	RUBBER AND PLASTICS PRODUCTS, n.e.c.	12
24	LUMBER AND WOOD PRODUCTS	13
39	MISC. MANUFACTURING INDUSTRIES	14
27	PRINTING AND PUBLISHING	15
38	INSTRUMENTS AND RELATED PRODUCTS	16
23	APPAREL AND OTHER TEXTILE PRODUCTS	17
25	FURNITURE AND FIXTURES	18
31	LEATHER AND LEATHER PRODUCTS	19
21	TOBACCO MANUFACTURES	20

Fig. A-5. Consumption, by industry type, of U.S. industrial energy in 1971. (Data from Fig. 1 of Ref. 138.)

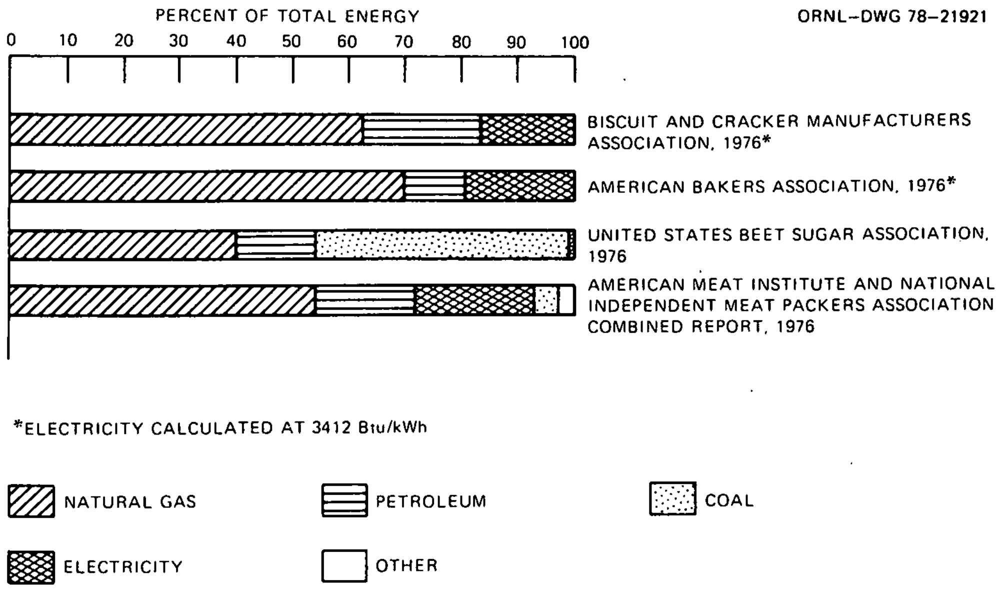

Fig. A-6. Fractional distribution of energy sources in representative food industries. (Data abstracted from Ref. 139.)

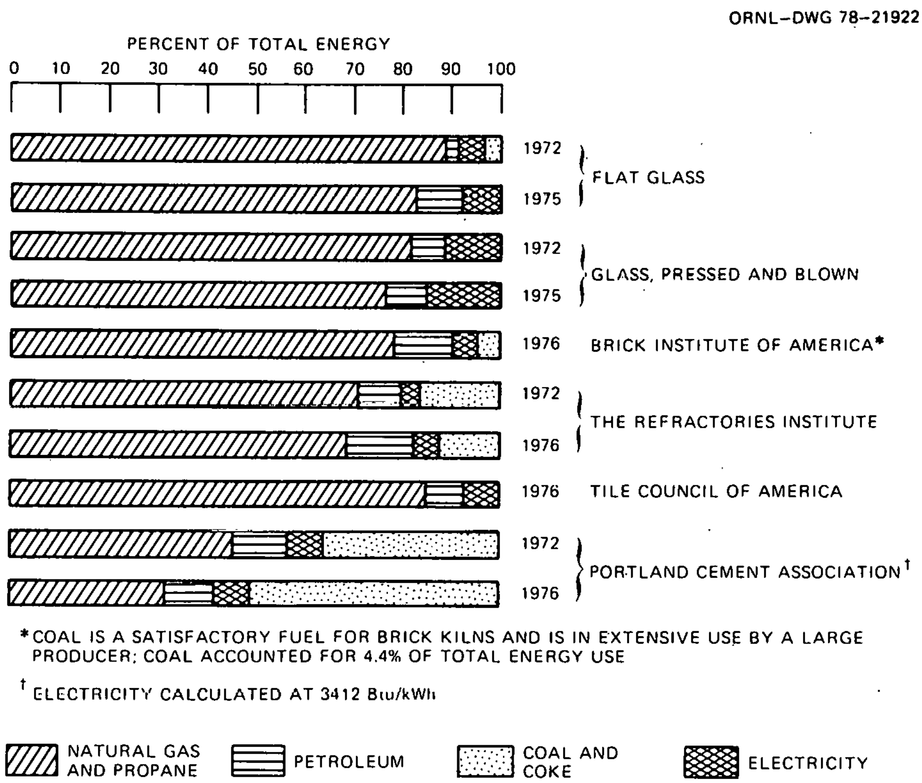

Fig. A-7. Fractional distribution of energy sources in representative high-temperature industrial processes. (Data abstracted from Ref. 139.)

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Appendix B

ELECTRODE BOILERS

Users of process steam, faced with eliminating natural gas and/or fuel oil as their energy source, are left with two choices — coal or electricity. Until very recently, coal-fueled boilers had seen little use in sizes below 250,000 lb of steam per hour. One manufacturer now reports an upsurge in orders for smaller, coal-fueled boilers and suggests that an incentive is anticipation of a national requirement that future fossil fuel steam generating facilities be capable of burning coal as an alternative to oil and gas.

The other alternative, the use of electric boilers, has also been stimulated by both prevailing and anticipated curtailments in natural gas and higher fuel oil prices. Figure B-1, based on figures supplied by three vendors, shows the locations, by states, of the total capacity of steam and hot water boilers with ratings above 1000 kW which were in use or planned in 1976. The regions showing the largest usage are also those in which natural gas curtailments are severe or electrical rates are favorable. Between 1934 and 1966, a European manufacturer[141] installed 270 electrode boilers; a majority were high-voltage units.

Electrical boilers and hot water heaters, particularly in the smaller sizes, are not a new development. The household hot water heater is an example. Hospitals, laboratories, pilot plants, and small-scale processors have used low-capacity units for steam and hot water for many years. Several thousand are in service. Until recently, Europe has led in the design and development of larger, higher capacity units designed for space heating in buildings and municipalities and for process steam. Electric steam and hot water generators are of two general types: indirectly and directly heated. The indirect type — domestic hot water heaters for example — uses submerged, sheathed heating elements to heat the water. In the higher capacity directly heated boilers, the water serves as the electrical conductor. Directly heated boilers are further subdivided into low- and high-voltage types, whether used to heat hot water or make steam, and also by specifying how the water is used to conduct the electricity. High-voltage boilers are now

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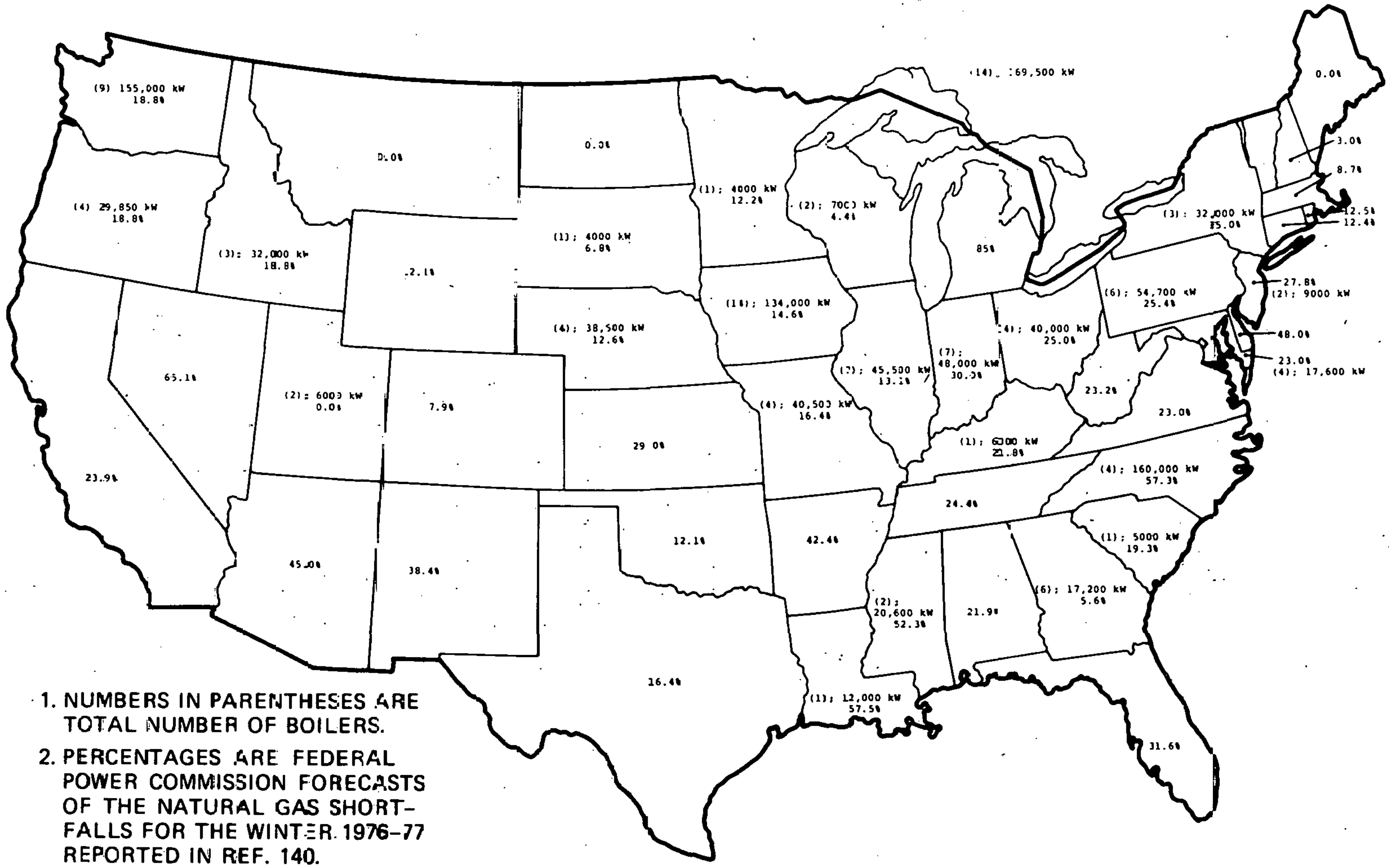

1. NUMBERS IN PARENTHESES ARE TOTAL NUMBER OF BOILERS.
2. PERCENTAGES ARE FEDERAL POWER COMMISSION FORECASTS OF THE NATURAL GAS SHORTFALLS FOR THE WINTER 1976–77 REPORTED IN REF. 140.

Fig. B-1. Electrode boiler installations, in-place or planned, in the United States in 1976.

usually defined as those designed to operate at voltages from 4,000 to 16,000 and with capacities above about 1500 lb of steam per hour.

The types and characteristics of American-made electric boilers for hot water and steam can be classified as follows:

I. Low-voltage heating element boilers

Service	For steam or high-temperature water
Output	12 to 8000 kW (up to ∿27,000 lb of steam per hour)
Voltage	208 to 600 V
Operating pressure	Up to 61 bars (60 atm = 880 psi)

II. Low-voltage electrode boilers

Service	For steam or high-temperature hot water
Output	400 to 2500 kW (∿1400 to 8500 lb of steam per hour)
Voltage	480 to 600 V
Operating pressure	Up to 21 bars (∿21 atm = 300 psi)
Output range	Stepless, ∿0 to 100% capacity for steam; 5% to 100% for hot water

III. High-voltage electrode boilers

Service	For steam or high-temperature hot water
Output	1000 to 20,000 kW for hot water
	1000 to 50,000 kW for steam (3400 to 170,000 lb of steam per hour)
Voltage	6 to 16 kV
Operating pressure	Up to 27 bars (∿27 atm = 400 psi)
Output range	Stepless, 10% to 100%

IV. High-voltage jet electric boilers

Service	For steam
Output	1000 to 50,000 kW (3400 to 170,000 lb of steam per hour)
Voltage	4 to 16 kV
Operating pressure	Up to 41 bars (∿41 atm = 600 psi)
Output range	Stepless, 0 to 100%

American vendors, some of whom are licensees of European companies, advertise high-voltage electric boilers rated to 50,000 kW, equivalent to approximately 170,000 lb of steam per hour.

Conceptually, the designs of typical high-voltage electrode boilers (Figs. B-2 to B-4) are simple. Three electrodes connected to a three-phase ac power source penetrate the top head of the vessel. The ac circuit is a grounded wye, with the boiler serving as the ground. The water is the current-carrying resistance element; therefore, in the event of a water loss, an open circuit results which tends to produce fail-safe operation. The power factor will be above 95%.

Load control in high-voltage electrode boilers is accomplished by adjusting the amount of water that is effective as a current conductor. Three prominent vendors of the higher capacity units use these different methods:

1. Adjust the water flow rate of the jet streams with a butterfly valve in the jet stream circulating loop (Fig. B-2).
2. Control the position of movable shields that surround the electrodes. The shields, by intercepting a variable fraction of the multiple jet flows in the boiler, control the number of jets that carry current (Fig. B-3).
3. Adjust the water level around the electrodes. The flow surrounds the electrodes except at very low operating levels (Fig. B-4).

