The Role of Tribology In Energy Conservation

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A review of the energy situation reveals the fact that the U.S. is the world's largest absolute and per capita consumer of energy. Moreover, nearly 50 percent of the total energy input into the economy is discarded. Two major energy users, the automotive vehicle and the steam turbine power plant, are identified as consuming over forty percent of the total U.S. energy needs, much of which is not usefully exploited. It is shown that tribology can play an important role in bringing about both direct energy savings as well as indirect benefits. An R&D plan in tribology is discussed which, when realized and implemented, offers a potential saving of 11 percent of total U.S. energy consumption.

INTRODUCTION

In 1970, the United States was responsible for about one-third of the world's energy consumption—64.5 out of 215 quadrillion (10^{15}) BTU—and three-quarters of this energy was derived from petroleum products. This would perhaps be acceptable if U.S. oil resources were plentiful, but they are not. As shown in Table 1, recoverable oil in the U.S. makes up less than 10 percent of the world's reserves, much below the 26 percent to be found in the territory of the Soviet Union. Moreover, while the Soviet Union has tapped only 6 percent of its deposits, the U.S. has already used up more than half of its oil resources. Even when compared to the world's most advanced countries, the rate of energy usage in the U.S. is exorbitant. Per capita, we consume three times (2) as much energy as Switzerland, and twice as much as Sweden or West Germany, even though the latter has as high a GNP per capita as the U.S.A.

Two solutions are available to us: find new energy resources, and better utilization of available energy. The projected functions of these approaches in the future of the economy are schematically portrayed in Fig. 1. We see that if we are content with present methods, the supply of energy will actually shrink, whereas the demand, due to an expanding economy and a rising population, will in twenty-five years grow some two-and-a-half times. The great gap between demand and supply will have to be filled in with new energy resources, primarily coal and nuclear fuels, and by an all-out effort of conservation and improved efficiencies in machines and processes. The role that tribology can play in the conservation part of this program constitutes the subject of this review.

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THE USEFUL ENERGY FRACTION

When one considers the subject of energy conservation, two paramount questions arise: (1) what areas of the economy are most responsible for unutilized or unproductive energy consumption? and, (2) how much of this nonutilization of energy is avoidable? While the first question can be answered by a direct energy balance, the second may include considerations bound up with the Second Law of Thermodynamics. These ramifications are briefly explained in the following paragraphs.

Direct Energy Balance

The direct system of energy tabulation is based on the simple notion of an arithmetic energy balance. In this approach, the performance of any economic sector, machine, or industrial process can be characterized by three quantities. Referring to Fig. 2, these are:

Total Input Energy—This represents the total energy required by or supplied to a given system, be it fuel, heat, electricity, or any other form of energy.

Useful Output Energy—Energy is supplied to a system in order to effect certain results, such as shaft work, locomotion, heating, refrigeration, etc. Thus, that portion of total energy which is converted to the desired result represents useful output.

Discarded Energy—That portion of the total energy, which is not converted to the desired purpose and is not otherwise utilized, represents discarded energy. This discarded energy is, as shown in Fig. 2, made up of two generic parts: one due to inherent losses in the thermodynamic cycle; and the other due to mechanical and

Table 1—Ultimately Recoverable Oil Reserves and Usage, [1]

Area	Reserves		% of Area's Reserves Used Up
	10^9 Bbl*	% of Total	
Soviet Union	514	26.3	6½
Communist Europe	62	3.2	10
Western Europe	47	2.4	4
Middle East	601	30.7	9
Asia	98	5.0	7
Africa	193	9.9	6
Mexico	22	1.1	17½
South America	155	7.9	23
Canada	70	3.6	7½
USA	190	9.7	52
Total	1,952	100	13

**Bbl–Barrels of crude oil or equivalent*

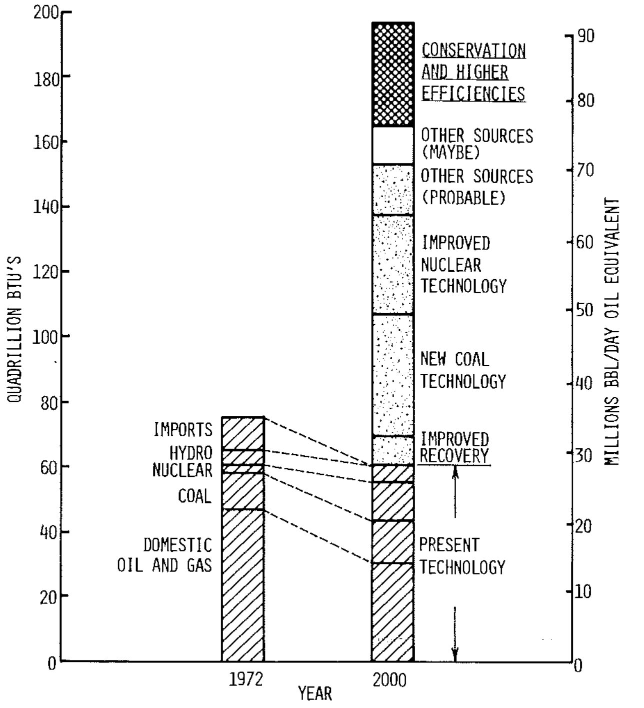

Fig. 1—Energy sources for the future

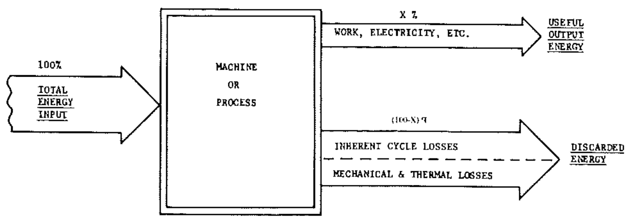

Fig. 2—Direct energy balance

thermal losses, such as leakage, friction, heat transfer, and others.

The energy accounting will here be conducted in terms of the four main sectors of the U.S. economy: transportation, electric utilities, industry, and the commercial-residential sector. The separate treatment of the electric utilities is, perhaps, an anomaly since, unlike the other sectors, it is not a user but a converter of one form of energy into another. However, since this conversion employs some of the largest pieces of machinery in the economy, it is important that it be treated as a separate entity.

