A strategy for tribology in Canada: enhancing reliability and efficiency through the reduction of wear and friction

National Research Council of Canada. Associate Committee on Tribology

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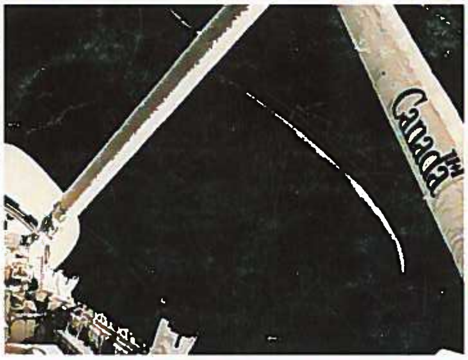
Enhancing Reliability and Efficiency through the Reduction of Wear & Friction



Canada

A Strategy for Tribology in Canada

Enhancing Reliability and Efficiency through the Reduction of Wear and Friction

Sponsored by:

National Research Council Canada
Associate Committee on Tribology

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FOREWORD

This report represents, in a very real way, the coming of age of tribology as an engineering discipline in Canada. This is the first attempt to determine the economic implications of poor tribological practice applied to the Canadian industrial environment. It describes in clear terms the benefits that can accrue to the Canadian economy through increased emphasis on tribology research and development and through the wide application of the knowledge so gained.

It was just twenty years ago that the word 'Tribology' was used for the first time. In the classic Jost Report to the British government in 1966, the authors recognized the essential interactions of the three engineering topics of friction, lubrication and wear and they coined the name 'Tribology' to encompass the interdisciplinary science and technology that is concerned with the behaviour of interacting surfaces in relative motion. Their pioneering study, by careful examination of ways in which tribology-related losses occurred, identified estimated savings to the British economy of more than 500 million pounds per annum through the use of improved tribological practice. Similar studies have been conducted more recently in the United States and in the Federal Republic of Germany and these studies have confirmed the very significant economic benefits to be gained by industry through a relatively modest investment in tribological research and its application.

Canada is not an industrialized country like West Germany, Great Britain, or even the United States. Although the manufacturing sector of the Canadian economy is technically advanced, on a par with these other industrialized nations, Canadian manufacturing still provides a much smaller contribution to the gross national product than do our resource industries of mining, forestry, agriculture and fishing. The resource sector of the Canadian economy is highly productive and generally well mechanized but it is not self-evident that the appropriate tribological research priorities for West Germany, the United States or Great Britain would apply in Canada, or would lead to similar benefits.

The National Research Council's Associate Committee on Tribology was formed in 1971 to bring together experts from universities, industry and government to increase the awareness in industry of modern developments in tribological practice and to encourage coordination in research and development in this field. The Associate Committee has been very effective through newsletters, seminars, conferences and courses in stimulating an awareness of the importance of tribology as a means of improving the performance of machines in extreme environments. However, tribology is a generic subject, linking many disciplines, with the results of its application appearing in all aspects of machinery and transportation. The losses engendered by poor tribological practice will be diffuse, and the benefits from increased knowledge and from research and development will be spread over many operations and probably many years. Hence industry has been slow to recognize the great advantages that can accrue to it by support of the necessary research and development and its application.

This report - "A strategy for tribology in Canada - enhancing reliability and efficiency through the reduction of wear and friction", for the first time puts into a Canadian perspective the importance of good tribological practice. The NRC's Associate Committee on Tribology, and the Conservation Task of the Panel on Energy Research and Development of the federal department of Energy, Mines and Resources which sponsored the Canadian study on which much of this report is based, are to be congratulated on bringing together in such a comprehensive and graphic manner the Canadian situation related to tribological practice.

Based on the information accumulated for this report, the Associate Committee on Tribology has developed a number of recommendations. These recommendations are aimed at enhancing an awareness of tribology and an increased activity in research, development and application. These recommendations should receive thoughtful considerations from government agencies, universities and industry. It is clear the potential benefits to the Canadian economy by addressing the recommendations of this report would be enormous.

I hope this report will receive a wide reading and that Canada will join other industrial nations in ensuring that the benefits possible from an increased understanding of tribology and its widespread application in all areas of industry will be realized.

E.H. Dudgeon
Associate Vice-President (Engineering)
National Research Council of Canada

Summary

SUMMARY

Canada is the worse for wear - and friction

Canada loses more than $5 billion annually due to friction and wear. (See Table next page.) It has been estimated that about $1.3 billion, or some 25% of these losses, could be saved through better application of existing technology and through research and development.*

This report deals with a strategy to achieve these savings through tribology R&D.

Tribology combines the many branches and specialities in science and technology concerned with understanding and combatting friction and wear.

Specifically, tribology is concerned with the design and manufacture of sliding and rolling bearings, piston rings, gears, cutting tools, and any other device in which surfaces interact, in sliding or other relative motion. Tribology is concerned with the correct use of materials for interacting solid surfaces, with the interaction of those surfaces with lubricants, with the chemistry, physics and use of lubricants and their additives. It is concerned with the reduction of friction and wear (or, in the case of belts, brakes, clutch plates, and similar devices, in achieving optimum friction with minimum wear) and is concerned with the avoidance of associated failures in machinery.

Similar tribological components (e.g. bearings) are used in different technologies, and similar tribological problems (e.g. abrasive wear) occur in different industries. Thus tribology is in itself a generic science and technology, concerned with the generation and dissemination of knowledge on friction, wear and lubrication, and with the application of that knowledge, to a very wide range of industrial products and equipment, from ploughs to space equipment, from prostheses to engines, from washing machines to railways, from computers to power stations, from paper mills to mines.

Estimates derived (in 1982 values) in a survey of agriculture, electric utilities, forestry, mining, pulp and paper, rail and road transportation, and wood industries, conducted for Energy, Mines and Resources Canada by D'Silva et al. [1] of Ontario Hydro.

In the sectors listed, total losses due to wear were estimated to exceed $3.9 billion and to friction $1.2 billion.

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* The figures quoted are estimates, derived from a survey of relatively limited scope and in relation to the items studied, the estimates are unlikely to be accurate to better than ±30% of the values quoted. Since the Canadian economy includes several other major sectors apart from those studied, it is clear that the total loss to the economy from friction and wear is a great deal higher than the figure of $5 billion even with the appreciable uncertainty in the magnitude of the individual estimates.

	Friction losses ($ million/year)	Wear losses ($ million/year)	Total losses ($ million/year)
Agriculture:	321	940	1,261
Electric utilities:	54	189	243
Forestry:	111	158	269
Mining:	211	728	940
Pulp and paper:	105	382	487
Rail transportation:	284	467	750
Trucks and buses:	126	860	986
Wood industries:	14	189	203
TOTALS:	1,226	3,913	5,139

Avoidable losses due to friction and wear are occurring because many who are involved in design, specification, operation, and maintenance of industrial equipment are unaware of current technology in tribology. There is also an inadequate level of R&D in tribology, through which the reliability and economy of industrial processes and products can be improved.

The estimates include the cost of the individual components (tires, rails, gears, bearings and the like) affected by wear and friction, the labour and other costs incurred in replacement operations and, generally, any consequential losses due to shortfall in production and additional costs of procedures substituted temporarily for those which have failed. The estimates do not include lost sales where, because of lower reliability or greater cost, a product is less competitive than those of rival companies here or abroad. For this reason too the estimated losses are underestimates of the total effect of friction and wear in the economy.

The estimates of losses and potential savings are in general agreement with estimates of this type produced in the UK, the Federal Republic of Germany and the USA, increasing the confidence which can be placed in them. Nevertheless, the reader is cautioned that the estimates involve considerable extrapolation from small samples, and subjective judgement, albeit by experts in tribology, and should serve to indicate primarily the general magnitude of the losses and potential savings. Indications of the general level of the problems of this kind have provided the impetus for major government funded programmes in tribology R&D in other countries, most recently in the Federal Republic of Germany and the USA, adding to the already significant level of tribology R&D in these countries.

Strategies against wear and friction in other nations

The very significant tribology programmes in the three countries mentioned have all been structured around considerable financial contributions from the respective national governments, while at the same time involving industry.

"Tribology centres" in the UK were established with government support which decreased as the income from R&D contracts and consulting increased. In West Germany, most projects in the current tribology programme are cost-shared by industry and government. In the USA, many of the tribology projects are being carried out under government contract in industrial R&D facilities. Government involvement in the USA seems to emphasize major new technologies, such as advanced engines, or on military applications (often the same areas), plus a strong involvement in promoting information systems in tribology.

The challenge in Canada

The major programmes to enhance tribology R&D in these three countries supplement an existing level of effort in tribology R&D, which is proportionally higher than that in Canada. Industry in Canada is already at some disadvantage, as a result of the lower level of technical know-how in tribology available to it here. This has significant implications for the competitiveness of Canadian industry, in terms of cost and reliability of its operations and manufactured products, in an international market which may be becoming more open.

It is essential that R&D in tribology be promoted in Canada, and that other measures be pursued to enhance the efficiency of Canadian industry and the competitiveness of its products, and to reduce the losses to the Canadian economy due to friction and wear.

Government agencies in Canada concerned with R&D and industrial development should take a strong lead in promoting tribology.

D'Silva et al. [1] indicated that there is a significant need for increased awareness among production personnel in industry of the measures available to reduce friction and wear, and a need for more appreciation of the potential benefits of R&D directed at combatting wear and friction. The given level of friction and wear tends to be accepted erroneously as normal. Undoubtedly a neglect of the study of friction, wear, lubrication, and the design and selection of bearings, seals, gears, and other tribological components, in the training of many technologists and engineers is a major reason for this situation.

The challenge is not just to those in industry who are already familiar with tribology and with equipment which relies on tribology, i.e. with the design and maintenance of bearings, seals, gears, clutches, brakes, belts, tires, chains, earth and rock moving equipment, mills, grinders, crushers, cutters, rolls, fans, etc. The challenge faces all who have responsibilities for investment and budget decisions.

Tribology is very much an "applied" science and technology. Consequently, R&D in many areas of tribology will only be effective if it is conducted with a strong industrial involvement. Much of the initiative in promoting tribology R&D will have to come from industry.

Because the benefits from tribology R&D are in some instances significant only when improvements are applied in a variety of items of equipment, or applied across an industry rather than in just one plant, the opportunities for improvement have often been neglected. Therefore, it is most appropriate that industry groups, as well as individual companies, become involved in tribology R&D.

It is the hope of the Associate Committee on Tribology that this report will help make the case for initiative and support for tribology R&D from companies and industrial groups, industrial and professional associations, as well as from R&D laboratories and agencies, both outside and within government.

As a committee reporting to a government agency, the Associate Committee on Tribology directs a number of specific suggestions and recommendations to government agencies. In several of these recommendations the expectation is that the agency or agencies concerned will provide a framework for industry participation in R&D, or will be initiating activities for technology transfer in the form of information and consulting services.

The Committee, with members drawn from industry, universities and government, is prepared to act as a catalyst in any way possible in any of the initiatives recommended. The Committee considers it urgent that steps be taken in Canada to enhance the knowledge of tribology among technical personnel in industry, to foster tribology R&D involving industry, and to improve the transfer of existing technology in this area to Canadian industry.

Recommendations

The strategy proposed is a co-ordinated effort directed at the simultaneous promotion of:

- tribology R&D in industry
- collaboration between industrial and non-industrial R&D organizations and laboratories, strengthening the connection between basic research, applied research, and implementation in tribology R&D
- technology transfer and information services focussed on the requirements of industry
- basic research in tribology
- education and training in tribology

Each recommendation is for a separate activity, involving different agencies or fitting different types of funding programmes. The recommendations are, nevertheless, considered a package, with the parts relating to each other. Co-ordination is advisable for the package to form a coherent strategy.

Clearly there are a number of government ministries and agencies which should and must have a role in the implementation of these recommendations, both in terms of the promotion of a national policy and in the funding and execution of particular programmes. These ministries and agencies include:

Agriculture Canada
Energy Mines and Resources Canada
Ministry of State for Science and Technology
National Defence
National Research Council Canada
Natural Sciences and Engineering Research Council of Canada
Regional Industrial Expansion
Science Council of Canada
Transport Canada

as well as several crown corporations.

Some of the recommendations identify particular agencies as potential participants. Others are directed at "relevant agencies", in the expectation that the appropriate laboratories, industrial organizations or companies, which will be key players, will be encouraged to take advantage of existing government funding programmes under which the recommendations can be implemented. It is also important that the relevant agencies recognize the urgent need to initiate measures which will promote tribology R&D, including increasing the human resources required, all the more so at a time of general economic difficulties and increasing exposure of industry to competition on technical as well as economic fronts.

Many of the recommendations focus on the contribution government agencies can make to foster tribology R&D and related activities, and a detailed argument is made in this report for government involvement in the promotion of this generic technology. Nevertheless, there has to be a corresponding initiative from industry and from agencies outside government, including universities, if there is to be progress in this area.

Industrial promotion of R&D in tribology and increased industrial involvement in programmes in this area will indeed be crucial if Canada is to keep pace with developments elsewhere in tribology technology.

Budget estimates, where appropriate, for government agency contributions and involvement in the implementation of some of the recommendations, are provided.

The Committee make the following ten recommendations:-

1. <u>Strengthening of Industrial R&D in Tribology</u>

   It is recommended that industry enhance its R&D efforts in tribology, taking full advantage of its own resources, industrial support programmes and support available through unsolicited proposals made to government.

2. Joint Government-Industry Support of "Mission-Oriented" R&D Programme in Tribology

It is recommended that a programme be developed to promote R&D, focussed on strengthening the connection between basic research, applied research, and R&D implementation, in tribology, by fostering collaboration in this area between industry and non-industry R&D establishments.

Specifically, it is recommended that the appropriate government agencies use existing funding mechanisms and take any other initiative necessary to promote an R&D programme in tribology to encompass projects proposed, upon solicitation, jointly by industry (one or more companies) and at least one other R&D partner (federal or provincial government laboratory, research association, university).

3. Strengthening of Consulting Services in Tribology

It is recommended that the National Research Council Canada and Atomic Energy of Canada Limited, jointly expand their consulting and contract R&D services to industry in tribology and support an expansion of expert consulting services in tribology, provided by the existing community of engineering and science consultants.

4. Human Resource Development

It is recommended that undergraduate-, graduate- and continuing-education in tribology be promoted.

Specifically, it is recommended that appropriate government agencies support at least two university centres for tribology, with a focus on graduate study at the masters level and on continuing education. The support should be in the form of contributions to fund the salaries of faculty and technicians devoted to the programme and for the purchase and maintenance of equipment for instructional purposes and for service to industry.

It is recommended that industry support education and training in tribology through all appropriate means, including grants, fellowships, and co-op plans.

It is recommended that university departments of engineering include one or more courses in tribology in their curriculums.

5. Strengthening Contract R&D in Tribology in Universities

It is recommended that the appropriate agencies, encourage and expand the award of contracts and contributions to Canadian universities for R&D in tribology.

It is also recommended that industry increase the placement of contracts with universities for tribology R&D.

6. Strengthening Research in Tribology in Universities

It is recommended that the Natural Sciences and Engineering Research Council (NSERC), through its grants programmes, encourage and expand awards for research in tribology at Canadian universities.

It is also recommended that industry substantially increase its support of tribology research in universities.

7. Strengthening of Information Services in Tribology

It is recommended that the National Research Council Canada develop and maintain information services in tribology directed to the needs of Canadian industry, in the areas of R&D, design, and maintenance, and to the needs of all other participants in tribology R&D in Canada. It is recommended that these services be developed in collaboration with information services in tribology in other countries and in collaboration with the industry groups being served in Canada.

8. Strengthening of In-House Programmes in Tribology in the National Research Council Canada

It is recommended that the current programmes in the National Research Council Canada in tribology R&D be reviewed by an advisory committee, with a view to identifying the additional contributions NRCC is best suited to make in tribology R&D, and to increasing the benefits NRCC can provide in tribology to Canadian industry.

9. Co-ordination of Tribology R&D Programmes

It is recommended that Energy, Mines and Resources Canada and the National Research Council Canada establish a joint interdepartmental committee, with representation from Agriculture Canada, Regional Industrial Expansion, Transport Canada, and any other department involved significantly in tribology R&D.

It is recommended that this committee report to the appropriate Assistant Deputy Minister in each department and the Vice-President (Laboratories) of NRCC, to co-ordinate the implementation of the recommendations on tribology programmes requiring agency funding. This committee should provide for liaison with NRCC's Associate Committee on Tribology (which can act to promote and co-ordinate strategy as indicated in Recommendation 9).

10. Promotion and Review

It is recommended that the National Research Council Canada provide full support for this stategy through its Associate Committee on Tribology (ACOT). ACOT can support the overall strategy by holding conferences and workshops for the review and promotion of tribology and, in particular, for the review of the implementation of the recommendations in this report. It is also recommended that ACOT expand its publication of reviews and other items of information on current tribology technology and tribology R&D. ACOT should provide advice, advisory committees, and hold special meetings, as required.

Further details on these recommendations are given in section 4.

Expansion from the present low level of R&D in tribology

The financial requirements for the implementation of these recommendations are modest (no more than the cost of a few miles of highway or a few city buses). While an expansion in R&D in tribology is urgent, this can only occur effectively and efficiently at a rate determined by the availability of qualified personnel and the interest and involvement of industry and the R&D community. There is a scarcity of technical personnel in this country available for and capable of carrying out R&D in tribology, and of evaluating and implementing existing technology. Furthermore, the existing level of activity in tribology R&D here is low. An expansion of R&D in tribology can therefore only start from a low level. There is much catching up to be done!

These recommendations are formulated with a time frame of about five years in mind. It is envisaged that there will be a review three or four years from now, upon which to base the next stage in this strategy to serve Canadian industry.

Budget estimates for some of the recommendations

Recommendation 2. The budget for a pilot programme for the development of industry collaboration with R&D partners in tribology R&D could be as follows (in $,000) in each of five consecutive years.

Year:	1	2	3	4	5
	500	1,000	1,800	1,300	800

The assumption is made here that each project will last three years and this is an estimate for projects initiated in years 1 to 3. It is also assumed that a programme of this type will be reviewed in years 2 or 3, and extended and expanded with whatever revisions may be required.

The mechanisms by which industrial involvement is obtained, and the technology transferred to industry, should be reviewed with as much care as will be given to a review of the individual projects.

Recommendation 3. A budget for the expansion of the existing centres of expertise in tribology, involving additional organizational, training, and promotional aspects during the first five years is likely to be at least $700,000 a year for three centres. Direct costs and normal consulting fees should be charged to all clients. Government support, as base funding, should remain steady, with the expectation that the income from fees charged to clients increases as the service is established and expands.

Recommendation 4. The budget for each such university centre, for a viable expansion in programme, would be at least $250,000 per year, committed for five years, with continuing support contingent upon review.

Recommendation 7. An information service will require a modest but continuing budget of the order of $150,000 per annum, in addition to income from user fees.

Recommendation 10. Publicity directed at the R&D community and the pertinent industry, as well as communication between participants in tribology programmes, are essential components of a strategy for the promotion of R&D in tribology. The Associate Committee on Tribology has held workshops and conferences over the years and issues a newsletter. These activities will have to be expanded to provide essential support for the recommended programmes. An appropriate budget for the support of a programme of meetings and publicity is $15,000 a year.

In all cases, specific budgets would be negotiated by the parties concerned, from whom the initiative for these programmes will obviously have to come. The estimates given here are merely intended to be illustrative, and are indeed very modest in relation to the potential benefits.

Potential R&D topics in tribology

Appendix 3 contains a list of topics identified by D'Silva et al. [1] for R&D in tribology in transportation, agriculture, pulp and paper, mining, forestry and wood industries, and utilities. These suggestions relate to established industries, for which there is some basis for the estimates of losses and potential savings.

There is some overlap between sectors, particularly with respect to projects concerning transportation equipment, since most industries use mobile equipment.

Another area of general application is R&D to reduce wear due to abrasion and erosion, including the development of abrasion and erosion resistant materials and coatings. It should be noted that what is abrasion or erosion resistant in one situation is not necessarily resistant in another situation, so there is much to be expected from both further detailed study and from the development of new materials and coatings.

In agricultural tillage, abrasion is affected by the chemical composition of the soil and the corrosive effect of fertilizers. Abrasion and erosion at both high and low temperatures is a major factor in bitumen recovery from oil sands in Northern Alberta, occurring in various forms at many stages in the mining, extraction and upgrading processes. A similar statement can be made for most mining operations.

A great variety of abrasion- and erosion-resistant materials are used in industry, or are potential candidates for use, including hard metalic alloys, polymers and ceramics. The current range of research into the wear of these materials and the range of current knowledge in the field is far from commensurate with the range of the applications and operating conditions involved.

Well-established ceramics such as alumina, and many newly developed ceramics, are being used in "high tech" applications as coatings and solid components, for instance in engines operating at high temperatures (and therefore greater intrinsic efficiencies). There are also many applications, some quite new, in established industries, such as mining, and pulp and paper. The tribology for these new applications is a considerable challenge. There is a growing interest in this area in Canada, following developments in other countries.

In the North, transportation (particularly on land and water) and industrial operations constitute, in more than one sense, a frontier involving many aspects of tribology, and should be of particular concern in Canada.

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Note: Some quantities in the tables may differ slightly from the original data so that totals are the exact sum of their addends.

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LIST OF ABBREVIATIONS

SI Prefixes

Symbol	Prefix	Multiplying factor
E	exa	10^{18}
P	peta	10^{15}
T	tera	10^{12}
G	giga	10^{9}
M	mega	10^{6}
K	kilo	10^{3}

SI Units and Units Permitted for Use With SI

Symbol	Name
a	year
d	day
J	joule
m	metre

Currency Units (which may be found combined with SI prefixes)

Symbol	Name
DM	Deutsche mark
£	United Kingdom pound
$	Canadian dollar
$us	United States dollar

General Abbreviations

ACOT	Associate Committee on Tribology (NRCC)
ACS	American Ceramic Society
AECL	Atomic Energy of Canada Limited
Ag	silver
ANL	Argonne National Laboratory (USA)
ASLE	American Society of Lubrication Engineers
ASM	American Society for Metals
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
Au	gold
BMFT	Bundesministerium für Forschung und Technologie (Federal Republic of Germany)
CANMET	Canada Centre for Mineral and Energy Technology (EMR)
CISTI	Canada Institute for Scientific and Technical Information
Cu	copper
CVT	continuously variable transmission

DOE	Department of Energy (US)
DN	duty number (diameter x revolutions per minute)
ECUT	Energy Conversion and Utilization Technologies (DOE)
EHD	Elastohydrodynamics
EMR	Energy, Mines and Resources Canada
FERIC	Forest Engineering Research Institute of Canada
IREQ	Institut de Recherche d'Hydro-Québec
MIT	Massachusetts Institute of Technology
NLGI	National Lubricating Grease Institute
NRCC	National Research Council Canada
NSERC	National Sciences and Engineering Research Council of Canada
NSF	National Science Foundation (USA)
OECD	Organization for Economic Co-operation and Development
Pb	lead
R&D	research and development
SAE	Society of Automotive Engineers
SI	International System of Units
SPE	Society of Plastic Engineers
TMS-AIME	The Metallurgical Society - American Institute of Mining, Metallurgical and Petroleum Engineers
UCLA	University of California in Los Angeles
UK	United Kingdom of Great Britain and Northern Ireland
US	United States (of America)
USA	United States of America
Zn	zinc

1 Introduction

1 INTRODUCTION

Losses to the Canadian economy, amounting to billions* of dollars a year, are caused by friction and wear. While some loss of this kind is often inevitable in mechanical equipment, and mechanical components of electrical equipment, losses due to friction and wear do not always have to be as high as they are.

This report indicates some ways in which these losses can be reduced, through research and development, information transfer, and education. Improvements in this area of technology are imperative in Canada, simply because most major industrial nations are already actively pursuing programmes to reduce friction and wear in industrial processes and products with mechanical components.

The losses due to friction and wear can be direct, e.g. friction causes a loss of useful work, a waste of energy. Indirect losses can be even more important, as the time required for routine maintenance, or to repair a failure due to wear can mean loss of production, far exceeding in value the cost of the critical or failed components. A further consideration is the reliability of manufactured products, which may be a factor in their marketability.

It is not unusual for a particular level of wear or friction in a piece of equipment to be considered "normal". There have been many instances of a reduction in a wear rate from what was considered normal some years previously, and there are instances in which an appreciable reduction has been achieved in friction. Often the achievement has been to reduce friction losses (e.g. by using a lubricant with a lower viscosity) without increasing wear at the same time. There is little justification for assuming that any wear or friction level above zero in a piece of equipment is normal and cannot be reduced by known means, or by further R&D.

