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A Review of Tribological Sinks in Six Major Industries

September 1985

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

PNL-5535

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PNL-5535
UC-95

A REVIEW OF TRIBOLOGICAL SINKS IN SIX MAJOR INDUSTRIES

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September 1985

Prepared for
Energy Conversion and Utilization
Technologies Division
Office of Energy Systems Research
Conservation and Renewable Energy
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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EXECUTIVE SUMMARY OF TRIBOLOGY SERIES

Experts estimate that in 1978 over four quadrillion Btu of energy were lost in the United States because of simple friction and wear--enough energy to supply New York City for an entire year. This translates to a $20 billion loss, based on oil prices of about $30 per barrel.[a] Because of the enormity of this energy loss, the Energy Conversion and Utilization Technologies (ECUT) Program in the U.S. Department of Energy (DOE) initiated a program in 1983 to study tribology--the science of friction and wear--to learn more about the causes of these energy losses (or tribological "sinks") and how to reduce them.

The ECUT Program itself was started in 1980 to encourage research to improve energy conversion and utilization efficiency. The enormous energy loss in tribological sinks has been targeted by the ECUT program as having significant potential for energy conservation. One goal of the ECUT Tribology Program is to reduce these energy losses by developing improved lubricants and more durable materials.

To support initial Tribology Program planning, ECUT conducted six surveys to gather three types of information about the current tribology problem in the U.S.:

1. The identification of typical industrial sinks
2. A survey of current U.S. Government tribology projects
3. The identification of tribology R&D needs based on industry perceptions.

The six ECUT-sponsored surveys are listed in Table ES.1. Each survey is being published as a separate volume with its own summary. This executive summary, which also appears in each of the six volumes, presents an overview of results from the six surveys and their implications for energy conservation. The results of these six surveys and their implications for energy conservation are presented in this summary. These results will be used to support further research planning for the ECUT Tribology Program.

TABLE ES.1. ECUT Surveys Reviewed in this Summary

1. A Review of Tribological Sinks in Six Major Industries. Imhoff, et al. PNL-5535, Pacific Northwest Laboratory, Richland, Washington.
2. Reduction in Tribological Energy Losses in the Transportation and Electric Utilities Sectors. Pinkus and Wilcock, Mechanical Technology Incorporated. PNL-5536, Pacific Northwest Laboratory, Richland, Washington.
3. Identification of Tribological Research and Development Needs for Lubrication of Advanced Heat Engines. Fehrenbacher, Technology Assessment and Transfer, Incorporated. PNL-5537, Pacific Northwest Laboratory, Richland, Washington.
4. Energy Conservation Potential of Surface Modification Technologies. Le Khac, DHR, Inc. PNL-5538, Pacific Northwest Laboratory, Richland, Washington.
5. Assessment of Government Tribology Programs. Peterson, Wear Sciences Corporation. PNL-5539, Pacific Northwest Laboratory, Richland, Washington.
6. Assessment of Industrial Attitudes Toward Generic Research Needs in Tribology. Sibley and Zlotnick, Tribology Consultants Incorporated. PNL-5540, Pacific Northwest Laboratory, Richland, Washington.

IDENTIFYING TYPICAL TRIBOLOGICAL SINKS AND MECHANISMS

ECUT's first step in collecting information about tribology was to identify significant tribological sinks and mechanisms. This information was needed to focus research on key technological problems. Because the industry, transportation, and utilities sectors account for most of the

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[a] Calculations in this summary are based on a $30 figure.

energy consumed in the U.S., ECUT concentrated first on the tribological energy sinks and mechanisms found in these three sectors. The report by Imhoff, et al., describes the most important tribological sinks typically found in industry, and the report by Pinkus and Wilcock describes tribological energy losses in the transportation and utilities sectors. Two specific studies assessed tribological problems in the metalworking industry and in the advanced diesel engine.

To identify areas in which tribology has a significant impact, the authors examined the energy consumed, the fuels used, and the primary products and processes found in the transportation, industrial, and utilities sectors. Once energy losses were identified, their magnitude was estimated. The estimates include both friction losses (direct losses) and material wear losses (indirect losses). The authors also estimated the energy savings potential in each sector and recommended some specific R&D programs to help achieve these energy savings.

<u>The Industrial Sector</u>

Tribological energy losses are pervasive throughout industry. Because reviewing all industries and industrial processes in detail would be impossible, the Imhoff, et al. survey, instead chose six representative industries (Mining, Agriculture, Primary Metals, Chemicals/Refining, Pulp and Paper, and Food Processing) that appeared to have the most significant tribological sinks and energy losses. These industries were selected because of their 1) major, nonthermal energy streams (such as machine drives); 2) high material wear rates and friction; 3) significant material transportation/alteration processes; and 4) total energy use.

The study identified important tribological sinks in each selected industry, based on both friction and material wear energy losses and on the tribological mechanisms and materials involved. Figure ES.1 and Table ES.2 show the key results for each of the six industries.

The first conclusion from this study confirmed earlier claims that losses from material wear are greater than energy losses from friction; the wear losses in five of the industries were found to be more than twice as large as the friction losses.(a) The study also concluded that reducing material wear rates to improve equipment life

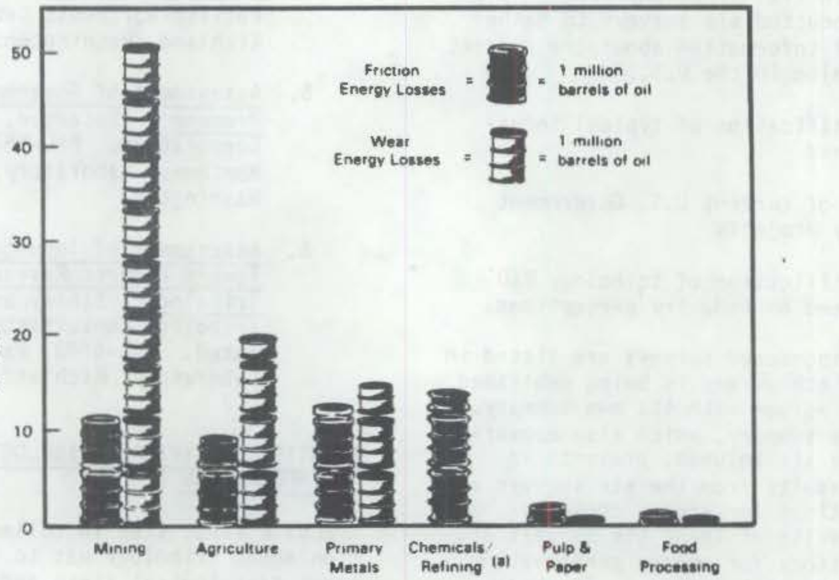

FIGURE ES.1. Annual Friction and Wear Losses in Surveyed Industries

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(a) These five industries had estimates of both friction and material wear losses; the sixth, Chemicals/Refining, did not have estimates of wear losses.

TABLE ES.2. Primary Mechanisms in Friction Energy Losses and Principal Materials Involved in Wear Energy Losses

Industry	Mechanisms	Materials
Mining	3-body Abrasion Friction	Iron, Steel & alloys, Aluminum, Rubber
Agriculture	3-body Abrasion Friction	Steel, Rubber, Lubricants
Primary Metals	Hot Rolling Inefficiencies	Steel & alloys
Chemicals/Refining	Friction, Erosion Abrasion	Not studied
Pulp & Paper	Friction	Steel & alloys, Chromium-Molybdenum alloys Grinding stones
Food Processing	Erosion, Abrasion	Steel & alloys

and reliability would also significantly improve industrial productivity. The industry representatives interviewed strongly emphasized the positive impacts that tribological research could have on operational productivity.

Tribology in the Metalworking Industry

In addition to the general review of tribological sinks in industry, ECUT sponsored a more specific study of tribology in the metalworking industry by Le Khac at DHR, Inc. The study estimated the energy conservation potential of using advanced surface modification technologies in this industry. These surface modification technologies are thermal, chemical, or mechanical treatments that reduce friction and wear at a material's surface without changing its bulk properties. The advanced surface modification technologies considered were ion implantation, laser surface hardening, electron beam surface hardening, and wear-resistant coating deposition. The author studied 70 percent of the metal-forming and metal-cutting machines used in the United States (except those associated with primary metals processing), identified tribological mechanisms, and estimated friction and wear energy losses. Potential energy savings from using surface-modified tools were also estimated.

The metal-forming machines studied were punches, presses and forges, and the metal-cutting machines studied were turning, drilling, milling, broaching, and sawing machines. Models were developed to estimate friction and wear energy losses and potential savings. The friction losses were estimated by adding friction losses at the motor drive system and at the tool-workpiece interface. Estimates of energy consumption were based on standard operating conditions (known friction coefficients, total working time, etc.) The indirect losses from wear were estimated based on the replacement costs of all metalworking tools used and discarded in one year.

Based on actual experimental or production data, the author estimated that the friction losses in all U.S. metalworking machines amount to 20.2×10^{12} Btu per year, or \$104.5 million. Of this energy loss, 1.8×10^{12} Btu per year, or 9%, could be saved using surface modification technologies to reduce friction. The wear loss was estimated to be 7.7×10^{12} Btu per year.(a) Possible energy savings using surface modification technologies to reduce wear could conserve 5.5×10^{12} Btu per year, or 71%.

Finally, the author estimated that tribological energy losses in all U.S. metalworking machines total 27.9×10^{12} Btu, equivalent to 4.8 million barrels of oil or \$144 million annually. More than a quarter of this loss could be saved using surface modification technologies to reduce friction and wear. These results are shown in Figure ES.2.

(a) Using 19.2 million Btu per ton as the embodied energy in steels.

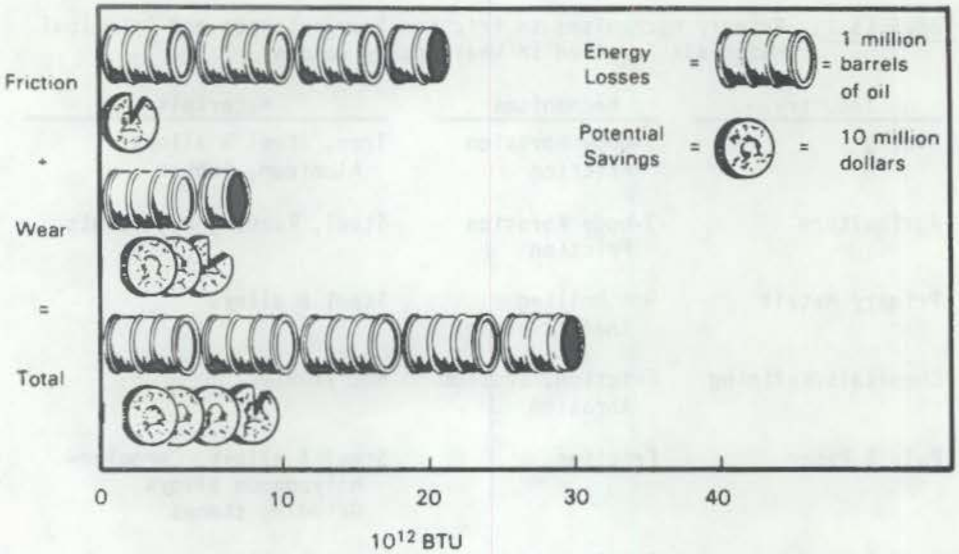

FIGURE ES.2. Annual Friction and Wear Energy Losses in the Metalworking Industry, and Potential Savings from Surface Modification Technologies

The Transportation Sector

The transportation sector is important both in terms of its energy consumption (26% of total U.S. annual energy consumption, or 19×10^{15} Btu, equivalent to $98 billion), and because of the high level of tribological losses. The Pinkus and Wilcock study primarily focused on the highway fleets (passenger cars, buses and trucks), which consume 77% of the total energy used in the transportation sector. The survey primarily addressed the conventional Otto cycle engine. However, other concepts were also considered, such as the adiabatic diesel, the gas turbine, and the Stirling engine; in addition, the Fehrenbacher report evaluated tribological activity in advanced diesel engines.

Figure ES.3 shows the principal automotive tribological sinks and the estimated energy savings. The principal automotive energy sinks are caused by the mechanical inefficiency of the engines and drive trains; most of the energy losses are due to friction.

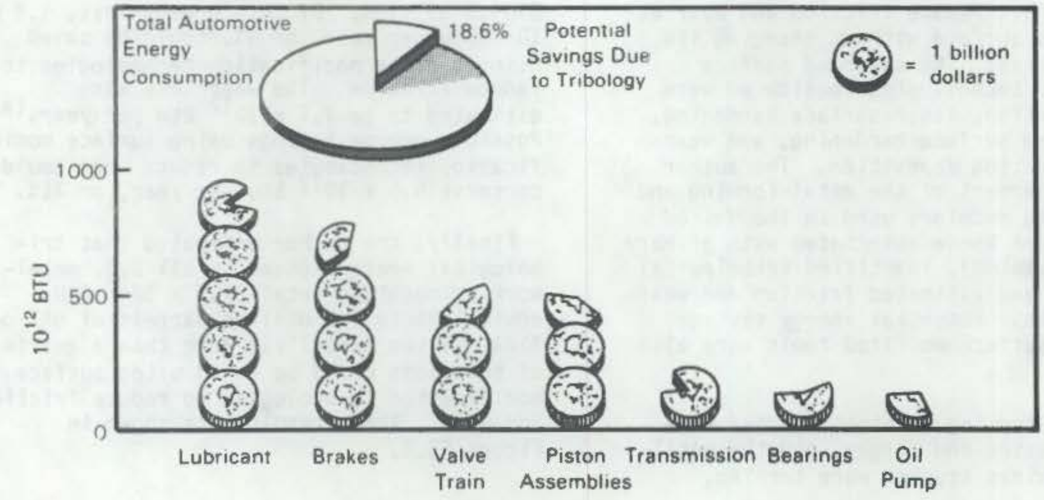

FIGURE ES.3. Potential Energy Savings Per Year for the Conventional Engine (Based on highway fleet size in 1976)

The survey by Pinkus and Wilcock revealed several tribological areas of particular concern for conventional engines, such as the piston ring assembly and the long-range effect of low-viscosity oil on engine wear. As shown in Figure ES.3, tribological improvements could save 18.6% of the total annual energy consumed by automobiles, or $14.3 billion.

Research on conventional engines often applies to unconventional engines as well. Except for the adiabatic diesel, the energy savings possible from tribological improvements to unconventional engines are less significant than those of the conventional Otto cycle engine. The major problems in unconventional engines are related to high-temperature tribological problems. Introducing adiabatic and minimum friction engines into the bus and truck fleets of the U.S. could save up to 2.9% of total U.S. energy consumption.

This survey also revealed the difficulties with devising adequate performance tests to quantify energy losses and evaluate new designs and products. Laboratory tests that accurately reflect real-world conditions are badly needed. The ability to test entire systems is vital, since tribological energy losses are often caused by complex interactions between all the components of a system.

Advanced Diesel Engines

Because of the great potential for energy savings, the ECUT study by Fehrenbacher examined the lubrication of advanced diesel engines in detail. The efficiency of these engines could be improved by about 10%; however, higher operating temperatures (1000°F and higher in the upper cylinder area) are required to reach this greater efficiency. As a result, the primary development challenge for these engines concerns friction, wear, and lubrication of the upper cylinder region. In fact, tribological advancements in these areas are essential if diesel engine performance and durability goals are to be reached. This study assessed these vital tribological concerns in both current and future technologies and recommended tribology R&D topics for further advanced engine development.

Both the mechanical design of the upper cylinder and the chemical effects of lubricants and fuel determine the friction and wear characteristics of the upper cylinder region. These two factors interact in a complex and sometimes synergistic manner. The geometry of the piston, piston ring, and cylinder directly affect the rate and nature of deposit formation, oil consumption, and friction. Efforts have been made to optimize the upper cylinder geometry in current diesel engine technology; this will also be a critical area in future developments. However, problems with upper cylinder deposits, bore polishing, and oil consumption still exist. This study indicates that these problems are caused by the chemical interactions between upper cylinder materials, oil degradation products, and fuel combustion by-products. Therefore, lubricants, oil degradation rates, and mechanisms will continue to be important research areas.

Although a great deal of research has been conducted on liquid lubricants, in most cases the lubricants have been tested without considering the tribological factors specific to the upper cylinder. Since the lubricants interact with the materials and environment of the upper cylinder, they must be developed and tested under similar conditions.

The ECUT study also pointed out that future advanced engine concepts will require ceramic upper cylinder materials able to withstand the higher operating temperatures. New lubricants will have to be developed, and solid lubricants are likely to play a major role. A major research effort will be needed in this area; again, the research must be conducted on a total system basis to be most effective.

The study concluded that many problems with current diesel engines will continue to exist in advanced diesel engines. Tribological problems in the upper cylinder region will be most critical in terms of engine performance and wear. Lubricant R&D is still a major research area in current technology, but total system materials and design considerations should be emphasized. Advanced diesel concepts will require new design approaches, but the tribology of the upper cylinder region will still be critical and may even be the limiting factor in achieving higher engine efficiencies. Extensive materials R&D will be required for advanced designs as well, especially in ceramics, ceramic composites and solid lubricants.

The Utilities Sector

The utilities sector was also reviewed for significant tribology sinks. This sector accounts for roughly 28% of total U.S. energy consumption. ECUT's review revealed that tribological improvements in efficiency and reliability could save 2.3% of the total energy annually consumed by utilities, or about $2.5 billion. As in the transportation sector, efficiency is a major factor.

However, reliability (especially in generating units) is just as important for energy conservation.

The data used in these studies were primarily for the utilities' power plants. The average power plant operates at an efficiency (output energy/input energy) between 30 and 40%. Mechanical losses account for 17-26% of the total energy used. Reliability problems that lead to generator shutdown require using standby equipment, which generally has less efficient fuel consumption. This causes losses both in terms of fuel economy, and revenue and labor costs. Tribological problems are estimated to cause as much as 5% of the reliability problems that require shutdown. Furthermore, tribology-caused shutdowns increase with the size of the power generating unit.

The ECUT survey found several tribological areas with significant energy savings potential, including gas path leakage, seals, and bearings on both the main turbine generator and on the various accessories. Different forms of bearing and lubricant problems (contaminated oils, pump problems, etc.) and vibrations are the leading causes of the plant shutdowns.

Figure ES.4 summarizes potential savings from improving tribological problems in the electric utilities. For accessories, the major concern is sealing problems with feedwater pumps. Friction and wear are implicated in much of the seal and bearing losses. The major problems identified in this study will require research on lubrication theory and advanced materials and coatings developments.

CURRENT U.S. GOVERNMENT PROGRAMS

The second part of ECUT's information collecting efforts involved identifying tribology R&D currently being sponsored or conducted by the U.S. Government. This information was needed to avoid duplicating existing research and to locate those areas that need more research support. The Peterson study identified 215 current projects sponsored by 21 different government organizations. The study classified these projects by subject, objective, energy conservation relevance, type of research, phenomena and variables being investigated, materials, and applications. The principal government sponsors include the Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), National Science Foundation (NSF), National Bureau of Standards (NBS), and DOE.

The study located these tribology projects initially by using information from literature searches. Data bases used included the Smithsonian Science Information Exchange, the Defense Technical Information Center's Research and Technology Work Unit Information System, and the Materials Science Abstracts of the National Technical Information Service (NTIS). The study located a

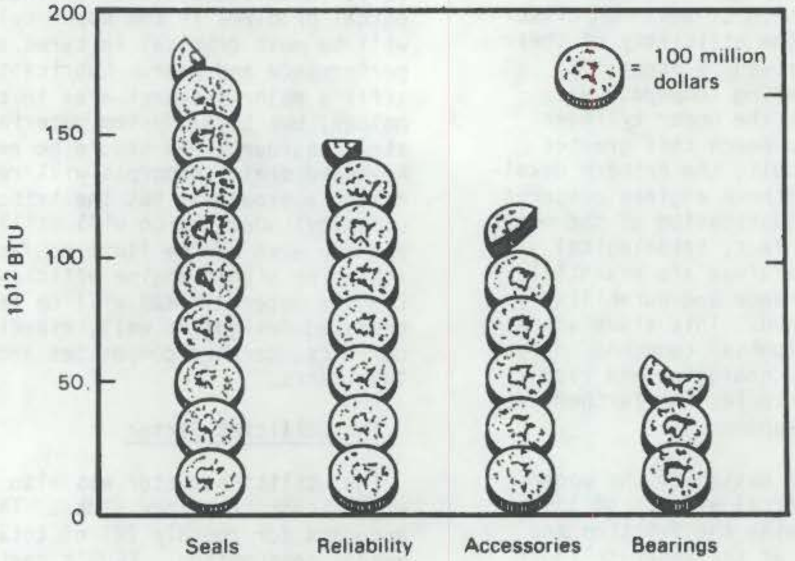

FIGURE ES.4. Potential Energy Savings for the Utilities (Based on estimates of installed capacity in 1983 and on an energy cost of $30 per barrel.)

total of 640 government-sponsored projects covering the fiscal years 1978-1983. These organizations were then contacted by mail, followed by visits and/or phone discussion. Of the original 640 projects, 215 were found to be current. A detailed description of each project is included in the report.

According to this study, until several years ago tribology research emphasized component development, fluid film and elastohydrodynamic lubrication, and concentrated contacts. Since then the emphasis has shifted dramatically, and research efforts now concentrate on lubricants, materials and coatings, and friction and wear mechanisms. There is still considerable interest in rolling contact bearings and seals, as well as in early failure detection in maintenance technology.

The study also concluded that most current tribology research is related to DOD objectives of longer life, low maintenance/failure-free machinery, and the basic understanding of friction, wear, materials, and coatings. High-temperature lubrication also continues to be a major objective in tribology research; the effects of new materials and solid lubricants on current temperature limitations are also being studied. Coatings are receiving the most attention in general materials development. Figure ES.5 shows a breakdown of the materials considered in the 215 projects.

The author also concluded that current programs generally do not emphasize energy or materials conservation. Design predictability and composite materials are other areas that are receiving little attention. Finally, the study concluded that current U.S. Government high-temperature lubrication work is the most applicable to energy conservation goals.

INDUSTRY PERCEPTIONS OF GENERIC RESEARCH NEEDS IN TRIBOLOGY

Because transferring information to industries is a major part of the ECUT program, ECUT conducted a survey of industry perspectives on tribology R&D needs. This survey, conducted by Sibley and Zlotnick, involved interviewing industry contacts to discover what research results are needed.

The authors held in-depth discussions with engineers and managers from 27 companies. These companies were chosen by defining different tribological categories (such as transportation, power plants, seals, gears, aerospace, etc.). At least one company was then selected for each category, and two or three were chosen for categories that are particularly important to the ECUT program. The purpose of this study was not to produce statistically significant findings, but rather to represent many different viewpoints and a variety of interests.

The authors' main emphasis was on determining the engineering limitations imposed by tribology considerations. They also tried to determine the type and funding level of current generic tribology R&D in each company, although only non-proprietary information was available.(a)

Based on the levels of generic tribology R&D in the 27 individual companies, the authors then estimated total tribology R&D in each industrial segment. Although this approach is obviously limited, reasonably

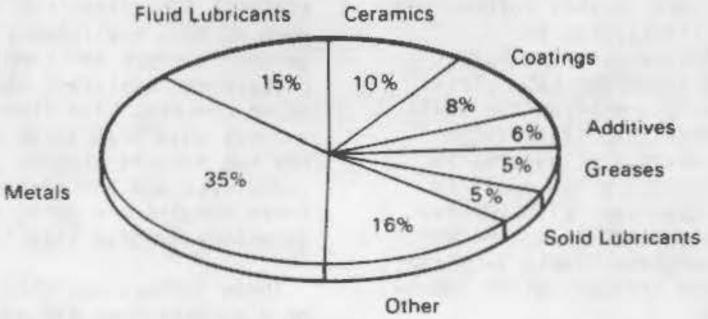

FIGURE ES.5. Materials Under Consideration in the 215 Current Government-Sponsored Tribology Projects

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(a) "Generic" R&D in this case is basic research that is not directed toward a specific end use or product.

TABLE ES.3. Estimate of Generic Tribology R&D and Total R&D Budget for Representative Industries (In $M)

Classification	Company	Total R&D[a]	Generic Tribology R&D[b]
Liquid Lubricants	Mobil	188	1
Transportation	Ford	1764	1
Aerospace	Pratt & Whitney	835	0
Powerplants	Caterpillar	234	0
Seals	Crane	10	<1
Rolling Elements	TRW	109	>0
Gears	Eaton	100	>0
Sliding Bearings	Tribon	0	>0
Filters	Pall	7	0
Small Mechanical	Xerox	565	>0
Ceramics	Norton	26	<1
Coatings	Union Carbide	240	<1
Forming	Bethlehem	46	<1
		4124	6

(a) From the report to the Securities and Exchange Commission for 1982. (Source: "Business Week," June 20, 1983.)
(b) Based on discussions with research staff and referring to only company-funded generic tribology R&D.

accurate estimates were developed of the amounts of generic tribology R&D being conducted in each of the industrial segments. The results for the individual companies are summarized in Table ES.3.

These authors concluded that industry funds only a very limited amount of generic tribology research. Some 'hidden' generic R&D is incorporated into the companies' design manuals, but much of this information is proprietary. As illustrated in Table ES.3, some industry segments have little or no generic tribology R&D. Tribology research efforts are often too small to be likely to improve the state-of-the-art; ceramics is an example of an area in which the funding levels are too small to promote significant advances, although industry has expressed considerable interest in this area. However, the liquid lubricant research budget in the transportation industries is substantial.

The industry representatives expressed interest in the ECUT Tribology Program, and also in obtaining a fundamental physical understanding of tribological mechanisms. The industry contacts also requested more effective presentations of research results, especially results in a form that design and development engineers could readily use. Another industry concern involved developing more realistic laboratory tests and more rational performance standards.

CONCLUSIONS

The six ECUT surveys summarized here were conducted to provide an overview of the major tribological sinks and the current state of U.S. tribology research. Although much of this preliminary ECUT work involved general surveys and samplings, the overall picture is consistent and reveals areas of major concern. The findings in the general surveys have been largely substantiated by the two focused studies on metalworking industries and the advanced diesel engine. These results are being used to support ECUT Tribology Program planning.

These surveys describe the current status of U.S. tribology R&D in 1984; the findings will be updated as necessary. Much of the information is necessarily somewhat speculative and theoretical, and many of the general findings have not yet been fully corroborated. This is due in part to the lack of previous research; improving this initial information should be an important goal of current research. In particular, identifying tribological mechanisms should be emphasized in order to define specific research projects. Further discussion with industry representatives is also needed.

The five key results from these ECUT studies are listed below:

1. Advanced tribo-materials, coatings, and lubricants must be developed to further improve energy efficiency. Although tribological improvements can be made with the current technology, new and innovative materials and designs (such as the advanced diesel engine) are needed to significantly increase energy efficiency.

2. Tribological mechanisms that shorten equipment life and cause excessive downtime and repair should be identified and studied. Initial research shows that these indirect energy losses from material wear are often greater than the direct energy losses from friction. In addition to the energy conservation impacts, reducing these losses could also significantly improve industrial productivity.

3. Generic tribological research will affect all three major sectors, since similar tribological mechanisms are found in many different processes. Although the transportation sector has the largest tribological energy loss and the greatest potential for energy savings, there is significant energy savings potential in all sectors. Thus research results must be effectively transferred to all sectors.

4. Meaningful performance tests and standards must be developed so that new designs and products can be accurately evaluated. Laboratory tests that accurately reflect real-world conditions are badly needed. Total system testing is vital, since tribological energy losses are often caused by complex interactions between all the components of a system.

5. Continuing communication with industry is critical to ensure that industry research needs are addressed and that the results are adequately transferred.

These results supported the development of the ECUT Tribology Program plan for 1985. The research program is divided into two parts. The Mechanisms component includes such areas as advanced tribo-materials R&D, identifying and characterizing tribological mechanisms, and developing performance test requirements. Projects in this area include developing new tribological materials, and modeling and experimental efforts to determine physical and chemical interactions and processes in tribological systems. Liquid and solid lubricants, tribological coatings and surface modifications, and ceramic and cermet materials are specific topics to be considered. The Mechanisms area also includes efforts to develop novel characterization and testing procedures and diagnostic tools and equipment to assess the performance of tribological systems.

The second part of the research program, Design, includes such topics as design and reliability modeling of components, systems, and system assemblies. Industry is directly involved in these projects. The Design area will also establish a data center to gather and disseminate information on tribology. These projects concentrate on generic tribology R&D, including energy losses from material wear.

Clearly, tribology research can have a major impact on energy use and conservation in the U.S. Much of the needed research identified in these studies is innovative and high-risk, which makes tribology a vital and appropriate area for ECUT support. Thus the ECUT Tribology Program, with industry participation and cooperation, will continue its efforts to reduce the enormous energy losses caused by friction and wear.

SUMMARY

Tribology is the science of friction and material wear. To provide preliminary descriptions of the major tribological sinks typically found in industry, Pacific Northwest Laboratory (PNL) summarized the tribological activities found in each sink and estimated the resultant energy and material consumption. This research supports the mission of the Department of Energy's (DOE's) Energy Conversion and Utilization Technologies (ECUT) Tribology Project, which is to explore innovative lubrication and materials concepts for mitigating friction and wear in energy conversion and utilization devices. The results of this study will serve as background information for the ECUT Tribology Program staff as they identify and prioritize generic research opportunities in tribology.

Friction and material wear occur throughout all industries and are involved in many processes within each industry. These conditions make assessing tribological activity overall in industry very complex and expensive. Therefore, a research strategy to obtain preliminary information on only the most significant industrial tribological sinks was defined. This approach would provide timely data for developing the research plan within current budget constraints and would indicate where further, more detailed assessments would be most beneficial. To meet these goals, six industries were selected and reviewed. This approach allowed a sufficiently detailed review of each of the six industries rather than a cursory review of all industries.

The industries examined were selected according to both the magnitude of overall energy consumption (particularly machine drive) and the known presence of significant tribological sinks. The six industries chosen are as follows:

- Mining
- Agriculture
- Primary Metals
- Chemicals/Refining
- Food
- Pulp and Paper.

The six industries were reviewed to identify and characterize the major tribology sinks. The initial energy and material consumption estimates are based upon technical analysis, industry contacts, and generally available data sources; the assumptions and limitations of the estimates are described in each industry chapter. The estimates are approximate, although they provide an effective basis for comparing the relative significance of the identified sinks. The descriptions only address the energy implications of each significant sink (both direct and indirect losses); issues such as effects upon industrial productivity, economic considerations, etc., are not included.

S.1 SUMMARY OF RESULTS

The study identified important tribological sinks in each selected industry, based on both friction and material wear energy losses and on the tribological mechanisms and materials involved. Figure S.1 and Table S.1 show the key results for each of the six industries.

The first conclusion from this study confirmed earlier claims that losses from material wear are greater than energy losses from friction; the wear losses in five of the industries were found to be more than twice as large as the friction losses.[a] The study also concluded that reducing material wear rates to improve equipment life and reliability would also significantly improve industrial productivity. The industry representatives interviewed strongly emphasized the positive impacts that tribological research could have on operational productivity.

S.2 INDUSTRY HIGHLIGHTS

The most significant results found in each of the six industries reviewed are summarized below. For each industry, the most significant sinks and the important implications are presented.

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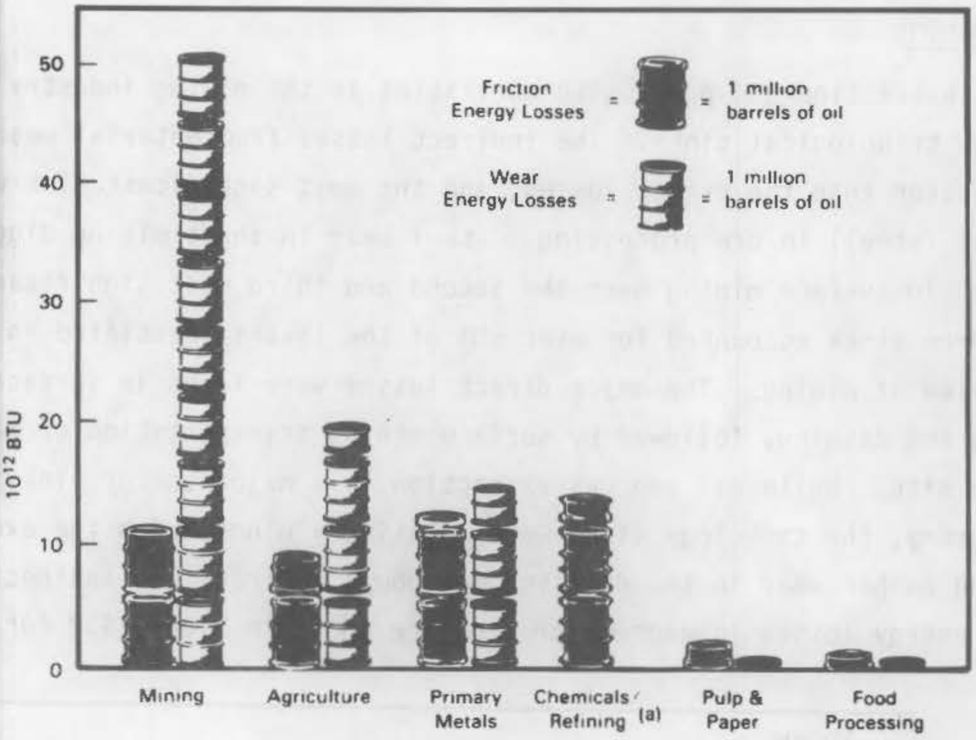
[a] These five industries had estimates of both friction and material wear losses; the sixth, Chemicals/Refining, did not have estimates of wear losses.



(a) Wear energy losses not estimated for Chemicals/Refining.

FIGURE S.1. Annual Friction and Wear Losses in Surveyed Industries

TABLE S.1. Primary Mechanisms in Friction Energy Losses and Principal Materials Involved in Wear Energy Losses

Industry	Mechanisms	Materials
Mining	3-body abrasion, friction	Iron, steel and alloys, aluminum, rubber
Agriculture	3-body abrasion, friction	Steel, rubber, lubricants
Primary Metals	Hot rolling inefficiencies	Steel and alloys
Chemicals/Refining	Friction, erosion, abrasion	Not studied
Pulp and Paper	Friction	Steel and alloys, chromium-molybdenum alloys, grinding stones
Food Processing	Erosion, abrasion	Steel and alloys

S.2.1 Mining

Ore extraction and processing activities in the mining industry result in important tribological sinks. The indirect losses from material wear were five times greater than the direct losses, and the most significant sink was material wear (steel) in ore processing. Steel wear in shaft mining digging and tire wear in surface mining were the second and third most significant sinks; these three sinks accounted for over 80% of the losses identified in this initial review of mining. The major direct losses were found in surface mining exposing and digging, followed by surface mining transportation of materials at the mine site. While oil and gas extraction is a major energy sink in the mining industry, the tribology sinks were relatively minor, with the exception of steel and rubber wear in the drilling mud pumps. Direct and indirect tribological energy losses in each major sink are shown in Figure S.2 for mining.

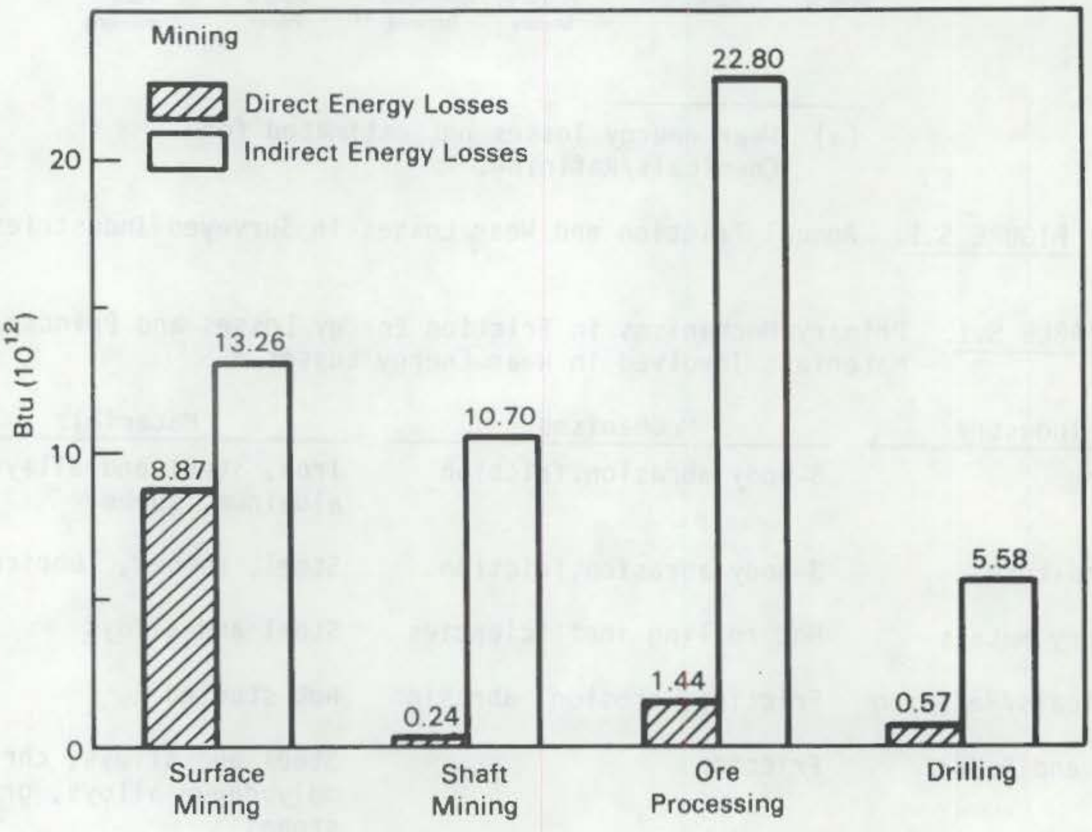
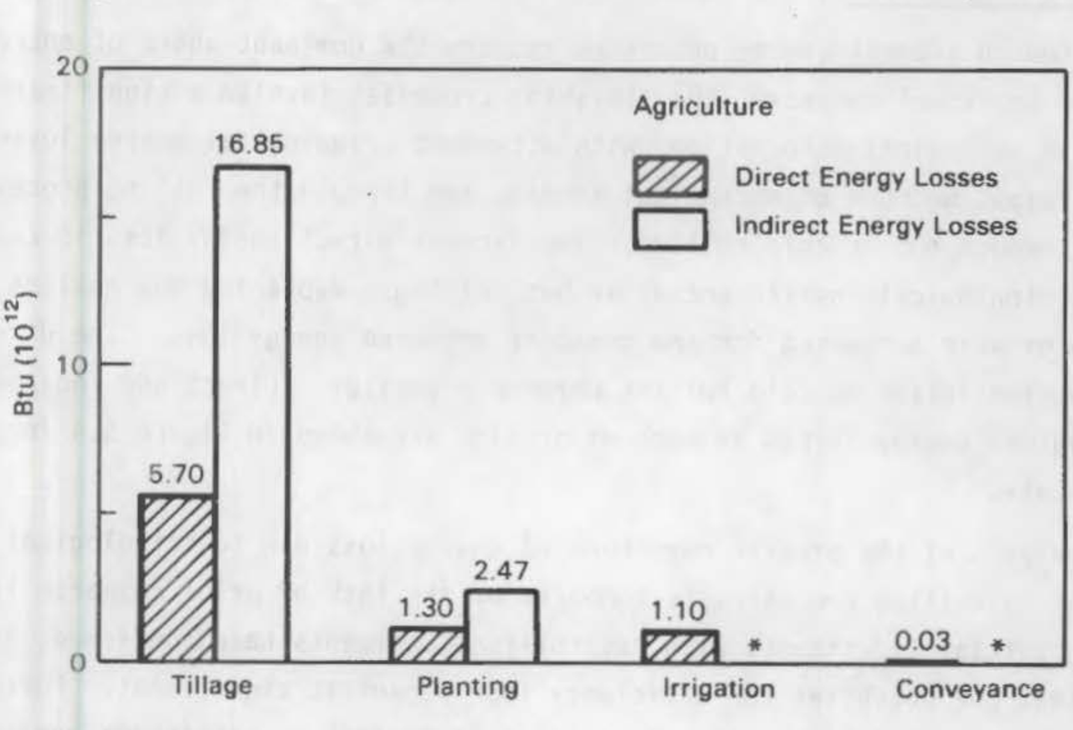


FIGURE S.2. Direct and Indirect Tribological Energy Losses in Major Sinks in the Mining Industry

The mining industry offers important applications for basic tribology research. Three-body abrasion and friction were the most frequent tribological mechanisms in the identified sinks; the resulting energy losses were generally more significant than in the other industries reviewed. Material wear in ore processing, extraction, and transporting resulted in significant embodied energy losses. Oil and gas extraction sinks contained relatively insignificant energy losses, although they are excellent examples of sinks where the most dramatic potential benefits might be productivity improvements (e.g., improved drill bit life reduces the need to pull drill pipe for bit replacement).

