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AN INDUSTRIAL TECHNOLOGY CALLED TRIBOLOGY--
THE UK EXPERIENCE AND ITS IMPLICATIONS

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27 AUGUST 1976

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broader issues are also discussed. These include the interdisciplinary approach, effective communication between academia and industry, and the concept of industrial technologies. Comments are offered concerning the lessons to be learned from the UK experience. Appendices provide brief descriptions of the proposed educational module in tribology, the symposium titled "Tribology 1976," and the practice of lubrication analysis including ferrography.

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AN INDUSTRIAL TECHNOLOGY CALLED TRIBOLOGY--
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I. INTRODUCTION

It is interesting that 10 years after its introduction one still feels compelled to define the word tribology before dealing with it. Such brief tutorials are generally not required in Britain, even among the lay public (at least those who read the *London Times*), but abroad, both east and west of Big Ben, quizzical looks still greet the use of the word. Britain is the land where tribology was born (more or less), nurtured, and finally developed into a fundable and even (perhaps) accurate way of describing an activity of science and technology. Tribology, for those who have not heard, is from the Greek, *tribos*, which means rubbing, and is: "the science and technology of interacting surfaces in relative motion and of the practices relating thereto."

Due to what many now think of as the prototype of technological fixes, the 1966 Jost Report[1], tribology has in many quarters become accepted as the answer to a central industrial and consumer problem: keeping machinery on line, and thus saving vast sums of money. The Report, now celebrating a decade of trial, said simply that tribology (the best tribology) should not be compartmentalized into packages labeled lubrication (chemistry), wear (metallurgy) and design (mechanical engineering), but rather that a new technological type was needed: a Tribologist. Thus a strong interdisciplinary effort was called for (when that word was coming into vogue) and government seed-money went into creating a new field.

To be sure, tribology had been practiced for a long time under the guise of lubrication and wear. To what extent the old days were of an interdisciplinary sort is anybody's guess; but the point is, there was no apparent recognition, until 10 years ago, that an actual need existed to approach these problems with a reorganized interdisciplinary tack.

Is tribology in reality the best approach to making the optimum dynamic mechanical system--and getting the best out of existing designs? Having spent a year traveling in the UK, covering research activities and developments in metallurgy and mechanical engineering, we felt both obliged and qualified (more of the former than the latter) to present to the US science and technology community our assessment of the state of tribology in Britain. This difficult (and, we recognize, rather pretentious) task has been most interesting and stimulating. We had opportunities to meet numerous people, prejudiced and neutral relative to tribology - and those who still do their fine work without concern for semantic details. These visits and conversations have been a delight. We have met excellent and always-cooperative people.

It is to be noted, however, that the apparently small geographical size of Great Britain can be deceptive. The amount of work on wear and lubrication is very large indeed, so that it was necessary to limit our study to only the "main activities." We left much out, and we did not have the opportunity to interview a number of individuals who are considered to be active figures in UK tribology. We offer our apologies to them--though it may be that they should feel relieved not to have been taken away from their important work by a couple of nosey Americans.

A brief statement of our motives for this study is in order. We had for a number of years heard about the rather innovative approach taken by the British in the field of lubrication and wear. Machinery breakdown and the cost thereof had, according to our current information, some 10 years ago reached unacceptable levels. The "solution" to this problem presumably lay in a new organizational framework, with an interdisciplinary approach and a healthy inoculation of government funds.

Of course, the problems have not disappeared. In fact, their solutions in these inflationary days are even more pressing; and, more importantly perhaps, engineering systems with more complexity than before have now to operate in difficult environments for long periods of time. The design of such high performance systems, for example as used in modern aircraft or in offshore petroleum machinery, requires the best possible engineering practice. Thus, it would be the best of all worlds if there were involved in the design stages a tribological expert who understood the state-of-the-art chemistry of lubrication, and who, with an expertise in materials selection, fully appreciated the actual design problems faced by the mechanical engineer. This goal is a commendable one. How far have the British come in realizing it? We sought an answer to this perhaps premature question - the field is in fact still young. More importantly, we sought to discover their victories and also their mistakes so that lessons might be learned from both.

The area of tribology has obviously extended beyond British shores, and there are active programs developing throughout Europe. In the US there are programs in wear and lubrication in a wide range of industrial and governmental laboratories, with the oil companies (albeit mostly invisibly) carrying a large part of the load. The university programs appear to be concentrated in mechanical engineering departments, with the metallurgists carrying on the research on wear. In fact, tribology workshops were organized by NSF in 1974 and by ONR during 1975 with representation from a number of academic institutions, and there have been recent meditations on the subject by the US Office of Technology Assessment. However, for the US at least, the concept of an overt interdisciplinary effort has not yet been established, and it is only recently that tribology started to be discussed in polite company.

There are cynics who will offer another definition of tribology: by rubbing two or more things together, one will get--not unlike a rabbit from a hat--research funds. Enough, in fact, to start three centers of tribology, to fund three academic chairs, to compile a large and comprehensive handbook (a prodigious task) and, perhaps most importantly, to advertise all of these things.