A survey conducted by D'Silva et al. of Ontario Hydro Research, for Energy, Mines and Resources Canada, provides an estimate for these losses at about 5 billion dollars per year for several sectors of the Canadian economy [1]. These sectors together account for only about one third of the national energy consumption. Other sectors will also be incurring losses of this type. Regardless of their magnitude, it is clear that the losses to the total economy, due to friction and wear, are much higher than 5 billion dollars annually.

The estimate by D'Silva et al. is in line with estimates derived in studies in the United Kingdom, the United States of America and West Germany, all countries in which major programmes have been sponsored by the national governments, to increase research and development (R&D) in tribology, the science and technology concerned with friction, wear and lubrication.**

*billion = 1000 million
**See appendix 1 for further information on the definition of tribology.

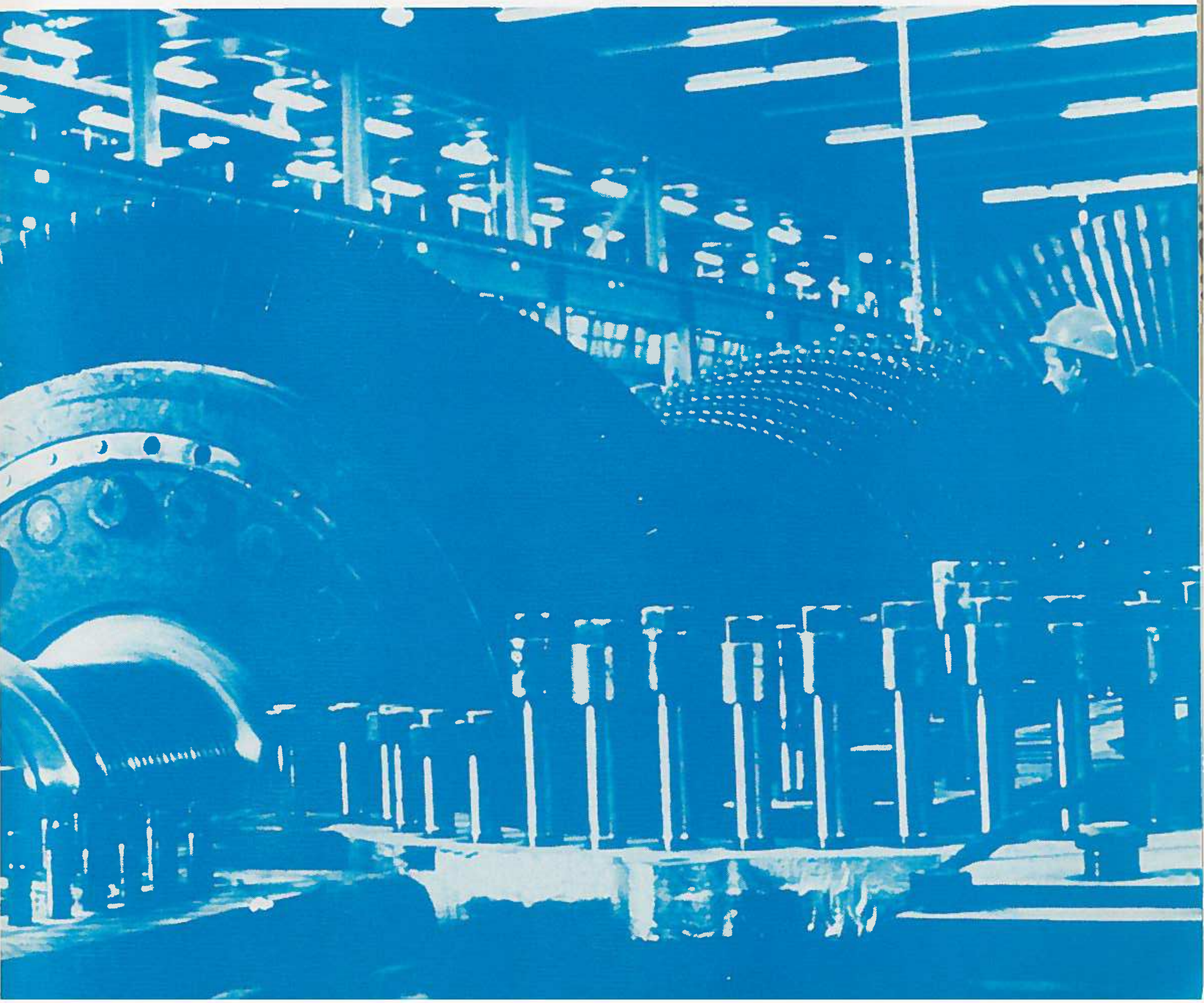
Details of the study by D'Silva et al. and some information from the studies in other countries are included here. With this background, and other material, suggestions are presented for enhanced R&D in tribology in Canada, involving government and the pertinent industries.

In part, these suggestions reflect concerns with traditional technologies of the established industries, particularly in the resource sector. They also relate to newer "high technology" industries, such as those employing numerically controlled equipment. The considerable complexity and cost of many such devices lead to increasing demands on the reliability and precision of the mechanical elements of these items. Sophisticated equipment is of no value when it breaks down, however small or "low tech" the failed component! Special demands in many new technologies are indeed creating corresponding high technology requirements in materials and coatings for bearings and other tribological components.

Particular attention is given in this document to industries which loom large in the Canadian economy. D'Silva et al. provide a guide to the sectors most relevant in this regard. It is also important that advantage is taken of Canadian opportunities in some emerging new technologies. The importance of tribology in new technologies cannot be determined from statistics of friction and wear losses in existing equipment. The main concern is the reliability required. The viability of Canadian industry is a primary objective. It must also be recognized that technology transfer is facilitated if it is a two-way business, so there has to be R&D in Canada, not onlyto advance technology directly, but also to facilitate technology transfer. International links are essential, particularly in the R&D community.

The Associate Committee on Tribology (ACOT) of the National Research Council Canada has benefitted from other input, particularly from a workshop held by ACOT, with representatives of industry, government and universities, at Montebello, Quebec, November 14-16, 1984 [2] to review the report by D'Silva et al., along with major presentations from leaders in tribology in the UK, USA and West Germany on the programmes in those countries.

2 Losses Due to Friction and Wear



2 LOSSES DUE TO FRICTION AND WEAR

2.1 Studies from Outside Canada

2.11 Summary and discussion of two UK studies

At the end of 1964, the Minister of State for Education and Science in the United Kingdom invited Mr. H. Peter Jost to consider, in consultation with other experts in lubrication engineering, the position of lubrication education and research in that country and to give an opinion on the needs of industry in this field.

The following is an excerpt from the text of Appendix 10 of the report of the working group [3], which deals with their estimates for the UK for the conditions and values in 1965:

> Estimates of the Effect of Improved Tribology on the National Economy
>
> . . . .
>
> Because of varying factors and conditions which make an accurate overall assessment of such potential savings difficult, a conservative approach was adopted by the Working Group in establishing the above estimates, although it was recognised that this was likely to result in an undervaluation of the potential savings.
>
> (a) Reduction in Energy Consumption Through Lower Friction
>
> Some 40,000 million Kwh. of electrical energy are used each year in the U.K., for driving machinery; the experts agree that about a third of this is lost in unnecessary friction. Assuming an industrial tariff of 1d./Kwh., this loss represents about £56 million per annum. In the considered opinion of the Working Group improved lubrication (Tribology) could save 25 per cent. of this loss, say £14 million. In addition thereto reduction in friction of internal combustion engines and of the items they drive, could effect savings of an equal amount, so that on these counts alone £28 million per annum might be saved.
>
> (b) Reduction in Manpower
>
> The greatest savings under this heading will be achieved by better tribological design, thus reducing the requirements of present operational manpower.
>
> In addition labour could be saved by the use of bulk, automatic and centralised oil and grease systems. Their effect would be greater in a large steel rolling mill with many thousands of bearings, readily adaptable for automatic and centralised lubricant application, than in machine shops with many hundreds of separate

machines. However, even in the latter case, labour might be saved by the introduction of mechanical bulk handling and distribution schemes.

Larger companies could save £10,000 or £20,000 a year; smaller companies much less and some, where lubrication does not demand any type of specialised treatment, negligible amounts only. An anticipated saving of £10 million per annum on a national basis is considered to be a reasonable estimate under this heading.

(c) Savings in Lubricant Costs

The total value of industrial lubricants sold in the U.K. is approximately £50 million per annum. Savings by better lubrication design, and better lubrication practices, e.g. better house-keeping, rationalisation of lubricant grades, improved circulation systems, and filtration, giving longer oil operating life, have been reported which — on a national basis — would be of the order of 20 per cent., say about £10 million per annum.

(d) Savings in Maintenance and Replacement Costs

The estimated total cost to the country of maintenance and replacement parts was calculated to be in the order of £800-£1,200 million per annum.

After consultation with a number of industrial concerns as well as with experts of the enquiry, the proportion by which maintenance and replacement cost could be reduced through improved tribological design and practice was assessed to be in the region of 20 per cent., equivalent to an annual saving of £160-£240 million.

Comparison can be made between this estimate and similar economies referred to in a paper by M. Baier*, in which savings of approximately £100 million were estimated to accrue in East Germany in respect of these items. On that basis, the equivalent figure for this country would be in the region of £300 million per annum.

Another comparison can be made by relating the total savings to those of the Steel Industry. By a process of extrapolation of figures actually recorded after a period of two years, approximate savings in this sphere within the East German Steel Industry of £3 million per annum were reported to accrue. At the rate of crude steel making capacity of the U.K. Steel Industry, these approximate savings would amount to £21 million per annum. This value compares

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* M. Baier: "Technical and Economic Problems of Lubrication in Industry", Institute of Economy in Engineering, Technical University, Dresden.

with the savings of £20 million per annum for the British Steel Industry obtainable after 5-7 years, as estimated by the Working Group.

On the basis of rating of output of all U.K. industries to that of the Iron and Steel Industry in the U.K., the estimated savings under this heading would be approximately £300 million per annum.

Whilst, in the light of the present investigation, the East German estimates appear reasonable, a more conservative method of assessment was adopted by the Working Group, although this may have led to deflated figures of savings being established.

Therefore the savings under this heading are estimated to be half-way between £160 million and £300 million, i.e. £230 million per annum.

(e) Savings of Losses Consequential upon Breakdowns

The consequential loss, including the cost of lost production caused by breakdowns and stoppages due to tribological causes can be extremely high. In the case of a modern strip mill of an integrated and balanced production steelworks, the loss for each minute might cost several hundred pounds.

In the case of a particular failure of a large turbo-alternator set, the cost of the repair may amount to £10,000 whereas the cost of the outage of the machine may exceed £330,000.

A calculated example of typical cost to a large airline operator of a bearing failure showed that whereas the cost of the bearing amounted to a few hundred pounds only and that of the engine repair to approximately £9,000 the consequential losses arising from the bearing failure would probably add another £18,000 to the bill to be borne by the airline.

When viewed on a national basis, the high consequential-loss-to-repair-cost ratio is considerably reduced by those industries in which spare capacity or standby machines are available. Taking this into consideration, the total savings in consequential losses obtainable through improved tribological design and practices was assessed to be at a level of approximately £115 million per annum.

(f) Savings in Investment due to Higher Utilisation Ratios and Greater Mechanical Efficiency

There was ample evidence to demonstrate that good tribological design and practices result in substantial savings under this heading.

Reports were received on the estimated unnecessary expenditure of approximately £1 million due to tribologically faulty-bearing design on one type of electricity generating equipment (a percentage of energy to drive the generating set being used in order to overcome that portion of the friction which could have been obviated by correct tribological design), and on an ore preparation plant where thorough attention to the question of wear and friction resulted in remedial action which in turn increased plant availability to an extent as to allow the closing down of a quarter of the particular plant. Nevertheless, there are some difficulties in making an accurate overall estimate of the savings under this heading. These difficulties increase when the savings in standby equipment, no longer required because of sound tribological design, are taken into consideration.

On the basis of an annual investment in machinery and plant of £2,200 million and allowing a saving of 1 per cent. thereof, a figure of savings of £22 million per annum would accrue.

(g) Savings in Investment through Increased Life of Machinery

One of the immediate consequences of improved lubrication (Tribology) design, the use of newer materials of construction, the use of surface treatments, etc., is reduced wear and thereby longer machinery life; saving in wear must mean saving in costs.

The investment in capital equipment and parts thereof, was calculated to be approximately £2,200 million per annum. Assuming that improved tribology in design and maintenance would increase the life of such machinery by one year in ten, but taking into consideration that an estimated 50 per cent. of such plant will require replacement due to obsolescence, the saving of investment per annum under this heading would be £100 million.

Conclusions and Summary

The above estimated savings within individual headings can be summarised as follows:

	Estimated Savings	£ Million p.a.
(a)	Reduction in energy consumption through lower friction	28
(b)	Reduction in manpower	10
(c)	Savings in lubricant costs	10
(d)	Savings in maintenance and replacement costs	230
(e)	Savings of losses consequential upon breakdown	115
(f)	Savings in investment due to higher utilisation ratios and greater mechanical efficiency	22
(g)	Savings in investment through increased life of machinery	100
		515

This summary shows that the most significant items constituting the total cost savings fall under the three headings of (d) Replacement parts and maintenance; (e) Consequential losses; and (g) Investment costs. Variations in the estimates of these three items affect the total more than the other items.

The total inaccuracy of the above is estimated to be no greater than 25 per cent., however, even if the inaccuracy in the estimates were 50 per cent. such differences would not materially alter the significance of the savings; these are, and remain, of a magnitude warranting thorough attention to and treatment of the subject of Tribology.

In 1981 Dr. Jost and Dr. Schofield presented the James Clayton Memorial Lecture on "Energy Saving through Tribology..." in which they tried to determine whether tribology can play a significant part in energy conservation in the United Kingdom [4]. The evidence considered in that study led to the conclusion that the application of tribological principles and practices could produce energy savings of considerable magnitude in the UK. Although only the major part of the users of 87% of Britain's energy were considered, the savings were estimated to be between 468 - 700 million pounds per year as in Table 2.01, assuming a 20% overlap. The transportation sector accounted for 56% of this figure, but the authors expect additional savings in that sector of about 350 - 900 million pounds per year in 1980 values, as the vehicles which existed then are replaced with ones using more effective transmissions and so on. These savings were expected to be obtainable within seven years by applying existing tribological knowledge including some of the most elementary kind and by performing medium term R&D in areas of high cost effectiveness, using resources of about 12 million pounds over a period of five years. Possible and significant savings due to improved tribology could range anywhere from simple prevention and reduction of "design induced or assisted" wear to the application of results of advanced technology, obtained by sophisticated R&D.

It was indicated that there is a lack of awareness of the role of tribology in the area of energy conservation. In contrast to their awareness of thermal factors, in the UK neither manufacturers nor users of equipment, nor the government, nor the professional bodies had fully identified the part that tribology could play in energy savings, and in savings to the economy in general. It was stated that significant and considerable savings could be obtainable, not only from reduced friction, but even more so from reduced wear and the reduction in consequential damages from wear.

The benefits of direct saving of energy through reduced friction are frequently only a small portion of the total potential savings that can be made through tribology. Energy saved by not having to make spare parts, and savings in materials needed to make the spare parts, and other advantages, such as better efficiency and more compact machines, derived from tribological considerations, could often outweigh the direct saving of energy.

TABLE 2.01

SUMMARY OF ESTIMATED ENERGY SAVINGS THROUGH TRIBOLOGY
1980 Values

(a) Transport sector	332 - 501 M£/a
(b) Industrial sector	173 - 253 M£/a
(c) Domestic sector	80 - 120 M£/a
	585 - 874 M£/a
Less: Overlap factor of 20 per cent (since not all savings are additive, an overlap factor has to be applied, which the US Report found to be of the order of 20 per cent.)	117 - 174 M£/a
Total estimated savings (after overlap adjustment)	468 - 700 M£/a

Estimated R & D effort in selected areas

(a) Transportation	7.2 M£	
(b) Industry	5.1 M£	
Total	12.3 M£	spread over 5 years

(Adapted from Jost and Schofield [4])

Since tribology is a generic technology, there is a duty for the state to intervene in the fields of motivation, education, training, and communication. What is meant by generic technology, is one yielding national benefits, which are very large, but which are spread, often thinly, over a large number of recipients, possibly making the benefits to an individual, or firm, or even an industry sector, quite small. If this duty were to be met, a major part of the savings through improved tribology could be achieved. In partial satisfaction of this end the UK government has founded three centres of tribology: one at Risley, Lancashire; one at Leeds, Yorkshire; and one at Swansea, Glamorgan. In this context the authors did not mention the National Engineering Laboratory in East Kilbride, which serves a somewhat similar function.

In the view of Jost and Schofield, tribological knowledge and improved practice should be able to effect an improvement in other energy consuming groups in the UK, including agriculture, which consumes one percent of that country's energy. [By contrast, in Canada, agriculture consumes about three percent of the total energy, and therefore has more significant frictional losses relative to the economy as a whole, assuming that the proportion of losses due to friction is about the same in both countries.]

Several important recommendations relevant to the Canadian situation were made in the Clayton lecture. Among these are:

a) industry should make a conscious effort to ensure that people responsible for designing, manufacturing and operating plant and machinery, are trained in energy and materials aspects of tribology;

b) industry should be encouraged to expedite its R&D effort in areas where large energy savings can be made, particularly in the transportation sector;

c) bodies responsible for education in energy conservation should ensure that tribology is included in all appropriate educational activities;

d) an education and training programme should be sponsored to produce tribology expertise at craft, technician and technologist levels with emphasis on the energy savings aspects of tribology;

e) new official standards should be set up to save energy and reduce design assisted wear;

f) a government research agency should extend its R&D funding of tribology to energy conservation;

g) the professional institutions in conjunction with other bodies, should identify and help to fund cost-effective R&D areas in tribology;

h) the professional institutes should arrange symposiums and conferences on various aspects of energy saving through tribology;

i) the government should fund US-style workshops;

j) the government should take part in investigations leading to joint research projects in topics in which significant economic savings through tribology can be made;

k) the government should organize the collection and dissemination of statistical data related to energy savings through tribology.

In the opinion of Jost and Schofield the application of tribological knowledge and some R&D effort could lead to savings in the region of 470 to 700 million pounds annually.

2.12 Studies from the United States of America

The American Society of Mechanical Engineers (ASME) Research Committee on Lubrication was organized in 1915 in order to propose, promote, obtain support for, and coordinate ASME sponsored research in the field of lubrication, and to interpret and disseminate the results for practical application. In 1976, the committee initiated work on the preparation of an R&D plan aimed at achieving energy conservation through tribology. This work,

TABLE 2.02

ENERGY CONSUMED AND REJECTED IN THREE PRODUCT AREAS (1975)

	EJ		% US Energy Consumption	
Product	Consumed	Rejected	Consumed	Rejected
Automotive Vehicles	13.3	10.0	19.5	14.5
Steam Electric Power Plants	17.4	11.4	23	15
Primary Metals and Metals Processing	4.1	?	5.5	?

(Adapted from ASME [6])

which was funded by the US Department of Energy, resulted in a report published in 1977 [5], which was revised in 1982 [6].

The estimated potential for savings in energy due to progress in tribology in the four major areas is illustrated in Table 2.03 adapted from the ASME report. The estimated total of a 5% saving in annual US energy consumption is equivalent to over 21 billion US dollars. This potential saving assumed that the R&D plan would stimulate and complement parallel work elsewhere; that the plan would be technically successful; and that the research results would be adopted and implemented commercially. In each of the four areas, specific research projects were formulated including objectives, technical background, work statements, estimated savings, cost, and priority. The research committee considered a wide variety of potential R&D programs. While it perceived the reduction of friction and wear as the most visible and immediate gain to be achieved, the committee also saw far-reaching indirect benefits from improvements such as more efficient thermal cycles by incorporating a higher temperature capability, reduced down time, lower weight, more compact machines, and longer life of capital equipment.

The major goals that the research committee wishes to see accomplished are:

A. Road Transportation

- Continuously Variable Transmission - to make the automotive engine run always near its maximum efficiency and permit the use of brake energy storage systems.

- Piston Rings - to minimize the frictional losses between pistons and cylinders.

TABLE 2.03

OVERVIEW OF REVISED ASME TRIBOLOGY R&D PLAN (1980 US DOLLARS)

		Potential Energy Savings			
Program Area	Type of Energy Used	% US Consumption	G$us/a	Estimated R&D Cost M$us	Benefit* Ratio
Road Transportation	Oil	2.2	8.9	16.1	55
Power generation	All Types	0.2	0.9	3.2	30
Turbomachinery	All Types	1.1	4.4	7.8	57
Industrial Machinery and Processes	All Types	1.8	7.2	7.6	93
TOTAL		5.3	21.4	34.7	62

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

(Adapted from ASME [6])

- Adiabatic Diesel - to eliminate, or at least minimize, the need for engine cooling and thus achieve a significant improvement in thermal cycle efficiency via engine redesign.

- Low Viscosity Engine and Axle Lubricants - to save energy through reduced internal friction.

B. Power Generation

- Low Friction Bearings - to reduce the high losses in the large turbulent bearings of electric utilities.

- Gas-path Seals - to reduce loss of working fluid past labyrinth seals by using active control to permit reduced clearances.

C. Turbomachinery

- Power generation goals apply here also.

- High Speed (>3 million DN) Rolling Element Bearings - to make possible more compact, more efficient turbines and compressors.

- Process Fluid Bearings - to facilitate the use of the process fluid as a lubricant, an item of growing importance in the energy recovery machines of the future.

- Gas-path Seals - to reduce working fluid loss via use of abradable blade tips and shrounds and via active control of blade tip clearance.

D. Industrial Machinery and Processes

- Friction and Wear Mitigation - by aiding the designer in the selection of appropriate bearing material pairs and lubrication systems for low friction and long life.

- Metal Processing - to minimize metal removal and metal shaping energy costs by applying tribological concepts to metal rolling, forming, warm working, hot working and near-net-shape forming processes.

Each of these programmes is summarized in Table 2.03 with respect to estimated cost and potential energy savings. These four programs, which offer a potential saving of over 21 billion in terms of 1980 US dollars, are estimated to cost 35 million US dollars. This does not include the cost to industry of incorporating the improvements indicated by the R&D work. The proposed programmes and expenditures were not meant to be the sole driving force behind the 5% energy conservation potential, but were meant to stimulate research, complement ongoing work, and offer a framework which could be modified and expanded in the course of its implementation. Moreover, the R&D plan could be formulated for 5 or 6 years only. The committee expected to have to change and expand the plan beyond that period, in accordance with subsequent developments.

The committee believed that funding of the recommended R&D plan and implementation of its findings would offer the potential of conserving over 5% of US energy consumption. Relative to the 1980 energy expenditure rate based on oil at 190 US dollars per cubic metre, this represents a saving of over 21 billion US dollars per annum, or about 300 000 m^3/d of oil. Not included in these figures was the payoff in the areas of raw material usage, manufacturing costs and so on, which utimately translates into substantial additional savings of energy and other national resources.

Although oil prices have been driven below 60 US dollars per cubic metre recently, which translates into a monetary saving of about seven billion US dollars per year, this still represents a substantial amount of money. Lower energy prices do not alter the fundamental nature of the arguments presented, but they do oblige planners to be very careful in their choice of R&D projects, particularly those directed at achieving energy savings.

2.13 An estimate of the savings to the Canadian economy, derived from studies in other countries

If we consider the Jost report [3], the Clayton lecture [4] and the ASME report [6], we can make extrapolations to the Canadian situation from estimates of savings due to improved tribology made in these reports. The report by D'Silva [1] does exactly this, and uses the following methodology to do so.

Each of the three reports estimated losses in a number of different industrial sectors. For each report and each sector, a factor was calculated that relates the indicated savings to data relevant to the whole sector. This factor was then applied to the equivalent Canadian data for each sector.

The procedures for estimating the savings are given in Appendix 2.

Improvements in technology may have occurred in Canada in the period since the reports were published, especially the Jost report [3], published in 1966, but to simplify matters, no correction for this purpose was applied to the data from these reports. As a result, some of the estimates extrapolated from the foreign studies may be too high, because some of the developments from the UK and the US would already be incorporated in Canadian practice. Where figures were calculated on an energy basis 10 $/GJ was used for transportation and 5.35 $/GJ for the other sectors.

Table 2.04 shows the calculated saving for the 1982 Canadian economy based on each of the three reports.

TABLE 2.04

ESTIMATES OF POSSIBLE SAVINGS TO THE 1982 CANADIAN ECONOMY THROUGH IMPROVED TRIBOLOGY BASED ON THREE FOREIGN REPORTS

REPORT	TYPE OF SAVING	R&D REQUIRED	CANADIAN SAVING
Jost Report (1966)	Direct Energy, Materials, manpower etc.	Some R&D	4.7 G$
Jost and Schofield (1981)	Direct and indirect energy	Short to long term R&D	889 to 1348 M$
ASME (1981)	Direct Energy	Long-term R&D	2.3 G$

Assuming that this approach is valid, in 1982 between 0.9 and 4.7 billion dollars were lost in energy and materials in the Canadian economy through friction and wear. The estimates from which these extrapolations were made differ not only in the type of savings reported, but also in the economic sectors considered. For example, one report considered only energy, while another took energy, manpower, materials and investment into account. A satisfactory rationalization of these differences would be difficult to achieve, and D'Silva et al. considered it beyond the scope of their report.