For a specified and constant voltage, the current, and hence the power input, is determined not only by the amount of water acting as a conductor but by the conductivity of the water that is actually carrying current. The operating conductivity of the water inside the boiler is a function of the amount and type of impurities, the pressure, and the temperature of the water that carries the current. This local operating conductivity is not always identical to the conductivity measured at an external water loop — the only practicable method of measuring conductivity in systems such as these. Operating procedures[142] that relate measured conductivity to performance variables, current, voltage, and pressure are an effective means of system conductivity control. Clean systems designed for zero makeup water do not experience difficulties with conductivity if provision is made to precipitate the small amounts of iron oxide that are invariably produced during operation. This is a standard water treatment procedure. Although the reasons for maintaining water

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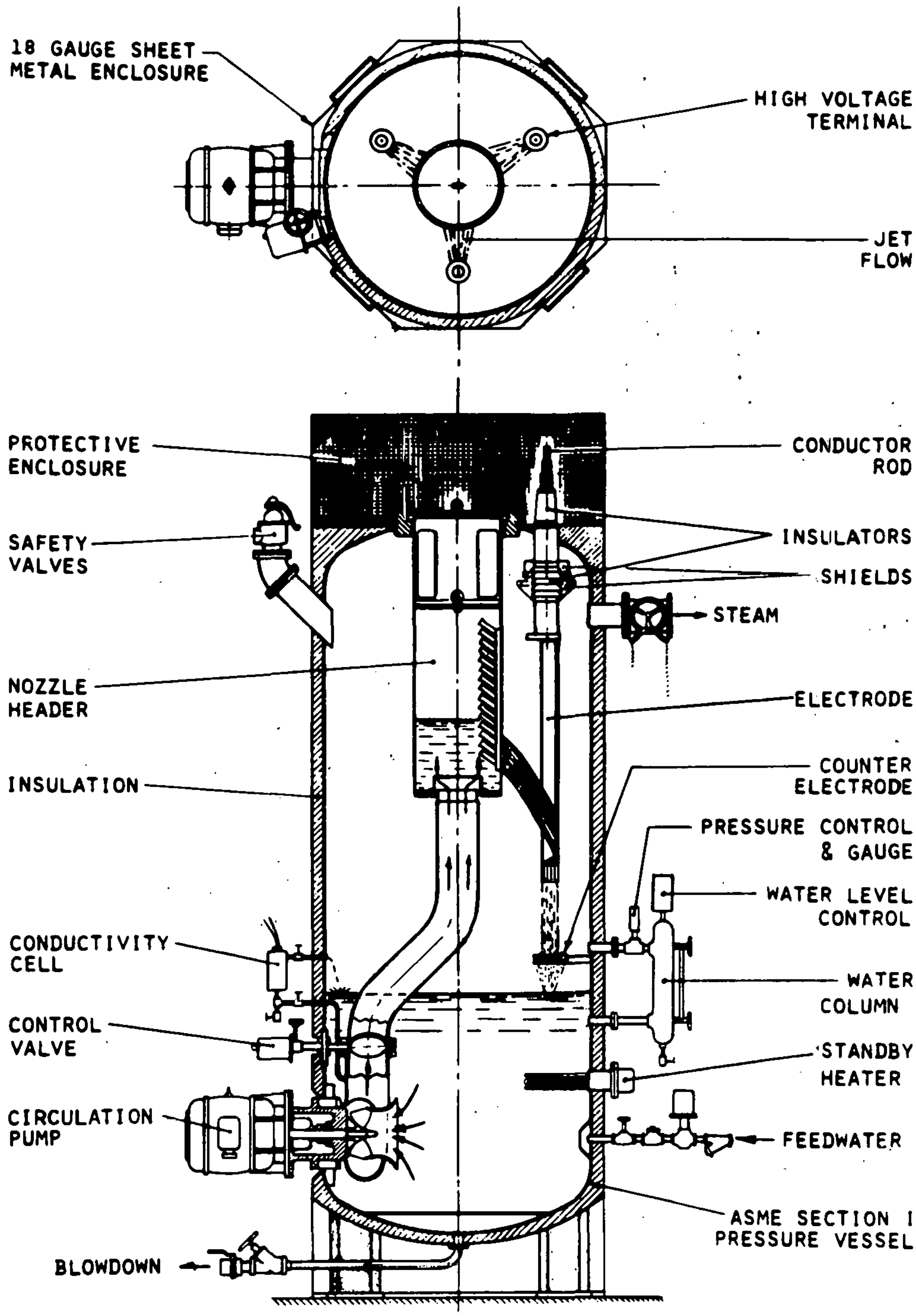

Fig. B-2. High-voltage electrode boiler. Jet flow (and steam rate) controlled with butterfly valve in internal circulation loop. (Figure courtesy of Hydro Steam Industries, Inc.)

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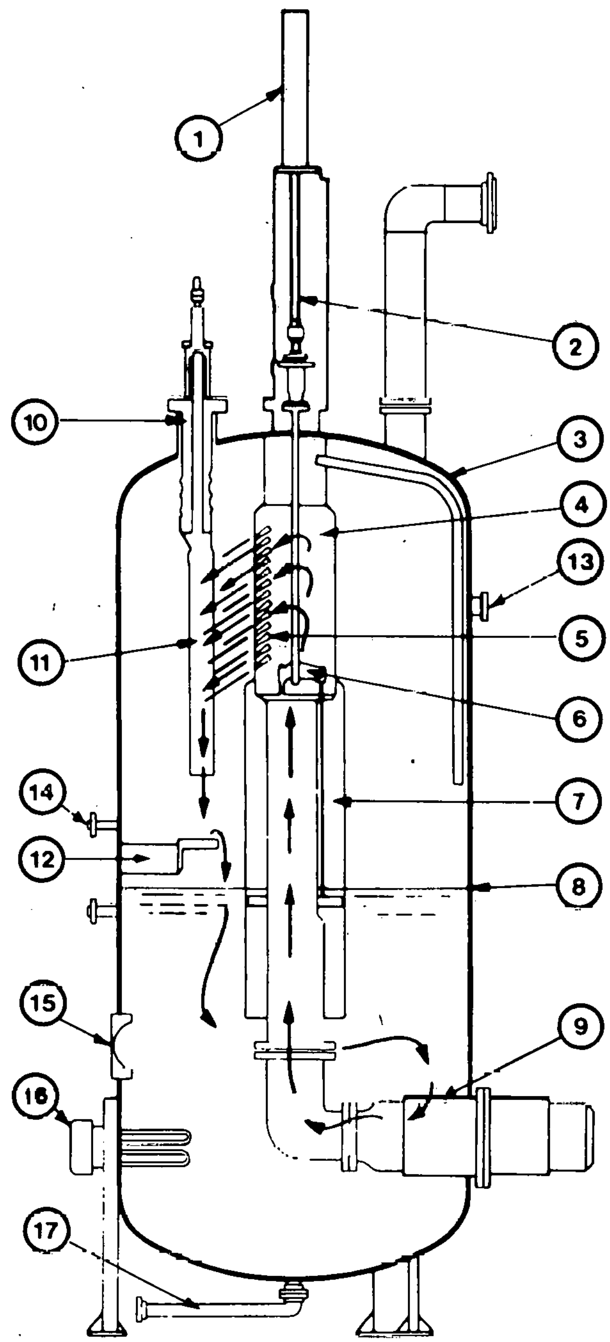

1. Control cylinder
2. Control cylinder rod
3. Boiler shell
4. Jet column
5. Jets
6. Control linkage
7. Control sleeve
8. Water level
9. Circulating pump
10. Insulator
11. Electrode
12. Counter electrode
13. Safety valve
14. Water level control
15. Manhole
16. Standby heater
17. Tank drain

Fig. B-3. A high-voltage, jet flow electrode boiler controlled by varying jet interception. (Figure courtesy of CAM Industries, Inc.)

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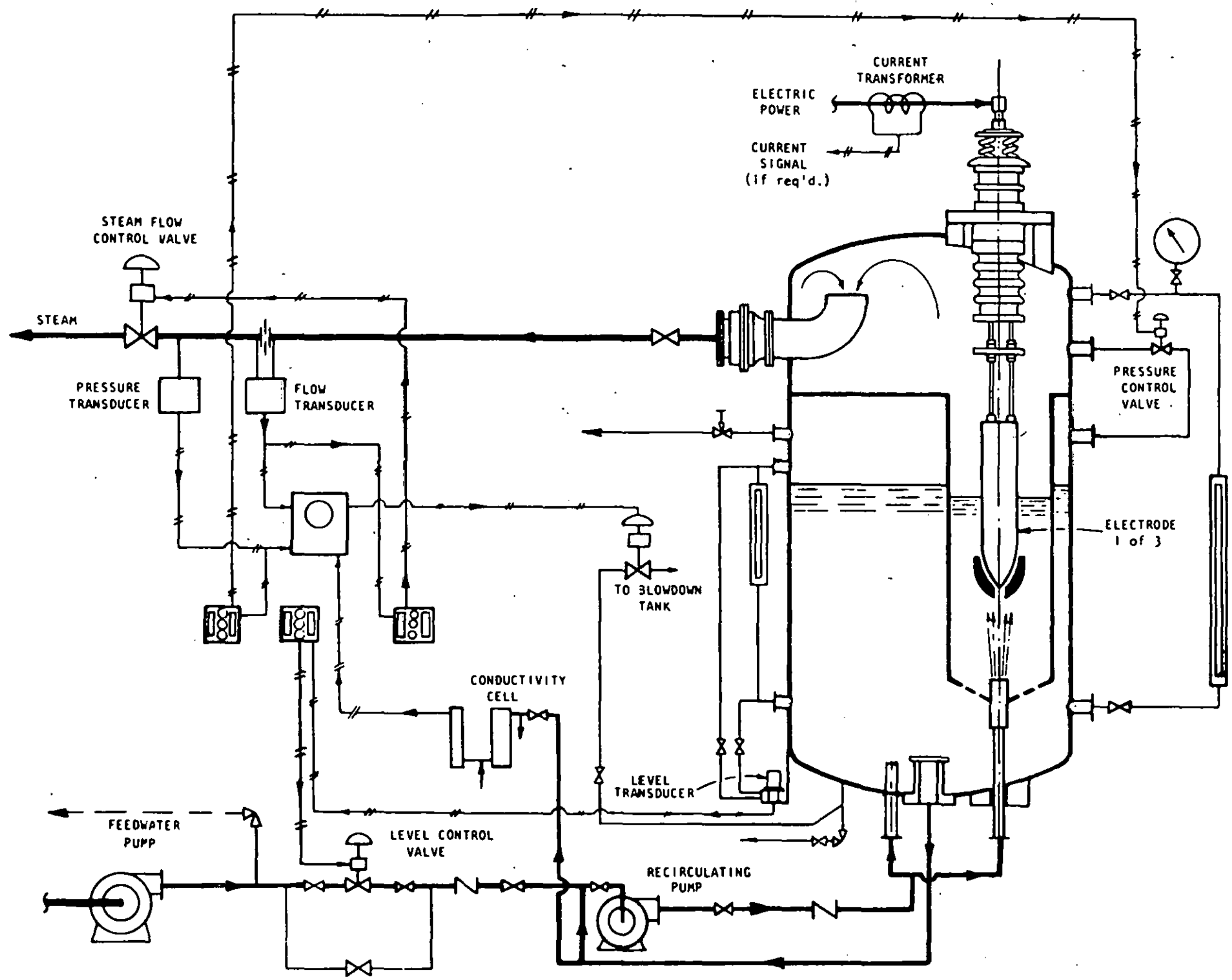

Fig. B-4. Submerged jet flow electrode boiler with controls. Steam rate is varied by controlling the water level around the electrode. (Figure courtesy of General Electric Co.)

quality in electrode and fossil fuel boilers are not identical, the methods of measurement and control are in the realm of standard practice and pose no extraordinary problems. Mineral deposits on the immersion heaters in smaller steam and hot water generators tend to reduce heater life and increase maintenance costs.

Jet spray steam boilers (Figs. B-2 and B-3) are usually operated with water having conductivities* from 700 to as high as 4000 micromho-cm.[142,143] The manufacturer of the submerged jet flow level controlled boiler (Fig. B-4) specifies the conductivity to be 50 to 200 micromho-cm at rated output. [The hot water boiler (Fig. B-7) requires conductivities from about 45 to 150 micromho-cm.[143]]

Startup times are short. If, during full shutdown, boiler pressure and temperature are maintained with low-power standby immersion heaters, as shown in Figs. B-2 and B-3, the transition from zero to full power is almost immediate.

Low-voltage (200 to 600 V) boilers (Figs. B-5 and B-6) are designed to run with the electrodes submerged in relatively still water. Output is dependent on either the submergence of the electrodes or the position of movable insulating shields interposed across the current paths.

Electrode boilers intended expressly for hot water production are often designed to operate similarly to low-voltage steam boilers and with the electrodes submerged in the water. Control is attained by varying the degree of submergence or by moving insulating sleeves that intercept the current paths in the water. The high-voltage, high-output hot water types employ internal, pumped, circulating water flow around the electrodes. Figure B-7 is a diagram of a high-voltage electrode boiler intended for hot water production.

The municipal steam and hot water heating systems in Toronto[122] and Hamilton,[123] Ontario (see Tables 5 and 6, Sect. 9), represent conditions that favor the use of electricity not only for heating but for industrial

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*The sales brochure for Fig. B-3 states ". . . softened water with feed water conductivities of 500 to 3000 micromho-cm (depending on voltage and kW) . . . ."

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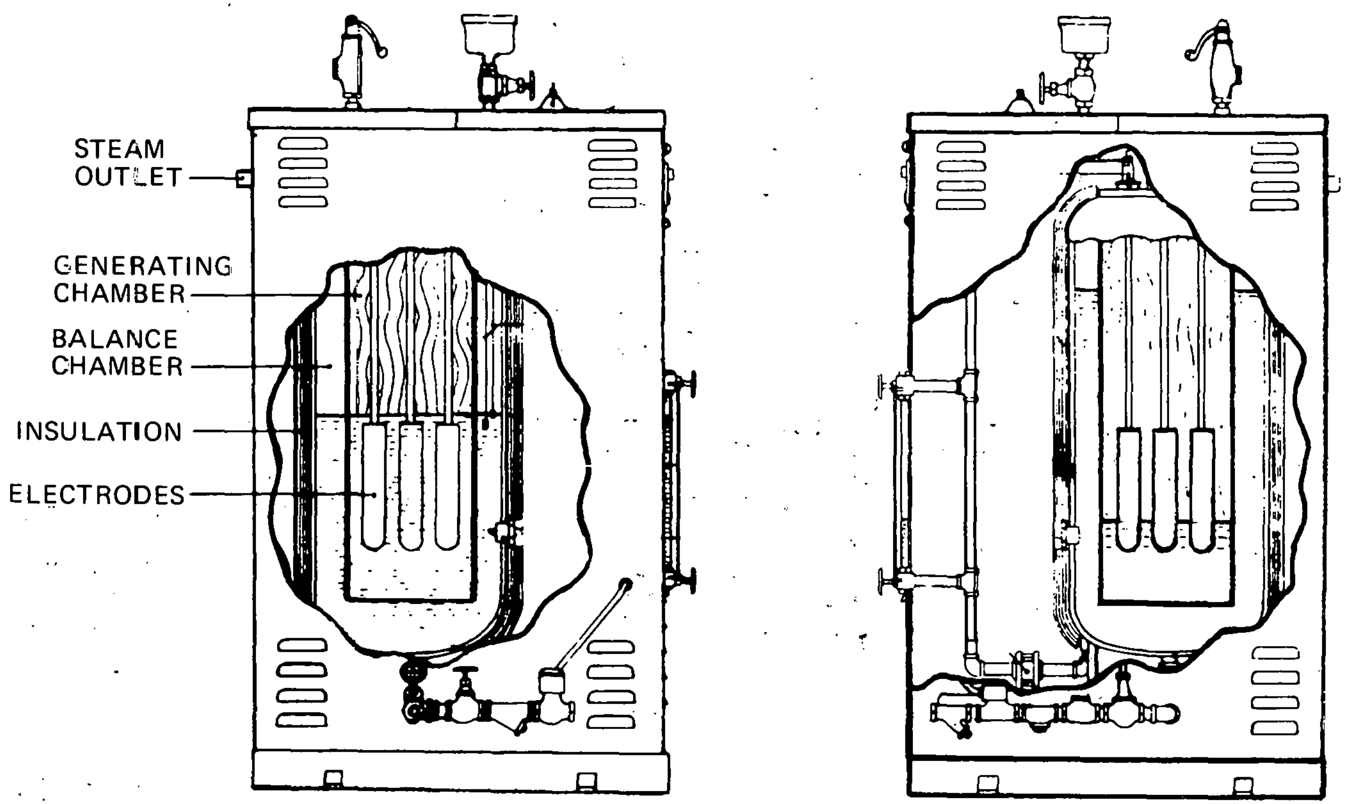

START-UP AND MAXIMUM OUTPUT

PARTIAL LOAD

POWER INPUT AND STEAM RATE SELF-REGULATED BY WATER LEVEL IN GENERATING CHAMBER. WATER LEVEL DETERMINED BY DIFFERENTIAL STEAM PRESSURE BETWEEN BALANCE CHAMBER AND GENERATING CHAMBER.

