ORNL/TM-5884

Energy Use and Distribution in the Pulp, Paper and Boardmaking Industries

Stephen I. Kaplan

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $5.50; Microfiche $3.00

ORNL/TM-5884

Contract No. W-7405-eng-26

Energy Division

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Stephen I. Kaplan

Date Published - August 1977

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

Prepared by the
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Oak Ridge, Tennessee 37830
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PREFACE

The author acknowledges with regret his frequent use of approximate values or broad ranges for energy conservation data in this report. However, when the basic similarities of process technique for paper and board manufacture are examined closely, a wide range of actual practice is seen to prevail. To have dissected and classified this spectrum in detail would have required far more manpower and time than was available, without materially improving the usefulness of this document to its anticipated users.

Particular thanks are due to those corporations within the Pulp, Paper and Boardmaking Industries which arranged for mill visits and interviews to permit the compiling of the information herein, and to the corporate staff members who provided knowledgeable comment and corrections on aspects of this report. (In deference to the companies which preferred not to be identified, none of the companies visited are cited.) Messrs. J. Duke, of the American Paper Institute, and R. Blosser and I. Gellman of the National Council of the Paper Industry on Air and Stream Improvement were especially helpful in suggesting sources of information. The comments of reviewers S. E. Beall and R. S. Carlsmith, ORNL, and C. W. Mandelbaum, ERDA, provided valuable guidance in making the substance of this report accessible to the intended reader.

In keeping with ORNL policy, energy data are expressed in SI (Systeme International) units. In some cases, a conversion to traditional paper industry units is not inserted following a citation of energy units, in the interest of readability; however, a conversion table is supplied as an appendix.

ENERGY USE AND DISTRIBUTION IN THE PULP, PAPER AND BOARDMAKING INDUSTRIES

Stephen I. Kaplan

ABSTRACT

The Pulp, Paper and Boardmaking Industries (PPBI) are major energy consumers in the U.S. economy, ranking fourth among all industry groups in this respect. Including the consumption of waste streams generated within the industry's manufacturing processes, the overall energy consumption in 1972 was 2.2×10^{15} Btu (2.2 quads or 2.3×10^{18} joules). Energy consumption is almost equally distributed between pulpmaking and recovery or regeneration of pulping chemicals, on the one hand, and pulp drying, papermaking and boardmaking, on the other.

The impact of proposed near-term pollution abatement regulations upon the industry's overall energy consumption is expected to be modest, with additional energy use for discharge control to both air and water aggregating less than 5%. Zero Pollution Discharge (ZPD) regulations could nearly double the energy requirements per ton of product however, due mainly to liquid effluent treatment requirements.

The energy savings predicted by the industry, assuming that ZPD is not required, is ∿10% below the 1972 level, per unit of product, by 1980. Full utilization of all industry alternatives for conservation could probably double this savings.

INTRODUCTION

Purpose

Historically, energy has been sufficiently cheap and abundant in this country so that minimizing the energy requirement per unit of production has rarely been a decisive factor in minimizing product cost. Not only have the economies of energy changed drastically in recent times, but the adequacy of our energy supply has become a national concern. This report is one of a series prepared under the sponsorship of the Energy Research and Development Agency to provide detailed information on the types, end-uses and respective quantities of energy consumed in key U.S. manufacturing activities. It is intended to furnish a single detailed compilation of data on typical practice throughout the Pulp, Paper and Boardmaking Industries (PPBI) for purposes such as policy planning and economic forecasting. As such, it is directed primarily toward the anticipated needs of such users rather than to the PPBI, and should not be considered as a design manual.

Scope

This study relates exclusively to the manufacturing aspects of the industries cited; i.e., harvesting of trees, transportation to the mill, conversion and shipping of finished goods are excluded. The specific segments of the industries covered, using the U.S. Standard Industrial Classification Manual[1] (SIC) include SIC-261, Pulp Mills; SIC-262, Papermills (Except Building Paper) and SIC-263, Paperboard Mills. Together these three categories accounted for approximately 93% of the total energy consumption of SIC-26, the Paper and Allied Products Industry Group, in 1971.[2]

The analysis is based primarily upon published data, supplemented by on-site interviews with operating personnel at several mills, and conversations with equipment manufacturers, members of trade and professional organizations related to the industry, and other persons with technical knowledge of the field. In most cases, individual opinions have not been attributed unless also published elsewhere. In order to exploit the broadest coverage of data for the analysis, published statistics for the calendar years 1971 and 1972 have been used, even though some later figures may be available as this is written.

PART I. EXECUTIVE SUMMARY

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1. THE PULP, PAPER AND BOARDMAKING INDUSTRIES

Overall Energy Demand

The Paper and Allied Products industry group ranks among the top five energy consumers in all U.S. manufacturing categories. This evaluation holds whether we consider direct fuel and energy purchases[2] or total energy consumption including that from feedstocks and process intermediates.[3,4] A large fraction of this energy is, in fact, produced internally. According to information compiled by the American Paper Institute,[3] 39.7% of the 2270 × 10^{15} J consumed by the industry in 1972 was derived from the combustion of wood wastes and spent pulping liquors, the largest single source of fuel. The other major fuel sources, in decreasing order of consumption, were fuel oils, 500 × 10^{15} J (the largest fuel oil use of any manufacturing group); natural gas, 476 × 10^{25} J and coal, 264 × 10^{15} J.

Commodity Flow Within the Industry Group

In a broad sense, the manufacture of board or paper is a two-stage process: first, the cellulosic raw material (raw or recycled vegetable fiber) must be disaggregated and processed to yield a uniform, tractable product that possesses the necessary color, texture, strength and mat-forming properties. This step may be mechanical or chemical, and is most often a combination of the two types of processes. The result is pulp, which may be produced either in dry, damp or slurry form as discussed in a later section of this report. While pulp itself is an article of commerce, it has virtually no direct uses except as an intermediate in the manufacture of paper or paperboard. The second step is purely mechanical, and consists of laying down slurried pulp in the form of a thin, porous mat and then pressing, drying and (sometimes) coating or impregnating it to form the desired product.

Paper and paperboard are produced from essentially the same raw materials. Their basic difference is one of thickness, although special properties are often developed by blending different types of fiber in the mat and by creping, polishing, coating, impregnating or other techniques. With the exception of recycled-fiber mills, the trend in establishing new mills has for many years strongly favored integrated mills, in which pulpmaking and paper- or boardmaking are carried out sequentially. However, situations still exist within the industry (Fig. 1) where due to transportation conditions, disparities between raw material location and energy availability, specialized market conditions or feed material requirements or various combinations of these, mills are able to survive and compete while producing pulp only, or while making paper products from purchased pulp. Additionally, integrated mills sometimes produce a surplus of one or more kinds of pulp that is then marketed to other users; conversely, an integrated mill may require a particular type of pulp in quantities too small to warrant an internal production line, and will consequently import this from another mill within its own corporation or buy it on the open market. Thus even though the energetics of manufacturing pulp, drying, shipping and re-slurrying it to make paper are highly unfavorable compared with piping it directly in wet suspension from the pulp mill to the paper machine, the former practice forms a commercially viable part of the industry.

Major Processing Techniques

Pulpmaking

The basic types of chemical pulpmaking are Kraft (alkaline sulfite), sulfite and semichemical, which are described in Part II of this report. In these, wood chips are digested in hot chemical solutions to remove part or most of the lignin which binds the wood fibers together. After digestion the cooked pulp, largely cellulose, is washed, mechanically dispersed and sometimes bleached before being sent to the pulp dryers or papermaking or board machines. The lignin-rich solution is concentrated by evaporation and recycled or otherwise disposed of. In many cases it can be burned for fuel and the chemicals recovered from the ash or slag.

In mechanical pulpmaking, pulp is formed either by abrading wet, cut logs against large rotating grindstones (stone groundwood) or by

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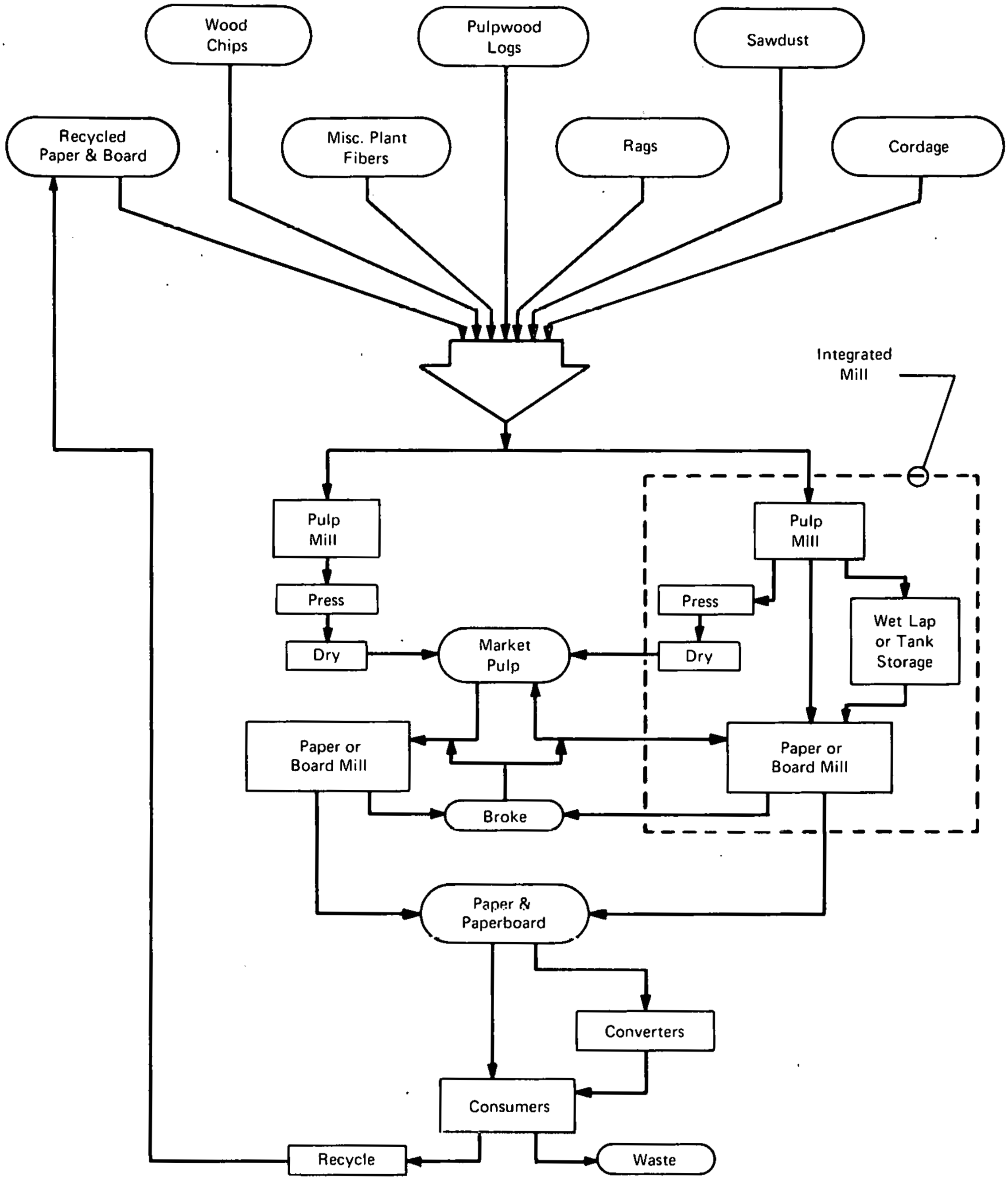

Fig. 1. Commodity flow in the paper products industries.

grinding wet wood chips between closely-spaced spinning disks (refiner groundwood). Most of the lignin remains in the groundwood pulp. Various intermediate processes (semichemical, chemimechanical) involving combinations of chemical and mechanical operations are also practiced.

Chemical pulping can be performed either batchwise or in continuous processing equipment; the trend is generally toward the latter in new mills. Mechanical pulping is inherently a continuous, "flow-through" operation. A variant, thermomechanical pulping, employs steam to soften the chips prior to and during refining, and is gaining popularity due to its lowered mechanical energy requirements and freedom from sulfur emissions.

Pulp drying, papermaking, boardmaking

These three categories of operation are broadly similar: A suspension of pulp is spread onto a porous surface which allows the water to drain and a mat of fibers to form. For pulp drying, the mat is lightly compacted by rolls and usually dried by hot air, while suspended on a porous belt. Paper and board are produced in dozens of varieties employing various types of dryers and additives; the major production methods are described in Part II.

Broadly speaking, the paper or board mat is compacted and dried by passage over and between an array of heated, felt-covered steel rolls, usually surrounded by a hood or a complete housing. The water evaporated from the mat is carried away by a current of warm air passing through the housing and exhausting to the atmosphere. The volume of air used for drying in paper machines is impressive. One machine's output may exceed 20,000 kg/hr of product, during which twice that weight of water may have been evaporated. Each kg of water removed requires 10 kg or more of dry air as a carrier.

The most common source of heat for fiber sheet drying is low-pressure steam, which is used to heat the drying rolls internally. For certain types of paper such as glazed-finish or tissue, drying is augmented by external air inpingement as the sheet passes over a special type of heated roll. The air blast is heated by direct firing, medium-pressure steam or electric coils. In certain applications, particularly for rapid drying of liquid coatings applied to the sheet, dielectric heating is also employed.

2. ENERGY ASPECTS

Process Energy Consumption

Energy is an important component in each of the major manufacturing steps for the PPBI. Receiving and pre-pulping operations consume less than 1% of the total energy budget; the major consumption, including losses is split approximately evenly between processes related to preparation of furnish* (pulpmaking, chemical recovery and bleaching), on the one hand, and pulp drying, papermaking and paperboard making on the other.

Energy use in pulping

Even for mills using nominally the same pulping process, equipment and energy consumption may vary considerably. Nevertheless, for broad statistical purposes, the industry may be lumped into a relatively few product lines. Table 1 shows the relative tonnage[5] and the approximate energy consumed for various categories of pulp produced by the PPBI in 1972.

Energy use in sheet forming and drying

The manufacturing characteristics and state of available statistics for the paper industry preclude a detailed and documented account of the energy consumed in forming each of the grades of paper and paperboard produced. In addition, paper and board machines are massive, capital-intensive aggregations of equipment which are frequently used to produce several different varieties of product, according to current demand. Their age, design, degree of in-house modification and energy

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*See Glossary, Appendix C.

Table 1. Estimated energy consumed for pulpmaking and bleaching in U.S., 1972

Pulping process	Production, 10^9 adkg[a]	Approximate mean energy per adkg, 10^6 J	Approximate total energy, 10^{15} J
Groundwood	4.2	6.3	26
Sulfite	1.9	9.0	17
Kraft	28.5	8.4	240
Semichemical	3.5	6.0	21
Defibrated	2.5	3.2	8
Dissolving pulp and miscellaneous	1.5	10.6	16
Recycled fiber	10.3	3.2	33
	52.4		361

[a]Air-dry kilograms.

efficiency vary widely within the industry. Hence neither the total energy required to produce unit weight of a given PPBI product, starting from raw wood, nor that energy needed to form and dry the product following pulp preparation, can be uniquely specified. A few generalizations can be made however regarding sheet forming and drying:

1. The major energy expenditure is in the form of heat, to evaporate moisture from the sheet.
2. The specific energy requirement is strongly influenced by sheet porosity, moisture content of the sheet entering the heated dryer section, and sheet thickness.
3. Energy recovery measures can affect the specific energy requirement by one-third or more.

Although the energy required to make a unit weight of paper or board may vary more than twofold from a light, porous paper to a heavy bristol, the sheet-forming and drying energy for most grades is estimated to lie within ±20% of the mean value for the industry group. Consequently as a rough approximation, the energy expenditure associated with manufacturing various PPBI bulk commodities from pulp can be estimated from tonnage statistics.

Production figures[1-3] for 1972 are shown in Table 2, together with approximate energy requirements based on product tonnage as a proportion of the industry total. The energy total shown for all products is developed in more detail in Part II of this report. The mean energy requirement for producing unit weight of product from pulp, as derived from the totals in Table 2, is thus 12×10^6 J/adkg ($\sim$10 million Btu/adt) which correlates satisfactorily with data from Refs. 6 and 7 and actual mill interviews.

Table 2. Production of major PPBI bulk commodities, 1972

Product	Quantity, 10^9 adkg	Approximate energy to form from pulp, 10^{15} J
Building paper	4.743	58
News, printing, writing, book paper	13.313	163
Packaging, industrial or bristols	6.152	75
Tissue	3.658	45
Unbleached kraft board	12.123	148
Bleached kraft board	3.402	42
Semichemical board	3.518	43
Combination furnish and wet machine board	7.021	86
	53.930	660

Environmental Regulation Effects on Energy Consumption

Environmental discharges from PPBI mills occur in solid, liquid and gaseous forms. The solids in some cases originate as wet sludges and require clarifier or settling pond treatment. The liquids may contain particulate matter (pulp wash water), chemicals (recovery plant wastes) or heat (steam plant condenser coolant). Conventional waste treatment plant techniques are employed for dissolved or suspended matter, and cooling ponds or towers are used for heat dissipation. Discharges to the atmosphere may again be either particulate, from fired power boilers and lime kilns, or gaseous, e.g., from spent liquor evaporators or digester vents.

Energy required for atmospheric discharge control is largely consumed by electrostatic precipitators and small gas scrubbers. The present requirements to satisfy EPA standards are relatively modest, $\sim 0.24 \times 10^6$ J/kg of product. Projected tightening of standards could lead to energy requirement increases of 2—2.5 times in some instances.[8,9]

The energy requirements for control of discharge to waterways under EPA projected goals for 1977 and beyond were estimated by two organizations.[10,11] For 1977 goals, increments over present control requirement were estimated to be $\sim 10^5$ J/kg of product by one group, and $\sim 3 \times 10^5$ to 10^6 J/kg by the other, depending upon the type of mill, implying an increment of up to ~3% in overall energy consumption. For zero discharge however, the energy requirement for paper products manufacture was estimated to nearly double.