Table 2 shows the levels of total energy consumed and energy discarded in the four individual sectors. In 1970, the percentage of energy discarded by all four sectors was 46 percent. In 1990, this percentage is expected to rise to 56 percent, mainly due to the growth of the utilties sector which, in twenty years, will have risen from 22 to 37 percent (*1*). At present, roughly half the energy consumed by the U.S. economy is being discarded.

When a breakdown of the kind given in Table 2 is presented, it often encounters criticism, to the effect that much of this loss of energy is inherent to the nature of the process. What these critics have in mind are the constraints dictated by the Second Law of Thermodynamics which, among other things, says that there is a limit to the percentage of work one can extract from a given quantity of heat. This aspect is taken up briefly in the next section.

The Second Law of Thermodynamics

While the First Law of Thermodynamics makes no distinction between various forms of energy, the Second Law states that, while it is possible to convert work completely into heat, on a cyclic basis heat can only partly be converted into work. The maximum work that can be obtained from a given quantity of heat is given by the Carnot efficiency η_c which is a function of only two parameters, the absolute inlet and outlet temperatures, T_i and T_o, of the system, namely:

$$\eta_c = \frac{\text{Work}}{\text{Heat in}} = \frac{T_i - T_o}{T_i} \qquad [1]$$

To get the highest possible efficiency, one must have the highest possible inlet temperature and the lowest possible outlet temperature. For a fixed outlet temperature, the rise in η_c with inlet temperature is shown in Fig. 3. However, under any conditions, the amount of work obtained will be less than the total heat delivered. Since work can always be completely converted into heat but not vice versa, work represents a higher and more useful form of energy, and its conversion or degradation into heat constitutes an irreversible loss of at least part of that energy.

Table 2—Total Energy and Energy Discarded in the USA, (*3*) & (*4*)

Data for 1970	Total Energy Input		Energy Discarded		
	10^{15} BTU	Percent of U.S. Total	10^{15} BTU	Percent of Sector	Percent of U.S. Total
Transportation	16.3	24	12.2	75	17.9
Utilities	15.1	22	9.8	65	14.4
Industrial	21.0	31	5.2	25	7.6
Commercial/Residential	15.9	23	4.0	25	5.9
Total USA	68.3	100	31.2	—	45.8

Projected Data For 1990	Total Energy Input		Energy Discarded		
	10^{15} BTU	Percent of U.S. Total	10^{15} BTU	Percent of Sector	Percent of U.S. Total
Transportation	33.1	25	24.8	75	19
Utilities	49.6	37	33.0	67	24
Industrial	28.8	22	9.1	32	7
Commercial/Residential	21.9	16	7.8	35	6
Total USA	133.4	100	74.7	—	56

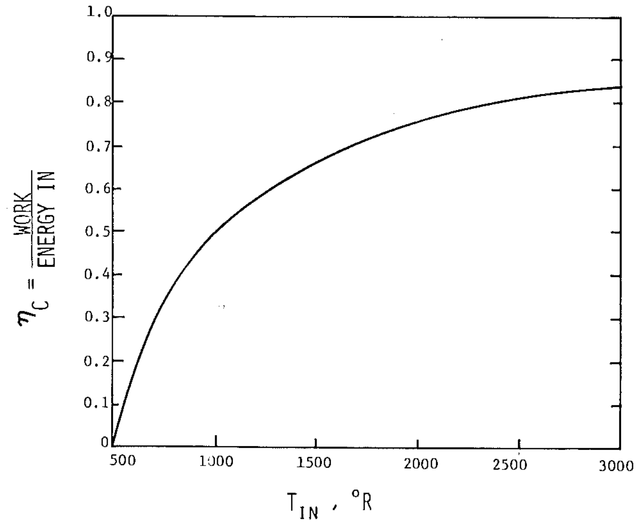

Fig. 3—Carnot efficiencies for T_{out} = 520°R (60°F)

When viewed in this light, the employment in the residential and commercial sector of electrical energy (which is equivalent to work energy) for heating and cooling is wasteful, even assuming that the conversion is 100 percent efficient. The direct use of fuel would result in a more efficient utilization of energy. On the other hand, the performance of machinery would come out to look better than appears from the figures in Table 2. Thus, for example, a steam turbine plant which generates steam at about 1000°F (1460°R) and discharges to a condenser at room temperature would have a Carnot efficiency of 63 percent (see Fig. 3). The actual efficiency of a steam power plant is somewhere around 32 percent so, in the sense of the Second Law, only about 50 percent of the Carnot energy is discarded, instead of 68 percent.

Likewise, if we take an internal combustion engine, where the stoichiometric temperatures are of the order of 3500°F, we have, for the Carnot efficiency, 86 percent. The actual efficiency of automotive vehicles is about 20 percent (see Table 3) so that, by the Second Law, 77 percent, $\left(\frac{86\text{-}20}{86} = 0.77\right)$, of the Carnot energy is discarded instead of 80 percent, the number obtained from a direct BTU accounting.

ENERGY USAGE IN THE U.S. ECONOMY

Transportation

The various means of locomotion within the transportation sector and the percentages of fuel they require are shown in Table 3. As seen, the automotive vehicle embracing cars, trucks and buses is responsible for 75 percent of all the fuel used in the sector. In terms of national consumption , they are responsible for 19 percent of the total. The automotive vehicles—there were 140 million in 1975—are the largest consumers of fuel. Furthermore, the fuel they use is exclusively a petroleum product; and the effectiveness of a passenger car in terms of energy consumed per passenger-mile is the lowest of all the means of transport. A regular size car uses five times as much fuel per passenger-mile as does a train, and twice as much as a commercial airliner (*7*).