The conclusions from the Jost report, applied to Canada are shown in Figure 1. The biggest item is the combined savings in maintenance costs, replacement cost and losses consequential upon breakdown. The second biggest item is savings in capital investment due to higher utilization ratios, greater mechanical efficiency and increased life of machinery. The Jost report is the only one of the three reports to deal with these aspects of the savings.

The same kind of treatment of the Clayton lecture and the ASME report is shown in figure 2. These relate only to energy savings through tribology. Both studies, whether extrapolated to Canada or not, ascribe the biggest potential for savings to the transportation sector. In Canada the transportation sector is somewhat more important and the industrial sector is somewhat less important than these sectors are in the UK and USA, a not altogether surprising circumstance given Canada's large area-to-population ratio.

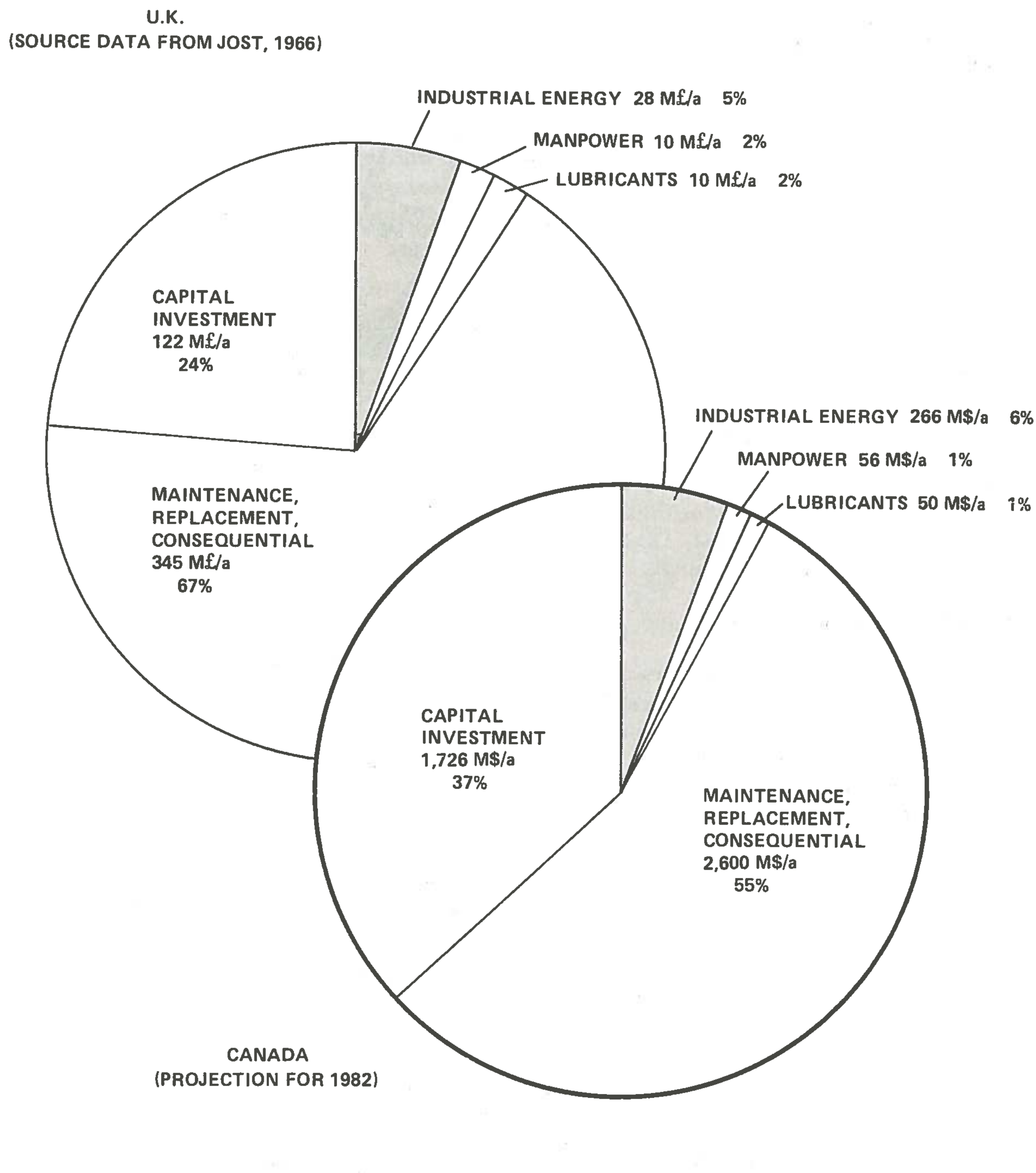


FIG. 1: REDUCTION THROUGH TRIBOLOGY, OF LOSSES DUE TO FRICTION AND WEAR
PROJECTIONS FOR CANADA IN 1982 CANADIAN DOLLARS FROM U.K. STUDY OF 1966

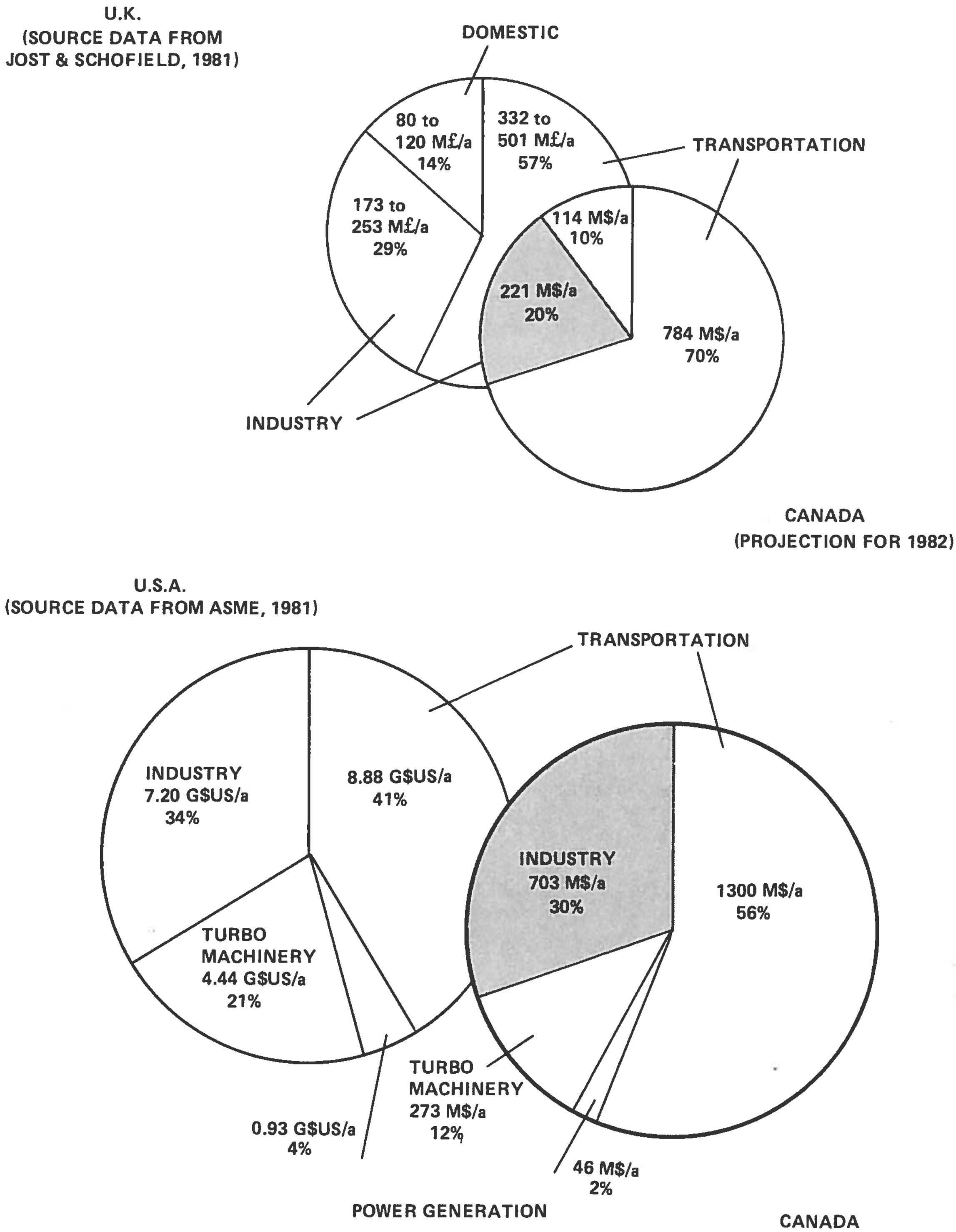


FIG. 2: REDUCTION OF ENERGY LOSSES THROUGH TRIBOLOGY
PROJECTIONS FOR CANADA IN 1982 CANADIAN DOLLARS FROM U.K. AND U.S.A. STUDIES OF 1981

2.2 Canadian Study

2.21 Sector selection

On the basis of energy costs, maintenance expenditures and other considerations, D'Silva et al. selected Canadian economic sectors which were believed to suffer the most significant losses due to friction and wear [1]. Some of the other considerations were the uniqueness of the economic sector to Canada and whether tribological problems were a significant cause of the viability of the sector in Canada.

2.211 Energy Use

Of the main energy using groups in Canada (Table 2.05), industry consumes 26% of the total energy; transportation, 24%; residences, 18%; commerce, 14%; electric utilities, 13%; and the remainder, 5%. The intention is to select groups where the impact of the savings is large and where the implementation of R&D leading to savings is relatively easy.

Within the largest energy using group, industry; the subgroups iron and steel, pulp and paper, mining, and general manufacturing together consume 18% of Canada's energy. Significant tribological losses probably occur in all these subgroups. The chemical industry, although consuming more energy than mining, was thought to be unlikely to provide significant opportunities for tribological savings since energy would be used here mainly for process heat.

The transportation sector is associated with large tribological losses [6], and within that sector, vehicles obtaining fuel from retail pumps account for 16% of Canada's energy consumption. The other five transportation subsectors together consume only half of that.

Agriculture which extracts only 3% of Canadian energy consumption, is a moderately attractive sector for investigation due to the severe environment in which the machinery and equipment operate. The following list, based on energy consumption, shows where the maximum potential for energy savings through the application of improved tribology is thought to lie.

CATEGORY	PERCENTAGE OF NATIONAL ENERGY CONSUMPTION
Pulp and Paper	5
Iron and Steel	4
General Manufacturing	7
Mining	3
Retail Pump Sales	16
Agriculture	3

TABLE 2.05

FINAL ENERGY USERS IN CANADA

1982

	ENERGY (PJ)	% OF TOTAL
INDUSTRY		
Forestry	22	0.3
Construction	38	0.6
Pulp and Paper	305	4.7
Iron and Steel	243	3.7
Smelting and Refining	155	2.4
Cement	44	0.7
Petroleum Refining	51	0.8
Chemicals	221	3.4
Other Manufacturing	436	6.7
Iron Mining	35	0.5
Other Mining	183	2.8
TOTAL INDUSTRY	1 733	26.6
TRANSPORTATION		
Railways	84	1.3
Airlines	119	1.8
Marine	112	1.7
Pipelines	79	1.2
Road Transport Fleets	151	2.3
Retail Pump Sales*	1 029	15.8
TOTAL TRANSPORTATION	1 574	24.1
AGRICULTURE	174	2.7
RESIDENTIAL	1 144	17.5
PUBLIC ADMINISTRATION	142	2.2
COMMERCIAL AND OTHERS	908	13.9
ELECTRIC UTILITIES	851	13.0
TOTALS	6 526	100.0

* Vehicles using fuel from retail outlets.

2.212 Repair Expenditure

A further manifestation of the loss caused by inadequate tribological practice is maintenance cost. Expenditures on both purchase and repairs of machinery and equipment are available from Statistics Canada [7].

TABLE 2.06

REPAIR AND CAPITAL EXPENDITURE COSTS
FOR MACHINERY AND EQUIPMENT IN CANADA FOR 1982

	Capital Expenditure M$	Repair Expenditure M$
ALL SECTORS		
Agriculture and Fishing	3 070	1 152
Forestry	61	216
Mining, Quarrying & Oil Wells	1 963	1 875
Construction	1 074	820
Manufacturing	8 352	3 963
Utilities	7 626	3 949
Trade	1 200	254
Finance, Insurance & Real Estate	526	106
Commercial	3 262	421
Institutions	638	152
Government	1 098	360
TOTALS	28 870	13 268

Clearly, repair expenditures are not due exclusively to lubrication and wear problems, however high repair costs in certain sectors should contain a proportionate amount of loss due to wear. A high ratio of repair to capital expenditure is a further indication of excessive maintenance costs. Forestry invests 3.5 times as much on repair as on capital equipment, but the total amount is small compared to the repair expenditure of manufacturing or utilities.

Considering both the magnitude of repair costs and the ratio of repair to capital expenditure as shown in table 2.06, the major sectors are:

UTILITIES
MANUFACTURING
MINING, QUARRYING AND OIL WELLS
FORESTRY
CONSTRUCTION
AGRICULTURE AND FISHING

TABLE 2.07

BREAKDOWN OF CAPITAL AND REPAIR EXPENDITURES FOR UTILITIES IN 1982

UTILITIES	Capital Expenditure M$	Repair Expenditure M$
TRANSPORTATION		
Air Transport	610	405
Railways	346	1 108
Water	421	176
Motor Transport	198	410
Urban Transit	211	184
Pipelines	86	23
Capital items charged to operating expenses	54	-
TOTALS	1 926	2 306
MISCELLANEOUS UTILITIES		
Grain Elevators	59	38
Electric Power	3 271	468
Gas Distribution	99	20
Others	50	38
TOTALS	3 479	564

Utilities, manufacturing, mining and agriculture are most susceptible to tribological failures. The first three of these major sectors are divided into subgroups in Tables 2.07 to 2.09. Attention was focussed on the four subsectors with the highest repair expenditures. Primary metals together with paper and allied industries have high repair expenditures in the manufacturing sector (Table 2.08). Although all the mining groups have large repair costs (Table 2.09), iron mines are the most significant and have problems that would be representative of most types of mining. Within this framework, the following list indicates where the greatest potential for improvement in material and energy consumption is thought to exist through improved tribology:

TRANSPORTATION
- Rail
- Motor transport.

MANUFACTURING
- Primary metals
- Paper and allied industries

MINING
- Iron mines

AGRICULTURE

The sectors selected for survey were:

PULP AND PAPER
WOOD INDUSTRIES
FORESTRY
IRON AND STEEL
TAR SANDS
OTHER METAL MINES

RAIL TRANSPORT

ROAD TRANSPORT
- i) urban (trucks and buses)
- ii) manufacturing

AGRICULTURE
ELECTRIC UTILITIES

These sectors were surveyed to determine awareness of potential savings through tribology and to help identify companies and personnel possessing the necessary information to assess R&D requirements for tribology in Canada.

TABLE 2.08

BREAKDOWN OF CAPITAL AND REPAIR EXPENDITURE FOR MANUFACTURING IN CANADA FOR 1982

	Capital Expenditure M$	Repair Expenditure M$
MANUFACTURING		
Food and Beverages	626	330
Tobacco	37	19
Rubber	234	118
Leather	8	7
Textiles	139	77
Knitting Mills	13	6
Clothing	15	7
Wood	211	231
Furniture	23	12
Paper and Allied Industries	1 534	835
Printing	142	39
Primary Metals	966	977
Metals Fabrication	202	143
Machinery	186	63
Transportation Equipment	499	248
Electrical Producers	260	81
Non-Metallic Materials	149	197
Petroleum and Coke Produders	292	77
Chemical and Chemical Producers	1 632	464
Miscellaneous	64	33
TOTALS	7 232	3 964

TABLE 2.09

BREAKDOWN OF CAPITAL AND REPAIR EXPENDITURE
FOR MINING, QUARRYING AND OIL WELLS IN CANADA FOR 1982

	Capital Expenditure M$	Repair Expenditure M$
MINING		
METAL		
Gold	79	46
Iron	47	297
Cu, Au, Ag	74	210
Ag, Pb, Zn	68	114
Others	153	139
TOTALS	421	806
NON-METALS		
Asbestos	9	56
Others	552	353
TOTALS	561	409
PETROLEUM	981	660

2.22 The preliminary survey

2.221 The Questionnaire

D'Silva et al. [1] designed a questionnaire and distributed it to approximately 230 companies representing various sectors of the Canadian economy. About 90% of these went to individual companies and associations representing the selected sectors, the other 10% were sent to companies outside the selected sectors, as a basis for comparison. In addition, a different questionnaire was sent to thirteen trade assocations.

Table 2.10 shows the distribution of questionnaire blanks sent and completed questionnaires received among the different sectors.

TABLE 2.10

DISTRIBUTION OF QUESTIONNAIRES ON A SECTOR BASIS

	NUMBER DISPATCHED	NUMBER RETURNED	% RETURNS RECEIVED IN CATEGORY
MANUFACTURING Wood industries Pulp and Paper Iron and Steel General manufacturing	90	38	42%
TRANSPORTATION Rail Air Urban	30	4	13%
MINING Iron Tar Sands Other Mines	57	18	32%
MISCELLANEOUS Forestry Agriculture Electrical utilities Others	53	14	26%
TOTAL	230	74	32%

2.222 Awareness of Tribology

The survey showed that 77% of the respondents were aware that friction and wear could be reduced in their present equipment, and 80% thought that R&D could further reduce these losses. Seventy-two percent thought that their equipment could be improved by both current information and more R&D, which is a measure of the awareness that there is a potential for reduction in friction and wear in present equipment. About 35% were aware of the scale of potential savings in maintenance costs and downtime, but only 7% thought there were large potential savings in energy consumption. Only 15% were able to make any estimate of wear losses. During the company visits which followed the preliminary survey, none of the personnel interviewed were able to estimate frictional losses.

In summary, most respondents were aware that friction and wear could be reduced, although very few were aware of the scale of potential savings.

2.23 Site visits

2.231 Methodology

Of the questionnaires returned, 28% indicated a willingness to supply further information, but only 4% of the completed returns demonstrated both the ability of the personnel to comment on tribology and recourse to an adequate level of information. It was necessary, therefore, to select some companies on the basis of recommendations from other sources and to recontact a number of significant companies failing to reply to the original survey. Twenty-six sites were selected for visits (Table 2.11).

TABLE 2.11

VISITS TO SELECTED SITES

Sector	Total	Companies	Institutes and Universities
Pulp and Paper	5	4	1
Forestry and Wood	3	2	1
Agriculture	6	2	4
Mining	3	3	
Transportation	4	4	
Electric Utility	1	1	
Manufacturing (within sectors)	4	4	
	26	20	6

To help with data gathering and analysis, the investigators used a standard prompt-type form, and, when permission was granted, supplemented this with tape recording.

2.232 Estimate of Tribological Losses

One indicator of tribological losses due to wear in Canada is the annual repair expenditure [7], table 2.06. Repair expenditures can result from non-tribological causes such as overloading, misuse, theft, and disasters like fire and flood. Some capital expenditure must also be a result of tribological failure. It is reasonable to assume that losses due to wear are somewhat less than the repair expenditures, which are about 13 billion dollars per year in Canada. A fairly large fraction of repair expenditures are probably to correct tribological failures, and this amount would be augmented by a small fraction of the capital expenditures, 29 billion dollars per year, which are also spent to correct tribological failures.

Tables 2.07 to 2.09 show the capital and repair expenditures for various economic sectors in Canada and the relative importance of these has already been discussed in section 2.21. Tables 2.12 to 2.17, which display estimates of losses due to friction and wear in various Canadian economic sectors, are adapted from the corresponding tables in D'Silva et al. [1], and the estimates are theirs. Tables 2.18 and 2.19, which summarize tables 2.12 to 2.17 essentially depend on the data from D'Silva et al.

Pulp and Paper

The losses due to wear in the pulp and paper industry are estimated to amount to some 380 million dollars per year. Important sources of wear in the industry are motor brushes and bearings, and also roll coverings and tires of barking drums. Consequential losses from wear were excluded from the survey, but could be significant: for instance, if a hog fuel conveyor failed, it could cost 200 000 dollars per week to substitute oil for hog fuel; or if a lime kiln failed it could cost half a million dollars per week to purchase the chemicals required instead.

The frictional losses are estimated to be about eight per cent of the total energy used in the pulp and paper industry. This energy is consumed largely in mechanical pulping and in pumping, and is worth about 100 million dollars per year.

Forest Industry

Estimates of the total energy consumed in the forest industry vary. Statistics Canada [8] estimated 26 PJ in 1981 while Ash and Knobloch [9] estimate 44 PJ. The energy usage seems to be declining, Statistics Canada estimates being 22 PJ for 1982 [8], 11 PJ for 1983 [10], and 13 PJ for 1984 [11]. D'Silva et al. estimate frictional losses at 22.9% of the highest figure, representing a monetary loss of about 110 million dollars annually. Refer to tables 2.05 and 2.13.

Some two-thirds of material losses are due to abrasive wear, a consequence of both contamination and inadequate equipment design. Total annual material losses in the Canadian forest industry are estimated to be approximately 160 million dollars, which represents about half the expenditure on maintenance of machinery.

Mining

The estimated wear losses in open-pit mining, milling, refining and tar sand operations are provided in table 2.14. Total material losses were estimated to be about 730 million dollars per year. About 10% of these losses occur in refining, and about the same proportion in the tar sands, whereas about 40% result from open-pit operations, and about the same proportion from milling.

The annual frictional losses are also summarized in table 2.14, and in monetary terms these are estimated at about 210 million dollars or roughly 20% of all the energy consumed in the mining sector.

In tar sands operations severe abrasion and erosion problems are caused during mining and extraction processes by the highly abrasive quartz-particles which make up about 85% of the oil sands. Additionally, operating

TABLE 2.12

ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN THE CANADIAN PULP AND PAPER INDUSTRY

PROCESS	WEAR MECHANISMS						Total Losses due to Wear M$/a	Losses due to Friction M$/a
	Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Other M$/a		
Wood Preparation	80	11	7		3		101	11
Mechanical Pulping	24	1	2			1	28	58
Chemical Pulping	19	1	14			2	36	4
Pulp Handling	4		32				36	
Market Pulp/Paper	17		15	2	6		40	10
Mechanical	8	8		1	3	12	32	
Chemical & Heating & Recovery	44		3			3	50	8
Manufacturing Services	20	14	19				53	14
Lubricants	1	1	1	1	1	1	6	
TOTAL	217	36	93	4	13	19	382	105

TABLE 2.13

ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN CANADIAN FORESTRY

PROCESS	WEAR MECHANISMS						Total Losses due to Wear M$/a	Losses due to Friction M$/a
	Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Chemical M$/a		
Harvesting and Processing	25	7		9	2		43	51
Loading and Transportation	29	6			8	4	47	31
Crew Transportation	25	7			3	2	37	10
Road Construction and Maintenance	12	3					15	19
Other Woodland Operations	10	2		3	1		16	
TOTAL	101	25		12	14	6	158	111

TABLE 2.14

ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN THE CANADIAN MINING INDUSTRY

PROCESS	WEAR MECHANISMS						Total Losses due to Wear M$/a	Losses due to Friction M$/a
	Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Chemical M$/a		
Open Pit	230	10		1	16	1	258	82
Milling	239	1	72		4	11	327	74
Refining	44	3	24		3	4	78	56
Tar Sands	38	1	21		2	1	63	
TOTAL	551	15	117	1	25	17	726	212*

* The figures in this column include an allowance for losses due to friction in tar sands operations.

temperature fluctuations from -40 to +35°C present a unique and difficult lubrication situation and contribute to a reduction in bearing lives in heavy equipment to typically about one-fifth of normal expectancy.

Agriculture

In the agricultural sector, mobile equipment, trucks and automobiles consume about three quarters of all the energy. Tractors and their implements, used for tilling, planting, forage production, harvesting, and processing, absorb about half the energy expended on farms. Frictional losses of internal combustion engines, transmissions, power take-offs and the rolling resistance of this equipment represent an important energy sink in this sector. The total annual loss due to friction amounts to about 320 million dollars.

Table 2.15 shows the cost of the frictional losses and that due to wear. Abrasion, experienced in metal-to-soil, metal-to-grain, and metal-to-metal contact, is the dominant wear mechanism. More than half the material losses can be attributed to mobile equipment. The total losses due to wear were about 940 million dollars in 1982. D'Silva et al. consider this estimate of material losses to be conservative, because both the capital expenditure due to equipment wear and the loss due to grain wear are ignored. They estimate that these losses combined are about 850 million dollars per year.