3. PERCEIVED TRENDS AND CONCLUSIONS

Energy Conservation Opportunities

Of the 2300×10^{15} J of energy consumed in 1972 by the PPBI, approximately 1300×10^{15} J or slightly over one half of this energy was actually used by the manufacturing operations (Fig. 2). Also, as mentioned previously, there is appreciable variation between different mills in operating efficiency. It is thus evident that in spite of a record of improving energy efficiency over several decades,[4] opportunities exist for further energy conservation in the PPBI. Whether a net decrease in energy use per weight of product yield continues in the future rests to some degree upon the environmental quality standards that the industry

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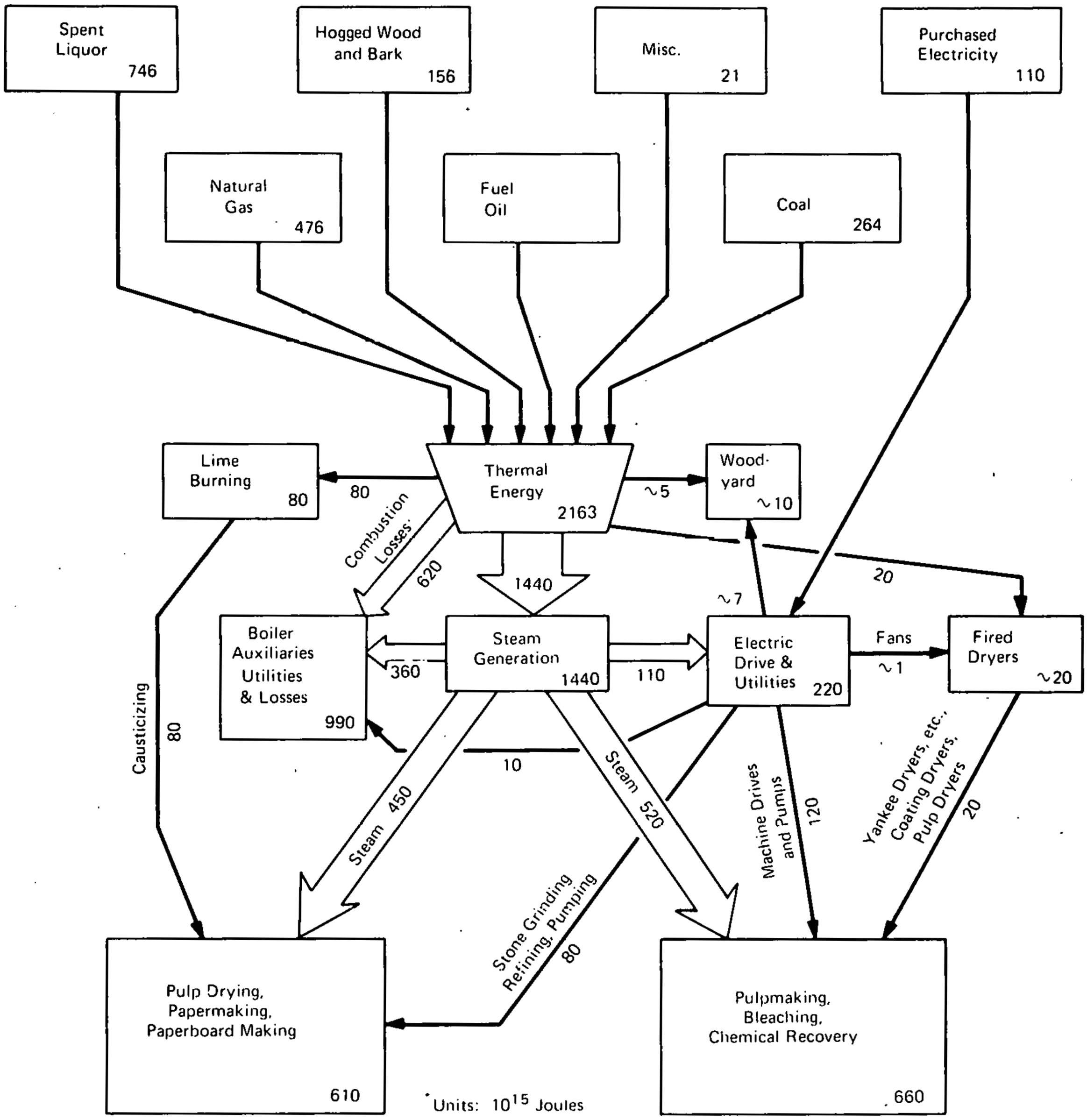

Fig. 2. Estimated energy distribution for the Pulp, Paper and Boardmaking Industries, 1972.

is called upon to meet, and the ability of the PPBI to develop more environmentally-compatible technology.

The main opportunities for conservation arise in the following activities:

1. Waste heat recovery
2. Pulping processes with improved yield or reduced energy input per unit of raw feed
3. Increased use of onsite power generation and "total energy" system techniques
4. Low-moisture sheet forming processes
5. Process control optimization

Because of the many steps using low-grade heat in the paper products processes, conservation of thermal energy down to low temperatures is feasible. One example involves the recovery of heat from paper machine dryer exhausts to heat wash water and incoming air for the dryers. Higher temperature heat recovery opportunities also exist in connection with power boiler stack gas, lime kiln exhausts and Yankee Dryer exhausts.

Process improvements, either by employment of higher-yield processes or more precise control of variables, achieve the desired objective of more product per energy unit expended. New process concepts such as biopulping (Chap. 4) are still in the development stage, but promise eventual energy savings by major reduction in the amount of heat required for delignification.

The concept of joint electricity and steam generation (see Chap. 5) was first exploited, in the PPBI, early in the 20th century. However, it later declined in popularity as the price of electricity fell. As Fig. 2 illustrates, however, onsite electric generation still accounts for ∿1/2 the electricity consumed in the industry. The concept is finding new favor, and new mill designs frequently specify 100% internal generation.

There is a large incentive to decrease the evaporative work required in drying paper and board after the sheet forming operation. Options being pursued include dry forming of the web; improved drainage of the web via water removal from both surfaces prior to pressing; and higher "nip" or roll pressure prior to the evaporative drying step.

Table 3 summarizes some of the measures bearing the most promising conservation potential and the projected savings realizable by their adoption. They are described in detail in Part II, Chap. 8. (Note: these measures are not cumulative, because many plants already incorporate one or more, to varying degrees, in existing operations.)

Table 3. Energy conservation measures applicable to the PPBI

Process area	Conservation measure	Approximate savings over nonuse, 10^6 J/adkg
Pulp digestion	Digester blow steam recovery	0.4 — 0.8
	Optimized process control	0.1 — 0.4
	Indirect steam heating of batch digesters	0.4 — 0.8
	Continuous vs batch digesters	0.5 — 2
Lime burning	Heat-conserving kiln design	0.5 — 1
Paper and board drying	Fully hooded dryers	0.5 — 1
	Economizer and inlet air recuperator	1 — 2
	Increase press roll nip	0.3 — 0.4
	Dry web from 2 sides[a]	2 — 4[a]
	Dry forming of web[a]	6 — 7[a]
Power generation	Back-pressure steam turbines	0.3 — 0.5
Pulp handling	Direct use of undried pulp in integrated mill	4 — 6

[a]In developmental stage. These processes are alternates, not cumulative.

Alternate Energy Sources

The raw material for the PPBI also furnishes a significant source of fuel, in the form of bark and concentrated spent pulping liquor. As noted in Chap. 8, the further use of unconventional fuels is being actively pursued by several paper companies. Not only are forest wastes, sawdust and previously unburnt bark from mill operations being used, but municipal, agricultural and industrial refuse are being investigated by some companies as fuel.

Anticipated Savings

In view of the overall similarities of operation between the paper and chemical industries, the experience of the latter should give some indication of the probable future of the former. Accelerated efforts in the process industries since approximately 1970 to conserve process energy have generated a specialized expertise in identification and remedying of plant energy waste which has been well documented.[12-14] From these efforts predictions have been made[14] that the average process plant can realize energy savings of 7—15% by diligent conservation efforts. Much of these are in the form of housekeeping actions — repairing leaks, adding insulation, etc. — but others require significant capital investment. The PPBI, through the American Paper Institute, have engaged in a voluntary energy-reduction program coordinated by the Federal Energy Administration, in which a planned reduction of energy, per unit of production, of 10% is anticipated[15] as an industry-wide average by 1980. In addition to housekeeping measures, improvements of the type cited in Table 3 will be employed. This assures that environmental discharge requirements will be held to levels comparable to those presently set for 1977. The goal thus defined is certainly feasible from a technological standpoint. Under compelling conditions of energy costs and attractive capital equipment-replacement incentives, an overall savings of 15% or more would appear attainable.

Potential Savings

As noted previously, most of the techniques listed in Table 3 are already employed to some extent within the more than 400 primary paper producing plants operating in the U.S. Aside from the still-developmental dry web-forming and 2-sided drying processes, full utilization of all the other techniques listed would provide a savings of ∿10 million J/adkg relative to the requirements in a nonuser mill. This would save roughly one-third of all the energy expended to make a unit weight of paper or board. From this perspective, the 10% energy savings goal represents a reasonable and significant reduction effort.

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PART II. PROCESS TECHNOLOGY

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4. MANUFACTURING PROCESSES

Raw Material Preparation

Wood handling and preparation

Although over 10^{10} kg of rags, straw, bagasse, cotton linters and recycled fiber are pulped annually, new wood constitutes by far the major part (nearly 90%) of the cellulosic raw material for paper products manufactured in the U.S.[16] This wood arrives at the mill in the form of pulp logs (1—2.5 m long); long logs (up to tree length); or chips. The broad objective of the wood preparation steps is to convert the heterogeneous raw material into a generally uniform bulk feed stock that can then be handled via continuous or reproducible batch processes.

Logs: Due to the diversity of feed arrangements, siting peculiarities and climatic and process requirements, log handling at the mill can be described only in broad terms. The basic steps include unloading; slashing of long logs to a uniform size that the barking and chipping equipment will accommodate; stacking in storage areas; recovery from storage and conveying successively to the barkers, chippers, and chip storage facility. Unloading and storing utilizes mechanical handling equipment that is powered either by petroleum-derived fuel or electricity. Some large mills unload via stationary or gantry crane and deliver to a conveyor for storage in large round ponds; a more common practice involves unloading via grapple-equipped mobile equipment and transporting to slashers or to dry storage piles in long rows. Subsequently, logs are recovered from storage and deposited either into a flume or onto a conveyor for transit to the barkers and chippers. The bark removed from the logs is shredded and stored for subsequent use as fuel, in most cases. The chips are then handled in the same manner as those received in bulk, described below.

Chips: In addition to the chips manufactured onsite via reduction of pulp logs, chips are utilized at a growing number of mills from direct bulk shipments. These are unloaded from the bulk containers either via a combination of crane-operated clamshell or mobile bucket loaders and belt conveyor, or directly via pneumatic unloader-conveyors.

Here again the energy source may be electrical or a combination of fuel-burning engine and electrical power. The chips are conveyed to storage piles or silos. Chips are also classified before pulping to remove over-size pieces, fines and other unsuitable material. Rejects are reclaimed by hogging to size; wastes are usually burned, e.g. for fuel.

Energy use: As implied in the foregoing descriptions, energy distribution between handling operations may diverge widely from one mill to another, although the same basic forms of energy end-use are commonly employed. A wide variety of fuel-burning mobile equipment is used for transportation within the woodyard, including rail cranes, crawler cranes, specialized rubber-tired lift vehicles, bucket loaders and others. Electrical drive is commonly employed for flume pumps, conveyors, barkers, chippers, screens and hogs. While no precise breakdown between electricity and direct fuel consumption is meaningful because of the diverse usage, an energy expenditure of $\sim 42 \times 10^6$ J/m^3 ($\sim 15 \times 10$ Btu/cord) for woodyard operations[17] falls within the range of normal practice. A reasonable apportionment of this mechanical drive energy is:

Mobile equipment	20×10^6 J/m^3	(essentially diesel)
Conveyors	2.8×10^6	(electric)
Wood conversion	20×10^6	(electric)

For stone groundwood pulping, which in 1972 produced about 9% of all pulp tonnage,[16] the chipping and screening steps (~ 0.4–$.17 \times 10^9$ J/m^3) do not apply, since the barked logs are fed directly to the grinders.

While it is convenient within the paper industry to express the feed material usage in volume units and production in tonnage units, a direct physical correlation between the two is possible only for a particular mill, and then only within broad limits. This condition exists because on the one hand, the usable weight of wood per unit volume received depends importantly upon log size and regularity, bark thickness and species (i.e., density) of the wood; while on the other, the weight of product per unit weight of actual wood feed will vary according to the pulping process used and the quantity of noncellulosic material (pigment, sizing, wax, etc.) added during manufacture. Although many large mills produce a single commodity or a very few closely-related products, others of appreciable size may make a dozen or more "major" products. The convertibility errors that would arise from product variations can be conveniently avoided, however, by relating energy consumption to a unit weight of dry pulp. Within the paper industry Bone-dry Pulp (bdp), containing no free moisture, is used as a reference term in pulp yields and other material balance expressions. Air-dry Pulp (adp) is an actually-produced commodity (e.g., market pulp, Fig. 1) and typically contains ∿10% moisture. Energy inputs to paper processing operations are typically expressed as energy units per unit weight a.d.p. or, equivalently, per air-dry weight (adt, or adkg) of fiber.

A rough average pulp yield for all the chemical and semichemical paper products produced in this country is about 0.54 kg bdp (or 0.60 kg adp) per kg of wood charged. Also, an "average" cord (3.74 m^3) of rough wood contains about 2.3–2.4 m^3 of solid, bark-free wood.[18] Pulping woods have an average dry specific gravity of ∿0.35–0.55; using 0.45 as an average, the weight of a cord of wood feedstock becomes 1050 kg; in turn, this represents about 570 kg of bone-dry pulp (640 kg adp) at 54% yield. Thus, 1000 kg of bone-dry chemical pulp requires about 1.75 cords of feed wood, plus or minus perhaps 20%. For mechanical (Groundwood) pulps the yield is about 90% instead of 54%, and a cord as described above would yield ∿950 kg of bone-dry pulp (∿1050 kg adp). Reconverting the energy apportionment given above for the woodyard in terms of pulp product yields:

	Chemical 10^6 J/kg adp	Stone ground 10^6 J/kg adp	Mechanical except stone ground 10^6 J/kg adp
Mobile equipment	0.136	0.07	0.07
Conveyors	0.02	0.01	0.01
Wood conversion	0.136	0.02[a]	0.07
	0.29	0.10	0.15

[a]No chipping required for stone groundwood.

Although the preceding analysis employs rather rough approximations, it provides a feeling of the relative scale of energy use in various parts of the wood preparation process. The energy expended in the woodyard represent less than 1% of the total consumed in transforming pulpwood into finished board or paper.

Pulpmaking Processes and Their Applications

From a paper products standpoint, wood is a composite of two materials: cellulose fibers, which constitute the prime raw material, and the ligneous (noncellulose) component that binds the fibers to form the wood structure. The principal objective of pulping is to decompose this matrix and recover the fibers in usable form. However, a sharp split into cellulose and noncellulose is only required for very specialized uses; varying fractions of the noncellulose material are acceptable for and routinely incorporated into many types of paper products, particularly where a high degree of permanence is not required.

The conversion of raw wood to pulp can be accomplished by a variety of methods that involve either mechanical disintegration reaction or, commonly, a combination of these. The choice of a method depends, among many lesser things, on the type of wood available and the products desired; not all pulping processes are equally suitable or economical for all applications. Generally, mechanical methods retain the largest fraction of noncellulose material. Feed materials and products characteristic of major pulping processes are shown in Table 4.

Mechanical processes

Wood pulp produced by mechanical abrasion is known as groundwood. Groundwood processes operate either directly upon cut logs (stone groundwood) or upon wood chips (refiner groundwood); in the latter case, some pretreatment such as steaming or chemical softening is frequently used to reduce the mechanical energy required for pulping. As the pretreatment becomes more complex, the distinction between mechanical and chemical pulping becomes relative rather than specific, and intermediate categories such as chemimechanical and semichemical pulping are involved to describe these processes. They are discussed separately, later in this chapter. Condensed flow diagrams for mechanical pulp processes are shown in Fig. 3.

Table 4. Characteristics of major pulpmaking processes

Characteristic	Process						
	Stone groundwood	Refiner groundwood	Thermomechanical	Chemimechanical	Neutral sulfite semichemical (NSSC)	Sulfite	Kraft
Raw materials	Spruce, pine, hemlock and poplars	Softwoods, hardwoods or mixed; resinous woods if pre-pressed; non-wood vegetable materials	Same as refiner groundwood	Hardwoods (with cold soda process); light hardwoods and less-resinous softwoods (with hot sulfite process)	Hardwoods, single or mixed; softwoods usable but require more refining.	Hardwoods, low-resin softwoods	Virtually any woody material
Products	<u>Unbleached</u>: board, partial newsprint furnish, cheap papers. <u>Bleached</u>: tissue, book, commercial and writing papers	Same as stone groundwood but stronger and higher quality due to longer fibers	Same as refiner groundwood	Partial furnish for newsprint and publication papers	<u>Unbleached</u>: corrugating medium, various boards <u>Bleached</u>: book and specialty papers	<u>Unbleached</u>: newsprint <u>Bleached</u>: tissue, towelling, glassine, food packaging board; book, bond, other fine papers; α-cellulose pulp for rayon manufacturing	<u>Unbleached</u>: bag and wrapping paper, linerboard, boxboard, containerboard <u>Semibleached</u>: newsprint, boxboard <u>Bleached</u>: bond, book, commercial and specialty papers; food container board; tissue
Pulp characteristics	Short fibers, hence limited strength	Improved fiber length and tensile strength	Like refiner groundwood	Similar to refiner groundwood; hot sulfite pretreatment gives good brightness	Long-fibered; strength approaches kraft, especially in bleached state	Light color; easy bleaching; can produce very low lignin product	Longest fibers. Very strong, especially in unbleached state
Typical yield	To 95%	To 95%	To 90^{+}%	85–94%	60–80%	45–55%	45–55%

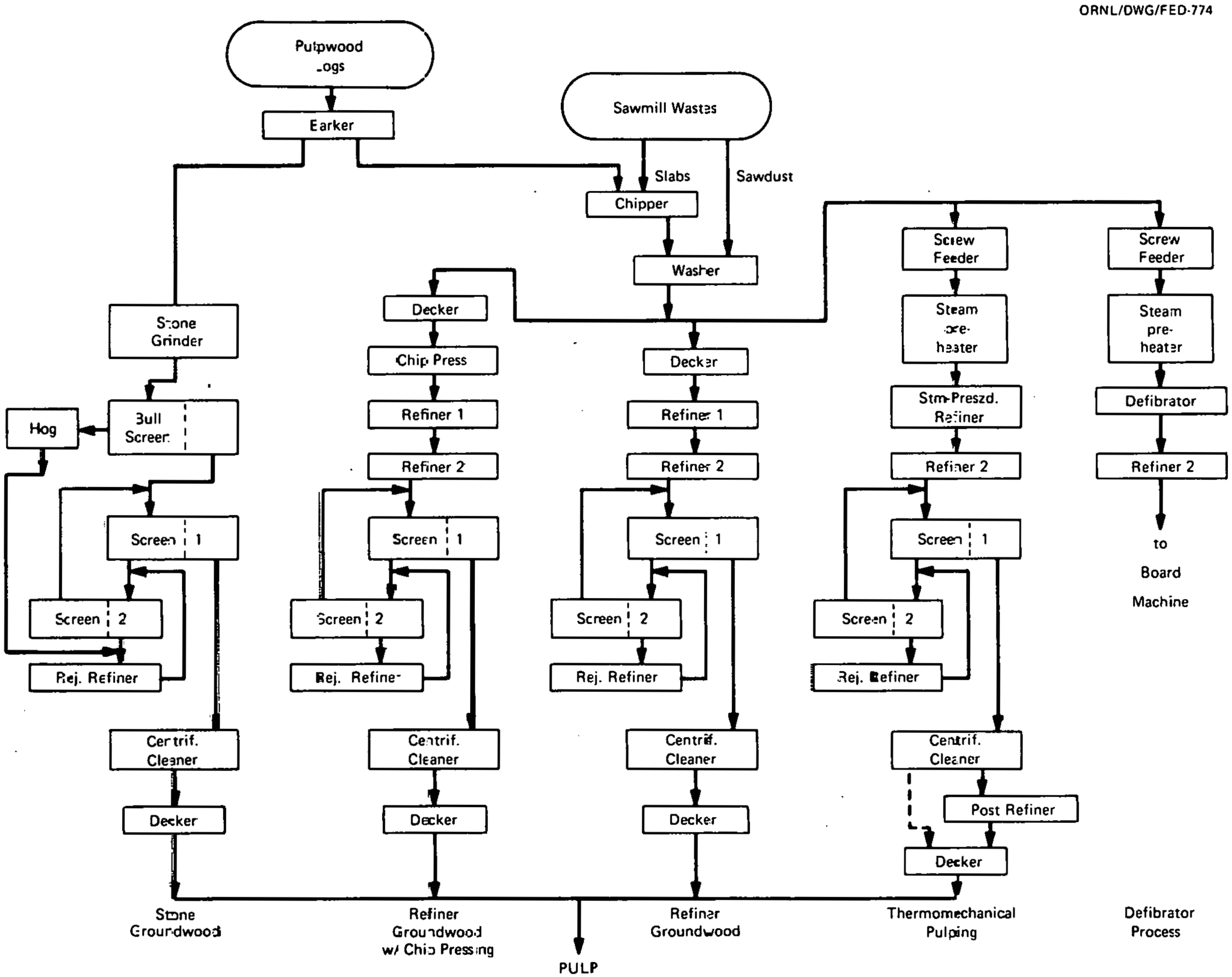

Fig. 3. Mechanical pulping processes.