TABLE 3—ENERGY CONSUMPTION AND EFFICIENCIES IN TRANSPORTATION DURING 1975, (5), (6)

BRANCH	10^{15} BTU/YR	PERCENT OF TRANSPORTATION	RATED-LOAD EFFICIENCY	ESTIMATED OPERATING EFFICIENCY
Automotive Vehicles	13.9	75	26.5%	20%
(Pass. Cars)	(9.6)	(52)	(25%)	(15%)
(Trucks & Buses)	(4.3)	(23)	(30%)	(25%)
Aircraft	2.0	11	35%	28%
Ships	0.74	4		
Railroads	0.55	3	35%	28%
Others	1.3	7		
Total	18.5	100		

TABLE 4—TOTAL ENERGY INPUT TO VARIOUS BRANCHES OF METAL INDUSTRY INCLUDING ENERGY FROM UTILITIES (7)

BRANCH	PERCENT OF U.S. TOTAL ENERGY	PERCENT OF U.S. ELECTRICAL ENERGY
Steel	6.0	2.5
Aluminum	1.5	4.0
Rest of Metals	1.0	1.5
Total	8.5	8.0

Although the energy utilization of the transportation sector as a whole is about 25 percent, the operating efficiency of the passenger car is, as shown in Table 3, only 15 percent; thus, nonutilization of energy by the passenger car amounts to some 85 percent, and, clearly, it represents the single most potent energy sink in the economy.

Electric Utilities

Some 78 percent of the present power generation equipment installed in electric utilities are steam turbine power plants. These plants account for 83 percent of the electric power delivered, due to the fact that gas turbines and diesel units are used mostly to meet peak-load requirements. Thus, steam turbine plants and the various associated equipment use 23 percent of the national energy total. Moreover, their share is expected to rise, for by the year 2000, 50 percent of all energy used in the other sectors is expected to come in the form of electricity.

The overall efficiency of a large steam power plant is some 32 percent. When transmission losses are included [some 8 percent of the power transmitted, (8)], the overall efficiency is less than 30 percent. Moreover, these efficiencies, as shown in Fig. 4, have not changed in the last ten years. As a result, any search for improvements in the electric utility sector should concentrate on the equipment contained in the steam turbine-generator power plant.

The Industrial Sector

The six most intensive energy consumers among the manufacturing industries are:

1. Food and kindred products
2. Paper and allied products
3. Chemicals and allied products
4. Petroleum and coal products
5. Stone, clay and glass products
6. Primary metal industries

These six branches of the economy require three-quarters of the total energy used by the U.S. industrial sector (3). In addition, these six also have a higher ratio of BTU used to dollar value of product than do the other manufacturing industries, and this by nearly an order of magnitude. Thus, their high consumption of energy is associated with a high ratio of energy per unit output.

For the purposes of the present study, the metal industry is the branch of main interest, as neither the petrochemical nor the food industries, nor the manufacture of stone, clay and paper is likely to offer much of a scope for savings via tribological progress. When the energy provided to industry by utilities is included in the accounting, the total energy input to the metal industry is as given in Table 4. This energy is used up in the tasks of:

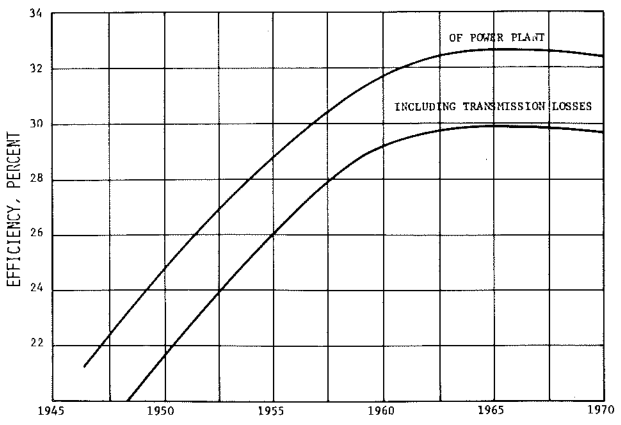

Fig. 4—Performance of power plants in public utilities

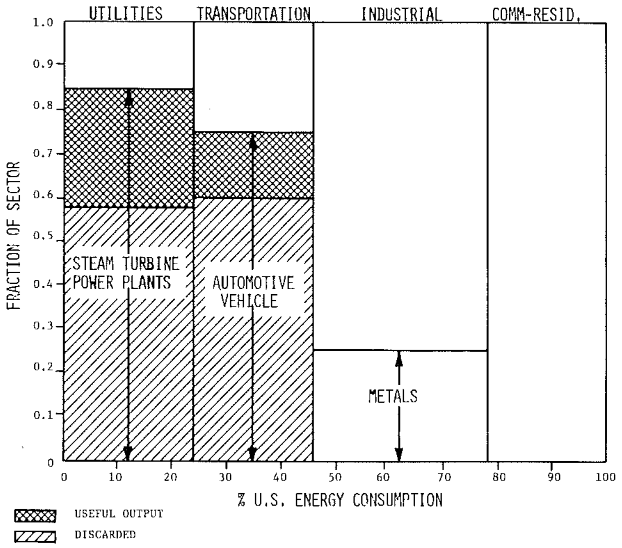

Fig. 5—Energy consumption in three product areas

1. Hot and cold strip rolling
2. Extrusion
3. Wire drawing
4. Forging
5. Stamping and forming

and in many other complex processes involving various forms of tribological loss.

The Commercial Residential Sector

In terms of total U.S. consumption, the energy consumed by the commercial-residential sector, including the power delivered to it by the utilities, is as follows (3):

Space Heating	18.0 percent
Refrigeration and Air Conditioning	4.7 percent
Water Heating	4.0 percent
Illumination	2.5 percent
Cooling	1.3 percent
Others	3.1 percent
Total	33.6 percent

Since most of the energy usage is in areas which involve little or no tribological technology, this sector is of little interest in the present review. The only relevant item would be the area of refrigeration and air conditioning. However, this equipment, in general, does not generate its own power but is driven by electricity. Thus, given its mechanical efficiency of about 80 percent, the only scope for improvement would be the 20 percent of mechanical losses. These amount to about 1 percent of the total U.S. energy consumption and would occupy a minor place as compared to the machinery in the other sectors.

A pictorial summary of the energies used and discarded by the various economic sectors is given in Fig. 5. The blocked out area represents the total U.S. energy consumption, with the four main economic sectors occupying blocks proportional to their individual energy demands. The items of major energy drain are identified within each sector, and it can be seen that two products—the steam turbine power plant and the automotive vehicle—consume over 40 percent of the total U.S. energy requirements, and that nearly three quarters of that energy is discarded.

TRIBOLOGICAL ENERGY DISSIPATION

Tribology may be defined as the science of the interactions between surfaces in close proximity which are moving one with respect to the other. The interplay of two primary factors is usually involved: one, the "load" or force normal to the interacting surfaces; the other, the friction force, parallel to the surfaces which seeks to restrain the motion.