Fig. B-5. Low-voltage (208 to 600 V) electric boiler. Maximum capacity, ~4000 lb of steam per hour. (Figure courtesy of Hydro Steam Industries, Inc.)

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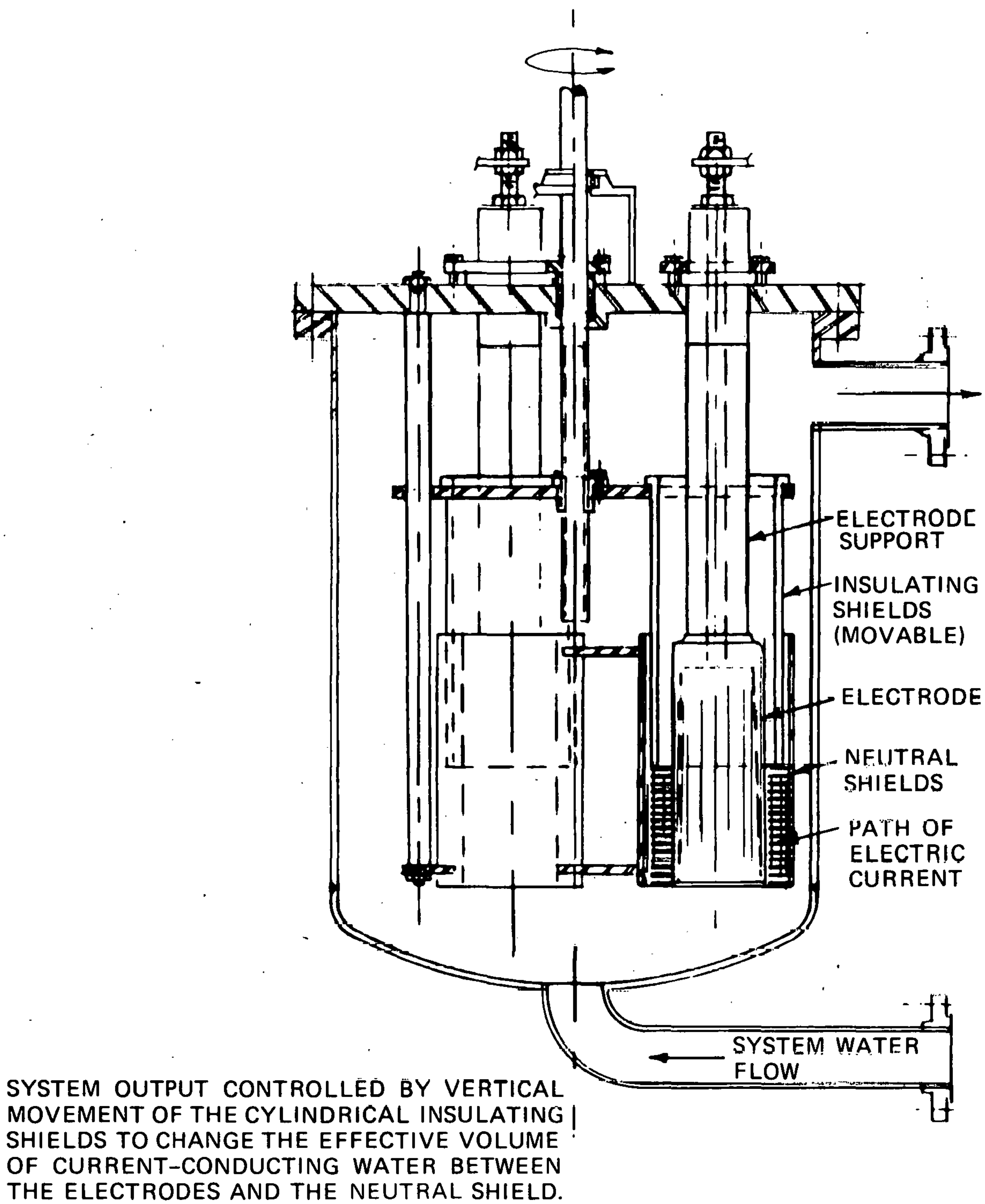

Fig. B-6. Low-voltage (600 V maximum) electrode boiler for making hot water. Maximum rating, ∿2400 kW. (Figure courtesy of CAM Industries, Inc.)

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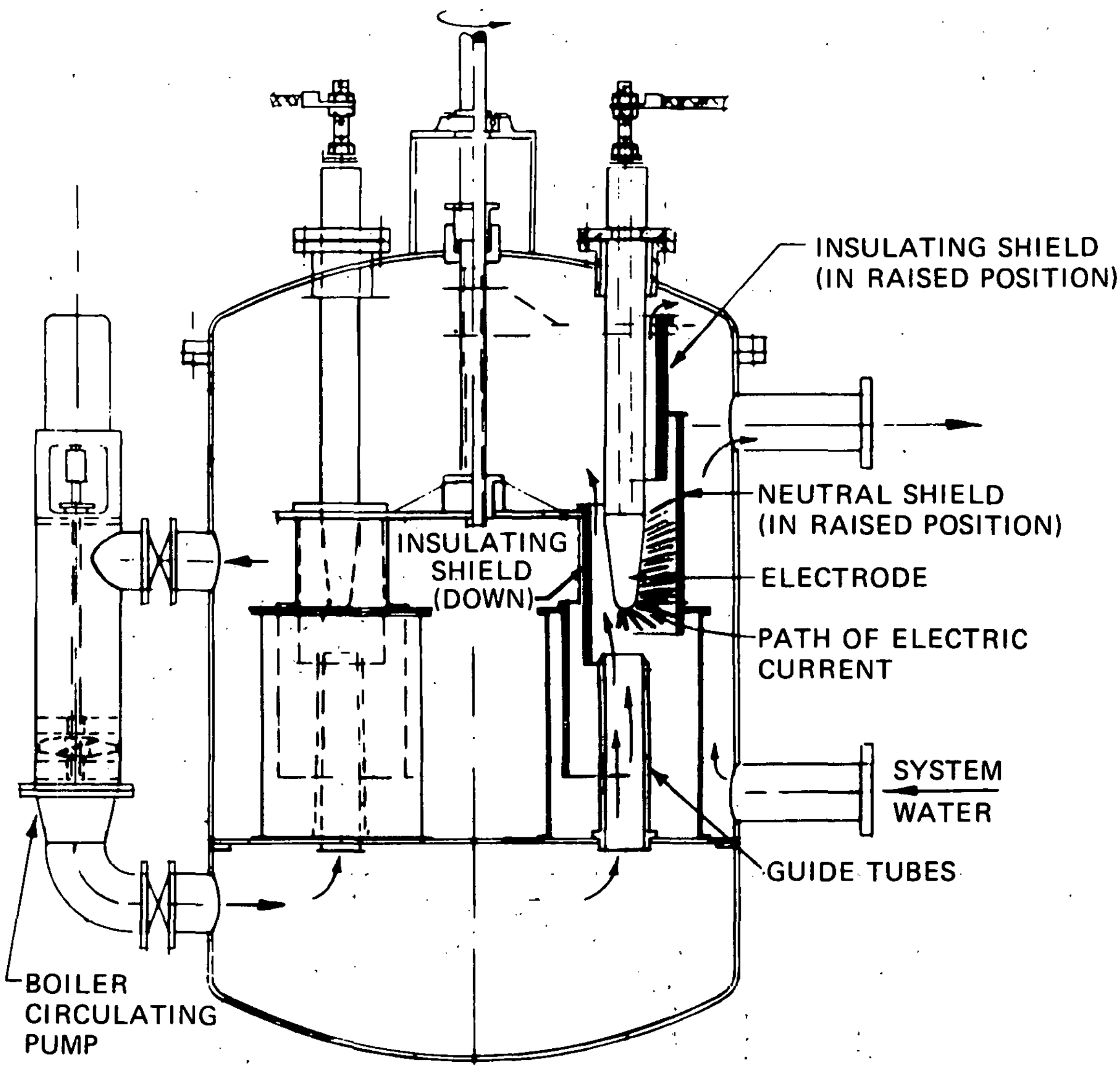

OUTPUT OF THIS PARTICULAR DESIGN IS CONTROLLED AS IN THE LOW-VOLTAGE BOILER SHOWN IN FIG. B-6.

Fig. B-7. High-voltage (4,160 to 13,800 V) boiler for making hot water. Maximum capacity, ~20,000 kW. (Figure courtesy of CAM Industries, Inc.)

applications; for example,

1. They emphasize the use of off-peak utility-generated power.
2. These systems employ energy storage.
3. The local prices for fossil fuels are expected to escalate rapidly.
4. The load is not only seasonal but also fluctuates on a much shorter time scale.

Figure B-8 is a flow diagram[122] of the system used in Toronto to heat the city center building complex. References 120, 129, 131–134, and 144–148 contain additional descriptive material and discussion on electrode boilers and their applications.

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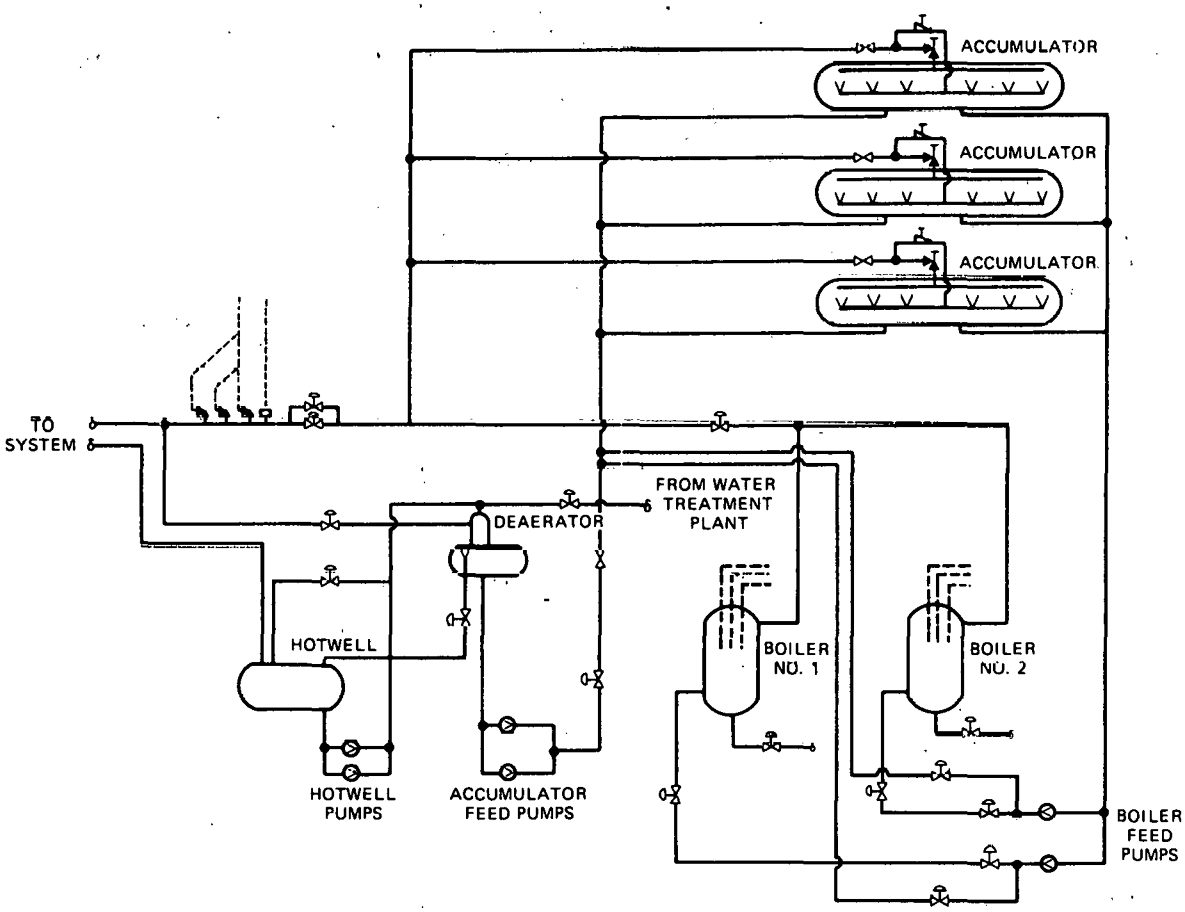

Fig. B-8. Flow diagram of electric boiler-accumulator system that has provided space heating since 1963 for six buildings in the city center building complex in Toronto (taken from Ref. 122).

Appendix C

INDUSTRIAL HEAT PUMPS

Electrical energy, converted to shaft power in a heat pump, offers a large potential for recovering the energy from low-temperature heat sources represented by discarded process streams. The general principles of heat pumps are well established. Household refrigerators and cold storage systems are, in reality, heat pumps with which heat is pumped out of the system and deposited elsewhere. Inverting the system enables energy, as heat, to be transferred, or "pumped," into the system. Residential heat pumps are arranged to move energy in both directions for winter heating and summer cooling. A fundamental thermodynamic principle requires the addition of energy from an outside source to produce energy transfers by heat pumping; however, the energy so transferred is greater than the added energy required to effect the transfer. The ratio of heat transferred to the energy used to produce the transfer is the coefficient of performance, viz.:

$$\text{COP} = \frac{\text{Energy, as heat supplied to process system}}{\text{Energy input to heat pump}} .$$

The essential requirements and components in a simple heat pump are:

1. An ample and continuous supply of low-temperature heat energy to evaporate liquid refrigerant at low pressure; water is a preferred source, river or lake water being excellent when lower-temperature thermal energy is to be produced. Waste heat streams (either gases or liquids) are potential sources of energy for heat pumps.

2. A compressor to convert low-pressure, low-temperature refrigerant vapor into vapor at higher temperatures and pressures.

3. A heat exchanger (condenser) that condenses the high-temperature, high-pressure refrigerant vapor and transfers the heat removed by condensation to a fluid stream, such as hot water or steam, that supplies heat to the processing plant.

4. An expansion valve that lowers the pressure of the high-pressure condensed (liquid) refrigerant, some or all of which is converted to low-temperature liquid.

5. A heat exchanger (evaporator) that transfers heat from the low-temperature heat source, such as air or river water, to the liquid refrigerant to produce low-temperature, low-pressure vapor in item 2 above.

6. A suitable refrigerant such as one of the Freons or ammonia. The optimum choice of refrigerants is based on many factors; some of the more important are

a. the thermodynamic and transport properties and chemical stability of the refrigerant as they relate to the temperatures of the heat pump system,
b. toxicity,
c. corrosion and compatibility of the refrigerant with the materials in the system,
d. flammability,
e. cost.