Stone groundwood: This type of pulping predates chip refining and is still a commonly used method. Essentially, barked logs precut to a uniform length are mechanically pressed against a massive revolving, wetted grindstone. The abraded pulp is suspended in the wash water and continuously piped from the grinders to reject-recovery and fiber-classifying stages that are much the same for all types of groundwood processes. Stone grinders are produced in several designs but develop a similar grinding action. The sides of the log contact the moving peripheral surface of the cylindrical "stone," which may be 1.5–2.1 m in diameter and rotate with surface speeds of 20–35 m/s.

The original stone grinder installations employed water power, and some New England mills still operate water-powered stones. More commonly the grinders are driven by large synchronous motors. The energy requirements for stone groundwood vary with the wood species being ground and the intended end product from the pulp, but generally run $4.8–6.3 \times 10^6$ J/kg. The grinder throughput can reach 10^5 kg/day; thus the connected power per machine can exceed 6000 kW.

Most of the energy expended in stone grinding is converted into heat. High-frequency pressure waves (∿20,000–50,000 Hz) are set up in the wood by the irregular impact of the moving grit; this intense pounding actually heats a layer of the wood near the abrading surface to a temperature above the boiling point of the contained moisture, and the consequent softening action contributes significantly to the defibering process. The permissible temperature rise at the interface between wood and grinder is limited by the need to maintain a hydrodynamic surface film in the contact zone however; otherwise the stone surface becomes clogged and control of the pulp characteristics is lost. Therefore, the rotating stone is continuously showered and the bottom of the stone is often immersed in water, so that little or no free steam generation occurs. The suspension of wood fibers leaves the grinder typically at 55°–65°C. The heat contained in the suspension or "stock" is beneficial in lowering the viscosity and surface tension during the subsequent screening, refining and blending steps, and does not represent an energy loss from the process.

Steaming or chemical pretreatment of whole pulp logs prior to grinding has been tried, as a means of reducing the grinding energy required;[19] such processes are not an important factor in modern papermaking however.

The pulp suspension leaving the stone grinders is next passed through a coarse screen ("bull screen") to remove slivers and shims that break off the logs during grinding or are unground residue from log scraps. The pulp is then pumped to finer screens that separate acceptable fibers from oversize splinter and fiber bundles. The large slivers and shims, constituting approximately 1% of the grinder output,[20] are normally fed into a hammermill ("hog"). The hogged fragments are then combined with the rejects from the fine screens and reground in a refiner (see below).

Refiner groundwood: This category of mechanical pulpmaking uses chips as the feed material. These are suspended in water as a thick slurry (10—30% consistency) and charged to refiners, which are high-speed disk mills. Refiners use either one rotating and one stationary disk or two counter-rotating disks, with differential speeds up to approximately 3600 rpm. The working faces of the disks are contoured in various grooved patterns, and the disks are typically spaced approximately 0.25—0.75 mm apart. The chips are pumped into the clearance between the disks, where they are torn into their component fibers by a combination of mechanical rubbing and hydraulic shear. The latter force accounts for most of the disintegrating action, as the alternate raised and grooved areas sweeping across the opposite face set up high-frequency pressure pulses in the slurry.[21]

The proportion of water to wood material feed is an even more important parameter in chip refining than in stone grinding, and must be carefully controlled to maintain pulp quality and minimize energy use. Two stages of refining are commonly used. Heat generation in the pulp is appreciable, and steam is generated in refiners operating at the higher consistencies.[22] Refiner disk sizes run typically from 0.9 to 1.25 m diam, and power inputs to over 3700 kW per machine may be employed. For grinding raw chips without steaming or other pretreatment, the energy requirements for modern refining practice range 5—15% higher per unit weight of wood than for stone grinding, to produce pulp of equivalent freeness.

Refining is performed in multiple stages, as indicated in Fig. 3; commonly two stages but occasionally three stages are employed. The energy distribution between first and second stages is customarily proportioned at about 2:1. The refiner output is fine-screened to remove oversize material, which is sent to reject refiners, analogous to the practice in stone grinding. Screen rejects are already partially refined, as compared with new chips, and hence require less power per unit of throughput; 1.7—2.2 × 10^6 J/kg (25—31 hpd/t) of solids throughput is typical. Since the screen reject rate typically comprises not more than 10% of the material flow however, the energy expenditure for this operation is small compared with that for the first and second stage refiners. Even though some recycling of chips occurs in the reject refiner loop, the overall energy consumption is normally in the range of 5—10% of that in the main stages. Essentially the same holds true for stone grinding.

Because of their bulk handling properties, uniformity and short impregnation time relative to logs, chips lend themselves well to thermal (i.e., steam) or chemical pretreatment. Either of these pretreatments lessens the mechanical energy required to refine the chips; discussion in this section will be confined to thermal pretreatment. A form of mechanical pretreatment is also used, as described later. The Defibrator is a continuous steaming and refining apparatus, originally used for making roofing felt, hardboard and other coarse-fibered products. A modification (thermomechanical pulping, Fig. 3) is now coming into use for making newsprint and other paper pulps. Chips are conveyed through a preheating chamber where they are treated for 2—3 minutes with steam under pressure. The chamber discharges into a screw conveyor that charges the heated chips into a disk refiner. The ligneous component of the wood is softened by the heat, permitting the refining to be carried out with less energy than in raw chip refining. Some representative examples are given in Table 5.

Where paper grades such as newsprint are made, pretreating time is lengthened, temperature is lowered slightly and the refiner itself is also pressurized with steam. A more finely-divided and versatile fiber results.

Table 5. Energy requirements for refining[23] thermally-softened wood chips

Product	Typical steam °C temperature	Steam use kg/adkg	Steam energy approximately J/kg × 10^6	Mechanical energy approximately J/kg × 10^6	Approximate total energy, J/kg × 10^6
Felt and insulating board	180	0.6	1.23	0.87	2.1
Hardboard	50	0.4	0.85	1.27	2.1
Newsprint[a]	20	0.25[b]	0.33[a]	7.55	7.9

[a]Thermomechanical pulping.

[b]Steam is required only for startup; self-generating thereafter.

Wet pressing is used to mechanically pretreat chips in some installations. The attractiveness of this treatment depends to some extent upon the type of wood being used; it is particularly beneficial with certain resinous softwoods. The chips are washed in hot water and charged to a device such as the Pressafiner, which is a screw press with a perforated shell. Pressing breaks the chips into small pegs or "shives," a more efficient shape for disk refining, and also removes 30–40% of the resins. The pressing step requires approximately 0.4 × 10^6 J/kg but can reduce the required refining power by at least a like amount. In experiments on Jack Pine, about 10% reduction in refining power has been observed, accompanied by improved strength properties in paper made from the pulp:[24]

Product	Energy required J/kg × 10^6	Burst[a] factor	Tear[a] factor	Breaking[a] length
Refiner groundwood	6.7	10.5	68.7	2580
Refiner groundwood, with Pressafiner pretreatment	5.8[b]	13.5	93.4	3130

[a]Higher values of these parameters denote improved strength.

[b]Includes energy consumed in Pressafiner.

How much of the improvement in pulp quality is due to resin removal and how much is the result of refining a more appropriate particle shape is not documented, but the resin removal does permit refining of certain woods that otherwise would be impractical as a raw material for pulping. The energy requirements and disposition for the mechanical pulping processes discussed above are summarized in Table 6.

Table 6. Energy requirements for mechanical pulping processes

Pulping process	Wood form used	Wood preparation energy 10^6 J/kg	Mechanical energy required 10^6 J/kg	Thermal energy required 10^6 J/kg	Total pulping energy required 10^6 J/kg
Stone groundwood	Logs	0.10	5.2–6.0	*a*	5.2–6.0
Refiner groundwood	Chips or sawdust	0–0.15[b]	5.2–6.7	*a*	5.2–6.7
Refiner groundwood with pressing	Chips	0–0.15[b]	5.6–6.7	*a*	5.6–6.7
Defibrator (hardboard)	Chips	*b*	∿0.6	1.3	∿1.9
Defibrator (insulating board)	Chips or sawdust	*b*	1.6–2.0	1.0–1.3	2.6–3.3
Thermomechanical[25]	Chips	*b*	4.3–6.4	0.2–0.5	4.5–6.9

[a]Assumes shower water heated by steam from refiners.

[b]Part of the chips, etc., are obtained from lumber mill waste, where only a minor portion of the original cutting energy can be allocated to this material.

Chemical pulping

Chemical pulping is an ancient method of recovering cellulose fiber from vegetable materials, and consists basically of dissolving away the ligneous binder without attacking the more inert celluloses. Almost two millenia ago the Chinese reportedly made paper from flax or hemp.[26] The fibers were obtained by first submerging bundles of the stalks in stagnant water; when the binder components were softened by rotting, the fibers could be separated by beating or scrubbing. Processes currently in use proceed much more rapidly, and involve heating small pieces of raw vegetable material (e.g., wood chips) in an aqueous chemical solution to react with and dissolve all or a part of the binder without injuring the cellulose fiber. Since the binder material comprises approximately one-half the weight of the wood, the more severe chemical processes yield a considerably lower fraction of pulp per weight of wood charged than do the mechanical processes which retain much of the lignin content in the product. On the other hand, paper from chemical pulp is much more resistant to aging, since the easily-oxidized wood constituents have either been removed or altered to less chemically reactive forms during the pulping. Thus, chemical pulp yields vary according to the amount of lignins removed during the digestion step.

Chemical pulping covers a rather wide range of processing: Chemi-mechanical Pulping employs a mild chemical treatment such as approximately 1/2 hr soaking in 30°—40°C soda solution or approximately 150—160°C sulfite solution to soften the chips, followed by mechanical refining to separate the fibers. Pulp yields range from about 85% to over 90% depending upon wood species and processing conditions. The method is used almost exclusively with hardwoods. Semichemical Pulping involves digestion in hot (160—190°C) sulfite or bisulfite ion-containing solution for 0.5—3 hours depending upon whether continuous or batch digestion is practiced, again followed by mechanical refining. Yields are 60—80%. In commercial practice, nearly all semichemical pulping is conducted with sodium sulfite-bisulfite solution at a pH near 7, and is hence referred to as Neutral Sulfite Semichemical Pulping or simply NSSC. Either hardwoods or softwoods may be processed by NSSC but hardwood pulping predominates.[21] The major commodity produced by this method is corrugating medium for packaging. Chemical Pulping utilizes any of a variety of hot (130—190°C) sulfur-bearing solutions to digest the chips for periods ranging from about 3 to over 6 hours. The chips are sufficiently softened that they disintegrate almost completely into fibers during the blowdown of the digester at the end of the cooking period; refining is mainly confined to processing of screen rejects.

The digestion step in chemical pulping may be carried out in either batch or continuous digesters. Batch digesters are the older of the two types, and are still preferred by some operators. They are gradually being supplanted by continuous digesters which, although more expensive, offer advantages in compactness, throughput and labor and energy utilization. The energy-associated benefits arise out of the lower and more uniform steam consumption of the continuous units and their ease of adaptation to automated control using computer programs. This step permits closer control of product uniformity so that the yield of pulp can be improved, for example, without increasing the incidence of reject material.[27] Traditionally with batch digestion, heating of the charge has been done via direct steam injection. The recent tendency is to use indirect heating via heat exchangers and continuous circulation. In addition to improving batch uniformity this step avoids dilution of the charge with condensate that must then be reevaporated before the fuel value and chemical content of the spent liquor can be recovered, and also provides clean condensate for return to the boilers or other energy-conserving application.

Because nearly all of the lignins are removed during full chemical pulping, yields are generally in the 50% range, as indicated in Table 1. The refining load decreases as more drastic forms of chemical digestion are employed; however, the increase in thermal energy use is generally larger than the decline in mechanical energy. Relative energy allocations are shown in Table 7.

The principal operations for two of the best-known full chemical pulping processes are shown in Figs. 4 and 5. The Kraft Process, Fig. 4, has become the predominant pulping route in the U.S. over the last 20 years for several reasons: (1) the exceptionally strong fiber it produces, (2) the wide variety of materials that can be pulped, (3) its capability for recovering, from the spent liquor, much of the process chemicals plus a large fraction of the thermal energy needed for the process, (4) its compatibility with mild steel process equipment for most of the operations. Sulfite pulping, while no longer a major process in terms of tonnage, is still used for high grade papers and for "dissolving pulp," used in rayon-based fiber manufacture. The process shown in Fig. 5 was the original mainstay of the chemical pulping industry in the U.S., employing calcium-base sulfite liquor. Several other variants are

Table 7. Energy end-use requirements for chemical pulping[6,7,17]

Energy end use	Process: Chemimechanical pulping 10^6 J/adkg	Neutral Sulfite Semichemical (NSSC) 10^6 J/adkg	Acid sulfite 10^6 J/adkg	Kraft 10^6 J/adkg
Digestion energy				
Steam	∿0–1.9	2.6–3.5	3.5–6.8	2.6–5.6
Refining energy				
Mechanical	3.3–5.6	0.7–2.3	0.5–0.7	0.5–0.7
Pumping, screening and washing				
Steam	0.5–0.7	0.5–0.7	0.5–0.7	0.5–0.7
Mechanical	0.6–0.8	0.6–0.8	0.6–0.8	0.6–0.8
Bleaching energy				
Steam	n.a.	∿1.2	0.8–1.0	1.2–2.3
Mechanical	n.a.	∿0.2	∿0.2	0.2–0.3
Approximate average	∿7.0	5.2–6.2[a] 6.6–7.8[b]	6.0–7.5[a] 7.0–9.9[b]	4.9–6.4[a] 8.1–10.4[b] 6.3–8.7[c]

[a]Unbleached.

[b]Bleached.

[c]Semibleached

preferred today because of their better adaptation to chemical recovery and pollution abatement procedures. While the differences involved in preparing the pulping solution and in treatment of spent pulping liquor for the different chemical pulping processes are numerous, there are also basic similarities as seen from an energy viewpoint: Wood preparation and post-digestion operations are nearly interchangeable. Even the digestion step itself consists basically of heating the chips in a liquid solvent. Thus while average cooking times for sulfite pulp are somewhat longer, the average energy expended to make a ton of chemical pulp by any of the several processes is not very different. The differences between chemical pulps, on the one hand, and between chemical and semichemical pulp, on the other, become even less when grades of differently-processed

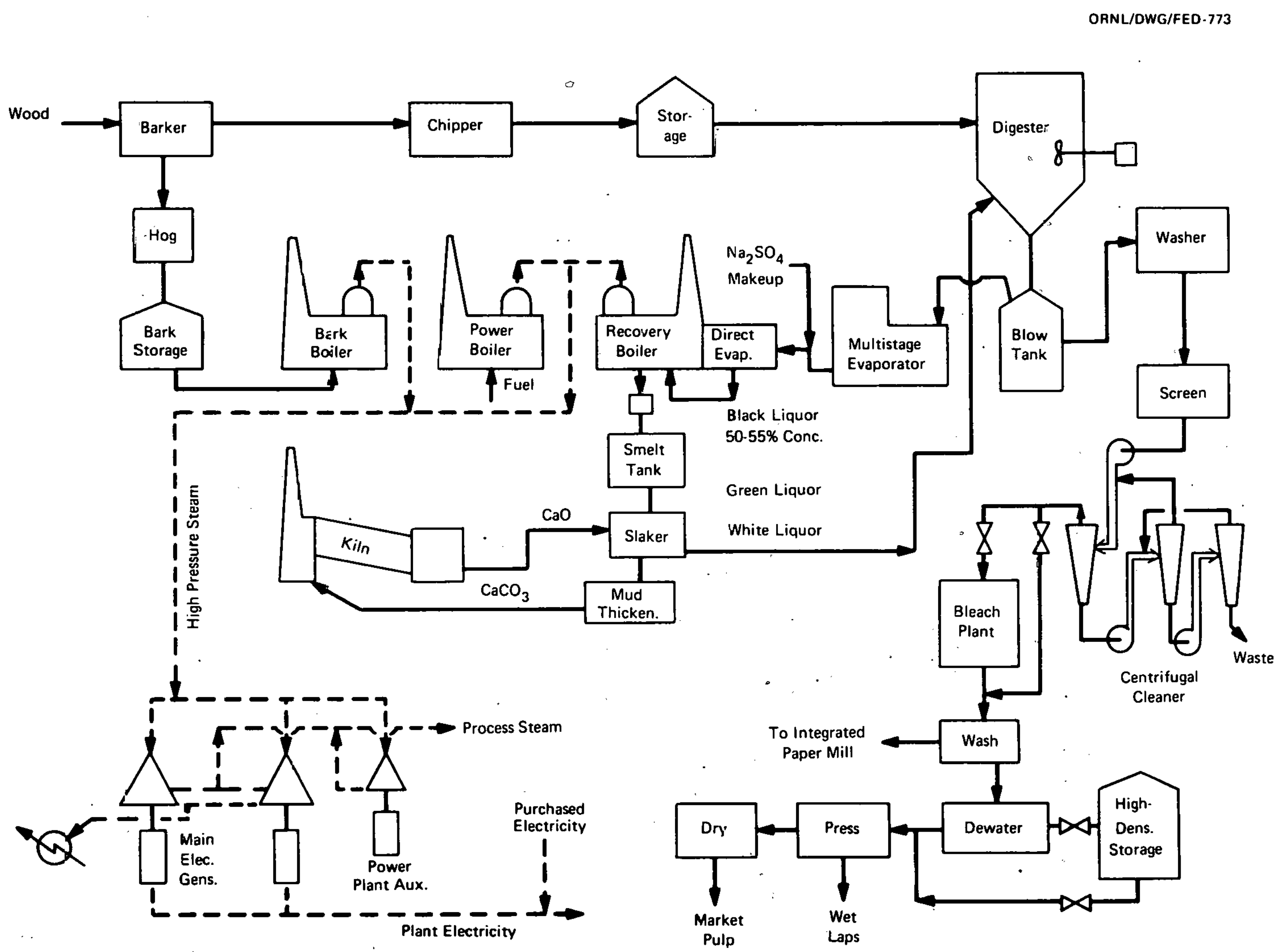

Fig. 4. Kraft pulpmaking process.