Energy dissipation occurs as a result of the work done in overcoming the friction forces. Reduction of this frictional work can represent a direct saving in energy consumption. In addition to this direct benefit, major indirect savings may be possible if the application of tribology and of tribological research and development permits the use of more efficient machinery. Another area of indirect savings lies in reducing the rate of wear in machinery, thereby saving the energy involved in producing the materials and in manufacturing replacements for worn out equipment.

There are thus three areas of energy consumption where the application of tribological research, development, and application can reduce energy consumption, namely: frictional energy, process inefficiency and wear.

Frictional Energy Dissipation

The three processes which contribute directly to energy dissipation are friction in direct contact, viscous shear and hysteresis losses. All of these are manifestations of the attractive forces between atoms or molecules, and of the existence of favored low potential energy states which must be overcome to achieve relative motion. All result in the degradation of low entropy energy into heat.

Direct contact friction, often occurring in pivots, joints and sliding assemblies, is influenced by the kind of material, by surface finish, by load intensity, and by relative surface velocity. Coatings and solid lubricants can be used to reduce this solid to solid frictional resistance. Sliding of this type always produces at least some degree of wear. Unfortunately, low friction coefficient and low wear rates do not go hand in hand. The designer of an energy efficient machine, therefore, will need to balance the energy bill for wear against that for friction, always seeking an optimum.

When direct contact friction is eliminated by the introduction of a lubricant film between the sliding surfaces, energy dissipation occurs due to viscous forces. Under most conditions, the energy consumed in shearing the fluid lubricant is controlled by simple laminar laws of fluid flow, but when the inertial forces become high compared to the viscous forces in the fluid film, turbulence is encountered. The result is greatly increased energy dissipation, as the tiny eddies of turbulence increase the momentum transfer between the sliding surfaces.

When lubricants are introduced between rolling and sliding surfaces, the increased fluid viscosity due to high pressure helps to maintain surface separation under high Hertzian loadings, reducing or eliminating wear, but the higher viscosity results in increased friction.

Finally, another phenomenon that results in energy dissipation is hysteresis. There are various forms of hysteresis. One, mechanical hysteresis, is a loss of energy within the bulk of solid materials and occurs for example in highly stressed rolling contacts. Magnetic and electrical hysteresis losses may occur in magnetic bearings and in bearings where magnetic and/or electric fields, as well as a lubricant film, are present.

CONTROL OF FRICTION

One does not, of course, always want friction to be low. "Non-skid" surfaces are essential to the operation of many kinds of machinery. High friction, for example, is essential for the press fit of one element to another in a rotating shaft assembly or in a nut on bolt situation. Another similar situation is the clutch which must have a high enough static friction to prevent relative motion when it is engaged. Recently, an automobile automatic transmission has been designed in which the 6 percent fluid coupling loss in high gear is eliminated by the addition of a clutch in the high gear train. In traction transmissions, fluids are required which will transmit maximum torque with minimum slip in order to minimize energy losses.

In rotating seals, the designer must seek to balance the reduction of losses due to friction against the process fluid losses due to increased leakage. In bearings, he may use additives effectively to reduce the coefficient of friction and to control or eliminate high friction behavior.

Process Inefficiency

The influence of tribology, in particular the influence of tribological research and development, on the conservation of energy in our economy lies not only in the effective control of friction and the reduction of frictional energy dissipation, but also in the significant interactive effects of tribology on process efficiency. Prime examples of this interaction are direct efficiency improvements and indirect improvements due to smaller weight or size of machinery.

The temperatures at which bearings and seals can operate exert a direct effect on the upper operating temperatures that can be tolerated in heat engine types of machinery. For example, bearing materials that can withstand rubbing with modest friction and low wear at high temperature may permit gas bearings to operate at high temperatures. Higher operating temperatures in a heat engine mean greater Carnot cycle efficiencies and energy conservation throughout the life of the machine. Opportunities for this type of saving lie in areas of gas turbines and other prime movers such as automotive and diesel engines.

Often the result of higher temperature capability is the ability to design smaller and lighter machines which results in indirect energy savings. The ability to run bearings at higher speeds can again result in smaller and more efficient heat engines.

Ecological Effects

In today's rapidly changing civilization, one often finds ecological advancement at the expense of energy conservation, and vice versa. There are areas, however, where the application of advanced tribological knowledge may permit advancement toward both objectives. Gas bearings, for example, may permit machines to operate without the discharge of lubricants or material wear particles to the environment while improving the overall machine efficiency, as has been discussed above. Process fluid bearings, whether gas or liquid, may permit the operation of machinery in a hermetic mode, again gaining in both efficiency and environmental benefits.

From another point of view, of course, a conservational use of energy, and the reduction in the use of new materials (which again require both the use of energy in refining and manufacturing and the mining of ore resources), result directly in reduced discharge of combustion products, reduced distortion of the earth's thermal environment and a reduction in the rate of extraction of material and fuel resources from the earth's surface.

SAVINGS VIA TRIBOLOGY: A SAMPLE STUDY

It was seen above that two specific products are responsible for over 40 percent of the nation's energy consumption. The question that now arises is to what extent the discarded portion (75 percent) of that energy can be reduced via tribological improvements. Since the automotive vehicle has the largest ratio of discarded-to-used energy, it is taken up here as a case study of the kind of savings possible via advances in materials, lubricants and other tribological innovations.

A generalized sketch of the energy distribution in a passenger car, used in a representative urban-highway mode of driving, is shown in Fig. 6. As seen, only about 12 percent of the energy input reaches the wheels; together with the 2-1/2 percent energy spent on driving the accessories, this is just about the 15 percent operating efficiency quoted earlier. Of the various sinks responsible for the drain of the other 85 percent of energy input, nearly all of them can be affected, whether directly or indirectly, by tribological innovation. We shall here, however, concentrate on only four areas, which promise to have a major impact on energy conservation, these being piston ring and skirt losses, low viscosity oils, the ramifications of using a continuously variable transmission, and the long range goal of introducing an adiabatic diesel. The energy losses involved, the potential gains to be accrued from tribological advances in these areas and the kind of research and development required to realize these advances are briefly discussed in the following paragraphs.