Elements 1-6 above are found in all compression-type refrigerators, air conditioners, and heat pumps.

Whereas the small, residential-size heat pump is a well-developed, off-the-shelf item, larger versions sized for industry have appeared only recently. Heretofore industrial processors have had little incentive for their use because energy has been cheap. A well-known company has recently developed high-capacity heat pumps[149] designed to reheat cooled process water to higher temperatures or to make steam from condensate. Figure C-1 is a schematic flow diagram of a heat pump as used for reheating used process water. Figure C-2 shows the performance curves published[149] by the manufacturer for these heat pumps when they are used as water heaters and with water as the heat source. From Table C-1, it is seen that these devices are offered in four models representing four different sizes. The maximum capacity, or rating, of each size is not the number in the "Heat Output" column; rather (see Fig. C-2), it is determined by the temperature of the heat source. The coefficients of

Table C-1. Advertised performance[a] of a heat pump producing 65.5°C (150°F) water from warm water at 35°C (95°F)[b]

Model	Water flows: 35°C source [m^3/hr (gpm)]	Water flows: 65.5°C delivery [m^3/hr (gpm)]	Heat output [10^3 Btu/hr (10^6 cal/hr)]	Power input (kW)
TP050	33 (145)	21 (91)	903 (228)	63
TP063	71 (312)	44 (193)	1930 (486)	132
TP079	106 (466)	66 (289)	2890 (728)	189
TP120	169 (746)	105 (463)	4630 (1167)	291

[a]These data are for a single-stage compression unit (Ref. 149).

[b]Data courtesy of Westinghouse Electric Corporation.

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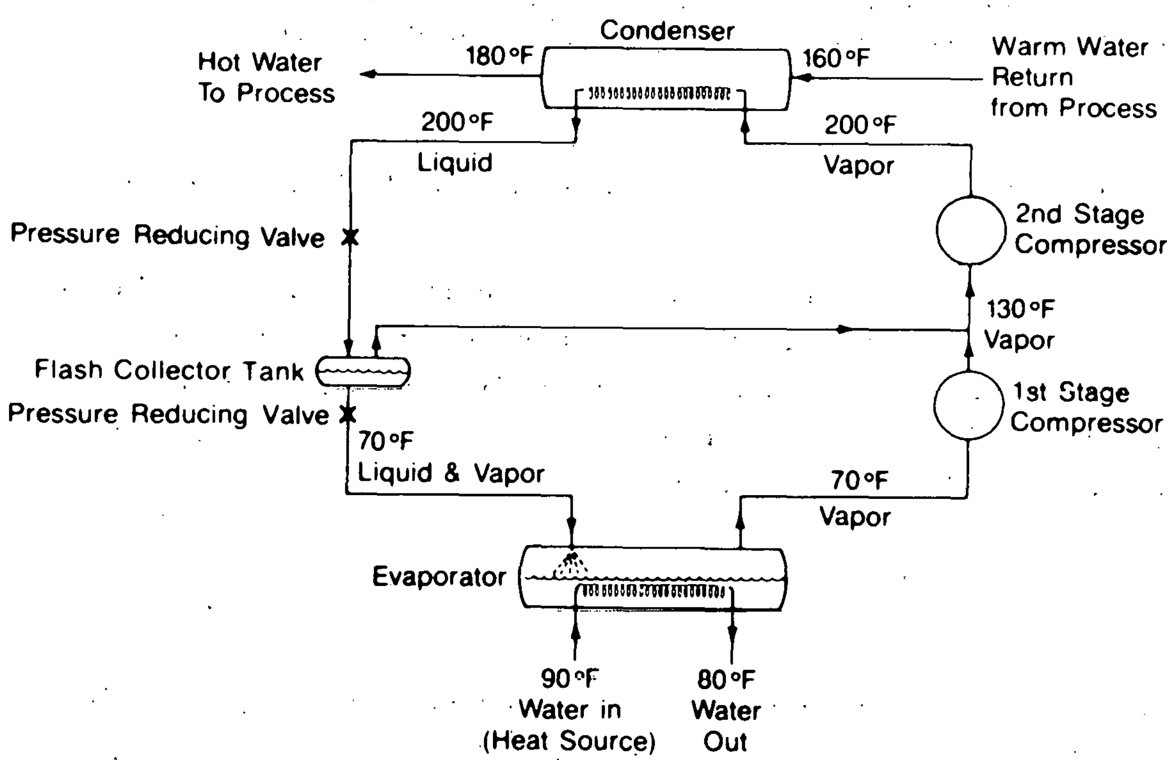

Fig. C-1. Schematic flow diagram of an industrial heat pump with two-stage compression. (Figure courtesy of Westinghouse Electric Corporation.)

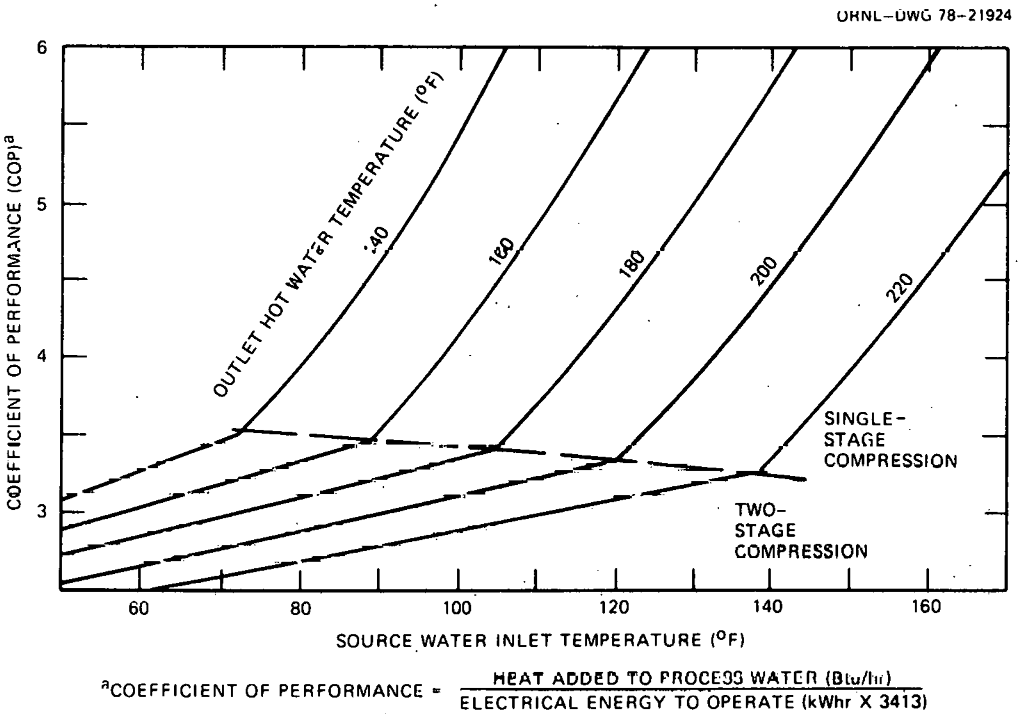

Fig. C-2. Advertised performance of one- and two-stage compression industrial heat pumps. (Figure courtesy of Westinghouse Electric Corporation.)

performance for the water temperatures shown in Table C-1 are from 4.2 to 4.7.

Viewed solely from the standpoint of energy conservation, the value of a heat pump as an energy saving device is easily determined. As a method of shifting industrial energy use from gas and petroleum by substituting electricity based on coal or fission energy, its merit is obvious; the literal equation reads

$$\begin{bmatrix}\text{Heat previously}\\ \text{wasted}\end{bmatrix} + \begin{bmatrix}\text{Electrical}\\ \text{energy}\end{bmatrix} = \begin{bmatrix}\text{Reduced usage}\\ \text{of gas and/or oil}\end{bmatrix} .$$

This is oversimplification. Economics must be included in any equation that is used to influence or to make a decision to use or not to use a heat pump. Figure C-3 shows a comparison of the energy cost for low-temperature process heat developed with oil, gas, and electrically powered heat pumps.

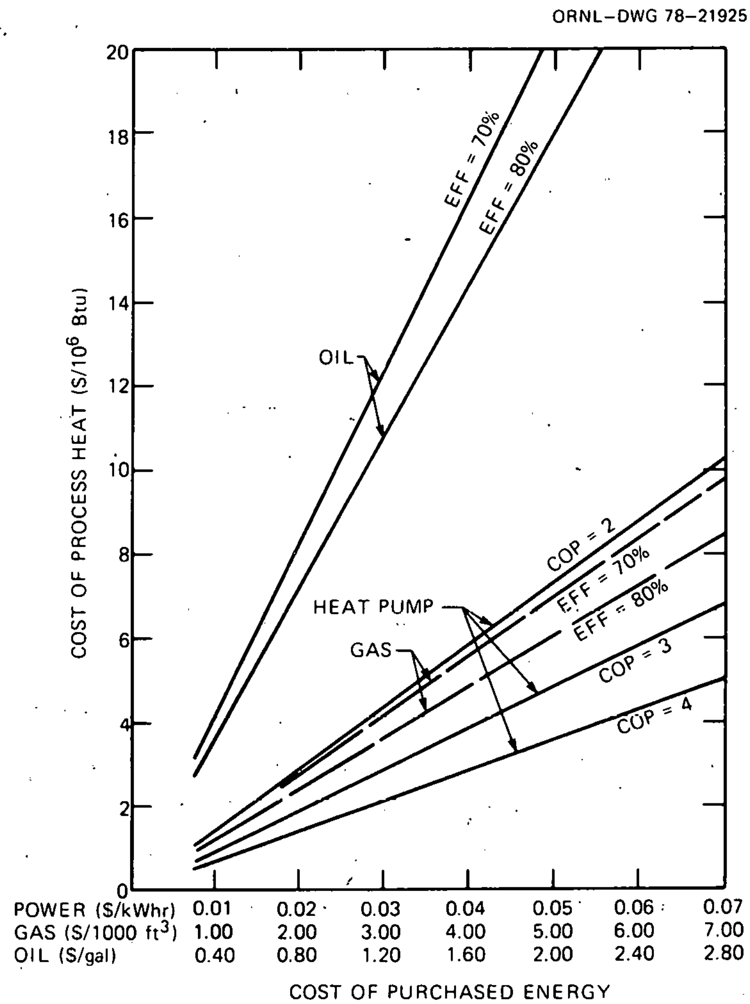

Fig. C-3. Energy costs of low-temperature [≤100°C (≤230°F)] steam or hot water developed with gas, fuel oil, and electrically driven heat pumps.

Economic Considerations

Capital costs

An editorial article in Ref. 150 credits this statement to the heat pump manufacturer:

> . . . the unit will have applications where large, new boiler capacity or vapor-recompression systems cannot be justified. But the installed cost of . . . (the heat pump) . . . will usually exceed that of a gas or oil fired boiler, so favorable economics hinge on lower energy costs from electricity than from oil or gas . . . .

In Ref. 151, the author of an editorial article writes:

> The initial cost of a system (heat pump) is high — some $30,000 or more than an oil burner of equal output . . . .

Unfortunately, this dollar comparison is not related to the capacity and cannot be applied quantitatively.

Operating costs

Equipment of this type needs little attention from personnel during operation. Maintenance experience is insufficient for estimating these costs.

Limitations and Applications

For reasons of chemical stability, the refrigerant temperature in the units listed in Table C-1 should not exceed 121°C (250°F). This limits energy delivery to temperatures of ⩽110°C (230°F).

Notwithstanding the 110°C (230°F) maximum temperature limit, there exists a large number and variety of uses and processes that are potential users. A partial list follows:

1. Food and beverage industries — for cooking and sterilizing, pasteurizing, drying, distilling, and evaporating. Virtually all food production requires process heat at temperatures within the range of heat pumps.
2. Space heating and service hot water in office and industrial buildings located near the waste heat source.
3. Glue curing and drying in the plywood and lumber industries.
4. Concrete block curing.
5. Metal fabrication processes — for plating baths, cleaning tanks, chemical treatment tanks, and paint and enamel drying facilities.
6. Textile production — for cleaning and for heating dye tanks.
7. Pulp and paper — to augment the process heat used for pulping and water removal throughout the process.

8. Chemical production — to augment use of low-temperature steam or other form of heat. Lower-temperature distillation processes are an example.
9. Petroleum processing — as a substitute for low-temperature steam now being generated with oil or gas. Petroleum refining and petrochemical production are characterized by a multitude of waste heat streams. The potential for heat pumps to become an effective way to obtain additional low-cost energy is high.
10. Public utilities — where a public utility not only provides electrical power but steam or hot water for process and space heat. Heat pumps, operated during off-peak loads, will improve the load factor and, in combination with energy storage, would supply low-temperature heat to users who would manage and schedule their energy requirements. Condenser discharge water would be the heat source.
11. Applications similar to items 1–10 above, based on energy derived from low-temperature geothermal sources, may offer promise.
12. Heat pumps interposed between a high-temperature process and a second, low-temperature, steam-using process. Figure F-1 (Appendix F) is a diagram illustrating this possible application with a glass-making operation serving as the waste heat source.
13. Other users: laundries and cleaning and pressing establishments use and waste low-temperature heat in the form of steam and hot water. Hospitals need low-temperature steam in autoclaves for sterilizing bedding and equipment. Heat pumps operate within the applicable temperature range, and their potential for these uses can be determined.

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Appendix D

THE STEEL INDUSTRY

Electrical melting with arc and induction furnaces is now the principal use of electricity for thermal energy in the production of steel and foundry products. It is a well-established process whose use has been increasing and is expected to increase further.* One reason for this trend is the improved product quality required by the ever-increasing sophistication of our technology.

Very large amounts of natural gas are used by steelmakers for reheating. Slabs, ingots, and billets of carbon and alloy steels destined to become a wide variety of shapes and sizes are heated to temperatures in the order of 1260°C (2300°F) for hot forming operations such as rolling and forging. Heat treatments to anneal, normalize, carburize, spheroidize, harden, temper, and stress relieve are carried out over a very wide range of temperatures below 1260°C (2300°F). Programmed heating and cooling cycles and controlled atmospheres are frequently required. Within the steel mills, the preponderant energy source for reheating is natural gas supplemented by fuel oil. Reheat energy may account for as much as 80% of the natural gas used by large, integrated steel plants.

At least 50% of the nation's steel is produced in Pennsylvania, Ohio, Indiana, and California — regions strongly dependent on gas and oil and (Fig. B-1) expecting or experiencing severe shortages with curtailments and cost penalties for excessive use.

Figure D-1 shows the distribution of energy sources in the steel industry in 1975. Note that the "cold metal" companies, whose processing begins with metallic iron, use large amounts of electricity and gas. The electricity is used for melting pig iron and scrap; the gas is used for reheating required by subsequent forming operations.

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*An article in the *Wall Street Journal* (Mar. 15, 1978) states: "Republic Steel Says It's Studying Plan to Reduce Pollution. Cleveland, Republic Steel Corp. is studying a plan involving a partial switch to electric-melt furnaces at its Warren, Ohio mill and . . . ."