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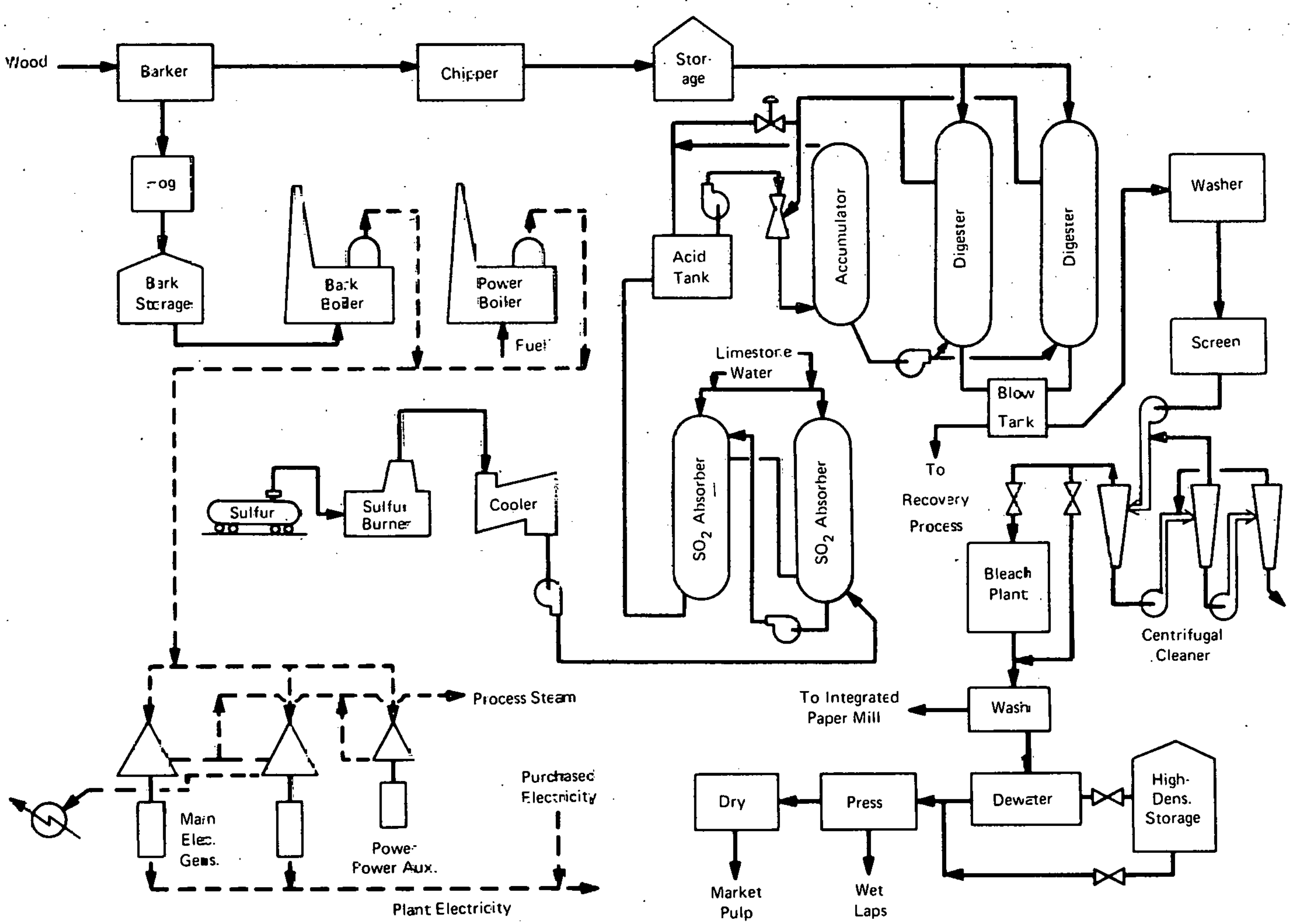

Fig. 5. Sulfite pulpmaking process.

pulps usable for the same end-product are considered: Bleached NSSC and semibleached Kraft pulp, for example, are approximately equivalent in physical properties when used as partial furnish for newsprint.

Other forms of chemical processing are being studied as means of improving yields, reducing environmental burdens or lowering pulping energy requirements. These are discussed in Chap. 8.

Recovery processes: When the wood digestion is completed, the spent digester liquor contains large amounts of organic material from the wood as well as important quantities of pulping chemicals. Under current economic conditions, recovery of values from the spent liquor is considered essential in order to remain economically competitive; in most cases such action would independently be required also, in order to comply with pollution abatement requirements.

In the Kraft Process, both energy and chemicals are recovered by burning the concentrated spent liquor in a recovery boiler. The chemicals are recovered as a molten stream ("smelt") from the furnace hearth and are quenched, redissolved and treated with caustic to regenerate the pulping solution. The spent liquor is first concentrated to ∿50% solids,[28] usually in multi-effect evaporators. A further concentration is made to 55–60%, often in a direct-contact evaporator in which hot flue gas from the recovery boiler is passed over liquor-covered surfaces to remove additional moisture. The syrupy fluid is then sprayed into the combustion chamber of the recovery boiler where it burns readily. The inorganic sodium compounds present are converted to sodium sulfide and sodium carbonate inside the furnace and fuse to form the smelt. When this is quenched in water and treated with unslaked lime, sodium hydroxide is regenerated and calcium carbonate precipitates as a mud. The solution of sodium hydroxide and sulfide (white liquor) is returned to the digesters as shown in Fig. 3. Sulfur losses are made up by adding sodium sulfate to the spent liquor before burning.

Kraft liquor commonly has a fuel value of around 15.3×10^6 J/kg (6600 Btu/lb) of contained solids, or around 8.4×10^6 J/kg as burned. Typically some 1250–1500 kg of spent liquor solids are fired per 1000 kg of airdry pulp produced, thus generating $17–21 \times 10^9$ J.

Except for the calcium acid sulfite process, the various sulfite pulping processes generally recover energy by burning concentrated spent liquor also. The energy content of the solids in sulfite liquor lies generally in the 17–19 × 10^6 J/kg range, depending upon process yield and the choice of chemical base. Since ammonium ion is decomposed into nitrogen and water in the furnace atmosphere, only sulfur and heat are recovered from spent ammonium-base liquor. Processes have been developed in which the ammonia base is replaced, e.g., by magnesium ion, before the liquor is evaporated for burning; however, they are not economic at the present time. Magnesium-base liquors decompose cleanly upon burning in a controlled excess of air to yield a fly ash rich in MgO and a flue gas containing the sulfur values as SO_2. These components are recovered and recombined to form fresh digester chemical charge. Sodium base liquors, when burned, yield a smelt that can be easily treated to furnish Kraft process makeup, or by more complex processing can be regenerated for recycle back to the sulfite digesters. Although calcium base liquor is combustible, it is seldom burned in the U.S. The oxide and sulfate formed in the furnace unite to produce a sticky fly ash that tends to cake on boiler surfaces, and the high sulfate content of the ash makes it undesirable for reuse in sulfite pulping. The material is marketable, however, as a viscosity-control additive for well-drilling muds or ceramic clays, or as a feed material in some fermentation processes. When burned, its heating value is similar to that of Kraft black liquor.

Spent NSSC liquors are chemically similar to sodium sulfite liquors but their fuel value is lower, since less lignin is removed from the wood during NSSC digestion. The fuel value is ∿12 × 10^6 J/kg of liquor solids,[21] which is not adequate to sustain combusion without the aid of supplementary fuel. The liquor can, however, be mixed in proportions of about 1:6 with Kraft black liquor and burned satisfactorily to provide the sulfur makeup for a Kraft mill. Alternatively it can be regenerated for NSSC use by several different means including pyrolysis in oil-burning furnaces or fluidized bed reactors or by co-firing in a Kraft recovery boiler plus supplementary processing to restore the required chemical form.

For energy recovery in spent liquor treatment, the liquor in most cases is first concentrated by evaporation to produce a combustible material. The average solids content of the spent liquor from 1000 kg of sulfite pulp is 1250–1500 kg.[7] Approximately 90–95% of this is recovered and sent to the evaporators at 10–15% solids concentration by weight. The approximate energy expended and recoverable from the liquor solids accompanying one ton of pulp from various processes is shown in Table 8.

Table 8. Energy recoverable from spent pulping liquors[29]

Process	Kraft	NSSC (yield = ∿75%)	Ammonium Sulfite	Other Sulfite
Weight solids from digester, kg/1000 adkg	1500	460	1250	1450
Weight solids to evaporator, kg/1000 adkg	1475	440	1100	1350
Weight percent solids	15.5	10	10	11
Dry fuel value, 10^6 J/kg	15.3	12.1	19.7	16.3
Heat theoretically recoverable, 10^6 J/adkg	22.6	5.3	21.7	23.1
Evaporator heat required, 10^6 J/adkg	(4.6)	(2.4)	(6.3)	(6.4)
Recovery process heat input and losses, 10^6 J/adkg	(6.4)	(3.0)[a]	(6.2)	(6.3)
Net heat recovery, 10^6 J/adkg	11.6	(0.1)	9.2	10.4

[a] Assuming SCA-Billerud Recovery Process.[30]

From the data in Table 8 it is apparent that large amounts of energy are recoverable via spent liquor combustion in several of the chemical pulping processes. Not all of this energy, however, is available for use in pulping or papermaking: In most cases it is desirable to regenerate pulping chemicals as well as heat from the digester effluent, an operation requiring a considerable net expenditure of energy.

In the Kraft process, the major energy input for chemical recovery occurs as high-temperature heat used to calcine the lime mud that results when the green liquor (dissolved smelt) is treated with burned lime in the slaker (Fig. 4). Commonly the calcining is done in a direct-fired rotary kiln, using fuel oil or fuel gas. (Powdered coal, a common fuel in cement kilns, is not used for direct firing in this instance because the silica thus introduced would tend to build up in the liquor and lead to scaling.) The fuel energy used to evaporate moisture from the mud and calcine it amounts to $\sim 7.6 \times 10^6$ J/kg of burned lime produced;[31] heat losses associated with kiln design and operation will account for an additional $1.7–8.1 \times 10^6$ J/kg, depending upon kiln length,* shell radiation and convection losses, and the degree of recovery of sensible heat from the flue gas and the discharged product. Since roughly 200 kg of CaO are required for chemical recovery per 1000 adkg of pulp, the lime-burning energy consumption lies in the range $1.9–3.3 \times 10^6$ J/adkg.

Sodium-base sulfite pulping requires more complex processing to recover recyclable digester chemicals than does Kraft, since combustion of the liquor does not efficiently regenerate the desired reagents (SO_2 and Na_2CO_3) for the digester charge. The recovery methods used for this pulping scheme and for NSSC pulping are similar. Generally the first step consists of burning the concentrated liquor in an oxygen-deficient atmosphere, with added fuel if required. According to the particular scheme selected, the solids recovered may contain sodium sulfide (Na_2S) and sodium carbonate, or carbonate only. In the former case the dissolved smelt or ash is further treated by one of several patented processes to separate Na_2CO_3, and the sulfides are burned to regenerate SO_2. A portion of the SO_2 is also recovered from the flue gas. Power consumption for a process typical of this class[32] is $\sim 2.2 \times 10^6$ J/adkg as low-pressure steam heat and $\sim 0.23 \times 10^6$ J/adkg as electric drive. The second scheme (SCA-Billerud Process[30]) sprays the spent liquor into hot oil-burner exhaust gas, where it decomposes into a carbonate, gaseous hydrocarbons, carbon powder and H_2S. The gases and powdered solids yield their heat in a waste recovery boiler to generate steam; after the solids are removed

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*Longer kilns cost more but allow lower calcining temperatures (and heat losses) because of the greater retention time provided for a given throughput.

the H_2S-rich gases are burned to produce SO_2 for reconstituting the digester liquor. The heat of combustion is recovered in a second steam boiler.

When used with NSSC liquor, the SCA-Billerud Process is reported to use about 45 kg of fuel oil/1000 adkg pulp for pyrolysis of the liquor; i.e., $\sim 2.1 \times 10^6$ J/adkg. Electrical requirements should be comparable to those of the processes in the first category, $\sim 0.23 \times 10^6$ J/adkg. The total heat recovered as steam from the boilers is about 4.6×10^6 J/adkg.

Pulp conditioning

After digestion and blowdown, chemical pulp is washed and coarse screened to remove undigested chips and fiber bundles. Semichemical pulp undergoes mild refining after washing (Table 7). After these respective stages, both types of pulp are in a condition comparable to refiner groundwood after secondary refining (see Fig. 3), and receive essentially the same treatment from this point on, to prepare them for use as paper or board machine furnish. If the pulp is to be bleached, this operation will usually be carried out after cleaning, as shown in Fig. 4. Energy is consumed in the bleaching operation for heating, mechanical drives for stock, shower and vacuum pumps, and for washers and deckers. Bleaching is carried out in successive stages, for several reasons. Chief among these are the reduced degradation of pulp properties resulting from multiple mild vs single harsh bleach steps, and the capability to use several different bleaching agents in sequence for synergistic benefits. The number of bleach stages differs with pulp feed material and intended usage, and may range from three to as many as eight. Softwoods generally require more bleaching than hardwoods, and sulfate pulps require more than other chemical pulps, to achieve the same degree of brightness. Typical bleaching energy requirements are included in Table 7.

Papermaking and Boardmaking Processes

Although there are obvious physical differences between extremes such as rag bond paper and boxboard, for example, the transition from paper to board in terms of physical properties is not clear cut, and the same type of machinery and forming techniques are used in the manufacture of both. In simplest terms, a mat of near-randomly oriented fibers is built up on a porous medium by deposition from an aqueous suspension. The mat is drained, compressed and then dried, chiefly by passing it over heated rolls. The evaporation of water from the web of paper or board is by far the most energy-consuming step in this phase of the manufacturing operation.

Machine stock preparation

Before the pulp is fed to the paper- or boardmaking machine it must be converted to an aqueous suspension, with a concentration closely specified according to the machinery used and the product to be made. To assure a product of uniform density, strength and other critical properties, the physical characteristics of the fibers and of the suspension itself must be kept within close tolerances. Consequently, the pulp is usually subjected to further mechanical operations prior to sheet formation. Figure 6 shows a generalized flowsheet for the process.

Pulp sources: Even in an integrated mill, part of the pulp output will frequently be put into wet lap or high density storage, to provide a surge volume that decouples the pulp mill output from the papermaking side of the plant. Since many products employ a blended furnish, wet or dry pulp from several sources may be added, including purchased market pulp or recycled paper or board materials. The pulps are dewatered or diluted as appropriate to give the desired consistency of the suspension.

Repulping: When dry market pulp or recycled materials are used as a fiber source, the stock must be resuspended in water. This is done in a pulper, a tank or vat equipped with one or more internal rotors to disintegrate the feed into its component fibers, resuspend these in a water slurry and drive the suspension through a perforated outlet plate. The pulpers are usually steam-heated. When the feedstock consists of used recycled fiber, the pulpers may be equipped with mechanical means for removing debris such as wire, plastic, sheets of wet-strength paper, etc. Where recycled printed matter is used to make a product requiring a clean, bright surface such as book paper, the waste paper pulp is de-inked by cooking (usually during the pulping process) for 1 to 2 hr in an

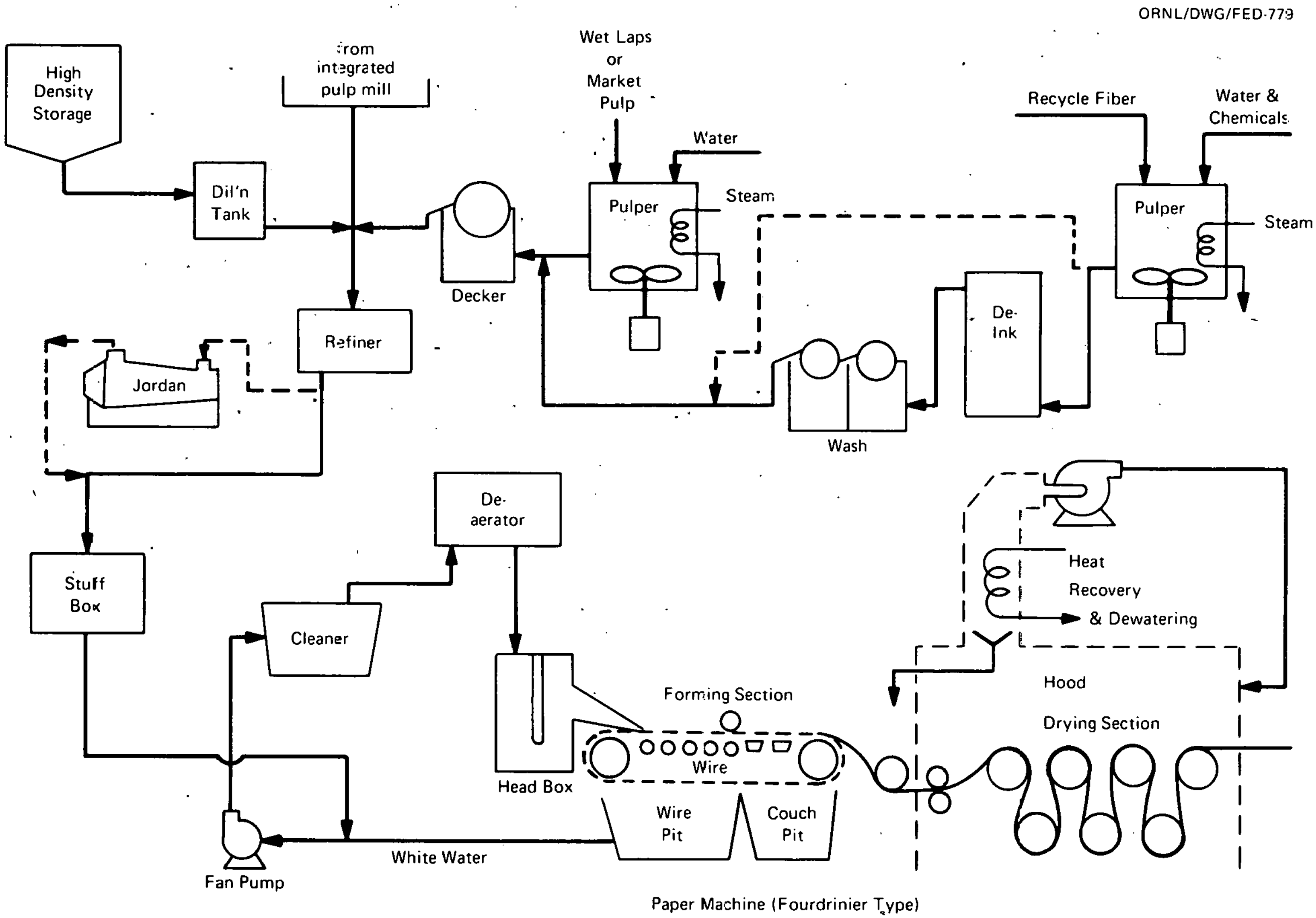

Fig. 6. Schematic diagram of papermaking process.

alkaline solution,[33] followed by washing. Cooking is done at atmospheric pressure, at temperatures in the range 120—160°F for high groundwood-content pulp, and 160—212°F for low-groundwood pulp. The mixture is agitated continuously during cooking. Bleach chemicals are frequently added to the cook, although in special instances a subsequent bleach stage is also used.

Deinking is not required for other products such as utility packaging materials, or in multi-ply coated board where the untreated fibers can be used in the inner plies as filler.

Resuspending of market pulp is less energy-consuming than the repulping of recycled board and papers. The baled pulp is relatively loosely consolidated, and free of foreign matter; not only does it redisperse easily but fine screening is unnecessary because of its inherent uniformity. An energy requirement of 0.5—0.6 hp per tpd ($\sim 41 \times 10^6$ J/1000 kg of throughput) is typical for such service.[34] Clean recycled broke from newsprint, coated papers and board materials require progressively more power, extending up to $\sim 87 \times 10^3$ J/kg, while wet strength paper may need upwards of 230×10^3 J/kg. Used materials containing refuse or dirt require additional power to process because finer exit screening is employed to minimize carry-over of foreign material.

Post-pulping treatment of recycled stock: During manufacture, paper products undergo mechanical compaction and, frequently, impregnation and coating treatments. These factors complicate repulping when the materials are recycled, such that a small but potentially valuable fraction of the fiber resists dispersal during the pulper operation. Used materials collected for recycle are also prone to contain unpulpable objects such as staples, rubber bands, foil, plastic mending tapes and paper clips, as well as dirt, all of which must be removed before the stock reaches the papermaking machine. Upgrading the fiber to usable quality involves reduction of the fiber bundles and removal of debris. This is accomplished by a wide variety of cleaning and defibering arrangements in various mills; the objective is to remove all contaminants while retaining and reclaiming as much of the unpulped fiber as possible. One process sequence used in a currently-operating mill includes the following:

a. Liquid cyclone separator — coarse stage

b. Liquid cyclone separator — fine stage

c. Screens

d. Dewatering equipment

e. Refiner

Following the refiner stage, the stock is in a condition comparable to that of resuspended virgin pulp, insofar as further processing is concerned. The mechanical power expended for thus cleaning and upgrading recycled pulp is estimated to be ~ 0.6–0.8×10^6 J/kg.

Beating: The ability of the pulp fibers to form strong interlocking bonds when matted together on the paper machine is strongly influenced by the degree of fraying or fibrillation of the fiber surfaces prior to their deposition. Preparation of the fiber surfaces to the desired condition is done by beating. This is a mechanical abrasion process that splits the outer covering of the fibers into tendrils, thereby increasing the surface area and enhancing the electrostatic properties of the fibers. The beating action is comparable to, but less vigorous than the refining action employed in mechanical pulp preparation. It is often performed in a Jordan, a special type of refiner in which a conical plug rotates within a conical shell. Vane-like blades on the plug sweep past a stationary set mounted on the inside of the shell, while the pulp suspension is pumped through the annulus. In addition to the fraying action, the Jordan can also be used to chop the fibers to a desired size, by adjustment of the plug clearance. In many installations refiners, both disk-type and cone-shaped, are used as beaters.