Transportation

Table 2.16 displays the losses due to friction and wear in the Canadian transportation system. About half the losses due to friction in this sector are due to rail-wheel contact, about one third arise from engines and transmissions, and about one sixth are due to braking.

Of the approximately 470 million dollars for material loss in rail operation each year, about 40% results from rail wear, 15% from wheel wear, 25% from motive-equipment wear and 20% from rolling-stock wear. Half the wear loss in rails is encountered in curves or in short tangent track between curves. Wheel wear is mostly due to brake/wheel contact, but is accelerated by sand impregnating the linings.

In truck and bus operation, tires account for about 40% of the total annual wear losses of about 860 million dollars, engines account for about 25%, brakes and linkages each account for about 15% of the losses. The main mechanism of wear is abrasion; contamination is the main cause of wear in engines.

Electric Power Generation

The total amount of electrical energy generated in Canada in 1982 was 1225 PJ, and of this, 68% was hydraulic, 21% originated from fossil fuels, and 11% came from nuclear energy. The total energy consumed in the conversion of raw energy to electrical energy, excluding thermodynamic losses was 108 PJ. It is estimated that 31% of this was consumed by electric motors in power plants driving boiler feed pumps, condensate extraction pumps, cooling water pumps, forced and induced draft fans, conveyors and similar equipment.

<u>TABLE 2.15</u>

<u>ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN CANADIAN AGRICULTURE</u>

OPERATION	WEAR MECHANISMS Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Chemical M$/a	Total Losses due to Wear M$/a	Losses due to Friction M$/a
Traction	189	57	11	1	25		283	130
Transportation	157	47	9	1	20		234	94
Tilling	32						32	24
Planting	27						27	2
Harvesting	162						162	10
Fodder Production	31						31	5
Miscellaneous	137		34				171	56
TOTAL	735	104	54	2	45		940	321

TABLE 2.16

ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN CANADIAN TRANSPORTATION (ROAD AND RAIL)

		WEAR MECHANISMS						
	Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Chemical M$/a	Total Losses due to Wear M$/a	Losses due to Friction M$/a
Road tires	332	0			16		348	
Railway wheels	26	2			41		69	210
Rails	4	89			104		197	
Engines, motors, generators	164	81			6	32	283	
								135
Transmissions	20	17			28	2	67	
Brakes	161						161	65
Bodies, couplings, linkages	57	41		12		27	137	
Other	35	11		5	8	7	66	
TOTAL	799	241		17	203	68	1328	410

The total frictional losses amount to about 50 million dollars annually. A very important part of this is the 0.5% of turbine-generator output lost at motor bearings which could be greatly reduced by designing rotors with only one bearing each.

The material and frictional losses in electrical utilities are exhibited in table 2.17. The total wear loss in 1982 was some 190 million dollars. The main mechanism of wear was abrasion which was responsible for about one third of the loss. Significant wear losses are attributable to transport and work equipment consisting of road and off-road vehicles such as passenger cars, trucks, brush clearing equipment, tractors, diggers, and cranes, plus devices such as compressors, vibrating compactors, and line stringers.

2.233 Estimate of Potential Savings

Table 2.20 depicts the estimated potential savings due to the reduction of friction and wear through improved tribology. The total annual savings are expected to surpass 1280 million dollars, about one third of which, or 420 million dollars will be due to reduced friction, and about two thirds of which, or 870 million dollars will be due to reduced wear. It is believed that the largest potential savings can be realized from reductions in wear in the transportation sector amounting to about 330 million dollars, and the largest savings in energy can be realized from the same sector, which amount to some 230 million dollars. Thus the total estimated potential savings for the transportation sector is 550 million dollars. The estimated saving from reduction in wear in agriculture is 230 million dollars. These two taken together amount to an annual saving of almost 800 million dollars, or more than 60% of the total realizable savings.

The estimates in this and the previous section were obtained by D'Silva et al. [1] from the descriptions of detailed losses and causes provided by plant personnel, from references to similar studies, and from knowledgeable individuals.

Estimates by D'Silva et al. for potential savings in individual industries are quoted here in the text and tables. All estimates of this kind are subjective and very approximate. A detailed study of existing losses and potential savings may be a helpful step in conjunction with specific R&D projects in the particular industries concerned, as was done in the current West German R&D programme in tribology (see Section 3.2).

The estimates quoted here should, nevertheless, suffice to indicate the general magnitude of the problems which should be addressed.

<u>Pulp and Paper</u>

The potential savings due to reductions in wear are estimated at 100 million dollars per year, which is 26% of the wear loss in the pulp and paper industry. The potential energy savings are estimated to be 20 million dollars per year, which is 20% of the losses due to friction in the industry.

TABLE 2.17

ESTIMATED LOSSES DUE TO FRICTION AND WEAR IN CANADIAN ELECTRIC POWER GENERATION

Type of generation	WEAR MECHANISMS					Total Losses due to Wear	Losses due to Friction
	Abrasion M$/a	Adhesion M$/a	Erosion/ Cavitation M$/a	Fretting M$/a	Other M$/a	M$/a	M$/a
Fossil Fuel	12	6	3	2	3	26	
Nuclear	6	2		0	2	10	
Hydraulic	16	9	17	2	7	51	
Common elements	35	14	10	22	22	102	54
TOTAL	69	31	30	26	34	189	54

TABLE 2.18

ESTIMATED LOSSES ATTRIBUTABLE TO VARIOUS MECHANISMS OF WEAR, BY ECONOMIC SECTOR

ECONOMIC SECTOR	MECHANISM							TOTAL
	Abrasion M$/a	Adhesion M$/a	Erosion M$/a	Fretting M$/a	Fatigue M$/a	Chemical M$/a	Other M$/a	M$/a
Pulp and Paper	217	36	93	4	13		19	382
Forestry	101	25	-	12	14	6		158
Mining								
Refining	44	3	24	-	3	4		78
Open Pit	230	10	-	1	16	1		258
Mills	239	1	72	-	4	11		327
Tar Sands	38	1	21	-	2	1		63
Agriculture	735	104	54	2	45	-		940
Transport								
Rail	138	128	-	5	174	20		465
Trucks/Buses	661	112	-	12	28	48		861
Electric Utility	69	31	30	26	-	-	34	190
Wood Industries	Breakdown of losses for wood industries is not available							189
TOTAL	2472	451	294	62	299	91	53	3911

Forestry

The estimated potential annual savings due to the reduction of friction in forestry are about 20 million dollars which is 20% of the energy loss in this sector. The data suggest that efforts should be directed particularly at the reduction of friction in primary equipment, including that for transportation and for cutting wood. The potential savings estimated to result from the reduction of wear are 40 million dollars, which is 23% of the wear loss in this sector. Work should be directed at reducing wear in crew transport equipment.

Mining

The potential savings from reducing friction in the mining industry are estimated at about 30 million dollars annually, or 13% of the total losses due to friction. The largest savings can probably be achieved by focussing on reducing friction in railcars and conveyors in underground mining, and in material handling equipment in the milling phase of the industry. The potential savings from reducing wear in the industry are estimated at about 90 million dollars a year, or 9% of the total wear losses. Promising results can probably be achieved by attempting to reduce wear in tires, buckets, brake systems, tracks, hoists and engines in open pit mining; in pumps, rods and balls, bearings and liners in the milling phase; and in crushing equipment in the refining phase of the industry. In tar sands operations, annual savings of 11 million dollars from the reduction of friction and wear are believed to be possible in the mining area alone, with one million dollars worth of this being achieved without ressearch or development work.

Agriculture

The potential savings from the reduction of friction in agriculture are estimated to be about 100 million dollars per year, or 32% of the total frictional losses in agriculture. Efforts directed at reducing friction in tractors and mobile equipment should achieve a saving of 37 million dollars, and reducing it in trucks and cars should result in a saving of 35 million dollars. The potential savings resulting from reducing wear in agriculture are estimated at about 230 million dollars per year, or 25% of the total losses due to wear. Attempts to reduce the wear in tractors and mobile equipment should result in annual savings of 71 million dollars; in trucks and cars, 58 million dollars; in grain harvesting equipment, 40 million dollars.

Transportation

About 230 million dollars per year, or 55% of the losses due to friction, is the estimated potential saving from reducing the friction in the transport industry. Reducing wear should lead to savings of about 330 million dollars each year, or 25% of the total wear losses. A potential annual saving of 168 million dollars could be realized by focussing on the causes of wear in wheels and rails. Three quarters of the 140 million dollars potential saving on rail wear each year could probably be achieved by improving the rail/wheel tribosystem, through:

TABLE 2.19

ESTIMATED LOSSES DUE TO FRICTION AND WEAR FOR CANADIAN ECONOMIC SECTORS

ECONOMIC SECTOR	Friction		Wear		
	Percentage of sector energy costs	M$/a	Percentage of sector maintenance costs	M$/a	Total Losses M$/a
Pulp and Paper	8	105	54	382	487
Forestry	23	111	51	158	269
Mining					
- Refining	22	212	28	79	940
- Open Pit			72	259	
- Mills			82	327	
- Tar Sands			26	63	
Agriculture	17	321	82	940	1261
Transportation					
- Rail	51	284	23	466	750
- Trucks/Buses	18	126	42	861	987
Electric Utility	11	54	46	189	243
Wood Industries	14	14	65	189	203
TOTAL		1 227		3 913	5 140

a) applying lubricant in the proper quantity and in the correct location;
b) lighter grinding at more frequent intervals;
c) continuing the programme of replacing short tracks with long welded
d) systematically cataloguing the reasons for rail replacement and taking appropriate action.

A US study indicates that one third of the total fuel cost could be saved by better lubrication of curved and tangent track [12]. This would amount to an annual saving of 166 million dollars in Canada, but would exacerbate some wear problems.

Electric Power Generation

The estimated potential saving from friction reduction in electricity production is about 10 million dollars per year or 23% of the total frictional losses in the industry. Friction could be reduced by adopting improved cooling methods and better bearing designs for steam-turbine generators. The potential saving from wear reduction in the industry is estimated to be about 40 million dollars annually, or 23% of the total wear loss. Research and development on hydraulic thrust and guide bearings, on steam-turbine generator bearings, on pumps and on valves should lead to useful reductions in wear.

General

Transportation equipment used in all sectors of the Canadian economy is an important source of friction and wear. Research and development directed at common elements in transportation equipment that are sites of friction and wear should be very fruitful in reducing losses.

2.234 Current Role of Tribology R&D in Industry

Pulp and Paper

Managers in the Pulp and Paper industry judged that R&D effort in tribology could reduce energy and material losses, but estimates of the range of potential improvement were varied. Most of the R&D activity of the major companies and of the Pulp and Paper Research Institute of Canada is centred on corrosion related problems. However, more recently attention has been directed toward failures due to wear which cause unscheduled down-time.

Forest Industry

The role of R&D in reducing tribological losses in the forest industry has already been recognized by several Canadian organizations. The Western Laboratory of Forintek Canada Corporation has carried out investigations into the reduction of energy consumption and improvement of wear resistance of saw teeth. The Forest Engineering Research Institute of Canada (FERIC) has presented a series of economic studies on frictional and other energy losses in forestry transportation. FERIC is also addressing questions pertaining to the relationship between road-surface quality and fuel consumption of logging trucks, and to the effect of diesel engine fuel temperature control. Canadian forest industry personnel support the opinion that tribological losses in present-day equipment can be reduced through R&D effort.

Mining

About one million of the estimated potential savings of 11 million dollars per year due to improved tribology in tar sands mining could be achieved with no R&D, and the remainder would require short to medium-term R&D. The industry already performs tribological R&D, both independently and in collaboration with the oil industry and other agencies such as CANMET.

TABLE 2.20

ESTIMATED POTENTIAL SAVINGS DUE TO IMPROVED TRIBOLOGY FOR CANADIAN ECONOMIC SECTORS

ECONOMIC SECTOR	Friction: Percentage of sector energy losses	Friction: M$/a	Wear: Percentage of sector wear losses	Wear: M$/a	Total Savings M$/a
Pulp and Paper	20	21	26	100	121
Forestry	20	22	23	36	58
Mining					
- Refining	13	27	8	7	115
- Open Pit			9	24	
- Mills			12	40	
- Tar Sands			26	17	
Agriculture	32	104	25	233	337
Transportation					
- Rail	69	195	36	168	363
- Trucks/Buses	25	31	18	159	190
Electric Utility	23	13	23	43	56
Wood Industries	20	3	20	39	42
TOTAL		416		866	1 282

Agriculture

Manufacturers of agricultural equipment supported the opinion that tribological losses in contemporary farm machinery can be reduced through R&D. In agriculture, waste due to wear is much more important than energy wastage due to friction. The distribution of potential savings through short-, medium- and long-term R&D have not been identified.

At present, farm equipment manufacturers perform very little R&D related to tribology. There was also a lack of awareness of the magnitude of tribological losses. Any relevant R&D in tribology is usually performed by some organization external to the farm equipment manufacturer, which may not necessarily be located in Canada. Agricultural machinery research centres in Canadian universities do not direct much effort to mitigating tribological losses. Agricultural engineering departments of Canadian universities include a limited treatment of the tribological aspect of farm machinery performance in their curricula.

Transportation

There are R&D facilities in Canada for all aspects of railway operations. The research departments of CN Rail and CP Rail have about 100 and about 20 staff, respectively. The Transportation Development Centre of Transport Canada has about 10 staff doing railway-related R&D. Both Bombardier Inc. (in Montreal) and the Canadian Institute of Guided Ground Transport (in Kingston) have research groups active in the development of mass transit systems. However, not much tribology R&D is performed at these locations. NRCC is active in railway tribology with facilities in Ottawa and Vancouver, working in collaboration with the railways, CANMET and universities.

The manufacture of truck and bus equipment and parts is a significant industry in Canada. Apart from limited in-house industrial R&D, some R&D is sponsored by Transport Canada and other government agencies and performed in industry and government laboratories. Little of this R&D appears to be related to tribological problems.

2.235 Sources of Equipment

A substantial amount of the equipment used in pulp and paper mills is manufactured abroad. Pulp and paper manufacturers feel that their equipment does not benefit sufficiently from recent advances in tribology, and they provide a steady stream of requests to equipment suppliers to improve the materials used.

Canada, USA, Scandinavia and Japan are the major manufacturers of the equipment used in the Canadian forestry industry.

Most of the extractive machinery used in the mining industry is imported, and although much of the equipment used in comminution, ball mills for example, is of Canadian manufacture, many of the critical tribological components, for example, balls and liners, are also often imported. In contrast, most spare parts for mining equipment are manufactured in Canada.

Although most of the heavy equipment used in the tar sands is of German and US origin, about 65% of it was designed in Canada. In many cases local suppliers are sought for spare parts. Industry personnel expressed concern over the reluctance of the Canadian steel industry to develop improved wear resistant materials.

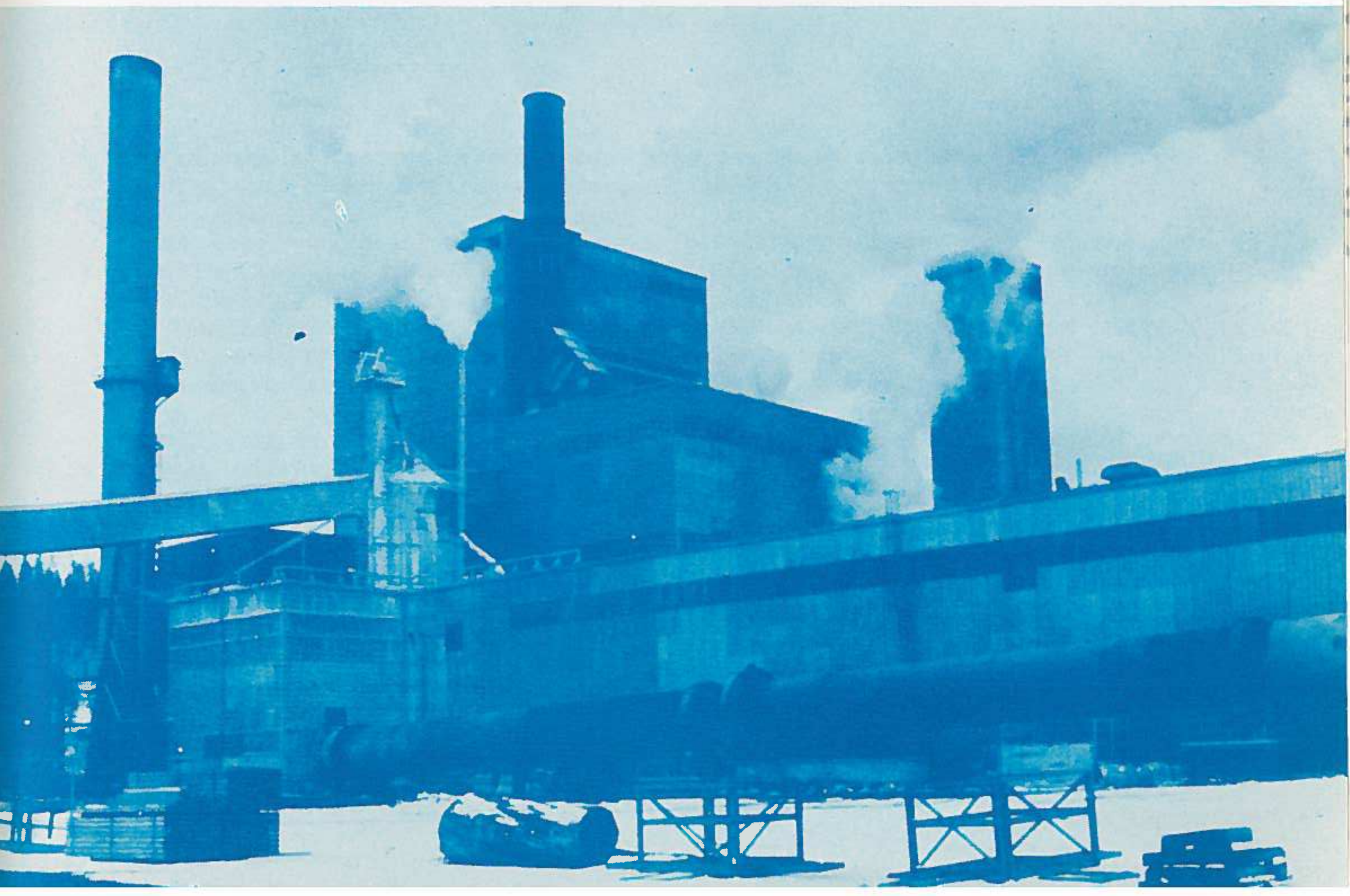
Some farm equipment used in Canada is manufactured in this country, but much is imported.

Railway rails, wheels and locomotives are made in Canada. Most spare parts are purchased from the original suppliers.

The sources of equipment for truck and bus transportation were not reported.

Almost 90% of the equipment and spare parts for electric utilities are manufactured in Canada, but innovations in the design of major equipment such as turbines, generators, and heat exchangers are generally initiated by parent companies abroad.

3 R & D Programmes in Tribology outside Canada



3 R&D PROGRAMMES IN TRIBOLOGY OUTSIDE CANADA

3.1 Tribology R&D in the UK

The Science and Engineering Research Council funds University research in tribology to the tune of 100 000 pounds per year. The 'Tribology Centres', based at the Universities of Leeds and Swansea, received government support for their first four or five years of operation only, and are now run on a self-financing basis. The turnover at the Leeds centre is approximately 100 000 to 150 000 pounds per year. Both the Ministy of Defence, and the Department of Trade and Industry fund research and development in tribology, but precise figures are not easily obtainable [13].

According to Dowson and Taylor [14], the nature and extent of research on tribology in the UK has changed in the past twenty years since the publication of the Jost report [3]. The demands on the design, manufacture and operation of machines have also changed during that period, with much greater emphasis now being placed on the efficiency and reliability of machines. A survey undertaken by Dowson and Taylor [14] showed 58 organizations performing research in tribology as shown in table 3.1.

TABLE 3.1

TYPES OF ORGANIZATIONS PERFORMING RESEARCH IN TRIBOLOGY IN THE UK (ADAPTED FROM DOWSON AND TAYLOR [14]).

Government establishments	3
Industry	23
Polytechnics	9
Universities	23
Total	58

The ranking of current research topics in the UK as determined in the survey is displayed in the left-hand column of table 3.2.

There does not seem to have been a quantitative assessment of all the benefits and costs of the additional tribology funding and the several developments, including three tribology centres, several university chairs in tribology, a tribology handbook, many post-secondary courses of various types, and new professional groups, which can be attributed to the recommendations of the Jost report.

An analysis of the benefits from consulting and contract work for industry at one of the tribology centres, indicated a benefit - subsidy ratio of almost 6:1 for the first four years of its existence, during which all three centres received government subsidies at a decreasing rate [1].

It was, however, noted that the overall level of activity of each centre was in direct proportion to the subsidy received, and the present lack of subsidy has been a financial handicap.

TABLE 3.2

CURRENT AND PRIORITY UK RESEARCH IN TRIBOLOGY - RANKING LISTS

	Current research topics	Priority research topics	
1	Hydrodynamic bearings	Technology transfer	1
2	Metallic wear	Surface coatings and treatments	2
3	Lubricants - additives	Metallic wear	3
=4	Reciprocating engines	Thermal effects	4
=4	Rolling bearings	Boundary lubrication	5
6	Polymers	Elastohydrodynamic lubrication	6
7	Elastohydrodynamic lubrication	Friction	7
8	Friction	Contact mechanics	8
=9	Thermal effects	Abrasive wear	9
=9	Contact mechanics	Polymers	10
11	Technology transfer	Reciprocating engines	11
=12	Piston rings - cylinder liners	Ceramics	12
=12	Surface coatings and treatments	Lubricants - additives	13
14	Bearing design	Bearing design	14
=15	Abrasive wear	Piston rings - cylinder liners	15
=15	Ceramics	Hydrodynamic bearings	16
17	Boundary lubrication	Rolling bearings	17

(Adapted from Dowson and Taylor [14].)

Dowson and Taylor [14] also conducted enquiries worldwide concerning research priorities and received 82 responses. The main finding of this survey, which indicates the ranking of priority research topics in tribology, is shown in the right-hand column of table 3.2. This list is headed by technology transfer, which is not really a research topic, but this shows the importance with which this process is viewed throughout the world. Another important finding was that surface coatings and treatments rose to second place from twelfth place on the list of current research, but the topic of metallic wear moved only from second to third place. Thermal effects in all major aspects of tribology also featured strongly in the responses, thus moving up from ninth to fourth place.

The highly regarded study of the mechanism of hydrodynamic lubrication lags the perhaps less well understood topics of boundary and elastohydrodynamic lubrication. The interest in the fundamentals of friction and contact mechanics rose only slightly, but the interest in abrasive wear rose from fifteenth to ninth place. The study of polymers dropped from sixth position in current research to tenth position in future priorities, whereas the study of ceramics rose from fifteenth place to twelfth, with work related to reciprocating engines dropping from fourth place to the position between the latter two topics. Except for bearing design, which maintained fourteenth position, all the remaining topics were considered less important as future priorities than current research activity would indicate.

It is important to understand that the tribological community considers all the research topics presented in table 3.2 as priority, and that none of these topics should be ignored. It is interesting to compare the list of priorities on the right-hand side of table 3.2 with the list of high-priority topics promoted by the West German Ministry for Research and Technology from 1978 to 1984, and presented in table 3.3. It should also be remembered that the ranking of priorities on the right-hand side of table 3.2 was developed worldwide as the result of the UK survey.

3.2 Tribology in West Germany

There is a long history of research in friction, wear and lubrication in Germany. Much of this work was spurred on by problems encountered at the time in emerging technologies, such as the railways and the automobile. This tradition has been maintained in East and West Germany, where both governments have been very aware of the need to promote research, development and technology transfer in tribology. The current programme in the Federal Republic of Germany, which has added additional momentum to tribology and its application in West Germany is of considerable interest.

Between 1975 and 1976 the Bundesministerium für Forschung und Technologie (BMFT) (Federal Ministry for Science and Technology) commissioned a study to lead to a coherent focus on tribology. This study was based on the premise that losses due to friction and wear amounted to about 10 billion DM per year in West Germany. (Later studies have shown this to have been a considerable underestimate.)

A substantial number of R&D proposals were submitted by research organizations in industry, government and universities for specific R&D projects in tribology. These proposals were evaluated by experts in the various subdivisions of tribology concerned. A major portion of the BMFT Tribologie report [15] contains the recommended proposals. In addition to the intrinsic scientific and industrial value of the proposals, a major criterion in the evaluation was the identification of several co-operating institutes or companies in the proposed project.

In all, 306 projects were proposed, out of which 173 were supported in the progamme [16]. Initially, the Federal Government's contribution to the programme was to have been about 35 million DM over 6 years. In the course of the programme this has been raised to 49 million DM over 8 years. Industrial partners in the projects have identified their contribution as exceeding 52 million DM, for a total cost of the programme close to 102 million DM.