Piston Ring and Skirt Losses

The operation of piston rings in an internal combustion engine represents a most complex process involving lubrication, sealing, hysteresis and elasticity of materials, thermodynamics, heat transfer, and other phenomena. The losses incurred in the operation of piston rings and skirts come from friction which is partly of a hydrodynamic and partly of a boundary lubrication nature; from hysteresis losses in the mating materials; from blow-by of combustion gases; and from wear which consumes energy in the process and degrades the rings' sealing function. It is estimated that of all the mechanical losses in the engine, which are of the order of 30 percent of the bhp, a quarter to a half is due to piston ring and skirt losses.

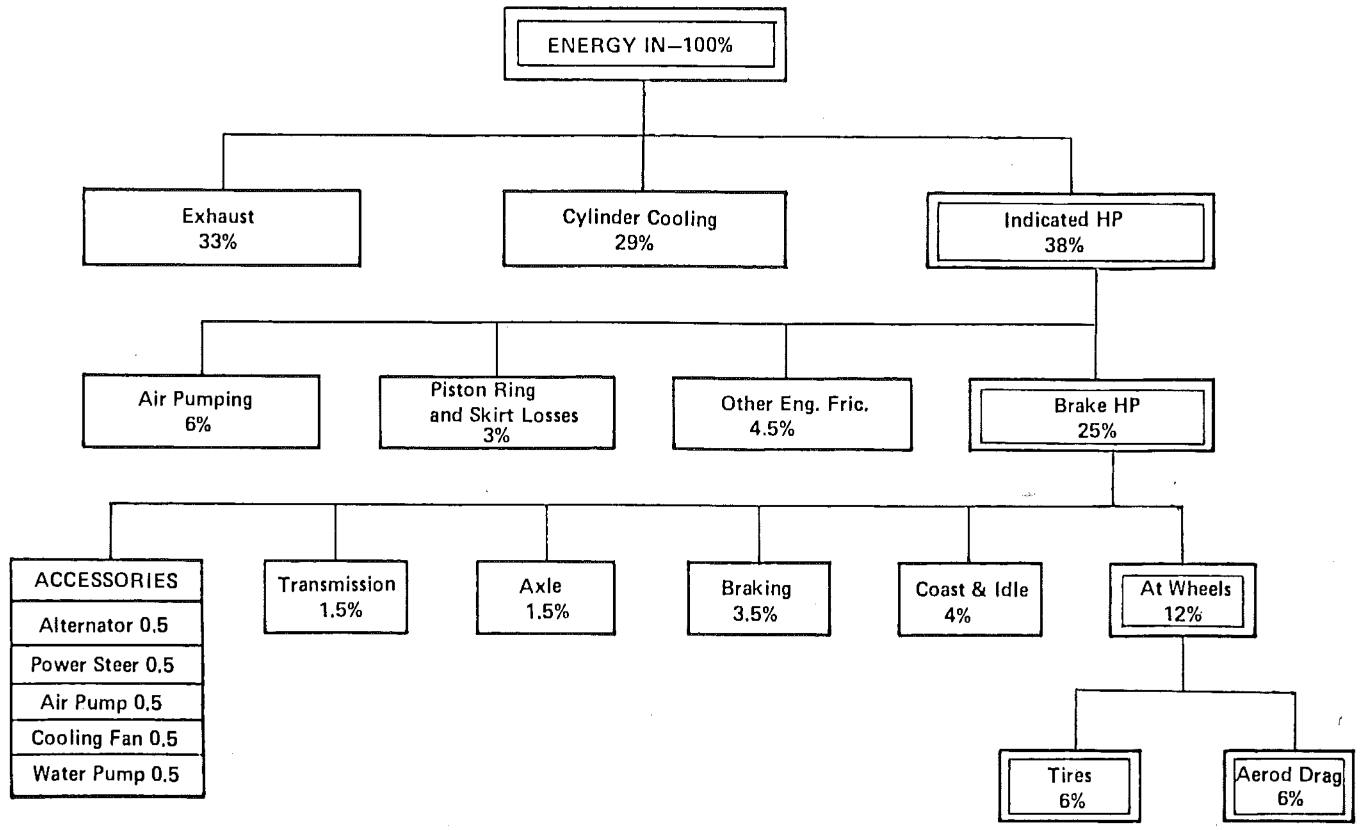

Fig. 6—Energy distribution in passenger car during a city highway EPA cycle.

Improvement in this area calls for studies covering nearly the entire spectrum of tribology and ranging from a new accurate method of measuring the involved losses to a basic understanding and modelling of the phenomena involved.

Implementation of the results of a successful R&D program in the above areas is estimated to reduce existing losses by one quarter.

Low Viscosity Oil

Tests run with oils of low viscosities have shown a potential improvement in SFC of the order of four percent (7) for city-suburban cold weather conditions, with about two-thirds coming from the reduction of friction in the engine, and one-third from a reduction of friction in the axle. There is little doubt that low viscosity oils offer an inexpensive and effective means of conserving fuel.

The potential difficulties with low viscosity engine oils are high oil consumption and a high wear rate. The first problem can probably be overcome by proper oil volatility and viscosity index (VI) control; while high wear rates can be decreased by VI control and proper additive treatment.

Further work in this area, including the use of additives, could raise the above gains to a 10 percent improvement in SFC (7). Thus, a program combining the use of additives with low viscosity oil could save about 220 × 10^6 bbl/yr or 1.8 percent of the total U.S. consumption.

Continuously Variable Transmissions (CVT)

A desirable innovation in automotive propulsion would be to operate the engine at its most efficient rpm for the power demand. To accomplish this, a continuously variable transmission must deliver the power at the rpm required by the vehicle including zero for idle and start, and a negative ratio for reverse operation.

Such a CVT would yield the following benefits:

1. The engine could always run at its most fuel-efficient setting.
2. By being able to accommodate the varying speed ratios of the engine and an energy storage flywheel, a CVT could be used for regenerative braking.
3. Auxiliary CVT's could drive variable and constant speed accessories.