S.2.2 Agriculture

For the major tribological sinks identified in agriculture, the indirect energy losses were estimated to be more than twice as large as the direct energy losses (see Figure S.3). The erosion of steel from tillage implements and the draft (pulling) requirements of tillage were the two largest sinks, followed by tractor tire wear and lubricant loss. Direct consumption and



*Not Significant

FIGURE S.3. Direct and Indirect Tribological Energy Losses in Major Sinks in the Agriculture Industry material wear in planting equipment were also important. The sinks in livestock production were relatively insignificant, and the losses in harvesting (i.e., combines) were not characterized because of the complexity of the process.

The main result from the agriculture analysis is the importance of the tribology activities in soil tillage. Both the direct and indirect losses in tillage are significant, and these losses can be reduced with further basic tribology research. The most frequent tribological mechanisms identified in the analysis were three-body abrasion and high friction. Energy consumption in irrigation is high, yet the tribological sinks were found to be relatively minor. The sinks involved in harvesting with combines appear to merit further review; the sinks involve more than 50 important parts that experience at least medium wear rates. Obtaining valid replacement rate data for combines, however, exceeded the resources available for this initial review.

S.2.3 Primary Metals

Although thermal energy processes require the dominant share of energy in the iron and steel industry, the finishing processes involve a significant degree of mechanical deformation, with attendant tribological energy losses. The principal methods of mechanical forming are through the rolling processes, either through hot or cold rolling. The largest direct energy loss is caused by the tribological inefficiencies in hot rolling. Replacing the rollers because of wear accounted for the greatest embodied energy loss. The direct and embodied losses in cold rolling were much smaller. Direct and indirect tribological energy losses in each major sink are shown in Figure S.4 for primary metals.

Analysis of the precise magnitude of energy loss due to tribological inefficiency in rolling processes is hampered by the lack of prior research in this field. Initial experiments with hot rolling lubricants have confirmed, however, that the potential for efficiency improvement is significant. Further tribological research into this process would address a significant energy sink and would yield valuable technical insight that could also be extended to other primary metals industries.

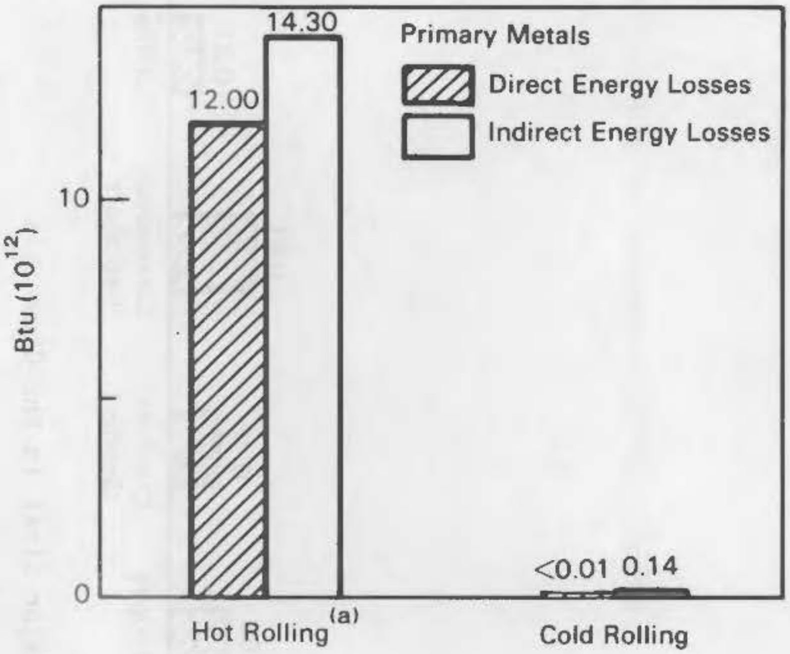


FIGURE S.4. Direct and Indirect Tribological Energy Losses in Major Sinks in the Primary Metals Industry

S.2.4 Chemicals and Petroleum

The chemicals and petroleum industries use enormous amounts of energy, and the nature of this energy use is very diverse. Studying tribological losses, which are widespread in these industries but small in comparison with the large process heat energy losses, is very difficult. A variety of assumptions were required to generate an estimate of direct tribological losses, and indirect losses were not quantified because of the complexity of estimating the replacement rates of the vast number of material parts in these industries. Most of the tribological sinks assessed were devices driven by electric motors. None of these devices had significant tribological losses as a percentage of input power requirements; the final values for annual energy losses depended primarily on the total stock of each type of motor-driven equipment in the industry. As a result, pumps, compressors and blowers were the most important sinks, with pumps alone accounting for over half of the direct losses. Other equipment such as mixers, crushers and grinders were about an order of magnitude lower in annual losses. The direct tribological energy losses are shown in Figure S.5.

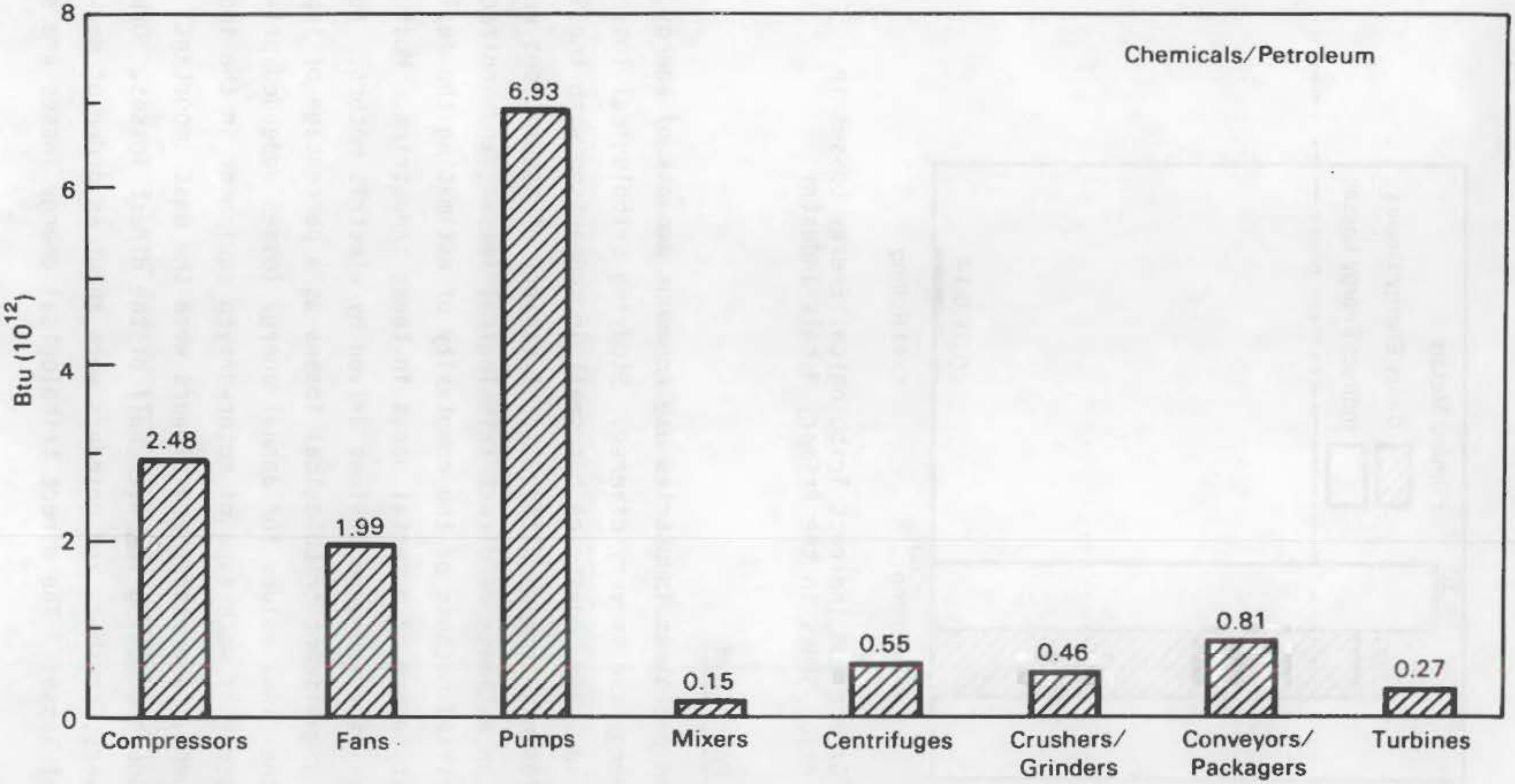


FIGURE S.5. Direct Tribological Energy Losses in Major Sinks in the Chemicals and Petroleum Industry[a]

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[a] Indirect losses were not quantified because of the complexity of estimating the replacement rates of the vast number of material parts.

The overall level of direct annual tribological losses identified in the petroleum and chemical industries was significant, although probably not as significant as the almost-unquantifiable indirect losses. Material wear occurs in most motor-driven chemical industry devices, and energy costs of replacement and downtime are high. A significant fraction of the failures are due to tribological causes. The reliability of such process equipment is extremely important to the industry because many processes operate 24 hours a day. Chemicals and petroleum industry interest in tribology is certainly high but is based primarily on factors such as indirect energy and production concerns. Additional review of the complex indirect losses of this industry is merited.

S.2.5 Pulp and Paper

The most significant tribological sinks found in the pulp and paper industry were 1) wood preparation and 2) pulp making. Other activities specifically identified as having significant tribological loss mechanisms were tree harvesting, pulpwood debarking, pulpwood chipping, stone-groundwood pulping, chip-groundwood pulping, and hydropulping. Except for harvesting, all of the operations are principally powered by electric motors. The combined annual tribological energy loss estimated for the three pulping processes was approximately 1.2 trillion Btu/year or 91% of the total energy loss estimated for the sinks reviewed. Steel and its alloys were the most common material types subject to wear; grinding stones were also used in mechanical pulping. Direct and indirect tribological energy losses in each major sink are shown in Figure S.6.

Tribological mechanisms are an essential and beneficial feature of the pulp and paper operations evaluated in this report. Friction is essential to activities such as pulpwood debarking, pulpwood chipping, and mechanical pulping. Although the total estimated tribological energy loss was not as large as estimates for the other industries reviewed, the pulp and paper industry does contain well-defined unit operations that can benefit from advancements in basic tribology research. However, further analysis of pulp and paper operations to better segregate "necessary" friction from "wasteful"

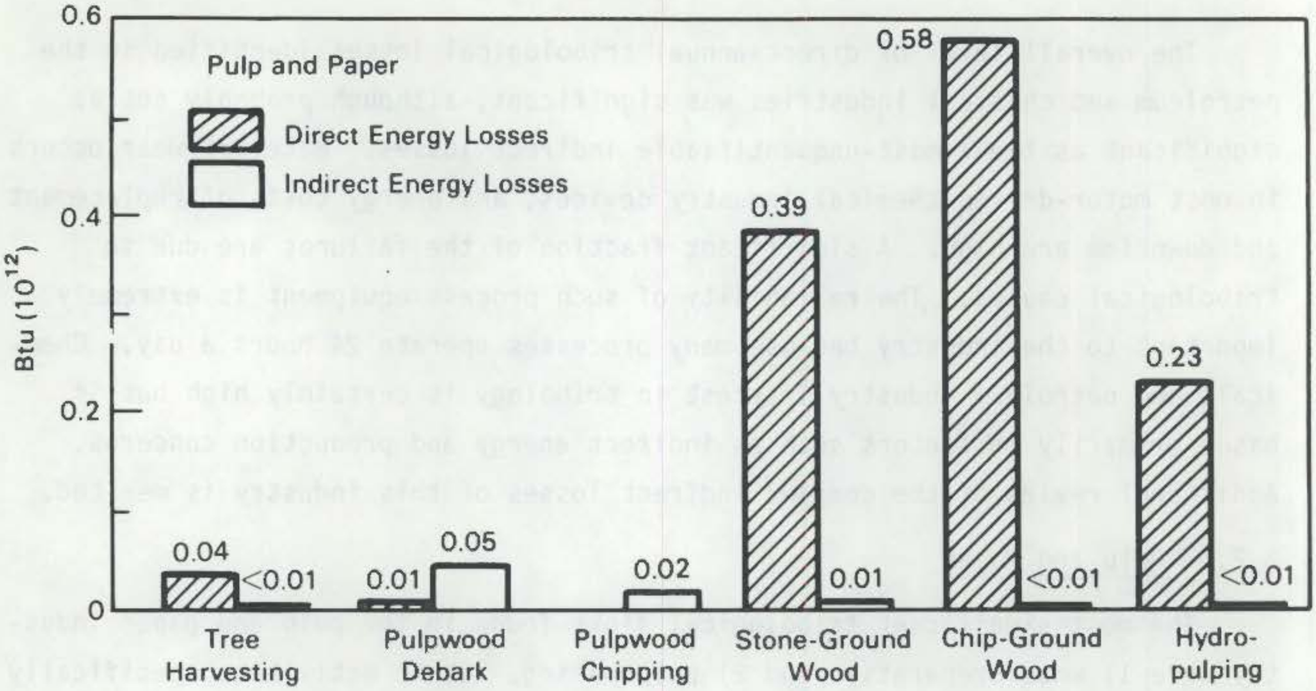


FIGURE S.6. Direct and Indirect Tribological Energy Losses in Major Sinks in the Pulp and Paper Industry

friction is needed. This concept may have implications for tribological mechanisms in other industries where the necessity of having a minimum level of friction is not as obvious.

S.2.6 Food Processing

The food processing industry includes an extremely large number of products and manufacturing processes. The diversity of the industry makes it difficult to generalize about tribological mechanisms and losses. Although many operations are functionally similar across product lines, the specific equipment is often unique to a particular product, making a generic analysis of individual operations very difficult. Size reduction and material conveyance were identified as the two most significant tribological loss activities. Size reduction operations (e.g. cutting, shredding, grinding) result in erosion and abrasion of equipment. Conveying is associated with the frictional wear of bearings, belts, and other parts. Electricity is the principal energy source for both size reduction and conveying operations. Five percent of direct energy input was attributed to frictional losses from conveyors. The total conveyor loss of 520 billion Btu/yr was the largest tribological sink identified for food processing. Direct tribological energy losses in each major sink are shown in Figure S.7.

The tribological sinks identified in the food industry are small compared to the other industries covered in this report. However, the two most important tribological activities identified for food processing (size reduction and conveyance) are also common to other industries. Tribological losses in conveyors and other transport systems seem particularly endemic to the manufacturing industry. Size reduction is especially important in mining and pulp and paper, as well as food processing. Size reduction operations often involve significant material wear. The development of more wear-resistant materials would dramatically reduce tribological losses in several industries.

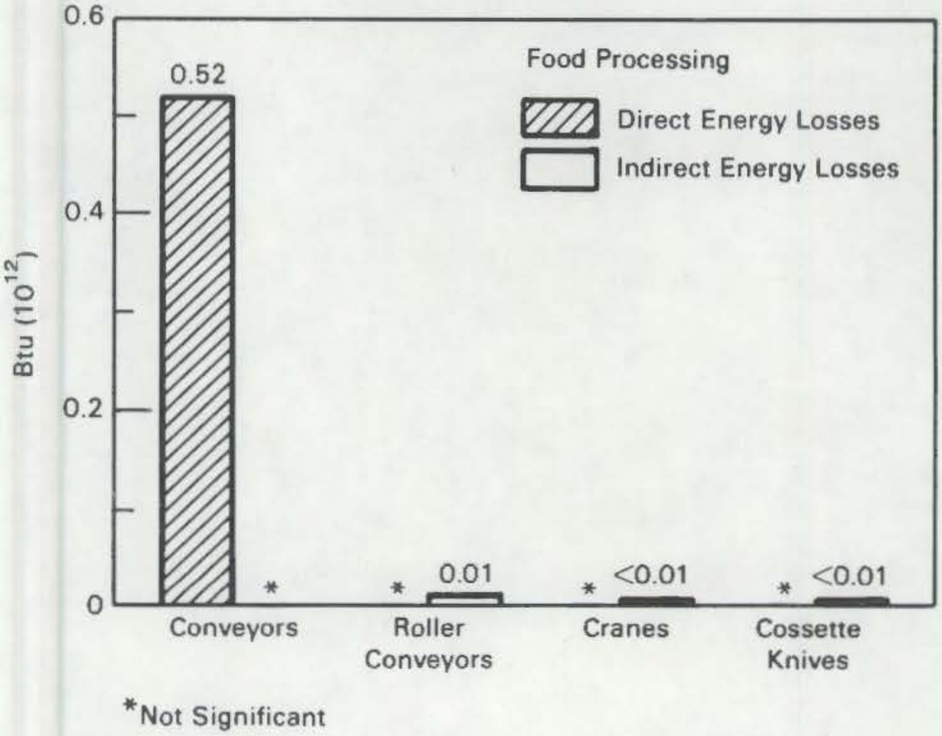
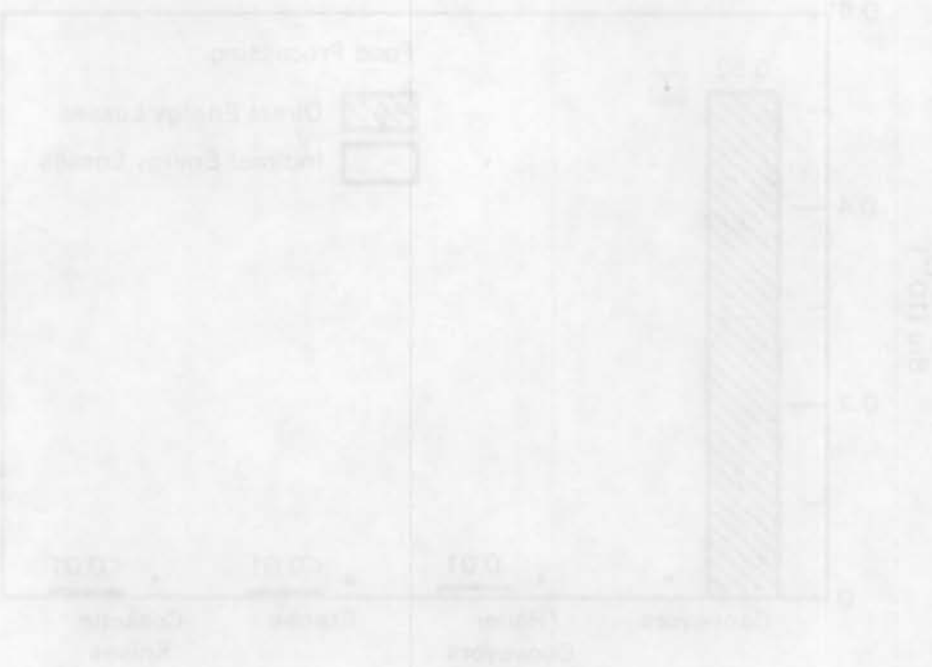


FIGURE S.7. Direct Tribological Energy Losses in Major Sinks in the Food Processing Industry conveyor loss of 520 billion Btu/yr was the largest tribological-type function for food processing. Direct tribological energy losses in each major sink are shown in Figure S-1.

The tribological sinks identified in the food industry are small compared to the other industries covered in this report. However, the two most important tribological activities identified for food processing (size reduction and conveyance) are also common to other industries. Tribological losses in conveyors and other transport systems seem particularly onerous to the manufacturing industry. Size reduction is especially important in mining and pulp and paper, as well as food processing. Size reduction operations often involve significant material wear. The development of more wear-resistant materials would dramatically reduce tribological losses in several industries.



*Not Significant

FIGURE S-1. Direct Tribological Energy Losses in Major Sinks in the Food Processing Industry

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1.0 INTRODUCTION

Tribology is the science of friction and wear of materials that move in contact with other materials. This report describes a preliminary review of tribology's impact in six major industries in the United States. In each of the six industries, the research identified processes where tribology was present and characterized the nature and magnitude of the associated energy losses and material wear.

1.1 BACKGROUND

Tribology occurs in all industrial processes and results in direct energy consumption and the wear of machines and materials. Finding better lubricants and wear-resistant materials to reduce these energy and material losses and to encourage more productive industry is the goal of the Tribology Program within the U.S. Department of Energy (DOE). The Energy Conversion and Utilization Technology (ECUT) Program Office within DOE is responsible for the multiyear program. The purpose of this research is to identify the location and importance of tribological losses in the industrial sector to provide background information to ECUT staff as they identify and prioritize generic research opportunities in tribology.

Previous research in identifying tribological sinks has been very general. For example, the American Society of Mechanical Engineers (ASME) conducted a tribology review (Pinkus and Wilcox 1977), but the study was very cursory because of the recognized complexity of the problem. A more detailed review was needed to identify 1) which industries had the most significant tribological sinks, 2) how much energy and material loss was attributed to these sinks, and 3) what generic types of tribology mechanisms were involved.

1.2 APPROACH

Initially, the primary goal of the review of tribology sinks was to conduct a preliminary review of major industries to locate and describe the nature of tribology sinks in those industries. The industries selected for possible inclusion in the study were as follows:

- Agriculture
- Mining
- Transportation Equipment
- Fabricated Metals
- Primary Metals
- Pulp and Paper
- Stone, Clay, and Glass
- Textiles
- Chemicals/Petroleum Refining.

In the first task of the review, the major processes in each industry were identified to estimate the location of major tribological sinks. The results, shown in Table 1.1, indicate that important tribological activities occur in all industries and in most major processes within each industry.

Detailed characterization of each tribological sink in the industries listed in Table 1.1 would have exceeded both the resources and time constraints initially allocated for the research. Therefore, the research approach was redefined to achieve the project goals within the time and funding constraints. A strategy for selecting and evaluating a smaller set of industries that appeared to have the greatest tribology sinks was pursued. The resulting strategy was selected because it narrowed the candidate industries to the six that appeared to have the most tribological activity, which allowed each individual industry to be more thoroughly examined.

The initial list of industry groups and the associated processes was reviewed by the staff at Pacific Northwest Laboratory (PNL) and Battelle-Columbus Laboratories (BCL) to select the five or six groups that appeared to have the most significant tribological sinks. The criteria for selecting this final set of industries included the presence of 1) major nonthermal energy streams such as machine drives, 2) high material wear rates/friction, and 3) material transportation/alteration processes.

In selecting the final set of industries, energy use in those industries was first reviewed. Figure 1.1 shows the energy-use data reviewed and indicates those industries having the largest energy use. For each of the top

TABLE 1.1. Candidate Industrial Process Categories

AGRICULTURE

- Preplant/Plant/Cultivation
- Harvest
- Irrigation
- Grain/Feed Handling
- HVAC

MINING

- Mining
  - Drilling
- Crushing
- Grinding and Classifying
- Beneficiation
- Pelletizing

TRANSPORTATION EQUIPMENT

- Hot Working
- Fabrication
- Plastics Production

FABRICATED METALS

- Forge
- Cast
- Cold Form
- Machine
- Heat Treating
- Finishing
- Joining
- Assembly

PRIMARY METALS

- Casting
  - Continuous Casting
- Milling
  - Hot Strip
  - Plate
- Welding
- Drawing

PULP AND PAPER

- Debarking
- Chipping
- Pulping
  - Refiner mechanical
  - Groundwood mechanical
- Mechanical Drying

STONE, CLAY AND GLASS

- Crushing
- Blending
- Grinding
- Kiln
  - Material Handling
- Cooling Fan
- Polishing Glass

TEXTILES

- Spinning
- Texturizing
- Weaving
- Knitting
- Finishing

CHEMICALS/PETROLEUM REFINING

- Pumping
- Compressing
- Mixing
- Agitating
- Crushing
- Extruding

industry groups, a breakdown of energy consumption by end use was then reviewed to identify the processes having the highest direct machine energy use. These results were reviewed by BCL staff members to obtain their recommendations based upon experience and industry contacts. The final set of industries chosen for the analysis is as follows:

- Mining
- Primary Metals
- Agriculture
- Chemicals/Petroleum Refining
- Food Processing
- Pulp and Paper Products.

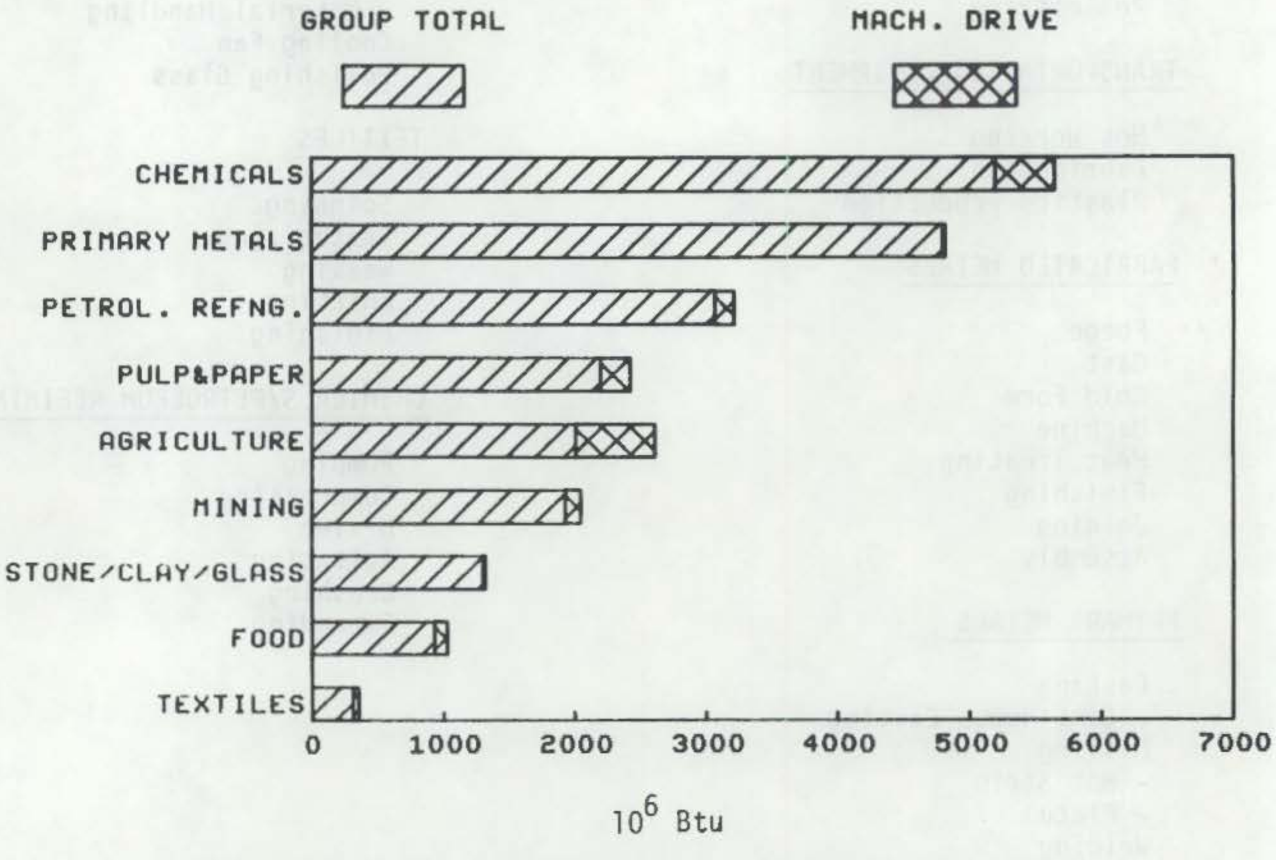


FIGURE 1.1. Energy Use in the Industries Selected for Analysis

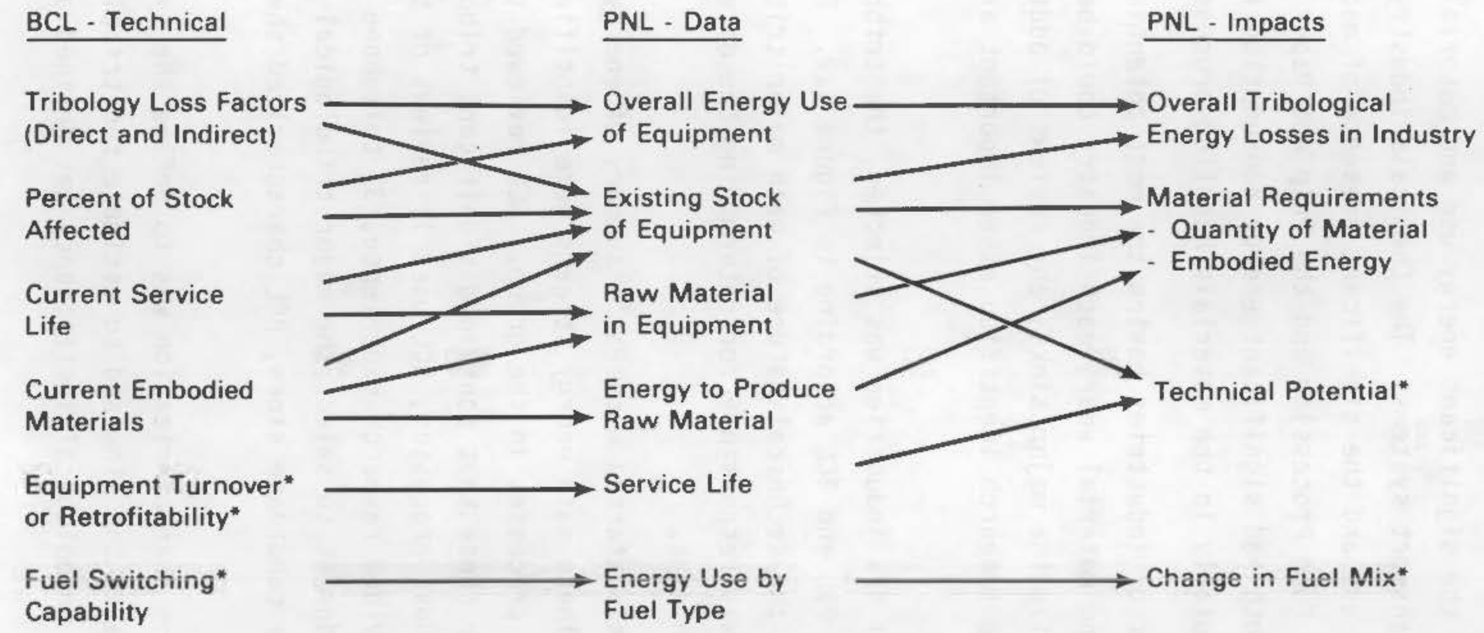
Mining was selected more for the high material wear rates and the large number of tribology sinks than for total energy use. The Primary Metals industries were included because they consume large quantities of energy and raw materials, and significant tribology sinks are involved in forming and processing the metals. The Agriculture sector was included because of the large number of tribology sinks and the significant energy use and material wear rates involved in tilling and transport systems. The Chemicals industry was selected because of the high energy use and the significant presence of machine drive for pumping, mixing, etc. Food Processing and the Pulp and Paper industries were chosen because they both had significant energy consumption rates and tribological sinks, particularly in the materials handling processes.

By focusing on the set of industries having the most potential for decreasing energy losses and material wear, each industry could be reviewed in enough detail to characterize the major sinks; any reviews of additional groups could be added later if the research identified other important areas for funding next year.

After the final set of six industries was selected, the tribologic sink review was divided between PNL and BCL according to Figure 1.2. BCL was responsible for describing the technical nature of each major tribological sink in each industry, and PNL was responsible for determining the direct and indirect energy impacts in each sink.

BCL's technical analysis started with PNL's summary of energy use in a specific industry group. These main energy streams were identified to identify the major energy-dependent processes in the group. BCL reviewed these and other processes to identify those that contained significant tribological activities. To identify those processes, BCL used 1) reviews of technical process literature, 2) previous research experience, 3) telephone contacts with industry, and 4) expert judgment to select the major tribological sinks in the group. After selecting the candidate sinks, BCL characterized the technical nature of the sinks.

The purpose of the sink characterization was to define the type of tribological mechanism(s) active in the sink and to estimate the tribological inefficiency of the sink. The tribological inefficiency was defined as a) the



*Means "defer until FY85"

FIGURE 1.2. Revised Information Flow Diagram

amount of energy lost to tribology (direct energy loss) and b) the amount of embodied energy lost to tribology (indirect energy loss due to material wear). These results were usually expressed as Btu/unit of service in the sink or as amount of material lost/unit of service provided.

An example of energy loss from tribological activities is soil tillage in agriculture. Direct energy loss stems from the portion of tractor power needed to pull the tool (i.e., plow, etc.) through the soil. Typically, 30% to 60% of the draft (pull) power is attributed to this activity. The direct loss would be estimated as energy needed per acre plowed. The total direct energy loss is then computed by including total annual tillage. The indirect losses stem from the need to replace plowshares as a result of soil abrasion. For example, the plowshares are worn at an average rate per acre plowed. Using the data of total acreage plowed, the total number of plowshares replaced annually can be estimated. This figure can be converted to annual indirect energy loss by estimating the embodied energy in these discarded plowshares.

1.3 CHAPTER CONTENTS

This report is divided into six chapters that separately discuss the tribological sinks in each of the six industry groups. Each chapter begins with a brief discussion of the energy consumed, the fuels used, and the primary products and processes of that industry. Then, the energy use in that industry is presented by end use and energy type. This introductory information is followed by discussions of the tribological sinks identified in the industry. For each tribology sink, the discussion includes the following:

- the tribological mechanisms
- the direct tribological inefficiency and energy loss estimates
- the indirect tribological inefficiency and energy loss equivalents.

Each chapter concludes with a brief overview of the nature and impact of the tribological activities within that group.

2.0 MINING

This chapter identifies and characterizes total energy use and tribological losses in the mining industry. Energy consumption is specified by fuel type for each of the major mining sectors (metals, coal, oil and gas, and nonmetals), and total energy consumption is compared to purchased fuels and electricity. The major processes and products of the mining industry are also briefly described, and those processes identified as having significant tribological losses are reviewed and described in more detail. The nature of each tribological sink and the mechanisms leading to direct and/or indirect energy losses are then characterized. Finally, the direct and indirect energy losses are estimated and the approach used to calculate those losses is identified. The chapter ends with a summary of the tribological losses estimated for mining.

2.1 INTRODUCTION

The mining industry, as defined by the 1972 Standard Industrial Classification (SIC) Manual, includes businesses that extract naturally occurring minerals as their primary activity. The major subdivisions of mining are metal mining (SIC 10), anthracite mining (SIC 11), bituminous coal and lignite mining (SIC 12), oil and gas extraction (SIC 13), and nonmetallic minerals, except fuels (SIC 14). Each of these subdivisions is broken into individual product and service categories such as iron ore, oil and gas field services, and crushed and broken limestone. Mining involves various activities that include geological mapping, drilling, quarrying, crushing, grinding, washing, loading, and transporting.

2.1.1 Energy Consumption in Mining

Total energy consumption in mining was ~2.4 quads in 1977, according to data presented in the 1977 Census of Mineral Industries (U.S. Census Bureau 1981. (As of May 1984, the 1977 data are the latest comprehensive energy consumption information available from the U.S. Census Bureau.) Oil and gas extraction accounted for nearly three-fourths of this total, whereas anthracite mining represented the smallest (0.1%) portion. Total energy consumption for each of the major two-digit classifications is shown in Table 2.1. The energy consumption data listed in Table 2.1 and in the following tables in this chapter have been derived from the 1977 Census of Mineral Industries (U.S. Census Bureau 1981).

Natural gas comprised about two-thirds of the energy consumed in mining. This figure is skewed, however, by the large proportion of natural gas consumption in oil and gas extraction, the dominant energy-consuming subdivision. Fuel oils are the dominant energy form in both of the coal mining categories; other significant fuel types are electricity, coal, and gasoline, in descending order of total consumption. Energy consumption data by fuel types are presented in Tables 2.2 through 2.7 for the total mining industry and each of its major subdivisions.

TABLE 2.1. Energy Consumption in Mining (1977)

SIC #	Classification Name	10^{12} Btu	% of Total
10	Metal Mining	165	6.9
11	Anthracite Mining	3	0.1
12	Bituminous Coal and Lignite Mining	126	5.3
13	Oil and Gas Extraction	1774	74.2
14	Nonmetallic Minerals, Except Fuels	323	13.5
	Total	2391	100.0

TABLE 2.2. Energy Consumption by Fuel Type in the Mining Industry (1977)

Fuel	10^{12} Btu	% of Total
Coal	63	2.6
Fuel Oil	364	15.2
Natural Gas	1614	67.6
Gasoline	44	1.8
Electricity	203	8.5
Other	102	4.3
Total	2390	100.0

TABLE 2.3. Energy Consumption by Fuel Type in Metal Mining (1977)

Fuel	10^{12} Btu	% of Total
Coal	12	7.3
Fuel Oil	42	25.3
Natural Gas	59	35.4
Gasoline	2	1.5
Electricity	50	30.5
Total	165	100.0

TABLE 2.4. Energy Consumption by Fuel Type in Anthracite Mining (1977)

Fuel	10^{12} Btu	% of Total
Fuel Oil	1.12	37.3
Natural Gas	0.0	0.0
Gasoline	.23	7.7
Electricity	.68	22.7
Coal and Other	.97	32.3
Total	3.00	100.0

TABLE 2.5. Energy Consumption by Fuel Type in Bituminous Coal and Lignite Mining (1977)

Fuel	10^{12} Btu	% of Total
Fuel Oil	60.7	48.0
Natural Gas	1.7	1.4
Gasoline	7.7	6.1
Electricity	34.6	27.4
Coal and Other	21.6	17.1
Total	126.3	100.0

Energy consumption data are also provided in the 1977 Census of Mineral Industries for purchased fuels and electric energy, which is a subset of the total energy consumption data presented above. Purchased energy represents less than half of the total energy consumption in the minerals industry

TABLE 2.6. Energy Consumption by Fuel Type in Oil and Gas Extraction (1977)

Fuel	10^{12} Btu	% of Total
Fuel Oil	201	11.3
Natural Gas	1411	79.6
Gasoline	28	1.6
Electricity	78	4.4
Coal	0	0.0
Others	56	3.1
Total	1774	100.0

TABLE 2.7. Energy Consumption by Fuel Type in Nonmetallic Minerals, Except Fuels (1977)

Fuel	10^{12} Btu	% of Total
Fuel oils	59	18.3
Natural gas	142	43.9
Gasoline	6	1.7
Electricity	37	11.6
Coal	38	11.8
Others	41	12.7
Total	323	100.0

(1.1 quad versus 2.4 quad). The difference primarily occurs in the oil and gas extraction sector, where 1.29 quad of energy consumption are nonpurchased; that is, they are produced and consumed on the premises. When only purchased fuels and energy are considered, the relative amounts of energy consumed in each of the mining sectors become more even, as shown in Table 2.8.

The mining industry produces many ore and mineral products, but when each product's importance is measured by factors such as number of establishments, value added, employees, and energy consumption, the list shrinks to a manageable number. The principal products that consume more than 10 x 10^{12} Btu during the mining process are identified in Table 2.9.