The principal investigators in 105 projects are in research institutes, including university departments. Every project by a research institute involves partners in another institute and several partners in industry. One third of these projects involve an industry association.

Industry provides the management of 68 projects, all involving co-operation between two or more companies and about half of them in conjunction with industry associations.

The emphasis on direct co-operation between research institutes, universities and industry is a deliberate attempt to bridge the gap between "fundamental" and "applied" research.

Dr. H. Czichos, Vice-President of the Federal Institute for Materials Research and Testing in West Berlin, provided an overview of the BMFT Tribology Programme at the ACOT workshop in Montebello [17]. His talk was derived in part from the role his institute has played in analysing the projects in this programme in terms of the background, intentions and subject matter of all the projects. From this it is evident that over half the projects are concerned with surface treatments, manufacturing, and abrasive wear, as shown in Table 3.3.

TABLE 3.3

PRIORITY AREAS OF TRIBOLOGY R&D IN WEST GERMANY

Research Areas	Percentage of Projects
Surface Treatment	20.9
Manufacturing	13.8
Abrasive Wear	10.1
Measuring and Testing Techniques	8.4
E.H.D.	8.4
Design	7.8
Sliding Bearings	7.8
Performance of Tribological Systems	7.2
Mixed Lubrication	5.4
Sliding Bearing Materials	4.8
Lubricants for Combustion Engines	3.0
Diesel Engines (Lifetime Improvement)	2.4

Table 3.4 identifies the areas of application and the machine elements concerned in the programme. Table 3.4 lists the types of wear and wear mechanisms predominant in the projects. (Simultaneous occurrence of several wear types and mechanisms is possible.)

Table 3.5 indicates the background interest for the projects. Evidently many projects relate to more than one item in the table.

TABLE 3.4

ASPECTS OF WEAR RESEARCH IN WEST GERMANY

Wear Types	% Projects Involved
Sliding Wear	54.8
Sliding Abrasion (2-body Abrasion)	16.1
Rolling Wear	15.1
Sliding Abrasion (3-body Abrasion)	10.7
Impact Wear	9.7
Fretting Wear	5.4
Fluid Erosion	5.4
Wear Mechanisms	
Abrasion	41.9
Adhesion	24.7
Surface Fatigue	21.5
Tribochemical Reactions	20.4
Surface Deformation	19.4

TABLE 3.5

BACKGROUND OF INTEREST FOR TRIBOLOGY R&D IN WEST GERMANY

Background of Interest	% Projects Involved
Materials	45.2
Reliability, Safety	43.0
Transferability	43.0
Economic Aspects, Costs	37.6
Lubricants	37.6
New Developments	34.4
Design	34.4
Running-in, Performance	33.3
Comparison	33.3
Computation	32.3
Economic Impact	32.3
State of Research	29.0
Failure Analysis	25.8
Selection	24.7
Maintenance, Condition Monitoring	19.4
Function, Performance	12.9
Stability	6.4
Fabrication	5.4
Quality Control	4.3

In both the UK and USA, detailed studies on the losses in the economy due to friction and wear preceded the major tribology programmes. While certain assumptions were made in West Germany on these losses, based on private analyses, before the BMFT Tribology Programme was launched, this programme included a few detailed studies of the losses in selected sectors.

In one such study the annual wear losses in unlubricated equipment and components in the mining industry is estimated to be 1.7 billion DM, in the iron and steel industry 1.2 billion DM, 1.1 billion DM in quarrying, 1.5 billion DM in the construction industry, 0.8 billion DM in the plastics industry, and 6.5 billion DM in transportation (all figures for unlubricated components, e.g. brakes, clutches and tires) [18].

In lubricated components friction is a major cause of loss in both the production of energy (mostly electrical) and the use of energy, particularly in industry and transportation, totaling between 11 and 20 billion DM a year [19].

Total direct costs due to friction and wear are estimated to be close to 39 billion DM a year [20].

Estimates of potential savings have been made for several economic sectors in West Germany. In energy production the estimated annual savings lie between 140 and 250 million DM. In the iron and steel industry, including pellet plants and blast furnaces, the optimum application of existing knowledge should produce savings of between 80 and 100 million DM a year, while R&D should readily add savings of a similar amount. (Each figure is about 3% of the annual repair costs.)

In the case of lubricated components in industry in general, it is estimated that the potential savings in maintenance costs can be as high as 50%.

3.3 Tribology R&D in the US

In his address to the workshop on economic losses due to friction and wear held in Montebello, Québec, in 1984 M.B. Peterson [21] stated that there had been an increase in the emphasis on tribology in the preceding few years, and in consequence three new programmes had been started. These are:

1. the Energy Conversion and Utilization Technologies (ECUT) programme of the Department of Energy (DOE);

2. a whole new series of heat engines under development which require tribological advancements;

3. a new programme to build a computerized tribology information system.

W. Winer [21] of Georgia Tech. has assembled some general information on tribology in the US, some of which is displayed in table 3.6.

TABLE 3.6

U.S. TRIBOLOGY - GENERAL INFORMATION

	No.	Personnel	Amount
Academic Institutions	38	58	3 M$us/a
Government & Non-profit	11	113	17 M$us/a
Industrial	43	145	29 M$us/a

No. of Projects	400 per year
Publications - Journals	2 000 pages per year

Sponsored by the ECUT programme of DOE, Wear Sciences Corporation conducted an assessment of current tribology work. It found that from 1981 to 1983, 650 projects were conducted by the US government of which 215 were current in 1984. Most, but not all of this work has military objectives. The applications under investigation are listed in table 3.7.

TABLE 3.7

APPLICATIONS OF TRIBOLOGY IN USA

Rolling Bearings	30	Sliding Contact	2
Engine Lubrication	22	Brakes	2
Seals	12	Brushes	2
Transmissions	6	Tires	1
Gears	5	Splines	1
Fluid Film Bearings	4	Valves	1
Rings	4	Cables	1
Tools/Dies	3	Couplings	0
Gas Bearings	2	Clutch	0
Bushing	2	Cams	0

The highlights of the current work on fundamentals comprise the friction of fluid components of oils and solid surfaces, improved definition of wear and surface damage mechanisms, microelastohydrodynamics and roughness effects in lubrication, and thermoelastic surface models of the failure process. In the field of ceramics, many organizations are building test rigs to study ceramic friction and wear, and rolling-contact bearing materials are being evaluated. For engine oils, temperature capabilities are being expanded to 316°C. Solid lubricants are being studied for high temperature applications. Coatings are being evaluated as solid lubricants up to 816°C, in the form of ceramics of controlled composition and thickness, and in the form of ion-implanted corrosion- and wear-resistant surfaces, displaying the dual property of wear resistance and lubricity in a solid. Polymer and metal composites are being appraised for their high-temperature capabilities and their wear lives. Foil-type gas bearings are being examined for their low-friction behaviour under high-temperature conditions.

Most of the work for the US government is performed to meet new design requirements, however some work is being done to reduce maintenance costs. Of the very high maintenance costs required to keep certain ships and aircraft of the US navy in operation, about 12% is due to wear. If this figure were to apply to military ships and aircraft in general it would represent a very large annual expenditure. The possibility of saving a small portion of this justifies a substantial amount of tribological research.

An important objective of the US programme is the advancement of tribological science. A panel of the ASME has recommended the work set out in table 3.8 to the National Science Foundation. These recommendations represent the then current thinking on the directions research should take in the future.

Advanced designs prompt much of the tribology research and development. Most advancements in transportation in the US have required improved tribological products. A contemporary interest is the development of advanced heat engines.

Some work is being undertaken to meet conservation objectives. As already mentioned, an ASME study [6] concluded that 5.3% of US energy consumption could be saved through economically achievable tribology R&D. Based on this, a new tribology programme has been initiated by the Department of Energy, and was described by T.M. Levinson at the Workshop that took place in Montebello, Québec in 1984 [22].

This tribology programme is part of the ECUT division which consists of six programmes: Combustion, Thermal Sciencs, Materials, Catalysis and Biocatalysis, Tribology, and Innovation. ECUT also monitors the activity in its six areas in the rest of the Department of Energy, including the Office of Basic Energy Sciences in the Office of Energy Research. As already pointed out, most of the tribology research in the US is being done by the Department of Defense. The tribology programme at DOE is the largest tribology programme outside the Defense Department.

According to Levinson, very little generic tribology research is occurring in the private sector, and there is a lack of coordination among tribology programmes, especially among those concerned with civilian problems.

At least fifty million dollars a year is being spent on tribological research and development in the USA, and although this may be a relatively small amount compared to the country's gross national product, it nevertheless represents a substantial effort.

TABLE 3.8

RECOMMENDATIONS TO NSF
A.S.M.E.

Modeling of Tribo-Systems

Tribo-elements are part of a larger mechanical system and the interactions among the tribo-elements and other components in the system are determining factors in the system performance. This modeling includes dynamic, thermal, chemical, nonlinear material properties, and real surface geometry effects. The modeling should include the full range of lubrication regime behavior (hydrodynamic, elastohydrodynamic, mixed film, boundary and unlubricated). It should cover not only tribo-element behavior during successful system operation but also the limits of tribo-element behavior in terms of wear and various modes of failure.

Material Behavior in Tribo-Elements

The tremendous range of environmental conditions to which tribo-elements are subjected require a large variety of materials. The environments include thermal, chemical, and stress both steady and unsteady. Material development is a never ending frontier of tribology. Because the near surface region of material is of primary importance to tribological applications not only the bulk material, but surface layers and surface modifications are important to materials studies in tribology.

Tribo-System Diagnostics

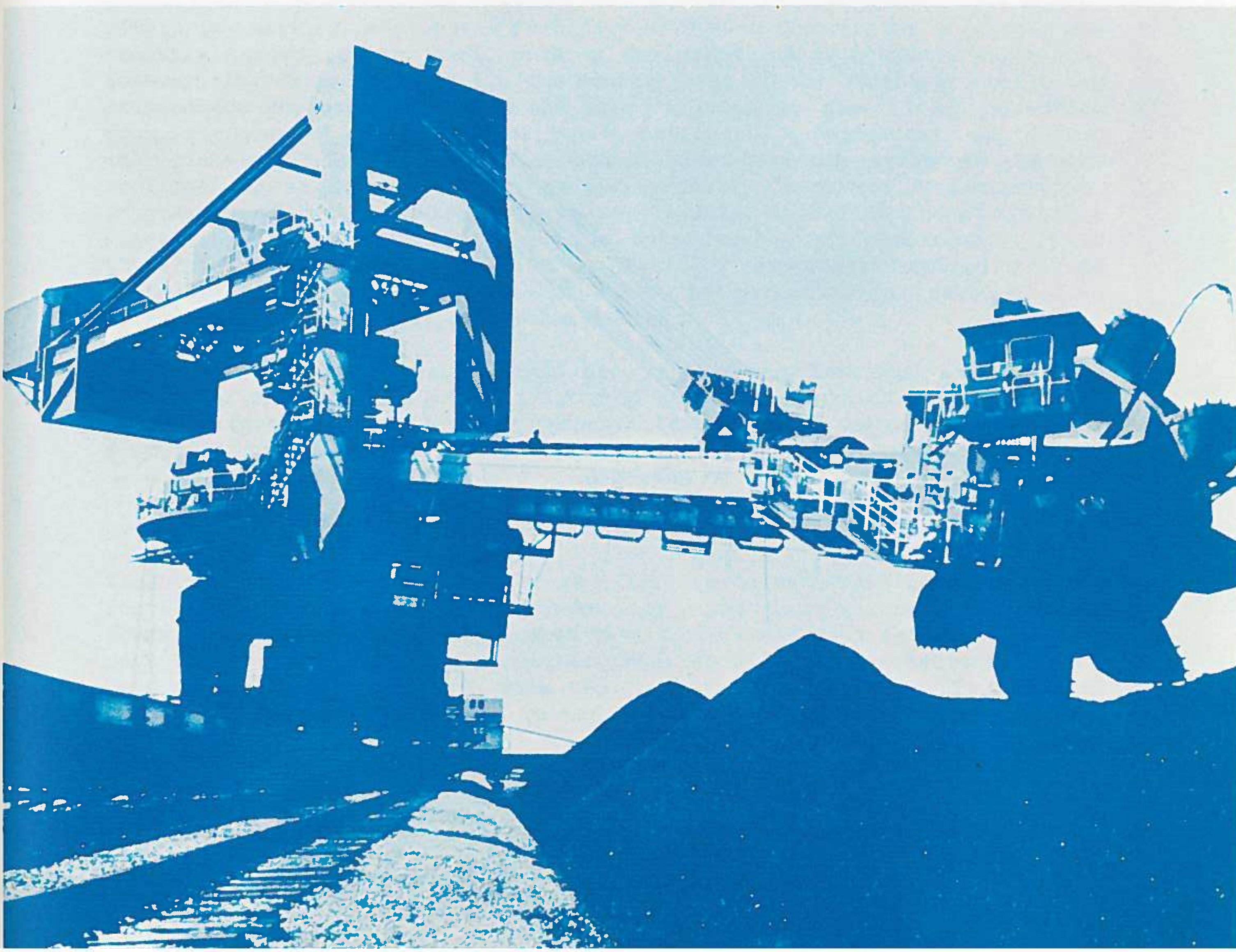
Tribo-element failures are often causes of mechanical system failure and downtime. The development of reliable on-line tribo-system performance monitoring techniques can help reduce unscheduled system downtime and therefore system reliability and productivity. On-site methods of monitoring and non-destructive testing in tribology should be developed.

Tribo-Technology Transfer

Fundamental knowledge in tribology must be transferred to the design and maintenance personnel to be of value. Computer database systems ("expert systems") should be developed to aid in the transfer of new information developed as well as existing tribological knowledge. Tribology as a field has many similarities in its state of development with those areas where advances in expert systems have been made (e.g., natural resource exploration and medical diagnostics) and would be a very appropriate field in which to advance the fundamental state of expert systems.

(From Peterson [21])

4 R & D in Tribology in Canada



4 R&D IN TRIBOLOGY IN CANADA

4.1 The Nature of Tribology

4.11 Tribology is a generic technology

A generic technology is defined here as a technology which is not specific to a particular machine or process. Bearings are an example of a generic machine element. A wide variety of machines contain bearings, from watches to tar-sand excavators. Wear is a generic phenomenon or process in technology. Abrasive wear is a problem in mining, agriculture, forestry and road construction. Wear with corrosion occurs in the nuclear power industry, in the chemical industry and in railroad equipment. These and many other instances can be mentioned to illustrate the generic nature of tribology which encompasses the study of wear, friction and lubrication, and the design of bearings and other machine elements.

In some cases the wear or friction is severe enough in itself to attract attention in the industry concerned and the potential benefit to individual companies of reducing wear or friction is sufficiently large to warrant company funding of its own R&D effort for this purpose. In other instances, where the industry supports a collective R&D establishment, an industry sector effort aimed at reducing friction and wear losses may be attractive.

Within any particular industry tribology will be a concern for more than one technical group of personnel, such as designers and maintenance engineers. However, the designer may serve the manufacturer of the equipment, while the maintenance engineer works for the user, relying to some extent on advice from vendors of both the original equipment, replacement parts and lubricants. Thus the total responsibility for the tribology of the equipment is split between many people, probably in several organizations, fragmenting both the knowledge base applicable to the equipment in this connection and the perception of the total technology concerned. It is therefore not surprising that the level of expertise applied to the tribology concerned may be low and that the potential for savings, even using existing knowledge, can be quite high.

It should be noted that appreciable savings in friction and wear in industrial plant can be achieved not only by solutions which may be supplied by consultants or suppliers in response to particular major problems, but also by improvements to a host of items which company personnel knowledgeable in tribology can provide over a period of time. Both R&D within the company and appropriate training of production and maintenance staff will provide a basis for this type of improvement.

Financial support from government is likely to be necessary as an incentive for R&D in this type of generic technology given these circumstances. Some forms of this type of R&D may indeed have to be completely funded by government if they are to occur. In other cases it will be reasonable to expect some financial participation from the industry which can benefit from it. Industry involvement can help, in any event, to ensure the relevance of the

R&D to the needs of the industry and so may be important, even in projects wholly or largely supported by government.

Joint industry-government funding with heavy involvement of industry in formulating individual projects is characteristic of the current West German tribology programme. Recognition of the important role of government in tribology R&D is evident in current US Department of Energy sponsorship of tribology R&D in industry as well as in other R&D organizations.

NRCC and other government agencies in Canada have a number of programmes to support R&D performed in industry. There is a substantial opportunity here for these programmes to be used to support industrial R&D in tribology, in some instances in topics also being pursued elsewhere but also in areas of special concern to Canadian industry.

Certain components, such as rolling element bearings and lubricants, are made by a few companies and utilized by many. In these instances the suppliers of the components support R&D directed towards their own product items. An optimum choice of tribological components may then depend less on the manufacturer, and more on adequate knowledge on the user's part. There may then be a need to enhance the customer's ability to select the best available component, through improved knowledge of tribology and ready access to information on tribology. An information service and related data banks are also tools of a generic nature (as they are in most disciplines), requiring significant government sponsorship, at least in the development stages of these tools.

4.12 Tribology is an interdisciplinary technology

Wear usually occurs as a combination of mechanical and chemical interactions between various materials. Even in typical abrasive wear, involving to all appearances just a hard abrasive cutting a softer component, the process may be affected by the environment, be it air or a fluid. Often the chemical aspect is enhanced by the raised temperature due to heat from friction and deformation at the cutting points.

The knowledge needed to understand a tribological process, in friction, wear or lubrication, is a blend of aspects of mechanical engineering, materials science, chemistry, physics and mathematics. Undergraduate university programmes in these disciplines have seldom included much tribology, except for a minor component from the viewpoint of the particular discipline concerned. The term "tribology" was adopted in Britain in 1966, and subsequently elsewhere, to give an identity to all aspects of friction, wear and lubrication as one subject area and thus focus attention on tribology at all pertinent levels of education, R&D and funding, commensurate with its economic significance.

All present practitioners of tribology have had a basic education in another science or technology e.g. mechanical engineering or chemistry, which differ considerably from each other, before specializing through graduate study, research, or work experience, in tribology. Tribologists have to acquire a knowledge of principles from branches of science and technology beyond that of their own basic education, synthesizing this into integral components of tribology as a separate discipline.

While the identification of tribology as a distinct science and technology is relatively recent, there has been a concern with friction and wear as far back as the building of the pyramids in ancient Egypt (when the slides used for transporting blocks of stone were lubricated). It is characteristic of this discipline that systematic knowledge of the principles of tribology developed much later than the technology of its application. Slow progress in the knowledge basis for tribology must now be recognized as a reason for a slow advance of this technology.

While there is some emphasis in this report on the needs of certain specific industry sectors, the basic aspects of friction and wear are common to many industries and a variety of devices. For example, thin film lubrication (reaction film, boundary, and elasto-hydrodynamic lubrication) occurs in rolling element bearings, gears, cams and in metal working. Thus basic research in tribology tends to have a wide application and thus is generic in another sense. Research tribologists can apply their specialist knowledge to a variety of industries and industrial equipment, even when their research projects are undertaken with particular industrial applications in mind. Since tribology has obvious practical applications, it may be tempting to restrict support for basic research in tribology to limited areas, on the basis of an emphasis on particular industries. In fact, a broad range in the science of tribology is relevant to most industries, and an emphasis on certain topics should only be one of degree.

Breadth in basic tribology research must be encouraged, but a particular concern must also be to encourage and support research in any newly emerging insights and the application of new investigative tools. Basic research is also critical in the tribology of new materials, or new applications of new materials, such as ceramics in engines, an example of how technological developments produce new demands in supporting technologies.

4.2 Existing Tribology R&D in Canada

A survey of tribology R&D in Canada made three years ago engendered a directory of facilities [23]. Using the results of this survey, and more recent information, it is estimated that current tribology activities resemble what is portrayed in table 4.1 based on an average cost of 100 000 dollars per person-year [24].

It appears that the effort is fairly evenly divided between wear and lubrication, and that very little work is done on friction per se. Because of the large size of the oil industry in Canada, there is a slight preponderance of work on lubrication.

The survey identified approximately thirty fairly large organizations in Canada that perform research and development related to tribology. Thirteen of these are universities, there are four manufacturing companies, four mining and metallurgical companies, three oil companies, three electric utilities, two railways, an atomic energy company, an energy research institute, and two federal government laboratories. Several smaller organizations also carry out tribological research and development.

TABLE 4.1

OVERALL LEVEL OF CURRENT TRIBOLOGY ACTIVITIES IN CANADA

	Research & Development		Basic Research	
	Professional person-years	Expenditure K$/a	Professional person-years	Expenditure K$/a
Universities	14	1400	11	1100
Federal Government	11	1100	5	500
Industry	30	3000	6	600
	55	5500	22	2200

The tribology of metal-to-thermoplastic contacts under normal and arctic conditions is being investigated at the École polytechnique de Montréal. Laval University is developing composite materials, including abrasion-resistant cermets, and is exploring abrasive wear mechanisms. At Memorial University research is performed on the friction of ice against other materials, with the intention of reducing the power needed to propel ships through ice-covered waters, and in order to understand better the forces exerted by moving ice on stationary ocean structures. Queen's University is exploring metalworking processes with particular emphasis on friction, flow and fracture; and is developing wear-resistant steels and surface-hardened steels using nitrogen-ion implantation. The metallurgical aspects of rolling wear and journal bearing material are being studied at the Technical University of Nova Scotia. The University of New Brunswick studies two-dimensional squeeze film phenomena. The University of Saskatchewan studies erosion in aqueous slurries of sand, iron ore, coal and potash, and develops fuel-efficient model vehicles. Tribology research at the University of Waterloo encompasses lubrication and wear in metal-deformation and metal-cutting processes, mixed-film and elasto-hydrodynamic lubrication, lubrication of compliant surfaces, including human joints, and erosive wear of plastic pipes. The University of Western Ontario performs basic research into adhesive wear. McMaster University and the Universities of Alberta, Sherbrooke and Windsor are also involved in tribological research and development.

JWI Limited develops wear-resistant screens for the paper industry. Heavy-duty friction materials are being developed at Echlin Canada Limited. Thomson Gordon Limited is developing elastomeric-alloy materials for marine stern-tube bearings. Westinghouse Canada Incorporated is examining the fretting and wear of nuclear reactor fuels and components.

In the mining and metallurgical industries, Alcan International studies hot and cold rolling processes. Falconbridge is looking into the development of wear-resistant castings and hardfacing alloys. The Noranda Research Centre is developing both abrasion-resistant materials for applications in mining and milling, and Zn-Al alloys for use in bearings. Sherrit Gordon Mines Limited is developing new metal products, including cast, wear-resistant alloys, thermal spray powders, abradable seals and bearings, and high-chromium cast iron studs as wear protectors.

Imperial Oil Limited, Shell Canada Limited and Petro Canada perform fundamental and applied research in wear and lubrication. Syncrude Research evaluates materials, processes, and components designed to resist the attack of abrasive tar sands during mining and processing. In addition, simulated service testing is performed on lubricants being developed for arduous operating conditions. A number of smaller companies are developing speciality lubricants for various applications including metal working, and also fire-resistant hydraulic fluids.

In the electricity generating industry, IREQ (Institut de recherche d'Hydro-Québec) carries on research and development in the tribology of electrical connections and other components, and related research into fatigue, fracture, cavitation, vibration and corrosion. Ontario Hydro explores the radiation resistance and degradation of lubricants and hydraulic fluids, studies seals, researches machinery and plant condition monitoring, and undertakes failure analysis and component wear investigations. B.C. Hydro and Hydro-Québec also undertake tribological research.

The rail research centres of CN and CP perform component and lubricant analysis. Atomic Energy of Canada Limited has successfully developed rotary seals, is investigating wear-resistant materials for water-lubricated mechanisms, and is studying friction under high-temperature and high-pressure conditions. The Department of National Defence is developing and applying x-ray fluorescence and spectrophotometric methods to measure wear in lubricated components, investigates mechanisms of bearing and gear wear, and carries out failure analyses of tribomaterials.

At the National Research Council Canada (NRCC), five groups have some involvement in tribology. In the Division of Mechanical Engineering, the Engine Laboratory has a rotor dynamics facility with which bearing health monitoring techniques are studied. The Fuels and Lubricants Laboratory evaluates re-refined and reclaimed oils. The Railway Laboratory has a full-scale wheel/rail test facility to evaluate wear, wheel/rail contamination and the effects of extreme temperatures on operation. The Tribology and Mechanics Laboratory houses, formerly known as the Western Laboratory, the main tribology research and development group at NRCC. The Laboratory specializes in investigations of the friction and wear characteristics of materials and components of mechanical systems involving sliding, rolling and impact motion. Typical recent and continuing projects include studies of brake friction in vacuo, rolling-contact wear of railway wheels and rails, sliding wear of gas-turbine seal materials, impact/fretting wear of metals and the effectiveness of boundary lubrication by tool-way oils and lubricant additives. Other fields of study are the static and dynamic characteristics of fluid-film bearings, and the development of lubrication systems for these bearings. The Industrial Materials Research Institute is another important centre of tribological research at NRCC. There, the plasma spraying of wear-resistant coatings is being examined, and studies of abrasive wear are proceeding.