The mechanical energy requirements for beating range from about 0.6×10^6 to 1.6×10^6 J/adkg, depending upon the stock used, the type and condition of the beaters and the product to be made. Dense papers such as parchment or glassine require a high level of beating of the pulp, while the requirements for tablet or cheap book paper would be much less.

Final cleaning: After the pulp is beaten to the desired level, its consistency is adjusted and it passes to the recirculating feed system of the paper (or board) machine. Here it is diluted with returning white water from the web-forming section. If the machine is a

Fourdrinier type making paper, the feed is usually pumped through a bank of liquid cyclone cleaners, often preceded by a centrifugal screen; after cleaning it proceeds to the headbox. In the case of cylinder machines, the nature of the board product rarely warrants the liquid cyclone cleaning step, and centrifugal screening alone is ordinarily considered adequate.

Liquid cyclone cleaners require considerable energy to operate. The pressure drop through a cyclone element is commonly 2.4–3.5 × 10^5 Pa (35–50 psi), and the primary recirculating flow may exceed 2.4 ℓ/sec per 1000 kg/day of machine capacity. A smaller amount, perhaps one-fourth as much, circulates in the secondary cleaning stage. The combined total may amount to $\sim 0.1 \times 10^6$ J/adkg of mechanical energy input at the fan pumps.

Web formation

Papermaking machines: Regardless of type, paper- and boardmaking machines combine three basic functional units: (1) the web-forming unit, or wet end, (2) the press section, and (3) the dryer. While the latter two sections are basically the same on all machines, there are two principal types of wet end, the Fourdrinier machine (Fig. 7*a*) and the cylinder machine (Fig. 7*b*). In the Fourdrinier machine a continuous, sheetlike stream of pulp suspension is sprayed from the headbox onto a wire, a horizontal endless moving belt of wire screen or synthetic fabric. The fibers are retained on the belt to form a mat or web, while the bulk of the white water drains through the wire into catch basins ("pits") underneath. As the web is carried forward on the moving wire it passes over slotted suction boxes, which drain additional moisture from the fibers. At the end of the wire section, the wire bends around the couch roll and the web is brought into contact with a moving belt of felt. The fiber mat clings to the felt and is lifted from the couch roll; felt and web together pass through a set of press rolls, the web is transferred to a second felt and pressed at least twice more. After the pressing steps, the sheet is looped in an over-and-under pattern on an array of heated rolls for final drying. In most applications the sheet is held against

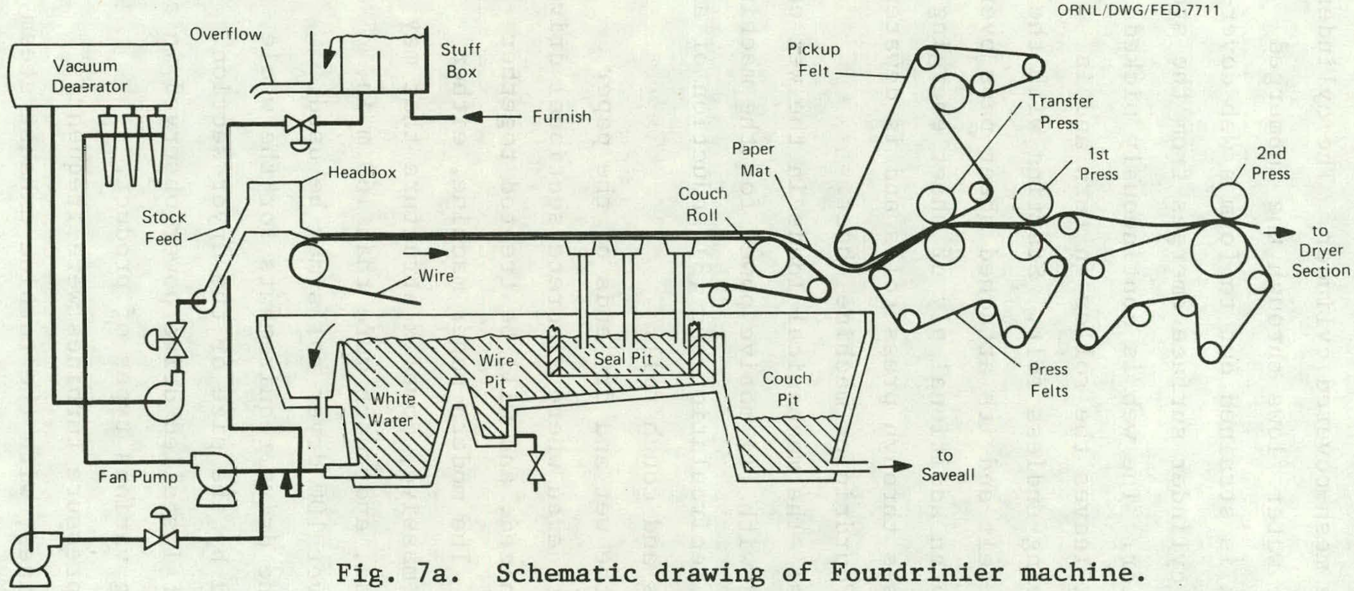

Fig. 7a. Schematic drawing of Fourdrinier machine.

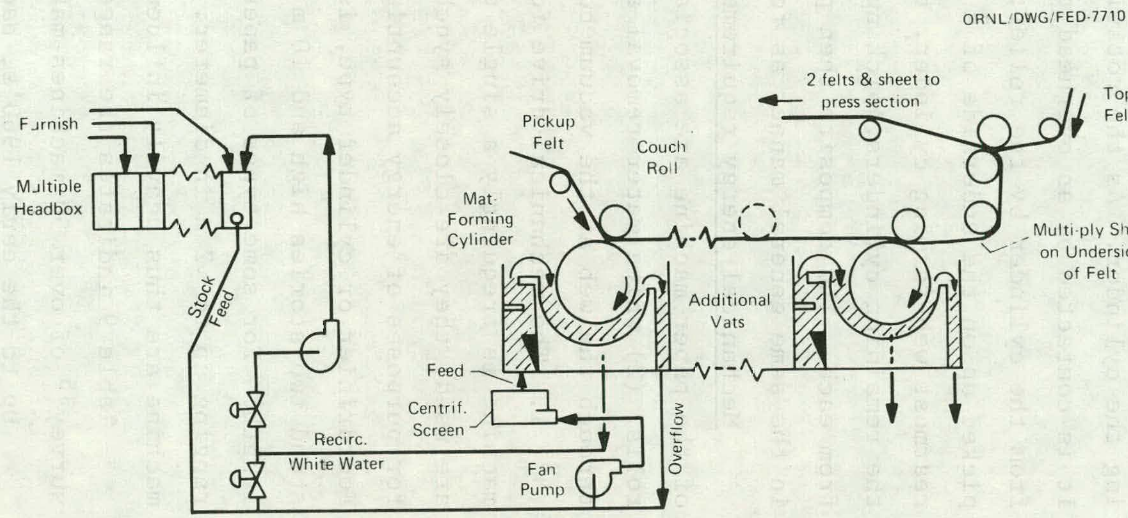

Fig. 7b. Schematic drawing of cylinder machine.

the rolls by endless belts of heavy felt; exceptions are Creping and Yankee Dryer Rolls, which will be discussed later.

In the cylinder machine, the wet end consists of from one to nine vats filled with flowing pulp stock suspension and each containing a partially-submerged, revolving wire mesh-covered cylinder. The cylinders are drained from the inside so that water flows through the submerged parts of the screen while the stock is strained out to form a web covering the cylinder. As the rotating cylinder surface emerges from the stock, it is contacted by an overhead roller. The web is continuously picked from the cylinder by the roller; it leaves the roller in turn and is picked up on the underside of a moving endless felt. Starting with the rearmost web-forming cylinder, the felt and its attached sheet pass over the remaining cylinders, picking up an additional ply of sheet emerging from each. The composite then passes through press rolls and is dewatered in the same general manner as for Fourdrinier machine sheet.

Mechanical energy requirements: The mechanical loads in the wet end of the paper machine are associated with (1) motive power for the machine rolls, (2) white water removal and recirculation and (3) induction of air through the web at the vacuum boxes and couch roll.

1. The mechanical drive for the wet and dry ends of the paper machine is frequently a single unit; even where discrete sectional drives are used, they are closely synchronized, and will be treated together for purposes of energy accounting. The modern paper machine, either Fourdrinier or cylinder type, is a massive, complex structure that may stand two stories high and 10 m wide, and reach more than 160 m in length. For some types of paper over 100 dryer rolls may be used, ranging up to ∿2 m in diameter. The drive requirements for the whole machine are thus heavily influenced by the size of the dryer section.

Table 9 indicates the range of installed drive power observed in a survey[35] of over 50 machines making various types of product.

Up to the early 1960's, back-pressure turbines were frequently specified as drives for paper machines, with the turbine exhaust steam being piped to the dryer rolls. The turbine drives a lineshaft running the length of the machine, with geared or belted takeoffs for driven rolls. Where such units are run on high-pressure steam, a

Table 9. Installed power capability for paper machine drives

Machine type	Product	Specific power, 10^6 J/adkg
Fourdrinier	Kraft linerboard	0.21–.35
Fourdrinier	Corrugating medium	0.12–.22
Fourdrinier	Printing and book papers	0.23–.70
Cylinder (3 to 8 cylinder)	Boxboard	0.14–.26

thermodynamically efficient energy use can be effected. Reliability of speed adjustment between sections, ease of backfitting and modernization, and flexibility of operation, particularly during product changeovers and system upsets, were surpassed by sectional drives using electric motors, however, once modern solid-state speed controls for large electric motors were perfected. Electric drives are now favored, although paper-machine drive turbines aggregating an estimated 0.3×10^6 kW were still in use in 1974, in unit sizes up to 2250 kW.[36] The principal application for nonelectricity-generating turbines in new paper mills is as power plant auxiliaries: i.e., drives for boiler draft fans and feed pumps.

2. The second large application for mechanical energy in the paper machine is the removal and recirculation of the white water that drains into the pits under the Fourdrinier wire or into the cylinders on cylinder machines. This load is handled by the fan pumps (Fig. *7a,b*), and was described earlier under Final Cleaning.

3. The vacuum boxes under the Fourdrinier wire are maintained at progressively greater negative pressure as the web moves toward the end of the forming table. The first boxes maintain a slight negative pressure by the action of the descending column of water leaving the box toward the pit; the subsequent boxes require mechanical assistance to maintain the desired vacuum however. Vacuum pumps also serve the vacuum boxes contained in the couch and press rolls. Together with the air handled by these pumps, about 10 tons of water are removed per ton of

fiber moving through the machine. While installations vary considerably, the energy consumption by vacuum pumps lies in the range of 0.1—0.6 × 10^6 J/adkg.

Thermal energy requirements: Heat is not an obvious major factor in the energy budget of the wet end of the paper machine. However, in the Fourdrinier machine, sheet formation depends importantly upon the characteristics of the stock flow through the distribution nozzle ("slice") onto the wire, and these properties in turn are affected by the temperature of the stock suspension in the headbox. The headbox is filled with recirculating white water from the wire pit — about 60—75% of the water leaving the slice — and fresh incoming stock that carries the other 25—40% of the water requirement. The latter usually runs slightly cooler than the white water, and the temperature of the mixed feed to the headbox is adjusted by injecting steam into the wire pit. Since the stock consistency at the slice is commonly near 0.5%, or about 200 kg of water per kg of fiber, some 50—80 kg of water per kg of fiber require heating. The desired temperature rise, typically ∿1.7—3°C, would thus involve a heat input of 0.35 × 10^6 to 0.95 × 10^6 J/kg of product. In some cases therefore, the thermal input can approach or equal the mechanical energy requirement for the machine drive plus the wet end auxiliary equipment.

Pressing and drying[37]

In the press section the sheet moisture is reduced from 3—4 kg down to 1 1/4—2 kg of water per kg of fiber, by mechanical pressing against an absorbent fabric belt. At 55—60% moisture content, depending upon the sheet material, further mechanical pressure will tend to crush rather than dry the sheet. Hence the final drying is performed by evaporation.

Typical dryer features: The principal mode of drying paper or board involves lapping the sheet over a large number of steam-heated rolls, as shown schematically in Fig *7a,b,* so that the desired amount of moisture will have been removed by evaporation as the sheet reaches the end of the array. The sheet is held against the rolls by partial wraps of felt, to promote close contact between rolls and sheet for good heat transfer. The confined areas between rolls are ventilated with air ducts to prevent accumulation of moist air. The entire dryer section is preferably enclosed in a moisture-resistant hood, with the following purposes:

1. Minimize the air flow requirements for removal of water vapor,
2. Isolate the dryer ventilation demand from the building space heating and cooling requirements,
3. Conserve dryer heat,
4. Facilitate the recovery of heat from the dryer exhaust stream.

The degree to which all of the above are implemented varies from mill to mill; generally some heat recovery is practiced at all but the smallest mills however.

Thermal energy requirements: Typically the residual moisture in paper and board as manufactured is 5% to 10% by weight, depending upon the product. As noted above, the sheet enters the dryer section carrying 1.25–2 kg of water per oven-dry kg (odkg) of fiber. Reducing this burden to a nominal 0.088 kg of water per odkg (i.e., about 8% by weight) via evaporation must consume at least $3.0–4.9 \times 10^6$ J/odkg or $2.8–4.5 \times 10^6$ J/kg of product.

Frequently, additional moisture will be added to the paper between latter stages of the drying operation in the form of sizes, coatings and coloring suspensions; these in turn must be removed by re-drying. Sizes may contain over 90% moisture; modern pigment and coating formulations are applied at ∿50% consistency.[38] The combined moisture addition from these sources may amount to 0.75–1 kg of water per adkg of base stock, and must also be removed. Some 20% of this moisture may be removed downstream of the steam-heated rolls by surface dryers, as discussed later; however, the total evaporation burden for the roll dryers may be 30–40% higher than the numbers presented for untreated sheet. This can raise the theoretical drying heat requirement for the steam rolls to $\sim 5.8 \times 10^6$ J/kg of airdry base stock (i.e., excluding the weight of the non-fiber additives).

In practice, only about 30–40% of the steam heat supplied is actually used to evaporate moisture from the sheet; some 25–35% is rejected in the condensate and the remainder is dissipated in heating the dryer air or through radiation and conduction to the surroundings. Actual steam consumption rates can vary from ∿7.6–14.5 × 10^6 J/kg of product. Consumption is affected not only by final and original moisture content but also by the thickness and permeability of the paper or board.

There are other types of drying apparatus that find more limited use in the paper products industry, for special purposes. For drying pulp, either conventional rolls may be used or alternately an air float dryer, in which a continuous sheet of pressed pulp is suspended by currents of hot air in a boxlike housing, is often used. As a third alternate the pulp may be wrung out in a rotary press, then granulated in a hammermill and flash-dried by dispersal into a fast-moving hot air stream. The heat requirements for pulp drying are lower than for paper and board, in general. A typical heat load[39] would be ∿5.2 × 10^6 J/adkg. Current dried pulp production in the U.S. is relatively small but not insignificant, with an estimated tonnage[40] equaling 7–8% of the 1974 U.S. paper and board production.

The Yankee, creping or machine glaze (MG) dryer roll is used in certain papermaking applications. The basic design of the roll is the same for all three designations, although the size and mode of use vary. The roll is internally steam-heated and bears a very highly polished surface; the still-damp sheet is rolled tightly against it so as to adhere with essentially no intervening air film. As the roll rotates, the exposed side of the sheet is dried by a stream of hot, high-velocity (up to 100 m/sec) air from a dryer hood that surrounds 2/3 to 3/4 of the periphery. If the drying is not carried to completion, the sheet adheres to the roll at the discharge point and is peeled free by a scraper blade ("doctor"), giving it a creped texture that may be preserved or removed according to subsequent treatment. If the sheet dries fully on the roll, it acquires a glossy surface on the roll side and detaches spontaneously. Heat input to the sheet is high because of the good conductive bond between the sheet and roll, on one side, and the very thin diffusion boundary layer on the air-swept side. Water removal rates as high as 720 kg/hr/m^2 of roll surface have been achieved in this way, compared to 32–64 kg/hr/m^2 for a conventional felted roll.[38] Commonly the air blast is heated to 300–450°C using electric resistance heaters, gas or oil fuel-fired indirect heat via finned tubes, or direct firing from gas or oil. Reportedly a tissue dryer has been satisfactorily operated in which the exhaust from an oil-fired gas turbine was used as the drying medium.[41]

Impingement drying requirements depend strongly upon the moisture permeability and retentivity of the sheet in this application, where appreciable moisture is being removed from the interior of the fiber web. A modern Yankee dryer, with the roll heated by steam at about 965 kPa (abs)* and a hood supplying air at 100 m/sec and 450°C will use about 6.4×10^6 J/adkg of sheet, assuming 65% moisture by weight in the entering material and 5% moisture at the removal point. Some 55% of the drying heat will be supplied by the air side. Dryer hoods operating at such conditions are equipped with heat recovery devices so that the supply air enters the heater section at a temperature around 315°C.[42] The annual production of paper products involving Yankee, creping and MG dryers is estimated to be between 4.4 and 4.6×10^9 kg, or around 8% of total production.[43] Air blast heaters of lower rating, as well as radiant heaters and occasionally dielectric units are used where extra capacity is needed and space requirements are restrictive, e.g., in retrofitting applications on existing machinery. The total installed capacity of these units is believed to be smaller than any of the applications described above.

The energy requirements for paper and paperboard sheet production are summarized in Table 10.

5. ENERGY CONSERVATION PRACTICE

The foregoing chapters indicate that except in groundwood mills, by far the largest portion of the energy use in pulp, paper and paperboard manufacture is in the form of heat. Figure 8 shows a breakdown of the energy consumed in making these three commodities in 1972, utilizing the aggregate figures of the American Paper Institute[44] and average values

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*Pressures are given in absolute units, in this report.