TABLE 2.8. Purchased Fuels and Electric Energy in the Mining Industry (1977)

SIC #	Classification Name	10^{12} Btu	% of Total
10	Metal Mining	165	15.1
11	Anthracite Mining	3	0.2
12	Bituminous Coal and Lignite Mining	118	10.8
13	Oil and Gas Extraction	483	44.3
14	Nonmetallic Minerals, Except Fuels	323	29.6
	Total	1092	100.0

TABLE 2.9. Principal Products of the Mining Industry

Iron ores(a)
Copper ores(a)
Lead ores
Zinc ores
Gold ores
Silver ores
Bauxite
Ferroalloy ores
Uranium ores
Radium ores
Vanadium ores
Mercury ores
Anthracite
Bituminous coal and lignite(a)
Crude oil(a)
Natural gas(a)
Natural gas liquids(a)

Dimensional stone
Crushed and broken limestone(a)
Crushed and broken granite
Construction sand and gravel(a)
Industrial sand(a)
Bentonite
Fire clay
Fuller's earth
Kaolin and ball clay(a)
Barite
Fluorspar
Potash(a)
Phosphate rock(a)
Rock salt
Sulfur(a)
Gypsum
Talc

(a) These products consume over 10 x 10^{12} Btu/yr during the mining process.

2.1.2 Mining Operation Activities

Mining operations can be broadly classified into exploration, extraction, and beneficiation activities. Many of these operations are common to most of the mineral products extracted. Differences in the equipment and technology used can be traced to the mineral's proximity to the surface, the characteristics of the mineral formation, and the intended downstream use of the product. For example, the proximity to the surface will determine whether the mineral is extracted by surface mining, shaft mining or drilling. Seam dimensions will affect the selection of "digging" equipment. Beneficiation operations will depend on the mineral concentration, surrounding gangue material, and the product form required for downstream consumption.

Mineral exploration activities begin with one or more of several types of surveys and, of course, an understanding of the expected geological occurrence. Types of surveys include magnetometer surveys, geological mapping, aerial photography, gravimetric surveys, and satellite mapping. To identify materials, physical samples must be acquired and tested. This process involves drilling or trenching to acquire samples and laboratory analysis to determine the quality of the raw material.

Mineral extraction activities include digging, loading, and transporting. Digging machinery is required to gain access to and to remove the mineral deposit. The type of equipment needed largely depends on whether the mineral is extracted through surface mining, shaft mining, or drilling. Draglines, power shovels, and bucket-wheel excavators are common excavating equipment used in surface mines. Removing especially hard materials may require drilling or blasting. The raw material extracted is transported to intermediate storage locations or beneficiation facilities by trucks, conveyors, or railcar, depending on the terrain and the transportation distance. Shaft mining requires specialized compact equipment, which is usually operated continuously. With the various types of shaft mining equipment, continuously rotating teethed surfaces cut away material from the wall and deposit it onto an attached conveyor system.

Beneficiation includes activities that increase the concentration of the desired mineral or improve its form. Typical beneficiating activities include grinding, screening, washing, and flotation. Gravitational and magnetic forces are also used to separate materials. Some ores may be leached with acids if physical separation techniques are impractical.

2.2 MINING OF METALLIC ORES, COAL, AND NONMETALLIC MINERALS

The two major methods for extracting ores, minerals, and coal are surface mining and shaft mining. The equipment used in these two types of mining have distinct differences. However, five common process steps are used in both:

- exposing (removing overburden)
- digging
- loading
- transporting
- ore processing.

In the following sections, the tribological energy losses from these processes in surface mining and shaft mining are described. In each section, the mining method is described and tribological losses for components that are major sinks in that area are summarized. The subsequent subsections will then present the assumptions and some of the supporting data used to calculate the direct and indirect energy losses.

2.2.1 Surface Mining

A representative surface mining operation[a] is shown in Figure 2.1. Examining an example surface mine will indicate how many of each equipment type is typically used. For example, at the Colowyo Coal Mine in Colorado, the equipment fleet consists of 77 major units and moves 31.5 million cubic yards of rock to mine 4.3 million tons of coal per year (Coal Age 1982). Colowyo's equipment can be broken down into the three categories:

- 4 diggers: 2 draglines, 2 power shovels
- 52 trucks: 3 water, 6 drills, 2 highway, 16 tractors and trailers, 25 haulage

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[a] 26th Quarterly Publication, July 1982, Common Surface Equipment Troubleshooting Note, Published by Common Surface Mining Equipment Troubleshooting.

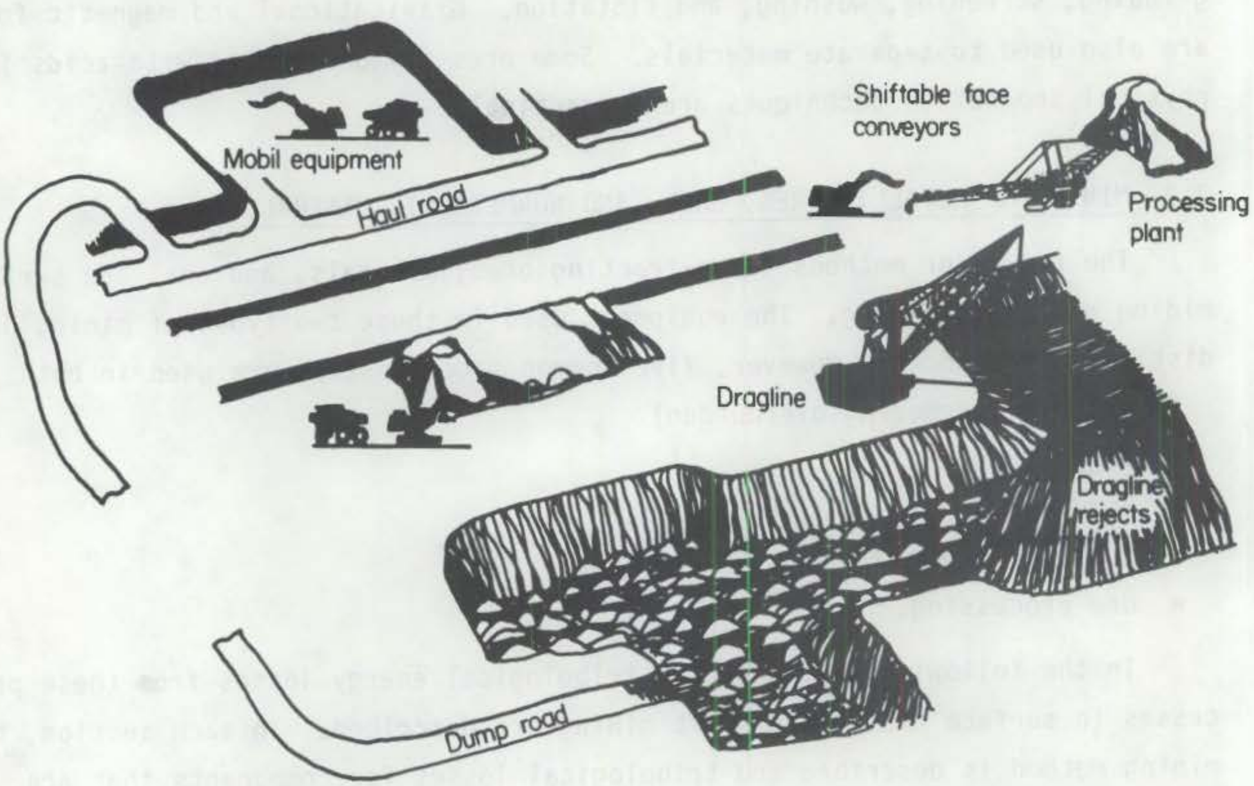


FIGURE 2.1. A Typical Surface Mining Operation[(a)]

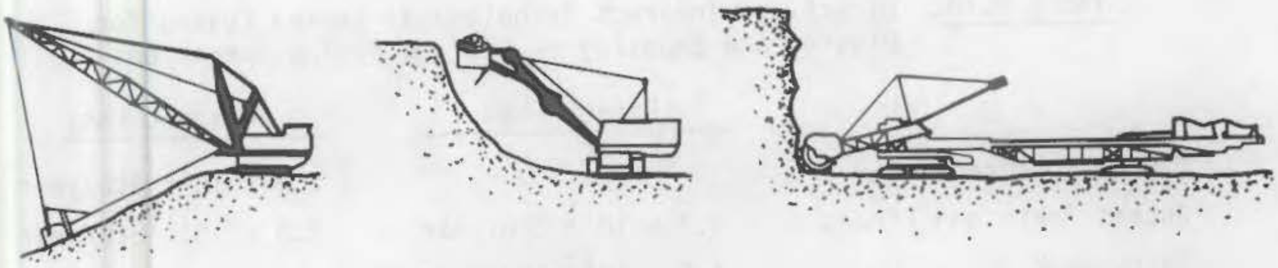
(a) 26th Quarterly Publication, July 1982, Common Surface Equipment Troubleshooting Note, Published by Common Surface Mining Equipment Troubleshooting.

- 21 loaders: 9 front-end loaders, 1 backhoe, 1 scraper, 3 graders, 7 dozers.

Estimates of the tribological energy losses for each of these types of equipment are presented in the following sections, according to the process steps.

Exposing and Digging

The mining of most materials requires that some type of overburden first be removed (exposing). The overburden may be as slight as a few feet of earth or may be as troublesome as a solid vein of rock. Overburden removal is handled in surface mining by three main types of equipment: the dragline, the power shovel, and the bucket-wheel excavator, all shown in Figure 2.2. Although the operating principles of the three are very different, they share



Dragline Power Shovel Bucket-Wheel Excavator

FIGURE 2.2. Surface Mining Exposing and Digging Equipment

several common components that comprise tribological energy losses. These types of losses are also common to digging equipment. In surface mining, once the overburden is removed, the material is harvested in much the same manner as it was exposed. The company may switch from a dragline used to remove overburden to several smaller power shovels to work out the vein, but the tribological energy losses will be similar. The components that comprise the main tribological energy losses for the dragline, the power shovel, and the bucket-wheel excavator are digger lubricant, bucket teeth and liners, carry-back (material stuck in the buckets of the diggers after dumping), and wire rope. These components are listed in Table 2.10 with their associated losses.

The direct energy losses were calculated as a percent of the total energy used by a digger. In arriving at the total energy consumption per cubic yard for a digger, the following four assumptions were made:

1. Bucket-wheel excavators may be discounted.
2. Direct loss mechanisms for the power shovel are similar to dragline direct loss mechanisms.
3. A dragline will operate at 90% of the capacity of a power shovel of the same bucket size.
4. Digger production rates and power consumptions may be scaled to bucket capacity.

Bucket-wheel excavators are being discounted because they represent such a small percent of the diggers (1%) (Watwood 1983). The assumptions on the production rates and power consumptions of the shovels and diggers were made by

TABLE 2.10. Direct and Indirect Tribological Energy Losses for Digging and Exposing in Surface Mining Operations

	Direct Loss	Indirect Loss
Digger Lubricant	--	2.9×10^{11} Btu/year
Bucket Teeth and Liners	3.7×10^{11} Btu/year	2.5×10^{11} Btu/year
Carry-Back	4.6×10^{12} Btu/year	--
Wire Rope	Small	7.0×10^{11} Btu/year

comparing production data from Pfleider (1968), Cummins and Given (1973), and from two of the major manufacturers, Bucyrus-Erie and Marion Power. Based on these assumptions, the power requirement was estimated at 3400 to 5800 Btu/cubic yard moved for electric power machinery. Error on this figure may be ±50% because it encompasses all large machinery and materials mined.

The number of tons of various materials moved yearly in the U.S. is given in Table 2.11. The total tonnage of materials moved annually in the U.S. can be converted to 8.0×10^9 cubic yards by using 1.4 tons/cubic yard (which was computed using a weighted average of densities of materials from Table 2.11). When multiplied by 5800 Btu/cubic yard, this yields 4.6×10^{13} Btu/year total power consumed by the "diggers" alone in all U.S. mining.

The lubricant loss is based upon information taken from the current COSMET(a) directory (Watwood 1983), which accounts for more than 90% of large-mining machinery in use in the U.S. A list of large-mining machines in operation is given below:

- ~384 draglines (primarily greater than 30 cu yd buckets)
- ~123 power shovels (as small as 5 cu yd)
- ~5 bucket wheel excavators.

The approximate amount of lubricant used by draglines, as provided by Marion Power Shovel, Marion, Ohio, is shown in Table 2.12.

(a) "COSMET" stands for Common Surface Mining Equipment Troubleshooting and is an association concerned with surface mining problems.

TABLE 2.11. U.S. Production of Principal Minerals from Surface Mines (1981)

	Approximate Ratio of Overburden to Ore	Short Tons of Ore Mined Per Year	Short Tons of Overburden Mined Per Year
Coal	13:1	504×10^6	6550×10^6
Copper	2.5:1	271×10^6	678×10^6
Iron	1:1	241×10^6	241×10^6
Crushed and Broken Stone	0.5:1	873×10^6	436×10^6
Sand and Gravel	0.5:1	755×10^6	378×10^6
Clay (all types)	1.7:1	45×10^6	76×10^6
Phosphate Rock	1.25:1	59×10^6	74×10^6
Total		2.75×10^9	8.43×10^9

TABLE 2.12. Yearly Lubricant Used by Draglines (gallons)

	Bucket Size	
	30 cu yd	150 cu yd
Multipurpose grease	2,000	3,000
Open-gear grease	900	1,750
Wire rope lubricant	300	600
Gear case oil	650	3,500
Walking cam lubricant (on machines >40 cu yd)	--	3,250
Total	3,850	12,100

The lubricant consumptions in Table 2.12 agreed with one mine manager's general estimate of 4000 to 6000 gallons/year for a walking dragline.[a] Assuming 4000 gallons/year for 507 large-mining machines (both draglines and power shovels), the consumption is about 2 x 10^6 gallons/year or 2.9 x 10^{11} Btu/year.

The direct power loss in a dragline or power shovel bucket has been estimated using a Bucyrus-Erie Model 1260-W Dragline as an example. The following is a list of standard operating parameters for this equipment:

- Rated Bucket Size: 35 cubic yards
- Actual Bucket Size: 39 cubic yards
- Empty Bucket Weight: 71,000 pounds
- Loaded Bucket Weight: 176,000 pounds (at 100 lb/cu yd)
- Drag Speed: 1 ft/sec
- Friction coefficient for steel on "Earth:" 0.2
- Bank Slope: 40°.

The power consumed by bucket-to-burden friction is 66 horsepower, which is 9% of the drag motor power of 1000 horsepower (at 75% capacity). The drag motors operate for ~40% of the total fill, swing, and dump cycle. The bucket friction then amounts to 0.8% of total dragline power consumption or 3.7 x 10^{11} Btu/year lost to bucket friction, as shown in Table 2.10.

Loss of bucket teeth and liners from abrasive wear is routine in the surface mining industry. Bucket teeth and liner life is most strongly affected by the type of material being dug. The materials are classified in Table 2.13 with a scale showing the effect on replaceable teeth and wear plates (ESCO Corporation undated). The scale is highly approximate and is only included to show the high variability introduced by changing materials. However, the 6- to 9-month limit at the high end of the scale was indicated consistently in conversations with field maintenance engineers and by product literature. The 15-minute blade life at the right end of the scale is observed when blades are ripping solid rock and are described as "smoking hot" from the high-abrasive

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[a] Personal communication on August 16, 1983, with Wilson McMannis, Manager of Consolidation Coal Company, Pennsylvania.

TABLE 2.13. Blade Life Under Various Digging Conditions (Pfleider 1968)

	Ease of Digging			
	Easy Digging	Medium Digging	Hard Digging	Rock
General Material Description	Loose, soft, free-running materials Close lying, which will fill dipper or bucket to capacity and frequently provide heaped load Overload compensates for swell of materials	Harder materials that do not require blasting, but break up with bulkiness causing voids in dipper or bucket	Materials requiring some breaking up by light blasting or shaking More bulky and somewhat hard to penetrate, causing voids in dipper or bucket	Blasted rock, hardpan and other bulky materials, which cause considerable voids in dipper or bucket and are difficult to penetrate
Specific Material Names	Dry sand or small gravel Moist sand or small gravel Loam Loose earth Muck Sandy clay Loose clay gravel Cinders or ashes Bituminous coal Very well-blasted material	Clay--wet or dry Coarse gravel Clay gravel, packed Packed earth Anthracite coal	Well-broken limestone, sand rock and other blasted rocks Blasted shale Ore formation (not of rock character) requiring some blasting Heavy wet, sticky clay Gravel with large boulders Heavy, wet gumbo cemented gravel	Hard tough shale Limestone Trap rock Granite Sandstone Taconite Conglomerate Caliche rock Any of these blasted to large pieces mixed with fines and dirt Tough, rubber clay that shaves from bank
Blade Life	6-9 Months			15 minutes

wear energy inputs. The indirect loss estimate for bucket teeth and liners was based on replacing 14,300 pounds of steel per bucket every 6 months.

Carry-back refers to material that is stuck in the buckets of the diggers after dumping. Carry-back creates the direct loss of having to lift useless weight, as well as reduced bucket capacity, which results in proportionately additional passes to remove a fixed amount of material. The degree of carry-back experienced is most strongly influenced by the type and moisture content of the material moved. Because these considerations vary with geography, U.S. maps that divided the U.S. by geology, geologic age, and mechanism of formation (Department of Interior 1970), parent soil (Marbut 1935), topsoil (Department of Interior 1970), and minerals distribution (Department of Interior 1970) were consulted. The compilation of these various classifications reduced the U.S. to five major divisions, as shown in Figure 2.3.

The geological areas can be typified as shown in Table 2.14. Each of the percentages in Figure 2.3 was based on an interview with a mine manager at

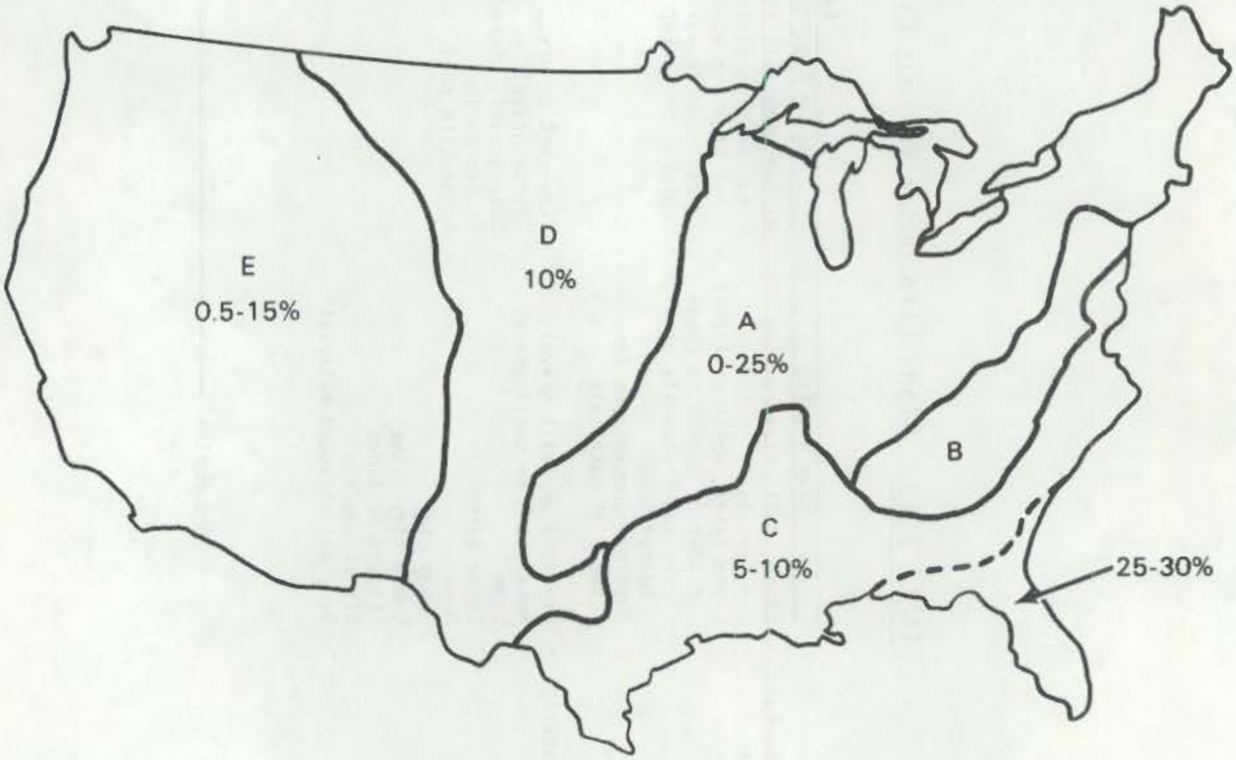

FIGURE 2.3. Percent Carry-Back in Major Geological Divisions (as indicated by mine managers)

TABLE 2.14. Characterization of the Five Geological Divisions

Section	Moisture Content	Parent Material of Soils
A	Usually moist but dry part of the time during warm seasons	Limestones, sandstones, clays, shale, oil, and tar sands
B	Usually moist but dry part of the time during warm seasons	Crystalline rock and granite, mica, field spar and quartz
C	Seasonably wet	Sands, clays, and limestones
Dotted section (Florida)	Marsh	Marine deposits, phosphate rocks
D	Subhumid, semidry climates	Great Plains material, deep topsoils
E	Typically dry, low in organic matter, never moist for more than 3 consecutive months	Alluvial fans, other desert accumulations and gravels, pumice volcanic rock

that location. Blasted rock in Region A and dry sand in Region E has 0% carry-back. Wet clay or phosphate mining in the Florida marshlands has carry-back as high as 30%. Considering these two figures, we chose 10% as a conservative estimate to use nationwide. When multiplied times the power consumption for the diggers, this yields 4.6×10^{12} Btu/year wasted through carry-back.

The wire ropes used in the diggers for hoisting fail from fatigue or fretting fatigue. The drag ropes used only in draglines also suffer from abrasive wear. PNL has done extensive research in this area, and the estimate of the indirect loss/year from draglines was taken from a PNL study (Beeman 1978).

Summary. Carry-back was the largest direct tribological energy loss found in this study of surface mining. Various methods of reducing the coefficient of friction in the bucket are being studied. For example, because carry-back was reported as being a greater problem during cold weather, buckets are sometimes continuously heated during the winter, which is also a direct energy loss. Polymer bucket liners have been tried and found to be successful in reducing carry-back where the wear rate is not so high that the liner is quickly destroyed. An ideal solution would be a consistent (all-season) low-friction liner with good wear resistance.

Loading

At some point in the mining operation, almost all of the material is assumed to be handled by some type of loader having a bucket capacity ranging from 10 to 20 cubic yards. Some material will be rehandled, and some overburden handled by draglines will not be handled by a loader at all. In the Colowyo Mine example cited earlier, these loaders were present 5:1 to the diggers. Loaders simply load material, which has often been piled or exposed by one of the large diggers, into a truck or onto a conveyor system.

For loading equipment, tribological losses are caused from abrasive wear by the material being moved. This wear affects the carriages, tires or treads, and buckets or blades. The direct and indirect loss mechanisms for the loaders are very similar to those previously discussed for dragline and power shovel buckets. The same life expectancies and observations of Table 2.13 are applicable to a loader's teeth inserts, blade inserts for scrapers and dozers, ripper blades that break up soil, and wear plates for buckets. The 6-to-9-months' replacement used as a conservative estimate cannot be estimated any more precisely unless local material types are considered.

The following parameters were used for estimating the direct loss for a front-end loader.

- Bucket Capacity: 10 cubic yards
- Operating Speed: 2-6 mph
- Capacity: 1800 cubic yards/hour
- Blade Angle: 22°
- Coefficient of Friction: 0.2.

The friction loss for the material sliding over the upper surface of the bucket or blade was estimated to be 7×10^{10} Btu/year. Scrapers and bulldozers are also used in loading, but the percentage of material they move was assumed small in comparison to other loaders.

Indirect losses from loading were estimated based on replacing the loader liner and teeth once every six months. The teeth and liners for a median-size bucket weigh ~700 pounds. Indirect losses of 6.1×10^{10} Btu/year were estimated.

Transporting

Transportation in mining may be divided into three main categories: trucks, conveyors, and railcars. The following general descriptions of these systems were taken from Cummins and Given (1973, pages 17-21). The principal tribological losses associated with surface transportation are summarized in Table 2.15.

Trucks are a very flexible transportation system and can climb steep ramps. However, they require good roads to minimize tire cost and are limited by economic considerations to an operating radius of about three miles. An interview with Cummins and Given (1973) indicated that trucks handle at least 70% of surface mining transportation.

Truck maintenance records at one mining operation indicated that the top 10 repair items account for 90% of those costs (Cummins and Given 1973). Six of the top 10 items may be traced to tribological failures, with tire replacement and repair representing 30% of the total operating cost.

Tire life is affected by many factors, including inflation, speeds, curves in load and dump cycle, road surface, loads, wheel position on truck, and road grade. A nominal value for the maximum life of off-the-road tires under favorable conditions was given as 6000 hours (Pfleider 1968, p. 582). An average life for front and rear tires when calculated for specific examples is

TABLE 2.15. Transportation in Surface Mining

	Direct Loss	Indirect Loss
Trucks	--	1.2×10^{13} Btu/year
Conveyors	3.8×10^{12} Btu/year	--
Railcars	--	--

~3000 hours. Data taken from a survey of hauling practices (Cummins and Given 1973, pps. 17-82) at 24 copper mines were used to estimate a typical truck capacity of 30 to 100 short tons and a production rate of 800 to 2200 short tons/shift. For all types of material, this yields an estimated tire capacity of 3 x 10^5 cubic yards per tire set. If 70% of the 8 x 10^9 cubic yards per year from Table 2.11 is moved by a truck with at least 4 wheels, then surface mining will consume at least 80,000 tires per year.

Belt conveyors are economical for high-volume, long-distance hauling and can handle grades up to about 40%. However, to get long belt life, conveyors must handle fairly small pieces of material, and sometimes have limited mobility. Some materials, principally sand, gravel, kaolin (clay), and phosphates, may be hydraulically conveyed. Hydraulic conveying involves pumping a slurry mixture cross-country in a pipeline. Although this method may dominate transfer of particular materials, the amounts are small when compared to the total amounts of material conveyed by conventional methods. The associated losses will therefore be discounted. Belt conveying will then be assumed to handle 20% of surface-mined materials (the remainder of materials that are not handled by trucking, with 10% left out for all other miscellaneous and railcar).

Conveyor losses are caused by many sources, such as friction in the pulleys, friction of the belt riding over the pulleys, and skirtboard friction from the conveyed material rubbing the sides of the conveyor. The amount of direct energy lost to each interface, excluding the power required to elevate the material, has been estimated by applying formulas published by the Conveyor Equipment Manufacturers Association (CEMA) (1979). The values assumed in estimating direct friction losses in conveyors in Table 2.16 were determined by examining values from mine surveys (Cummins and Given 1973) to apply the CEMA formulas for estimating direct friction losses.

Conveyors were indicated to be very advantageous for haulage distances greater than 10,000 feet. Under the assumptions given above, the direct tribological loss in a belt conveyor was 2 x 10^5 Btu/2000 tons/1000 horizontal feet conveyed. The total direct loss from conveying was calculated based on transporting 20% of all surface-mined materials an average distance of 17,000 feet.

TABLE 2.16. Values Assumed for Estimating Direct Friction Losses in Conveyors

Parameter	Typical Ranges	Nominal Value Used
Belt width	14 - 72 in.	48 in.
Conveyed material weight	50 - 150 lb/cu ft	104 lb/cu ft
Belt speed	250 - 1000 ft/min	500 ft/min
Belt capacity	20 - 8000 tons/hr	2000 tons/hr
Distance conveyed	30 ft - 30 mi	Calculated per 1000 ft

Several examples were calculated, and these losses amounted to 30% to 50% of the power required to drive a conveyor.

Railcars are similar to conveyors in that they can handle high volumes well over long distances. They can also handle coarse, blocky materials. Railcars, however, have a high initial capital cost and are limited to ~3% grade. The literature and interviews indicated that railcars were a declining technology in surface mining, being replaced by trucks or conveyors where new equipment purchase is economically feasible. The losses in railcars therefore were discounted.

2.2.2 Shaft Mining

Shaft mining differs from surface mining in that there is very little of the exposing (removal of overburden) or loading that has been previously described. In shaft mining, the deposit of coal, ore, or mineral is typically removed by a continuous mining system. The continuous miner has many variations, and we will broaden the usual definition to include borers and long wall planers because they all involve some rotating auger or drum studded with teeth, which we will call the cutter drum assembly. This assembly rotates against the mine surface, removing chunks of material with its rows of teeth. The material is then simultaneously gathered, partially crushed, and fed onto an attached conveyor. This conveyor then carries the material to either a dumping station or to the surface. An example of one type of continuous mining machine is shown Figure 2.4. The components that compose the main tribological losses for continuous mining systems are given in Table 2.17 and discussed below. Table 2.18 summarizes the annual U.S. production of underground minerals.

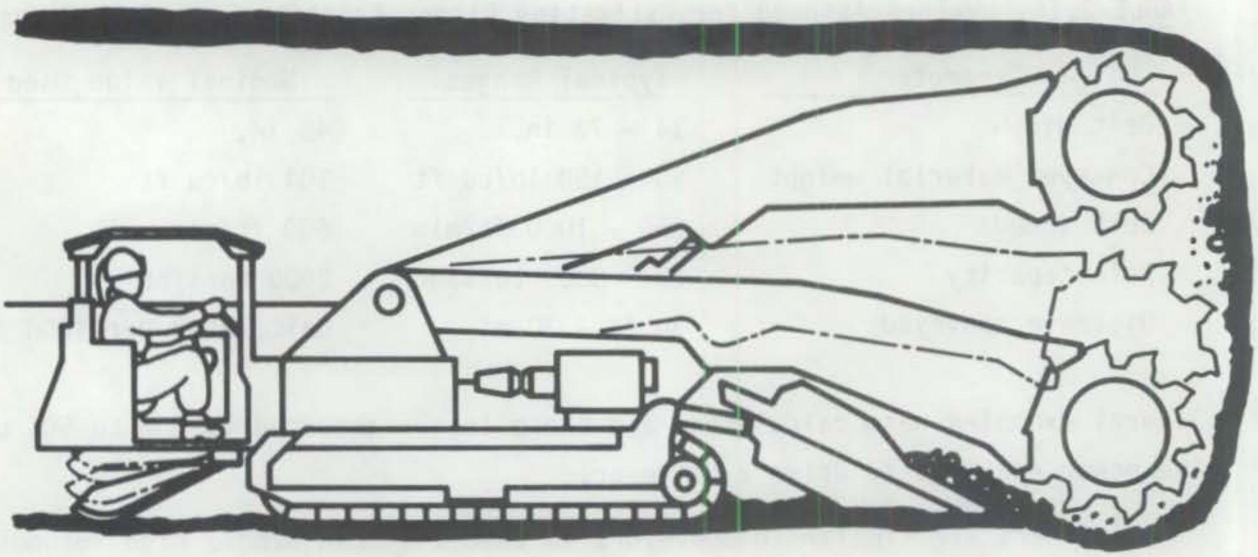

FIGURE 2.4. One Type of Continuous Mining Machine

TABLE 2.17. Shaft Mining

	Direct Loss	Indirect Loss
All types of lubricants	--	3.7×10^{12} Btu/year
Cutter Drum Parts (primarily tooth inserts)	Small	7.0×10^{12} Btu/year
Conveyors	2.4×10^{11} Btu/year	--

TABLE 2.18. U.S. Production of Principal Minerals from Underground Mines (1981)

Mineral	Short Tons of Ore Mined Per Year (million)
Coal	312
Copper	68
Iron	5
Potash	17
Total	402

Lubricants

Many types of hydraulic equipment are used in shaft mining. Roof bolters, roof support jacks, drills, loaders, and the continuous miners all use hydraulics. Much of the lubricant loss can be attributed to improper selection and maintenance of lubricants. Lubricant contamination by dust, air or water is a major cause of wear in hydraulic machinery, bearings, and gearing in the mining industry because a contaminated fluid carries particles that accelerate the tribological processes that the lubricant was intended to combat. In some shaft mining applications, the lubricant must be deliberately diluted with water to reduce fire hazards. This lubricant compromise causes increased wear rates in hydraulic systems.

Seal leakage can account for up to 5000 gallons per day of lubricant loss in long-wall cutter operation. This loss is mainly observed on the 100 to 150 hydraulically actuated roof supports. The fluid lost is typically 5% oil in a water emulsion. Therefore, up to about 250 gallons of oil per day may be lost.

Cutter Drum Parts

Interviews with researchers from several manufacturers of continuous mining systems revealed that the mining action of the teeth is more of a fracture mechanism than a cutting action. A cutting action would involve significant friction losses, whereas fracture of the material involves less friction losses.

Other friction interfaces consistently indicated by the manufacturers and one mine operator were the chassis bottom, propulsion treads, and conveyors. Tribological losses in the first two wear areas were indicated as being negligible. The conveyor losses, however, will be discussed in the following section.

The replacement rate of the continuous miner teeth was estimated both by a mine manager and manufacturers of the equipment.(a) On the average, where some

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(a) Personal communication with Frank Kendric, Product Manager for Continuous Miners, Joy Manufacturing Company, Pennsylvania, February 14, 1984.

rocks are encountered in the cutting, 1 cutter bit will need to be replaced per 5 tons of ore. Cutting pure coal, potash, soda ash, or salt will require 1 bit per 20 tons.

Conveyors

The same assumptions used for conveyors in surface mining apply here. The principal materials conveyed, taken from Table 2.18, are coal, iron ore, copper ore, and potash. The average distance conveyed in shaft mining is ~12,000 feet.

2.3 ORE PROCESSING

Grinding (e.g., milling, pulverizing) materials that have been mined results in a significant amount of both direct and indirect tribological energy losses. Although "ore processing" is used in processing a large range of materials, most of the discussion in this section will focus on metals because of the large tonnages involved and the highly abrasive behavior of metal ores.

Processing components that experience tribological energy losses include the following:

- crushers
- grinding mills
- slurry pumps
- cyclone separators.

As discussed in the following paragraphs, while the other components should not be ignored, grinding mills account for the largest tribological energy losses.

2.3.1 Direct Energy Losses in Ore Processing

In the copper industry, ~30% of the total energy expended is used to concentrate the ores from typical values of 0.5% copper ores (as mined) (Chang, Danver and Cigan 1975). Concentration is accomplished by crushing and grinding ores into powder (85% minus 100 mesh) from which gangue (rock and useless minerals) and metal are separated. This process requires about 24×10^6 Btu per ton of copper produced. Of this energy consumption, about 0.25% is lost in the mill support bearings; 1.5% is lost in the main gears; and up to 0.75% is lost in additional reducer gears when they are required. The bearing friction loss in milling various metals was computed by assuming a conservative total tribological loss of (.25 + 1.5) = 1.75% (ignoring reducer gear losses). Table 2.19 summarizes direct tribological energy losses from bearings in selected milling operations in the U.S.

2.3.2 Indirect Energy Losses

The wear rates for key steps in ore processing are listed in Table 2.20. As the table indicates, wear of ore grinding equipment represents the largest indirect tribological loss in ore processing. This loss comprises an average of about 1.5 pounds of iron alloy (balls, rods and liners) per ton of ore or minerals ground. Alternatively, in milling coal for power plants, only 0.004 pound of steel is worn per ton of coal processed. This difference

TABLE 2.19. Direct Tribological Energy Losses in Grinding

Industry	Year	Grinding Energy (10^{12} Btu)	Direct Tribological Portion of Grinding Energy (Bearing Losses) (10^{12} Btu)(a)
Copper	1973	39.5	0.69
Aluminum	1973	3.5	0.03
Iron	1973	40.9	0.72

(a) Bearing losses in grinding = 0.75% x grinding energy.

TABLE 2.20. Wear Rates in Key Ore Processing Steps (Tefler 1980)

Process Step	Wear Rate (grams metal/tonne)
Crushing	50
Screening	2
Grinding	700
Pumping	5
Classifying	3
Mineral separation	2

reflects the observed variations in abrasion between coal and other materials. Because this wear represents an embodied energy of ~35 x 10^6 Btu per ton, the indirect tribological energy loss for ore grinding is estimated to be ~26.25 x 10^3 Btu per ton of ore or minerals ground per year. Based on the production figures presented in Tables 2.11 and 2.18 for materials that are typically ground (iron ore, copper ore, clay, phosphate, and potash), the total tribological loss associated with wear from grinding is ~1.85 x 10^{13} Btu/year.

Crushing constitutes the second greatest source of indirect energy loss. The magnitude of loss in ore crushing is only about 7% as large as that for ore grinding per ton; however, more minerals are subject to crushing. The total tribological loss associated with crushing is estimated to be 4.3 x 10^{12} Btu/year.

2.3.3 Other Ore Processing Activities

The remaining areas where tribology influences ore processing include slurry pumps and cyclone separators. Slurry pump impellers and cases are subject to erosion and low stress abrasion, and they require fairly frequent replacement. Generally, back-up pumps are included to allow the system to continue operating during pump maintenance. Although wear of slurry pump components is significant to plant operations, it does not constitute nearly as much embodied energy as does wear of grinding mill media.

Cyclone separators are used to separate fine ore particles from larger particles that must return to the mill. Although they do experience wear, the resultant material loss is not a major concern. Of minor importance is that orifice wear can affect classifier efficiency. Consequently, frequent maintenance checks are needed.

2.4 DRILLING

A rotary drilling rig, shown in Figure 2.5, is used primarily for oil and gas extraction, and to a lesser extent for water, sulfur, carbon dioxide, and geothermal wells. The three rig components with significant tribological losses are shown in Figure 2.5: the mud pump, drill string, and bit.

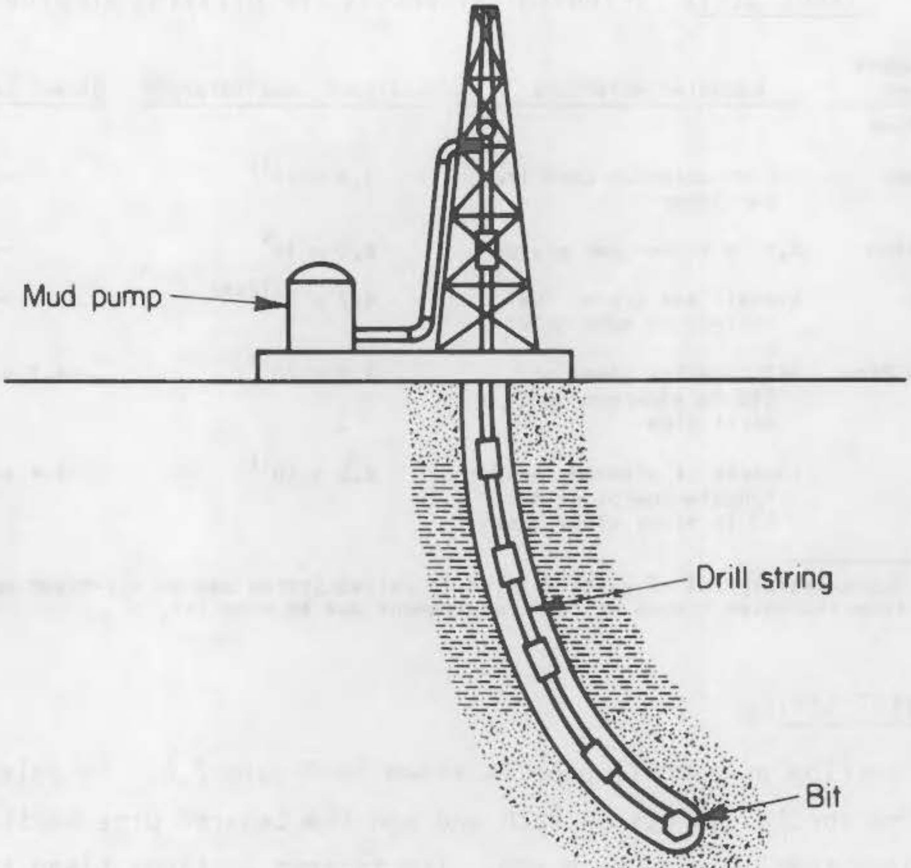


FIGURE 2.5. Rotary Drilling Rig--Tribological Components Having Significant Tribological Losses

The bit, which cuts or breaks the rock, screws on to the drill string, which is several pipe sections fastened together with special joints. The drill string is driven from above ground, generally by a diesel engine, and subsequently turns the bit. The mud pump is used to pump a lubricant/coolant down the drill string, through the bit, and back up the hole, carrying away chips cut by the bit. Table 2.21 summarizes the significant tribological losses for drilling components. The following sections contain more detailed descriptions of the components listed in Table 2.21, including their geometry, function, and failure mechanisms.