4.3 Tribology Opportunities in Canada

4.31 General considerations

Tribology is not an end in itself. Rather it is a part of the means to various ends. Low friction bearings, non-stick fry pans, wear resistant surfaces are not developed for their own sake, but as requirements for, or useful improvements to, engines, kitchens, shovels, ploughs etc. Tribology, as an applied technology, has to be considered in conjunction with other technologies. Yet, tribology is all too easily ignored with unfortunate results in a rush to develop new products in other technologies. Many a new technological development has been held up by tribological problems when these became apparent, as was the case with the rotary (Wankel) engine.

Notwithstanding the applied aspects of tribology, there is also a scientific basis to it, which can readily be ignored if the focus is solely on application. There is still much to be learned on how surfaces of solid objects interact in sliding and rolling and on how lubricants modify or control this interaction. Ideas which appear to explain what is already known to work, may fail us as we use higher speeds and loads than hitherto, as machines get bigger and faster, or we employ new or unfamiliar materials, such as ceramics instead of metals. Wear lives or friction levels which were acceptable hitherto may no longer be so; perhaps because our competitors do better, perhaps because we can no longer afford the maintenance costs, or perhaps because the equipment has now to act more precisely and more reliably than before.

Fundamental research is, as always, the means through which our scientific understanding of tribological processes and mechanisms advances, and remains the basis on which tribologists can serve the advancing technologies requiring tribological components.

D'Silva et al. [1] have clearly demonstrated the large magnitude of the losses to the Canadian economy due to friction and wear, and have provided estimates for these losses for several sectors. This Canadian study confirms the general thrust of studies in other countries. Some of the findings in other countries can also be applied to Canada. Indeed it was the intention, when the Canadian study was proposed, that it would not attempt to duplicate in all aspects what had been done elsewhere. Rather, the Canadian study focusses on some areas of particular importance to Canada; taking into account and building on studies in other countries.

Where the Canadian study is of limited scope as, for example, in relation to manufacturing, we can usefully note the conclusions and actions in other countries. In some areas there is overlap and confirmation of findings elsewhere, as for mining. On the other hand D'Silva et al. provide very definite indication of the magnitude of the losses due to friction and wear in other resource industry and transportation sectors, which loom large in Canada, but have not received as much prominence in similar studies elsewhere. In particular, the importance for Canada of tribology in agriculture and in forest-related industries, including pulp and paper has been shown. These sectors were not given the same attention in the studies in the US, UK, or West Germany.

Recommendations for tribology R&D can focus very broadly on the needs of particular sectors. The general statement can be made that tribology R&D is urgently needed in all the sectors just mentioned, for which the losses at present are high. Somewhat narrower recommendations for R&D can be formulated by noting which specific types of friction and wear are most prominent in the data in the D'Silva et al. study, or which types of equipment suffer most from friction and wear.

Very specific proposals can also be made, directed at problems in existing machine components, where friction and wear has been recognized as unnecessarily severe.

Tribology is not only of importance in established technologies. Many current or future developments may be affected by, and even limited by, tribological problems. While these developments may not yet be very significant to the economy, this can change dramatically.

The development of knowledge, and its application, are both often quite unpredictable, so we should consider where tribology as a science is going and endeavour to decide where, in the spectrum of subdivisions of tribology, a Canadian contribution can be made. These considerations may be linked to a consideration of the present and future shape of industry. It is also pertinent to consider the presence and strength of other scientific disciplines in Canada.

4.32 The basis for proposals

D'Silva et al. [1] have provided a basis for selecting industries in which the need for improved tribology is high. From a national point of view the need can be viewed in terms of the total economic benefit which might be derived from improved tribology applied in that industry.

The survey provided indications of the total losses due to friction and wear in a number of sectors

In terms of those estimated friction losses by sector, we can rank the sectors as follows, in descending order:

Transportation
Agriculture
Mining
Forestry
Pulp and Paper

listing only sectors for which D'Silva et al. estimate that the losses exceed 100 million dollars per year.

In wear losses the ranking is

Transportation
Agriculture
Mining
Pulp and Paper

listing only sectors in which the total estimated losses exceed 200 million dollars per year.

It is inevitable that estimates of the potential savings from reducing friction are more speculative than the estimates for the total losses. With this caveat we can use the estimates by D'Silva et al. to rank the sectors in terms of total potential savings.

The ranking of sectors by potential savings in friction is the same as the ranking derived above for total friction losses.

The ranking for total potential savings in wear losses is

Transportation
Agriculture
Pulp and Paper
Mining

Here the losses or savings for both rail and road transportation were combined. Looking at these industries separately, the friction losses in rail transportation appear to be more significant than those in road transportation, and both trail agriculture. In potential savings from reducing friction losses, rail transport still heads the list while road transport trails agriculture.

In wear losses, road transport trails agriculture, while rail transport follows below mining. In potential savings, rail leads road and both follow agriculture.

Judging by these criteria all the following industry sectors: agriculture, rail and road transportation, mining and pulp and paper are good candidates for more tribology R&D appropriate to each sector. Factors other than the potential savings may, however, influence the choice of a sector on which to focus an R&D effort. These factors include the nature and strength of the R&D community and institutions already in place for the industry, and the likelihood of dissemination and adoption of new developments in the industry.

4.33 Project suggestions in the study by D'Silva et al.

D'Silva et al. [1] had occasion, in the course of their study of the friction and wear losses, to visit a number of companies and some research establishments, to both view the industrial plant concerned and to discuss friction and wear problems with members of the industries affected. On the basis of these visits and the tribology literature a number of specific suggestions for R&D were formulated, as listed in Appendix 3.

These suggestions are arranged by sector. However, many apply to more than one sector, particularly the items relating to mobile equipment.

Vehicles are used in most industries, so that friction and wear at tires, brakes, clutches, bearings, and transmissions are relevant in all these industries. This is true too of the electric power utilities, which are affected by these losses as well as by the losses in generating plant. R&D to reduce friction and wear in transportation equipment should clearly have benefits in many sectors. This type of R&D is also receiving attention in West Germany. In the USA, the focus appears to be on advanced engines and transmissions.

Abrasive and impact wear are typical and prominent wear processes in all equipment in contact with soil and rock, and so are of major concern in agriculture and mining. Other studies indicate that this is also of concern in the construction industry, where a great deal of excavation occurs. In the processing of ore the same types of wear process occur in a different manner, with the scale of the interaction differing considerably from item to item in the equipment concerned. The abrasive material handled puts a particular stress on transportation equipment, including railways, in these industries. As noted in table 3.3, abrasive wear ranks third in the topic areas being pursued in the West German tribology programme, and it also ranks quite high in the priorities identified by Dowson and Taylor [14], as shown in table 3.2.

At the process end of pulp and paper operations, wear mechanisms are combined with corrosion. (This is not an unusual combination in wear in other situations - even where corrosive fluids are not obviously present.) Pumps and compressors are exposed to the same kind of problems as this type of equipment is exposed to in many chemical process industries. Cutting and chipping operations have similar wear and friction situations in forestry, forest product, and pulp and paper industries.

Seals are an integral part of many bearing assemblies. Seals often have to protect bearings from environments which would cause considerable damage to unprotected bearings. Seal technology is particularly critical in many applications.

In part, tribology is a matter of design, i.e. a determination of shape and form of bearings, gears etc. A major aspect, however, is the choice of materials, including lubricants, for bearings and other tribological components, to satisfy external constraints upon the component design or choice, as well as providing an optimum function from the point of view of the tribology involved. Often the criteria for the material can be best satisfied by applying a coating.

The development of wear resistant materials, including materials which are applied as coatings, is clearly an important technology from the point of view of tribology. This not only concerns the production of the materials, but also the technology of the application of materials as coatings. Many of these materials can be used in combination, as alloys or as composites, leading to innumerable possible material compositions. The wear resistance, and the frictional properties, may depend critically on the method of manufacture or method of application as a coating, as well as on the system, including fluids, in which the material is used.

4.34 Priorities derived from the study by D'Silva et al.

4.341 General

The figures in the study by D'Silva et al. [1] show the pre-eminence of abrasion as a wear mechanism. The estimated losses due to abrasion add up to about 2.5 billion dollars per year, out of a total for wear losses of about 4 billion dollars per year. In the past abrasive wear has not been a priority in wear research, but the picture is changing, particularly when a concerted effort is made to direct research and development towards pressing current problems, as is evident in the West German tribology programme. This trend is also occurring in the UK [14].

The various possible mechanisms of friction do not appear as subdivisions of the losses due to friction in D'Silva et al. or in any other study considered here. Friction is usually a concern in lubricated systems and the objective is normally to minimize frictional losses while maintaining the reliability of components concerned. The reduction of friction is then a matter of R&D in lubrication, including lubricant development and component design, the latter including materials selection.

In full-film fluid lubricated systems one can often reduce friction by changing to a lubricant of lower viscosity. However, there is then the danger of increasing the wear rates or increasing the likelihood of catastrophic failure. These dangers may lead a designer or supplier to specify a lubricant which is more viscous than it need be, employing a safety factor which is more liberal than necessary.

This is understandable if the personnel in question do not possess the knowledge of tribology required to evaluate the lubrication requirements properly. Indeed a consideration of both the design of the components, including choices of materials, and the lubricant, at the same time, may have been the route which would have led to savings, as several cases from practice show.

In other words, the reduction of losses due to friction is often a question of optimizing lubrication, in the context of the overall design of the equipment. There are several types of mechanisms in lubrication, including boundary lubrication, hydrodynamic lubrication, and elastohydrodynamic lubrication. In severely loaded situations the lubrication regime tends to be either boundary or elastohydrodynamic. Here, apart from the optimum design of the components and the choice of the materials for the solid surfaces involved, the type of lubricant and the type of additive added to the lubricant is critical, so that the appropriate protective films are formed on the interacting surfaces by chemical and physical reactions. This is a very active field in current basic tribology research.

Lubricants are usually produced by large oil companies who maintain substantial R&D establishments directed at lubricant formulation, most of which is based on proprietary information. These oil companies are also active in other areas of tribology R&D.

If a client industry is large, such as is the case with the automotive industry, the necessary collaboration exists between supplier and client in the combined development of components and lubricants. A different situation can pertain with smaller and more diverse client industries, such as the manufacturers of specialized transportation equipment, the manufacturers and users of industrial machinery, and with metal working generally where each client tends to have to select from the range of lubricants already available from the lubricant manufacturers. In these cases it makes sense to foster R&D in lubrication in the broadest sense (i.e. including system design, as well as lubricant formulation) to improve on current technology.

4.342 Specific

From an examination of the estimates by D'Silva et al. [1] for the losses due to friction and wear in individual industries and by type of component, adding the estimates for similar types of wear and friction in similar components, seven topics emerge as specific candidates for R&D. Each of these involve losses of at least 100 million dollars per year.

The application of each potential R&D topic is by no means limited to the sectors noted. These are merely the sectors for which the topic appears in the report by D'Silva et al., with a specific estimate of losses from the type of process concerned. In general the potential for application of the R&D is much wider than indicated.

The actual application of any R&D suggested by this list will depend on the way the R&D is performed.

Research may be performed in a basic scientific manner. Indeed there has been far too little of this type of research in the areas referred to below. However, this leaves open the question of mechanisms for applying the knowledge gained to actual practice, and there are many problems in the application of laboratory work to practice, particularly the prediction from laboratory results, when the scale of the parameters involved differs very widely.

At the other end of the scale, research performed with a particular industrial application in mind, can be successful in that application. However, if it has been performed by, or in close collaboration with a particular company, the transfer of any resulting technological improvements to the whole industry sector in question may be slow, and an application to related problems in other industries may be even slower. This applies more strongly when the improvement to the basic knowledge in question is limited, making it difficult to extrapolate to circumstances differing from that studied.

It is the opinion of the Associate Committee on Tribology that basic research should be undertaken with effective knowledge of the industrial systems in which the new knowledge may be applied. It is also essential that R&D is undertaken aimed directly at specific operations in specific industries. It is an advantage if more than one company is involved in any such project, not least in formulating the project and providing technical support. Failing the joint involvement of several companies in a particular project, the sole participation by a single collaborating company should not be discouraged. From the D'Silva et al. report the following topics emerge as good candidates for R&D, listed here in terms of obvious objectives, rather than the methods of attack. The methodology is best developed by those actually performing the R&D in question.

The losses identified by D'Silva et al. [1] for the situations listed in the industries surveyed are indicated as follows. Since the scope of the survey was necessarily limited, it should be stressed that in each case the type of loss concerned will be much larger, particularly when other industries are included.

1. Reduce abrasive/impact wear of flexible components, such as tires and belts. Losses about 800 million dollars annually.

    Applications include truck and bus transportation, agriculture and mining.

2. Reduce abrasive/impact wear of rigid components, such as ploughs and shovels. Losses about 600 million dollars annually.

    Applications include agriculture and mining.

3. Reduce friction/wear at rail/wheel contacts. Losses about 500 million dollars annually.

    Applications include rail transportation.

4. Reduce wear due to lubricant contamination in engines. Losses about 100 million dollars annually.

    Applications include truck and bus engines.

5. Reduce cutting tool wear. Losses about 100 million dollars annually.

    Applications include the pulp and paper, forestry, and wood-products industries.

6. Reduce wear of high friction materials. Losses about 100 million dollars annually.

   Applications include truck and bus transportation.

7. Reduce wear at elevated temperatures and loads in elastohydrodynamic lubricated contacts (transmissions). Losses about 100 million dollars annually.

It is emphasized in this report that the bulk of tribology R&D should be closely linked to the needs of industry, and that the initiative for much R&D in tribology, even where government support is needed and appropriate, should come from industry. However, given the generic nature of tribology, it is inevitable that some of the tribological problems in industry will be either seen as relatively minor in any given company, or will be of short duration if they are given some expert attention. Once the company has tackled a wear or friction problem (if it does indeed tackle it rather than accept it as normal) and has solved it, whether with its own resources or with outside help, the problem is likely no longer of much interest to that company's personnel.

However, tribology centres and consultants associated with them, will readily perceive any common pattern in the requests for assistance they receive over a period of time from many companies in the same industry or from widely different industries, and so will be in a good position to undertake, or recommend, R&D projects to tackle the problem as a generic concern.

Tribology centres can therefore serve the additional important function of being a "feed-back" channel by which generic R&D needs in tribology would be identified.

4.35 Areas of concern

4.351 Tribology as a Technology within Technologies

Tribology is likely to be critical to the reliability and efficiency, and hence to the commercial success, of most mechanical and many electrical products.

Shortcomings, limitations or failures in many technologies, both well-established and emerging, are often due to inadequate tribology or tribological failures. Occasionally a failure can be quite spectacular even though the tribology relates only to a relatively small component, as was the case in the Mississauga rail incident, when thousands of people were evacuated from their homes. However, in most cases inadequate tribology, in the form of premature wear or unnecessarily high friction, tends to be accepted erroneously as normal or inevitable.

The development of all power technologies using water, steam, internal combustion, and nuclear energy has depended on tribology. Many kinds of electrical equipment, from generators to switchgear to printers depend on tribology. Even in nominally static structures such as bridges and roads there is tribology to be considered, such as at the pads incorporated in the deck supports in most bridges and in the design of the surface of paving.

4.352 Qualified Human Resources

It is evident from the survey by D'Silva et al. [1], that a scarcity of personnel who are up to date in the basics of good tribological practice, or who are even aware that there are significant options in the tribology relevant to the industrial equipment or products which they deal with, are serious matters in the face of current technological developments in other major industrial nations. Compared with major European nations, the USA, and Japan, there are very few people in Canada qualified to take full advantage of tribology in their sphere of activity, be it in consulting, design, operation or maintenance.

Any strategy to enhance R&D in tribology will largely fail to accomplish its objectives, unless the strategy includes measures which will promote the increase of qualified human resources.

Fortunately, much can be accomplished by training and education in tribology which builds on prior technical training. Through both short and extended courses and programmes, further education of professionals and technologists who have a prior education in engineering, materials science, physics, chemistry, mathematics and mechanical technology, will do much to ensure that tribological practice in industry will be enhanced. In the UK, short courses have indeed been a major activity of the tribology centres and university and college departments with a focus on tribology.

In the longer term there will also have to be an appreciable increase in Canada in the effort devoted to tribology at all levels of post-secondary education. At present most offerings of courses in tribology are made on an ad-hoc basis in Canada. In most Canadian universities tribology is only a recognized topic if there happens to be a faculty member on staff who insists on offering the subject. Typically, a faculty member who provides instruction in tribology will have been appointed to fill a vacancy in some other area and any course offered in tribology is an option likely to be dropped as soon as that instructor leaves.

There are, of course, historical reasons for this situation, and appropriate courses cannot be offered unless qualified instructors are available. An R&D strategy for tribology has to include measures which will promote the appointment of qualified tribologists at a number of Canada's universities and technical colleges. However, appointments can only be made if appropriate qualified personnel is available. Therefore, an expansion of courses and research programmes at the graduate level will be needed to increase the pool of tribologists available for both academic and industrial positions.

4.353 Technology Transfer

Neither existing knowledge nor new knowledge produced through research and development can be of much value without the transfer of that knowledge to industry. Most innovations in tribology will have application in a wide range of industry since tribology is a generic technology. It is therefore especially important in a technology like tribology that appropriate mechanisms for technology transfer are in place and that technology transfer is recognized as an important part of a strategy for tribology R&D. This concern was strongly expressed at the 1984 Montebello workshop [2]. Technology transfer was also identified in the Dowson and Taylor survey [14] as a high priority and it is a major component of the current ECUT/DOE programme in the USA [22].

Technology transfer occurs through information services, through advice from consultants, through courses and through the temporary or permanent transfer of personnel. In some cases it is also a question of the movement of equipment.

A strategy to encourage technology transfer will have to be such as to encourage the development of sources of information and expertise in tribology as well as to encourage the utilization of the technology by the appropriate recipients. The strategy will have to include the development and enhancement of sources of information on tribology in libraries, databanks, and the like. The strategy should also encourage the development of consulting services. It will be important to reach the relevant industrial and advisory personnel to make them aware of the opportunities for their companies and industries through improved tribological practice.

4.354 Opportunities for Tribology R&D for Canadian Industry

The survey by D'Silva et al. [1] has highlighted several sectors of Canadian industry in which losses due to friction and wear are very significant. The losses in agriculture, transportation, mining, pulp and paper, forestry and wood product industries are all large enough to justify, and indeed make it imperative, that more tribological R&D is focussed on these particular sectors. Tribology R&D is bound to also be important in other sectors, such as manufacturing, which of necessity were not surveyed by D'Silva et al.

A number of suggestions have been made by D'Silva et al. for projects which will benefit the sectors surveyed. These suggestions are listed in detail in Appendix 3.

Attention is drawn to the several topics relating to transportation equipment. Since transportation equipment is important in many industries in addition to the transportation industries, R&D in tribology in this area should benefit a very large portion of the economy.

A second general thread which runs through these suggestions is an emphasis on combating abrasion and erosion. The scientific study of the mechanisms of wear involving abrasion and erosion has hitherto suffered some neglect relative to other areas of tribology. Much the same can be said for studies on a technological scale of abrasion and erosion. There has, however, been an appreciable increase in recent years in the interest shown in the R&D community in these topics and the time is clearly ripe for more work to ensure that Canadian industry, particularly the resource sectors, will remain abreast of current technology in this regard.

In general, in the wide range of equipment in industry subject to abrasion and erosion, this type of wear can be combatted by employing resilient materials, such as elastomers, by surface treatments hard-facings, or other classes of hard materials, such as ceramics. There is a great deal of scope for R&D in the development and application of these materials and processes, linked to work on tribological applications.

Surface modification and treatment, the coating of surfaces with hard-facings and the utilization of ceramics in new applications such as engines, are all technologies in which there is a great deal of current interest. These pose considerable challenges in tribology, as most of these developments are aimed at applications in which wear and friction are limiting factors. The tribology required to ensure minimum friction and wear, in some cases through lubrication for very severe conditions, tends to be of a very high degree of sophistication.

A very large proportion of the energy and wear losses in agriculture can be ascribed to the movement of tools in soil. The process by which agricultural tools wear evidently includes impact, abrasion and chemical action (affected by fertilizers). A lack of concern for tribology or a lack of knowledge of the subject among investigators in this area is likely to have delayed progress, so the prospects for improvement are good.

The users of agricultural equipment, i.e. farmers, are not generally knowledgeable about tribology, and it may be unrealistic to expect enough farmers to acquire this knowledge to provide any influence on the manufacturers of the equipment they use. This is in contrast to the situation in some other major industries, such as mining, where most users are companies operating on a scale large enough to permit the employment of engineers potentially capable of developing technical specifications for equipment component modification or replacement. Consequently, agriculture presents a special challenge and a clear case for government encouragement and intervention to promote R&D to reduce friction and wear on soil engaging tillage tools.

D'Silva et al. point to the development of the continuously variable transmission (CVT) as a project of considerable tribological importance. This R&D area involves the design and development of a new class of transmissions which could replace conventional transmissions and thereby dramatically reduce the losses due to friction in transportation. This project is not aimed so much at improving equipment of a type currently in wide use, but rather at replacing what is current, the conventional gear box.

This R&D area requires the utilization of a range of technologies and scientific knowledge, of which tribology is one essential component. However, there are important differences between the aspects of tribology involved in the CVT and those which apply to conventional transmissions. This is an example of an area where the tribological demands in the design are of a high order, involving much new knowledge and new directions in research and development in tribology.

The CVT is an example of a new 'high tech' technology in which success will depend on mastering the tribology involved. The "ceramic engine" already referred to above is another such example. The increasing automation of manufacturing through numerical control and robotic devices brings with it a host of stringent demands in terms of the precision and reliability of complex machine components, many of which depend critically on tribology for that precision and reliability. On a larger scale, the development of high-speed rail transportation modes, and the economic operation of shipping and other modes of transportation in the Arctic will depend critically on tribology.

In summary, a strategy for R&D in tribology, has to take into account the needs of established industries and technologies in conventional situations, the needs of conventional industries and technologies in new and harsher environments, and the requirements arising in new technologies.

4.36 <u>The realization of an R&D strategy in tribology</u>

Two characteristics of tribology tend to exert opposite influences on industry participation in tribology R&D. On the one hand tribology is very much an applied science and technology, with obvious application in industry and so one would expect considerable industrial participation in tribology R&D. On the other hand most specific topics in tribology apply to a variety of devices used in many different industries, i.e. this is a "generic technology", and the benefits to any individual company from tribological improvement are often modest in relation to the R&D required to make the improvement, so that individual companies tend to place a low priority on tribology R&D.

There are some very significant exceptions to the above, in which the benefits to a company from changes in tribological practice are far from insignificant. It is nevertheless evident from the survey by D'Silva et al. [1], confirming much anecdotal evidence from other sources, that a great many companies do not appreciate the benefits of having good advice on tribological matters, or of supporting R&D in this area.

The interdisciplinary nature of much of tribology is a third characteristic which adversely affects industry participation. For instance, the typical mechanical engineer in industrial employment, who has not taken continuing education or graduate courses in tribology, is unlikely to know enough chemistry or metallurgy to appreciate these aspects of many of the wear and lubrication problems encountered.

A fourth problem affecting tribology is the perception by many industrial personnel that the current level of wear or friction is normal in a piece of equipment. Even if it is obvious that rather severe conditions exist, for instance if abrasion is involved, there is often little reason to assume that the wear rate cannot be reduced. The problem is a lack of awareness of the potential benefits from improvements in tribological practice, when the current practice is accepted as "normal".

The major purpose of this report is to encourage R&D which will benefit industry, but unless industry participates in the R&D, it is not likely to reap the optimum benefit. Industry participation, and the generation of industry participation, has to be a key component in recommendations formulated here. Yet, we are also concerned with a number of factors which agencies of government are best equipped to deal with, including the collection and transfer of information, the development of technical expertise, and the promotion of R&D which is applicable to a range of industries rather than to a specific industry or company.

Some R&D projects in tribology are undertaken in industry when the need or opportunity, along with potential benefits, have been identified. Undoubtedly the existence of a critical situation for the company in question and the presence of appropriate facilities and personnel for the R&D in the companies concerned are conditions for the undertaking of R&D projects by individual companies or company groupings.

Various government programmes providing support for R&D will reduce the risks to the company performing the R&D. The assistance these programmes provide is valuable not only where incentives are appropriate; the programmes can and should be used to provide contracts for the performance of R&D which will benefit an industry sector. While the initiative for contract R&D can come from government, it is preferable that the initiative comes from industry, as this makes it more likely that the work will meet a need, and that the work will be performed with interest and appropriate expertise.