Table 10. Energy requirements for papermaking and boardmaking

Operation	Mechanical energy 10^6 J/adkg	Thermal energy 10^6 J/adkg
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	6.4–8.1
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

for the unit operations cited in this report. The total 1972 energy consumption of 2270 × 10^{15} J may also be dissected in the following way:

End use	Energy, 10^{15} J
Mechanical operations:	
Woodyard	10
Boiler fans and pumps	10
Pulpmaking	80
Sheet forming, drying, finishing	120
Total	220
Thermal operations:	2050
Total	2270

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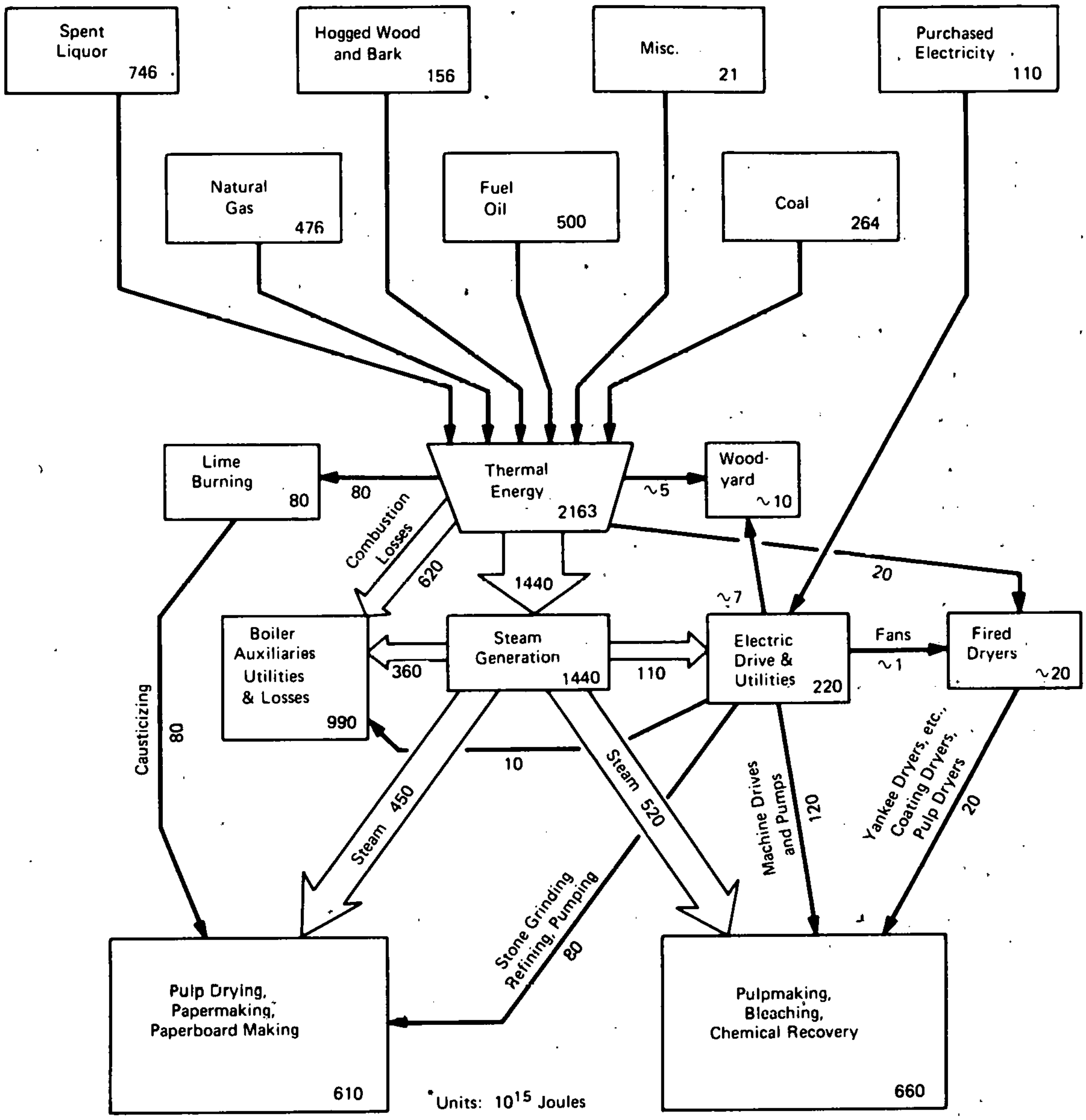

Fig. 8. Estimated energy distribution for the Pulp, Paper and Boardmaking Industries, 1972.

In-Plant Electric Generation

By the above reckoning, mechanical energy accounts for about 10% of the overall energy consumed. Reference to Fig. 8 reveals that some 970×10^{15} J were utilized as steam heat in the manufacturing processes, in 1972. Since the heating steam is used at pressures of ∿450—1140 kPa (50—150 psig), the roughly 6:1 ratio of steam to mechanical energy requirements is thermodynamically favorable for in-plant generation of electricity. This means that an appropriately-equipped plant can generate its own electricity using back-pressure or extraction steam turbines that are driven with high-pressure steam at modern electric-station conditions. The exhaust or extraction steam from the turbines is furnished at process steam conditions. Under these circumstances the amount of recoverable heat energy in the process stream can be 3—5 times the amount of electrical energy generated, and if this energy can all be used productively by the plant, the overall efficiency of energy use may exceed 70%. In an electric utility, the generator turbines exhaust to condensers that reject their heat to the environment, and only 30—40% of the fuel energy fired to the boilers is utilizable. Hence the paper or board mill can generate part or all of its electrical requirements with more efficient fuel utilization than an electric utility station could achieve, assuming that the mill is of a sufficient size so that the capital charges on the generating equipment are small compared with the cost of the energy consumed.

The possibilities of in-plant power generation are well appreciated by the industry, as evidenced by the nearly 50% of electrical requirements supplied by this means (Fig. 8). Some individual plants generate up to 100% of their electrical requirements.[45]

Limitations: Generating electricity via back-pressure turbine-generator sets that receive steam from the boilers at, say, $6.2\text{—}8.3 \times 10^3$ kPa, 482°C (900—1200 psi, 900°F) and exhaust at process steam pressure represents an ideal for maximum recovery of fuel energy. This arrangement is widely employed in Scandinavia[46] and particularly in Finland, where electricity costs are high even by current U.S. standards. However, the exclusive use of back-pressure turbine-generator sets for power in a paper mill requires a degree of interaction between mill and utility not commonly encountered in the U.S., plus exceptional stability of operation, if the system is to realize the economies of which it is capable. This occurs because of the rigid linkage between steam and electric production inherent in such a system. In Scandinavia the mill's generators are tied into the electric utility grid. The steam output at the mill is closely regulated by the use of devices such as balancing condensers in the exhaust system. Action to minimize steam wastage following a severe process upset would need to be tempered by consideration of the effect it would have on the grid conditions. An example might be a sheet break on a large board machine; reportedly[47] such an occurrence can cause an abrupt decrease in (dryer) process steam demand of as much as 10^5 kg/hr — enough to supply roughly 15 megawatts of associated electric generating capacity.

In the U.S. and other regions where energy costs are still relatively lower, mills rarely if ever tie their steam and electrical capacity rigidly together via exclusive reliance on back-pressure turbines. At least two options are available to permit more flexibility between steam and electric production at the mill: (1) Multiple turbogenerator sets are used, with at least one unit exhausting to a condenser. Process steam is supplied via an extraction point, and some trade-off between condensed and extracted steam is available without affecting the electrical output. (2) Part of the plant electric power is generated and part purchased. Either of these means allow process upsets to be confined to the mill and not passed back to the electric utility.

In addition to efficiency considerations, many other important factors influence the decision on what fraction of the plant's electrical requirements should be generated onsite. Among the foremost are: reliability of electric supply, especially for relatively small power plant installations; maintenance cost of equipment; relative assurance of fuel supply for the utility's generating sets, as compared with those of the mill; the local cost of fuel and electricity, and the efficiency of existing equipment. Where new capital equipment is contemplated to alter the existing power-generating capabilities, further constraints may come into play; these include space for new facilities, handling capacity for additional fuel and waste effluents, and delivery time and availability of new equipment. Obviously any or all of these could render a power supply upgrading plan unworkable, no matter how sound the justification on energy conservation alone.

Thermal Energy Conservation Practices

The Pulp, Paper and Board industries, because of their historic involvement with massive quantities of thermal energy, have developed numerous techniques for heat conservation where economic benefits would result. Predictably these have focused most intensely on the heat-containing effluents that are at the highest temperature, occur in largest volume and are the easiest to reclaim. Under the pressure of rising resource costs and new environmental control regulations however, the list of applications has grown substantially. Not all of the methods now in use are fully exploited throughout the industry, and opportunities for upgrading of conservation practices exist at many individual plants. Table 11 lists alphabetically the major categories and some plant applications of thermal energy conservation technique presently employed within the paper industry.

Heat exchangers: The use of heat exchangers for energy conservation is widespread throughout the process industries, and the practices of boiler air preheating and feedwater preheating are largely standardized. The use of digester blow tanks has supplanted open blow pits in the industry, although there are still mills where the blow steam is vented directly to the atmosphere without heat recovery. A common batch digester blowdown pressure is ∿240 kPa, and the water content of the digester frequently reaches 8 kg per kg of oven-dry pulp. The sensible heat in the water can flash about 400 kg of 5 psig steam per 1000 kg oven-dry pulp, much of which is recoverable by the use of economizers for wash water heating. Direct contact evaporators are in widespread use in the Kraft and soda pulping processes, where black liquor is directly contacted by hot flue gases from the recovery boilers as a final drying process. This measure has been criticized as a prime source of odor emission; however, partial oxidation of the weak liquor is being successfully used as a remedial measure in many plants.

Table 11. Thermal energy conservation practices in the paper industries

Technique	Application	Points of use
Heat carrier reuse	Steam energy cascading	Dryer rolls Mechanical drive turbines on paper machines and auxiliaries
	White water recovery	Pulp washing, stock dilution
Heat exchange	Economizers	Boiler stacks Digester blow tanks Direct contact evaporators Dryer hoods Refiners
	Regenerators and recuperators	Boiler air preheaters Dryer hoods Lime kilns
Latent heat recovery	Thermocompressors	Steam-heated dryers
	Two-stage steam heating	Batch digesters
Process optimization	Steam load leveling	Continuous vs batch digesters[44]
	Quality control	Digester cooking period automated control[48] Dryer pocket ventilator control[49]

As the technology of direct-impingement air drying has been refined to produce the very high drying rates now associated with Yankee dryers, heat recovery devices such as economizers and regenerators have become standard equipment on these items. Other types of sheet dryers including air suspension dryers of the type used to dry pulp and coated sheet as well as conventional steam roll dryer hoods, are also frequently equipped with such heat recovery devices. In the latter instance the heat recovery is maximized by the use of a closed dryer hood; this allows a reduction in air flow by as much as 60% of that required for a canopy-type hood,[50] permits controlled recirculation of the dryer air, and permits better heat recovery by virtue of the reduced volume and consequently higher exhaust temperature of the air. The arrangement also facilitates control of the machine room space ventilation, independent of the dryer requirements. Even a well-hooded dryer uses about 10 kg of air per kg of moisture removed;[51] in the absence of separate ducting and space conditioning, the machine room climate will be largely controlled by the dryer load. The saving in drying steam achievable by full hooding has been estimated at 5–10%.[52] Heat exchangers are justifiable on a conservation basis even for the relatively low temperature air (typically 70–90°C) in a steam roll dryer hood. A well-designed recuperator (inlet air heater) section can reportedly recover ∿10% of the dryer input heat, and by adding water-heating economizer sections upstream and downstream from the recuperator, another 10–20% can be saved.[53]

As noted during the description of Thermomechanical Pulping, steam is generated during high-consistency refining. In this case it is used to pre-soften the wood, but it has also been employed to heat water for chip washing.[54]

<u>Lime kilns</u>: The calcining of lime, an essential step in the recovery of pulping chemicals in the Kraft process, can consume as much as 16×10^6 J/kg of burned lime produced (∿3.2×10^6 J/kg of dry pulp), although the theoretical heat requirement is less than half of this figure. By careful attention to kiln design including insulation and regenerative air preheating, energy requirements as low as 8.1×10^6 J/kg of CaO produced are reportedly achieved in Scandinavian practice.[46]

<u>Latent heat recovery</u>: The practices of steam cascading and mechanical or thermocompression are most commonly used in connection with steam-heated roll dryers. In the first technique, relatively high-pressure steam (to ∿1140 kPa) is fed to those rolls requiring comparatively higher temperatures; the exhaust and condensate from these is passed to a flash tank where lower-pressure steam is regenerated, and this in turn is used in dryer applications where lower temperatures suffice. Thermocompression, sometimes used in complement with cascading, involves recycling the wet steam exhausted from a dryer by passing it to a flash tank as before, but then upgrading it for more efficient reuse by injection of higher-pressure steam. This scheme allows a wider gradation of steam pressures and a lower overall heat input for the same drying capability, relative to the

cascade system alone, at the expense of a more complicated system. Whether it is warranted seems to depend strongly on individual product mix and choice of motive power (electric vs turbine) for the paper machinery, among other factors. Mechanical recompression of steam via a turbocompressor is also used in a few installations.

Mechanical drive turbines: During the 1950's and 1960's in particular, back-pressure steam turbines were popular as drives for paper machines. Since these can be operated on high quality main steam like a generator turbine and provide steam for the dryers at the exhaust, they are theromodynamically efficient. However, in cases where more than one grade of paper or board is produced on a machine, the ratio of motive to dryer steam may not remain constant. This and other previously-cited mechanical considerations have reduced the appeal of mechanical-drive turbines in this application. In most cases the same energy efficiency can be achieved through other design alternatives.

Digester operation: Much attention, both in this country and abroad, is focused on improved digester practice as a means for energy conservation. In electricity-scarce countries particularly, two-stage steam heating of digesters is favored; i.e., initial heating is performed with low-pressure process steam, with ∿1140 kPa steam reserved for the finishing stages of the cook. By conserving the use of turbine extraction steam, this practice allows additional electrical generation for the same overall steam flow through the main turbines. Such heating is also preferably carried out via heat exchangers rather than the old method of direct steam injection; this obviates the dilution of the charge which would preclude recovery of low-pressure exhaust and condensate, require additional evaporation of the spent liquor and increase steam load for digestion. The change from direct to indirect heating can reduce digestion steam requirements as much as 15–20%.[46] A more sophisticated and also rewarding practice concerns automation of the digester cooking cycle, based upon on-stream analysis of the pulp condition during the cooking cycle. By reducing the standard deviation of product properties, the practice permits a higher yield of pulp per batch because the need to overcook to assure minimum product characteristics is greatly reduced.[48] Although the improvements cited are in terms of productivity gain, these should be proportional to energy savings (2.5 to 10% in typical cases). Finally, the use of continuous vs batch digesters as an energy-saving practice has been cited.[46,55] The basis for the reduction in energy required per ton of pulp (up to 60%, compared to direct-heated batch digesters) is mainly due to the following characteristics of the process: (1) Shorter cooking times result, due to reduced heatup time; (2) steam load is steadier, reducing turbine steam flow perturbations with a consequent efficiency gain; and (3) the continuous-flow design provides inherently better opportunity for regenerative heat recovery.

White water recycling: Although white water conservation has been customary in many mills because of the resources it contains (heat, chemicals, finishing agents and fiber fines), older and smaller mills in particular have frequently found it expedient to discard white water. Environmental control regulations have compelled a sharp reduction of this practice in recent years, with consequent energy conservation benefits in some cases, at least. One Great Lakes Area mill official cited a heat savings during winter months of ∿9000 kg/hr of steam, attributable to recycling of white water.[56]

6. ENERGY RESOURCES, CONSUMPTION AND DISTRIBUTION

Geographic Aspects

Purchased energy consumption

Although Pulp, Paper and Board Industry (PPBI) mills are found in all parts of the country, their distribution is not uniform, and hence their impact on area energy consumption varies from one geographic region to the next. The extent of this variation is shown in Table 12. In terms of consumption relative to the other manufacturing industries as specified in SIC[1] Categories 20 through 39, the proportion of PPBI consumption is actually larger than the Table 12 numbers indicate. This is because the industry sector totals were taken from statistics[57] compiled by the Bureau of Mines, which defines the Industrial Sector much more broadly than does the Census of Manufactures. The marked concentration of mills in the New England, South Atlantic, East South Central and Pacific regions where

Table 12. Energy purchases by the pulp, paper and paperboard industry (PPBI) compared to total industrial energy purchases, 1972

District	Industry variable	Units	Purchased coal	Purchased electricity	Purchased gas	Purchased petroleum products	All purchased energy	All purchased fuel energy
New England	Total industrial energy use	10^{15} J	5.6	82.7	75.6	285.4	450.5	367.8
	PPBI energy use	10^{15} J	0.0	9.3	1.8	86.8	99.9	90.6
	PPBI % of total	%	0.0	11.1	2.4	30.4	22.1	24.6
Middle Atlantic	Total industrial energy use	10^{15} J	1047.9	352.4	674.7	679.5	2759.2	2406.9
	PPBI energy use	10^{15} J	38.9	11.8	14.7	76.8	142.2	130.4
	PPBI % of total	%	3.7	3.4	2.2	11.3	5.2	5.4
East North Central	Total industrial energy use	10^{15} J	1999.9	581.0	1767.0	826.5	5182.9	2783.9
	PPBI energy use	10^{15} J	129.3	17.2	82.3	27.9	259.5	242.3
	PPBI % of total	%	6.5	3.0	4.7	3.4	5.0	8.7
West North Central	Total industrial energy use	10^{15} J	169.1	141.6	742.7	278.7	1334.2	1192.5
	PPBI energy use	10^{15} J	4.3	2.8	29.0	1.1	37.2	34.4
	PPBI % of total	%	2.6	2.0	3.9	0.4	2.8	2.9
South Atlantic	Total industrial energy use	10^{15} J	576.6	362.8	766.3	705.0	2435.7	2072.9
	PPBI energy use	10^{15} J	66.1	14.3	47.2	188.0	319.0	304.7
	PPBI % of total	%	11.5	4.0	6.0	26.7	13.1	14.7
East South Central	Total industrial energy use	10^{15} J	472.2	347.4	638.6	205.0	1668.1	1320.6
	PPBI energy use	10^{15} J	25.2	11.1	87.1	34.3	157.7	146.6
	PPBI % of total		5.3	3.2	13.6	16.7	9.5	11.1

Table 12 (continued)

District	Industry variable	Units	Pur- chased coal	Purchased electricity	Purchased gas	Purchased petroleum products	All purchased energy	All purchased fuel energy
West South Central	Total industrial energy use	10^{15} J	26.9	306.3	4871.4	2085.5	7294.4	6988.1
	PPBI energy use	10^{15} J	0.0	11.8	139.4	46.0	199.8	188.0
	PPBI % of total	%	0.0	3.9	2.9	2.2	2.7	2.7
Pacific	Total industrial energy use	10^{15} J	69.6	347.9	1006.3	681.1	1217.5	869.5
	PPBI energy use	10^{15} J	0.0	31.7	74.3	42.8	157.2	125.5
	PPBI % of total	%	0.0	12.9	7.4	13.4	12.9	14.4
Mountain	PPBI % of total[a]	%	—	∿1.5	∿0.5	<0.1	<0.1	<0.1

[a]Estimated from 1971 data.

NOTE: Totals may exceed the sum of the individual sources shown, due to minor contributions from other purchased energy sources.

there are large forested areas, is clearly evident from the percentage figures. There are sizable PPBI also in other central parts of the country, although the high concentration of other energy-intensive industries in these areas tend to mask the PPBI consumption.

Purchased electricity consumption: Table 12 indicates that the PPBI accounts for over 10% of the industrial purchased electricity consumption in two regions, New England and the Pacific States. From Fig. 9 it can also be observed that purchased electricity is more heavily relied upon for power by the PPBI in these regions. Thus the industry will be more sensitive to any shortfall in electricity availability in these areas than in other parts of the U.S., if the combination of effects still exists when a shortage occurs.

The case for onsite electric generation: In principle, there are economic incentives for a mill to generate electricity onsite up to the point where its own electrical needs are met, assuming that the exhaust heat from the generator drive can be usefully exploited. If the electrical requirements exceed this criterion, further generation may still be achievable before the cost of generation exceeds the cost of purchased electricity. In practice this position is often modified by other constraints including space, capital costs and electric supply reliability considerations, among others. As the motivations for energy conservation increase however, the arguments deserve periodic reexamination.

The relative efficiency of in-plant electricity generation under paper industry conditions vs the generation by an electric utility has been pointed out in the previous chapter. A comparison of electric generation at 75% overall thermal efficiency (4.79×10^7 J/kWhr), obtainable under modern in-plant generating conditions where low pressure process steam can be utilized productively, and at the $\sim$33% efficiency (1.10×10^7 J/kWhr) achieved in 1972 by electric utilities indicates that every joule of electrical energy thus generated in-plant conserves over 1.7 J in regional fuel energy consumption. Thus in New England for example, Table 12 shows electric energy purchases by the PPBI of 9.3×10^{15} J in 1972. If 40% of this amount could be generated internally instead of purchased, the thermal energy equivalent of 1 million barrels ($\sim 1.6 \times 10^5$ m^3) of oil would be saved.