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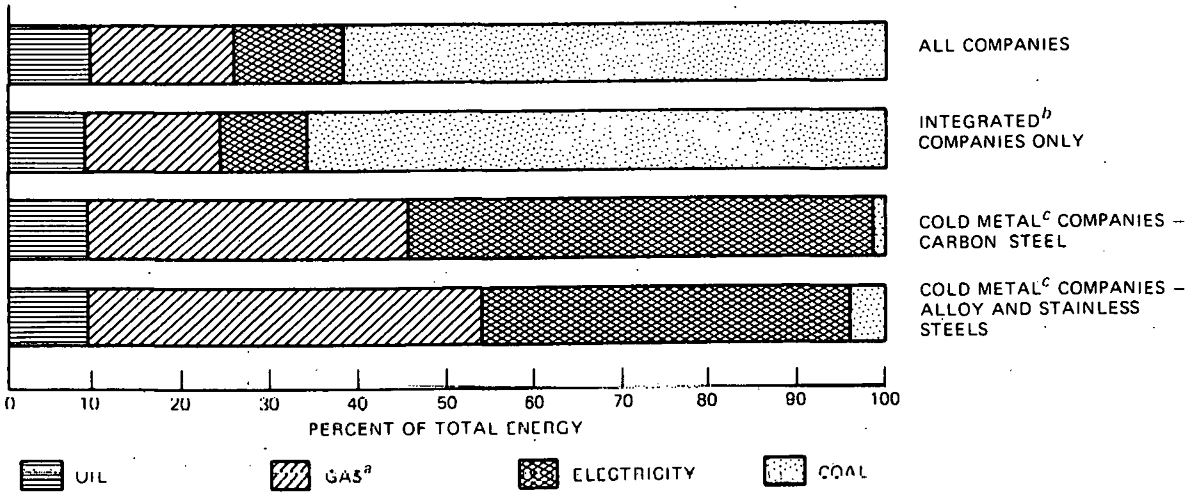

[a]THE STEEL INDUSTRY USES ~6% OF THE TOTAL NATURAL GAS REQUIRED BY INDUSTRY.

[b]"INTEGRATED" COMPANIES ARE ENGAGED IN ALL PHASES OF STEEL PRODUCTION, FROM ORE TO FINISHED PRODUCT.

[c]"COLD METAL" COMPANIES DO NOT HAVE PROCESSING FACILITIES (BLAST FURNACES) FOR REDUCING ORE TO METALLIC IRON.

Fig. D-1. Distribution of energy sources in the steel industry in 1975. Data courtesy of the American Iron and Steel Institute.

Steel producers concede that the use of gas or oil is relatively inefficient in reference to the minimum energy required to raise the temperature of the material and to effect the structural transformations required for forming and heat treating.

Table D-1 is a comparison of the actual vs the theoretical absolute minimum energy requirements for two typical reheating operations with natural gas.

The use of computed theoretical minimum energies as a basis for comparison does not imply that these minimums are attainable. Regardless of the energy source or the method of its application, heat losses to the outside world are and will be inevitable.

The usage figures in Table D-1 are from two quite different operations. The slab heating (item 1) involves large, thick slabs undergoing reheat to a very high temperature prior to rolling into plates or strip. Typically, this is a large-scale and preferably continuous operation. The slab data do not disclose whether the heat input includes the energy required to bring the furnace to operating temperature. The bar heating

Table D-1. Comparison of actual and theoretical minimum steel reheating energy usages[a] of natural gas

Application	Energy used [kWhr/ton (Btu/ton)]		Ratio of theoretical to actual
	Actual	Theoretical minimum[b]	
1. Slab or billet reheating from 38 to 1232°C (100 to 2250°F)	674 (2,300,000)	(717,000)	0.31
2. Slab or billet reheating from 649 to 1260°C (1200 to 2300°F)		123 (420,000)	
3. Alloy bar heat treatment from 38 to 749°C (100 to 1380°F)	449 (1,532,000)		0.26

[a]These data are from Refs. 152-154.

[b]The theoretical minimum energies are based on average heat capacities of 0.160, 0.167, and 0.154 cal/g-°C (Btu/lb-°F) for usages 1, 2, and 3 above, respectively.

data (item 3) is for a low-tonnage, batch-type process and represents only the heat required to bring the bars to soaking temperature [∿750°C (1380°F)]. The furnace had been modernized with improved insulation and the gas burning carefully controlled to optimize combustion efficiency. In spite of the wide differences in these two processes, the energy usages are remarkably alike. It is reasonable to assume that well-managed steel reheating processes using gas will have (theoretical/actual) ratios from 0.25 to 0.30 (i.e., energy deposition efficiencies* from 25 to 30%).

It is frequently assumed that utility-generated electrical power can be delivered to an industrial user with 32% efficiency referred to the energy content of the primary fuel (coal, oil, gas, or fission). Electrical energy for reheating, to compete with natural gas, must be deposited in the steel with an efficiency of about 80% or more if the

*The addition of recuperators will increase the efficiency of large gas-fired reheating furnaces to 35-40% (Ref. 155).

sole consideration is gross primary energy usage. Well-designed induction heaters have efficiencies of 60 to 65%. This simple comparison is naive since it neglects all other normal cost factors, product quality, and, perhaps most important, the ability of particular industrial processors to survive if gas shortages limit their operations.

Induction heating with electricity is a process widely accepted by the fabricators of finished metal components. It is well adapted for heat treatment of large production runs of components such as gears, cams, sprockets, and bearing races; it is particularly well suited for situations in which the heat deposition can be or should be localized in the component. With some exceptions, induction heating has not yet received wide application by primary metal producers for reheating required by the various forming operations that follow raw metal production.

Two notable exceptions are the induction slab heating facility operated by the McLouth Steel Company, Trenton, Michigan, and a bar heating system in the Chicago area. McLouth employs six induction heating lines to reheat cast slabs prior to rolling. The slabs are received after casting, preferably while still hot, and, in each line, are passed successively through three induction heaters rated at 20, 10, and 5 MW, respectively. The slabs, with maximum dimensions of 0.30 × 1.52 × 7.92 m (1 × 5 × 26 ft), are heated to an average temperature of 1260°C (2300°F). In Table D-2, the energy costs and usages in the McLouth operation are compared with typical values based on fossil fuel reheating for the same purpose.[152]

This tabulation indicates that induction heating in the present state of the art uses 35% more primary energy at the generating plant than that contained in oil or gas used at the mill. The energy cost to the user is reduced with induction heating. The comparison is incomplete for use as a firm guideline in making a decision. The data in Table D-2 do show that electrical reheating may be the preferred choice for economical plant operation. Of equal, perhaps greater, importance is the reduced dependence on a large, uninterrupted supply of natural gas.

The bar reheating installation[156] is used to restore rolling temperature [∿1230°C (∿2250°F)] to continuously cast bars 7.5 in. square.

Table D-2. A partial cost comparison of fossil fuel and induction heating for large steel slabs

Heating method	Cost ($/ton)
Fossil fuel heating	
Energy: 674 kWhr/ton (2.3×10^6 Btu/ton) @ \$2.00/10^6 Btu	4.60
Scale loss, 2.0% @ \$200/ton	4.00
Total	8.60
Induction heating[a]	
Electrical energy at mill, 295 kWhr/ton (1.0×10^6 Btu/ton) @ \$0.02/kWhr	5.90
Scale loss, 0.50% @ \$200/ton	1.00
Total	6.90

[a]Based on fuel energy at generating plant, 908 kWhr/ton (3.1×10^6 Btu/ton).

By the time the bars reach the heaters, they have lost some heat and possess a temperature gradient decreasing from the center. Induction heating is peculiarly adapted to this use because heat deposition tends to be concentrated near the surface where the temperature loss is highest. The temperature increase produced by these 60-Hz induction heaters is relatively small [∿100 to 150°C (200 to 300°F)]. About 65% of the electrical energy input to the induction coils is deposited as heat in the product.

The operators of this facility have also considered induction annealing of thin sheets after rolling is completed. Gas is now used for this operation, and the present net yield of product is about 96 1/2% (3 1/2% spoilage). Induction heating at 460 kHz as a continuous, final operation becomes attractive for this sheet annealing operation if the yield is increased to 99% and if 50% or more of the heat content of the hot, annealed material is transferred to the cold strip before it enters the induction annealer. The higher costs of the frequency conversion equipment required for the higher frequencies needed to heat thin sections now tends to discourage the adoption of induction annealing in this application. Effective methods to transfer heat from hot to cold sheet steel have not been devised.

Many steel producers and other industrial users are of the opinion that gas pricing must and will be deregulated.[157] A very large group of industrial users anticipate winter season gas curtailments if current conditions continue to prevail.[157,158] Whether or not deregulation will increase the supply is conjectural. The long-term forecasts envision a shortfall. Should deregulation take place, the prices of natural gas will experience a quantum jump. Price increases, curtailments, and eventual scarcity, either singly or in concert, will make electrical substitution a more attractive alternative. Figure D-2 (extrapolated data in Table D-2) shows reheating costs per ton for increased prices of gas and electricity. One steel plant official notes that at his plant natural gas and electricity prices have increased by factors of 2.7 and 2.3 during the last five years. If these trends continue, the natural gas and electricity costs in Table D-2 will become $\$14.60/10^6$ Btu and \$0.106/kWhr in ten years. The energy cost difference (\$1.70) in Table D-2 will become \$5.32/ton in favor of electricity in 1985. Intuitively, these total energy cost increases seem high. In any event, future energy costs are open to surmise. This is a major factor in making decisions involving energy usages.

From this preliminary survey, it is concluded that the energy costs of electricity to reheat steel during processing are now or will soon become comparable to the costs of reheating with gas or oil. The substitution of electricity for gas in the very energy-intensive steel industry will produce a very substantial reduction in natural gas usage. A large fraction of this reduction will take place in areas that are now anticipating periodic shortages in the immediate future. In terms of the number of applications and the total tonnages processed, electrical reheating is currently not receiving wide application by the primary steel processors. Capital costs of electrically powered reheating systems, insufficient returns on investments, uncertainties with respect to future energy costs, and lack of experience all tend to retard development and adoption of induction and resistance heating for primary ferrous metal processing.

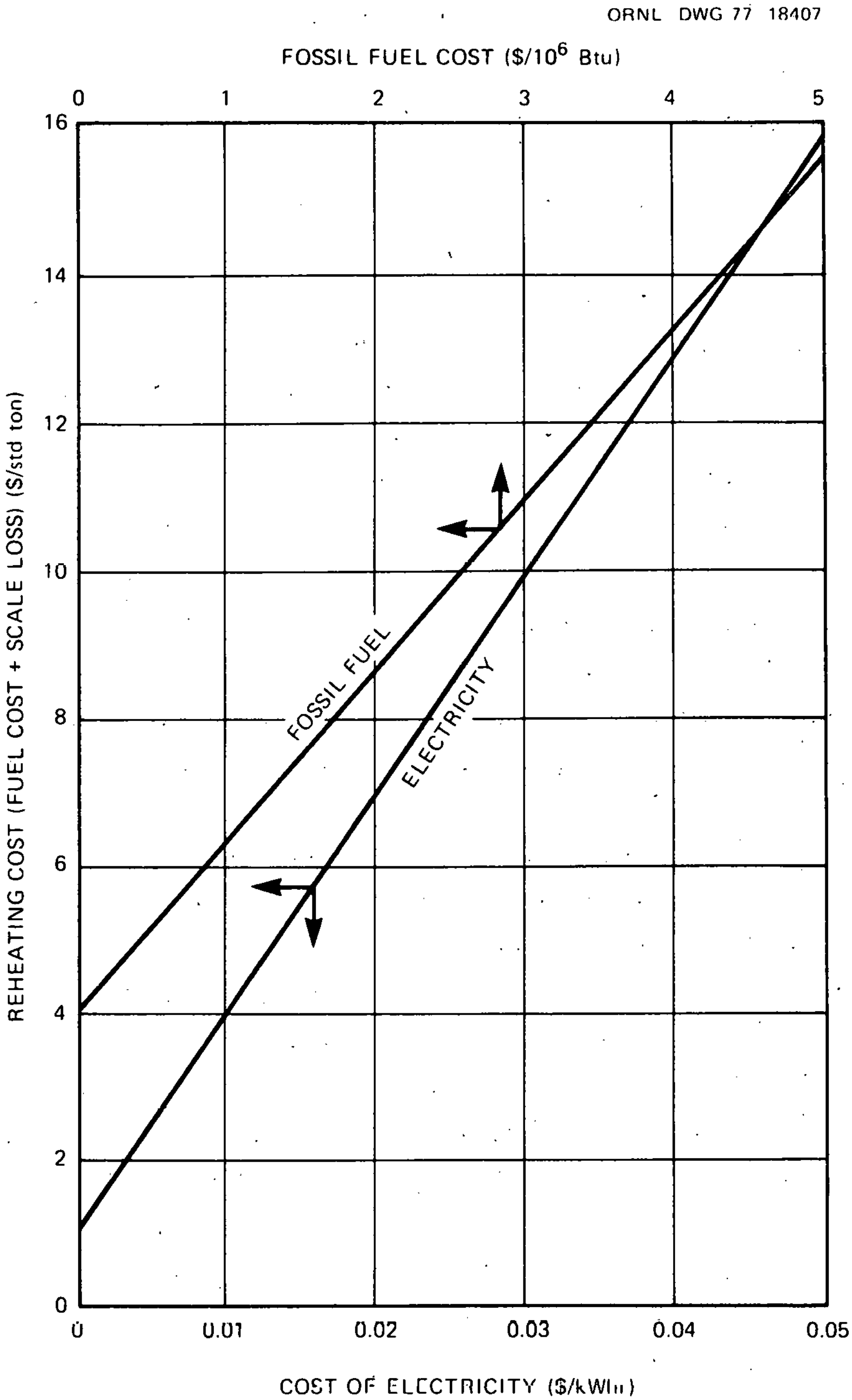

Fig. D-2. Costs of fuel and scale loss with electrical and fossil fuel versus unit costs of energy.

Research and Development Programs for Increased Electrification in the Primary Steel Industry

Induction heating is well understood and is receiving wide application as a manufacturing method. Its application as a process suitable for large tonnage rates in steel mills is gaining ground. The accelerated development of systems for these uses may be worthwhile.

Resistance heating of rods and wires for reheating between size reductions appears to be inherently very efficient and is used in some applications. Reduction to widespread practice has not been accomplished but should respond to concerted engineering development.

The development of very high power, efficient induction and resistance heating systems will increase productivity in the primary steel industry. These systems will be designed as an integral component in continuous, high-speed production lines for sheets, bars, structural shapes, tubes, wire, etc. They will produce the initial and intermediate reheating required between forming passes and final anneals and heat treatments. Such systems, to be effective, will be capable of very high heat deposition rates.

Typically, large-scale induction heaters deposit about 60 to 65% of their input electrical energy in the work. The possibility of improving this heat deposition efficiency should be examined. The use of induction heating requiring frequencies above 60 Hz is inhibited by the costs of frequency conversion equipment. The development of efficient, versatile components that produce a wide range of frequencies capable of depositing energy into a wide range of product sizes and shapes will stimulate increased use of electrical power by the metal producers. A parallel effort to recover and reuse the available energy in hot, processed steel products will conserve energy regardless of the method used for heatup.