TABLE 2.21. Tribological Losses for Drilling Components

Component Name	Embodied Materials	Indirect Loss (Btu/yr)	Direct Loss (Btu/yr)
Mud Pump			
Liner	150 lb chromium cast iron per liner	1.9×10^{10}	--
Piston	2.5 lb rubber per piston	6.0×10^{9}	--
Mud	Asphalt and diesel fuel (oil-based muds only)	4.7×10^{12}(a)	--
Drill Pipe	540 lb alloy steel or 320 lb aluminum per drill pipe	2.6×10^{11}	4.3×10^{11}
Bits	Inserts of diamond, and/or tungsten carbide in 40 lb alloy steel base	6.2×10^{11}	1.4×10^{11}(b)

(a) Approximately 20% of wells drilled in United States use an oil-based mud.
(b) From increased torque or time requirement due to worn bit.

2.4.1 Drill String

One section of a drill pipe is shown in Figure 2.6. Notable features include the special joints on each end and the tapered pipe sections approximately three feet long on each end. The tapered sections blend the pipe ends to the long center section of the constant cross-sectional area.

The drill string is smaller in diameter than the drill bit and consequently smaller than the hole drilled. A direct tribological loss results because of friction at the interface of the drill string and drill bit. The bit tends to deviate from drilling a straight hole because of several factors, including the high load on the bit, the hardness of the rock formations being drilled, and inclinations of the earth's formations. The resultant curvature in the hole causes the drill string to rub at the tool joints as it bends around these curves. Table 2.21 shows the resulting energy loss.

The loss was calculated using the assumptions of Table 2.22, which were found in the literature (Dunnett 1974; Lubinski 1961) and obtained through conversations with drilling contractors and drilling component manufacturers. The force generated at the pipe-to-hole wall by the bending and tension of the pipe was arrived at by A. Lubinski as "A tentative but rather conservative

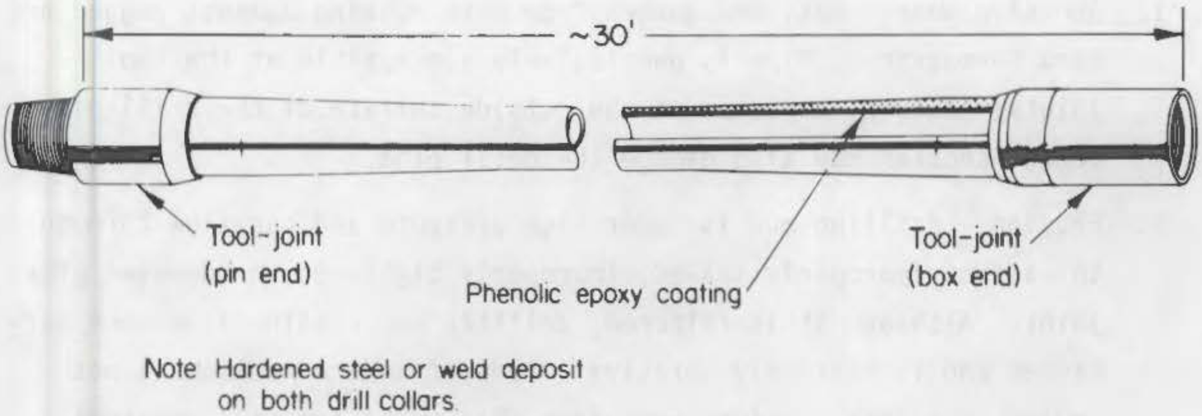


FIGURE 2.6. Anatomy of a Drill Pipe

TABLE 2.22. Operating Conditions of a Rotary Drilling Rig

Value	Range	Nominal Value
Drilling Speed	0 to 200 rpm	100 rpm
Pipe Outside Diameter	2.4 to 6.6 in.	4.5 in.
Pipe-to-Wall Friction in Drilling Mud	0.05 to 0.25	0.10
Pipe Length Between Tool Joints	18 to 45 ft	30 ft
Hole Curvature	0 to 10°/100 ft	1.5°/100 ft
Force at Pipe-Wall Interface	0 to >6000 lb	2000 lb
Drilling Penetration Rate	5 to 50 ft/hr	50 ft/hr

value of the maximum tolerable value of the tool joint-to-wall force ..." (1961). The conservative estimate of this force will lead to a conservative estimate of the direct loss. The faster end of the typical drilling penetration range was also used to yield the most conservative estimate of the direct energy loss.

The drill pipes that make up the drill string are attacked by various mechanisms, both tribological and otherwise, which result in indirect loss of drill pipe components and eventually the entire drill pipe. The causes and sites of tribological attack on the pipe are as follows:

1. Abrasive Wear - cuts and gouges from pipe rubbing against ragged and hard formations. Pipe is particularly susceptible at the tool joints; however, abrasion of the outside surface of the drill pipe center section may also damage the drill pipe.
2. Erosion - drilling mud is under high pressure and can flow through threads of improperly sealed, improperly tightened, or damaged pipe joint. Although it is filtered, drilling mud retains fine rock particles and is extremely abrasive. Even if severe erosion is not caused by a leak, uniform wear from this mechanism will eventually reduce the pipe cross-sectional area, thereby reducing the pipe's load-carrying capability.

The causes and sites of attack of nontribological mechanisms are listed below because they interact with and are compounded by the tribological mechanisms.

1. Corrosion - occurs particularly in dents and scratches in tool joints caused by tongs and chains used to tighten pipe sections together or slips used to suspend pipe. Drilling lubricant (mud) often contains corrosion inhibitors, but pipe can rust away while standing idle in racks exposed to air. Insides of pipes are protected from corrosion (and wear to some extent) by a coating of phenolic epoxy.
2. Fatigue - the drill string must endure cyclic stresses when rotated in a crooked hole. The failure often occurs at a stress riser caused by any of the above mechanisms (such as an abrasive-wear scratch).

Drill pipe is reconditioned several times before being retired as an indirect loss. A drill pipe's life cycle is as follows. It starts out as Class 1, new pipe, in accordance with the American Petroleum Institute's Inspection and Classification System. As it is used, it is inspected at various times for wall wear, dents, crushing, stretching, cuts, gouges, corrosion, cracks, and erosion. In some cases, a complete tool-joint replacement is welded on to save a drill pipe. As a pipe degrades from the above mechanisms, it is moved to Class 2 and Class 3 for weakened pipe. These classes of pipe will not be used in critical applications such as very deep holes where a pipe failure is very costly. The extent of the repair performed on drill pipe is evidenced by the existence of companies whose sole purpose is to repair pipe defects. The life predictions for the drill string were taken from conversations with one of the companies that repair drill pipe.

2.4.2 Mud Pumps

As previously described, a mud pump delivers cutting fluid (called drilling mud) down the drill string to flush drilled chips to the surface. The entire mud pumping system is shown in Figure 2.7. The mud flows from the supply tank, down the drill string, and back up the hole to return to the mud tank. During this trip, the mud performs several functions, including removing the cuttings from the hole, cooling and lubricating both the bit and drill string, and exerting hydrostatic pressure to support the hole wall.

Drilling Mud

The term "drilling mud" indicates a liquid (water or oil) with solid in suspension. The water-based fluids are used more often than the oil-based fluids because water is less expensive than oil, and a typical hole will require thousands of gallons. The properties of the mud are adjusted by additives. Hundreds of additives are produced under various trade names; however, their intended function may be broken down into just a few categories. Some additives adjust the viscosity and flow properties; some adjust the density of the mud, and others plug leaks in the hole wall by a process called filtration.

Although the mud passes through mechanical desanders and desilters, a large fraction of the drilled solids remain in suspension (Goldsmith and Hare 1982). The mud is then a fine slurry of rock and minerals that is highly abrasive. The effects of the abrasive wear of the mud on the drill string have already been discussed. The following discussion focuses on abrasive wear in the mud pump itself.

Mud Pump Cylinder Liners

The pumping of the highly abrasive mud, as described above, has long been recognized as a significant wear problem. For this reason, the mud pump has

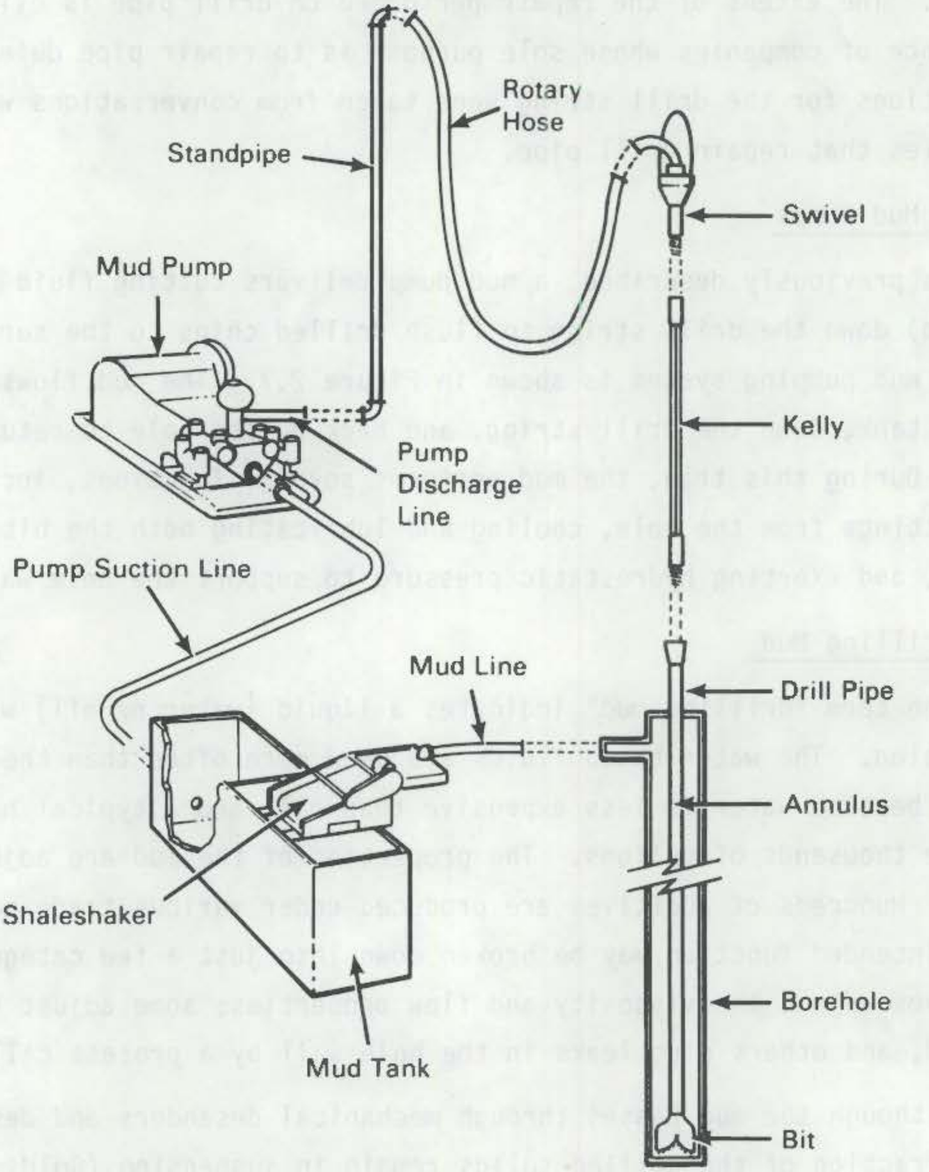


FIGURE 2.7. Drilling Mud Pumping System

been designed with expendable internal parts. The core of the pump is shown in Figure 2.8. In that figure, the cylinder liner (shown in cross section) is a replaceable insert in which the rubber piston reciprocates. The chamber typically operates under very high pressures of ~2000 psi. Fine particles of mud are trapped at the piston-cylinder interface and cause three-body abrasive wear and erosion as the mud leaks past the piston (Lewis 1981).

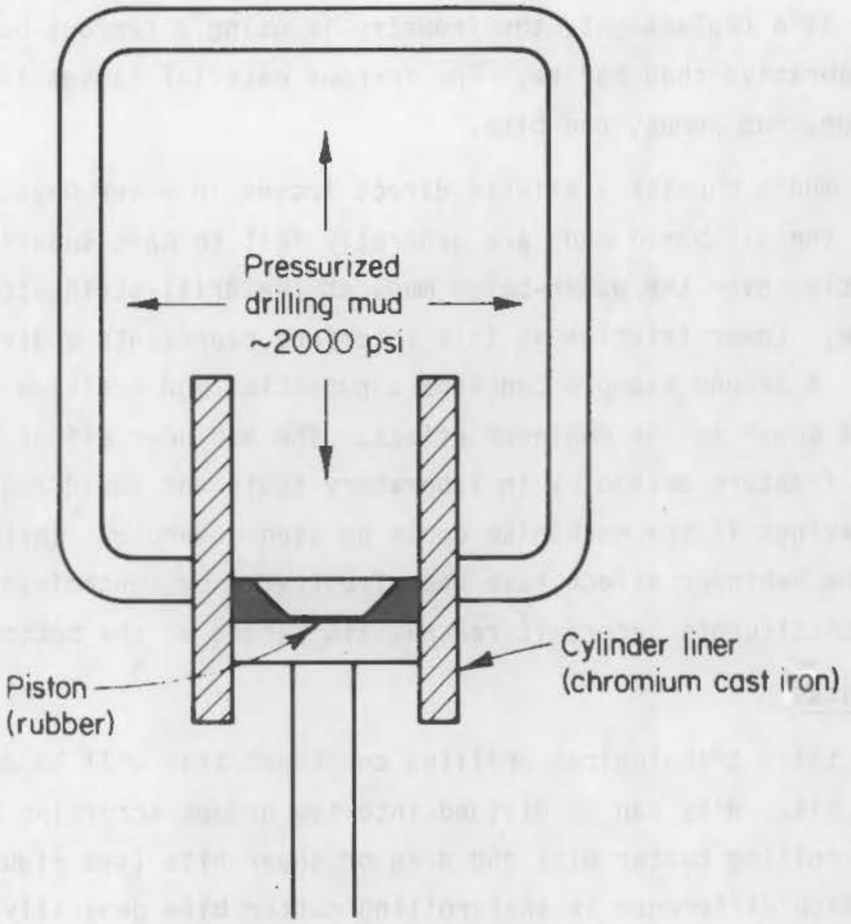


FIGURE 2.8. Schematic Drawing of Mud Pump Compression Chamber

Mud Pump Pistons

A mud pump piston, shown in Figure 2.8, is typically a 6- to 7-inch-diameter rubber disk bolted to a steel piston rod. The pistons are also destroyed by the wear at the piston-wall interface. They typically must be replaced 10 times as often as the cylinder wall. This replacement frequency requires breaking down the pump as often as every 5 to 10 days.

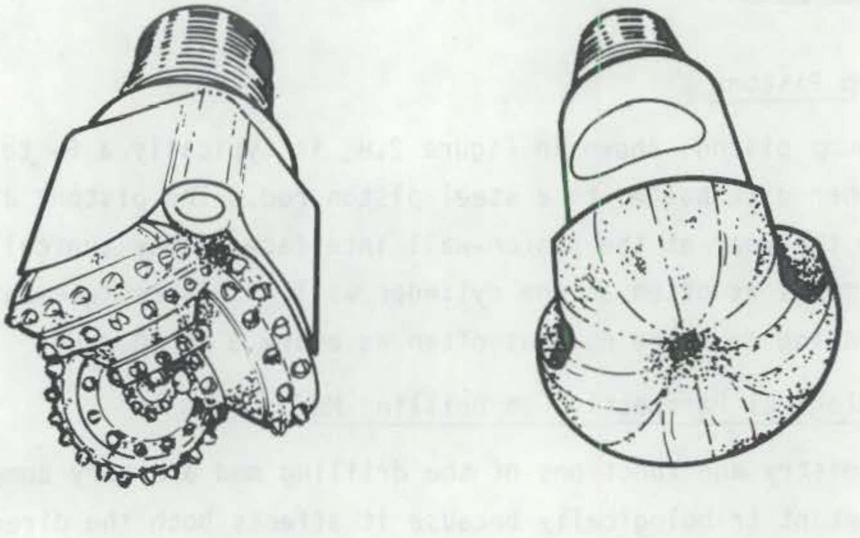
A Tribological Perspective on Drilling Mud

The chemistry and functions of the drilling mud are very complex. The mud is very important tribologically because it affects both the direct and indirect losses of many of the other components in the drilling rig. For example, barite is a mineral product commonly used to vary the mud density. Drilling contractors and product manufacturers indicated that a barite shortage exists. As a replacement, the industry is using a ferrous-based compound that is more abrasive than barite. The ferrous material causes increased wear on drill pipe, mud pumps, and bits.

The mud's chemistry affects direct losses in other ways, also. For example, the oil-based muds are generally felt to have superior lubricating capabilities over the water-based muds at the drill-string-to-hole-wall interface. Lower friction at this interface represents a direct energy savings. A second example concerns a potential mud additive to enhance a phenomena known as the Rebinder effect. The Rebinder effect has been shown to aid rock fracture mechanics in laboratory tests and could represent a direct energy savings if the mechanism could be used downhole. Initial attempts to induce the Rebinder effect have been frustrated by contaminants that dilute the active constituents before it reaches its target at the bottom of the hole.

2.4.3 Bits

The third tribological drilling component that will be considered is the drilling bit. Bits can be divided into two groups according to their basic design: rolling cutter bits and drag or shear bits (see Figure 2.9). The basic design difference is that rolling cutter bits generally have three cones



Rolling Cutter Bit

Shear or Drag Bit

FIGURE 2.9. Two Basic Drilling Bit Designs

supported by bearings, whereas the shear bits are rigidly fixed to the drill string. The tribological attacks and defenses of each type of bit are described below. More emphasis will be given to the rolling cutter bits because they represent ~90% of the current bit market.

Shear Bits

Most shear bits currently in use are polycrystalline (man-made) diamonds mounted on tungsten carbide--extremely wear-resistant materials. The main cause of failure for these bits was reported to be three-body abrasive wear. The wear sometimes degrades the surrounding alloy, allowing the inserts to be lost. Under extreme mud pressure and velocities, the surrounding metal will also erode. As stated above, however, the general cause of failure is abrasive wear in the extremely aggressive environment at the bottom of the hole.

Rolling Cutter Bits

This type of bit consists of three alloy steel cones each having rows of teeth. The teeth can be composed of a solid hard material or a diamond or carbide insert, or can be studded with wear-resistant inserts. The rollers are supported by both radial and thrust bearings. Rolling cutter bits fail because of seal failures, which lead to bearing failures, wear of the inserts and supporting material and, occasionally, fracture of a cone or erosion of the steel that supports the inserts. Conversations with two major bit manufacturers indicated that 75% to 80% of the bits fail in the bearing seals, and this failure allows drilling mud to abrasively destroy the bearing. The bearing seals are weakened by extreme pressures, high temperatures from geothermal and frictional heating, chemical attacks from corrosive deposits drilled, or simply abrasive attack of the drilling mud. The remaining 20% to 25% of the bits were indicated to simply having been worn out in three-body abrasive wear.

A Tribological Perspective on Bits

The bit condition directly affects the direct energy losses in the drill string. If a bit is worn, the drilling rig operator can either allow reduced penetration rates or raise the drill string load and resulting torque to maintain a given drilling rate. If the bit penetration rate is reduced 50%, the drill string will have to turn twice as long, and all of the energy consumed during the longer drilling time is the result of reduced bit performance. If the drilling load and torque are raised, the additional torque requirement represents a direct energy loss. The indirect and direct losses have been estimated and are included in Table 2.21.

These two parameters, the rate of penetration and drilling torque, are therefore two of the drilling parameters that are monitored and used to determine when the drill string should be pulled to change bits. The process of pulling up a drill string, called "tripping out" by the industry, is costly both in terms of time and energy. For this reason, there is continuing research on bit life.

One technology that is being used more frequently partly because of tribological advancements is the downhole drilling motor. There are two designs of bit drives that do not rely upon the drill string to rotate the bit but rather generate the torque at the bottom of the hole. These are called downhole bit motors. Both of the designs convert the hydraulic energy of the drilling mud to mechanical power. Because the drill string is not required to turn, frictional energy losses are reduced and indirect loss savings result from reduced damage to the drill pipe.

2.5 SUMMARY OF TRIBOLOGICAL ENERGY LOSSES IN MINING

Tables 2.23, 2.24, and 2.25 summarize the tribological energy losses associated with the principal mining operation activities. The generic tribological mechanisms contributing to energy losses for each operational activity are identified in Table 2.23. Direct and indirect energy losses are given in Tables 2.24 and 2.25, respectively. Additional information on the principal energy form consumed by an operation, the energy loss rate, material type worn, and material wear rate is also provided in Tables 2.24 and 2.25.

Three-body abrasion was identified most often as contributing to tribological losses in mining activities. The next two most common sources were impact wear and high friction. Of course, the most commonly occurring loss mechanisms are not necessarily the cause of the largest energy losses. While it is important to recognize where and how tribological losses are occurring, the information provided in Table 2.23 is more qualitative than quantitative.

TABLE 2.23. Generic Tribological Loss Mechanisms in Mining

Operational Activity	Generic Tribological Mechanism[(a)]					
	(1)	(2)	(3)	(4)	(5)	(6)
Surface Mining						
Exposing and Digging	X	X	X	X		X
Loading	X		X			
Transporting	X			X		
Shaft Mining						
Digging	X		X			X
Transporting	X			X		
Ore Processing	X		X	X	X	X
Drilling						
Mud Pumps	X				X	
Drill Pipe	X	X		X	X	
Bits	X	X	X		X	

(a) (1) Three-Body Abrasion.
(2) High-Stress Gouging.
(3) Impact Wear.
(4) High Friction.
(5) Erosion.
(6) Lubricated Wear.

Indirect tribological losses are almost five times greater than direct losses in mining. Indirect tribological losses are associated with the wearing out of equipment and also include lubricant losses and drilling mud consumption. The principal indirect loss items are crushers, grinders, truck tires, digging equipment teeth, and drilling mud. Carbon or low-alloy steel is the most common material subject to wear and also contributes the most to the indirect energy total.

Direct tribological losses are associated with the energy to overcome friction between two surfaces. The most important direct loss items are power

TABLE 2.24. Annual Direct Tribological Energy Losses in Mining

Operational Activity	Principal Energy Form Consumed	Energy Loss Rate	Total Energy Loss (10^{12} Btu)
Surface Mining			
Exposing and Digging	Electricity	625 Btu/yd^3	5.0
Loading	Diesel	9 Btu/yd^3	0.07
Transporting	Electricity	528 Btu/ton-mile	3.8
Shaft Mining			
Digging	--	--	--
Transporting	Electricity	528 Btu/ton-mile	0.24
Ore Processing	Electricity	1.75% of grinding energy	1.44
Drilling			
Mud Pumps	--	--	--
Drill Pipe	Diesel	1200 Btu/ft drilled	0.43
Bits	Diesel	400 Btu/ft drilled	0.14
			11.12

TABLE 2.25. Annual Indirect Tribological Energy Losses in Mining

Operational Activity	Material Type Worn	Material Wear Rate	Total Energy Loss (10^{12} Btu)
Surface Mining			
Exposing and Digging	Steel	27,250 ton/yr	1.2$^{(a)}$
Loading	Steel	1,750 ton/yr	0.06
Transporting	"Rubber"	0.03 lb/yd^3	12.0
Shaft Mining			
Digging	Steel	1 lb/ton	10.7$^{(a)}$
Transporting	--	--	--
Ore Processing	Steel	1.5 lb/ton	22.8
Drilling			
Mud Pumps	Cast iron, "rubber"	2 lb iron/1,000 ft 2.5 lb rubber/10,000 ft	4.7$^{(b)}$
Drill Pipe	Alloy steel, aluminum	7.3 lb steel/1,000 ft 4.3 lb alum./1,000 ft	0.26
Bits	Alloy steel	69 lb/1,000 ft	0.62
			52.34

(a) Total energy loss includes lubricant loss.
(b) Total energy loss includes drilling mud consumption.

shovels, draglines, and conveyors. Direct energy loss activities in mining were found to be consumers of electricity and/or diesel fuel. The largest direct loss items (noted above) principally consumed electricity.

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3.0 AGRICULTURE

Agriculture is the work of cultivating the soil, producing crops, and raising livestock. Mechanization has replaced most human and animal labor in agriculture over the last several decades, and this machinery and other farming materials require enormous amounts of energy. An important element of this agricultural energy consumption can be attributed to tribology. The purpose of this chapter is to identify where significant tribology sinks exists in agriculture and to estimate the energy consumption in these sinks.

3.1 INTRODUCTION

The agricultural industry includes several major groups of the Standard Industrial Classification (SIC) (Table 3.1). Some of these groups overlap with other main industry groups, such as chemicals and mining. This chapter focuses on crop production because it accounts for 80% to 90% of the total agricultural energy budget. A limited review of tribology sinks in livestock production is also included. The tribological sinks in agricultural chemical production and mining are covered in the mining and chemicals chapters (2.0 and 5.0) of this report, so are not included here. Agricultural services were excluded from the review because of the apparent lack of tribology sinks having significant energy use.

3.1.1 Agriculture End-Use Energy Consumption

The primary mechanized activities in crop production include 1) soil preparation, 2) planting, 3) cultivation, 4) harvesting, 5) processing, and

TABLE 3.1. Major Agricultural Groups of the Standard Industrial Classification

SIC Code	Description
01	Crop Production
02	Livestock Production
07	Agricultural Services
28	Chemical (mainly 287-agri chemicals)
14	Mining (mainly 147-chemical and fertilizer mining)

6) transportation. For livestock production, the main mechanized activities include feed transport, husbandry, processing, and market transportation.

The total energy consumption in agriculture in 1978 was 2.037 quad and is shown in Tables 3.2 and 3.3 for each end use in crop and livestock production, respectively. For crop production, soil preparation before planting accounts for 0.173 quad per year, largely for powering agricultural machinery. Planting and cultivation consume less energy, 0.097 quad annually. Harvesting requires about 0.154 quad per year, while transportation requires 0.197 quad per year.

TABLE 3.2. Energy Input by Farm Function and Region for Crop Production, 1978 (U.S. Department of Agriculture 1980)

Farm Function	Total (billion Btu)	Percent
Preplanting	173,388	9.5
Planting	47,516	2.6
Cultivation	49,997	2.8
Harvest	154,125	8.5
Farm Pickup	129,767	7.1
Fertilizer Applic.	12,873	0.7
Pesticide Applic.	16,897	0.9
Farm Trucking	67,733	3.7
Farm Auto-Crops	60,767	3.3
Grain Handling (Vehs)	1,903	0.1
Grain Handling (Mach)	116	0
Crop Drying (On-Fm)	71,482	3.9
Irrigation	252,147	13.9
Frost Protection	39,829	2.2
Fertilizer	651,876	35.9
Pesticides	68,202	3.8
Electricity	5,802	0.3
Miscellaneous	14,142	0.8
Total	1,818,562	100.00

TABLE 3.3. Energy Input by Operation and Region for Livestock Production, 1978 (U.S. Department of Agriculture 1980)

Operation	Total (billion Btu)	Percent
Lighting	5,829	2.67
Feed Handling	64,808	29.66
Waste Disposal (Vehs)	23,345	10.68
Waste Disposal (Mach)	1,586	0.73
Water Supply	5,169	2.37
Livestock Handling	2,547	1.17
Space Heating	5,757	2.63
Ventilation	6,114	2.80
Water Heating	9,737	4.46
Milking	2,711	1.24
Milk Cooling	4,451	2.04
Egg Handling	104	0.05
Brooding	26,679	12.20
Farm Vehicles	36,493	16.70
Farm Auto-Livestock	8,607	3.93
Other	14,592	6.67
Total	218,529	100.00

The primary energy stream in livestock production is the handling of feed and livestock (0.067 quad per year). The other main energy streams include waste disposal, 0.025 quad; ventilation, milking, and egg handling, 0.014 quad; and transportation at 0.045 quad. The total of these end uses is 0.15 quad, representing 68% of total livestock production energy use and 11% of the total energy use in agriculture. This energy information was used to identify the agricultural processes having the most significant energy use. Transportation of crops/livestock on roadways was excluded because these tribological mechanisms and energy losses are addressed in separate research for the Tribology Program by MTI. In this chapter the main tribological sinks are identified and described, including the mechanisms involved in the sinks and the estimates of direct and indirect energy use in the sinks.

3.1.2 Major Agricultural Processes

As noted earlier, the two major agricultural processes that consume the most energy are crop and livestock production.

Crop Production

Two indicators of a historical trend in crop production, human labor per acre and pounds of machinery per acre, are shown in Figure 3.1. Although the exact magnitude of values, such as pounds of machinery used to produce an acre of grain, is uncertain, the trend has clearly been toward increased mechanization.

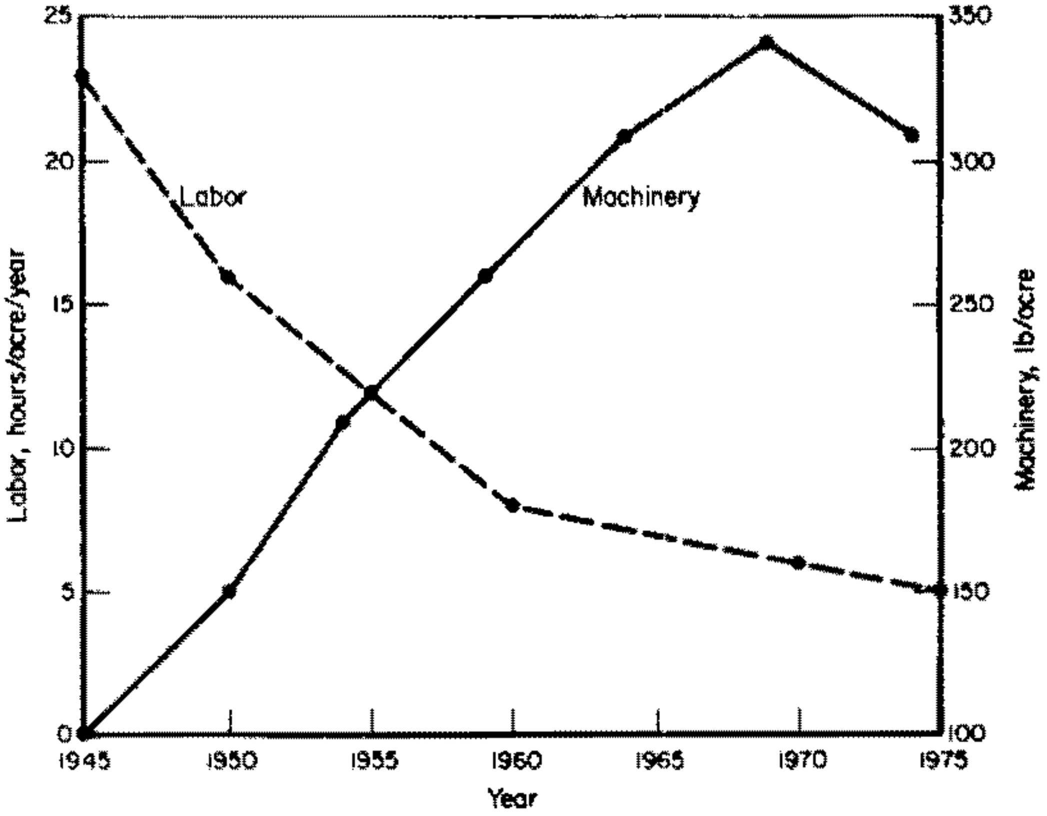

FIGURE 3.1. Labor and Machinery Inputs for Production of Grain Corn

Managing machinery costs has become a vital concern of the American farmer. A review of the industry for tribological losses showed that some machinery costs, such as capital recovery and other fixed costs, had been tracked and computed accurately. Machine life expectancies are well established, and fuel and labor inputs to farming can also be predicted with confidence. Repair and maintenance costs, however, are highly variable and are subject to much more speculation in the literature. Various studies have applied statistical analysis to samples as large as 1400 farms in one case and over periods as long as 8 years in another case (Fairbanks, Larson and Chung 1971; Bowers and Hunt 1975; Clark and Johnson 1975; Smith and Oliver 1975; Richardson, Jones and Atwood 1967; Hunt Undated; Holn 1975; Bowers 1975; and Lockeretz 1977). The difficulty remains, however, in determining what portion of machinery failures may be attributed to tribological mechanisms.

The total acreages used in 1983 crop production for various crops are shown in Table 3.4. The farms that produced these crops could be classified in two broad categories. The first category may be described as the family farm, typically ranging in size up to 700 acres. This farm would support several tractors in the 50 to 150 horsepower range. The various pieces of machinery on these farms operate 100 to 500 hours per year (Fairbanks, Larson and Chung 1971; Bowers and Hunt 1975; Clark and Johnson 1975; Smith and Oliver 1975; Richardson, Jones and Atwood 1967; Hunt Undated; Holn 1975; Bowers 1975; and Lockeretz 1977).

The second classification, a corporation farm, encompasses much larger acreages. Hunt (undated) describes a corporation farm as having at least 10,000 acres. This type of farm can support thirty 100-horsepower tractors, or might use fewer but larger capacity tractors (ranging from 150 to 400 horsepower). The various pieces of machinery would operate about 1000 hours per year.

Up to this point, tractors are the only farm equipment that has been specifically named. Surveys of all farm machinery can easily include close to a hundred distinct items; however, many of the items are very few in number or consume very little energy and therefore have not been included in this tribological energy loss evaluation.

TABLE 3.4. Crop Production Acreages for 1983 (U.S. Department of Agriculture 1983)

Crop	Area Planted (1000 acres)	Area Harvested (1000 acres)
Corn (all purpose)	82,000	73,000
Hay (all)	--	61,000
Wheat	87,000	79,000
Soybeans	72,000	71,000
Cotton	11,000	9,700
Fruit	--	--
Sorghum (grain)	16,000	14,000
Vegetables	2,200	2,200
Rice	3,300	3,300
Tobacco	--	910
Oats	14,000	11,000
Barley	9,600	9,100
Sugar cane	--	760
Sugar beets	1,100	1,000
Peanuts	1,300	1,300

The initial step in identifying the major tribology sinks for crop production was to prioritize U.S. crops by energy use. The processes and machines corresponding to these crops were then examined for tribological energy sinks. Figure 3.2 quantitatively compares the energy inputs for the crops. The data indicate that the top four crops, corn, hay, wheat, and soybeans, constitute 58% of the total energy consumed in crop production (Industrial Energy-Use Data Book 1974). The energy consumed by these crops suggests that the various processes used in raising these crops should be emphasized in considering tribological energy sinks. The machinery used on these crops is also used for many of the smaller volume crops. Therefore, the study of the top four crops incorporates technologies of most crops produced.

Table 3.5 shows, according to the production processes, the machinery used in crop production. The table shows that even over the wide variety of crops, a few machines are common to a particular process. Column two of the table,

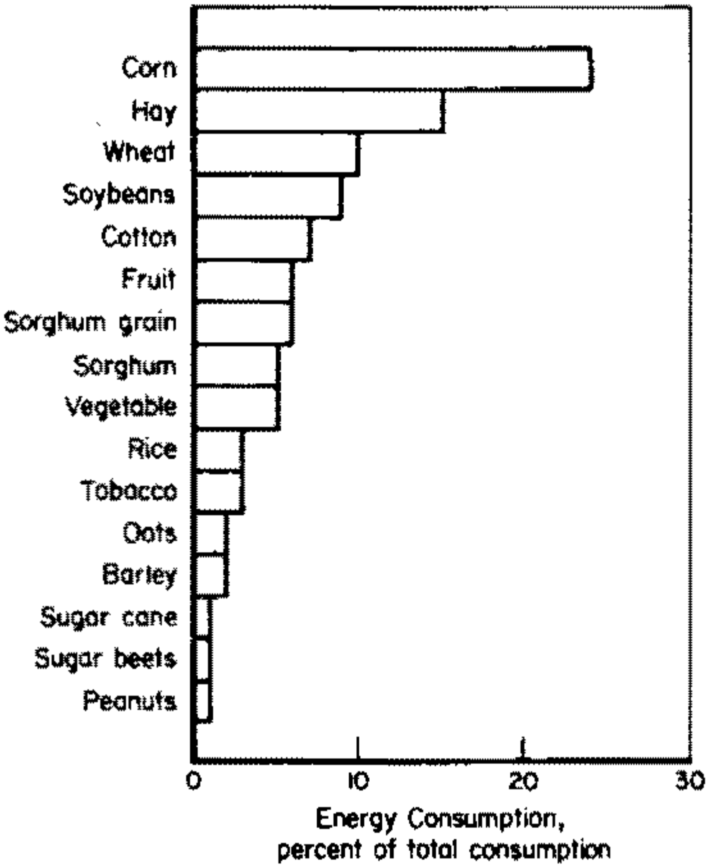

FIGURE 3.2. Energy Consumption in Crop Production by Respective Crop

which represents the tillage process, shows that seedbed preparation is performed by a tractor pulling one or more of a variety of implements. The only notable exceptions are hay and fruit, neither of which require primary tillage. Column three of Table 3.5, the process of planting, shows that row crop planters and grain drills are adapted to plant most crops. The only exception in a major crop is the planting of some small grain seeds (such as hay) with broadcasters.

Irrigation (column four) is applied to varying extents according to crop type and meteorological location. Centrifugal pumps are used primarily to drive one of five major irrigation system types.

Several special-purpose machines are used in harvesting specific crops (column five), such as sugar beet diggers and blueberry pickers. However, a

TABLE 3.5. Machinery Used in Crop Production

Crop	Tillage(a)	Planting	Irrigation % of Crop (1978)	Harvest	Transportation
Corn	Tractor and A-G	Row Planter	13	Combine with corn head	Conveyors, augers, wagons and trucks
Hay	Infrequent	Tractor, disk and broadcaster	22	Mower, conditioners, hay rake, baler	Front-end loaders and conveyors
Wheat	Tractor and A-G	Grain drill (90%) broadcaster (10%)	6	Combine with grain head	Similar to corn
Soybeans	Tractor and A-G	Row planter and grain drill	2	--	Similar to corn
Cotton	Tractor and A-G	Row planter	37	Combine (50%) handpick and custom machines (50%)	Similar to hay
Fruit	--	--	66	Handpick and custom machines	Conveyors, wagons and trucks
Sorghum	Tractor and A-G	Similar to corn	15	Combine with corn head	Similar to corn
Vegetables	Tractor and A-G	Varied	58	Combine (for several types), custom machines and handpicked	Conveyors, wagons and trucks
Rice	Tractor and A-G	Airplane or grain drill	100	Combine	Similar to corn
Tobacco	Tractor and A-G	Transplanted	13	Combine and handpicked	--
Oats	Tractor and A-G	Grain drill and broadcaster	2	Combine	Similar to corn
Barley	Tractor and A-G	Grain drill and broadcaster	22	Combine	Similar to corn
Sugar cane	Tractor and A-G	Lister	NA	Topper, windrower	Front-end loader and trucks
Sugar beets	Tractor and A-G	Lister	NA	Sugar beet harvester	Conveyors, wagons and tractors
Peanuts	Tractor and A-G	Row planter	23	Combine	Conveyors, wagons and trucks

---

(a) Entries in this column are coded as follows:
A. Moldboard plow, B. Disk plow, C. Chisel plow, D. Field cultivator, E. Harrow, F. Disk cultivator, and G. Row cultivator.

very high percentage of crops (71%) are harvested with a combine. The combine will be described and illustrated in a later section where its tribological components are examined in detail. The only major crops not harvested with a combine are hay and forage. Hay involves an almost entirely different process of mowing, raking, and baling. Forage harvest is performed with a machine called a "forage harvester."

Crop handling and transportation is the final category included in Table 3.5. The machinery commonly applied are augers and conveyors, which load wagons and trucks for transportation to the first stations of the food processing industries.

In summary, crops fit very well into the classification scheme used, with the exception of hay, which must be considered separately in nearly all steps of crop production.