There are undoubtedly many R&D projects, not least in connection with tribology of an advanced nature, which can be promoted through government contracts with specific industrial R&D establishments.

However, the generic nature of tribology R&D will often make it of considerable importance that the technology developed is disseminated widely. It is also likely that a combination of basic and applied research is required, which may best be ensured through the collaboration of more than one company and the involvement of laboratories in universities, government or other major R&D organizations. A deliberate strategy is needed to encourage this kind of interaction in pertinent R&D initiatives.

A number of suggestions are provided here for specific R&D projects in tribology which are relevant to industry in Canada. However, the conduct of most, if not all, of these projects, and the implementation of the results derived, will depend on the interest and involvement of the pertinent industry and the availability of qualified investigators and designers. The participation of industrial companies and organizations, and the initiative of the engineers and scientists concerned, are prerequisites for the successful execution of these R&D projects.

The technical expertise in Canada, which can be applied to tribological projects is dispersed in industry, government laboratories, research foundations and associations, and universities, much of it of a specialized nature. A strategy for the encouragement of appropriate R&D in tribology should encourage the joint involvement of industry and research organizations outside industry, in projects of mutual interest.

This type of partnership will also be important for the development of an expertise in tribology in research groups and organizations, which will be available to a variety of partners in industry on a continuing basis. This is clearly the policy being pursued through current tribology programmes in the Federal Republic of Germany, where there already are a number of centres of expertise in tribology.

Centres of expertise have been a major component in the R&D strategies adopted in other countries. In the U.K. three designated "tribology centres" were created in the 1960s and have continued to serve industry well, alongside an expanded R&D effort in tribology in industry, university science and engineering departments and other organizations.

The U.K. centres of tribology were all created at locations at which considerable expertise already existed in tribology, and the existing expertise became the basis for each centre. Several centres of expertise in tribology do exist, or are emerging, in Canada.

Here we distinguish, for the purposes of the present discussion, between "centres of expertise" in tribology and "tribology centres". The former is taken to be a location where an appreciable amount of research or development in tribology occurs, typically more research than development though this is not necessarily the case. The latter is a centre established for the express purpose of offering a range of services in tribology to industry, including R&D under contract, consultancy, testing and information services, and courses of various lengths and coverage.

We can take a "centre of expertise" in Canada to be a location where at least two professionals, with support staff, are devoting a major portion of their work to tribology, in particular where the institution concerned has a continuing commitment to R&D in tribology. With this criterion the Tribology and Mechanics Laboratory in Vancouver of the Division of Mechanical Engineering and the Industrial Materials Research Institute near Montreal, both within the National Research Council Canada, the Chalk River Laboratories of Atomic Energy of Canada Limited and the Mechanical Engineering Department of the University of Waterloo, qualify as current Canadian centres of expertise in tribology R&D outside private industry.

These centres of expertise could certainly form the basis of a network of "tribology centres" in Canada, in the sense that they could be expanded to offer the range of activities and services of a tribology centre with a strong emphasis on service to client companies. This expansion would require a deliberate policy on the part of the host institutions, government agencies and other interested parties on the question of funding, support services, and the direction and co-ordination of effort both within and between the centres.

This leaves open the question whether centres of tribology, or centres of expertise in tribology, would also be needed in other locations. If other centres are needed, the manner in which they would be established, promoted, directed, and funded, also has to be addressed at a later stage.

As a first step it would be advisable to build on existing expertise, with measures to ensure that this expertise is accessible, on equal terms, anywhere in Canada where there is industry which can benefit from it. The problems in providing access can be solved with appropriate government support.

The centres should see it as their role not only to build and expand on their present expertise, but also to adopt structures and practices which will facilitate the sharing of their expertise on the widest possible basis and, in particular, to foster expertise in tribology in the independent consulting community. There are undoubtedly many engineers and scientists who will be able and willing to provide consulting services in tribology (along with activities in other fields) in major and minor centres of industry, if they can associate themselves with one or more centres with tribology expertise and specialized equipment.

Several issues are significant to tribology R&D in Canada. The development of expertise, the dissemination of existing information, the involvement of industry in the R&D, and the promotion of R&D in tribology in critical existing and emerging industries are probably the most important ones. Of these the development of expertise and the dissemination of information are probably the most critical factors, upon which all efforts to develop in other aspects will depend.

The losses in Canada due to friction and wear amount to more than five billion dollars a year. An increase, amounting to one percent of this figure, in the annual expenditure in Canada on R&D directed towards reducing these losses (not an increase in the amount spent on maintenance, which may be a common response to such losses) would be a modest increase in R&D expenditure. One percent amounts to at least $50 million a year, of the order of ten times the current R&D in this area.

The recommendations presented here imply expenditures by government adding up to less than $5 million a year, with the annual costs of several of the individual recommendations costing less than the value of a modest executive home, or the size of many special grants made by government research agencies to individual university departments for major equipment and facilities. In short, these recommendations are modest.

The recommendations are modest because it is recognized that the enhancement of R&D in tribology has to go hand in hand with the development of expertise in the subject area. For this reason alone, the strategy for an enhancement in tribology R&D, covering an initial period of about five years, has to be modest. Furthermore, the funding mentioned relates only to support by federal government agencies for the programmes recommended. Several of the programmes will depend on the involvement of industry, from which funding can be expected in the form of cost-sharing, user fees, contracts and grants, providing an increasing portion of programme costs as the involvement increases.

Most of the recommendations imply a review of the programmes proposed three or four years after initiation. An important aspect of many of these reviews should be the evaluation of the involvement of industry, and the success in providing a service to industry. A continuation and expansion of many of the programmes beyond the pilot stage should be possible, to a level commensurate with the full extent of the tribological problems and the potential benefits being addressed and with the expertise available to address it.

4.37 Recommendations

4.3701 Strengthening of Industrial R&D in Tribology

R&D performed in and by industry must be a key ingredient in any R&D strategy. R&D projects selected by industry for performance "in-house", are going to be ones of immediate concern to industry and the results are likely to be implemented. Clearly this type of R&D should be encouraged, mainly because valuable R&D is thereby performed, but also because the presence of R&D personnel in industry is a key factor in technology transfer in general to and within the industry. In respect of tribology the interaction between specialists both outside and within industry is a key element in progress in this area, as in any other aspect of technology.

Several of the following recommendations relate to R&D which would at least partly involve organizations outside industry. They should not, however, be construed as statements placing less emphasis on industry than on government and other non-industrial R&D establishments. There is currently so little R&D in tribology in Canada, and so much which could be done in this area to benefit the nation, that all forms of increased participation in tribology R&D will be welcome, especially R&D projects conceived and performed in industry.

Several programs and mechanisms exist for government support of R&D by industry, with criteria depending somewhat on the nature of the project. There is every reason for industry to take advantage of these for tribology R&D.

It is therefore recommended that industry enhance its R&D efforts in tribology, taking full advantage of its own resources, industrial support programmes and support available through unsolicited proposals made to government.

4.3702 Joint Government-Industry Support of 'Mission-Oriented' R&D Programme in Tribology

Various funding programmes already exist for government partnership with industry and R&D organizations in joint R&D projects. These programmes should be taken advantage of, and other initiatives taken, to carry out tribology R&D on projects of direct interest to existing industry.

Projects could be in the areas of agriculture, forestry, manufacturing, mining, pulp and paper, transportation, or in new and 'frontier' technologies such as ceramic engine components and northern transportation. A deliberate initiative should be taken by the government agencies to solicit the project proposals in tribology, in a manner which will produce a steady growth in quality projects in the programme and a co-ordination and identification with other components of this tribology R&D strategy.

All projects should involve a meaningful industrial contribution, commensurate with the potential benefits from the project to the participating company (or companies). Current expenditures in tribology R&D in Canada appear to be in the order of $8 million per year in industry, government and universities. A pilot programme which will raise this very low expenditure by at least one-quarter should be feasible.

It is proposed that the budget for a pilot programme be as follows (in $,000) in each of five consecutive years.

Year:	1	2	3	4	5
	500	1,000	1,800	1,300	800

It is envisaged that most of the projects funded here would run for three years, and it is assumed that the projects involved will be started in years 1 to 3 of the programme, with the larger projects starting in years 2 and 3, giving the budget distribution indicated here for a five-year commitment to a pilot stage.

A comparison with tribology programmes in other industrial nations and the needs here, as tabulated in this report, will indicate the extremely modest level at which this programme is proposed. However, an increase in the level of tribology R&D should go hand in hand with an increase in both the level of qualified personnel to conduct the work and the involvement of industry. It therefore makes sense to start with a modest pilot programme with the expectation that this is the first step towards attaining an effective level of nation-wide industry-government collaboration in tribology R&D.

The programme, in particular the solicitation and evaluation mechanisms, should be evaluated in its second and third years, so that if it is justified a continuation can be in place in the fourth year.

It is therefore recommended that a programme be developed to promote R&D, focussed on strengthening the connection between basic research, applied research, and R&D implementation, in tribology, by fostering collaboration in this area between industry and non-industry R&D establishments.

It is recommended that the appropriate government agencies use existing funding mechanisms and take any other initiative necessary to promote an R&D programme in tribology to encompass projects proposed, upon solicitation, jointly by industry (one or more companies) and at least one other R&D partner (such as a federal or provincial government laboratory, a research association or a university).

4.3703 Strengthening of Consulting Services in Tribology

Expert consulting services in tribology are in short supply in Canada, especially services directed at the solution of relatively minor problems, and the problems of relatively small companies. In many cases all that is needed is the advice of an expert. In other cases some relatively sophisticated investigation is required using expensive analytical equipment for a short time.

At least three major centres of expertise in tribology, possessing sophisticated facilities, already exist within the National Research Council Canada and Atomic Energy of Canada Limited, at laboratories in Vancouver, Montreal, and Chalk River. These centres are already handling consulting work for industry, along with their own ongoing R&D programmes.

A relatively modest expansion of the consulting services at these centres would greatly enhance the benefit Canadian industry can draw from these centres, which would thereby operate in a fashion similar to "tribology centres" in other countries.

Each organization has the opportunity to develop means and programmes by which the information and consulting services are provided in association with, rather than in competition with, independent consultants. Since there are currently very few independent consultants in Canada providing a specialized service in tribology, a deliberate effort should be made to encourage expertise in tribology among independent consultants, by working in association with them.

The recruitment and utilization of consultants and the support and guidance given to them at the three centres should be co-ordinated as a common effort, making the resources of the three centres available on equal terms throughout the country.

The associate consultants would act from their usual offices as collaborators with the centres, and as agents, according to the complexity of each task and the requirement for specialized services from the centres.

In most cases the consultants in question will be working full-time in consultancy either in commercial companies or in research organizations, but this programme should also be open to the involvement of university-based consultants, who normally only offer consultancy part-time.

This association between centres and consultants can include the provision of specialized services in testing and information, which can support the consultants, under appropriate contract arrangements. It can also include the joint investigation of problems and the joint evaluation of solutions.

One obvious reason for the promotion of the involvement of independent consultants in tribology, in association with centres, is the distance between all existing centres of expertise in tribology, especially the three which have been identified here, and many potential clients. Independent consultants operating in several other centres of population and industry will be able to form a useful partnership with the major establishments of R&D in tribology, provided the appropriate mechanisms are in place. The business orientation of independent consultants should enhance the effectiveness of the arrangements.

Each centre will have to hire at least one extra professional, and provide support staff to operate this programme. Notwithstanding the likely re-direction of some of the effort of other staff to make this programme possible, particularly as consulting activities increase, it is not recommended that this programme involve the curtailment of any R&D in tribology which is already being undertaken. Changes in the longer term R&D programme in the centres should occur as a response to opportunities arising from an increased interaction with industrial clients through consultancy activities.

Some funding should be available, initially over a period of five years, but renewable upon review, to support time, travel, and other incidental costs of both the consultants and members of staff at the centres which will be necessary in their interaction, and also to fund the initial organizational costs and the co-ordination of this programme at the three centres.

A budget for these additional organizational, training, and promotional aspects during the first five years is likely to be at least $700,000 a year for an additional seven professionals to be distributed among the three centres. Direct costs and normal consulting fees should be charged to all clients. Government support should remain steady, as base funding, contingent upon the adherence to the programme, and provided that the income from fees charged to clients increases as the service is established. However, in due course it is likely that the workload originating from locations remote from each centre will be taken up by newer centres. One can expect these to be established as the available pool of expertise in tribology in the country increases and as the demand for services in tribology increases.

It is therefore recommended that the National Research Council Canada and Atomic Energy of Canada Limited, jointly expand their consulting and contract R&D services to industry in tribology and support an expansion of expert consulting services in tribology provided by the existing community of engineering and science consultants.

It is recommended that federal government funding be made available through the budgets of these three agencies for "seed money" for this programme, to be used to solicit interest and involvement of consultants, to support contractual arrangements under which selected consultants will be made familiar with the facilities and expertise available at the centres, through orientation meetings and courses, and to support the publicity which will be needed to make potential industrial clients aware of the services available to them.

This recommendation is for a modest expansion and/or re-direction of effort at laboratories at which the federal government already has an appreciable investment in facilities and human resources. This does not preclude similar developments at other organizations, drawing upon experience gained from this proposed programme. While strengthening the activities of the very few independent tribology consultants in this country at the present time, this programme is also quite likely to lead to the formation of new full-time independent commercial consulting companies specializing in tribology.

4.3704 Human Resource Development

There is very little focus on tribology in universities, where engineers receive their basic education and where further study, in the form of graduate and continuing education programmes, is offered. Existing offerings tend to be adjuncts to individual research programmes, readily exhibiting a bias towards the research topics being pursued, and with much of the laboratory equipment used determined by the requirements of the research programme.

Deliberate action is required to change this situation to provide basic and advanced tribology courses with a broad practical focus. The need to increase support for tribology research and development at universities is addressed separately, though there clearly can be a link between the two types of programme. Enhancement of undergraduate instruction in tribology and the offering of more continuing education in tribology for graduate engineers and technologists must be tackled as a distinct task.

Education and training in tribology at all post-secondary levels is crucial to the successful implementation of any programme to enhance R&D in tribology. The 1966 study on tribology in the UK [3] was primarily aimed at education and training in tribology, and the recommendations in R&D were almost secondary to the recommendations in education. Without adequate knowledge of tribology among those concerned with design, maintenance and the operation of industrial equipment there can be no adequate implementation of the fruits of any R&D programme. In addition it will not be possible to go far in any R&D programme unless a greater number of engineers, scientists, and technologists conversant with tribology are available in Canada than at present.

Education in tribology must be enhanced in the form of continuing education through courses of various lengths, for practising scientists, professional engineers and technologists, and in the form of graduate studies for scientists and engineers, particularly at the masters degree level.

The involvement of industry in graduate programmes, through grants to university departments, and the support of students through participation in co-op programmes and fellowships, should be encouraged.

Some education and training of this type is already available in this country, but a considerable expansion is essential. At the university level a substantial and permanent focus on tribology is needed at several locations. Such a focus requires a commitment of faculty and technician resources, the provision of equipment for teaching purposes (some of which will also be test equipment), as well as the provision of equipment for research projects.

University faculty who are active in basic research are usually able to obtain the equipment needed for their specific research projects. However, research equipment is usually designed for specific research projects and is often not suitable for instructional purposes in the courses referred to here, particularly continuing education courses. If research equipment is used in courses, this results in a distortion of the courses towards the limited focus of the research programme.

A continuing education programme in tribology will require a wide range of equipment, much of it more suited to routine testing rather than to basic research, and the equipment will not be of much value without personnel to maintain and service it. The availability of these resources should therefore not be left to the accidental requirements of basic research by faculty members.

Participant fees for continuing education programmes for personnel employed in industry, consulting, or government, can be expected to cover the incremental costs to an institution incurred in the mounting of courses, but can hardly be expected to cover the cost of the purchase and maintenance of equipment, nor cover many of the organization expenses, especially in the early years of such a programme. The fees paid by graduate students at universities are insignificant in relation to the costs to the institution for the support of the students, the study and research they undertake, and the cost of faculty time in their supervision and instruction.

The budget for each such centre, for the minimum expansion in programme which would be viable, would be at least $250,000 per year, committed for five years, with continuing support contingent upon review.

It is therefore recommended that undergraduate, graduate and continuing education in tribology be promoted.

Specifically, it is recommended that appropriate government agencies support at least two university centres for tribology, with a focus on graduate study at the master's level and on continuing education. The support should be in the form of contributions to fund the salaries of faculty and technicians devoted to the programme and for the purchase and maintenance of equipment for instructional purposes and for service to industry.

It is recommended that industry support education and training in tribology through all appropriate means, including grants, fellowships, and co-op plans.

It is recommended that university departments of engineering include one or more courses in tribology in their curriculums.

4.3705 Strengthening Contract R&D in Tribology in Universities

Much engineering and scientific work at universities is being supported by contracts from government departments. The support can cover any R&D activity, including design, required to develop an area of technology. There are definite opportunities here for the development of R&D

capabilities in tribology in the universities, especially in some of the areas indicated in the suggestions listed in this report, including the areas which are emerging as critical in newer and existing technologies.

There is, furthermore, an opportunity here to encourage the development of more expertise in tribology in universities, which can be consulted by industry, as well as employed in R&D and teaching.

Much of the funding of research conducted in universities, is a response to the interests of the community of research workers. Indeed, no expansion of R&D in tribology at universities can be expected unless members of faculty apply for grants, contributions and contracts under the various opportunities available to them.

While work of this type does depend on the interest and initiative of the principal investigators, it can be encouraged by the solicitation of proposals in specific topics of concern to the contracting department. The support need not be confined to the support of basic research, but can cover any R&D activity, including design, required to develop an area of technology.

Industry is also encouraged to place contracts with universities for tribology R&D, or to join government agencies in such contracts (in which case this would be in line with the recommendation of section 4.372). While not excluding work of a proprietary nature being performed under the usual conditions in universities for such work, there is an opportunity for Canadian industry to make more use of universities for contract R&D of a generic nature, under conditions which will ensure the broadest dissemination of the benefits produced.

There is also an opportunity here for government agencies to link the support provided to university based R&D to R&D support provided more directly to industry. There is, furthermore, an opportunity here to encourage the development of expertise in tribology in universities which can be consulted by industry, and thus increase the knowledge of tribology among graduates in the engineering disciplines and physical sciences.

It is therefore recommended that the appropriate agencies, encourage and expand the award of contracts and contributions to Canadian universities for R&D in tribology.

It is also recommended that industry increase the placement of contracts with universities for tribology R&D.

4.3706 Strengthening Research in Tribology in Universities

Many research projects at Canadian universities, particularly in basic research, are originated by the principal research workers involved. The distribution of grant funds tends to reflect the distribution of the research interests in the academic community. In some grants programmes, such as the operating grants from NSERC, the decisions on awards are primarily based on the judgement of peer groups, i.e. engineers and scientists well established in R&D. The track record of the applicant(s) as research workers is a major criterion in the award of a grant. Under this system, established to safeguard excellence and protect freedom in basic research, two factors may act against an expansion of tribology research.

A young investigator is most likely to initiate his or her first independent research work in areas with which the investigator is already familiar and has a track record as junior research worker. Given the present low level of tribology research in Canada it is unlikely that this area will be tribology.

Committees evaluating applications in any of the traditional branches of science and engineering (physics, chemistry, mathematics, mechanical engineering, metallurgy, materials science) are unlikely to include tribologists. A member of such a committee may tend to consider applications for research in tribology as peripheral to the area for which the committee is responsible, and less interesting than some of the issues more central to the discipline. Indeed tribology does bridge all the disciplines mentioned here, and as such is peripheral to each. NSERC should exercise particular care to reduce this problem in funding tribology research.

NSERC adopts a mission-oriented approach in other award programmes, in particular those for strategic grants and associated equipment grants. Applications for such grants in the area of tribology under these programmes should be encouraged and solicited.

It has been noted here than an increase in the pool of qualified manpower in tribology R&D in Canada is also of primary concern. There is therefore an opportunity to associate, where appropriate, the encouragement of tribology research under major research grants to the support of graduate studies and continuing education in tribology.

It is therefore recommended that the Natural Sciences and Engineering Research Council (NSERC), through its grants programmes, encourage and expand awards for research in tribology at Canadian universities.

There is also an opportunity for industry to increase its support of research in tribology in universities, not least in research of a basic nature. Research in tribology must often be on a large scale in terms of equipment and other resources, if it is to relate closely in scale to the dimensions, velocities, and forces, etc. on which the tribological phenomena concerned (friction, wear and lubrication) as they occur in many forms of industrial equipment. Research which is going to produce knowledge of some immediate value in the tasks faced by industry is not always inexpensive, and it would definitely be in the interest of Canadian industry to provide substantial support such basic R&D in tribology in universities.

It is also recommended that industry increase the placement of contracts with universities for tribology R&D.

4.3707 Strengthening of Information Services in Tribology

Consulting services function as channels for information, and the strengthening of consulting services is addressed in a separate recommendation. There should also be improvements in the content and means whereby all users of information, in all facets of R&D, can obtain information pertinent to their activities. In practice this means the development of databases of various kinds and the development of appropriate means of access to the databases.

An information service will only be of value if it is accessible and if it contains information of a type, form and content which is of value to the user. Databases containing references to the scientific and technical literature are often mainly of value to the research worker. This can be a severe restriction on the use of this kind of database, if the community of interested research workers is small, as is the case in tribology in Canada. The challenge is to ensure that databases in tribology, to be developed and supported in Canada, contain information of value in maintenance, design and specification, for industries of importance in Canada. It is also important that the techniques whereby access is gained to the information are also tailored to the needs of the industrial user.

Much work of this kind has been going on in other countries, and a major tribology information system is currently being sponsored by the Department of Energy in the U.S.A. This is therefore an area where international collaboration will be pertinent and fruitful.

An involvement from Canada in international efforts in tribology information systems should be in the form of contributions which focus on particular needs of Canadian industry, complementing the contributions of other countries. NRCC, through CISTI, is already collaborating with DOE, contributing components which originated under the auspices of ACOT. NRCC is also collaborating with the Canadian Institute of Mining and Metallurgy in the exploration of the development of a wear data-base for the mining industry. This is considered by ACOT to be a very important activity, and it is recommended that the programmes in this area be supported and expanded.

Current activities in this area are in terms of short projects, and exploratory activities, for which the costs are being absorbed by the organizations involved. This kind of operation requires the involvement of specialists in databank design and operation as well as specialists in tribology, along with routine operators. The mix of personnel required will depend on whether one is concerned with a start-up phase or the maintenance of an established operation. While the nature of the personnel commitment will vary in time, a continuing service will require a modest but continuing funding for the equivalent of at least one professional with support staff and facilities, i.e. a budget of the order of $150,000 per annum, in addition to income from user fees, which should rise as operations expand, and cover the incremental costs of the service to users and the cost of expansion.

It is therefore recommended that the National Research Council Canada, develop and maintain information services in tribology directed to the needs of Canadian industry, in the areas of R&D, design, and maintenance, and to the needs of all other R&D in tribology in Canada. It is recommended that these services be developed in collaboration with information services in tribology in other countries, in particular current Department of Energy (DOE) programmes in the USA, and in collaboration with the industry groups being served.

4.3708 Strengthening of In-House Programmes in Tribology in the National Research Council Canada

The current five-year plan of NRCC places emphasis on strengthening its relationships with industry.

An appreciable amount of tribology R&D is being performed in various NRCC laboratories, involving a considerable investment in skill and equipment. This represents a very valuable resource which should be expanded and exploited, in line with the current five-year plan of NRCC to increase the emphasis on involvement with industry. A review by a body incorporating industrial representatives knowledgeable in tribology should be helpful in this regard.

It is therefore recommended that the current programmes in the National Research Council Canada in tribology R&D be reviewed by an advisory committee, with a view to identifying the additional contributions NRCC is best suited to make in tribology R&D, and to increasing the benefits NRCC can provide in tribology to Canadian industry.

ACOT is prepared to provide, or recommend on, members for advisory committees on tribology.

4.3709 Co-ordination of the Tribology R&D Programmes

Just as tribology is interdisciplinary in a technical sense and relates to a variety of industries and economic sectors, so the recommendations made here relate to the responsibilities of several agencies of government.

Much of the potential benefit from the individual programmes will be lost if each is undertaken in isolation, or if similar initiatives are undertaken by several agencies without adequate information transfer and co-ordination.

All the agencies listed above should have an involvement in the tribology strategy. The funds required to implement the recommendations are in each case relatively modest, and even in aggregate do not amount to a very large programme. Nevertheless the potential benefits to the economy are substantial and some attention should be paid at a senior executive level in the agencies concerned to the promotion of the R&D and to inter- and intra-departmental co-ordination.