The use of salt or liquid metal baths with hot and cold sheets, bars, or billets moving counterflow may be a worthwhile development to recover reheat energy used for final anneals. Water-cooled induction coils in conjunction with an industrial heat pump may be capable of producing substantial amounts of process steam from induction reheat energy now being lost.

References 159–161 contain additional information on reheating in the steel industry.

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Appendix E

THE PULP, PAPER, AND PAPERBOARD INDUSTRIES

The producers of paper and related products are the fourth highest users of energy in the United States.[162] Energy distributions and usages in 1972, reported by Kaplan,[163] are shown on Table E-1 and Fig. E-1. Process steam is the principal energy medium. Neglecting all economic considerations, there are no technological barriers to producing nearly all the heat energy required to make paper with utility-generated electricity for shaft power and in electrical boilers. Heat pumps, if warranted by a system analysis, may become an effective means of conserving energy.

The total 1972 energy consumption of 2270×10^{15} J may also be subdivided in the following way:

Process or operation	Energy 10^{15} J	Energy 10^{12} Btu[a]
Mechanical operations		
Woodyard	10	9.5
Boiler fans and pumps	10	9.5
Pulpmaking	80	75.8
Sheet forming, drying, finishing	120	113.7
Total	220	208.5
Thermal operations	2050	1943.0
Total	2270	2151.5

[a]British thermal units = Joules × 9.478×10^{-4}.

Table E-1. Energy requirements for papermaking and boardmaking

Process	Mechanical energy (10^6 J/adkg)[a]	Thermal energy (10^6 J/adkg)[a]
Deinking	0.05–0.23	2.3 3.5
Repulping	0.05–0.93	
Refining (secondary fiber)	0.6–0.8	
Beating	0.6–1.6	
Final cleaning	0.1	
Fourdrinier (wet end) drive	0.2–0.7	
Cylinder machine (wet end) drive	0.1–0.2	
Paper machine auxiliary drives	0.1–0.6	
Furnish temperature adjustment		0.35–0.9
Steam roll drying		7.6–14.6
Air drying of pulp, etc.		4.6–5.8
Yankee dryer (air and steam)	0.1–0.2	
Calender, winder, etc.	0.1	
Deinked paper (total)	1.7–4.6 (2.1, av)	11.6–18.6
Virgin-fiber paper or board	1.2–3.1 (2.4, av)	8.1–15.1

[a]adkg = air-dried kilogram.

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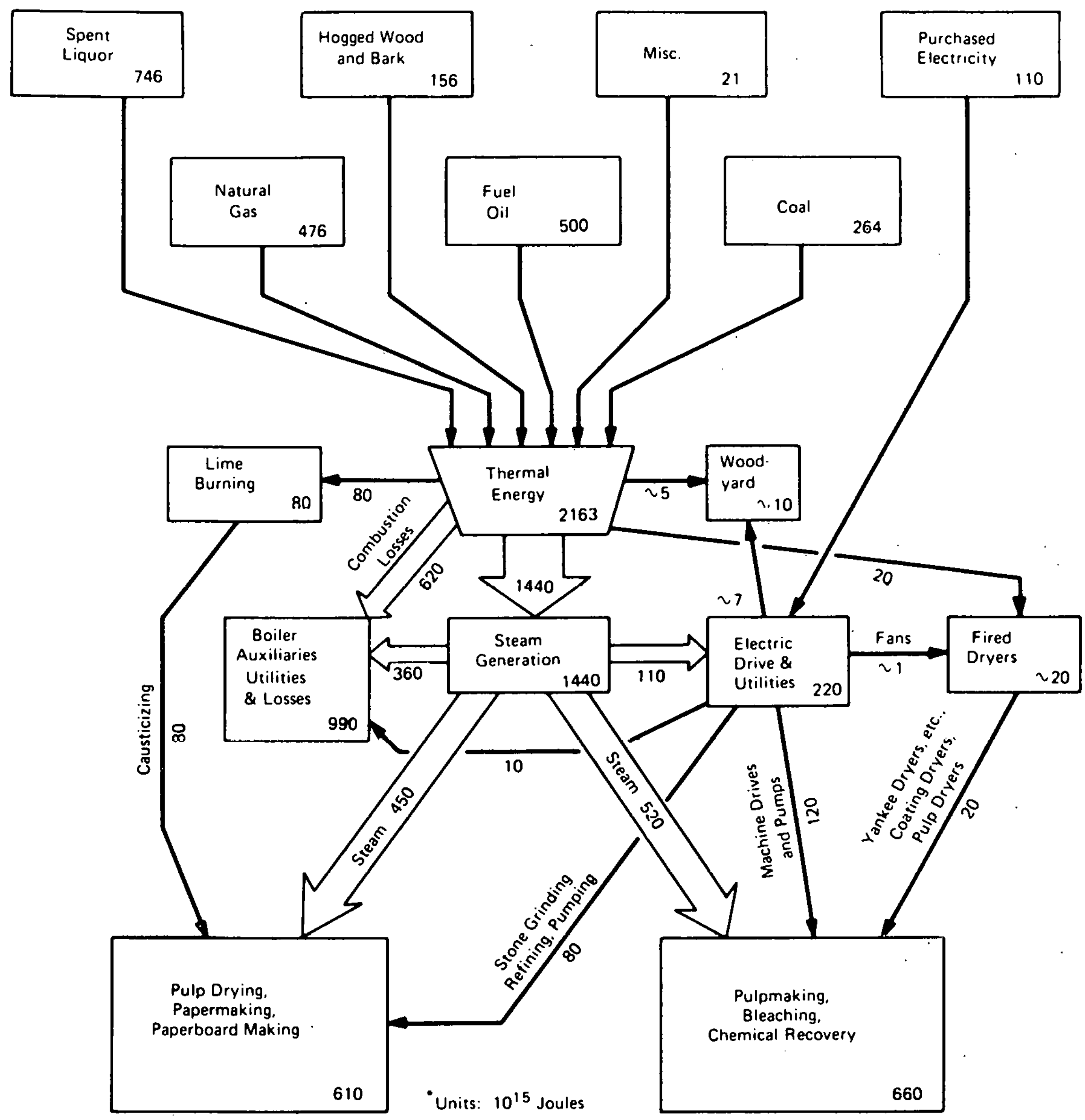

Fig. E-1. Estimated energy distribution for the pulp, paper, and boardmaking induotrico, 1972 (from Rcf. 163).

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Appendix F

THE GLASS INDUSTRY

Glassmaking is very energy intensive, uses large quantities of natural gas, and, in the immediate future, is dependent on a continuing supply of gas or fuel oil. The principal usage is for melting, with lesser but not insignificant amounts required to anneal finished products.

The technology required to melt glass electrically has been developed. A prominent member of the glassmaking community, a company with a long-standing reputation for heavy emphasis on research and development, has developed and is using an electric glass furnace in a continuous, round-the-clock production operation. Another processor is planning to install an electrically powered unit.[14] This furnace is extremely efficient; waste heat production is negligible compared with that from a gas-fired unit. In contrast to traditional practice, based in part on operator judgment, this electric melter is completely instrumented and controlled. The electric glass furnace is inherently responsive to instrumented control methods. This characteristic enables the use of rigorous procedures designed to assure quality and to minimize energy consumption.

The operators of this facility are extremely enthusiastic about the results obtained with this furnace. Were it not for the costs of removing and replacing[77] existing gas-fired furnaces and uncertainties with respect to obtaining an expanded, continuous, and reliable supply of electricity at an acceptable price,* they would convert all their glass melting operations to electricity.

Annealing is the other processing operation in the glass industry in which substantial amounts of gas are used. Manufactured glass components require annealing to remove locked-in stresses developed by the forming process. The temperatures and time-at-temperature required to anneal a component depend on the composition of the glass and, in some

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*D. E. Leibson (Ref. 76) has testified that electrical melting is attractive when the price of electrical energy is not more than 1 1/2 times the price of fossil fuel energy.

cases, on the thickness. Glasses of types that represent the bulk of the production are annealed at temperatures from 400 to 550°C (750 to 1020°F). These temperatures are attainable in electrically heated ovens with available components.

The ability to substitute electricity for gas or fuel oil is being demonstrated with productive, profitable operating units. The current choice of energy for glassmaking is now primarily an economic decision.

The generally high temperatures that prevail in glass processing suggest that a glass plant is an ideal candidate for incorporation into a multiprocess industrial complex. The possibility that waste heat from a glass producer will serve the energy needs of a lower-temperature process such as food processing, paper production, distilling, etc., deserves attention. A study that considers applying energy storage, heat pumping, and load management should be considered (Fig. F-1).

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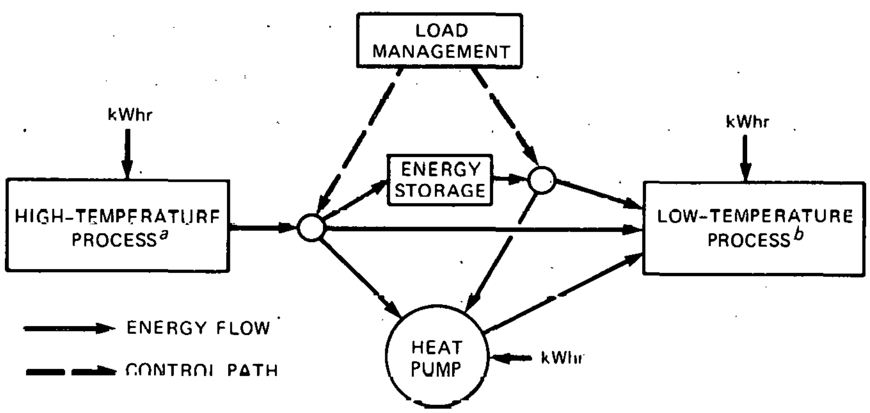

[a] GLASS, CERAMICS, BRICKS, AND LIME PRODUCTION ARE EXAMPLES.

[b] FOOD, TEXTILES, AND MISCELLANEOUS MANUFACTURING ARE EXAMPLES.

Fig. F-1. A two-industry energy grid pro quo system.

Appendix G

THE BRICK INDUSTRY

The brick and tile industry is almost wholly dependent on gas (86%) and oil to fuel its kilns. The development and use of coal-fired brick kilns[164] are under way and are proving successful.* The use of direct electrical heat is not contemplated. In the general area of energy usage, the principal efforts are confined to conservation practices within the framework of existing methods.

The energy-using procedures ("burning") take time to complete. These procedures[165] are

1. Drying: the evaporation of free water from the brick or tile; takes place at temperatures up to 204°C (400°F).
2. Dehydration: the removal of chemically retained water; takes place at temperatures from 149 to 982°C (300 to 1800°F).
3. Oxidation at temperatures from 538 to 982°C (1000 to 1800°F).
4. Vitrification at temperatures from 871 to 1316°C (1600 to 2400°F).

The thermal processes, drying and burning, require from 48 to 150 hr to complete, depending on the type of kiln, the type of brick or tile being fired, and the raw material composition. The principal factors contributing to the lengthy heating and cooling cycle are

1. Vitrification, the chemical changes required to convert clay mixtures to brick; proceed slowly.
2. Rapid temperature changes are detrimental. Excessive rates of water removal, heating, and cooling produce cracks and checks and unacceptably high spoilage.

The general trend in brick manufacturing has been from batch-type kilns to continuous flow, tunnel kilns. The tunnel kiln, as the name implies, is a long, narrow enclosed refractory lined channel. The

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*General Shale Products, a very large producer, is capable of using coal for nearly 50% of its production.[78,164]

bricks, transported on cars, pass through controlled temperature zones as they traverse the kiln. Waste heat from the kiln is used to dry the bricks.

Research and development efforts centered on brick processing are conducted principally by the ceramicists and ceramic engineers in colleges and universities. Clemson, Alfred, and Ohio State universities are actively engaged in such efforts.

The prospects of electrical substitution in the brick and tile industry appear remote. Should oil and gas become unobtainable or their costs become prohibitively high, coal will probably become the more attractive alternative.

Coal and ash handling, pollution, and product contamination are deterrents to using coal-fired brick and tile kilns.

Bricks are not considered to be good conductors of electricity. At the temperatures used to dehydrate and vitrify, it may develop that brick burning can be accomplished by radio-frequency, dielectric heating. No final conclusions should be drawn as to the possibilities for electrical substitution and energy-saving methods in these industries without well-founded answers to these questions:

1. Is vitrification inherently a process that requires a long time to complete; that is, what are the theoretical thermodynamic minimum times and energies required to produce the structural changes that convert clay to brick?
2. Is it possible to reduce energy usage by composition alterations that operate to
   a. Reduce dehydration and vitrification time and energy. It has been suggested that research directed at speeding up the rate processes governing vitrification may be effective (e.g., determine whether or not the reactions respond to the addition of catalysts).
   b. Reduce the susceptibility to cracking and checking induced by rapid temperature changes.
3. What are the electrical properties (i.e., resistivity and dielectric constant) in the material during the burning process?

Electrical energy, to convert clay into bricks and tile, must be applied with these characteristics:

1. The heat is directed into the product and produced by internal generation.
2. The heating cycle time is relatively short.

Unless it develops that, during the burning process, bricks respond or can be made to respond to electricity like a metal, brick production is an unlikely candidate for large-scale electrical substitution. Heat pumps may be effective to supply additional heat for lower-temperature water removal.

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Appendix H

FOOD PROCESSING

Food processing ranks sixth in industrial energy usage.[162] With few exceptions, this energy is used at moderate temperatures for cooking, baking, drying, and pasteurizing. Electrical power is used for refrigeration. Large amounts of process steam generated in oil- and gas-fired boilers are used to convey and transfer heat and, in some cases, to generate power. Little or no new technology is required for almost 100% conversion to utility-generated electricity for the primary energy source.

Because the temperatures used in these processes are mainly moderate ones [<260°C (<500°F)], the incorporation of heat pumps and absorption refrigeration would be an excellent means of reducing the total energy requirements, regardless of the primary energy source. The malt beverage, meat packing, beet and cane sugar, and wet corn processing industries are suggested as particular processes for further study. The reasons for these choices are outlined below.