ORNL/DWG/FED-770

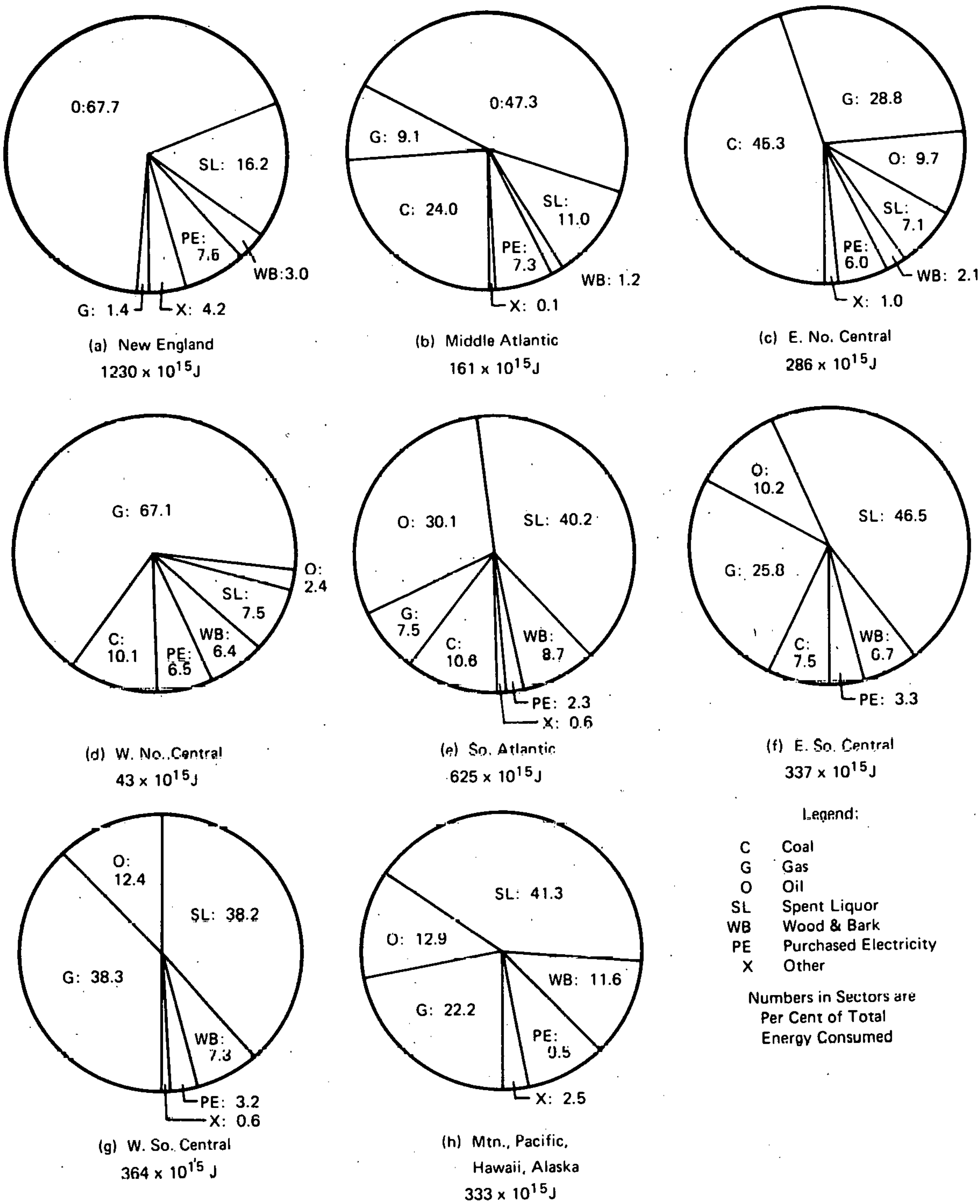

Fig. 9. 1972 energy consumption of the Pulp, Paper and Board Industries[58] by source and region.[59]

Energy Resource Options

Major energy requirements

Although individual cases vary in their flexibility, the energy use characteristics of the PPBI as a whole make it highly adaptable to changing fuel availabilities. The main forms of energy required are two, namely low-pressure steam for process heat and electricity for mechanical drive. Both of these energy forms are what might be termed "central station" energy — that is, they can be generated at a single location on the mill site in a large plant where efficiencies of scale can be realized, and locally distributed to consuming sites within the plant. Production of the two energy forms is complementary and conducive to major energy savings, and can be sustained by burning any of a wide variety of fuels. Many plants currently operate adjacent boilers burning fossil fuel, bark and spent digester liquor, all producing steam at a common set of conditions. In some instances four or more differently-fueled boilers may be operated simultaneously.[60] The practice of ordering or refitting boilers with the capability of burning any of a choice of fuels — coal, oil or gas, for example — is also practiced.[61,62]

Special energy requirements

Although the bulk of the energy used in papermaking falls within the category just described, situations exist where individual unit processes have special fuel or energy requirements with more limited interchangeability. The major instances are lime calcining and air-impingement paper drying.

Lime calcining: This operation, an indispensable part of the Kraft recovery process, can be carried out either in a rotary kiln or fluid bed calciner. The preferred fuels for either unit are gas or heavy oil, although coal-fired kilns are used. Direct firing of powdered coal to the kiln interior is not satisfactory in this application, as explained in Chap. 5. The 1972 energy requirements for this operation over the entire U.S. were an estimated 80×10^{15} J out of a total of 2270×10^{15} (fig. 8).

Fired dryers: Air-impingement dryers are used in special product-drying applications where steam heated roll dryers are either inadequate if used alone or are not well-suited to the requirements. These include Yankee Dryer hoods, dryer section refitting to obtain added capacity in minimum space requirements, the rapid drying of liquid coatings, and market pulp drying. Here again the required heat is generated at the point of use, in current applications of the technology at least. Gas and oil are the favored fuels; electricity, although relatively expensive, is used on occasion. For low temperature applications (125°—175°C), steam coils have been used. The total amount of energy consumed by this application in the U.S. (1972) is estimated to be $\sim 20 \times 10^{15}$ (Fig. 8).

7. IMPACT OF ENVIRONMENTAL CONTROL MEASURES

Basis for Environmental Control Requirements

Airborne emission

The current authority for Federal environmental control derives from the Clean Air Act of 1970, which modified and superseded the Air Quality Act of 1967. It directed the Environmental Protection Agency (EPA) to develop and promulgate standards for air quality. The EPA then prepared two sets of standards, each covering six types of air pollutants. Primary Standards (to protect the public health), to be met by mid-1975, and Secondary Standards (to protect crops, livestock, property etc.) to be met within a reasonable time. EPA then required State Implementation Plans to be made available within nine months after the Standards were published. State plans include emission limits for specific industries, and compliance schedules.

Discharge to waterways

The Federal Water Pollution Control Act, as amended in 1972, directed the EPA to develop and promulgate Guidelines to form the basis for permissible discharges of pollutant materials to navigable waterways. EPA produced a series of Guidelines specific to various industries, including a Phase I Guideline for the PPBI promulgated in May 1974.[63] A further

Guideline is provisionally scheduled for public review in September 1975,[64] to cover portions of the industry not already considered in the earlier document. The Guidelines list upper bounds for effluent discharges from various types of mill, covering Biological Oxygen Demand, Total Suspended Solids, Color and pH. Limits are cited for one-day totals and 30-day average. Two graded sets of limits are presented: the first is based upon "Best Practicable Control Technology Currently Available" (BPCTCA) and must be fully implemented by 1977; the second is based upon "Best Available Technology Economically Achievable" (BATEA) and is to be implemented by 1983. The Act also sets a goal of Zero Pollutant Discharge by 1985.

In addition to carrying responsibility for criteria definition and standards development, the EPA is also directed to encourage technological development and enforce quality levels for discharged effluents.

Types, Sources and Treatment of Contaminant Emissions

The large power generating facilities associated with PPBI mills produce wastes similar to those of comparable utility power plants and are subject to the same environmental control restraints. Additionally the fabrication of paper products generates a set of characteristic effluents requiring further treatment before they can be discharged to the environment in compliance with current control standards.

Atmospheric emissions

There are four general categories of atmospheric emissions from paper mills: sulfur oxides, reduced sulfur compounds, fly ash and particulate sodium compounds. Those emissions arising from combustion of solid or liquid fuel are chiefly sulfur dioxide (SO_2) and fly ash; natural gas combustion does not release significant amounts of airborne contaminants.

Table 13 presents representative SO_2 and fly ash emissions to be anticipated from burning various fuels in a mill boiler.[65] The remaining important airborne effluents are particulate sodium compounds and reduced sulfur compounds including H_2S, mercaptans and organic sulfides, all of which are generated during one or more phases of chemical pulping. In at

Table 13. Sulfur dioxide and fly ash production from the combustion of various fuels in an auxiliary boiler

Fuel	kg per 1000 kg fuel	
	SO_2	Fly ash
Bark	1.0–1.5	10–20
Oil (2% S)	40	0.9–1.0
Coal (2% S)	40	60–80
Natural gas	Trace	Trace

least one case, objectionable reduced-sulfur compound emission has been observed from a plant using a nominally sulfur-free (i.e., Soda) pulping process.[66] The sulfur was introduced as a fuel impurity in the lime kiln and as a water supply contaminant.

Sulfur dioxide is also generated in or available for potential escape from certain mill processes other than fossil fuel burning, including lime calcining, sulfur burning, recovery boiler operation and various steps in sulfite and NSSC pulping. There are no significant airborne contaminants emitted during mechanical pulping, excluding the contribution from power plant operation.

Treatment techniques for atmospheric emissions

Noncondensible gases: The important contaminant noncondensible gases are the various sulfur-bearing gases mentioned above. The major source of SO_2 is the combustion of fossil fuels, spent liquor or sulfur, and wet scrubbing of the exhaust gases is the principal method of abatement.[67] Reduced sulfides and sulfhydrides (mercaptans) are emitted from atmospheric vents and leaks associated primarily with Kraft process equipment including digesters, blow tanks, brown stock washers and liquor evaporators. Where the volume of contaminant carrier gas is sufficiently small to be accommodated by the combustion air feed to the limekilns, the pollutants are commonly collected in a header and ducted to the kilns for incineration. The exiting SO_2 is then scrubbed and converted to an insoluble sulfide for land disposal. Black liquor oxidation, e.g., via aeration in packed towers, is used as a means of reducing or eliminating organic sulfide pickup by hot flue gas in direct-contact black liquor evaporators. Finally, careful control of liquor-to-air ratio in the recovery furnace is essential to avoid reduced-sulfur-compound emission in the flue gas.[68]

Particulate emissions: The combustion of spent digester liquor of all types is a strong source of particulate emission, and electrostatic precipitation is the most common abatement technique. Venturi scrubbers are used in some Kraft installations in connection with direct-contact liquor evaporation, as noted below. Other important particulate emitters include lime kilns and power boiler furnaces (see Table 13). In the direct-contact liquor evaporators often used in conjunction with Kraft recovery boilers, hot flue gas contacts films or fine droplet suspensions of spent liquor. The net effect is a strong particle-trapping action rather than particle generation,[69,70] with trapping efficiency reportedly ranging from 40—50% for cascade and cyclone types to 90% and above for venturi type units.[70,71] Particle trapping is practiced on Kraft recovery furnaces for economic as well as pollution-abatement reasons, since the fume is nearly 100% sodium sulfate. A collection efficiency of 90—95% is considered adequate for economic purposes.[72]

Solid and liquid effluents

Effluents in these categories arise from pulping, sheet manufacturing and power generating operations in all types of mills. Some of the more important effluents from an environmental standpoint are listed in Table 14. The solids discharged (e.g., to landfill) vary with fuel type, mill process and fuel forms. The quantity of waste water discharged from mills ranges from less than 4 to more than 400 m^3 per 1000 adkg;[73] while part of this variation reflects differing needs in the various mill processes, local practice appears to be the major influence.

Treatment techniques for discharge to waterways

Except for those streams that contain volatile odorous materials, paper mill effluents are treatable via conventional waste disposal

Table 14. Solid and liquid contaminant streams

Principal contaminants	Waste stream
Liquids	
Heat	Condenser cooling water
Reduced sulfides	Kraft digester blow condensate Black liquor evaporator condensate Brown stock wash water
BOD or color	Sulfite digester liquid Secondary fiber deinking solution Barker rinse water White water Bleached stock wash water Stripped blow condensate
Solids	
BOD, color, turbidity or silting effect	Fly ash Lime mud Bark fines Trash from secondary fiber pulpers Clarifier and settling pond sludge

techniques, including pH adjustment, agglomeration and settling of particulates, filtration, and air oxidation to reduce BOD to acceptable levels. Sludges and trash are variously incinerated, sent to landfill or burned for heat recovery, depending upon their composition and the most feasible local means of disposal. Liquid streams that are heavily contaminated with reduced sulfides, such as digester flow condensate and liquor evaporator condensate, may be stripped of volatile odorants in a stripper column.[74,75] The odorant stream is then burned in an incinerator or a lime kiln. The stripped waste may then be returned to the process or handled as aqueous waste in conventional treatment plants.

Energy Aspects of Environmental Control

Major controlling factors

The preceding chapters have documented the impressive quantities of energy, water and wood necessary to produce paper products, and the general nature of the waste streams emanating from mills of various types. The magnitude of the quantities involved means that highly efficient decontamination is required to meet modern environmental discharge requirements. Over the last several years, engineering-economic studies have been commissioned to estimate the energy implications of compliance with both the short-range (1975–1977) and longer-range (1983, 1985) environmental discharge standards prescribed under current legislation. Not surprisingly, a net expediture of energy was found necessary to attain compliance.

Air pollution: The major investigation to date on requirements for air pollution abatement within the PPBI[8] was produced for the National Air Pollution Control Administration in 1969. J. E. Robertson, a co-author of the study, summarized the impact of its findings on PPBI energy requirements.[9] He concluded that for Kraft mills alone, current abatement practice will require about 10% more electrical energy expended per ton of product than would be dictated by economy considerations alone. If the standards are later tied to developing technology, as is already the case with water standards, he estimates that overall increases on the order of 25% (i.e., 5.8 to 7×10^5 J/kg of product) might be required in some future cases. The major cost items are the collection systems for reduced sulfur compound-bearing gas streams, and the scrubber systems for power boiler stacks. The increased energy loads come chiefly from fan power requirements for gas transport and scrubbing.

A relatively small amount of thermal energy ($\sim$90,000 J/kg of product) is also expended for airborne pollution abatement. This is used to heat the large volume of wet, oxygen-deficient exhaust gases from the black liquor oxidation units. This stream, which may exceed 0.3 m^3 per kg of product, is ducted to the recovery boiler air intake to incinerate the odor-bearing components.

Energy and Environmental Analysis, Inc., in an energy conservation study of the PPBI[76] sponsored by the Federal Energy Administration, considered the industry-wide impact of the energy loads cited in Ref. 9 and concluded that an increase of 1–2% in overall energy consumption could be expected, allowing for the technical advances already in effect and the differing degree of impact on the various segments of the industry. In seeking to meet or anticipate air quality standards, plant designers presently make demands upon particle removal devices that approach the state of the art, and operating information on the energy requirements for sustained performance at 99+% removal efficiencies is limited. Hence it is possible that the estimated energy increment for air pollution in Ref. 76 is low. Even a doubling in impact over that estimated would still leave opportunity for a net improvement in PPBI energy conservation however.

Water pollution: Water treatment energy costs have been investigated by Arthur D. Little, Inc.[10] for the National Council on Air and Stream Improvement and by WAPORA, Inc.[11] for the EPA. A. D. Little prepared estimates of energy requirements for the PPBI to meet the 1977 waterborne effluent standards (Best Practicable Control Technology Currently Available, BPCTCA) and the 1985 EPA Goal of Zero Discharge. They concluded that the impact of meeting BPCTCA requirements would be small; ". . .less than 0.5% of the energy the industry now purchases."[77] Assuming, however, that the 1985 Zero Discharge goal becomes a requirement at some point, however, two additional estimates were made. The first estimate assumes that the overall size of the industry remains essentially the same, but that water use is reduced to current median levels — about 26% reduction in overall consumption — in which case the additional energy required would be $\sim 1.3 \times 10^{18}$ J, or about 86% of the current annual energy purchases. The second estimate assumes that water use declines to 50% of median levels — about 63% reduction overall — and predicts for this case an energy increment about half of the above level. These latter two estimates, converted to a per-unit weight basis, imply a mean energy requirement of ~ 2.4 and $\sim 1.2 \times 10^7$ J/kg (~ 6000 and ~ 3000 kWhr/ton) of product respectively, in addition to the energy already required for paper goods production.

WAPORA, Inc. did not estimate the energy requirement for Zero Discharge. For BPCTCA however, energy increments of $\sim$2.4–12 × 10^5 J/kg were estimated for various types of mill. The industry-wide mean increase, based upon these figures, amounts to an increment of $\sim$2.3% of energy consumption or $\sim$3.6% of energy purchases.

Summary

The major conclusions of the pollution control energy studies cited above are tabulated as follows:

Pollution category	Reference	Incremental increase forecast for PPBI energy consumption		
		Near-term	1983	Zero discharge
Airborne	9	1%	2.5%	NA
	76	1–2%	NA	NA
Waterborne	77	0.5%	NA	+40–70%
	11	2.3%	?	NA

In summary, the estimated incremental requirements for energy consumption for near-term airborne and waterborne effluent standards are moderate enough so that attainable energy-conservation levels (i.e., on the order of 10–15%) can still effect a net energy savings overall. The WAPORA estimates for 1983 standards likewise do not preclude a net energy savings; however, the apparent near-doubling of energy requirements to achieve zero discharge would be highly disruptive. Not only would such an increase definitely obviate any net savings in energy consumption, but it would also increase significantly the power budget of the entire industrial sector in several regions of the country (see Table 12).

8. ENERGY ASPECTS OF FUTURE STRATEGIES

In the PPBI, as in other large, internally-competitive process industries, research and development is carried out at the corporate level to maximize the profitability of existing processes and to develop new processes that offer improved economic return. Additionally, certain areas of research, statistical data gathering and process analysis, including energy-related subjects, are cooperatively sponsored by the industry through the Institute for Paper Chemistry, American Paper Institute and the National Council for Air and Stream Improvement.

In the past, process improvement or development has not always resulted in lowered energy consumption per unit of production. In addition to its decreasing availability however, energy is also becoming an increasingly important economic factor. In 1973, energy costs for five major paper companies[70] averaged 7–8% of total operating costs. Since that time, of course, prices have continued to increase, and expensive fuel substitution measures have become necessary for many of the industry's mills. Thus the growing economic importance of energy in the PPBI requires that energy conservation be critically evaluated in current and future manufacturing policy.

As a result of continued and diligent research, alternate pulping and sheetmaking techniques have been develped that promise significant advances in conservation of feed materials and energy. While some companies have announced plans to implement certain of these in new plants,[79] commissioning of new capacity will remain gradual in spite of the apparent industry trend toward larger plant sizes,[80] in the interests of production efficiency. At the same time, new equipment costs are rising. The capital cost of a Kraft plant, for example, reached ∿$0.25 million per ton/day (38 kg/hr) of capacity[81] in 1974, approximately double what it had cost in 1965. While prices for paper industry products are increasing also, the limited capacity of the industry for capital spending[82] and the heavy requirements for environmental control equipment will tend to favor process improvement and equipment upgrading, in preference to new plants. Exceptions to this trend will occur where environmental restrictions together with local factors such as site space, cooling water, transportation requirements, etc., dictate a major process revision.[83] (Note: Subsequent to the drafting of this report, an analysis by the Council on Wage and Price Stability[84] concludes that by virtue of price rises anticipated or already concluded in the PPBI, plus a record of successful stock issues and borrowings, new plants will continue to be constructed where market demands warrant.)

This chapter selects for review some current areas of modification or upgrading in the PPBI that can affect energy conservation now or under projected future operating requirements. In most cases, their relative importance can only be qualitatively assessed.

Resource-Related Activities

Higher-yield chemical pulping processes

Much has been said regarding the PPBI capability to supply a high fraction of its energy requirement from feed and process wastes, as opposed to purchased fuels. In the absence of more productive uses for these materials, energy generation via burning is indeed a desirable means of disposal, although it is not necessarily profitable. In those sulfite processes where liquor combustion does not regenerate pulping chemicals for example, the associated capital costs can make energy recovery uneconomic even at 1975 prices,[85] although the energy recovery does tend to offset the cost of pollution abatement that discharge of the unburned liquor would otherwise entail.