There are a number of possible CVT arrangements using mechanical, hydraulic, electrical, or hybrid systems. One promising candidate is an all-mechanical system in which traction transmits the power from one rolling element to another, and in which the surfaces are separated and protected by a thin film of traction lubricant. Achievement of the high power density required of an automotive traction CVT calls for sophisticated mechanical design and trade-off which must be considered in combination with lubricants of the highest possible coefficient of traction. Normal stresses in traction contacts and associated rolling element bearings must be at levels consistent with a tolerable transmission fatigue-wear life and with practical materials and techniques of component fabrication.

The development and widespread adaptation of a CVT system would yield a 25 to 30 percent improvement in automotive fuel economy (7).

Translated into national terms, the above represents a 4 to 5 percent saving in total U.S. energy consumption. Additional gains could be obtained by coupling the CVT with a flywheel regenerative braking system in which case a 50 to 80 percent gain in fuel economy could be gained, or a 7 to 9 percent reduction in the total U.S. energy bill. Moreover, the savings would all be of petroleum.

The Adiabatic Diesel

The automotive engine which holds out the greatest promise but which also presents a formidable challenge for the tribologist is the adiabatic diesel. The essence of the adiabatic diesel is to do away with the cooling of the engine and use the hot exhaust gases to drive a turbine whose output would augment the propulsive power of the vehicle. With the adiabatic diesel and other advances in engine technology, the BSFC of such an advanced truck diesel could drop from the present 0.36 to something like 0.22, a nearly 40 percent gain in fuel economy, as shown in Fig. 7.

In such an engine, component temperatures of the order of 1000 to 1500° F will have to be endured. New materials, perhaps ceramics, will be required, and it may well be that no lubricants can be found to operate for any length of time under these conditions. One of the possibilities is to float the piston on a film of gas. The latter would, of course, have the additional advantage of reducing frictional losses to negligible levels.

The fuel gains on trucks and busses graphed in Fig. 7, due to an advanced adiabatic diesel, translate into a saving of the order of 1.7 percent of U.S. energy consumption (7). In the case of the passenger cars, due to shorter trips, frequent stops and starts, etc., similar gains could not be achieved. The use of an advanced adiabatic diesel on passenger cars is estimated to yield only a third of the benefits accrued by trucks and buses, yielding an additional saving of 1.3 percent of U.S. energy consumption. The potential savings due to an advanced adiabatic diesel would add up to 3 percent of U.S. energy consumption, or 370 million bbl/yr.

After allowing for some overlapping of the potential gains, the total gains due to tribological progress in the above four areas of automotive technology amounts to a saving of 7.4 percent of the total U.S. energy bill. In terms of 1976 consumption, this is equivalent to about 900 million barrels of fuel, or, at $12 a barrel of crude, to a saving of over $10 billion per year.

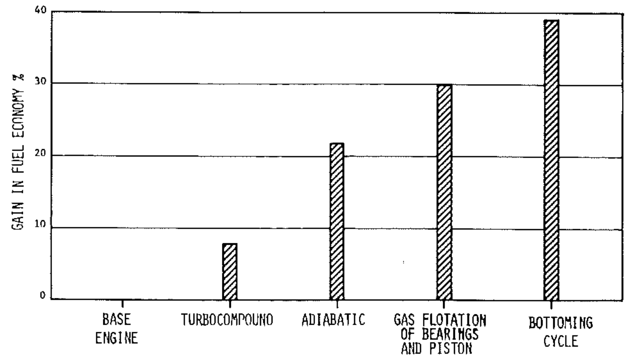

Fig. 7—Fuel economy gains on trucks and busses due to an advanced diesel.

Energy Conservation Via Tribological Progress

Tribological Studies

The fact that tribology can have a significant impact in saving energy and raising the performance of machinery was, of course, always clear to its practitioners. Lately, however, this realization has penetrated not only the engineering community as a whole, but even outside of it, so that governments have taken a hand in sponsoring and funding tribological studies aimed at energy conservation. The first of these comprehensive studies was undertaken in Great Britain where the Jost report (*9*), sponsored by the Department of Education and Science has indicated that, in worn equipment alone, over a billion dollars a year could be saved in the United Kingdom by improved lubrication practices. Subsequently, Jost (*10*) estimated that, in the U.S., a similar study indicates a potential saving of the order of $16 billion/year.

Another recent study was conducted in West Germany, (*11*), on behalf of the Ministry of Research and Technology which in addition to documenting the friction and wear losses (some $4 billion per annum) also formulated a research plan to reduce these losses. The abstract of the published document portrays the scope of the project as follows:

> "The study in question reveals the economic significance of Tribology and represents the present level of technology and knowledge in the fields of friction, wear, and lubrication in the Federal Republic of Germany.
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> "The study is concerned with subjects dry, boundary, and lubricated friction. In addition, a number of special problems with overlapping significance is treated in connection with the system components material and lubricant. In consideration of the all-embracing tribosystem, the subjects metalworking processes, tribologically aided design, and maintenance are discussed in separate paragraphs.
>
> "The rather complicated problems arising in connection with testing of tribotechnical systems are treated in a separate paragraph measuring and testing techniques.
>
> "Each section shows a number of proposals for research and development projects of high priority. Their realization could mean an increase of technical knowledge and a decrease of economic losses caused by friction and wear, as well as a reduction of maintenance charge and production deficit."

By far the most ambitious undertaking is the recently completed study sponsored by ERDA and carried out by the Research Committee of Lubrication of the ASME. The published document, "Strategy for Energy Conservation through Tribology," prepared by the authors (7), sets down its objectives as follows:

1. To assess the possible impact of tribological innovations on energy conservation and on the promotion of advanced energy technologies.
2. To identify those areas where the application of existing or new tribological knowledge is expected to yield substantial benefits, whether direct or indirect.
3. To recommend an R&D plan in the tribological sciences for possible implementation by government agencies and industry.

Development Programs in Tribology

Achievement of savings in energy usage through the application of tribological engineering will require a number of pathfinder programs. These range from demonstrations and the application of existing technology to advanced research and development in areas where progress will yield substantial payoffs in energy conservation.

The spectrum of possible research, development and application areas in tribology is extremely broad. To achieve greater energy conservation, and at the same time to have a rational program in terms of cost and feasibility a number of factors need to be considered, namely: potential payoff, likelihood of success, cost of program, cost of implementation, and time to application.