Meat packers are the largest user[166] of energy among the food processors; Fig. H-1 and Table H-1 indicate that nearly 70% of this

Table H-1. Energy usage by the meat packing industry[a] during the period July–December 1975

Energy source	10^{12} Btu	10^{9} kWhr	Percent of total	
Natural gas	11.23	3.29	56.1	69.4% (natural gas, fuel oil, propane)
Fuel oil	2.61	0.76	13.0	
Propane	0.05	0.01	0.3	
Coal	1.42	0.42	7.0	
Electricity	4.29	1.26	21.4	
Other	0.46	0.13	2.3	
Total	20.06	5.88	100.0	

[a]Data based on reports by 40 meat packing firms to the American Meat Institute.[139]

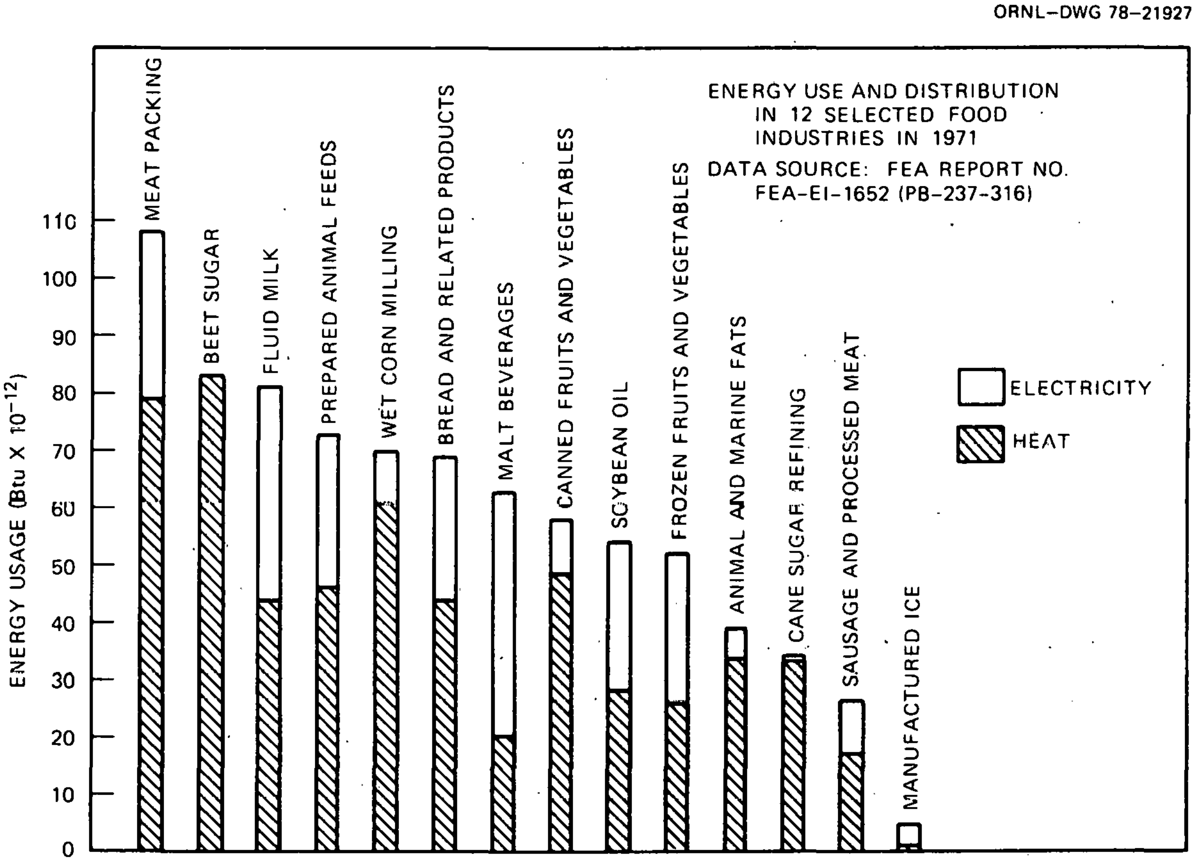

Fig. H-1. Energy use and distribution in 12 selected food industries in 1971 (source of data: Ref. 166).

energy is derived from natural gas and petroleum. Figure H-2 is a diagram of the maximum energy usage by a medium-sized plant in operation at full capacity during the day shift.[167] This packing plant is essentially a one-shift, five-day-week operation. Figure H-3 shows an hourly averaged energy demand curve for this particular plant. This meat packer uses no coal; approximately 70% of his energy is from natural gas and fuel oil, with the remainder from purchased electricity.

The conceptual design of an advanced energy system for this or a similar plant should be considered for these reasons:

1. The scarcer fuels — oil and gas — are used in large amounts for energy as heat.
2. The wide variation in energy use (Fig. H-3) during a typical operating day opens the door to the use of energy storage plus

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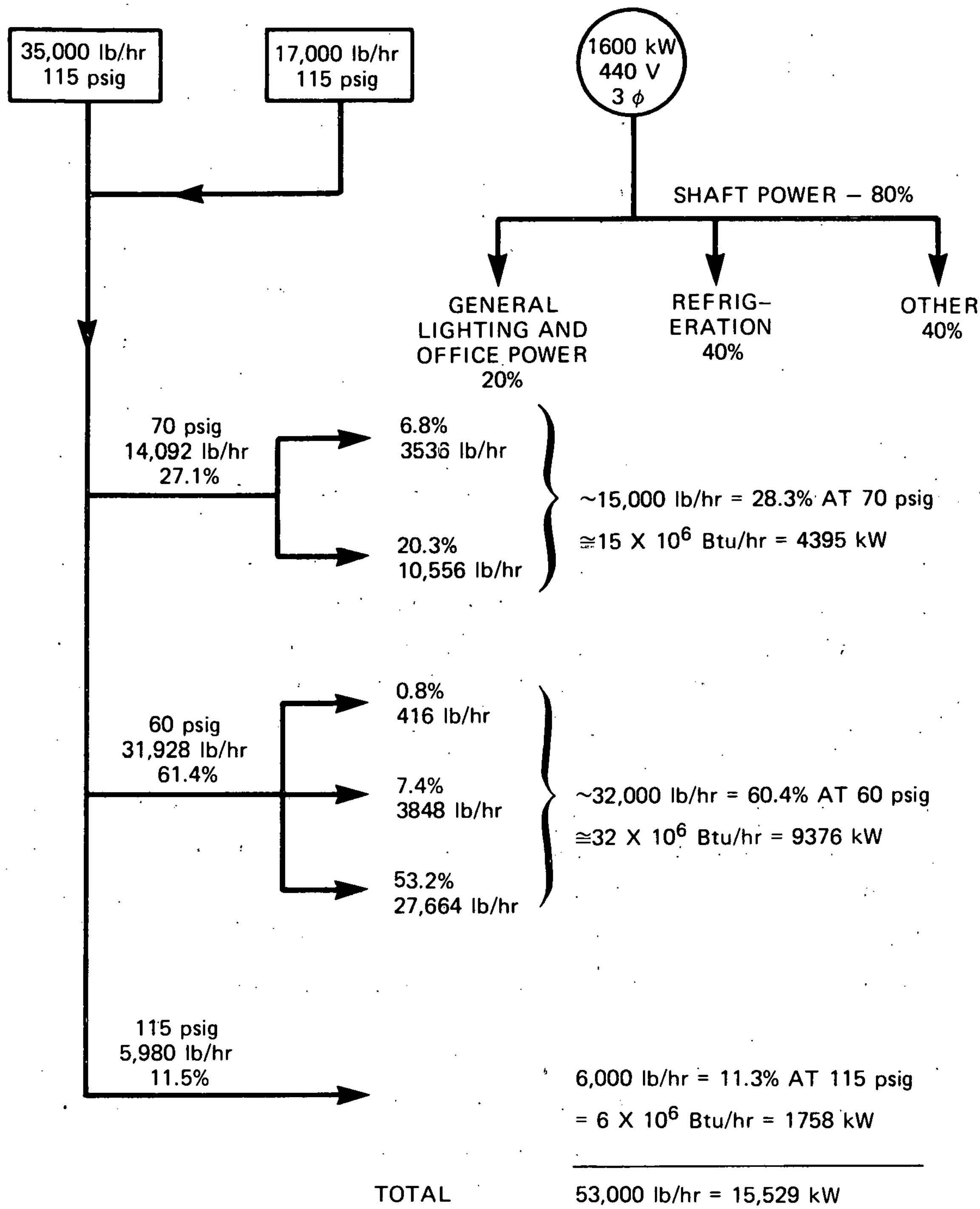

Fig. H-2. Energy consumption and distribution in a typical medium-sized meat packing plant.

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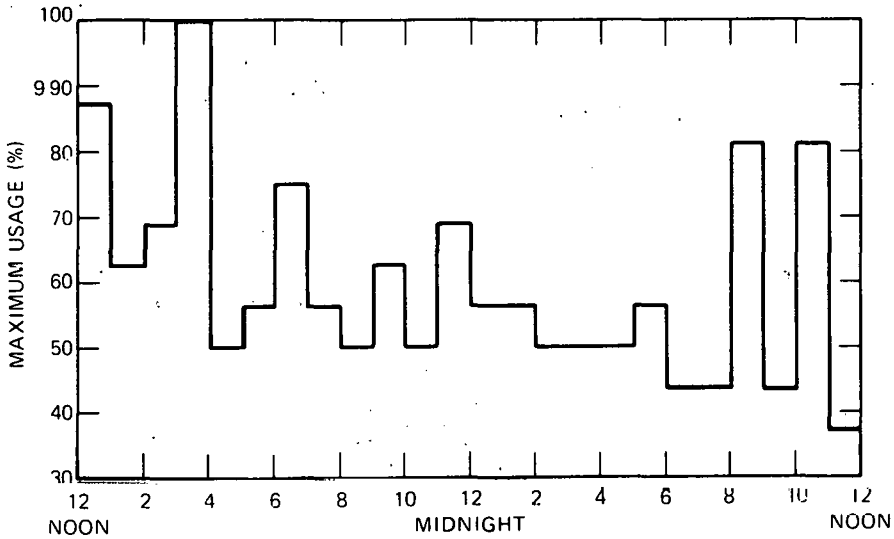

Fig. H-3. Fuel oil demand for a process steam boiler in a meat packing plant. (100% is equivalent to a steam usage of 50,000 lb/hr.)

load management that takes into consideration off-peak discounts or quantity discounts for utility-produced electricity. Steam generation in electric boilers may be economical.

3. Waste heat at relatively low temperatures is available; heat pumps and absorption refrigeration may be attractive.
4. The benefits accruing mutually to the participants of consortiums with users of high-temperature energy should be determined. A semicontinuous operation such as meat packing, distilling, or brewing may provide an effective and economically productive waste heat sink for a steel mill or glass plant, as noted in Appendix F.

It is recommended that this or a similar meat packing plant be used as a model on which to base the design of a high-efficiency electrical energy system. The system design would be a cooperative effort involving the meat processors and a suitable architect-engineering organization. Design criteria will include the stipulation that either fission or coal replace natural gas or petroleum as the primary energy source. A well-engineered system should be constructed and operated as a parallel alternative to the conventional fossil-fueled boiler plant.

Among the food industries, the processing of fluid milk, malt beverages, and frozen fruits and vegetables are also better than average candidates for examining the possibilities for absorption refrigeration, energy storage, electrode boilers, and heat pumps for saving energy and for electric substitution.

From Fig. H-1, it can be seen that these processors use purchased electricity and heat energy in approximately equal amounts. A very large fraction of the shaft power (purchased electricity) is for refrigeration.

The malt beverage industry is particularly recommended as a likely prospect for developing conceptual designs incorporating energy-saving departures from traditional practices because this industry is growing, as evidenced by the new plant construction that is being planned.

Beet Sugar Processing

Salient characteristics

Beet sugar processing typifies many food industries and also may be an extremely likely prospect for technological improvements directed to reduce total energy usage because

1. On both a per-dollar value of product shipped and on a total gross heat energy basis, beet sugar production uses more heat energy than any other food product (Figs. H-1 and H-4).
2. Sugar is a basic, essential food.
3. To varying degrees, depending on location, operation is seasonal, a characteristic common to many food processing plants.
4. The basic technology and methods are little changed from those of the last century. Several plants built around 1900 are in operation. The "average plant" (weighted by plant capacity) was erected 50 years ago.[168] In general, a preponderant majority of the factories were designed and built in times when energy was inexpensive and plentiful. One operator acknowledged that, per pound of sugar, U.S. producers often use twice as much energy as their European counterparts. Modernization has been conducted on a piecemeal basis. A beet sugar factory is a large-scale operation representing a very large investment. Plant alterations and

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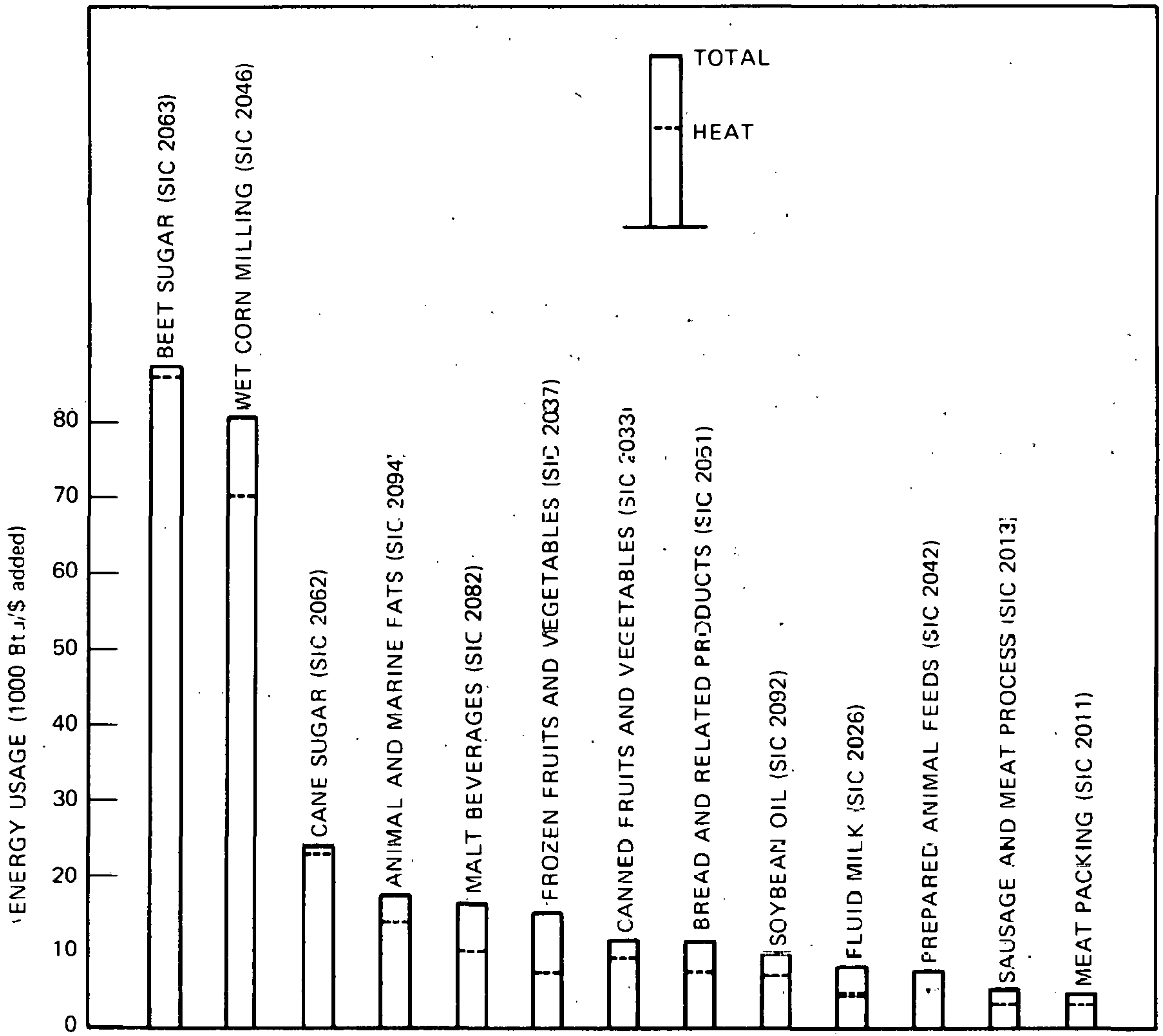

Fig. H-4. Energy usage per dollar value of products shipped in selected food industries (1971).

replacements are expensive and involve substantial expenditures of capital. The industry is very competitive, profit margins are narrow, and capital funding is restricted accordingly. The use of thermal energy is at low temperatures and in well-understood processes such as boiling, evaporating, and drying. Process steam in large quantities is used to transport and transfer thermal energy. Usual practice is to generate steam and a portion of the plant electric power with in-house steam plants.