Livestock Production

The energy used in livestock production is typically less than one-fifth of total energy used in agriculture. Of the total energy input, beef and dairy cattle consumed 65%, hogs 17%, and chickens 14%. In 1982, the U.S. Department of Agriculture (1983) reported that the livestock produced constituted 115 million cattle, 53 million hogs, and 246 million chickens. As with crop production, the various types of livestock were examined for machinery required in the various production processes.

In Table 3.6 the livestock production processes that were found to be subject to tribological mechanisms are listed as column headings. The row headings are the various types of livestock produced: cattle, sheep, hogs, and turkeys and chickens. The table shows that even over the wide variety of livestock, a few machines are common to a particular process.

Automatic systems often feed and water livestock. Grain and other solid food concentrates are carried from silos and storage bins directly to the feeding troughs through conveyors and augers similar to those described in crop production. Water is also supplied by automatic systems. Blowers of various sorts are used to distribute bedding, to control temperature, and to dust

TABLE 3.6. Machinery Used in Livestock Production

Livestock	Feeding & Watering	Nurturing	Waste Removal
Beef & Dairy Cattle	Mechanical bale handling, silo unloader, grain grinding & mixing, automatic waterers	Blowers for bedding distribution & temperature control	Tractor loaders, drag chains, pumps, conveyors
Sheep	Small; many sheep are grazed on open pasture	Tick control: dusting blowers and pumps for sheep dip baths	--
Hogs	Mechanical feeding troughs	Blowers for temperature control	Drag chain conveyors on wash down systems, tractor loaders
Turkeys & Chickens	Automatic feed conveyors and automatic waterers	Blowers for temperature control	Wet and dry waste removal via pumps & conveyors

animals for insect control. These blowers commonly operate in a hot, dusty environment, which causes associated bearing failures.

In the third process column of Table 3.6, two concepts of waste removal are shown. In some areas, such as livestock loafing sheds, manure is sometimes allowed to accumulate and is then removed with a tractor loader. In other cases, such as high production chicken farms, the waste is constantly collected and disposed of by hydraulic or dry conveyors.

3.2. MAJOR TRIBOLOGICAL SINKS IN AGRICULTURE

Table 3.7 summarizes the tribological losses for all crop production as broken down into processes. The components at which the losses occur are also briefly indicated in the table. The processes by which these values were derived are briefly described in the following sections.

3.2.1 Sources of Tribological Losses

In this section, aspects of the agricultural processes that affect tribological losses and the sources of these losses for crops and livestock production are discussed. The discussion is divided by process type and focuses on specific components of agricultural machines that suffer significant friction and wear. The processes discussed include tillage, planting, fertilizer and chemical application, irrigation, harvesting, crop handling and transportation, and livestock production.

Tillage (including cultivation)

Tillage is generally divided into several categories, with the following definitions:

1. primary tillage - serves to break sod, turn under residue, kill weeds, and loosen the plow layer
2. secondary tillage - any working of the seedbed up to the point of planting, which serves to pack or loosen the seedbed, break clods, kill weeds, and smooth the seedbed
3. cultivation - after planting, primarily accomplishes weed control and breaks the ground crust to improve water absorption characteristics.

TABLE 3.7. Summary of Tribological Losses in Crop and Livestock Production

Direct Losses

Process	Machine	Site of Direct Loss	Direct Loss (Btu)
Tillage	Implements[a]	Parts that engage soil	5.7×10^{12}
Planting	Planters	Parts that engage soil	1.3×10^{12}
Irrigation	Pumps	Impeller	1.0×10^{12}
Transportation	Crop Conveyors	Bearings	2.9×10^{10}
	Feed Conveyors	Bearings	1.2×10^{10}

Indirect Losses

Process	Machine	Component Name	Component Material	Indirect Loss (annual use, 1983)
Tillage	Implements[a]	Tool points	Steel	4.5×10^8 pounds
	Tractor	Tire	Rubber	4.6×10^7 pounds
		Lubricant	Petroleum	2.7×10^7 gallons
Planting	Planters	Tool points	Steel	1.1×10^8 pounds
Harvest	Combine	Bearings	Steel	Not quantified
		Chains	Steel	Not quantified
		Belts	Rubber	Not quantified
		Thresher parts	Steel	Not quantified
		Header parts	Steel	Not quantified

(a) Listed in Table 3.5.

The number of trips over the field to accomplish each of these goals is important because each additional trip contributes to the direct energy loss associated with tillage. The number of trips varies with crop type and soil condition at the time of plowing; however, an average schedule that was used in the direct loss calculation is given in Table 3.8 for conventional tillage, minimum tillage, and no tillage. The minimum tillage schedule was used in the

TABLE 3.8. Trips Over the Field (Phillips and Young 1977)

	Conventional Tillage	Minimum Tillage	No Tillage
Plowing	1	1	1
Disking	2 or more	0 or more	0
Planting	1	1 or 0	1
Spraying	0 or more	0 or 1	1
Cultivating	2 or more	1 or 2	0
Harvesting	1	1	1
Total Trips	7 or more	4 or 5	4

calculations and reduces the number of trips over the field to five (two less than conventional tillage). In either case, the machinery used for each trip is a tractor and one or more implements.

Tractors. In 1983 there were 4,600,000 tractors (exclusive of steam and garden type) on U.S. farms (Department of Agriculture 1983). They comprised 278 million tractor horsepower, powered by gasoline, diesel fuel, and propane. The types and sizes of tractors can be classified in many ways; however, the only distinction necessary for this study is the size classifications: 1) 50- to 150-horsepower units and 2) greater than 150-horsepower units, mentioned earlier. Tillage operations place the highest power demands on the tractor, and subsequently, tillage is the critical factor that dictates the tractor engine size required. Most (perhaps 80%) of this power is transferred through the tractor tires to the tillage implement. It is at this tire-to-earth interface that the single most significant tribological loss, excluding the engines, occurs in tractors.

Agricultural tires typically operate at high slip percentages of 10% to 20% (Holn 1975). (Slip is relative motion between the tire and ground). The transfer of large amounts of power at high slip requires that the tire be replaced or retreaded about every 1000 to 2000 hours of operation. For this study, replacement of two rear drive tires sized to fit a 60-horsepower tractor was assumed (the average computed from the agricultural census quoted above and also indicated in the literature, although not exhaustively investigated). Used in conjunction with the total number of annual operating hours extracted from the data of Table 3.4, tractor tires result in an indirect loss of 4.6 x 107 pounds of rubber per year.

The power take-off drives (PTOs) on tractors were also reviewed. PTOs are usually extensions of the drive system that provide power for stationary machines such as pumps, sows, mowers, etc. The PTOs, while identified as a medium wear item, account for a small tribological sink, and minimal wear rate information was found. Therefore, they were not included in the final analysis.

Another indirect loss, lubricant, was calculated for our average size tractor based on manufacturers' recommended maintenance schedules and a discussion with a farmer. This loss magnitude is indicated in Table 3.7.

Tillage Implements. Tillage has long been recognized as an energy sink. Research of some tillage-related technologies still under development was initiated as early as 1960. For this study, the voluminous research literature on the tribological mechanisms of the tillage process was reviewed. A composite of the findings commonly agreed upon is used for this discussion.

A plow must "scour" to operate properly. In technical terms, this phenomena implies that the best performance occurs when the plow is smooth. The presence of any roughening, such as "rust," greatly increases the draft requirements. Some work has been done to attempt to instill lubricated wear. The abrasive wear depends primarily on the strength and hardness of the plow's metal in its maximum work-hardened state, which results from the tilling process. The effects of these tribological influences are discussed below.

The major types of tillage equipment discussed in this study are listed in Table 3.9. Thirty to sixty percent of the draft (or pulling power) requirement of tillage implements is required to overcome the parasitic forces that arise directly from friction of the implement engaging the worked material. Because of the high draft forces required to till earth, this amounts to a significant tribological energy sink, both directly through friction and indirectly through wear. In Table 3.9, the total energy inputs per acre are reported. Frictional loss values were given in several references and were also calculated from soil tillage dynamics taken from text on principles of farm machinery. The values

TABLE 3.9. Major Types of Tillage Implements Considered for Tribological Losses

Implement	Energy Input[(a)] (Btu/acre)	Direct Tribological Loss (Btu/acre)	Indirect Tribological Loss (lb steel/acre)	Description and Comments
Moldboard plow	62,000	19,000	0.11	Plow 8 inches deep with 5-bottom plow
Disk plow	62,000	19,000	0.18	5-24 in. disk
Chisel plow	41,000	12,000	--	16 ft wide
Field cultivator	20,000	6,100	--	16 ft wide
Spring tooth harrow	8,700	2,600	--	16 ft wide
Disk harrow	18,000	5,500	0.62	16 ft wide
Row crop cultivator	15,000	4,600	0.12	6 rows
Rotary hoe	7,100	2,100	--	24 ft wide
Powered rotary tiller	--	--	--	15 ft wide

(a) Smith and Oliver (1975).

were found to agree (Kepner undated; Shipper et al. 1980; and Culpin 1976). Although the draft requirements for different implements vary, the percent of draft due to friction consistently ranged from 30% to 60%. The second column of Table 3.9 is the tribological losses calculated for each implement using the somewhat conservative figure of 30% of the total energy input for each implement type.

In Table 3.9, a rate is also given for the indirect losses of the implement's replacement parts that engage the worked material. Examples of such parts include plowshares, plow moldboards, plow landslides, disks, tapered roller bearings, which support disks, tines for chisel plows and field cultivators, and points for subsoilers and row cultivators. These parts are made from carbon steels, alloy steels, and cast iron. An approximate life of 100 to 150 hours for disks and plowshares was calculated. Assuming a similar life for all of these components that engage the worked material, the associated weights of the components were then used to arrive at an approximate value of pounds of metal per acre tilled. Because of variations in the soil composition and tilling conditions, more accurately estimating the wear rate across the nation is difficult. However, this conservative estimate will show the magnitude of the metal involved in what farmers consider routine maintenance items.

Planting

Table 3.10, which lists major types of planting implements considered for losses, has been constructed similarly to Table 3.9 on tillage equipment. Planting is very similar to tillage operations from a tribological viewpoint. One component of the draft requirement results from friction forces and creates a direct loss. The furrow in which the seed is planted is opened with disk and cultivator tool points, so there is an associated wear loss, just as in tillage. The only large difference is functional, in that a planter simultaneously places the seed in the ground and often fertilizes while it performs a light cultivation process.

Fertilizer and Chemical Application

Fertilizer and chemical equipment has been included only because they comprise a major percentage (up to 50%) of the total agricultural energy use. The tribological energy associated with applying fertilizers, however, is generally quite low in comparison to other tillage operations. Therefore, the

TABLE 3.10. Major Types of Planting Implements Considered for Tribological Losses

Implement	Energy Input(a) (Btu/acre)	Direct Tribological Loss (Btu/acre)	Indirect Tribological Loss (lb steel/acre)	Description and Comments
Row crop planter	17,000	5,100	0.12	12 ft wide
Grain drill	12,000	3,600	0.26	9-13 ft wide
Broadcaster	Small	Small	--	--

(a) Taken from Smith and Oliver (1975).

energy is mainly required in the manufacture of the fertilizer, which is discussed in Chapter 5.0 on the chemical industries.

Irrigation

In 1974 about 35 million acres were irrigated in the U.S. using on-farm pumped water, for a total of 69 million acre-feet of water. This pumping required an estimated 260 trillion Btu, or about 21% of the total energy consumed in farm production (Holn 1975). By 1975, 54 million acres were being irrigated (Lockeretz 1977). These data indicate the importance of irrigation in the general agricultural energy picture. The scale of importance is reduced considerably, however, when the component attributed to tribological losses is extracted from these data.

Irrigation is commonly accomplished with one of the following systems: surface irrigation (open ditches), a solid-set sprinkler, a big gun sprinkler, or a center-pivot sprinkler. Culpin (1976) indicated that the center-pivot system consumes significantly more energy than the other types combined. This pressurized sprinkler system (approximately 200 feet of head pressure) requires much more pumping energy than surface irrigation.

Centrifugal pumps have been found to be particularly well suited for irrigation applications such as the center-pivot system. Efficiencies for irrigation pumps were reported as high as 75%, and an average value was estimated as 60% by one irrigation engineer (Lockeretz 1977). Of the 40% inefficiency, 1% or less may be attributed to tribological causes. One percent of the national use given above then amounts to a sizeable one trillion Btu per year. However, reducing a component of the inefficiency, which is already less than 1%, could prove difficult.

Harvesting

The two types of equipment described in this process are combines and hay and forage harvesters.

Combines. The modern combine is a complex machine, performing five basic crop harvesting functions:

1. cutting and feeding
2. threshing
3. separating
4. cleaning
5. storage and handling.

Many combines are self-propelled, which adds to the complexity and embodied materials of the engine, power train, electrical, and hydraulic systems. As was noted in the previous classification of farm machinery, the combine is used to harvest many types of crops. The combine is adapted for use with various crops mainly by selecting the harvesting attachment mounted on the front. Figure 3.3 shows a modern self-propelled combine with one of the two basic types of heads--a cutting platform for gathering small grains. The other type of head is designed for row crops such as corn. The tribological losses in the two types of heads are slightly different, although on the same order of magnitude. The tribological losses for the main body of the combine, which performs functions 2 through 5 listed above, are similar for all crops.

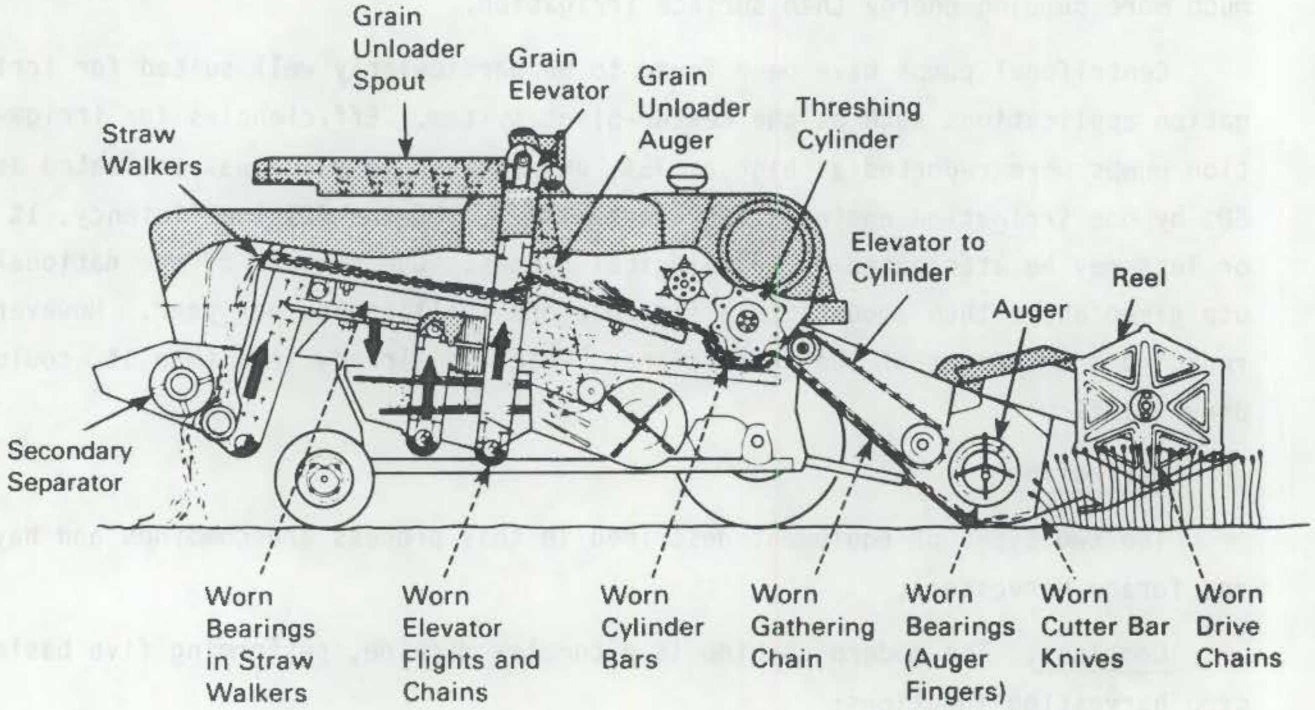

FIGURE 3.3. Grain Combine Harvester with Example Tribological Sites Indicated

Sources of tribological losses in the combine are indicated in Figure 3.3 by the dotted arrows. Indirect losses, small in magnitude but persistent in occurrence, characterize the machine. Conversations with farmers indicated that stocks of these high-replacement items, such as bearings, are kept on hand and routinely replaced. By correlating replacement schedules and machine capacities, each of the tribological components, listed in Table 3.11, was estimated to be replaced at least once every 1000 acres harvested. This estimate is tenuous because of 1) the many different parts and 2) the large differences in the replacement rates of these parts. For example, a typical combine has 40 different bearings, 18 different drive belts, and more than 10 chains. The belts are replaced every one to three years, bearings every one to two years, the conveyors every three years, and the chains every two to three years. The indirect tribological losses for each part are minimal, but the cumulative loss is worth review. This review, however, would require a detailed analysis to develop reasonable estimates of energy and material losses; such an analysis was beyond the resources available for this review, although such a review will be recommended for later consideration.

Hay and Field Forage Harvesters. The harvesting of hay is different from the harvesting of grain crops in that the plant stalk is part of the desired commodity. The hay harvest consists of mowing the crop, raking the crop into windrows, conditioning the hay, and finally baling the hay for transport and storage. Conditioning the hay can refer to any of several processes such as turning the windrow, bruising the hay with rollers, or aerating the windrow to speed drying. Table 3.11 concentrates on the machines that cut the crop and experience wear as a result.

Sometimes the entire plant of various grain crops, such as corn or soybeans, is harvested by chopping the crop into small pieces called silage. Silage is stored green (with a relatively high-moisture content) in silos where it ferments into a desirable feed for livestock. An indirect tribological loss is associated with the various arrangements of choppers and shredders in field forage harvesters. The tribological machine components are listed in Table 3.11.

TABLE 3.11. Major Types of Harvesting Machinery Considered for Tribological Losses

Combined Crops

Gathering Head Type	Tribological Machine Element: Name	Material	Number of Parts
Grain	Cutter bar, knives & guards	Steel	36 knives and guards
Corn	Snapping plates, trash knives, gathering chains	Steel	On 4-row head: 8 plates @ 3-4 lb/plate 8 chains @ 5 lb/chain
Either	Drive & elevator chain, thresher parts,	Steel	1 chain @ 10-20 lb
	bearings		12-24 (1-2 in.) ball and plain type
	Drive belts	Rubber	6-18 (3 ft) V-belts

Hay and Forage Crops

Implement Name[(a)]	Tribological Machine Element: Name	Material	Number of Parts
Mower			
Flail type	Flails,	Steel	30-60 flails @ 1.5 lb/blade
Cutter bar	Knives & guards		36 knives and guards
Baler	Ram knife, twine knife & hay gathering fingers	Steel	1 blade (24 x 3 x 0.25 in.)
Forage harvester	Flails & chopping cylinder blades	Steel	30-60 flails @ 1.5 lb/blade 8 blades (12 x 3 x 0.25 in.)

(a) Miscellaneous hay conditioning equipment that was discounted includes tedders, turners, crimpers, and rakes. These items accounted for minimal tribological sinks and were less commonly used.

Crop Handling and Transportation

Grain crops are handled with augers and conveyors. The conveyors may be of the chain, flight, belt or bucket type. The augers and conveyors are used to move crops onboard the harvester and from the harvester to trucks or wagons for transport to treatment or storage stations. At storage stations, such as silos, the crop is often handled twice by an auger or conveyor, once to load the silo from the top and once again at the silo unloader.

A direct tribological loss is associated with friction in the conveyor pulleys, friction of the belt or chain riding over the pulleys, and skirtboard friction of the conveyor or conveyed material. The amount of direct energy loss to these interfaces, excluding the power required to elevate the material, has been estimated by applying formulas published by the Conveyor Equipment Manufacturers Association (1977). Parameters for the calculation were taken from specifications for an elevator selected from the Implement and Tractor Red Book (1983). A few of the nominal parameters used in the calculation are listed in Table 3.12.

The losses ranged from 4% to 20% of the drive motor power. Each of the crops in Table 3.4 was assumed to be conveyed once under the typical conditions given above. Therefore, losses in the percentage of crops conveyed by auger are assumed to be as great as those of a conveyor. The total weight of conveyed material was calculated by associating corresponding average densities (U.S. Department of Agriculture 1983) with each of the crops of Table 3.4. The direct tribological losses calculated under these assumptions for conveyance were 2.9×10^{10} Btu.

Livestock Production

The tribological losses in livestock production are smaller than some of the previously considered industrial areas. Livestock mainly adds another component to the sum of losses attributed to conveyance systems and pumps.

TABLE 3.12. Some of the Nominal Parameters Used in Calculating Direct Tribological Losses in Crop Handling and Transportation (Implement and Tractor Red Book 1983)

Parameter	Nominal Value
belt or chain width	16 in.
belt or chain speed	760 ft per min.
conveyed material density	45 lb per cu ft
distance conveyed	200 ft

For example, a milk cow requires 30 gallons of water per day--15 gallons for drink, and 15 gallons for cleaning and milk cooling (Culpin 1976). Cattle not in milk production required only 10 gallons per day. The national average milk cow feed ration was reported to be 5280 pounds per year.

Using the more conservative value of 10 gallons of water per day (the reduced requirements of calves and increased requirements of milk cows balance out somewhat), the total water requirement that must be pumped for cattle alone is 4.2×10^{11} gallons per year. A tribological loss is associated with this pumping requirement; however, as noted before, it is small.

Calculating the feed conveyance requirement using the national average given for a milk cow (possibly slightly higher than for cattle not in milk production) leads to 6.1×10^{11} pounds per year for all cattle. Because the conveyance systems are very similar (sometimes identical) to those used in crop production, the tribological losses in these units were calculated similarly. This leads to a direct loss of 1.2×10^{10} Btu, the largest direct tribological energy loss detected in livestock production. This figure is somewhat conservative in that it does not include conveyance for waste removal from the average cow.

3.2.2 A Tribological Perspective On Crop and Livestock Production

Tillage is a large sink of direct tribological energy losses because of parasitic friction at the working tool interfaces. Harvesting contains significant indirect tribological losses because of the considerable two-body and three-body abrasive wear in the combine's many mechanisms.

Ways to reduce these losses have been researched. Antifriction coatings have been successfully applied and found to reduce draft requirements by as much as 30% (Wismer et al. 1968). Problems with this technology include its high cost and high wear rate. Research is currently being performed to develop abrasion-resistant polymers that will replace current antifriction coatings at less expense.

Fluid lubrication has been applied successfully at the tillage interface (Schafer et al. 1979). Three percent polymer in water solutions is metered to plow interfaces through ports in the moldboard. In addition to draft reductions of 10% to 30%, it is possible to plow some acreages previously untillable because of the soil's adhesion characteristics.

Vibration of tillage toolpoints has been under investigation for several years as a method to lower the friction force at the tool-to-soil interface (Wismer et al. 1968). Some recent investigations that carefully control the direction and nature of the driving impulse are experiencing success. Technological obstacles include large power consumptions, noise, and vibration.

Transfer of power to the tillage implement via mechanisms other than the tractor tires is being considered to bypass the associated inefficiencies (Hendrick 1980). Rotary tillers, driven by an auxiliary driveshaft from the tractor engine, are an accepted part of current tillage technology. Drawbacks or limitations of this approach center on overtilling. Some researchers and farmers believe that rotary tillers' high energy input to the soil destroys important soil structure.

No significant tribological activities were identified in livestock production. Conveyors, pumps, blowers, and motors were all present in livestock production, but the tribological losses associated with them are small.

3.3 SUMMARY OF TRIBOLOGICAL SINKS IN AGRICULTURE

The most significant tribological sinks in agriculture are in soil cultivation and crop production. The sinks that merited analysis are as follows:

- crop production
  - tillage
  - irrigation
  - transportation
  - planting
  - harvesting
- livestock production
  - feeding and watering
  - waste removal
  - nurturing.

Several agricultural end uses that have significant energy consumption were excluded from this chapter. Agricultural chemical and fertilizer production were excluded because the associated tribological sinks are discussed in the chemicals and mining chapters. The transportation of agricultural products focuses only upon material handling via conveyors and similar devices. The tribology of the tractor engines and all truck hauling are addressed in other tribology program research.

The generic tribological mechanisms contributing to energy losses in each sink are identified in Table 3.13. Tables 3.14 and 3.15 present the direct and indirect energy losses, along with additional information on the energy and material types affected by the tribological activity.

The tribological mechanisms identified in the research are indicated in Table 3.13 according to the sink(s) in which they are present. Three-body abrasive wear was by far the most common activity, being significant in all sinks except irrigation. The second most common tribological mechanism was lubricated wear, which was present in the sinks involving transportation of crops or feed and animal waste. However, frequent occurrence of a tribological mechanism does not necessarily imply the importance of tribological energy use.

The direct and the indirect energy use (i.e., embodied energy in worn materials) of the tribological sinks are shown in Tables 3.13 and 3.14. Indirect losses were more than two times greater than the direct losses. Steel erosion of tillage implements and tractor draft requirements in tillage were the most significant energy sinks identified. Steel was the most common material subject to wear and also contributed the most to the indirect energy total. The material replacement of bearings, drive belts and chains, and knife blades in combines was reported to be high; these materials were considered to have medium wear rates. The net tribological losses, however, could not be accurately estimated by this research project because of the complexity of the problem and the resources needed to determine accurate wear rates and material replacement rates.

TABLE 3.13. Summary Table for Tribological Energy Losses in the Agricultural Industry

	Generic Tribological Mechanism						
Tribology Sinks	3-Body Abrasive	2-Body Abrasive	High Stress Gouging	Impact Wear	High Friction	Erosion	Lubricated Wear
Crop Production							
Tillage	X				X		
Planting	X				X		
Irrigation		X				X	
Harvest	X	X					
Transportation	X						X
Livestock Production							
Feeding & Watering	X					X	
Nurturing	X						X
Waste Removal	X						X

TABLE 3.14. Annual Direct Tribological Energy Losses in Agriculture

Process	Machine Involved	Site of Direct Loss	Direct Loss (10^{12} Btu)
Tillage	Implements[a]	Parts that engage soil	5.7
Planting	Planters	Parts that engage soil	1.3
Irrigation	Pumps	Impeller	1.1
Transportation	Conveyors	Bearings	0.029
Total			8.13

(a) Implements include moldboard plow, disk plow, chisel plow, field cultivator, harrow, disk cultivator, and row cultivator.

TABLE 3.15. Annual Indirect Tribological Energy Losses in Agriculture

		Component		Indirect Material Loss	Equivalent Energy Loss
Process	Machine	Name	Material	(annual use, 1983)	(10^{12} Btu)
Tillage	Implements[a]	Tool points	Steel	4.5×10^8 lb	9.91
	Tractor	Tire	Rubber	4.6×10^7 lb	3.05
		Lubricant	Petroleum	2.7×10^7 gal	3.89
Planting	Planters	Tool points	Steel	1.1×10^8 lb	2.42
Total					19.27

(a) Implements include moldboard plow, disk plow, chisel plow, field cultivator, harrow, disk cultivator, and row cultivator.

The direct energy losses were most significant in the draft requirements necessary for soil tillage. Planting and irrigation were the next most important; conveyance of crop and livestock material (excluding highway travel) was the least significant of the identified sinks.

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4.0 PRIMARY METALS - THE IRON AND STEEL INDUSTRY

Industries that comprise the Primary Metals category (SIC 33) are involved in processing both ferrous and nonferrous materials.

4.1 GENERAL INDUSTRY DESCRIPTION

Materials processed by the primary metals industries include iron and steel, aluminum, copper, zinc, and lead. These industries are listed by their 4-digit SIC classification in Table 4.1. Table 4.1 also shows the amount of fuel and electricity purchased in each of these SIC categories in 1980. Besides this purchased energy, many of these metal industries produce a significant quantity of fuel internally as the by-product of their processing. Therefore, the total energy use is larger than that shown in the table. In an analysis of the industry in 1972, Battelle estimated that the total energy consumed exceeded the purchased energy in primary metals by ~80% (Battelle 1975). This estimate is consistent with DOE data that show total energy consumption in the primary metals industry to be ~3.8 quad.

Of the industries that compose primary metals, the iron and steel industry is by far the largest energy consumer. In 1980 the iron and steel industry consumed 2.52 quad of energy [American Iron and Steel Institute (AISI) 1982], which represents 66% of the energy used in primary metals. The second largest energy consumer was the aluminum industry, which accounted for ~0.72 quad (AISI 1982). Because of the dominant energy consumption evidenced in the iron and steel industry and the similarity of processes across the primary metals industries, the analysis in this chapter will focus on iron and steel.

Although the iron and steel industry is still a major employer in the U.S. economy, employment and production in that industry has decreased significantly since the late 1970s. In early 1980 iron and steel industry employment was slightly above 500,000, and the production of iron and steel products exceeded 100,000 million tons per year. In 1982, employment was down to 289,000 and product shipments were down to 61,567 million ton. This decline can be attributed to many factors, including the effects of a national recession, increasing competition from foreign industries, and the aged, less efficient condition

TABLE 4.1. Purchased Fuels and Electricity in Primary Metals Industries [Annual Survey of Manufactures (ASM) 1981]

SIC Code	Industry Group and Industry	Purchased Fuels and Electricity (trillion Btu)
33	Primary Metals Industries	2,276.8
331	Blast Furnace, Basic Steel	1,381.5
3312	Blast Furnaces and Steel Mills	1,282.1
3313	Electrometallurgical Products	51.0
3315	Steel Wire and Related Products	12.8
3316	Cold Finishing of Steel Shapes	14.6
3317	Steel Pipe and Tubes	21.0
332	Iron and Steel Foundries	159.7
3321	Gray Iron Foundries	111.0
3322	Malleable Iron Foundries	10.8
3324	Steel Investment Foundries	4.0
3325	Steel Foundries, NEC	33.9
333	Primary Nonferrous Metals	473.9
3331	Primary Copper	53.0
3332	Primary Lead	12.1
3333	Primary Zinc	16.2
3334	Primary Aluminum	359.8
3339	Primary Nonferrous Metals, NEC	32.8
3341	Secondary Nonferrous Metals	39.3
335	Nonferrous Rolling and Drawing	158.0
3351	Copper Rolling and Drawing	22.9
3353	Aluminum Sheet, Plate, and Foil	68.2
3354	Aluminum Extruded Products	19.9
3355	Aluminum Rolling, Drawing, NEC	7.4
3356	Nonferrous Rolling, Drawing, NEC	16.0
3357	Nonferrous Wiredrawing, Insulating	23.5
336	Nonferrous Foundries	39.4
3361	Aluminum Foundries	27.8
3362	Brass, Bronze, Copper Foundries	5.3
3369	Nonferrous Foundries, NEC	6.3
339	Miscellaneous Primary Metal Products	24.9
3398	Metal Heat Treating	17.0
3399	Primary Metal Products, NEC	7.8

of U.S. equipment when compared with foreign plants. Historically, the industry has followed the national business cycle because a large portion of the products are used for highly cyclical construction and consumer durables. Reduced shipments to the construction and auto industries between 1973 and 1980 accounted for nearly 60% of the 27.6 million ton decline in U.S. steel shipments [Office of Technology Assessment (OTA 1980)]. Because of the recession's significant impact on this industry, 1982 was not considered to be a good "typical" year for the analysis. Although an analysis of the future markets for the industry is well beyond the scope of this study, estimates by OTA (1980) and the AISI (1982) predict production to be relatively stable over the decade at an output approximately equal to that in 1980. Therefore, the analysis in this chapter will be conducted with 1980 statistics.

In 1980 the iron and steel industry employed 399,000 workers and shipped 83,853,000 tons of products. These products are shipped in various forms, including structurals, plates, bars, pipes and tubes, wire, tin mill products, and sheets. The percentage distribution of these products and their projected values in 1985 and 1990 are shown in Table 4.2. In 1980, 87.5% of the shipments were carbon steel products, 1.3% were stainless and heat resisting, and 11.2% were other alloys (OTA 1980).

Figure 4.1 is a very general schematic of the major processes involved in producing iron and steel. These steps include preparing the coking coal and the iron ore, smelting the iron in a blast furnace, producing steel in a steelmaking furnace, casting the steel into ingots or creating stock through a continuous process, and rolling and forming the steel into the desired products. These processes are further detailed in Table 4.3.

Overall energy use in the iron and steel industry has been declining in the late 1970s and early 1980s because decreased production and increased use of energy conservation measures. Overall energy use by fuel type from 1978 to 1982 as compiled by the AISI is shown in Table 4.4.

The distribution of energy use in the major energy-consuming processes is shown in Figure 4.2. The figure clearly shows that a large amount of energy is consumed in the thermally intensive processes. The blast furnace alone

TABLE 4.2. Projection of Product Mix in U.S. Steel Production, 1976-2000 (OTA 1980, p. 141)

Product	Distribution of Product Mix (%)			
	1976[(a)]	1980	1985	1990
Structural	10	12	12	12
Plate	9	10	10	10
Rails	2	2	2	2
Hot-rolled bars	9	7	7	7
Other bars	7	9	9	9
Pipes and tubes	9	11	13	15
Wire	3	2	2	2
Tin mill products	7	7	6	6
Hot-rolled sheet and strip	17	15	15	14
Cold-rolled sheet and strip	20	17	16	15
Galvanized sheet	7	8	8	8

(a) Average of 1975-77 used to eliminate fluctuations.

consumes ~40% of the energy used in the industry, followed by heating and annealing, which consumes 15%; steelmaking, which consumes 10%; and coking, which consumes 10%.

One of the difficulties in tracking the energy use in this industry is that a large portion of the energy consumed is generated internally. Figure 4.3 shows the distribution of the different forms of energy as well as the recycling of the by-product gases. This figure again shows the dominant energy use of the thermally intensive processes.

The tribological energy sinks are not, however, marked by these thermally intensive processes but by mechanical processes. The most significant mechanical processes occur during the initial stages of ore preparation (e.g., pelletizing) and in the secondary or finishing processes (e.g., rolling and milling). Figure 4.1 also shows the materials flows through these processes and traces the processes to the products that are produced. Both the thermal and mechanical processes will be described in more detail in the next section.

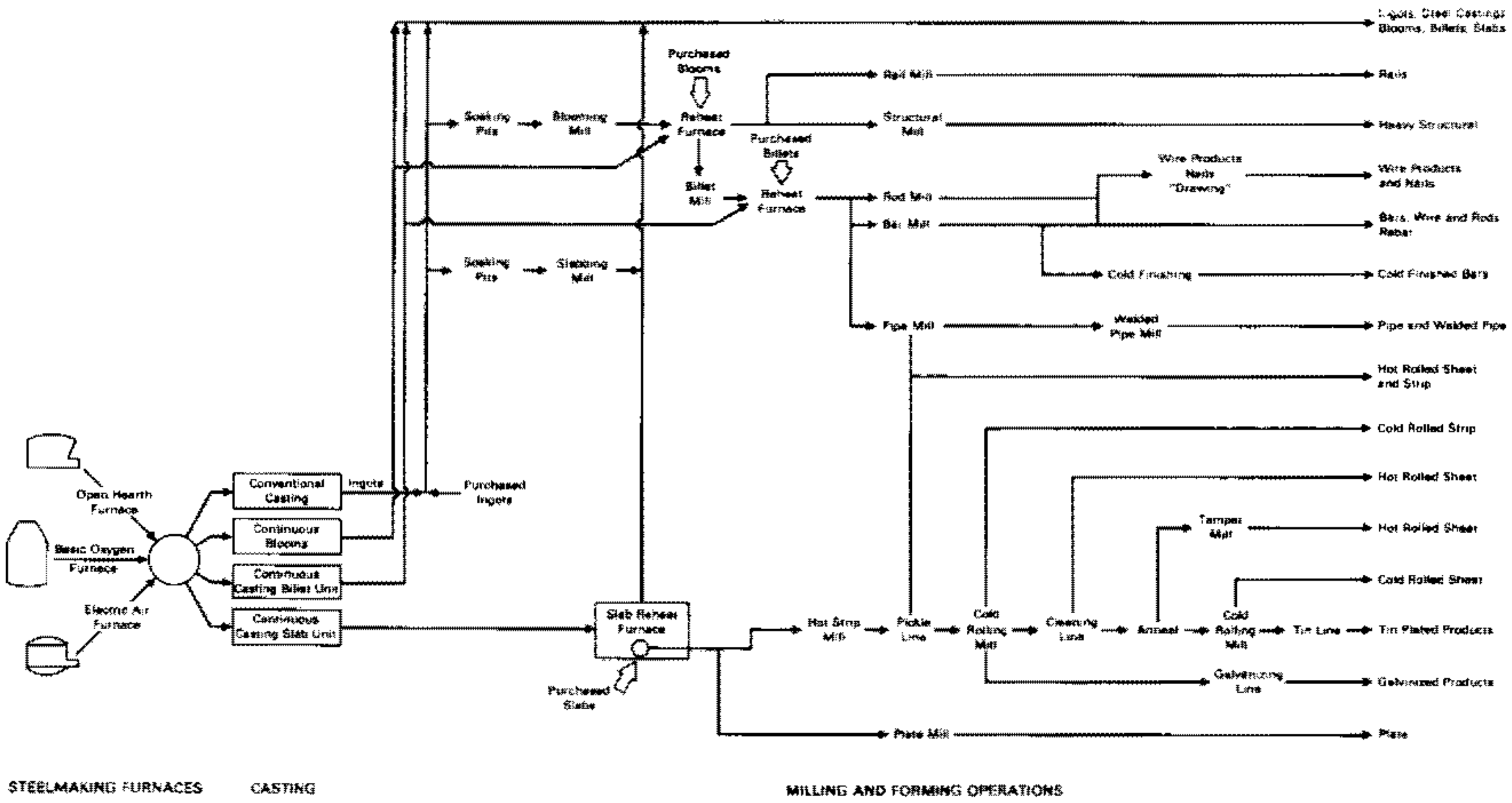

FIGURE 4.1. Major Processes Involved in Producing Iron and Steel

TABLE 4.3. Energy Services and Major Processes in the Iron and Steel Industry (OTA 1980)

Energy Service	Major Processes
Beneficiation	Sintering
	Pelletizing
Coking	By-product coke oven/wet quench
	By-product coke oven/dry quench
	Formcoking
Ironmaking	Blast furnace
	Blast furnace with hydrogen injection
	Direct reduction--gas
	Direct reduction--coal
Steelmaking	Basic oxygen furnace
	Electric arc furnace
	Open hearth furnace
Primary finishing	Ingot casting/soaking/breakdown mill
	Continuous casting
	Ladle preheating
Secondary finishing	Batch reheating/rolling
	Continuous reheating/rolling
	Electric induction reheating/rolling
	Direct rolling
	Cold rolling
Heat treating	Direct tube furnace
	Radiant tube furnace
	Electric furnace

TABLE 4.4. Fuel Use and Energy-Related Trends in the Steel Industry (AISI 1982)

Fuel Use Per Ton of Steel Shipments (10^8 Btu)(a)	1976	1977	1978	1979	1980	1981
Coal, coke	22.4	20.0	17.2	17.9	18.2	16.0
Coal, steam	0.8	0.8	0.8	0.8	0.8	0.8
Natural gas	6.7	6.2	6.1	6.4	6.7	7.0
Purchased coke	1.7	1.2	1.7	1.9	1.2	0.8
Fuel oil	2.7	2.8	2.9	2.1	1.3	1.1
Liquefied petroleum gas	0.7	1.0	0.6	0.3	0.2	0.2
Purchased electricity(b)	1.7	1.7	1.7	1.7	1.8	1.9
Totals, 10^6 Btu	36.7	33.7	31.0	31.1	30.2	27.8
Cost,(c) 1982 dollars	128.4	120.6	113.7	114.0	109.4	105.6
Recent Trends						
Shipments, 10^6 tons	89.4	91.1	97.9	100.3	83.9	87.0
Raw Steel, 10^6 tons	128.0	125.3	137.0	136.3	111.8	119.9
Yield, %(d)	69.8	72.9	71.5	73.6	75.0	72.6
Continuous cast, %	10.6	12.5	15.2	16.9	20.3	21.2
% of raw steel						
Open hearth	18.3	16.0	15.6	14.0	11.7	11.2
Basic oxygen process	62.5	61.8	60.9	61.1	60.4	61.1
Electric arc furnace	19.2	22.2	23.5	24.9	27.9	27.7
Total purchased scrap, %(e)	36.0	40.0	40.0	43.0	48.0	--

(a) Based on representative generating heat values.
(b) Assuming 3412 Btu/kWh.
(c) 1982 average prices applied to yearly figures.
(d) Shipments divided by raw liquid steel. The decline in 1981 is an artifact of a sharp increase in inventory.
(e) Percent of total metallic feedstocks.