As higher-yield processes become feasible, the availability of combustible wastes for energy generation decreases. However, the processes can be economically attractive since the raw wood being conserved is more costly than the energy component of the finished product. A comparison of typical energy-recovery capabilities of several chemical pulping processes was presented in Table 8. The lower-yield processes, i.e., in the range around 50%, show a substantial net energy recovery from liquor burning; the relatively high-yield NSSC process provides essentially zero net energy, but pulping chemicals are recovered in the option cited. In the case of NSSC and other semichemical processes, the reduced lignin removal resulting from the milder cook necessitates additional mechanical energy from refiners to complete the defibrating operation. Newer processes such as polysulfide and oxygen pulping, which attain high yields by inhibiting the solubility of holocellulose and selectively dissolving lignin, apparently do not require extra refining. Decreased energy recovery via spent liquor combustion is, however, a generic consequence of higher pulping yield.

The loss of waste-stream energy due to higher-yield pulping is partially offset by the reduction of digester and evaporator heating loads, and by the lowered energy requirement for trapping and disposal of the airborne and liquid effluents generated during digestion, evaporation and burning of spent liquor. Except, perhaps, with the high energy expenditures predicted for achieving zero pollutant discharge, adoption of high-yield chemical pulping processes does not result in net energy conservation because the quantity of recoverable energy per unit of product falls off faster than the evaporator load, as the yield rises. A further side effect is that the recovery energy deficit must be made up by purchased energy.

Raw material utilization

Alternate new fiber sources: As prime virgin fiber becomes in short supply, alternate sources of pulpable material have been investigated by the PPBI. One of these is whole tree chipping, in which tops and branches trimmed from pulpwood during logging operations are chipped at the forest site in mobile units. This material is then shipped to mills where it is blended with virgin wood chips and pulped.[86] A possible intermediate step considered is mechanical classification to remove a bark-rich fraction for burning, with the wood-rich remainder being blended into the pulper feed. A second source receiving increasing exploitation is sawdust and wood waste from lumber and veneer mills.[87] In the future, other agricultural products such as kenaf, cornstalks, wheat straw, bagasse, etc., may come into more common use.[88] The economic importance of these practices to the PPBI is large, in terms of lower feed costs and reduced labor and woodyard requirements; however, their energy conservation potential is probably minor. The actual pulping of these feeds is no different from that of ordinary wood feeds from an energy standpoint, except for the slight lowering of yield and its effects upon the recovery process. Any significant differences would have to occur in the wood preparation steps, which however, account for less than 1% of the industry's annual energy use (Fig. 8).

Alternate fuel materials: The large body of experience with the PPBI in successful use of process waste fuels including liquor concentrates, bark and wood wastes has prompted the investigation of other potential sources from outside the industry. Fractionated municipal wastes have been successfully burned in trial runs[89] in a paper mill boiler in Oregon, and at least one major paper company is actively investigating the use of municipal wastes from urban centers in the northeastern U.S.[90] Wood wastes from lumber mills are also burned for fuel. Exploitation of these sources represents energy from material not otherwise contributing to the national energy requirement. Since this contribution would otherwise need to be supplied from conventional resources, it constitutes conservation of the conventional purchased energy supply. Statistics are not yet available on the extent of use of such materials as energy sources; potentially however, waste materials could be a major PPBI fuel source if they can be economically recovered and transported. While fuel utilization efficiencies and particulate discharges are less favorable from waste combustion than from conventional fuel use, sulfur content is generally lower. Pollution control energy requirements should be comparable to those of bark-burning boilers.

Recycled fiber feed: Observers of the PPBI have pointed out[91,92] that although paper or board manufacture from recycled fiber consumes less energy overall than equivalent production from virgin fiber, the average consumption of purchased energy tends to be higher, per unit of product. This comes about because of the energy recoverable from chemical pulping and wood preparation wastes during the processing of virgin fiber. While this statement is valid when comparing recycled fiber processing with Kraft processing, for example, it does not hold universally. As pointed out earlier in this chapter, the net energy recoverable from spent chemical pulping liquor combustion varies inversely with the process yield, and approaches zero for NSSC under certain conditions at a yield of approximately 75%. Since the overall energy required to produce paper or board from secondary fiber is less than from virgin pulp via NSSC, it follows that the purchased energy for the former must also be less than for the latter. Mechanical pulping likewise relies on purchased energy, except from bark burning; hence recycled fiber should also enjoy an energy advantage over mechanically pulped fiber. Mechanical and semichemical pulps amounted to 19% of the virgin pulp produced in the U.S. in 1972 by all methods.[93]

Environmentally-Related Actions

Chemical pulping

A pulping approach that has occupied much research effort in the PPBI is Non-Sulfur Pulping. Properly this includes oxygen pulping, mentioned briefly above; other approaches delignify by hot digestion with an organic solvent, such as an amine, alcohol[94] or ketone.[95] By eliminating sulfur as a pulping chemical, these simplify the environmental control mechanisms required; however, oxygen pulping, in one process at least, is a voracious consumer of electricity.[96] Other energy-related advantages claimed by organic solvent processes include simplified recovery of pulping reagents via distillation, preferential extraction of lignins and a waste lignin stream that is essentially 100% combustible. A cursory consideration of these processes suggests that they can provide a net surplus of energy from the recovery process; they were not intensively evaluated in this survey however. The organic processes have not as yet found commercial acceptance.

Biological pulping

This process category has received less attention than Non-Sulfur Pulping, to date. For example, over 1000 species of wood-attacking fungi are known, but most of these have not yet been screened for pulping properties.[97] Genetic researchers in Sweden, however, have isolated a strain of fungus that preferentially digests lignins in wood while leaving the cellulose content intact.[98] Other possibilities for biopulping agents would include bacteria and yeasts.

Once such factors as adequate speed, process reproducibility, control conditions and the physical properties of the product have been standardized, biopulping methods might prove to require significantly less energy than conventional pulping. Except for initial warming, this type of process might not require heat addition; in fact, low-grade heat could conceivably be a by-product of such a reaction. Any energy savings estimate at this point is purely speculative, but in principle, part or all of the digester heat load — some 2–5 × 10^6 J/adkg — might be avoided.

Thermomechanical pulping

The use of steam in conjunction with mechanical refining significantly reduces the mechanical energy required to produce pulp. Although the overall energies expended are roughly comparable for mechanical and thermomechanical pulping (see Table 6), the electric drive requirements for the latter are thus lower. Recent refinements are also improving the heat recovery from the thermomechanical process.[99] Since the process generates no combustible waste streams, aside from bark chips and sawdust produced during wood preparation, most of its energy must come from purchased fuel. The process was first used commercially in Europe and is now finding a substantial foothold in North America.[100,101] The absence of digestion and evaporation steps is beneficial from a pollution-control standpoint; in comparison with other virgin pulp processes, the effluents are low in contaminants[102] and should therefore require relatively less energy for meeting advanced environmental control requirements.

Improvements in Process Technique

Cited throughout this report are examples of technical advances that have energy-conservation potential for at least some areas of the PPBI. Not all of these are in common use at present, but many if not most of them are being evaluated and implemented by the more progressive companies in the industry. A real and important margin of savings is achievable simply by general tightening-up; the industry acknowledged this in mid-1973[103] and cited a 7% reduction as a reasonable goal for most mills. Savings projected for the overall industry are 15% by 1978, but individual mills may in some instances achieve much more. One company is reportedly able to increase the capacity of a Kraft mill by ∿25% without a corresponding powerhouse expansion,[104] because of onsite energy made available through conservation measures. Other companies are finding that further pursuit of supposedly well-worn conservation strategies can still offer substantial energy recovery potential in specific instances. Several final examples of these are summarized below.

Thermodynamic efficiency

Although recovery boiler conditions are commonly held to 6.2–8.3 × 10^3 kPa, 482°C (900–1200 psi, 900°F) steam as a practical limit, one major company burning oxidized Kraft black liquor generates steam at 9.5 × 10^3 kPa, 496°C (1375 psi, 925°F), enabling the boiler output to match that of existing fossil-fuel equipment and to take advantage of presently-installed large turbogenerator units without modification.[105]

Moisture control

Pressing: Depending upon the type of sheet being produced, modern roll pressing conditions commonly range[106] from about 140 kg per lineal centimeter for paper grades, to around 215 kg/lin cm for the heavier board grades, with the limit governed by the ability to press without crushing the fibers in the sheet. At 214 kg/lin cm, exit moisture conditions for 42-lb linerboard have been measured[107] at 57–58% water by weight. Pressing technology continues to improve however. One U.S. mill recently reported[108] adding a third press with 286 kg/lin cm capacity into a linerboard machine, thereby adding 15% to existing production by increasing the drying capacity. This represents approximately 150 kg additional moisture per 1000 adkg removed mechanically rather than by heating, an energy savings of $\sim$150 × (2800 kJ/kg) 0.4 × 10^6 J/kg (360,000 Btu/adt), based upon the new production rate.

Sheet forming: Increasing attention is being given to the mechanics of forming the initial mat of fibers that are pressed and dried to produce the final sheet of product. Conventional Fourdrinier and cylinder formers produce a mat with different properties on the two sides, and the amount of moisture that can be extracted from the sheet at the wet end is affected by the heterogeneous properties of the sheet plus the one-sided drainage pattern. New designs of forming equipment,[55,106] by delivering a more homogeneous mat to the press section, allow more efficient mechanical dewatering. Water contents as low as 45% are believed attainable,[109] which would enable thermal drying energy savings up to ∿50% of present requirements. Reportedly a newsprint machine is being equipped with a former of this type on a trial basis.

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APPENDICES

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Appendix A

ABBREVIATIONS RELATED TO THE PPBI

adkg	Air dry kilogram (weight of material with 10% moisture content)
adp	Air dry pulp (nominal 10% moisture)
adt	Air dry ton (weight of material with 10% moisture content)
API	American Paper Institute
BATEA	Best available technology economically achievable
BPCTCA	Best practicable control technology currently available
cd	Cord (wood volume measurement)
EPA	Environmental Protection Agency
ERDA	Energy Research and Development Agency
hpd/t	Horsepower-days per ton
MG	Machine glaze
NCASI	National Council of the Paper Industry on Air and Stream Improvement
NSSC	Neutral Sulfite Semichemical
odkg	Oven dry kilogram
odp	Oven dry pulp (0% moisture)
odt	Oven dry ton
pli	Pounds (force) per lineal inch
PPBI	Pulp, Paper and Board Industries
SIC	Standard Industrial Classification
tpd	Tons per day
ZPD	Zero Pollution Discharge

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Appendix B

CENSUS REGIONS OF THE U.S.

ORNL/DWG/FED-7712

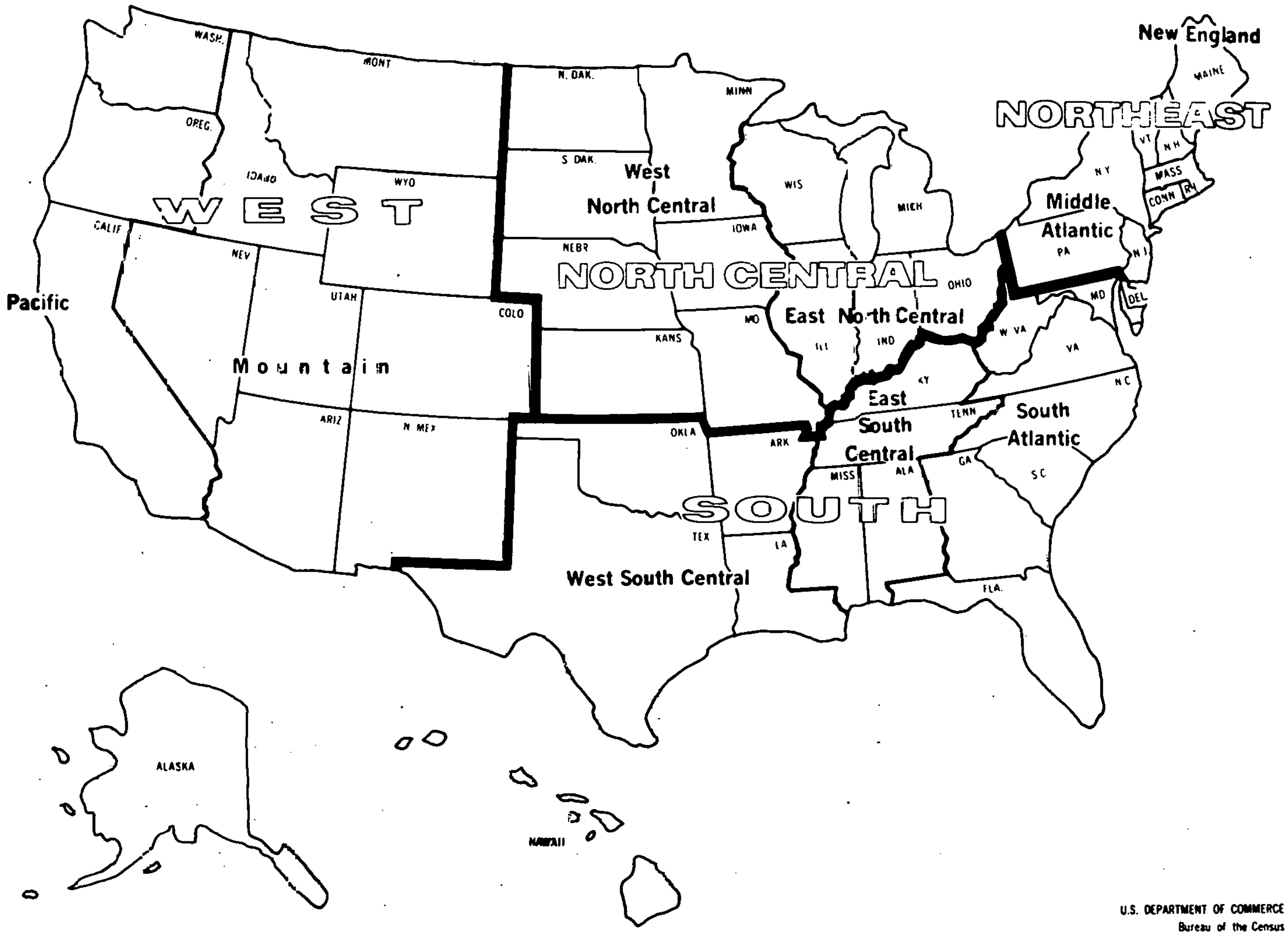

Fig. B1. Census regions of the United States.

Appendix C

GLOSSARY OF TERMS

Air dry	A defining condition for the product from a pulp, paper or board mill, denoting a moisture content of 10% by weight.
Beating	A mechanical shearing and abrading process by which pulp fibers are split or frayed, to improve the strength and formability of the subsequent sheet.
Broke	Partially or completely manufactured sheet that does not leave the machine room as salable paper or board. The category includes the scrap from such finishing operations as rewinding, trimming and cutting into sheets. Broke is commonly recycled through the web-forming process by mechanical dispersion (repulping) and blending with the stock en route to the paper or board machine.
Causticizing	The treating of green liquor with burned lime or other alkaline material during the preparation of fresh digester liquor.
Consistency	The weight percent of solids contained in a water suspension of wood chips or fiber used for pulp, paper or board manufacture.
Cord	A volume of stacked logs measuring 4 ft × 4 ft × 8 ft (1.2 × 1.2 × 2.4 m, approximately).
Cylinder machine	A papermaking machine in which a rotating cylinder with a porous curved surface is immersed in a liquid suspension of fibers. Liquid penetrates the curved surface and is drained away, leaving a mat of fiber deposited on the outside of the cylinder. The mat is detached and conveyed to a roll press and dryer (see Fig. 7).
Decker	A rotary filter resembling the mat-forming portion of a cylinder machine, used to increase the consistency of pulp suspensions.
Digester	A vessel in which wood chips, etc., are cooked with chemical solutions to produce pulp.
Dissolving pulp	A very pure grade of cellulose pulp produced as feedstock for the rayon industry.
Dry end	The pressing and evaporative drying portion of a paper machine.
Fine paper	Grades of paper containing less than 8% filler (nonfiber solids) by weight.

Fourdrinier machine	A papermaking machine in which a thin sheetlike stream of fiber suspension is directed onto a porous, horizontal moving belt, forming a mat. After water is removed from the mat by gravity and suction, the sheet passes over rollers and into press and dryer sections (see Fig. 7, text).
Freeness	A measure of the rate at which water will drain from a pulp suspension; hence a determinant of the sheet-forming and drying characteristics of the pulp.
Furnish	The mixture of pulp(s), chemicals and liquid making up the feed to a paper machine.
Hot	A hammer mill used to shred bark and waste wood, usually for burning.
Integrated mill	A mill that produces its own pulp for subsequent local fabrication into paper or board products.
Jordan	A machine consisting of a cone-shaped plug with a patterned surface rotating with an adjustable clearance inside a conical shell. When pulp is passed through the clearance, the fibers undergo chopping and beating.
Lignin	The organic, noncarbohydrate fraction of wood that stiffens the fibers and binds them together.
Liquor	<u>Black liquor</u>: The spent reagent solution from the pulp digestion step in the Kraft Process. <u>Green liquor</u>: The solution of dissolved smelt from the Kraft recovery furnace. <u>Red liquor</u>: The spent reagent solution from the pulp digestion step in the Sulfite Process. <u>White liquor</u>: The fresh Kraft cooking liquor formed by causticising and clarifying Green Liquor.
Machine glaze	The shiny finish produced on that surface of paper held in contact with a Yankee or MG Dryer roll until it is dry enough to detach spontaneously.
Market pulp	Pulp produced for sale.
Oven dry or bone dry	Condition describing a paper or board product containing zero moisture.
Pulp	A manufactured fibrous cellulosic material used in the production of paper, board and cellulose derivatives such as synthetic yarns and films. Pulp is made chiefly from wood but also from other vegetable materials.
Pulping or pulp-making	The production of pulp from vegetable raw materials by mechanical and/or chemical means.
Recovery	The processing of spent digester liquor to regenerate pulping chemicals and exploit the heating value or other valuable properties of the material.

Refiner	A machine containing one or more metal disks with a patterned surface that rotate within a housing, sweeping past a stationary or differentially moving disk with a close clearance through which a fiber suspension is pumped. (See Refining, below.)
Refining	Separation of wood or other vegetable raw material into individual fibers by thermal softening, mechanical shear and abrasion, carried out in a refiner.
Smelt	The mixture of molten inorganic material, chiefly sulfides and carbonates, obtained when concentrated spent digester liquor is burned in a recovery furnace.
Stock	A liquid suspension of pulp, with or without added chemicals.
Wet end	The mat-forming portion of a paper or board machine, upstream of the press section.
Wet laps	Sheets of moist pulp containing 30–45% fiber solids, prepared by forming a pulp mat on a cylinder and pressing it between rolls.
White water	The solution, containing papermaking chemicals and fiber fines, that drains from the fiber mat on a paper machine as pulp is converted into paper or board.
Wire	The moving screen or fabric belt on which the mat is formed in a Fourdrinier machine.
Wood conversion	Preparation of logs for the pulping process by removal of bark, cutting to size, and/or chipping.

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Appendix D

TABLE OF UNIT CONVERSION FACTORS

To convert from	To	Multiply by
British thermal units (Btu)	Joules (J)	1.055×10^3
Btu/ton	J/kg	1.161
Cords	m^3	3.74
Feet per minute (fpm)	m/sec	5.08×10^{-3}
Gallons per minute (gpm)	liter/sec	63.1×10^{-3}
Horsepower-days (hpd)	Joules (J)	64.4×10^6
Horsepower-days/ton (hpd/t)	J/1000 kg	70.9×10^6
Gallons (gal)	m^3	264
Cubic feet (ft^3)	m^3	35.3
Pounds/linear inch (pli)	kg/lin cm	17.9×10^{-3}
Pounds/in.^{2}	Pascals (Pa)	6.90×10^3
Tons (t)	kg	909

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