Based on consideration of these factors, a number of program areas have been selected and recommended for implementation in the ASME document, (7). Each area contains a number of specific projects for each of which the objective, technical background, work statement, potential energy payoff, and an estimated cost of the R&D work required are outlined. The plan is open-ended as it is expected that the nature of these programs and the program mix will undergo modification as research and development are accomplished and as the economy changes and grows.

Programs have been selected which relate to the economic areas of Road Transportation, Industrial Machinery and Processes, and Power Generation and Turbomachinery Equipment. The recommended projects which have impact on the first of these areas relate to traction transmissions, piston rings, the adiabatic diesel, and engine oils; wear and metal processing projects are recommended in the Industrial Machinery and Processes area; and bearings and seals in the Power Generation and Turbomachinery Equipment area.

The potential impact of these programs, compared to their cost, is shown in Table 5. This shows that implementation of the recommended R&D programs could result in a reduction in U.S. energy consumption of some 11 percent. More than half of this is in the road transportation category which is completely dependent upon oil and its derivatives. If the R&D cost is multiplied by a factor of 10 to allow approximately for the total cost through implementation, the potential annual savings that can be achieved are roughly one hundred times the implementation cost for the areas of Road Transportation and Industrial Machinery and Processes. The potential savings in the area of Power Generation and Turbomachinery Equipment are much smaller compared to the estimated R&D costs, although substantial annual benefits can still be obtained.

Research and development work in several of the program areas is expected to benefit more than one economic area. Table 6 shows this interrelationship and indicates where major and minor impacts would be expected.

While it is not the intent of this paper to delve into the nature of specific program requirements, the general nature of each of the tribological R&D areas outlined in Table 6 deserves some elaboration.

Three areas are identified under Road Transportation namely transmissions, Otto cycle engines, and adiabatic diesel engines. Traction type transmissions show particular promise as a means of providing infinitely variable coupling between the engine and the wheels, but complex tribological problems need to be overcome before they can attain successful application.

The area of Lubricant Properties and Lubrication includes programs in both the development of and the properties of traction fluids, the use of low viscosity lubricants in Otto cycle engines, concepts and techniques for extreme temperature lubrication, and metal processing lubrication.

Materials and Coatings includes programs on materials for traction contact areas, piston ring materials and coat-

Table 5—Potential Impact of Recommended Tribology Program

Economic Area	Potential Energy Savings		Estimated R&D Cost Millions of Dollars	Benefit Ratio*
	% U.S. Consumption	Billions of Dollars Per Year		
Road Transportation	7.4	11	12.6	87
Power Generation and Turbomachinery Equipment	0.7	1.0	7.3	14
Industrial Machinery and Processes	2.8	4.2	3.7	113
Total	10.9	16.2	23.6	69

$$\text{*Benefit Ratio} = \frac{\text{Savings}}{10 \times \text{Cost of R\&D}}$$

TABLE 6—IMPACT OF RECOMMENDED R&D PROJECTS ON ECONOMIC AREAS

RECOMMENDED AREAS FOR TRIBOLOGY R&D	ROAD TRANSPORTATION			INDUSTRIAL MACHINERY AND PROCESSES	POWER GENERATION AND TURBOMACHINERY EQUIPMENT	ESTIMATED COST OF R&D (MILLIONS) OFDOLLARS
	TRANSMISSIONS (TRACTION TYPE)	OTTO ENGINES	ADIABATIC DIESEL ENGINES			
Lubricants, Lubricant Properties and Lubrication	M	M	m	m	M	5.6
Materials and Coatings	M	M	M	M	M	4.8
Wear	m	M	M	m	M	0.7
Sliding Bearings	m	M	M	M	m	4.4
Rolling Element Bearings	m			M	M	1.7
Seals	m	m	m	M	m	1.0
Metal Rolling and Processing				M		3.1
					Total	21.3

Code M—Major; m—minor

ings, high temperature Babbitt-like materials, and rolling element bearing materials with high fracture toughness.

The category of Wear includes programs on the mechanism of wear by foreign particle (the influence of dirt in wear-out of machinery), and support of the Wear Control Handbook project.

The Sliding Bearings Program includes study of water-lubricated bearings, the design of better turbulent bearings and process fluid bearings, such as those using refrigerants or gases.

The development work recommended on Rolling Element Bearings is directed toward developments aimed at making possible very high speed operation. Small ball bearings, cylindrical and tapered roller bearings are needed which have the capability of operating at 3 million DN or more. Speeds of this magnitude are one of the key requirements toward attaining higher speed, lighter and more efficient turbomachinery.

The recommended activity in seals is concentrated on the area of gas path seals for turbomachinery. Work on abradable structures, and on active control of seal clearance, can lead directly toward increased efficiency in turbomachinery.

Metal Rolling and Processing is suggested as an area for research and development primarily because of the large quantities of energy consumed in this industry. At this point in time, the ASME report could not pinpoint specific programs, but recommended that an Advisory Group be formed to determine the most effective areas for attack.

Examination of Table 6 shows that the first four tribology areas have a very broad major impact on the economic areas. The latter three areas are considerably more specialized in their economic impact. The tribology area having the broadest impact across the board is Materials and Coatings.

A research and development program of this magnitude and complexity requires planning, coordination and some degree of centralized administration, with the Federal government taking on the leadership role. It is also highly desirable that the technical community in tribology be directly involved in influencing the conduct and course of the program. To accomplish these objectives, an advisory board managed by the ASME has been established as part of the overall activity. Persons competent in each of the important sectors of the field of tribology are being appointed to the board to provide appraisals, forecasts and recommendations to the sponsoring agencies. Cost sharing by industry, particularly in programs leading directly to early implementation, is also favored as a means of achieving greater "reality" in the implementation work.

SUMMARY

Two specific product areas have been identified as being responsible for a high portion of the total U.S. energy requirements. These products are the automotive vehicle, 19 percent, and the steam turbine power plant, 23 percent, making a total of 42 percent of U.S. energy consumption.* The operating efficiency of an automotive vehicle is only 20 percent, while that of a steam turbine power plant, when transmission losses are included, is some 29 percent. Consequently, nearly three-quarters of the energy input to these two products is discarded without being utilized.