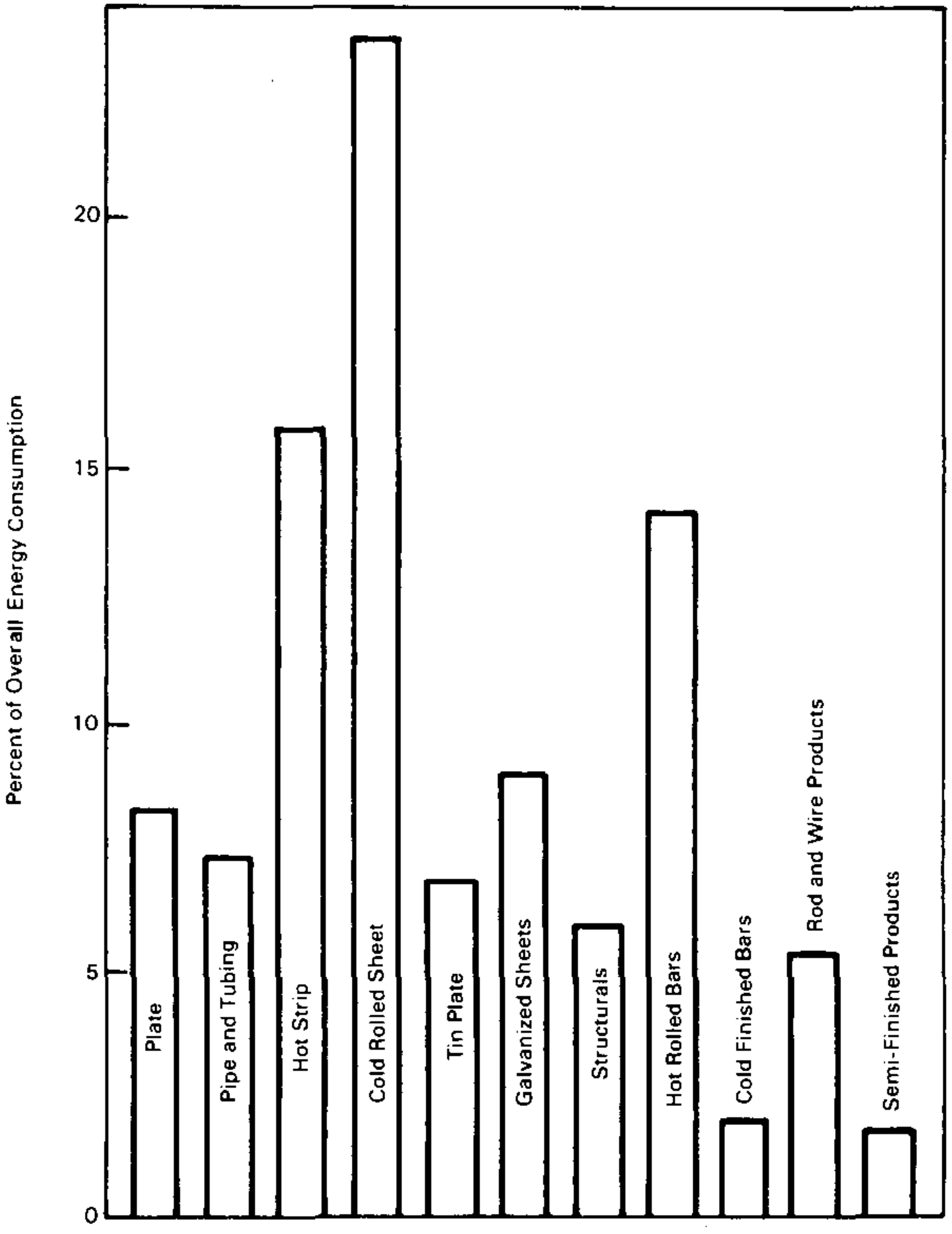

FIGURE 4.2. Distribution of Energy Use in the Major Energy-Consuming Processes

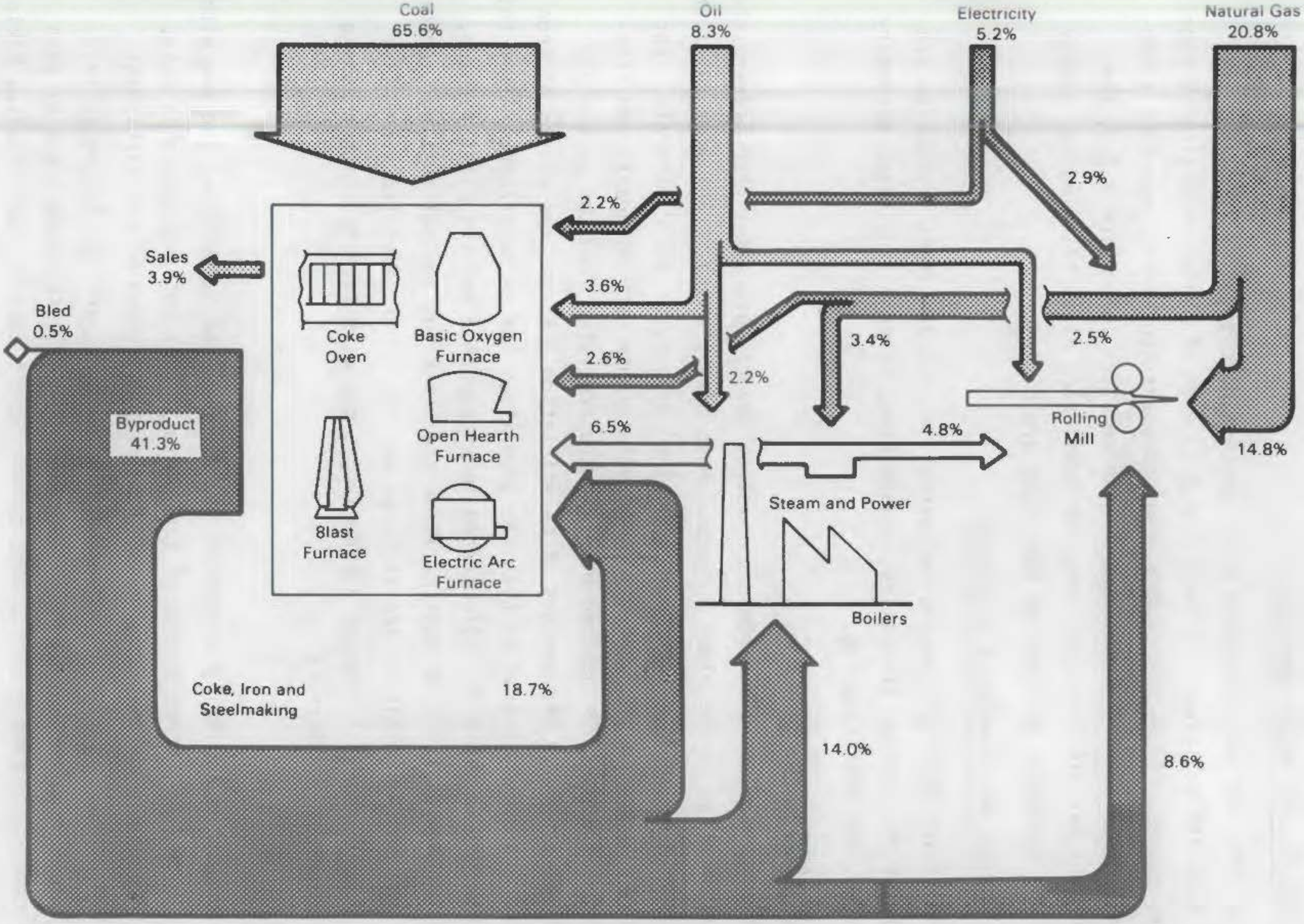

FIGURE 4.3. Distribution of the Different Forms of Energy and the Recycling of By-Product Gases

4.2 ANALYSIS OF MAJOR PROCESSES

In this section, the seven major processing categories (outlined in Table 4.3) are analyzed. In Section 4.2.1, each of these processing categories are introduced. In Section 4.2.2, the processes containing important tribological energy sinks are reviewed in more detail. In Section 4.2.3, the reasons why certain processes were not considered major tribological energy sinks and therefore left out of the study are discussed.

4.2.1 Major Iron and Steel Processes

The seven major processing categories in iron and steel production are beneficiation, coking, ironmaking, steelmaking, primary finishing, secondary finishing, and heat treating.

Beneficiation

The beneficiation of iron ore involves several processes that prepare the ore for smelting in the blast furnace. Most metallic ores are a mixture of the desired metal-bearing minerals and undesired gangue, or waste minerals. For example, iron oxides are commonly mixed with gangue such as quartz and iron-bearing silicates. The desired minerals are separated from the gangue and concentrated through the process of beneficiation. First, the chunks of iron ore are crushed and ground so that the impurities can be separated. After this refining, the iron ore is agglomerated in preparation for the blast furnace. The most common methods of agglomeration are sintering and pelletizing. Generally, the courser particles are sintered and the finer particles are pelletized. Both processes produce a burden that can withstand the high crushing forces in the blast furnace.

Coking

Iron ore is typically converted to metallic iron by reducing the ore with carbon. The most common source of the carbon in current ironmaking is coke. Coke is generally derived from metallurgical coal, which blends particular characteristics of sulfur content, volatile content, and caking properties. About 1.46 tons of metallurgical coal are consumed in the production of each ton of coke (A.D. Little 1978). The conversion of coal to coke involves baking the coal in a coke oven for 16 to 18 hours in temperatures as high as 1100°C.

The volatiles are driven off from the coke in gases, and the coal is transformed into hard, porous coke that is about 90% pure carbon.

Ironmaking

In the ironmaking process the coke, agglomerated iron ore, other iron-bearing materials (e.g. scrap), and flux (e.g. limestone and dolomite) are charged into the top of the blast furnace. Heated air is blown in at the bottom of the furnace. This hot air burns the coke as it descends to heat, reduce and melt the charge. The iron oxide is converted to liquid metallic iron and is collected at the bottom of the furnace. As mentioned earlier, this is the largest energy-consuming step in making iron and steel.

Steelmaking

The molten iron produced by the blast furnace, or pig iron, is then further processed to make steel. Steelmaking is a process in which undesirable amounts of other chemical elements such as carbon, manganese, phosphorus, sulfur, and silicon are reduced and removed from the pig iron. Other elements such as fluxes and alloying materials are added to produce the desired steel properties (OTA 1980).

Three principal types of equipment are used in steelmaking: the basic oxygen furnace (BOF), the electric arc furnace (EAF), and the open hearth furnace. The most widely used steelmaking furnace is the BOF, which produced 61% of the nation's steel in 1979 (OTA 1980). The advantages of the BOF are its fast processing rates and its ability to produce carbon steel as well as the various alloyed steel. The steel is refined at a rate of 32 minutes per batch by an intense chemical reaction produced in the charge of iron, scrap, and lime.

The EAF produced 27% of the nation's steel in 1980. This furnace produces steel by creating an electric arc in the scrap charge. The advantages of this furnace are its ability to accept charges of 100% scrap (the BOF is limited to about 30%) and its economy in small-scale operations. These small-scale operations, known as mini-mills and speciality shops, are the segments of the steel industry that have not been declining as much as traditional integrated plants. These small-scale plants have the advantages of being able to produce their products entirely from scrap, thereby avoiding much of the cost associated with processing raw iron ore and being able to tailor their products for specific markets. The cost advantage of scrap-based production is estimated to be $130 per ton (32%) less expensive than production from iron ores.

Open hearth furnaces are the oldest of the three steelmaking furnaces. Use of this furnace peaked in the 1940s and 1950s and has been declining steadily since the faster BOF came into use in the 1960s. In 1980, the open hearth furnace furnished 12% of the domestic steel production.

Primary Finishing

The primary finishing step involves casting the molten steel and preparing the steel into rough, semifinished shapes. The two methods most commonly used are ingot casting and continuous casting. The conventional route involves ingot casting, in which the liquid steel is carried by a refractory lined container, known as a ladle, to a series of molds and poured to form ingots. After the ingots cool, they are stripped and placed in "soaking pits" where they are reheated in preparation for rolling. The reheated ingots forms are then rolled into blooms (rectangular forms), billets (square forms) and slabs.

A more recent alternative primary finishing technique involves continuous casting. In continuous casting the liquid steel is formed directly into the semifinished forms. By avoiding the intermediate casting and reheating steps, the continuous casting technique is more energy-efficient than the conventional process and has a higher product yield. Energy consumption can be reduced by one-half, while product yields can be increased from 82% with the conventional method to 96% with continuous casting.

Secondary Finishing

Secondary finishing involves converting the semifinished forms that are produced in primary finishing into the eventual steel products. In secondary finishing the slabs, blooms, and billets are reheated and processed through hot and cold rolling into the plates, bars, pipes, and sheets that are the final products. The most significant mechanical energy losses occur in these rolling operations. Much of the analysis of tribological energy sinks will center around these processes.

Heat Treating

Heat treating is frequently the final step in the finishing operations. The principal purposes of heat treating are to relieve stresses that develop in the steel during processing, to obtain full recrystallization to a more uniform grain structure, and to improve ductility to a level suitable for forming operations (OTA 1980). Common methods of heat treating include annealing, normalizing, spheroidizing, hardening, tempering, carburizing, and stress relieving.

4.2.2 Processes Containing Significant Tribological Sinks

Because friction, wear, and lubrication are associated with motion, the most likely areas for improving tribological energy use are those involving driven machinery. Therefore, the following discussions focus primarily on processes involving mechanical motion.

The most significant areas for tribological energy losses in the manufacture of primary metals are milling and the hot and cold rolling processes. Ore milling is discussed as a subtopic of the Mining Industry in Chapter 2.0. Hot rolling and cold rolling, which are used to produce 90% of U.S. steel products (Darby and Arons 1979), are discussed below.

Hot Rolling

Hot rolling is the predominant technique used in the mechanical processing of iron and steel. Several different types of hot rolling mills are used in processing different steel products. These mills generally fall into two categories: primary mills and finishing mills. Primary mills are used in the initial rolling of the steel ingots or the continuously cast forms. These mills include slab, bloom, billet and plate mills. In some cases, products are shipped directly after these primary hot rolling steps. In other cases, steel is further processed in secondary hot mills, which include pipe, rod, rail and bar mills. The relationships among the various hot rolling mills is shown in Figure 4.1. The electrical energy consumption and the material yields of the major types of hot rolling mills are shown in Table 4.5. Because of the prevalence of hot rolling, it is the primary candidate for energy savings through tribological improvements.

TABLE 4.5. Typical Yields and Electrical Energy Consumption of Hot Rolling Processes

Mill Operation	Yield (%)	Electrical Energy Consumption (million Btu per ton)
Slabbing/blooming mill	85	0.32
Plate mill	80	0.95
Hot strip mill	96	1.05
Temper mill	97	0.35
Billet mill	97	0.47
Rod mill	93	0.82
Bar mill (hot roll)	93	0.53
Bar mill (cold finish)	96	0.21
Structural mill	96	0.44
Pipe mill	90	0.89

The practice of hot rolling varies widely from plant to plant and its energy requirements depend on many factors, including total reduction, reduction per pass, rolling speed, yield, thermal treatments, downtime and mill size. Energy requirements also vary measurably with the equipment scheduling. Maximum efficiency is achieved with continuous, around-the-clock operation. Reducing this schedule to a six-day week increases energy use by 10%, and reducing the schedule to two shifts per day (14 hours per day) increases energy losses by another 5% to 10%.

Within an integrated steel plant, hot rolling accounts for the major portions of electricity, maintenance, and lubricant consumption. Processes associated with hot rolling account for over 50% of the electricity used in integrated steel plants. Approximately 65% is used in reheating and 35% goes to powering the mills. In 1980, about 30 to 35 trillion Btu of electricity were used in driving hot rolling mills. Hot rolling also accounts for 66% of the maintenance costs and 89% of the plant's lubricant consumption.

Hot rolling is performed at a high temperature so that the metal is soft and susceptible to large deformations. At this high temperature the metal can "recrystallize" after it is deformed to maintain its original (before rolling) properties.

The main causes of roll wear in hot rolling operations are abrasive wear by oxides formed on the roll and work piece surfaces, and thermal cycling of the roll surface. Tribological improvements are most likely to affect the abrasive wear aspect of roll performance. The severity of the abrasive condition depends upon the hardness of the oxides formed in the rolling process. Oxide hardness varies with oxide composition, which depends on the temperature at which the oxides are formed. For example, wüstite (FeO) forms at under 1650°F and is soft (HV[a] 270-350). At temperatures above 1650°F, magnetite (Fe_3O_4) and haematite (Fe_2O_3) begin to dominate with hardness of HV 420-500 and HV 1030, respectively. Roll wear can be reduced by minimizing the formation of the harder oxides, magnetite and haematite. This formation can be minimized by keeping the roll temperature below 1650°F.

Hot roll lubrication is helpful for minimizing roll temperature in two ways. First, the oil/water mixture cools the rolls directly. Second, the improved performance of lubricated hot rolling mills enables mill operators to apply less preheat furnace and reduces roll wear.

The direct and indirect energy losses in hot rolling are discussed separately below, followed by a summary of the major findings in the analysis of hot rolling.

Direct Energy Losses in Hot Rolling. The mechanical deformation of iron and steel that occurs by hot rolling has significant friction and wear problems involving both the roller and the material being rolled. Before the advent of high-temperature lubrication in hot rolling devices, the typical efficiency of the process ranged from 60% to 70%. Lifetimes for hot rolls vary significantly with size and service, but a roll often needs to be replaced several times a year.

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[a] HV is the Vickers hardness number, which is a microhardness technique employing a diamond pyramid indenter.

During the past several years, hot rolling efficiency has improved significantly because of the experimental application of liquid lubrication in the U.S. (Cichelli and Poplawski 1980), England (Williams 1980), and Japan (Suzuki and Ueda 1976). Energy consumption could be reduced through one of three different approaches:

- Reduce direct energy consumption in the mill drive motor while keeping all other mill operating parameters constant. Using liquid lubricant in this capacity has reduced energy consumption 15% to 25% according to various European, Japanese, and American mill operators (Williams 1980).
- Increase the amount of reduction taken during each pass, thereby reducing the number of passes needed to produce a fixed amount of product. (This is another way of saving mill-drive-motor power as well as increasing mill capacity.)
- Reduce the amount of preheat energy required in the soaking pits since the metal does not have to be as soft when hot rolled with a lubricant.

The third approach may prove to save the most energy since, in addition to reducing soaking pit energy consumption, lower rolling temperatures offer additional advantages. These advantages include less scale formation (scale is abrasive to the work rolls and is also costly to machine away), less lubricant boil-off, and less roll cooling requirements.

In the U.S. steel industry, an estimated 12 trillion Btu of energy were consumed by friction in the hot rolling operations of integrated plants. Consequently, if 8% were recovered with hot roll lubrication by the first approach above, the industry could save about 1 trillion Btu per year. If the third approach were adopted, about 8 trillion Btu could be saved annually by reduced metal loss due to scale removal. Additional savings of 11 trillion Btu would be realized through reduced soaking pit energy consumption (Cichelli and Poplawski 1980). These energy gains would be offset only partially by a lubricant consumption of only about 40 cubic centimeter per ton of steel rolled.

Indirect Energy Losses in Hot Rolling. In addition to the direct energy losses cited above, significant energy losses result from material wear and from the lubrication used. As a result of the abrasion and thermal fatigue cracks incurred during rolling, the rollers need to be reground frequently. Hot rolls are reground about once per shift with 0.020 to 0.030 in. of the roller removed. Hot rolls are typically replaced when about 10% of their diameter is lost by grinding. In this analysis approximately 0.1 lb of roll material is lost for every ton of steel processed.(a) About half of the embodied material loss is due to wear and half is due to thermal fatigue cracking. Approximately 210,000 tons of rolls are replaced each year, with an embodied energy content of 6.3 trillion Btu.

Hot-rolling lubrication can reduce indirect energy consumption in two ways:

- reduced roll wear, which results in less frequent roll reconditioning and replacement
- better product surface quality, which enables mills to produce more premium-grade product without additional process steps.

Williams (1980) reported that in Japan and the U.S. roll life has increased 20% to 40% when hot-roll lubrication has been used.

Summary of Major Findings for Hot Rolling. Hot rolling mills compose a major element of the tribological energy losses that occur in the iron and steel industry. Although there are a variety of hot rolling mills, the major tribological losses are common. The average efficiency of conventional hot rolling processes is 60% to 70%, with an overall energy use of 30 to 35 trillion Btu. However, recent advances in high-temperature lubrication technology have increased this efficiency by approximately 8%. Tribological factors also contribute to about half of the material degradation of the rolls. This results in a material loss of 210,000 tons of steel, with an embodied energy content of 6.3 trillion Btu.

(a) Based on a reversing mill with rolls 24 inches in diameter and 56 inches wide.

The technologies associated with hot rolling lubrication are currently quite young. Among the possible issues considered for additional optimization are the following:

- base lubricant selection (currently ester-based synthetics are favored for their higher temperature capabilities) and viscosity optimization
- lubricant additive formulations (currently extreme pressure and emulsifiers are used)
- delivery method (involves selecting the best location for applying the lubricant and the proper mixture of oil and water.)

Cold Rolling

Cold rolling is a secondary finishing step that further refines the quality of the hot rolled forms into the shipped products. In general, any steel product that is to be thinner than ~0.049 in. (0.125 cm) must be rolled further in a cold rolling mill.

Cold working is performed at a temperature that will soften the metal somewhat, but below the temperature that will "recrystallize" the metal. As such, cold working deformations increase the hardness of the metal by altering the shape of the grains of which it consists. Consequently, intermittent annealing is often required after a certain amount of cold working to enable it to be deformed further. Cold rolling operations generally involve smaller deformations than hot rolling operations. Surface finish quality and dimensional control are generally more important in cold rolled products than in hot rolled products.

Although cold rolling is used in producing far fewer products than hot rolling, its energy intensity is greater because the material is less malleable. Approximately 25 billion Btu of electricity were used in cold rolling operations in 1980.

The direct and indirect energy losses in cold rolling are discussed separately below.

Direct Energy Losses in Cold Rolling. Although cold rolling is more energy-intensive than hot rolling, the mechanical efficiency of the process is comparatively higher because of the widespread use of lubricants. Estimates of mechanical energy efficiency in cold rolling range from 60% to 90%. This translates to an energy sink of about 2.5 to 10 billion Btu of electricity annually.

Indirect Energy Losses in Cold Rolling. Because of the strict finishing requirements of cold rolled products, less wear is tolerated on cold rolling equipment than on hot rolling equipment. Cold rollers are typically reground two or three times per eight-hour shift with 0.003 in. to 0.005 in. removed from the diameter of the cold roll with each regrind. The principal concern in regrinding the roller surface is the high surface quality desired for cold rolling products. Generally, these rolls are replaced when 10% of their diameter has been lost. In this analysis, approximately 0.2 lb of roll were assumed to be lost with each ton of steel processed.(a) Because less material is ground away when compared with the hot rolling rollers, cold rollers last three to five times longer. Approximately 4200 tons of cold rollers are replaced each year, representing an embodied energy content of 0.14 trillion Btu.

4.2.3 Processes Not Containing Significant Tribological Losses

In this section, the processes not containing important tribological losses and excluded from the study are discussed.

Primary Iron and Steelmaking Processes - As described earlier, the primary energy-consuming processes in ironmaking and steelmaking are the thermal processes. The largest thermal processes occur in the initial stages of material processing in the coke ovens, blast furnaces, and steelmaking furnaces. Although these processes represent a very large percentage of the energy consumed in this industry, they are almost entirely thermal, and little potential for energy savings from tribological improvements was noted. As a result, the primary processing steps were excluded from further analysis.

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a) Based on a 5-stand mill with 10 work rolls.

Ore Grinding - This is a necessary process step in producing aluminum. Consequently, the principles discussed in the mining chapter (Chapter 2.0) apply to aluminum manufacture. However, only about 2 trillion Btu are consumed annually in grinding aluminum. Similarly, because aluminum products are rolled, some direct energy losses discussed in steel hot rolling are applicable. However, due to its lower hot-hardness, aluminum requires much less energy to roll than is required by steel.

Sintering and Pelletizing - After most of the gangue has been separated from iron ore, the ore is agglomerated into granular lumps by sintering or pelletizing. Sintering is accomplished by heating the powdered ore from 2400°F to 2700°F to bond the particles. Pelletizing is a similar method that incorporates a small amount or bonding agent before the powder is rolled into pellets while being heated to about 2400°F. Fuel requirements for sintering and pelletizing are 1.6 million Btu per ton and 0.6 million Btu per ton, respectively. However, almost all of this energy is thermal input and therefore does not involve a significant amount of tribology. Although some chronic wear problems have been reported, they do not appear to merit in-depth study.

Bearings - Bearings for the rolling mills typically weigh 100 lb to 200 lb and are kept in service from anywhere between 7 months and 20 years. Because the amount of material loss in bearing replacement is small compared to the roll material replaced, bearings were not examired further.

Aluminum Production - Refining aluminum recuires more energy per ton than the other common metals (iron, copper) (Chiogioci 1979). However, the vast majority of this power is consumed in digesting bauxite in caustic soda under heat and pressure, which initiate the production of alumina. By comparison, the tribological problems involved with aluminum processing are less serious than those of iron and copper. This is partially because almost all bauxite consumed in the U.S. is imported and therefore mining-related tribology energy sinks are deferred to other countries. A further mining consideration is that bauxite is usually found near the surface and therefore requires little overburden handling.

4.3. SUMMARY

Although the iron and steel industry is one of the largest energy-consuming industries in the economy, most of this energy is directed toward the thermal processing of materials. Tribological energy losses are, however, important in the secondary or finishing operations, in which the iron and steel is mechanically deformed into the shipped products. The principal categories of metalworking operations with tribological energy losses are hot rolling and cold rolling. The direct and indirect energy losses are summarized in Table 4.6, and the mechanisms of tribological loss are summarized in Table 4.7.

Hot rolling is the most widely used method of forming the steel products into various product shapes. This category comprises a wide variety of mills including slabbing, blooming, plate, hot strip, bar, and pipe mills. The principal component of tribological inefficiency in these mills is the abrasive wear caused by the oxide scales that form on the roll and work pieces. An estimated 12 trillion Btu of energy are lost due to friction and 14.3 trillion Btu are lost indirectly due to wear-related replacement of the work rolls and removal of scales that form on the work piece.

The other principal category of metalworking is cold rolling. Cold rolling is used in refining the size and finish of certain steel products, and its use is consequently much more limited than hot rolling. It is estimated that 5 billion Btu of energy are lost to friction in cold rolling and that an additional 140 billion Btu are lost in the roll material replaced.

This preliminary analysis indicates that a sizable direct and indirect energy losses can be attributed to tribological inefficiencies in iron and steel hot rolling processes. Research relevant to these losses would address a significant energy sink and would add to the technical understanding and control of processes that would benefit other primary metals industries.

TABLE 4.6. Direct and Indirect Energy Losses Analyzed in the Iron and Steel Industry

Sink	Energy Loss	Fuel Type	Material Loss	Embodied Loss	Other Indirect Energy Loss
Hot Rolling	12 trillion Btu	Electricity	210,000 tons	6.3 trillion Btu	8.0 trillion Btu
Cold Rolling	5 billion Btu	Electricity	4,200 tons	0.14 trillion Btu	--

TABLE 4.7. Tribological Mechanisms in the Iron and Steel Industry

Sink	3 Body Abrasion	2 Body Abrasion	High Stress Gouging	Impact Wear	High Friction	Erosion	Lubricated Wear	Adhesive Wear
Hot Rolling	✓	✓			✓			✓
Cold Rolling		✓			✓		✓	✓

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5.0 CHEMICAL AND PETROLEUM REFINING INDUSTRIES

In this chapter, total energy use and tribological losses in the chemical and petroleum refining industries are identified. Energy consumption is specified by major industry sectors (industrial inorganics, plastics, drugs, etc.) for various fuel types. Tribological losses in the process operations of the two industries are identified, and operations having significant tribological losses are then reviewed and described in more detail. For each operation, the nature and magnitude of the tribological losses are also estimated. This information is used to calculate the total direct tribological loss from that operation in the whole industry. These losses are summarized in a table at the end of the chapter. Indirect losses are briefly examined, but only in a qualitative manner. Because many assumptions had to be made in developing these figures, the major causes of uncertainty are noted and discussed.

5.1 INTRODUCTION

According to the 1972 Standard Industrial Classification (SIC) manual, the chemical industry (SIC 28) includes establishments producing basic chemicals or manufacturing products by predominantly chemical processes. The industry has eight major 3-digit SIC subdivisions, which are listed in Table 5.1. Many of these subdivisions use combinations of similar process steps, commonly known as unit operations. Some of these operations are also common to the petroleum and coal products industry (SIC 29). SIC 29 is listed in the classification manual as including establishments primarily engaged in petroleum refining, manufacturing of asphalt paving and roofing materials, and compounding of lubricating oils and greases from purchased materials. However, only petroleum refining itself will be considered in this report. Three 3-digit SIC subdivisions are listed in Table 5.1 for the petroleum industry.

5.1.1 Energy Consumption in Chemical and Petroleum Refining

Energy consumption in the chemical and petroleum refining industries is changing rapidly because of technical improvements brought about by increased competition and energy costs. Because of these changes, the data presented here are from the 1981 Annual Survey of Manufactures (ASM) (Bureau of Census

TABLE 5.1. Purchased Energy Consumption in the Chemical and Petroleum Refining Industries (in 1981)

SIC #	Classification Name	Purchased Energy (10^{12} Btu)	% of Total
281	Industrial Inorganics	562	21.4
282	Plastic Materials and Synthetics	418	15.9
283	Drugs	77	2.9
284	Soaps, Cleaners, Toilet Goods	55	2.1
285	Paints and Allied Products	16	0.6
286	Industrial Organics	1042	39.6
287	Agricultural Chemicals	367	14.0
289	Miscellaneous	92	3.5
	Total	2629	100.0
291	Petroleum Refining	1064	93.6
295	Paving and Roofing Materials	58	5.1
299	Miscellaneous	15	1.3
	Total	1137	100.0

1981), rather than 1977 Census of Manufactures (Bureau of Census 1981), used in the other chapters of this analysis. Although the ASM is incomplete in comparison with the 1977 Census of Manufactures (Bureau of Census 1981), the latest census available, it includes some of the changes in recent years.

The ASM presents data on consumption of purchased fuels plus electricity generated and used on site. The refinery industry, in particular, burns considerable portions of its process stream (which is not a purchased fuel) for energy, so this purchased energy information does not give the total energy consumption. However, as discussed later, it does include the energy flows of tribological importance.

Purchased energy consumption in the chemical industry was about 2.6 quad in 1981. Two major subclassifications producing basic chemicals, the industrial organics and industrial inorganics sectors, consumed close to two-thirds of this total. Petroleum refining consumed 93.6% of the 1.1 quad of energy consumed by the petroleum and coal products industry. Energy consumption for each three-digit classification in the chemical and petroleum refining industries is shown in Table 5.1.

A significant proportion of the purchased energy consumed by both the chemical and petroleum refining industries is natural gas. In the chemical industry, natural gas comprises 56% of the total, followed by electricity with 17.2%, coal with 14.1%, and fuel oil with 5.7%. Refineries consume 78.5% natural gas, 9.8% electricity, 5.4% fuel oil and almost no coal. Table 5.2 details this distribution.

Electricity is an energy form of particular interest for this study because of its use to drive motors, which power a variety of machines. Both the chemical and petroleum refining industries generate considerable amounts of power themselves. The purchased and generated electricity in 3-digit SIC subclassifications of both industries is detailed in Table 5.3. As shown in the table, the subclassifications of industrial organics and industrial

TABLE 5.2. Purchased Energy Consumption by Fuel Type in the Chemical and Refining Industries

Industry	Fuel	10^{12} Btu	% of Total
Chemical	Coal	370	14.1
	Fuel Oil	151	5.7
	Natural gas	1472	56.0
	Electricity	452	17.2
	Other and/or Not Specified	185	7.0
	Total	2630	100.0
Petroleum Refining	Coal	5.76	0.5
	Fuel Oil	61.8	5.4
	Natural Gas	893	78.5
	Liquid Petroleum Gas	9.04	0.8
	Electricity	11.1	9.8
	Other and/or Not Specified	56.4	5.0
	Total	1037.1	100.0

TABLE 5.3. Electricity Consumption in the Chemical and Petroleum Refining Industries (kWh x 10^6)

SIC #	Name	Electricity Purchased	Electricity Generated and Used	Electricity Used	% of Total
281	Industrial Inorganics	60,110	3,143	63,253	44.4
282	Plastics and Synthetics	21,287	1,406	22,693	15.9
283	Drugs	4,673	W(a)	--	--
284	Soaps, Cleaners, Toilet Goods	2,294	W	--	--
285	Paint and Allied Products	878	W	--	--
286	Industrial Organics	30,135	4,733	34,868	24.5
287	Agricultural Chemicals	9,920	570	10,490	7.4
289	Miscellaneous	3,041	193	3,234	2.3
		132,338	10,045	134,538	94.5
2911	Petroleum Refining	30,964	5,420	36,384	95.8
295	Paving and Roofing Materials	1,238	17	1,255	3.3
299	Miscellaneous Petroleum and Coal Products	344	--	344	0.9
		32,546	5,437	37,983	100.0

(a) Withheld to avoid revealing information about individual companies.

inorganics consume about two-thirds of the total. Refining consumes almost 96% of the electricity consumed in petroleum and coal products.

One important factor in any analysis of the chemical industry is its extreme diversity. Hundreds of thousands of chemicals are produced by thousands of distinct processes. Often the same product is produced by different processes in different plants. Large proportions of the energy, however, are consumed in the basic industrial organics and inorganics sectors in producing very basic chemical products. The top 50 of those products in 1983, by pounds of production, are shown in Table 5.4. Petroleum refining is somewhat more uniform, but differences in the quality of the crude feedstock and the required output product mix cause difficulties in making generalities about this industry as well.

5.1.2 Industry Activities

The chemical and petroleum refining industries generally have their processes designed and analyzed by unit operations. These unit operations are basic reaction, mixing, crushing or other steps in the sequence of operations leading from feedstock to final product. There are many unit operations, and many ways they can be combined into a process. As noted previously, often several processes can be used to manufacture the same product from the same feedstock. The process used is primarily based on the its relative economics, which depend on the process design, local factors such as the availability of cooling water or electricity, and even the size of the planned installation. Many plants for basic chemicals are huge because the material cannot be produced cheaply enough on a small scale to be competitive.

The chemical industry's diversity makes analyzing a particular type of energy loss (e.g., tribology) exceedingly difficult. Information on friction and wear is not routinely available, and the day-to-day energy consumption of that friction and wear is not usually of concern to the industry. Most of the energy consumption in the industry is for process heat and is derived from gas, oil, coal, and other fuels. Any tribological losses generally form part of the electrical energy use, as noted earlier, because electric motors are used for most shaft drives. Use of engines and turbines for purposes other than electricity generation in the chemicals and refining industries is ignored in this study. Also, it is assumed that all electric power generation is by turbines rather than engines. Therefore, in the analysis of tribological losses, electrical energy consumption data must be used, which are available for various 4-digit SIC subsections of the chemicals industry and for petroleum refining.

TABLE 5.4. Top 50 Chemical Products in 1983 (in pounds of output)

Rank	Product	Output (billions of lb)	Rank	Product	Output (billions of lb)
1	Sulfuric Acid	69.45	26	Formaldehyde[a]	5.40
2	Nitrogen	42.03	27	Hydrochloric acid	5.22
3	Lime[b]	28.80	28	Ethylene glycol	4.46
4	Oxygen	28.73	29	p-Xylene	4.11
5	Ethylene	28.59	30	Ammonium sulfate	3.94
6	Ammonia	27.37	31	Cumene	3.30
7	Sodium hydroxide	20.46	32	Potash[c]	2.87
8	Chlorine	19.92	33	Acetic acid	2.79
9	Phosphoric acid	19.90	34	Phenol[d]	2.61
10	Sodium carbonate[e]	16.93	35	Carbon black	2.50
11	Nitric acid	14.75	36	Butadiene[f]	2.31
12	Propylene	13.98	37	Aluminum sulfate	2.29
13	Ammonium nitrate[g]	13.24	38	Acrylonitrile	2.15
14	Urea[h]	11.54	39	Vinyl acetate	1.96
15	Ethylene dichloride	11.25	40	Calcium chloride[i]	1.88
16	Benzene	9.48	41	Acetone	1.87
17	Ethylbenzene	7.86	42	Sodium sulfate[j]	1.71
18	Carbon dioxide[k]	7.15	43	Cyclohexane	1.69
19	Toluene[l]	7.12	44	Propylene oxide	1.58
20	Styrene	6.99	45	Titanium dioxide	1.51
21	Vinyl chloride	6.95	46	Sodium silicate	1.45
22	Methanol	6.62	47	Adipic acid	1.42
23	Terephthalic acid[m]	5.69	48	Sodium tripolyphosphate	1.34
24	Ethylene oxide	5.58	49	Isopropyl alcohol	1.21
25	Xylene	5.57	50	Ethanol	1.10
				Total Organics	165.17
				Total Inorganics	333.41
				GRAND TOTAL	498.62

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[a] 37% by weight.
[b] Except refractory dolomite.
[c] K_2O basis.
[d] Synthetic only.
[e] Synthetic and natural.
[f] Rubber grade.
[g] Original solution.
[h] 100% basis.
[i] Solid and liquid.
[j] High and low purity.
[k] Liquid and solid only.
[l] All grades.
[m] Includes both acid and ester without double counting.

Sources: Bureau of Mines, International Trade Commission, C&EN estimates

The industry activities that use electricity are fairly limited compared to those that use heat, but they still must be generalized to make this analysis manageable. The final categorizations chosen for examination are turbines, pumps (of all types), compressors, blowers, mixers and agitators, grinders, centrifuges, conveyors, packaging machines, and other mechanically complex devices. These categorizations are obviously gross simplifications because there are thousands of types and sizes of pumps, for example. Without careful study of specific industrial processes, however, further subdivision of the categories is not possible. Also, these categories were not chosen because they were all suspected of being very important tribological sinks. For example, centrifuges, of course, must run very smoothly and are therefore already very carefully designed tribologically and do not stand out as a possible area of large loss.

Given the categorizations, the next step of the analysis is to establish a relationship between tribological estimates made on an individual-piece-of-equipment level and the data for electricity use by various sectors of the chemical and petroleum industries. This step is very important and difficult. Loss estimates highly depend on the process in which a piece of equipment is used. Various processes have various types of mechanical and nonmechanical equipment that uses electricity. Relating equipment and energy use information, without tedious process-by-process evaluations of the whole industry, requires careful planning and gathering of available data. The approach taken in this study is outlined in the next section.

5.2 PROCESS ANALYSIS APPROACH

To determine tribological losses from the electricity data requires a simplified set of models for processes taken to be representative of the chemical industry. For this preliminary review, two approaches were possible. The first was to generate several generic processes that roughly typify the characteristics of basic types of steps taken in chemical manufacturing and the general methodology for petroleum refining. These processes might include those involving a great deal of solids handling, those involving largely gases, or those involving a great deal of mixing.

A second approach was to use published models of industrial processes. A useful set of processes is contained in work completed by Drexel University for the Department of Energy (DOE) in the late 1970s (Hamel and Brown 1979). The report of that work contains information on 48 important chemical processes and on petroleum refining. The chemical processes belong to 14 different 4-digit SIC subclassifications in which electricity data are available (listed in Table 5.5). Because of this subclassification, an approach using the Drexel models was chosen.