An initiative is needed to establish a co-ordinating body providing communication and, where appropriate, joint funding of programmes in tribology, such as may be the case for programmes fitting recommendations 4.371 to 4.374. The Associate Committee on Tribology encourages its parent, NRCC, and the agency it has worked most closely with, EM&R, to take the initiative with other agencies to form an inter-agency consultative committee to promote and co-ordinate the tribology programmes recommended.

It is therefore recommended that Energy Mines and Resources Canada and the National Research Council Canada establish a joint interdepartmental committee, with representation from Agriculture Canada, Regional Industrial Expansion, Transport Canada, and any other department involved significantly in tribology R&D.

It is recommended that this committee report to the appropriate Assistant Deputy Minister in each department and the Vice-President (Laboratories) of NRCC, to co-ordinate the implementation of the recommendations on tribology programmes requiring agency funding. This committee should provide for liaison with NRCC's Associate Committee on Tribology (which can act to promote and co-ordinate strategy as indicated in Recommendation 4.379).

4.3710 Publicity, Promotion, Feedback, and Review

The effect of the several components of the strategy proposed here for tribology R&D will be less than may be expected if there is no co-ordinated policy of information and review involving the participants in the programmes and the pertinent industries and sectors of the R&D community. The Associate Committee on Tribology of NRCC is already a forum with members from industry, universities and government concerned with tribology. This committee, like other associate committees, holds seminars and workshops from time to time. It also issues a "Tribology Newsletter".

ACOT is therefore the obvious choice of an organization to hold conferences and workshops and issue bulletins, directed at promoting the programmes in the strategy, providing opportunities for all parties involved to share information on progress and results, and to give industry and the R&D community in general the opportunity to find out how the maximum benefit may be obtained from the programme.

The frequency of seminars and workshops required will be greater than those hitherto held by ACOT. It is likely to be advisable to hold similar sessions in different locations across the country. It will be appropriate to sponsor speakers from ACOT, from the groups involved in the tribology R&D programme, and experts in particular aspects of tribology, to speak at the seminars or workshops or at meetings held by other organizations.

Much of this type of activity typically relies on volunteers who donate their time, and on their employers who commonly pay the expenses. The demands of the proposed programme exceed those which might reasonably be underwritten in this fashion. At the very least, the expenses of organizers and key speakers will have to be covered. Payment of clerical staff involved in meetings organization, record keeping, and the production of records of the proceedings, and translation between the official languages, will have to be provided for.

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The editorial work for the production of the Tribology Newsletter is currently a volunteer effort, with a modest printing budget. An expansion to promote the tribology strategy and cover the resulting programmes and meetings can best be handled with a professional editor/manager hired under contract, working with an editorial committee and production staff.

The success of these activities will depend as much as ever on the time and effort of volunteers from the tribology community. For the duration of the recommended programmes there should be an increase of at least $15,000 a year in the budget allocated by NRCC to ACOT, to provide for non-recoverable expenses incurred on behalf of ACOT in these activities.

It is therefore recommended that the National Research Council Canada, through its Associate Committee on Tribology (ACOT), hold regular conferences and workshops at different locations across Canada for the review and promotion of tribology R&D in Canada and, in particular, for the review of the implementation of the recommendations in this report.

It is recommended that ACOT provide, as appropriate, advisors and advisory committees for individual projects in the tribology strategy, and that ACOT devote special meetings, as appropriate, for detailed review of any or all of the projects.

It is recommended that the NRCC through ACOT expand and enhance its publication of reviews and other items of information on current tribology technology and tribology R&D, to support the programmes in the proposed strategy.

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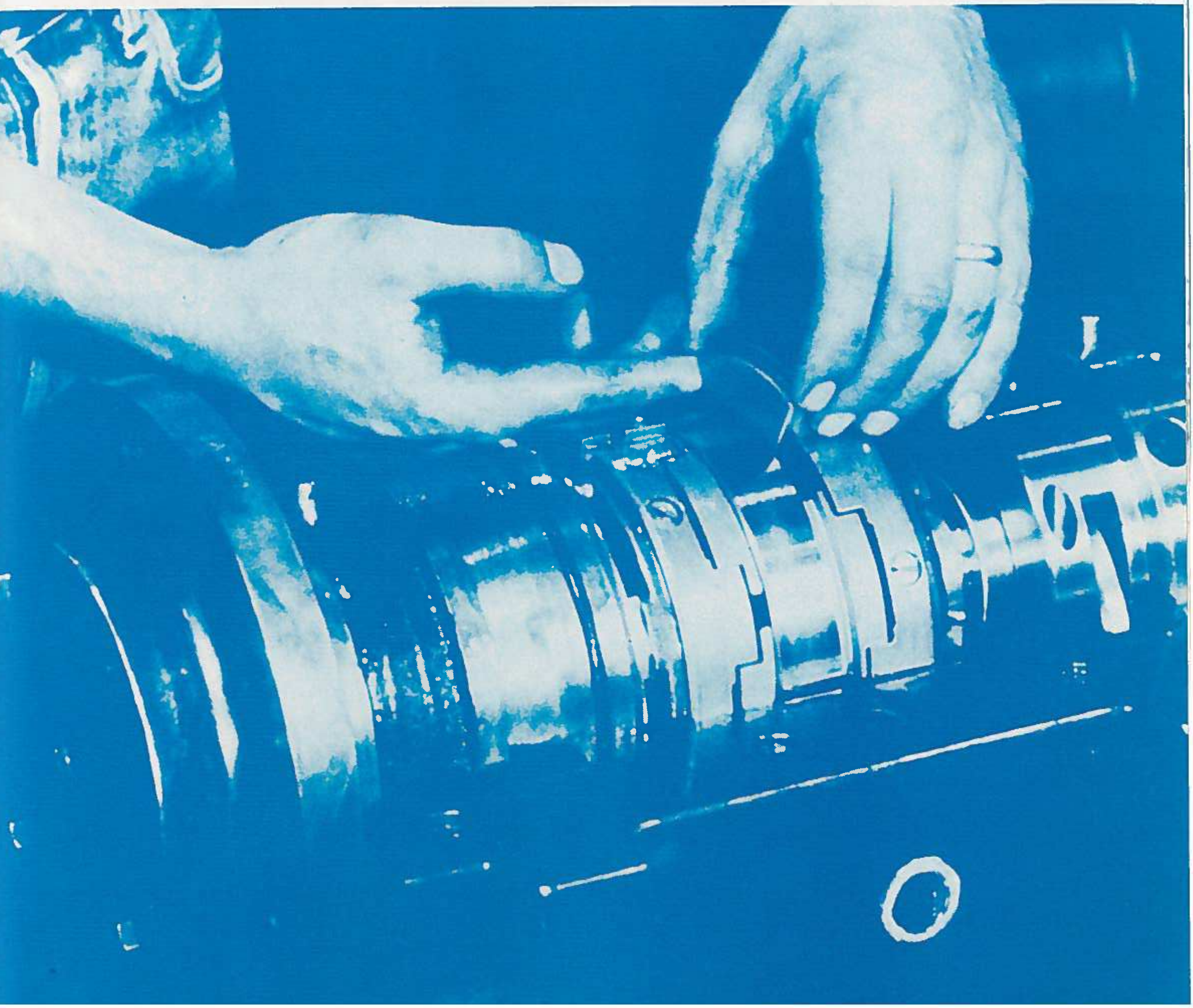
6 Acknowledgements



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Appendixes

Appendix 1

The definition and meaning of tribology

According to the Jost report [3] tribology is defined as follows:

> TRIBOLOGY
> is the SCIENCE and TECHNOLOGY of interacting surfaces in
> in relative motion and of the practices related thereto.

This term includes the subjects of friction, lubrication and wear, e.g.:

The physics, chemistry, mechanics and metallurgy of interacting surfaces in relative motion including the phenomena of friction and of wear.
Fluid film lubrication e.g. hydrostatic, hydrodynamic, aerostatic and aerodynamic.
Lubrication other than fluid film, e.g. boundary and solid lubrication.
Lubrication in special conditions, e.g. during metal deformation and cutting processes.
The properties and operational behaviour of bearing materials.
The engineering of bearings and bearing surfaces (e.g. plain and rolling bearings, piston rings, machine slides, gear teeth, etc.) including their design, manufacture and operation.
The engineering of bearing environments.
The properties and operational behaviour of fluid, semi-fluid, gaseous and solid lubricants and of allied materials.
The quality control and inspection of lubricants.
The handling, dispensing and application of lubricants.
The management and organisation of lubrication.

H. Czichos [24] elaborates concerning the multidisciplinary aspect of tribology: Since tribology is defined as "Science and technology of interacting surfaces in relative motion", it includes not only the work of physicists, chemists and materials scientists interested in the surface properties of materials but also the work of engineers who use "interacting surfaces" for the transmission of motion, forces, work, etc., in various types of machinery. Therefore, tribology is connected with several branches of science and technology, like physics, chemistry, materials science, mechanical engineering, lubrication engineering, etc.

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Appendix 2

Extrapolation of Savings due to Improved Tribology in Canada from Foreign Studies [1]

2.1 Extrapolation of savings from the Jost report

The energy and material savings through improved tribology were estimated using 1965 data from the Jost report [3], in the following manner. The figures were calculated using Canadian data for 1982 unless otherwise stated.

(a) Reduction in energy consumption through lower friction saving = 7.5% of electrical energy used by industry plus an equal value from internal combustion engines in industry
2x [proportion saved] × [industrial electrical energy] × [electric energy price]
2x [0.075] × [4.9 × 10^{17}J] × [3.6$/GJ]
Estimated saving = 265 M$

(b) Reduction in manpower

Saving = 0.13% of cost of manpower in manufacturing industry [3]
[Proportion saved] × [Wages and salaries in manufacturing industries]
[0.0013] × [43.4 G$]
Estimated saving = 56.3 M$

(c) Savings in lubricant costs

Saving = 20% of lubricant sales [3]
[Proportion saved] × [volume of lubricant sales] × [price]
[0.20] × [885 × $10^3 m^3$] × [283 $/$m^3$]
Estimated saving = 50 M$

(d) Savings in maintenance and replacement costs

Saving = 20% of maintenance and replacement costs [3]
[Proportion saved] × [Annual repair cost for machinery and equipment]
[0.20] × [13268 M$]
Estimated saving = 2654 M$

(e) Savings of losses consequential upon breakdown ignored.

(f) Savings in investment due to higher utilization ratios and greater mechanical efficiency

Saving = 1% of expenditure on new equipment and machinery [3]
[Proportion saved] × [Annual cost of new equipment and machinery] [7]
[0.01] × [28871 M$]
Estimated saving = 289 M$

(g) Savings in investment through increased life of machinery

Saving = 5% of expenditure on new equipment and machinery [3]
[Proportion saved] × [Annual cost of new equipment and machinery] [7]
[0.05] × [28871 M$]
Estimated saving = 1444 M$

Summary

(a)	Reduction in energy consumption through lower friction	265
(b)	Reduction in manpower	56
(c)	Savings in lubricant costs	50
(d)	Savings in maintenance and replacement costs	2654
(e)	Savings of losses consequential upon breakdown	ignored
(f)	Savings in investment due to higher utilization ratios and greater mechanical efficiency	289
(g)	Savings in investment through increased life of machinery	1444
		4758

2.2 Extrapolation of saving from Jost and Schofield

The energy and material savings for 1982 through improved tribology in Canada were estimated using 1979 or 1980 data from Jost and Schofield [4], as follows:

2.21 Transport Sector

2.211 Group 1: Savings obtainable without R&D

$$\frac{\text{[Estimated UK savings]} \times \text{[Production cost]}}{\text{[UK vehicle sales]}}$$

The production cost of vehicles in Canada was $25700 M$ [1]

$$\frac{(79 \text{ to } 140 \text{ M£})}{11780 \text{ M£}} \times 25700 \text{ M\$} = 172 \text{ to } 305 \text{ M£}$$

2.212 Group 2: Savings obtainable through medium-term R&D

$$\frac{\text{[Estimated UK savings]} \times \text{[Canadian annual fuel bill]}}{\text{[UK annual fuel bill]}}$$

$$\frac{\text{[Canadian annuel fuel bill]}}{\text{[UK annual fuel bill]}} = \frac{11800 \text{ M\$}}{4870 \text{ M£}} = 2.42 \text{ \$/£}$$

2.2121 Piston rings and cylinders

33 M£ × 2.42 $/£ = 80 M$

2.2122 Transmissions

(123 to 182 M£) × 2.42 $/£ = 288 to 441 M$

2.2123 Lubricants and viscometrics

(97 to 146 M£) × 2.42 $/£ = 235 to 354 M$

2.2124 Total estimated group 2 saving in the transport sector

613 to 875 M$

2.213 Total estimated transport sector saving

785 to 1180 M$

2.22 Industrial Sector

2.221 Savings through improved performance

$$\frac{\text{[Estimated UK savings]} \times \text{[Canadian annual energy bill in manufacturing]}}{\text{[UK annual energy bill in manufacturing]}}$$

The total Canadian manufacturing energy bill in 1982 was 7780 M$ [8]

$$\frac{\text{[Canadian manufacturing energy bill]}}{\text{[UK manufacturing energy bill]}} \times \frac{7780 \text{ M\$}}{4900 \text{ M£}} = 1.59\text{\$/£}$$

2.2211 Power Generation Turbines

energy losses in bearings
(22 to 29.5 M£) × 1.59 $/£ = 35 to 47 M$

seal losses
17 M£ × 1.59 $/£ = 27 M$

rotary pump seals
3 M£ × 1.59 $/£ = 5 M$

2.2212 Manufacturing and Process Industries

(70 to 140 M£) × 1.59 $/£ = 111 to 222 M$

2.2213 Secondary Savings in Industry

(24 to 26 M£) × 1.59 $/£ = 38 to 41 M$

2.2214 Total Estimated Industrial Sector Savings

216 to 343 M$

2.23 Domestic Sector

$$\frac{[\text{Estimated UK savings}] \times [\text{Canadian domestic energy bill}]}{[\text{UK domestic energy bill}]}$$

The total domestic energy consumption in Canada for 1982 was 6120 M$ [8]

$$\frac{(80 \text{ to } 120 \text{ M£}) \times 6120 \text{ M\$}}{4293 \text{ M£}} = 114 \text{ to } 171 \text{ M\$}$$

2.24 Summary

	Savings M$		
Transportation	785	to	1180
Industrial	216	to	343
Domestic	114	to	171
	1115	to	1694

An overlap factor of 20% was applied by Jost and Schofield [4], because the savings were not all thought to be additive. Hence the result was multiplied by 0.8. Final estimate of total saving 892 to 1355 M$

2.3 <u>Extrapolation of savings from the ASME report</u>

Potential energy savings for Canada were estimated from information in the ASME report [6] using Canadian data for 1982 [8]. The ASME report uses 1975 data which have been updated to 1980 values. A common formula is used for all four sectors.

$$\frac{[\text{Estimated proportion of US energy saved}] \times [\text{Cost of energy sector}]}{[\text{Proportion of US energy consumed by sector}]}$$

2.31 Transportation

$$\frac{0.022 \times 11800 \text{ M\$}}{0.195} = 1331 \text{ M\$}$$

2.32 Power Generation

$$\frac{0.002 \times 4548 \text{ M\$}}{0.23} = 40 \text{ M\$}$$

2.33 Turbo machinery (aircraft)

$$\frac{0.011 \times 636 \text{ M\$}}{0.0275} = 254 \text{ M\$}$$

2.34 Industrial processes (primary metals)

$$\frac{0.018 \times 2128 \text{ M\$}}{0.055} = 697 \text{ M\$}$$

Total 2322 M$

The actual figures used by D'Silva et al. [1] were slightly different, but the methods and the result is essentially the same.

2.4 Canadian energy rates for 1982 to 1983

	$/GJ
Electricity	3.6
Heating Oil	4.6
Crude Oil	4.7
Natural Gas	5.4
Diesel fuel	8.5
Gasoline	11.1

Appendix 3

Potential R&D topics in tribology identified by D'Silva et al.

Sector	Phase of Operation	Area of R&D - Description		Estimated Potential Savings, M$
TRANSPORTATION	Urban and Road (Trucks and Buses)	1.01	Development of friction materials for brakes (fibre-reinforced resin, or sintered metal-based types). Optimization of brake-counter-surface mass design for the typical usage cycle (with consideration to temperature rise vs cooling rate).	10
		1.02	Development of brake drum seals to minimize the effect of contamination on wear-out life of brake drums.	10
		1.03	Development and implementation of regenerative braking system.	60
		1.04	Improvement of seals and lubrication of linkage and bushings.	28
		1.05	Material and design development of tires.	17
		1.06	Development/co-ordination of efforts related to CVT (continuously variable transmission).	160
	Railway	1.07	Improvement/development of lubrication system for wear and friction control on the gauge (inside) side of the high (outside) rail in curved track. This development will evaluate the application of lubricant to the wheel flange rather than the rail, as is presently the case.	166
		1.08	Economical and technical feasibility study of the optimum lubrication of the full track (on the gauge side) to maximize the reduction in frictional energy losses and to minimize the resulting wear damage.	166

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description	Estimated Potential Savings, M$
		1.09 Continuous grinding of rails; economical feasibility study followed by process development if proved to be feasible.	11
	Tillage and Planting	2.01 Evaluation of the implementation of the zero-tillage (or minimum tillage) concept; economical and technical feasibility. Defining the regions within Canada where this approach can be implemented.	260
		2.02 Parametric study of the various parameters which affect the wear and frictional energy losses of tillage tools. The study will evaluate the tool mateial/coating and its geometry under various abrasion mechanisms encountered in practice; namely, low stress, high stress and gouging. Also, evaluate the related structural design of the equipment, e.g., stump-jump design and effect of pre-compacting.	5
AGRICUL-TURE	Planting/Harvesting	2.03 Simulation and evaluation of the abrasive wear mechanism of various materials/grains combinations with particular consideration to "combines" and pneumatic grain conveyors and airflow seeders. The latter application is characterized by its abrasive/erosive action.	32 + 30
		2.04 Economical study of the optimum tool resharpening cycle, from energy and maintenance cost view point - generation of data base for users.	4
		2.05 Development of friction materials for brakes (fibre-reinforced resin, or sintered metal-based types). Optimization of brake-counter-surface mass design for the typical usage cycle (with consideration to temperature rise vs cooling rate).	5

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description	Estimated Potential Savings, M$
		2.06 Development of brake drum seals to minimize the effect of contaimination on wear-out life of brake drums.	6
		2.07 Development and implementation of regenerative braking system.	66
	Planting/Harvesting	2.08 Improvement of seals and lubrication of linkage and bushings.	4
		2.09 Material and design development of tires.	5
		2.10 Development/co-ordination of efforts related to CVT (continuously variable transmission). (Areas 2.05 to 2.10 are similar to areas 1.01 to 1.06 respectively.)	185
	Wood Preparation	3.01 Mechanics and mechanism of wood cutting; cutting tool materials and geometry, and optimization of the process parameter (speed, tool sharpness, feed rate, ...).	12
		3.02 Process development for wood treatment and debris removal prior to wood cutting.	6
		3.03 Material development for wood handling equipment.	8
	Mechanical Pulping	3.04 Characterication and contol of the dynamics of the pulp refining system: plates design and clearance, number of refining stages, and accommodation of feedback control system.	3
		3.05 Mechanics and mechanism of wood fibre removal by grinding - characterization through some process parameters measurements.	3

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description	Estimated Potential Savings, M$
PULP AND PAPER	Chemical Pulping and Pulp Handling Equipment	3.06 Fundamental and applied study of the erosion of various materials by solid particles entrained in liquid jet. The study considers the effects of temperature, the geometry of the container/pipe/bend, flow conditions and surface characteristics (finish, hardness and geometry).	10
	Market Pulp/Paper Machine	3.07 Wear of elastomers used in roll coverings; within the flow- and pressure-limited situations: material development and improvement of press design.	5
		3.08 Development of felt material for higher wearing qualities with satisfaction of other requirements (permeability, surface smoothness and non-compressibility).	1
		3.09 Development of forming fabrics for improvement of wear characteristics.	1
	Dry End Operation	3.10 Material/coating development for improvement of abrasive wear/fretting characteristics of wires. Consideration should be given primarily to the lubricant/lubrication system during manufacturing and during operation.	2
PULP AND PAPER	Chemical and Heat Recovery Systems	3.11 Process development feasibility study: - substitution of extended heat transfer surfaces (chains) with other means to enhance the process of heat transfer at this end. - temperature control of the calcination process.	4
	Motor-Pump/Fan Drives	3.12 Variable or adjustable speed drive (ASD) to reduce energy consumption and consequential high speed wear rate.	10

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description		Estimated Potential Savings, M$
MINING	Seals	4.01	Development of seal material and design for hostile environments, both for bearings and hydraulic seals. The former has a much higher potential savings 90%. Applications are: trucks and mills, handling equipment, floatation and crushing equipment.	18
	Materials/coatings	4.02	Development of more economical abrasion resistant materials/coatings. Applications are: shovels, support equipment, mills, material handling equipment, crushing and refining equipment.	22
		4.03	Development of more economical erosion resistant materials/coatings. Applications are: mills, material handling equipment floatation and refining tanks and agitators.	9
		4.04	Development of more economical impact and wear resistant materials/coatings. Applications are: grinding balls, rods and liners.	10
	Tires	4.05	Improvement of tire design and development of materials of higher wearability.	8
	Ropes/Cables	4.06	Material/coating development for improvement of abrasive wear/fretting characteristics of wires. Consideration should be given primarily to the lubricant/lubrication system during manufacturing and during operation. (Area 4.06 is similar to area 3.10.)	2
	Harvesting and (wood cutting)	5.01	Mechanics and mechanism of wood cutting: developing material/coatings and proper geometric design of cutting tools.	5

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description		Estimated Potential Savings, M$
FORESTRY AND WOOD INDUSTRIES		5.02	Material/coating development for improvement of abrasive wear/fretting characteristics of wires. Consideration should be given primarily to the lubricant/lubrication system during manufacturing and during operation. (Area 5.02 is similar to area 3.10.)	7
	Loading and Transportation, crew transportation, and road maintenance	5.03	Development of tire material and design to improve its wearability.	3
		5.04	Effect of road condition on energy losses and rate of wear of tires of different materials and design. The study provides data for economical justification of optimum road maintenance cycle.	6
		5.05	Development of friction materials for brakes (fibre-reinforced resin, or sintered metal-based types). Optimization of brake-counter-surface mass design for the typical usage cycle (with consideration to temperature rise vs cooling rate).	5
		5.06	Development of brake drum seals to minimize the effect of contamination on wear-out life of brake drums.	6
		5.07	Development and implementation of regenerative braking system.	18
		5.08	Improvement of seals and lubrication of linkage and bushings.	5
		5.09	Material and design development of tires. (Areas 5.05 to 5.09 are similar to areas 1.01 to 1.06 respectively.)	26
	Wood Processing	5.10	Materials/coatings development for wood handling equipment and chains.	20

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description	Estimated Potential Savings, M$
UTILITIES	Fossil Power Generation	6.01 Development of abrasive and erosive resistant materials/coatings for coal and ash handling equipment.	7
	Nuclear Power Generation	6.02 Hardfacing techniques and self-lubricated materials compatible with radiation environments, required to extend wear life without sacrificing the reliability of operation.	3
	Hydraulic Power Generation	6.03 Development of cavitation resistant materials and repair procedure for implementation on turbine runners to reduce downtime and labour costs.	10
		6.04 Development of erosive-abrasive resistant materials/coatings to reduce energy losses by penstock surface wear. Development of monitoring technique of surface roughness deterioration of penstock.	8
	Common/Turbine Journal and Thrust Bearings	6.05 Studying the use of tilted pad and laminar flow bearing designs. Also, the use of a one bearing-per-turbine shaft design to reduce energy losses.	4
		6.06 Improvement of lubrication system with effective and reliable cooling and filtration methods and adoption of a particle count monitoring system to reduce abrasive wear rates.	3
	Common/valves	6.07 Development of a reliable seal design and development of erosive/corrosive resistant plug and seal materials. Development of hard-facing techniques to reduce wear losses.	2
	Transportation and Mobile Work Equipment	6.08 Improvement of seal material/design. Development of wear monitoring system to implement effective preventive maintenance methods.	6

Appendix 3 (cont'd)

Sector	Phase of Operation	Area of R&D - Description	Estimated Potential Savings, M$
UTILITIES	Conductors and Line	6.09 Material/coating development for improvement of abrasive wear/fretting characteristics of wires. Consideration should be given primarily to the lubricant/lubrication system during manufacturing and during operation. (Area 6.09 is similar to area 3.10.)	4
	Motor-Pump/Fan Drive	6.10 Variable or adjustable speed drives (ASD) will reduce energy consumption and consequential high rate wear.	5
		6.11 Improved shaft sealing techniques and lubrication systems.	2

Adapted from D'Silva et al. [1]. The figures presented are theirs, rounded to the nearest million dollars, and are not necessarily endorsed by ACOT.)