Better energy utilization in the above areas can be achieved by the mitigation of friction and wear in machinery and by the employment of better materials, lubricants and sealing methods. Such progress in tribological technology would contribute not only to direct energy savings but, perhaps more importantly, it would make possible the utilization of higher pressures and temperatures and thus raise cycle efficiency; by introducing smaller bearings running at higher speeds, the machines can be made more compact and thus save in materials and manufacturing costs; and by raising machine reliability, it would prevent failures and simplify maintenance. As an example, it has been estimated that improved sealing in steam turbines could raise the output of utilities by 1/2 percent, which represents a saving of 1 billion in capital equipment alone (*7*).

A sample analysis of the automotive vehicle showed that a 40 percent improvement in fuel economy is possible by progress in the vehicle transmission, lubricants, diesel engine and piston ring performance. This represents a 7.4 percent reduction in total U.S. energy requirements. Similar advances in the economy as a whole offers the potential of an 11 percent saving of total U.S. energy needs. To accomplish these savings, advances in materials, lubricants, bearings, and seals are required as well as in tribological systems integration.

No less important than the accomplishment of the R&D plan in tribology is the implementation of its findings and recommendations. This must have the support of the engineering community as well as of industry and government bodies. Educational and legislative means may have to be employed to persuade and induce the country to accept the required changes and head in the direction of increased energy conservation because it represents the greatest historical challenge to the economic life of the U.S.A.

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*These dates are for 1975.

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DISCUSSION

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Authors Pinkus and Wilcock place tribology in the front rank of the technologies critical in energy conservation. In this paper, as in its important precursor [authors' Ref. (*7*)], they repeatedly and appropriately remind us of the pull-through gains often flowing from the traditional advances associated with tribology. Both the automotive traction transmission and adiabatic diesel engine are pertinent illustrations. Each requires for success difficult advances, with key contributions from the tribologists, and each promises gains in fuel economy many times the sum of the individual savings.

We are indebted to the authors for sifting through an intractable mass of statistics and concentrating the results in a useful format. Of particular interest was the analysis of the energy flows in the automobile. This has already found wide circulation and attention via the earlier publication. The authors are encouraged to better reference the source data of Fig. 6 so that others might mine the same vein. (References for Fig. 1 and 4, and Tables 5 and 6 would also be useful.)

Hidden unused in the authors' reference list (*6*) is a classic paper by Reistad on the sadly neglected subject of thermodynamic availability analysis. When conservators and tribologists finally get around to rediscovering this most powerful analytic tool, we shall no longer need to struggle manfully with fuzzy concepts like "unproductive energy," "wastage," "discarded energy," "inherent cycle losses," and even "energy conservation" (energy will take care of itself; it's scarce fuel we need to conserve). Moreover, we can avoid inappropriate comparisons with the over-invoked Carnot engine, and stop scratching our heads over the proper choice of an upper Carnot cycle temperature. All these blessings, wrapped in a Second-Law language and arithmetic of LOSS, await exploitation. An availability analysis of the author's automobile case would be a most welcome start and an interesting companion piece.

It is hoped that the authors will continue the vital work of digging out and exposing information of this sort so necessary in pinpointing new opportunities to improve effective fuel use (if not "conserve energy").

AUTHORS' CLOSURE

The authors welcome Dr. Miller's constructive comments. First with regard to the sources of some of the data given in the paper, Fig. 6 has been constructed from a number of individual elements, the largest contribution being Ref. (*5*). The data on air pumping and piston ring and skirt losses were reworked from the material presented at the 1977 Tribology Workshop, Refs. 18 and 7 of the subsequently published ASME document, listed as Ref. (*7*) in the authors' paper. The overall data on exhaust losses, cooling and indicated horsepower can be obtained from any standard text, e.g., "Internal Combustion Engines" by B. H. Lemmings and E. F. Obert (International Textbook Co., Scranton, Pennsylvania).

Data on heat rates are available from any utility compendium as well as from the Edison Electric Institute. The transmission losses contained in the lower graph of Fig. 4, were taken from Ref. (*8*). Tables 5 and 6 are merely reworked forms of Tables 5.1 and 5.3 of Ref. (*7*).

Finally, as to the source of Fig. 1, the authors are humbly embarrassed. To the best of their recollection, this figure has appeared in *Mechanical Engineering.* They are, however, unable to provide the specific reference and they would be grateful to any reader who may locate the issue in which Fig. 1 has originally appeared.

The authors share Dr. Miller's high opinion of the Reistadt paper, Ref. (*6*), on availability. However, its cursory treatment in their paper which deals with tribology-energy relations was a result of due consideration and not of neglect. The authors have included a brief discussion on the ramifications of Carnot efficiencies to make the reader aware of the fact that the direct BTU accounting system is not the only and not always the most appropriate tool for an energy balance. To venture into the realm of thermodynamic criteria of availability would have, in the framework of this particular paper, obscured rather than elucidated the subject under discussion.

As an example of such potential complexities, consider the conversion of 1 watt of electrical energy into residential heat. If we restrict ourselves only to the process at the home being heated, then assuming a conversion efficiency of 100 percent, the effectiveness of the process in terms of availability is, according to Reistadt, only some 17 percent, i.e. mostly wasted. Yet by the definition of the authors' paper where useful output is defined as "that portion of total energy which is converted to the desired result"—no wastage occurred at all and the entire watt was usefully exploited. The important point of the above example, of course, is that electricity, which is equivalent to work, is by the implications of the Second Law of Thermodynamics, a higher form of energy, and its direct conversion of "degeneration" into heat is wasteful. As a practical illustration of this, we may consider utilizing the watt of electricity, not for direct transformation into heat, but for driving a heat pump. With the COP of residential heat pumps being of the order of 2, the heat delivered to the household would then be about twice the work input, that is twice as high as that obtained from direct conversion.

What emerges is that there are at least three criteria for energy accounting: direct BTU, Carnot efficiency and effectiveness based on thermodynamic availability. From an engineering standpoint, none of these can be applied automatically across the board and great discernment and proper qualifications are called for to place the usage of any of these concepts in the proper and correct reference frame. The authors tend to disagree that the use of availability as the overriding test in energy statistics would as Mr. Miller put it, once and for all make us "stop scratching our heads." They fear the opposite, namely that the scratching may assume injurious proportions.