TABLE 5.5. Chemical Processes in the Drexel Data Base

SIC Numbers	Industry Subclassification
281	Industrial Inorganics
2812	Alkalies and Chlorine (5 processes)
2813	Inorganic Gases (3 processes)
2816	Inorganic Pigments (5 processes)
2819	Industrial Inorganic Chemicals (5 processes)
282	Plastic Materials and Synthetics
2821	Plastic Materials and Resins (5 processes)
2822	Synthetic Rubbers (5 processes)
2823	Cellulosic Man-Made Fibers (5 processes)
2824	Non-Cellulosic Organic Fibers (5 processes)
283	Drugs
2834	Pharmaceutical Preparations
286	Industrial Organics
2865	Cyclic Crudes and Intermediates (3 processes)
2869	Industrial Organic Chemicals (3 processes)
287	Agricultural Chemicals
2873	Nitrogenous Fertilizers
2874	Phosphatic Fertilizers (4 processes)
289	Miscellaneous
2899	Chemical Preparations Not Elsewhere Classified (2 processes)
291	Petroleum Refining
2911	Petroleum Refining

5.2.1 Drexel Industrial Process Data

The Drexel information was reviewed by the Electric Power Research Institute (EPRI) as part of a study of industrial energy data bases (Isser and Limaye 1982). Some of the points made in that report are a good preface to this study's effort to use the Drexel data in tribological assessments. EPRI's data base was developed as part of a waste energy study. To obtain information for that data base, handbooks, previous energy conservation studies and industry periodicals were used. Because the models are synthesized as typical rather than as exemplars, no documentation is given. Perhaps because the Drexel work was originally intended for waste energy studies, in some cases information on electricity is questionable. The most noticeable problems, however, are in cases of electricity self-generation and may not affect consumption estimates. The Drexel study is criticized because it presents a level of detail that often does not logically hold together and certainly is not substantiated in the report. For brief data manipulation efforts such as this study, however, it is the best information available.

As noted above, the Drexel data cover 48 processes in 14 subdivisions of the chemical industry. The 12 other subdivisions at that level of classification (4-digit SIC) each consume much less electricity than the 14 categories. Information from energy use and chemical process guides (Shreve and Brink 1977) was used to combine the electricity distribution among pumps, compressors, etc., in the 48 processes into distributions for the 14 SIC categories. The 12 minor categories were mostly finished goods (soaps, fertilizers) requiring high-tribological-loss packaging and finishing operations. They were therefore conservatively evaluated using the average electricity distributions from the 14 more basic SICs.

5.2.2 Tribological Loss Estimation

The most basic and important step in this analysis was estimating tribological losses in the categories of equipment listed above. This estimation was very difficult because overwhelming generalizations had to be made about parameters that are very important to tribology. For example, a wide variety of types of pumps that have many different bearing arrangements and friction and wear parameters are being used. These types can be discussed separately, but to extrapolate losses on a nationwide, multiprocess level, very broad estimates were required. The wide variety of materials being pumped was equally a problem. Similar concerns arise for other types of equipment. Investigating tribological losses in the chemical and petroleum refining industries is therefore severely hampered if its results are to be extrapolated beyond a very specific range of equipment and processes. This overview was hampered almost to the point of dysfunction by its very broadness. The estimates of direct tribological losses as a function of electric power consumption given in the next section must therefore be treated as only an attempt at quantification. The summary section briefly discusses indirect losses.

5.3 DIRECT TRIBOLOGICAL LOSSES FOR CHEMICAL PROCESS EQUIPMENT

This section contains assessments of a simplified and generalized subset of chemical and refining industry equipment that is applied to a wide range of chemical processes. Turbines will be discussed first because they are the only tribologically important piece of equipment under study here that is not driven by electricity; they are used for producing the electricity. Electric motors, which drive the remainder of the equipment, are then reviewed for losses. Finally, pumps (of all types), compressors, fans and blowers, mixers and agitators, grinders, centrifuges, and conveyors and other mechanically complex devices are discussed.

5.3.1 Turbines

Turbines have many sources of losses. Some of these losses are fluid mechanical, such as blade tip blow-by or other turbulent phenomena. Others sources develop over time because of blade degradation from erosion, deposition or corrosion. Erosion (which is a tribological phenomena) is a severe problem in research gas turbines burning dirty fuels but is a less serious problem in steam or natural gas turbines, which are generally used in the chemical and refining industries. Utility steam turbines require regular rebuilding as well, but how closely utility procedures correspond with the situation in the chemicals industry is unknown, so indirect tribological losses in turbines will not be discussed.

Direct losses estimated for the utility turbines (Pinkus and Wilcock 1977) will be discussed, however. These large turbines generally have 10 sleeve-type fluid film bearings and 2 thrust bearings with journals 1 to 2 feet in diameter, running at 3600 rotations per minute (rpm). These bearings usually run in the turbulent regime, with losses of 0.5% of plant output. The smaller turbines in industrial generating sets will certainly have higher losses than the utility turbines, so these estimates are conservative.

5.3.2 Electric Motors

The electric motor industry is highly standardized, and data on motor inefficiencies are readily available. Most of the losses in a standard motor are not related to tribology--only 5% of the losses are attributable to friction in the motor and windage through the casing; about one-third to one-half of this can be attributed to bearing friction alone. Motor efficiency depends on motor size and varies at full load from 83% for 1 horsepower, 3-phase, 4-pole energy-efficient motors to 94.5% for 200 horsepower motors (Andreas 1982).

Given that many of the motors in the chemical and petroleum refining industries are large but may not be of this energy-efficient type, an overall efficiency of 90% can be assumed. Losses due to tribology are then about 0.2% of power input. Many motors do not run at full load all the time; the chemical industry is investing heavily in adjustable speed drives because this significantly increases efficiency. The adjustable speed drives increase tribological losses, however, so the simplified analysis presented here is conservative. Also, this motor loss is much lower than the tribology loss in the device being driven, so much lower that it is well within the uncertainty of the loss estimate for a given device. Therefore, it is not added to the device estimates in this analysis because they are only round number figures. This further enhances the conservatism of the results.

5.3.3 Pumps

Two major types of pumps are used in the chemical and petroleum refining industries--centrifugal and reciprocating pumps. The former are the workhorse of the industry, while the latter are especially useful when high pressures are needed and the intermittent nature of the pumping is not a problem. Centrifugal pumps are made in a considerable variety of types and sizes. They may be horizontal or vertical, single or double suction, and single or multistaged. Capacities are available up to 600,000 gallons per minute and horsepowers up to 65,000 (Evans 1976). These pumps are often oversized in installations because of the possible need to start with a full load of fluid.

Efficiency depends on sizing and many fluid mechanical effects, as well as tribological effects (Matley 1979). The latter include bearing friction, seal friction and efficiency reductions due to erosion of the pump impeller. The latter effect is probably the most important. During the initial weeks of operation, erosive damage to the impeller can alter the geometry of the impeller contours. This change can reduce pump efficiency by 5% or more. Once the change occurs, the new geometry is maintained or further degraded for the rest of the pump's life.

Reciprocating pumps can provide high-pressure output quite readily and are available in many different forms. Their operating characteristics are inflexible, however, and in many pumping situations they have lower overall efficiency than centrifugal pumps (50% to 90%). Larger pumps with more sophisticated designs are more efficient. Seal friction is the most important tribological loss because seals are tight packages. The losses in the packing can be more than 5% in some cases. Leakage past the seals as the result of wear can increase losses proportionally to the flow rate of the leak. Most leakage situations are very small percentages of pump capacity, however.

Considering the diversity of types of pumps and process situations encountered, 4% of pump power was conservatively estimated to be lost by various tribological mechanisms. Indirect losses are very difficult to assess because wear is a function of both pump design and the product handled. Wear is very important, however. Bearings apparently cause problems in many process industry centrifugal pumps. Thirty percent of all centrifugal pump failures can be traced to the failure of rolling element bearings (Barnard and Sowrey 1984). The indirect loss implications of this are not known, however, because they depend on the distribution of failures throughout industry.

5.3.4 Compressors

There are two basic types of compressors, dynamic and positive displacement compressors, which correspond to centrifugal and reciprocating pumps. There are two classes of dynamic compressors and four general types of positive displacement compressors, but they were not separately analyzed for tribological losses. In all compressors, erosion wear can be significant if the gases being processed are not free of liquids and abrasive particles, and if the erosion is severe, it can degrade performance as well as shorten operating lifetimes. The most important direct energy losses in compressors were from shaft and other types of seals (Matley 1979), which are more complex in compressors than in pumps because gases escape much more readily. In many cases, leakage has only a minor effect on efficiency, however, and after the range of compressors and likely gas streams were considered, tribological losses were set at 4% of power input.

5.3.5 Blowers

Blowers, whether the axial or centrifugal configuration, basically act as large fans and are used to move large volumes of air at close to atmospheric pressure. For example, they provide inlet air for process furnaces and drive exhausts. Many fluid mechanical losses occur in a blower, but tribological losses are relatively small. Friction losses occur in the transmissions used between motor and fan and vary between 2% and 5% (Matley 1979), but many blowers do not use transmissions. Bearing losses alone are quite low, only slightly greater than those for the electric motor. Therefore, an overall estimate for the loss was set at 1% of input power.

5.3.6 Mixers and Agitators

Several different types of mixers are used in the chemical industry. Agitators will not be distinguished from mixers in this study because the tribological concerns are similar. The mixers range from small portable machines clamped onto open tanks, to side-entering devices used for blending, to heavy-duty, multiple-stage top-entering machines. As with blowers, the primary source of tribological loss is the transmission used to keep the paddle speed lower than motor speed. Its amplitude depends on the type of transmission and extent of reduction necessary. A value of 1% of input energy was selected based on moderate speed reductions in industrial quality transmissions.

5.3.7 Centrifuges

Centrifuges are important devices for extracting liquid from process materials without heating them, as for example, when separating suspensions. The centrifugal forces that accomplish this task depend on speed of rotation of the centrifuge drum, and they therefore rotate at very high speeds on carefully designed bearings. Their tribological losses can be estimated to be at least comparable to those for steam turbines, or 0.5% of power input.

5.3.8 Crushing and Grinding

Crushing and grinding operations occur in the plastics and inorganic chemicals industries, in making drugs, and in other chemical applications. The estimate for the tribological losses of 1.75% of input power, as developed in the mining chapter, was used here also.

5.3.9 Conveyors, Packagers, Balers, and Other Complex Devices

Conveyors are used in occasional solids-handling applications in the chemicals industry, as well as in other industries discussed in this report. There are many types of conveyors, including screw conveyors, bucket elevators, bucket carriers, and roller belts. The type used depends on the distances and other transport needs and the solid being transported. More detail is given in Chapter 7.0 on the food processing industry. Industrial sources give 5% of input power as an accurate estimate for friction losses in conveyors. These losses occur in bearings and rollers, in pins and bushings in chains, among elements in unit conveyors, and in contacts with adjacent surfaces. Losses in packaging devices, balers, and other complex machines are estimated to be at the same 5% level because of similar types of friction.

5.4 SUMMARY AND CONCLUSIONS

The analysis methodology and assumptions about direct tribological losses developed in this study were used to calculate the tribological losses in the chemical and petroleum refining industries. These results are shown in Table 5.6. Descriptive material on possible tribological mechanisms was also

TABLE 5.6. Loss Mechanisms in the Chemical and Petroleum Refining Industries

Process Equipment	Friction	Erosion	Abrasion
Compressors			
Radial Flow Centrifugal	✓	✓	
Axial Flow Centrifugal	✓	✓	
Reciprocating	✓		
Rotary	✓		✓
Fans and Blowers			
Axial Flow	✓		
Centrifugal Flow	✓		
Pumps			
Reciprocating	✓	✓	
Rotary Positive Displacement	✓	✓	✓
Centrifugal	✓	✓	
Mixers	✓	✓	
Centrifuges	✓		
Crushers, Mills and Grinders	✓		✓
Conveyors, Packagers, Balers, etc.	✓		✓
Turbines	✓	✓	

collected and is summarized in Table 5.7. Table 5.7 is not strictly comparable with similar tables in other chapters in this report, however. The industries under study are too varied for it to be complete.

The variety in the industries makes analyzing specific types of losses (e.g., tribological) very difficult. Too many kinds and sizes of equipment and kinds of process streams exist to count the details of each, even if such information were available. These details are not available, however, because specific information on processes is often a closely guarded industrial secret. This preliminary effort used estimates and assumptions at several stages of the analysis to determine tribological losses in chemicals and petroleum refining. They are listed here as an aid to those using the results of this study or wishing to improve upon it. In the order in which the estimates and assumptions were made in the analysis process, they include the following:

TABLE 5.7. Direct Tribological Losses in the Chemical and Petroleum Refining Industries

Process Equipment	Energy Consumed	Tribological Loss (%)	Total Energy Loss (10^{12} Btu)
Compressors	Electricity	4	2.48
Fans and Blowers	Electricity	1	1.99
Pumps	Electricity	4	6.93
Mixers	Electricity	1	0.153
Centrifuges	Electricity	0.5	0.0546
Crushers, Mills, and Grinders	Electricity	1.75	0.464
Conveyors, Balers, Packagers, etc.	Electricity	5	0.805
Turbines	Various fossil fuels	0.5	0.2667

- Estimates - Percentage of power input or output attributable to tribology.
- Assumption - Only implements driven by electric motors are significant.
- Assumption - All electricity generation is by turbine-driven generators.
- Estimates - Drexel study process energies.
- Estimates - The contributions Drexel processes make to full 4-digit SIC classifications in which electricity use data were available.
- Assumption - The 4-digit SIC groups for which Drexel data were not available could be evaluated using averaged data from other processes.
- Uncertainties - In 1981 Annual Survey of Manufactures data, which are from a statistical survey and not a complete census.

Many of these estimates and assumptions are purposely conservative. Some of the uncertainty in the estimates could be removed by a much more thorough study of the industry, which would probably find somewhat enlarged tribological sinks. Such an effort would involve building a chemical process industry data base, however.

Within the limitations of the current analysis, the direct loss results show that tribological losses from a particular sink basically depend on how prevalent that sink is in the industry. None of the devices examined had a huge percentage of tribological losses. For this reason, pumps, which are universal in the chemical and petroleum refining industries, contribute over half of the direct tribological energy loss. Compressors, blowers and mixers are also big contributors, while less common operations like crushing, conveying and packaging have smaller tribological losses. Centrifuges, as might be expected, provide only a very small (<0.5%) contribution to the losses from these electric-motor-driven devices. Analysis of nonelectric devices was restricted to turbine-generators, which have a relatively minor tribological contribution on the same order as crushers. Unlike most of the electrically driven equipment, turbines, of course, are not specific to the chemical industry.

Indirect losses are probably impossible to calculate with any accuracy. No attempt was made to do so in this analysis. Material wear is common for motor-driven components in the industry, however. Many equipment failures are due to tribological causes. In the petroleum refining industry, for instance, 30% of all pump failures are caused by the failure of rolling element bearings (Barnard and Sowrey 1984). In addition to the indirect energy losses from equipment replacement, large energy costs result from process shutdowns for overhauls, especially if they are unscheduled. The reliability of process plant equipment is of paramount importance because many plants run 24 hours a day. Chemical and petroleum industry interest in tribology is based more on these indirect energy and production concerns than on direct losses.

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6.0 PULP AND PAPER

In this chapter, total energy use and tribological losses in the pulp and paper industry are identified and characterized. Energy consumption is specified by fuel type for each of the major pulp and paper sectors, and total energy consumption is compared to purchased fuels and electricity. The major processes and products of the pulp and paper industry are briefly described, and those processes identified as having significant tribological losses are reviewed and described in more detail. The nature of each tribological sink and the mechanisms leading to direct and/or indirect losses are then characterized. Finally, the estimates of energy losses and the calculational approach taken are identified. Tribological losses estimated for pulp and paper are summarized at the end of the chapter.

6.1 INTRODUCTION

The pulp and paper industry, as defined for this study, includes businesses engaged in harvesting trees, debarking, cutting, chipping, pulping, and producing paper, paperboard, building paper, and building board. This specifically includes logging camps and logging contractors (SIC 2411), pulp mills (SIC 2611), paper mills (SIC 2621), paperboard mills (SIC 2631), and building paper and building board mills (SIC 2661). Sawmills and establishments that manufacture paper products from purchased paper were not included in the analysis.

6.1.1 Energy Consumption in Pulp and Paper

Purchased fuels and electric energy consumption in pulp and paper totaled ~1.2 quads in 1981 according to data presented in the 1982 Census of Manufactures (U.S. Census Bureau 1983). (As of May 1984, the 1981 data are the latest comprehensive energy consumption information available from the U.S. Census Bureau.) Paper and paperboard mills dominate the purchased fuels category by combining for over 85% of the total for pulp and paper. Purchased fuels and electric energy consumption are shown for each of the four-digit classifications in Table 6.1. The energy consumption data listed in Table 6.1 and in the

TABLE 6.1. Purchased Fuels and Electric Energy in Pulp and Paper (1981)

SIC #	Classification Name	10^{12} Btu	% of Total
2411	Logging Camps and Logging Contractors	36.8	3.1
2611	Pulp Mills	85.4	7.2
2621	Paper Mills	591.4	50.0
2631	Paperboard Mills	444.9	37.6
2661	Building Paper and Building Board Mills	25.4	2.1
		1183.9	100.0

following tables in this chapter have been derived from the data in the 1982 Census of Manufacturers (U.S. Census Bureau 1983).

Purchased energy in pulp and paper is spread fairly evenly among the principal fuel types. Natural gas is the most predominant fuel but still only accounts for about one-third of the purchased energy total. Coal and residual fuel oil each accounted for a little over 20% of the total. Coal usage has continued its gradual increase of recent years, while residual fuels consumption has declined from that of the late seventies. Distillate fuel oil use has declined to the point where it is no longer a significant fuel. Both natural gas and electric energy purchases have been relatively constant over the past decade. Purchased energy consumption data by fuel type are presented in Tables 6.2 through 6.7 for the pulp and paper industry and each of its major subdivisions.

In addition to the purchased fuels and electric energy reported by the Census Bureau, 50% of the total energy consumed in the pulp and paper industry comes from self-generated sources, such as waste wood (hogged fuel), bark, spent liquor, and hydropower. Table 6.8 summarizes self-generated energy production for the pulp and paper industry. Much less fuel is purchased by pulp mills than by paper mills because of the large amount of energy recovered from spent liquors.

6.1.2 Pulp and Paper Operational Activities

The production of paper from raw forest products involves three separate stages. First, trees are harvested, debarked, cut, and chipped to produce raw

TABLE 6.2. Purchased Energy Consumption by Fuel Type in the Pulp and Paper Industry (1981)

Fuel	10^{12} Btu	% of Total
Electricity	148.76	12.6
Distillate	14.64	1.2
Residual	263.63	22.3
Coal	243.66	20.6
Natural Gas	390.66	33.0
Liquid Petroleum Gas	1.31	0.1
Other and/or Not Specified	121.23	10.2
	1183.89	100.0

TABLE 6.3. Purchase Energy Consumption by Fuel Type in Logging Camps and Logging Contractors (1981)

Fuel	10^{12} Btu	% of Total
Electricity	1.71	4.6
Distillate	8.68	23.7
Residual	1.99	5.4
Natural Gas	0.41	1.1
Liquid Petroleum Gas	0.10	0.3
Other and/or Not Specified	23.89	64.9
	36.79	100.0

TABLE 6.4. Purchased Energy Consumption by Fuel Type in Pulp Mills (1981)

Fuel	10^{12} Btu	% of Total
Electricity	10.71	12.5
Distillate	0.16	0.2
Residual	35.39	41.5
Natural Gas	21.42	25.1
Other and/or Not Specified	17.72	20.7
	85.40	100.0

TABLE 6.5. Purchased Energy Consumption by Fuel Type in Paper Mills (1981)

Fuel	10^{12} Btu	% of Total
Electricity	85.67	14.5
Distillate	3.69	0.6
Residual	131.75	22.3
Coal	155.91	26.4
Natural Gas	174.83	29.5
Liquid Petroleum Gas	0.74	0.1
Other and/or Not Specified	38.81	6.6
	591.40	100.0

TABLE 6.6. Purchased Energy Consumption by Fuel Type in Paperboard Mills (1981)

Fuel	10^{12} Btu	% of Total
Electricity	47.63	10.7
Distillate	1.63	0.4
Residual	90.78	20.4
Coal	87.75	19.7
Natural Gas	180.23	40.5
Liquid Petroleum Gas	0.14	--
Other and/or Not Specified	36.74	8.3
	444.90	100.0

TABLE 6.7. Purchased Energy Consumption by Fuel Type in Building Paper and Building Board Mills (1981)

Fuel	10^{12} Btu	% of Total
Electricity	3.04	12.0
Distillate	0.48	1.9
Residual	3.72	14.6
Natural Gas	13.77	54.2
Liquid Petroleum Gas	0.33	1.3
Other and/or Not Specified	4.06	16.0
	25.4	100.0

TABLE 6.8. Self-Generated Fuels in the Pulp and Paper Industry (1981)

Fuel	10^{12} Btu	% of Total
Waste Wood	150.3	13.8
Bark	104.7	9.6
Spent Liquor	816.9	75.0
Hydropower	9.5	0.9
Other	8.4	0.8
	1089.8	100.0

material. Next, cellulose fibers are separated from the wood either by chemical digestion or by mechanical grinding. Finally, the aqueous solution of small cellulose fibers (pulp) is used to form sheets of intermeshed fibers through various drying and pressing operations. The first and last processes have undergone gradual changes in manufacturing technique. The second process, that of producing pulp, has undergone substantial changes in the past 50 years of papermaking.

Pulp and paper are manufactured in two different mill settings, referred to as integrated and nonintegrated mills. Integrated mills produce pulp and paper from pulpwood or purchased wood chips through chemical and mechanical processes that render the solid wood pieces into a fibrous mass known as pulp. These mills tend to be relatively large, with average capacities of about 300,000 tons per year, and are located in areas of ample pulpwood supply and cheap transportation. Nonintegrated mills produce pulp by using waste paper as a source of cellulose fibers, rather than virgin pulpwood. These mills are necessarily located close to sources of waste paper (i.e., in more industrialized areas) and tend to be much smaller, with capacities ranging from 3,000 to 30,000 tons per year (Chiogioji 1979).

Each mill type is associated with a distinct set of tribological loss mechanisms. The process of removing timber, cutting and debarking pulpwood, and finally chipping the pulpwood logs into usable chips relies upon abrasive cutting processes. The process of chopping debris-laden stocks of converted wastepaper for use in nonintegrated mills also requires abrasive cutting, although of a different type. Both mill types require pumping of fibrous slurries with possible tribological losses occurring during pumping.

Many other processes in this industry incur wear and friction. In the following sections, the more important tribological loss mechanisms in the pulpmaking and papermaking processes are summarized. Because different processes are used to manufacture different products, a survey of current production figures is first presented, followed by a tribological analysis of the most widely used processes.

6.1.3 Industry Production Levels

Paper products include newsprint, printing and writing papers, tissue, packaging paper, and paperboard. Table 6.9 shows production figures for 1980 (Griffin et al. 1984). The product having the largest volume was paperboard used in making corrugated containers and flat boxes, with printing and writing papers having the second largest volume.

The manufacturing processes used to produce paper products have changed significantly. The use of the groundwood process by which cellulose fibers are produced by mechanical grinding decreased from 41% of the total pulp produced in 1920 to 10.4% in 1970. In contrast, the use of the Kraft process by which cellulose fibers are produced by a chemical digestion process increased from 4.9% of the total pulp produced in 1920 to 69.7% in 1970 (American Paper Institute 1971). Table 6.10 shows the 1980 figures on wood pulp production by process (Griffin et al. 1984). According to these statistics, the Kraft and mechanical groundwood processes account for 85.4% of the total pulp production.

TABLE 6.9. 1980 Paper and Paperboard Production (Griffin et al. 1984)

Product	1000 Short Tons	% of Total
Newsprint	4,673	7.6
Printing/Writing	15,219	24.7
Tissue	4,352	7.1
Board	31,524	51.2
Packaging/Other	5,802	9.4
	61,570	100.0

TABLE 6.10. 1980 Pulp Production (Griffin et al. 1984)

Pulping Method/Source	1000 Short Tons	% of Total
Sulfite	1,846	3.7
Kraft/Soda	38,586	76.3
Semichemical	4,043	8.0
Mechanical	4,579	9.1
Other Wood Pulping	1,508	3.0
	50,562	100.1
Wastepaper	14,667	

The sulfite process, which produced 41% of the total volume of wood pulp in 1920, represented only about 3.7% of the total in 1980.

The Kraft pulping process involves the digesting of the wood chips in a sodium hydroxide/sodium sulfide cooking liquor to remove the lignin, which binds the cellulose fibers together in the wood. The cooking liquor and lignin is later burned in a Kraft recovery boiler to produce process steam. The Kraft process has become predominant for three reasons: a wide variety of wood species can be used; it produces high-quality, bleachable, strong pulp; and the process chemicals are less corrosive than those used in the sulfite process.

The groundwood process is almost chemical-free and uses mechanical grinding to produce fibers or fiber bundles. Two processes are typically used. In the first process, debarked logs are loaded against a rotating grindstone, and grinding debris is suspended in wash water to produce pulp. In the second process, wood chips are ground between two rotating disks to produce ground fibers. In both cases, a short precooking process is sometimes used to soften the wood and to reduce the mechanical energy needed to grind the wood.

The sulfite process is a chemical process similar to the Kraft process, although only nonresinous softwoods can be used. The cooking liquor is usually calcium sulfite or bisulfite. A similar process, referred to as neutral sulfite semichemical pulping, uses a hot neutral sulfite solution to soften wood chips prior to mechanical shredding and grinding. This process is used to produce about 8% of the total amount of wood pulp.

The three processes yielding the greatest percentage of pulp were examined for tribological losses: the Kraft process, recycled pulp, and the groundwood process. The initial steps of wood chip production and the final process of the paper mat production were also examined. These mechanical and chemical processes are outlined in the following sections of this report.

6.1.4 Processes Not Containing Significant Tribological Losses

In collecting and compiling data on tribological losses in the various processes, several processes were assumed to have little or no tribological losses and therefore were not studied further. These areas are briefly discussed below.

Wood Product Transportation

The process of removing cut wood from the forest to areas for cutting and chipping is performed by trucks and tractors. No attempt was made to determine tribological losses in these conveyance vehicles.

Wood Bark and Fines Transportation

The debarking and pulp separation processes produce wood bark and pulp fines, which are transported by conveyor to combustors for generating heat. This transport process uses rollers and belts, which may represent a slight tribological loss. These losses, however, are assumed to be negligible compared to the relatively severe conditions present in the debarkers.

Energy Recovery Processes

Processes involving the generation of energy from the burning of process liquors in recovery boilers were not analyzed. These processes are energy intensive but are generally tribologically efficient. Processes using process steam, such as driers, were also considered to be tribologically efficient.

The larger tribological losses were assumed to occur because of the many cutting, debarking, and chipping operations intrinsic to the paper industry. Attempts were made to quantify the losses in processes using these operations.

6.2 ANALYSIS OF TRIBOLOGICAL LOSSES IN THE PULP AND PAPER INDUSTRY

Direct and indirect tribological losses were estimated for the various processes used to produce pulp and paper. Direct losses were considered to be actual energy losses due to attempts to overcome friction, such as motor bearing losses or energy used to remove material through a friction-type process. Indirect losses were considered to be energy lost from removing metal or material from wearing surfaces.

Paper production involves three general subprocesses: wood preparation, pulpmaking, and papermaking. Wood preparation involves converting raw woodstock into uniform bulk feedstock, while the pulpmaking process involves chemically and mechanically converting the feedstock into pulp. The final process, papermaking, involves the formation of a thin mat of cellulose fibers that are pressed, rolled, and dried into finished paper.

Figure 6.1 shows the main stages of the papermaking process and the products produced at various stages. Debarked pulpwood can be chipped for later digestion or for disk grinding in the groundwood process. Prepared pulp can be processed into paper using several methods, although the Fourdrinier process or the cylinder process dominates the industry. Rolls of paper are later cut to shape for shipping. The three main processes are described in the following sections.

6.2.1 Wood Preparation

This section details the losses incurred during tree harvesting, pulpwood debarking, and pulpwood chipping. Although tree harvesting equipment is available, tree cutting was assumed to be done by hand-held chain saws. The logs are then cut to 4-foot or 8-foot lengths and are debarked using different debarking techniques. The debarked pulpwood is then chipped for chemical pulp production or ground for groundwood production. Figure 6.2 shows the general processes of wood preparation.

Tree Harvesting

Pulpwood is prepared from harvested trees ranging in diameter from 4 to 14 inches, and from 4 feet to full-grown tree height. Pulpwood is delivered to

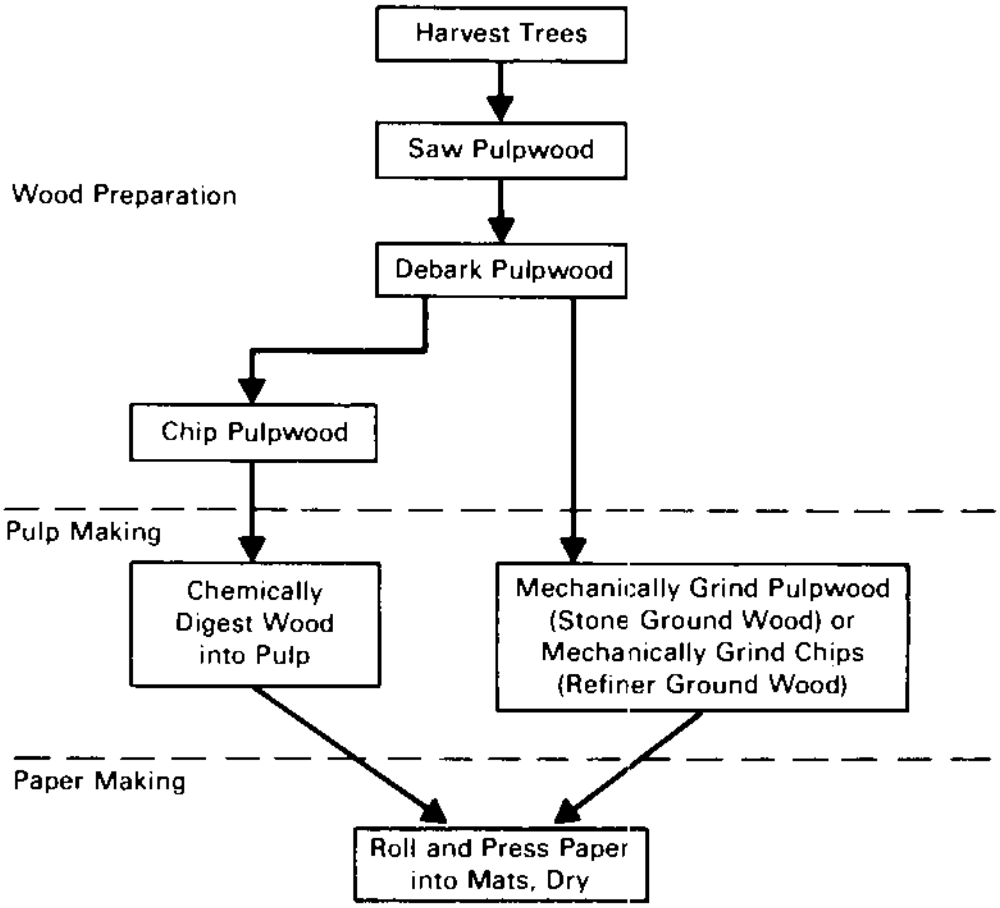

FIGURE 6.1. General Stages of Paper Making

mills in units of cords, which are each 128 cu ft of stacked wood. (The traditional definition of a cord is a 4 x 4 x 8 ft section of stacked wood.) One cord of debarked wood will typically yield 80 to 90 cu ft of solid wood, which in turn is converted to 200 to 220 cu ft of loose chips (Merrill 1970). After debarking, the cord will yield between 600 and 700 lb of bark.

Pulpwood density depends upon the type and age of the wood and the location. For young trees, the average density ranges from 25 to 26 lb/ft^3. Mature trees show a slightly higher density, ranging from 28.1 to 31.6 lb/ft^3. Current logging trends lean toward harvesting young trees, so an estimated average cut wood density is around 27 lb/ft^3 (Zobel 1970).

The 1983 harvest figures list 85 x 10^6 cords of pulpwood consumed (Paper Trade Journal 1985). A large amount of energy is required to harvest this

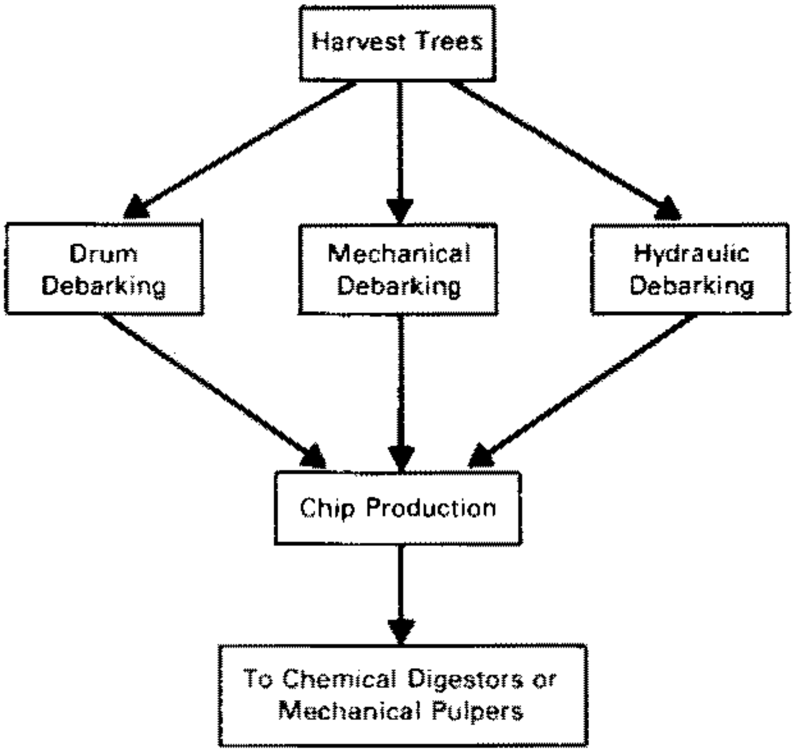

FIGURE 6.2. General Processes of Wood Preparation

wood, primarily because of friction during the cutting process. The direct energy lost by cutting was estimated by estimating the power output of the chain saws used to cut the trees and the time needed to cut the trees into 4-foot sections.

The energy needed to cut the trees was estimated by assuming that 2 people are able to fell and cut five 5-foot diameter 200-foot-high trees in one 8-hour shift. This translates into about 150 cords of wood per shift. The chain saw size typically ranges between 6 to 8 horsepower. Assuming 50% use and that 50% power loss due to friction during cutting, the direct loss is estimated to be 1/2 x 1/2 x 2 people x 7 hp x 8 hr/150 = 0.19 hp-hr/cord. Assuming a total pulpwood consumption of 85 x 10^6 cords, this translates into 4.04 x 10^{10} Btu/yr loss due to friction during cutting. This direct energy loss is due to friction between the chain and the bar and between the saw blades and the wood. Most saws have lubricating systems to minimize these losses and to keep the cutting edges cool.

Indirect losses due to chain and bar wear were estimated by assuming that the chain is replaced after 40 resharpenings and that the chain is resharpened after every shift. Initial chain weight is estimated to be 2 pounds. The total material loss due to chain wear is estimated as follows:

number of cords/chain = 150 cords/2 chains x 40 resharpening
= 3,000 cords/chain

total wear = 85 x 10^6 cords x 1 chain/3000 cords x 2 lb/chain
= 28 tons.

indirect loss = 28 tons x 35 x 10^6 Btu/ton
= 1 x 10^9 Btu.

The chain bar was estimated to weigh 16 pounds for a 48-inch chain saw. Chain wear is characterized by wearing of the flange outside of the chain groove. The chain bars are regrooved periodically to improve performance. Assuming the chain bars have 5 times the life of the chains, the total material loss due to chain bar wear can be estimated as follows:

number of cords/chain bar = 150 cords/2 chains x 200
= 15,000 cords/chain bar

total wear = 85 x 10^6 cords x 1 bar/15,000 cords x 16 pound/bar
= 45 tons of steel

indirect loss = 45 tons x 35 x 10^6 Btu/ton
= 1.6 x 10^9 Btu.

Table 6.11 lists estimates of direct and indirect losses for tree harvesting activities based on 1983 pulpwood production figures.

TABLE 6.11. Annual Direct and Indirect Losses in Tree Harvesting (*Paper Trade Journal* 1985)

Process	Total
Direct	
Friction during cutting	4.0×10^{10} Btu
Indirect	
Wear of chain teeth	1.0×10^{9} Btu
Wear of chain bar	1.6×10^{9} Btu

Pulpwood Debarking

The debarking process takes cut pulpwood and removes bark prior to chipping or grinding. Although pulp can be made from pulpwood that has not been debarked, higher quality paper is usually made from debarked wood. Also, bark is more abrasive than the underlying softwood, and chippers and grinders, which process debarked wood, exhibit longer life.(a) The most common methods of debarking logs are barking drums, mechanical debarkers, and hydraulic debarkers. Each of these methods is examined in the following paragraphs.

Barking drums are large rotating conduits that tumble logs together and thus remove the bark. The drums range in diameter from 7 to 16 feet, with 14 feet being the most common diameter. The most common length is 80 feet. The drums are rotated at 5 to 7 rpm by an electric motor ranging from 400 to 500 hp at 1750 rpm for the 14-foot diameter, 80-foot long drum.

Wear in the barking drums occurs when grit from the logs being debarked abrades against the drum's internal shell. To protect the shell itself, "lifters" are installed. A steel plate that is 3/4 inch thick, 12 inches wide, and 20 feet long is bent and welded to the steel shell of the drum. Drums tend to require little maintenance, although the drums are refurbished every 3 to 5 years by welding new lifter plates.

The output of the drum debarker is highly seasonal. Softwood output during the summer, 85% debarked, is around 145 cords/hr, while winter output using

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(a) Obtained through conversation with Mr. Lorne Greenwood, Carthage Machine Company, Carthage, New York.

frozen wood is only 75 cords/hr, 85% debarked. Average output is estimated to be 115 cords/hr.

Indirect losses from barking drums result from the wear of lifters. Indirect losses were estimated by assuming that the lifters are replaced after 4 years, for a total metal loss rate of 22 cu ft per year. This estimate was made by assuming 18 lifters are positioned around the circumference of a 14-foot diameter drum that is 80 feet long. Because the drum debarker is a high-output device, it was assumed that 85% of the pulpwood consumed was debarked in this way, for a total throughput of 73×10^6 cords/yr. The number of drum debarkers in service was determined by estimating a per-annum service of 2500 hr, with an average output of 115 cords/hr. The resulting total indirect loss is 4.8×10^{10} Btu/yr.

Mechanical debarking is used in smaller pulp mills and sawmills. Because the mechanical debarker operates with one stick at a time, the output of the debarker is less than that of the larger drum debarker. The most prevalent design consists of a rotating ring of knives, which peel bark from sections of cut pulpwood as it is drawn through the ring by a set of spiked wheels. This process, known as ring debarking, is essentially an abrasive cutting process, and all direct tribological losses were assumed to be due to friction at the knife-bark interface. Large ring debarkers are capable of handling logs up to 40 inches in diameter, although smaller log sizes are more prevalent. Indirect losses occur when abrasive cutting elements wear and are replaced. Specifically, losses can be categorized as follows:

- direct tribological losses
    - bearing losses in ring motor
    - bearing losses in feedworks motor
    - friction losses in debarking
- indirect tribological losses
    - wear of knives
    - wear of feedwork spires.