Conclusions and Recommendations

1. Sufficient technology and proven methods and components exist for using electricity to generate the steam needed by beet sugar producers. Cane sugar milling and wet corn processing have similar energy requirements and are equally good prospects for electrical substitution. The present trend is conversion from gas to coal and, in some cases, to oil. A large fraction of the beet sugar processors are near large supplies of coal. If conversion to electricity becomes economically feasible, it will be with the provision that all elements in the energy system, including the utility that supplies the power, be extremely reliable. Unscheduled shutdowns are prohibitively expensive.

2. Although the immediate benefits of, and future prospects for, electrical substitution seem remote, the beet sugar industry may be an ideal area to search for better ways to use and save process steam. The results would be generally applicable to a wide variety of processes. Nearly all food processing, pulp and paper production, and wood products would benefit. Actions that can be considered to implement such a program are outlined below.

   a. The services of an architect-engineer should be enlisted in a cooperative effort to develop factory designs in which the application of energy conservation techniques is a primary consideration. Emphasis on recovering low-grade heat will be a primary design criterion. The potential of heat pumps and absorption refrigeration should be explored in depth.

   b. The storage of sugar beets, although not a process in the strict sense of the word, presents a unique opportunity to determine the merits of applying, on a very large scale, energy storage combined with heat pumps and refrigeration. Sugar beets in uncontrolled storage lose approximately 180 to 225 g (0.4 to 0.5 lb) of sugar per ton per day.[169] By stabilizing the climate in the storage pile with adequate ventilation so that the temperatue is maintained in the 1 to 4°C (34 to 40°F) range, this loss can be reduced to around 0.2 lb per ton of beets per day. The yield of refined sugar, crudely estimated, would be increased by about 136,000,000 kg/year (300,000,000 lb/year), and, at $0.20/lb,* would have a value of $60,000,000/year. A large, 5000-ton/day factory would, on the same basis, increase its yearly gross income by $3,000,000. (Note: The U.S. Department of Agriculture and the beet sugar producers are working to develop methods that reduce the storage losses. The scope of this effort has not been determined.)

3. The production of hot water as the medium for diffusing sucrose from the sliced beets plus its subsequent removal is the principal energy use in sugar beet refining. The possibility that reverse osmosis is capable of improving energy efficiency should be investigated. Limited work is under way in this area. European producers are believed to be pursuing this technology vigorously, but their results are not available.

4. Lime, an energy-intensive product, is used in substantial amounts to clarify raw sucrose solutions obtained from beets. Ion exchange may be an applicable technique with further development.

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*Since this report was written, the price of sugar on the Chicago market has fluctuated at levels substantially less than $0.20/lb.

Appendix I

THE PORTLAND CEMENT INDUSTRY

Opportunities to use more electrical energy in the manufacture of portland cement appear limited. This evaluation, albeit cursory, is based on these characteristics of the process:[170]

1. Final temperatures required by the process chemistry are 1427 to 1482°C (2600 to 2700°F).
2. The product, unlike metals, is not inherently susceptible to the reception of heat from electrical sources.
3. Coal* is an effective substitute for gas. Changeovers to coal have been and are under way.

In connection with item 1 above, electrical arc furnaces are capable of developing the high temperatures required to complete the process. If gas is replaced with electricity instead of with coal, it will be for economic reasons. The methodology is not presently available. The product, dry cement, is environmentally detrimental unless confined, and electrical heat, regardless of how applied, will not eliminate all environmental problems.

Portland cement production is a uniformly continuous, 24-hr per day process and is very energy intensive. To be profitable, cement plants must operate at or near full capacity. Therefore, the opportunities for load management and peak shaving are limited, particularly because heat storage at very high temperatures does not seem promising. Methods to reduce energy usage are being developed by designing improved hardware and systems that reduce heat losses and increased heat recovery. For example, a modern cement kiln is much shorter than its predecessor. Fluidized-bed preheating has been introduced with good results. The split-level system with a second process using low-grade heat as suggested in Appendix F may be applicable.

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*Up to a point, the producers of portland cement can use high-sulfur coal because, within limits, the by-products (sulfates) are not detrimental to the product.

The industry is aware of and is working on its problems. Cement plants are large and costly. Changes and improvements are not easily accomplished because capital is in short supply and the components within the plant are expensive.

Appendix J

THE FOUNDRY INDUSTRY

Energy consumption patterns in the foundry industry are similar to those in the "cold metal" sector in the steel industry (Appendix D). High temperatures [>538°C (1000°F)] are required to melt pig iron, scrap steel, copper, brass, and aluminum. Some castings require additional heat treatment. Low-temperature [<538°C (1000°F)] heat is used in ovens to cure molds and cores.

Successful foundry operation is very sensitive to the cost and availability of energy. Electrical melting is a well-established practice that is being increasingly used. Foundry operators, operating individually and as a group through The American Foundrymen's Society,[171] have been very actively promoting measures that improve energy efficiency and economy.[139]

Electricity or coke is capable of supplying the major fraction of the energy required to operate a foundry. There are no technological reasons to prevent the foundry industry from becoming virtually independent of large and continuing supplies of gas and oil. Economics will determine the rate at which such independence is achieved.

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Appendix K

THE CHEMICAL INDUSTRY

The producers of chemicals use more energy than any other industrial group. Table K-1 indicates that process steam and purchased electricity account for 50% and 30%, respectively, of this group's total energy usage. Steam consumption for processing is principally saturated steam at low or moderate temperatures although much is generated at higher temperatures (see Table K-2) and is used to develop in-house electricity and shaft power in high backpressure or bled turbines before being used as a source of process heat.

The chemical industry is very diverse with over 11,000 plants of 1300 companies producing over 10,000 products. Reding and Shepherd[63] have listed the six chemicals that use the most energy in their production (see Table K-3). Nydick et al.[172] report that 90% of the chemical industry's process energy is consumed in 1900 plants that produce these products:

1. SIC2812 — Alkalies and chlorine
2. SIC2816 — Inorganic pigments
3. SIC2819 — Industrial inorganic chemicals
4. SIC2821 — Plastic materials and resins
5. SIC2822 — Synthetic rubber
6. SIC2823 — Cellulosic man-made fibers
7. SIC2824 — Organic man-made fibers
8. SIC2865 — Cyclic intermediates and crudes
9. SIC2869 — Industrial organic chemicals
10. SIC2871 — Fertilizers

The producers of chemicals and petroleum products have much in common. As the name implies, the petrochemicals are a valuable source of business for the petroleum refiners. Within the 50 largest companies, the oil companies' sales amounted to 26% of the total. Note also that, except for chlorine, all the energy-intensive chemicals listed in Table K-3 depend heavily on natural gas or petroleum for all or part of their feedstock and for energy as heat.

The technological potential for replacing natural gas and oil with electricity for chemical processing energy is very large. If (see Table K-1) all process steam were generated with electricity, the chemical

Table K-1. Fuel sources, with temperature ranges and energy forms, used in the chemical industry in 1971[a]

Energy form	Energy source and amount (10^{15} Btu)						
	Electricity	Coal	Natural gas	Oil	Other	Totals	Percent of total
Steam		0.400	0.940	0.120	0.040	1.500	50
Nonsteam							
T < 1000°F			0.095	0.020		0.115	4
T = 1000–1500°F			0.155	0.015	0.180	0.350	11
T > 1500°F			0.110	0.020		0.130	4
Subtotals		0.400	1.30	0.175	0.220	2.095	69
Purchased electricity[b] at 10,000 Btu/kWhr	0.930					0.930	31
					Total	3.025	100
Percent of total	31	13	43	6	7		

[a]*Source*: Ref. 172.

[b]An additional 29.4×10^9 kWhr, equivalent to 0.294×10^{15} Btu at 10,000 Btu/kWhr, is generated in-house.

Table K-2. Temperature ranges of the steam used for chemical processing[a]

Temperature range	Steam utilized	
	10^{15} Btu	Percent of total
<182°C (<360°F)	0.44	30
182–274°C (360–525°F)	0.98	67
>274°C (>525°F)	0.04	3
Total	1.46	100

[a]*Source*: Ref. 172. In Ref. 172 it is noted that (1) 13% of chemical processing steam is generated in waste heat boilers and (2) about 90% is generated at temperatures above 204°C (400°F).

processing group would be getting about 80% of its total energy with purchased electricity. Obviously, the realistic potential for increased electrification is much lower. Chemical processing is too diverse, complex, and competitive to permit an accurate appraisal in this report. However, it should be recognized that the chemical processors are very actively engaged in plant modifications and new plant designs centered on energy reduction and on reducing their dependence on natural gas and oil for energy. More so than many industrial groups, they are well staffed with engineers to maintain and improve their competitive position. When it is shown that electricity is a competitive substitute for natural gas and/or petroleum, it is reasonable to assume that a typical chemical processor will not hesitate to make the change.

Large amounts of gas and petroleum-based energy are consumed by this industry. It will be worthwhile to explore, in detail, the possibility that particular chemical processes are potential candidates for electrical substitution.

Table K-3. Energy consumption by the six largest energy users in the chemical industry[a]

Product	1973 production [10^9 kg (10^9 lb)]	Energy consumption		
		Process [10^9 kWhr (10^{12} Btu)]	Feedstock [10^9 kWhr (10^{12} Btu)]	Total [10^9 kWhr (10^{12} Btu)]
Ethylene and related products	15.2 (33.4)	112 (382)	316 (1078)	428 (1460)
Ammonia	13.7 (30.3)	80 (272)	101 (345)	181 (617)
Chlorine	8.7 (19.2)	117 (399)	0 (0)	117 (399)
Styrene	2.7 (5.0)	15 (51)	25 (87)	40 (138)
Methanol	3.2 (7.0)	10 (34)	27 (92)	7 (126)
Acetylene	0.27 (0.58)	2.4 (8.3)	11 (39)	13.4 (47)
Totals		338 (1146)	481 (1642)	817 (2787)

[a]*Source*: Ref. 63.

Appendix L

THE PETROLEUM INDUSTRY

Petroleum refiners are the third largest users of process energy in the industrial sector. Table L-1 shows fuel consumption and distribution by fuel source for 1976. Table L-2 shows a breakdown of the energy forms used in refineries in 1971. Although these data are seven years old, it is reasonable to conclude that the fractional distribution of steam, electricity, and direct heat have not changed appreciably since then. Table L-3 gives the results of an estimate of the nonsteam energy consumption and distribution fractions by temperature bands for refining processes. From these data, it is concluded that

1. Fuel oils, natural gas, and by-product gas are the principal fuels and have supplied approximately 75% of the energy required by refining processes.
2. About 80% or more of refinery process energy is used at temperatures less than 538°C (1000°F), and most of the remainder is used at temperatures in the range of 538 to 699°C (1000 to 1200°F).

Refiners, in common with chemical processors, are actively engaged in developing methods to reduce their consumptions of natural gas and petroleum. Alternative energy sources (coal, nuclear energy, and electricity) are receiving serious attention.

The temperatures required by the directly heated processes in a refinery are easily obtained with electrical heaters. Electrically produced process steam presents no technological problems. Hypothetically, a typical refinery can be almost completely electrified. Technology is not the major consideration.

Realistically, if conditions dictate that refiners replace oil and natural gas with other forms of energy, electricity may either be or become a preferred choice for many applications if the conditions described in Sect. 8 are favorable. In this connection, it is noted that many refineries are located in areas where processors are subject to very stringent regulations governing the environment — air quality in particular.

Table L-1. Fuel consumption[a] by petroleum refineries in 1976[173]

	Fuel consumption (10^{15} Btu)	Percent of total	
Crude oil	0.0028	0.1	10.7
Distillate oil	0.0270	0.9	
Residual oil	0.2785	9.7	
Liquified petroleum gas	0.0424	1.5	65.3
Natural gas	0.7382	25.6	
Refinery gas	1.1000	38.2	
Petroleum coke	0.4331	15.0	
Coal	0.0047	0.2	
Purchased steam	0.0382	1.3	
Purchased electricity	0.2145	7.5	
Total	2.879[b]	100.0	
Total gas and oil			76.0

[a]This tabulation represents the response of 51 company members of the American Petroleum Institute. These 51 companies operate 93% of current U.S. refinery capacity. (Reported in Ref. 173.)

[b]This total, by linear extrapolation to 100% of U.S. production, would be 3.097×10^{15} Btu/year.

Table L-2. Fuel distribution to combustion processes[174] in the petroleum industry in 1971[a]

Process requirement	Oil and gas[b]		All fuels	
	10^{15} Btu	Percent of total oil and gas	10^{15} Btu	Percent of total
Steam generation				
Under 200 psi	0.014	1	0.027	1
Over 200 psi	0.536	38	0.952	35
Total steam	0.550	39	0.979	36
Direct contact combustion	0.014	1	0.082	3
Process heaters and furnaces	0.747	53	1.550	57
Internal combustion (gas turbines, etc.)	0.099	7	0.109	4
Total	1.410	100	2.720	100

[a]Based on Census of Manufacturers (1971 Survey), supplemented with industry data.

[b]52% of total fuel.

Table L-3. Energy distributions,[a] by temperature and source fuel, of nonsteam heat energy used for petroleum refining in 1974

Source fuel	Energy distribution at temperatures (°F) of				Total energy (10^{15} Btu)
	100–300	300–600	600–1000	1000–1500	
Fuel oils	0.0220	0.0199	0.1567		0.199 (11%)
Gases[b]	0.1558	0.1417	1.0476	0.0709	1.416 (76%)
Petroleum coke				0.2439	0.244 (13%)
					1.86
Subtotals	0.178	0.162	1.204	0.315	
Percent of total	9.6	8.7	64.8	16.9	
Total nonsteam energy used for temperatures <1000°F	1.54×10^{15} Btu/year (83% of nonsteam)				

[a]These data abstracted from Table 4.21 of Ref. 172.

[b]All gases (natural gas, liquefied petroleum gas, and refinery gas).

Any attempt to quantify the potential additional uses for electricity by petroleum processors must be founded on thorough engineering-economic analyses beyond the scope of this report. It is sufficient to note that the potential for replacing large amounts of oil and natural gas with electricity is determined by economics.

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