Table 6.12 lists typical operating specifications for a ring debarker. The cutting ring is driven by a 60-hp electric motor, while the feedworks is

TABLE 6.12. Typical Specification for Ring Debarker

Process	Specification
Cutting geometry	Radially positioned tungsten carbide knives
Cutting ring power	60 hp
Feedworks power	40 hp
Linear throughput	120 ft/min

driven by a 40-hp motor. Typical linear foot throughput is 120 ft/min. Assuming an average log diameter of 12 inches, this particular ring debarker is capable of debarking about 60 cords/hr. Other estimates have been set at 30 cords/hr (Merrill 1970).

Assuming that 50% of the energy is consumed by friction and assuming an average output of 40 cords/hr and a power usage of 30 hp during debarking, the direct tribological loss in debarking is estimated to be 0.35 hp-hr/cord. Assuming 10% of the pulpwood is debarked using ring debarkers, 7.5 x 10^9 Btu/yr would be expended.

Estimates of indirect tribological losses were made by estimating the amount of cutting head material lost during ring debarking. Rings typically have 24 teeth with carbide inserts brazed onto the knives. The knives with the tungsten carbide inserts typically last between 3 to 4 months of operation, 1 shift per day, before being replaced.(a) With an average of 30 cords/hr, the carbide inserts last about 14,000 cords. Repair to the knives usually involves brazing on new inserts and discarding the old, with a loss of about 20 grams per insert. The total material loss is estimated to be 580 pounds of carbide. Table 6.13 summarizes tribological losses in mechanical debarking.

Hydraulic debarking is a nonabrasive technique in which bark is removed from pulpwood through high-pressure jets, which impinge on the surface of the cut wood. Jets of high-pressure water or steam under pressure (1400 to 1500 psi) are directed through narrow nozzles. Use of this technique is prevalent in the Pacific Northwest where log diameters are too large for drum

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(a) Estimates given by Nicholson Manufacturing, Seattle, Washington.

TABLE 6.13. Direct and Indirect Tribological Losses in Mechanical Debarking

Process	Tribological Losses
Direct Losses	
Friction losses during debarking	7.5×10^9 Btu/yr
Indirect Losses	
Wear of cutting elements	1.5×10^7 Btu/yr

debarking. This technique requires large amounts of power to drive the high-pressure pumps, which must operate continuously whether or not a log is being debarked. Typical turbine or motor size is 1,200 hp at 3,600 rpm.

The use of hydraulic debarkers is restricted by its relatively low output compared to drum debarkers and problems in treating the water after use. To reduce pollution of streams with bark pieces, water used in hydraulic debarking must be filtered and separated before being released. In addition, clogging or erosion of the jet nozzles occurs when recycled water is not sufficiently cleaned. The lack of significant tribological sink mechanisms and minimal usage of this debarking technique (~5% of debarking) results in insignificant tribological losses for hydraulic debarking.

Pulpwood Chipping

Debarked pulpwood is either converted to groundwood pulp directly without further processing, or it is converted to wood chips for producing refiner pulpwood or pulp through chemical digestion. Because 80% of wood pulp is estimated to come from the Kraft process, a considerable quantity of wood chips is produced.

The process of chipping is a combination of abrasive cutting and fracture of the pulpwood. The most common chipper in use is the disc chipper, which uses a series of blades mounted on a rotating disk 8 feet to 12 feet in diameter. Typical capacity for the disc chipper is 120 cords/hr.

The face of the disk has a series of radial knives, which shear the pulpwood as it is fed against the face of the disk. Once formed, the chips move through chip slots in the face of the disk to the reverse side of the disk, where they are gravity fed or blown out of the chipper. Because of the harsh conditions inside the chipper, parts are replaced routinely. Table 6.14 shows estimates of repair/replacement frequency for crucial parts of the chipper. The cutting knives are resharpened after every 8-hour shift, but the blades are finally replaced after about 1000 hours of operation. The disk uses numerous face plates to decrease wear. The shrouding around the disk wears from impact with flying wood chips and is typically replaced every 2 years. Other wear surfaces include the feed-in chute, which is protected by weld deposits of wear-resistant alloys.

Indirect losses during chipping were estimated by assuming that the blades and face plates are totally replaced during service. Each blade weighs about 25 pounds and is replaced twice a year. For a machine with 13 blades, the total material loss per year per machine is about 650 pounds per machine. The face plates are heavier and are replaced with the same frequency, for a material loss of 1820 lb/yr. The shroud can be expected to lose about 1000 pounds during 1 year of service.

Table 6.15 summarizes the indirect losses during chipping. Calculations are based on an industry fleet of 280 chippers, which were derived from the 1983 pulpwood production and a capacity of 120 cords/hr.

6.2.2 Pulp Production

Pulp is produced by separating cellulose wood fibers from the connective lignin in the wood. The process is performed chemically through digestion or

TABLE 6.14. Weight, Size and Replacement Frequency for Chipper Components[a]

Part	Approximate Size/Weight	Typical Replacement Frequency
Knives	36 in. x 6 in. x 1/2 in.	1000 hr
Chip slots	Not available	500 hr
Disk face plates	70 lb each	1000 hr
Shrouding	2000 lb	4000 hr

(a) Information obtained from a conversation with Mr. Lorne Greenwood, Carthage Machine Company, Carthage, New York.

TABLE 6.15. Indirect Losses in Chipping

	Weight Loss Per Machine Per Year (lb)	Energy Loss (10^9 Btu)
Blade wear	650	3.2
Face plate wear	1820	8.9
Shrouding	1000	4.9

mechanically through further grinding of chips or solid pulpwood. The following techniques of forming pulp were examined: Kraft pulpmaking, groundwood pulp, and pulp from recycled secondary fiber.

Kraft Pulpmaking

Kraft pulpmaking is a chemical process in which little abrasive or shaking wear occurs. Slight corrosion problems may occur due to the severity of the chemical stock. Most direct tribological losses can be traced to pumping losses during pulp processing. These losses were not tabulated during this study.

Groundwood Pulp

Groundwood pulp refers to pulp produced from debarked pulpwood or chips by mechanical grinding. Groundwood pulp produced directly from debarked pulpwood is referred to as stone groundwood because of a large abrasive grinding stone that produces fibrous pulp. Groundwood pulp produced directly from chipped pulpwood is referred to as chip groundwood. Chips used to produce chip groundwood are sometimes preheated with process steam to reduce the energy required for further grinding. Both processes will be reviewed separately.

Stone Groundwood.

Stone groundwood is produced directly from debarked pulpwood by loading the pulpwood against a large rotating grinding stone. Grindstones typically measure 67 inches in diameter and range from 54 to 69 inches wide to accommodate 4- or 5-foot lengths of cut pulpwood. Surface speed at the cutting edge is typically around 10,000 ft/min, which translates into a rotational speed of 570 rpm.

The major energy expenditure in stone groundwood pulp is the power used to rotate the grinding wheel. Electric motors ranging from 3,000 to 10,000 hp are used; the typical size is 6,500 hp.(a) For this power expenditure, roughly 50 to 70 tons of pulpwood are produced per day. Approximately 90 stone groundwood pulpers are in use in the United States today.

Because the process relies on abrasive cutting of wood, direct friction losses occur at the stone-pulpwood interface. Loading of pulpwood against the grinding stone is usually regulated so that the full available power is used (Perry 1970). The following formula for grinding can be used to obtain efficient grinding conditions:

$$\text{Power} = A \times V \times P \times F$$

where A = grinding area
V = peripheral speed of pulpstone
P = grinding pressure
F = friction coefficient.

Assuming that 98% of the motor horsepower is used in the grinding process and assuming an average capacity of 60 tons/day, the average energy used to produce a ton of pulp at one grinder is 106 hp-day/ton. This translates to 2.2×10^6 Btu per ton of pulpwood. Other estimates have been set at 4.5×10^6 Btu per ton for stone groundwood.(b) Estimates given by one manufacturer of grinding stones set the energy expenditure somewhat lower, between 1.2 and 1.8×10^6 Btu/ton.(a) An average energy expenditure would be around 2×10^6 Btu/ton of pulp produced. Assuming that 10% of this is due to recoverable friction losses, the direct tribological energy cost is 0.2×10^6 Btu per ton of pulp produced.

Indirect losses were estimated by calculating the amount of grinding wheel lost during pulp generation. Pulpwood stones (pulpstones) are made by forming grinding wheel material around a steel shell. The initial material thickness is around 5 inches, and the wheel is used until half of the material has worn away. Assuming an initial wheel diameter of 67 inches and a width of 54 inches,

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(a) Estimates given by the Norton Company, Worcester, Massachusetts.
(b) Information provided by CE/Bauer Company, Springfield, Ohio.

this represents a material loss of 15.8 cu ft per wheel. Depending upon the nature of the cut pulpwood, these stones must be replaced every 1 to 4 years.(a) Using an average life of 2-1/2 years, this represents a material loss of 6.3 cu ft per year per stone. Because about 90 grinders operate in the United States, the total yearly material loss is estimated to be 570 cu ft of abrasive wheel material. Direct and indirect losses are summarized in Table 6.16.

Chip Groundwood

Chip groundwood, sometimes referred to as refiner groundwood, is produced from already chipped pulpwood. The technique involves grinding uniform chips between two rotating disks, followed by a centrifugal separation of fibers. Prior to grinding, the wood chips are usually treated with process steam to soften the wood and reduce grinding time and energy. Chips are frequently washed prior to grinding to remove abrasive grit.

The refiner is sized according to disk diameter and motor horsepower; the typical size is a 56-inch diameter, 10,000 hp unit.(b) For pulp processing, the two disks are forced together by hydraulic cylinders and kept out of mutual contact by the chip feedstock. Chips of uniform size are introduced via screw feed at a continuous rate.

The grinding surfaces of the two disks are made from a chromium-molybdenum alloy (white cast iron), which exhibits an as-cast hardness of 55 Rc. Recent new heat treatments have succeeded in increasing this hardness to 60 Rc with an accompanied increase in wear resistance. As-cast disks last between 500 and

TABLE 6.16. Direct and Indirect Losses of Stone Groundwood Pulp Production

Process	Tribological Losses
Direct Loss	
Friction during cutting	3.9×10^{11} Btu/yr
Indirect Loss	
Loss of grinding wheel material	1×10^{10} Btu/yr

(a) Estimates given by the Norton Company, Worcester, Massachusetts.
(b) Information provided by CE/Bauer Company, Springfield, Ohio.

750 hours before the grinding surfaces of the disk have to be replaced. New hardened surfaces reportedly last up to 1000 hours.[a]

The grinding surface of the disks consists of a series of radial ridges 1/8 of an inch high. Wood fiber bundles are sheared between two ridges on the opposing disk surfaces. The surfaces are effective in producing pulp until the ridges become worn down. After wear, the surface segments that form the ridged surface are unbolted from the body of the disk and replaced with new segments.

As in the analysis of other similar equipment, a recoverable friction component of 10% was applied to the energy requirements of the disk refiners to estimate their direct tribological loss. Because this is a mechanical process similar to stone groundwood pulping, energy levels of both stone groundwood and refiner groundwood are expected to be similar. Large refiners operate at energy levels of 100 to 120 hp-day/ton. Assuming an annual production of 2930 x 10^3 tons, this translates into 0.58 x 10^{12} Btu loss total per year for refiner-produced groundwood.

Indirect losses were estimated by observing that the ridged surface segments of the two disks are replaced entirely after the ridges on the surface are worn. The surface segments collectively resemble a donut-shaped section of 1-inch thick material measuring 56 inches in total diameter, with an inner hub diameter of 36 inches. This leaves a grinding surface area of 10 square feet. Replacing both disks represents a loss of 1.7 cubic feet of material. Disks are assumed to be replaced 4 times a year, for an estimated material loss per machine of 1.7 tons.

The number of refiners in service was calculated by using an estimated output of 120 tons per day per machine. Assuming 250 working days per year, each refiner supplies 30,000 tons each year. With total estimated production figures of 2930 x 10^3 tons, this translates into about 100 operating units in the United States.

The number of disk refiners now in use exceeds 100, although many of the units are used as secondary refiners for chemical digesters to aid in further

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(a) Information provided by CE/Bauer Company, Springfield, Ohio.

refining that is pulp already digested. In these units, energy expenditure component wear is far less than for units that produce mechanically generated pulp alone. Therefore, the estimate of 100 units that produce mechanically generated pulp is believed to be an accurate estimate.

Indirect losses from wear were estimated by multiplying the estimated-per-machine loss of 1.7 tons of material by the number of units, giving a total material loss of 170 tons per year. Indirect and direct losses for chip groundwood are summarized in Table 6.17.

Secondary Fiber

As the cost of woodpulp increases, the use of pulp manufactured from secondary fiber also increases. Approximately 20% of paper products are now made from recycled secondary fiber, for an approximate yearly output of 15 x 10^6 tons. Sources of secondary fiber include newsprint and paperboard with a variety of inks and paper finishes on the surface. The process of producing pulp from this fiber consists of the following steps: (1) pulping or defibering, (2) cleaning and screening, (3) washing out contaminants, (4) dewatering and thickening, (5) bleaching, and (6) bleach washing and thickening.(a) Of these six processes, the last five are mostly chemical bleaching and washing processes having very little tribological loss. The first process--pulping or defibering--involves the chopping and mulling of solid waste paper into digestible pieces of paper fiber. Because this process involves energy expenditure

TABLE 6.17. Direct and Indirect Tribological Losses of Chip Groundwood Production

Process	Tribological Losses
Direct Loss	
Friction during pulping	5.8 x 10^{11} Btu/yr
Indirect Loss	
Replacement of disk-grinding plates	8.5 x 10^9 Btu/yr

(a) Information provided by Black-Clawson Company, Middletown, Ohio.

during chopping, plus considerable indirect losses due to mechanical wear, it was examined for direct and indirect tribological losses.

In the initial stage of defibering, raw stock is fed directly into a large cylindrical vessel fitted with a series of rotary vanes that shear and mulch the waste paper. One representative design uses a large cylindrical vessel with a fluted bottom to direct waste paper to the bottom. At the bottom of the vessel, a series of rotating vanes or blades 6 feet in diameter rotate at a top speed of between 3,400 and 4,000 ft/min. The secondary pulp is filtered through screens in the vessel bottom and sides and recirculates for more defibering. Horsepower requirements for this vessel range between 250 and 500 hp, with 400 hp being an average value. Output ranges from 350 to 500 tons/day, depending on the base stock composition. The process mix is heavily watered to facilitate mixing and agitation of the slurry.

Indirect losses due to wear of the blades are controlled by using Stellite hard facings that are strip-cladded to the blades at a thickness of 3/16 inch. Wear of these blades is extremely variable, with replacement of the hard facing performed every 1 to 5 years, depending on the nature of the feedstock.(a) Assuming reasonable care, new hard facing is probably applied every other year at scheduled downtimes for plant maintenance. Assuming a total blade surface area of about 12 square feet (each blade measures 1-1/2 x 1 ft) and a strip clad thickness of 3/16 inch, the material volume loss due to wear is estimated to be 162 cu in. per year per machine. Because the density of Stellite is around 0.3 lb/in.^{3}, this translates into a weight loss of 48 pounds per year per machine.

The number of hydropulpers in service was estimated by assuming an output of 400 tons of pulp per day per machine, with 250 possible working days. This translates into 100,000 tons produced per machine every year. To produce 15 x 10^6 tons of paper product from secondary pulp, approximately 150 hydropulpers would be required, which would produce a total weight loss of 3.6 tons per year.

Direct losses due to process friction during defibering were estimated by examining the motor power levels during fiber agitation. With an average motor

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(a) Information provided by Black-Clawson Company, Middletown, Ohio.

size of 400 hp and a production rate of 400 tons of pulp per day, the amount of energy used to cut and mix the waste paper is about 15 x 10^3 Btu/ton of pulp produced, assuming 25% of the available power is used to overcome friction. This translates to direct losses of 2.3 x 10^{11} Btu/yr. Table 6.18 summarizes direct and indirect tribological losses for secondary defibering.

6.3 SUMMARY OF TRIBOLOGICAL ENERGY LOSSES IN PULP AND PAPER

Tables 6.19, 6.20, and 6.21 summarize the tribological energy losses associated with the principal pulp and paper operational activities. The generic

TABLE 6.18. Direct and Indirect Losses During Secondary Defibering

Process	Tribological Losses
Direct Loss	
Loss due to cutting	2.3 x 10^{11} Btu/yr
Indirect Loss	
Blade wear due to friction	1.8 x 10^8 Btu/yr

TABLE 6.19. Generic Tribological Loss Mechanisms in Pulp and Paper

Operational Activity	Generic Tribological Mechanism (1)	(2)	(3)	(4)
Wood Preparation				
Tree Harvesting	X			
Pulpwood Debarking	X		X	X
Pulpwood Chipping	X			
Pulping				
Stone Groundwood	X	X		
Chip Groundwood	X	X		
Hydropulping	X			X

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(1) Abrasion.
(2) Adhesion.
(3) Corrosion.
(4) Erosion.

TABLE 6.20. Annual Direct Tribological Energy Losses in Pulp and Paper

Operational Activity	Principal Energy Form Consumed	Energy Loss Rate	Total Energy Loss (10^9 Btu)
Wood Preparation			
Tree Harvesting	Gasoline	480 Btu/cord	40
Pulpwood Debarking	Electric	890 Btu/cord	7.5
Pulpwood Chipping	--	--	--
Pulping			
Stone Groundwood	Electric	0.2×10^6 Btu/ton pulped	390
Chip Groundwood	Electric	0.2×10^6 Btu/ton pulped	580
Hydropulping	Electric	15×10^3 Btu/ton pulped	230
			1247.5

TABLE 6.21. Annual Indirect Tribological Energy Losses in Pulp and Paper

Operational Activity	Material Type Worn	Material Wear Rate	Total Energy Loss (10^9 Btu)
Wood Preparation			
Tree Harvesting	Steel	1.7 lb/1000 cords	2.6
Pulpwood Debarking	Steel	38 lb/1000 cords	48
Pulpwood Chipping	Steel alloys	11 lb/1000 cords	17
Pulping			
Stone Groundwood	Grinding stone	0.29 ft^3/1000 ton pulped	10
Chip Groundwood	Cr-Mo alloy	116 lb/1000 ton pulped	8.5
Hydropulping	Steel	0.48 lb/1000 ton pulped	0.18
			86.28

tribological mechanisms contributing to energy losses for each operational activity are identified in Table 6.19. Additional information concerning the principal energy form consumed by an operation, the energy loss rate, material type worn, and material wear rate is also provided in Tables 6.20 and 6.21.

Abrasion was identified most often as a tribological loss mechanism for pulp and paper operational activities--abrasion was cited as a loss mechanism for each of the activities examined in detail. Other loss mechanisms noted were adhesions, corrosion, and erosion. Although the information in Table 6.19

is more qualitative than quantitative (i.e., the most commonly occurring loss mechanisms may not be the cause of the largest energy losses), it does indicate tribological mechanisms that are likely to be significant in the pulp and paper industry.

Direct losses were estimated to be more than an order of magnitude greater than indirect losses. Direct tribological losses are associated with the energy to overcome friction between two surfaces. Direct energy loss activities in pulp and paper are largely powered by electricity. The principal tribological energy loss activities are mechanical pulping of chips and logs and hydropulping of recycled paper.

Indirect tribological losses are associated with the wearing out of equipment and the material that is physically worn away. The principal indirect loss items in pulp and paper are associated with drum debarkers, chippers, and mechanical pulpers. Steel and steel alloys are the most common materials being worn. A significant amount of wear also occurs in the grinding stones used for stone-groundwood pulping.

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7.0 FOOD PROCESSING

This chapter identifies and characterizes total energy use and tribological losses in the food processing industry. Energy consumption is specified by fuel type for the industry as a whole, and total energy consumption is identified for each of the nine 3-digit SIC (Standard Industrial Classification) subsets of the industry and the top 10 energy-consuming 4-digit SIC industries. The major processes and products of the food processing industry are briefly described, and those processes identified as having significant tribological losses are reviewed and described in more detail. The nature of each tribological sink and the mechanisms leading to direct and/or indirect losses are then characterized. Finally, the estimates of energy losses and the calculational approach taken are identified. The tribological losses estimated for food processing are summarized at the end of the chapter.

7.1 INTRODUCTION

The food processing industry includes businesses engaged in the processing of raw agricultural inputs into packaged food products as their primary activity. The major subdivisions of food processing are meat products (SIC 201), dairy products (SIC 202), preserved fruits and vegetables (SIC 203), grain mill products (SIC 204), bakery products (SIC 205), sugar and confectionery products (SIC 206), fats and oils (SIC 207), beverages (SIC 208), and miscellaneous foods (SIC 209). Each of these subdivisions is broken into individual product categories such as meat packing plants, fluid milk, wet corn milling, and malt beverages. Food processing involves a wide array of activities that include pressing, trimming, peeling, blending, screening, milling, washing, conveying, and packaging.

7.1.1 Energy Consumption in Food Processing

Total energy consumption in food processing was about 0.9 quad in 1981, according to data presented in the 1982 Census of Manufactures (U.S. Bureau of Census 1983). (As of May 1984, the 1981 data are the latest comprehensive energy consumption information available from the U.S. Census Bureau.) Energy consumption is specified by fuel type for the industry as a whole in Table 7.1.

TABLE 7.1. Energy Consumption by Fuel Type in the Food Processing Industry (1981)

Fuel	10^{12} Btu	% of Total
Electricity	148.5	16.3
Distillate	24.7	2.7
Residual	60.4	6.6
Coal	119.0	13.0
Coke	1.7	0.2
Natural Gas	471.0	51.6
Liquid Petroleum Gas	6.6	0.7
Other	81.3	8.9
	913.2	100.0

Natural gas is the predominant fuel in the food industry, providing over 50% of the energy requirement. Electricity, coal, and fuel oil are the three next most common energy forms in order of consumption. Most of the fossil fuels are used to provide process heat and some space heating, refrigeration, and electric generation. Electric energy is used to operate a wide variety of mechanical activities.

Energy consumption is spread fairly evenly among the nine 3-digit SIC subsets of the food industry (see Table 7.2). No single group represents an exceptionally large or small portion of total consumption. Energy consumption at the 4-digit SIC industry level is similarly distributed (see Table 7.3). Wet corn milling, the largest energy consumer at the the 4-digit level, accounts for only 10% of the food industry total; the top ten 4-digit industries together represent 54% of food industry energy consumption.

The energy consumption data presented above and in the following tables in this chapter were obtained from the <u>1982 Census of Manufactures - Fuels and Electric Energy Consumed</u> (Bureau of Census 1983). The data are for consumption of purchased fuels and electric energy by manufacturing establishments for producing heat and power. These figures do not include energy forms produced and consumed at the same establishment, such as coke oven gas, blast furnace gas, still gas, petroleum coke, etc. However, little fuel is produced and consumed

TABLE 7.2. Energy Consumption Within the Major Food Processing Industry Subgroups (1981)

SIC #	Classification Name	10^{12} Btu	% of Total
201	Meat Products	103.4	11.3
202	Dairy Products	87.3	9.6
203	Preserved Fruits and Vegetables	113.6	12.4
204	Grain Mill Products	153.3	16.8
205	Bakery Products	50.2	5.5
206	Sugar and Confectionery Products	127.8	14.0
207	Fats and Oils	109.1	11.9
208	Beverages	111.9	12.3
209	Miscellaneous Foods and Kindred Products	56.4	6.2
		913.0	100.0

TABLE 7.3. Top Ten Energy-Consuming Food Processing Industries at the 4-Digit SIC Level (1981)

SIC #	Classification Name	10^{12} Btu	% of Total Food Industry
2011	Meat Packing Plants	61.4	6.7
2026	Fluid Milk	31.1	3.4
2033	Canned Fruits and Vegetables	42.9	4.7
2038	Frozen Fruits and Vegetables	30.2	3.3
2046	Wet Corn Milling	92.4	10.1
2051	Bread, Cake, and Related Products	38.8	4.2
2062	Cane Sugar Refining	29.9	3.3
2063	Beet Sugar	72.2	7.9
2075	Soybean Oil Mills	44.9	4.9
2082	Malt Beverages	53.1	5.8
		496.9	54.3

within the food processing industry, so purchased fuels should be a close approximation of total energy consumption.

The food processing industry produces thousands of individual products to suit the tastes of consumers. In contrast to other industries, such as primary metals, where a single homogeneous product can often be associated with a 4-digit industry, 4-digit food processing industries may have hundreds of product forms (e.g., canned fruits and vegetables). Because of the large number of individual product forms, energy analyses usually focus at the 4-digit SIC classification and at an associated generic processing plant representative of all product forms within that classification. In lieu of trying to list the "principal" individual products of the food processing industry, Table 7.4 lists all of the 4-digit SIC groups.

TABLE 7.4. Major Product Classes Within the Food Processing Industry

Meat Packing Plants
Sausages and Other Prepared Meats
Poultry Dressing Plants
Poultry and Egg Processing
Creamery Butter
Cheese, Natural and Processed
Condensed and Evaporated Milk
Ice Cream and Frozen Desserts
Fluid Milk
Canned Specialities
Canned Fruits and Vegetables
Dehydrated Fruits, Vegetables, and Soups
Pickles, Sauces, and Salad Dressings
Frozen Fruits and Vegetables
Frozen Specialties
Flour and Other Grain Mill Products
Cereal Breakfast Foods
Rice Milling
Blended and Prepared Flour
Wet Corn Milling
Dog, Cat, and Other Pet Food
Other Prepared Feeds
Bread, Cake, and Related Products
Cookies and Crackers
Raw Cane Sugar
Cane Sugar Refining
Beet Sugar
Confectionery Products
Chocolate and Cocoa Products
Chewing Gum
Cottonseed Oil Mills
Soybean Oil Mills
Other Vegetable Oil Mills
Animal and Marine Fats and Oils
Shortening and Cooking Oils
Malt Beverages
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Wines, Brandy, and Brandy Spirits
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Bottled and Canned Soft Drinks
Other Flavoring Extracts and Syrups
Canned and Cured Seafoods
Fresh or Frozen Packaged Fish
Roasted Coffee
Manufactured Ice
Macaroni and Spaghetti
Other Food Preparations

7.2 FOOD PROCESSING OPERATIONAL ACTIVITIES

The numerous products and production pathways of the food processing industry make it difficult to generalize about the operational activities. Each of the thousands of products tends to have unique processing requirements. Nevertheless, several generic operations that occur with some regularity among the many product classes can be identified.

Upon entering the plant, the raw agricultural material is typically cleaned first. Cleaning or washing may also occur at intermediate locations within the process. Several different size reduction operations may be used as preparatory steps for mixing, heating, and chilling. Various separating procedures are used first to break the raw material into components and later to extract the final product before packaging and storage. Separation can be achieved by either mechanical, thermal, or chemical means. A more detailed listing of specific operational activities is presented in Table 7.5 for heating, size reduction, and mechanical, thermal, and chemical separations.

7.2.1 Analytical Approach

The food processing industry was initially examined at the 4-digit SIC level (see Table 7.4) to determine which operations should be evaluated further for tribological losses. Size reduction and material conveyance are two generic activities common to most food processing processes that were

TABLE 7.5. Food Processing Operational Activities

Generic Operation	Specific Operations
Mechanical Separation	Pressing, trimming, stripping, settling, filtering, inspecting/grading, peeling, pulping, screening, centrifuging
Thermal Separation	Drying, evaporating, roasting, crystallizing
Chemical Separation	Ion exchange, liming, extracting, stripping
Size Reduction	Grinding, slicing, cutting, crushing, shredding, scalping, scaling
Heating	Curing, smoking, cooking, pasteurizing, scalding, blanching, baking, brewing, sterilizing

identified as having significant tribological losses. Size reduction operations (e.g., cutting, shredding, grinding) typically result in erosion and abrasion of knives, rollers, bars, hammers, and similar equipment. Frictional losses in conveying are associated with the wear of bearings, belts, pump impellers, conveyor screws, and other related parts. Both of these processes are chiefly powered by electricity; therefore, the tribological energy losses would be a fraction of the electricity consumption figure identified in Table 7.1.

Because the food processing industry is diverse, unit operations had to be evaluated collectively rather than individually. Conveying processes are amenable to an aggregate level analysis and will be discussed in detail in Section 7.3. Size reduction operations, while important tribologically, are more process-specific and not as easily evaluated generically. Tribological evaluations of size reduction and mixing equipment are presented in Section 7.4.

7.3 TRIBOLOGICAL LOSSES IN FOOD PROCESSING CONVEYING SYSTEMS

Transportation within the food processing plant represents a major source of tribological losses. This section analyzes direct and indirect tribological losses associated with conveyors and other transportation mechanisms. For the principal loss mechanisms, equipment design and operation are described and the tribological energy losses are estimated.

7.3.1 Direct Tribological Losses Associated with Conveyors

Direct tribological loss estimates for conveyor systems are based on an analysis of information presented in Casper (1977) and estimates of sizes, efficiences, and other operating characteristics. The types of conveyors included in the estimates are 1) unit conveyors where the product is supported on rollers, 2) belt conveyors where the belts are supported on rollers, and 3) screw conveyors. The total estimated direct tribological loss is 5.21 x 10^{11} Btu, which represents 0.06% of total energy consumption and 0.35% of electric energy consumption in the food industry. The major portion (greater than 2 x 10^{10} Btu per group) of the tribological energy loss is associated with the industries listed in Table 7.6. These industries have an obvious common factor: they all involve the handling of many individual units such as cans, bottles, or boxes.

7.3.2 Indirect Tribological Losses in Conveying Systems

Indirect tribological losses are associated with wear mechanisms, which are characteristic of individual types of equipment used to move materials around the processing plant. The characteristics of various material-moving mechanisms are discussed below to highlight the tribological losses.

Screw Conveyors

The screw conveyor is usually a long-pitch, plate-steel helix mounted on a shaft supported by bearings within a U-shaped trough. As the screw rotates, the material fed to it is moved forward by the thrust of the lower part of the helix and is discharged through openings in the trough bottom, usually at the end.

The steel helicoid is cold rolled in one continuous strip. The cold rolling provides a tapered section with greatest thickness at the shaft and a thin edge with a hardness greater than the original strip. If contact with the steel screw affects food products, then stainless steel, bronze, aluminum, or Monel metal may be used. For abrasive products, the helix may be cast-iron

TABLE 7.6. Estimated Direct Tribological Losses from Conveyors in Selected Food Industries

SIC #	Industry	Tribological Loss
2033	Canned Fruits and Vegetables	1.08×10^{11} Btu
2038	Frozen Fruits and Vegetables	4.78×10^{10} Btu
2032	Canned Specialty	4.63×10^{10} Btu
2026	Fluid Milk	3.29×10^{10} Btu
2011	Meat Packing	2.79×10^{10} Btu
2077	Animal and Marine Fats and Oils	2.78×10^{10} Btu
2082	Malt Beverage	2.62×10^{10} Btu
2038	Frozen Specialty	2.35×10^{10} Btu
2086	Soft Drink	2.15×10^{10} Btu

sections bolted to the shaft. For sticky materials, a ribbon helix may be used to prevent buildup along the line between the helix and the shaft.

A thrust bearing is located at the input end of the conveyor. For free flowing, nonabrasive materials, the trough may be deeply filled and the rotating speed may be higher than for heavier, more abrasive materials. The length of the individual screw conveyor is limited by the torque capacity of the center shaft or pipe. When the material is to be moved a distance greater than is possible with a single screw, the individual units are connected in series, one unit feeding the next. Most abrasive materials are handled at lower cross-sectional loads than nonabrasive materials to attain maximum economical life of the conveyor and its parts. For abrasive materials, hard surface flighting is added generally just near the outer portion of the work surface.

The bearings at the end of the screw are outside the trough. Sealed ball bearings are generally used, with a thrust bearing at the one end. Hanger bearings within the trough in the food industry are generally unlubricated plastic sleeve bearings. For materials that are sensitive to small changes in temperature, heat from friction in a hanger bearing may be a problem.

The life of a screw conveyor is a function of the service it receives. A grain auger generally has a life of 3 to 5 years, where the usage may be 24 hours a day during peak season and 16 hours a week during off season. Because of coating with plastics, troughs are much less subject to wear than they used to be. To date, coating the augers has not been very successful, however. The average life of an auger used with abrasive materials may be less than 1 year. In such environments hard steel and high-quality sealed bearings are used.

In the food industries, using screw conveyors for materials containing oils (e.g., peanut butter) results in minimal indirect tribological losses. The dimensions of the trough and the auger are sized to insure there is no contact, and the oil in the material itself provides a lubricant for the bearing surfaces.

sealed bearings at either end. One manufacturer of medium-duty conveyors for the food industry stated that the average life of a roller conveyor is 5 to 10 years, based on a 10-hour day. The bearings are replaced every 5 years.

The wear of the bearings is due mainly to turning of the roller and is little affected by the loading of the product passing over every 5 to 10 seconds. Based on the above manufacturer's portion of the medium-duty conveyor market in the food industry, 3.6 million bearings are replaced each year with an average weight of 3 ounces, or 680,000 pounds of metal per year. This is equivalent to an indirect energy loss of 1.2×10^{10} Btu/year.

Pallet chain conveyors in the food industry are used to convey beer bottles to the filling station or other small pans and trays that rest on a surface beneath the item. Plastic chain links and carrier parts have reduced tribological energy losses greatly in the past decade.

Belt conveyors for unit loads are similar to standard flat belt conveyors except for their closely spaced idler rollers. The friction factor for roller-supported belts is 3% to 5% for canvas and rubber belts. For steel-supported belts, the friction factor is 20% for both belt types. For hardwood-supported belts, the friction factor is 25% for canvas belts and 30% for rubber belts.

Monorail or overhead trams take many forms. The item is supported from or hung from two or more wheels on the monorail. The units may be self-powered, free rolling, or pulled by an adjacent chain. Light-duty underhung cranes also fall in the same category.

The life of an underhung crane is 8 to 9 years of normal use. The single and double ball bearings used in the wheel to support the crane (and similarly monorail conveyors) have a life of 2 to 10 years, depending upon usage (average about 6 years). The wearing items on these cranes are the wheels themselves. Both wheels and bearings are replaced at the same time. One company, which commands 10% of the underhung crane business, replaces 2000 forged steel wheels per year at 3 pounds per wheel. This is three tons of steel per year. Assuming that there are 4 times as many monorail conveyors in the food industry as there are underhung cranes, the total amount of metal replaced per year for both monorail conveyors and underhung cranes is 150 tons. This represents an indirect loss of 5.25×10^5 Btu/year.

Pumps

Pumps used in the food industries have the critical design constraint of avoiding contamination of the food product. Less viscous fluids are conveyed with centrifugal pumps. Viscous products may be pumped with augers (such as peanut butter as mentioned above) or a mono pump. No external lubricants are used because of the potential of contaminating the food product being pumped. Piston pumps are limited to special metering devices.

Centrifugal pumps are made with a variety of materials, and in many cases the impeller and casing may be covered with a corrosive- or abrasive-resistant material such as stainless steel, rubber, polypropylene, and stoneware. When the pump is used with suspensions, the ports and spaces between the vanes must be large enough to eliminate the risk of blockage. This does not mean that the efficiency of the pump is necessarily reduced. Special pump designs may be used to overcome this problem and also provide subatmospheric pressure at the glands and bearings to protect them from grit. Because high pressures are seldom required in the food industry, such designs present no penalty. Metal-to-metal contact is avoided to reduce wear debris.

The mono pump uses a specially shaped helical metal worm, which rotates in a stator made of rubber or other similar material. The liquid is thus forced through the space between the stator and rotor. Stator replacement is required at regular intervals, but this factor is outweighed by the advantages of uniform flow, quiet operation, and the ability to pump against high pressures and to handle corrosive and gritty liquids.

7.4 TRIBOLOGICAL LOSSES IN OTHER FOOD PROCESSING OPERATIONS

7.4.1 Size Reduction Equipment

Wear is a significant concern in some areas of the food industry, such as the Cossette knives used for sugar beet size reduction. Sugar beets come to the processor with a lot of grit and sand on them. Cossette knives are used to cut the sugar beets into 1/8 x 1/8 x 2 inch strips from which the sugar is leached. Wear debris is not a problem here because it is not contained in the sugar solution that is extracted. Instead, the debris is carried away with the other solid residues.

Large banks of Cossette knives must be reworked or replaced daily because of the dulling which results from abrasive wear from dirt on the beets. In a day's production, these knives will be used to cut up to 2000 tons of beets at a typical processing plant. In the United States 72 plants use Cossette knives. The operation of 4 of these plants is summarized in Table 7.7.

A typical Cossette knife is 3/16 x 4 x 6 inches or 4.5 cubic inches of high carbon steel, which weighs 1.27 pounds. This amounts to 10.6 pounds of knives per thousand tons of beet production. In 1974 there were 23.4 million tons of beets processed. Thus, for the entire U.S. sugar beet industry, about 124 tons of steel per year are consumed. This is equivalent to an indirect energy loss of 4.3×10^9 Btu/year.

7.4.2 Mixers

Telephone interviews with design engineers associated with the food industry indicated no major problems with wear in mixing equipment. Friction losses in bearings and gear-reducers were also found not to be significant.

7.4.3 Other Size Reduction Equipment

For other types of size reduction equipment, wear causes concern, but not nearly to the extent of the Cossette knives. A typical puree operation involves cutting up clean fruits and vegetables for which a few grams of wear

TABLE 7.7. Cossette Knife Replacement and Sugar Beet Production, 1983 Summary for Four Plants

Plant	Knives Replaced	Sugar Beet Production (ktons)	Knives per kton Production
1	632	220	2.873
2	5540	352	15.739
3	1536	286	5.371
4	3460	374	9.251
Ave.	2792	308	8.309

debris are generated for every few million pounds of food processed. This debris is trapped in the food, but it is below the contamination levels permitted by the government regulations. Nonwear breakage or chipping of surfaces is considered a more dangerous problem because large debris results.

Rendering plants involve somewhat more wear because rendering involves size reduction of animal bones. Meat by-products can also create corrosive wear problems. Components specifically subject to this sort of damage include the exteriors and rotating parts of the size-reducing equipment.

Construction materials for size reduction equipment include mostly 304 stainless steel with some heat-treated 17-4 stainless steel where additional strength and better wear resistance is needed. Stellite 6 and Stellite 1 hard facings are used on areas needing high wear resistance.

7.5 SUMMARY OF TRIBOLOGICAL ENERGY LOSSES IN THE FOOD INDUSTRY

Analysis of the food processing industry identified size reduction and material conveyance as the two most significant tribological loss activities. The generic tribological mechanisms contributing to energy losses are identified in Table 7.8 for each of the operational activities for which losses were estimated. Direct and indirect losses are given in Tables 7.9 and 7.10, respectively. Additional information on the principal energy form consumed by an operation, the energy loss rate, material type worn, and material wear rate is also provided in Tables 7.9 and 7.10.

The direct losses estimated for conveyors was the largest tribological sink identified for food processing and was an order of magnitude greater than the sum of all indirect losses estimated. Conveying systems are chiefly powered by electricity as are size reduction operations. Direct losses in conveyors are attributed to abrasive and frictional tribological mechanisms.

Indirect losses resulted from the wearing away of material due to erosion, abrasion, and/or rolling friction. The principal material types being worn are low magnitude of direct losses for conveyors but are significant in specific food industry groups such as sugar beet refining.

TABLE 7.8. Generic Tribological Loss Mechanisms in Food Processing

Operational Activity	Generic Tribological Mechanisms (1)	(2)	(3)
Conveyance			
Conveyors		✓	✓
Cranes			✓
Roller Conveyors			✓
Size Reduction			
Cossette Knives	✓	✓	

(1) Erosion
(2) Abrasion
(3) Rolling Friction

TABLE 7.9. Annual Direct Tribological Energy Loss in Food Processing

Operational Activity	Principal Energy Form Consumed	Energy Loss Rate	Total Energy Loss (10^9 Btu)
Conveyors	Electricity	5% of load	520

TABLE 7.10. Annual Indirect Tribological Energy Losses in Food Processing

Operational Activity	Material Type Worn	Material Wear Rate	Total Energy Loss (10^9 Btu)
Roller Conveyors	Alloy steel	3.6×10^6 bearings/yr	12
Cranes	Steel	1.0×10^5 wheels/yr	5.3
Cossette Knives	Alloy steel	10.6 lb/1000 tons sugar beets	4.3
			21.6

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