Should the US import the concept from Britain? An answer to that question is what this report is all about and what started us on our quest. Here, we examine the present UK tribology scene in light of the original motives for the establishment of the field and in view of the predictions and proposals made by the promulgators of the concept. This overall view, it is hoped, may help someone decide what concerted action might be taken by the US technological community.

II. BACKGROUND

1. The Seeds of Industrial Discontent

In the early 60's a collective opinion began to form among the UK industrial engineering community that much of the manufacturing equipment in use at the time was showing a significant increase in failure rate. Concern for the eventual effects of this trend was intensified by concomitant economic attitudes, particularly restraint in capital investment, and the increasing use of continuous processes in which the breakdown of component machinery was especially unacceptable. No doubt many causes were cited as contributing to the problem, but those related to friction, lubrication, and wear emerged with a strength of conviction that led to government action.

At the direction of the Department of Education and Science (DES), a Working Group was formed "...to investigate the present state of lubrication education and research in this country and to give an opinion on the needs of the industry thereof." The Working Group reported in 1966^[1] and, in what is often referred to as the "Jost Report" (after Dr. H. Peter Jost), provided a documentation of problems, recommended solutions, and potential rewards; the report has come to be the initial impulse for an enormous amount of activity in the UK and, today, in many parts of the world.

The Working Group saw three major causes for what they perceived to be the neglect of a subject of great technological and economic importance: (1) the interdisciplinary nature of the subject; (2) advances in technology, only recently (in 1966) influencing production methods, were necessary to focus attention on the problem; and (3) "lubrication" was a much-used but supremely inadequate term for the "description of the sphere of 'transference of force from one moving surface onto another.'" In this last-listed item, the Working Group revealed an interest in terminology that might well have been what led them to an act that appears to be quite important in the light of future events: in consultation with the Editors of the *Supplement of the Oxford English Dictionary*, they postulated that "The science and technology of interacting surfaces in relative motion and of related subjects and practices," be known as "Tribology." The definition is repeated here because it warrants more than a cursory examination. If taken literally, it assigns to tribology both the elegance of a science and the relevance of a technology. The coiners were clearly looking for breadth, as well, since "related subjects and practices" are also included: with such far-flung boundaries, tribology encompasses an immense family of physical situations.

The report of the Working Group contains two additional items that are especially noteworthy here. The first of these was the celebrated prediction of savings to be realized by proper applications of sound tribological methods--an annual amount of £515 million that, at the time

of the report, represented 1.5% of the GNP. The enormity of this potential economic windfall was not lost on Westminster where, on 11 August 1966, the then-Minister of Technology Rt Hon Anthony Wedgewood Benn announced the establishment of a Committee to advise on the implementation of the recommendations of the Working Group. Secondly, and among these recommendations, was the concept of Centres or Institutes of Tribology. These institutions will be described in a subsequent section of this report. The remainder of this section describes the activities and impact of what has become known as the "Jost Committee." Jost (whose full particulars included, as of 1972, CBE; DSc; CEng; FIMechE; FIProdE; Hon AMCT; Hon MIPlantE; Group Managing Director, KS Paul Limited; Director, Williams Hudson Limited; and Director, Stothert and Pitt Limited) was the Chairman of the Committee on Tribology from its inception through its final report, submitted 18 December 1972[2].

2. The Committee on Tribology

As previously noted, the Committee on Tribology was established in 1966 by the Ministry of Technology. This sponsorship was maintained through October 1970, when the Committee came under auspices of the Department of Trade and Industry. Here we shall outline the goals of the Committee, its *modus operandi*, and its accomplishments.

The terms of reference of the Committee were[2]:

- "(a) To advise the Minister of Technology on measures to effect technological progress and economic savings in the sphere of tribology.
- "(b) To advise Government departments and other bodies, where required, on matters associated with tribology.
- "(c) To examine as a matter of priority, and to make recommendations on, the best practicable means of introducing to industry the latest techniques on tribology.
- "(d) To report to the Minister of Technology annually on its own activities and on trends and developments in the field of tribology, considered to be of technological or economic significance to the nation."

With a Chairman and some 16 members (the membership fluctuated slightly over the years), the Committee set about to organize itself in such a way as to be able effectively to promote the recommendations of the DES Working Group. Initially this included the establishment of an Education and Training Committee, a Research and Liaison Committee, and a Tribology Centres Working Panel. This organization was supplemented in 1968 by elevation to Committee status of the Information and Publicity Working Party

and, as the Committee on Tribology proceeded in its activities, some sixteen additional working groups and panels were eventually formed. In all, some 118 individuals became involved.

(a) Education and Training Committee

The task of this Education and Training Committee (ETC), paraphrased here, was to: (1) Advise the Committee on Tribology concerning the materials that should be included in education and training courses at all levels and for general as well as specialist knowledge, and (2) to assist and advise in the development and use of these materials in educational and other bodies. The DES Working Group had perceived that the subject of education and training was of crucial importance in its endeavors to introduce tribology into industry--an observation fully acknowledged by the main Committee. Thus the activities of the Education and Training Committee appear to have been roughly equally divided between the design of educational programs, and the identification of ways and means for, in the words of the Committee, "penetrating the education system."

The ETC, chaired by D. Dowson (Professor of Engineering Fluid Mechanics and Tribology, Univ. of Leeds), consisted of about a dozen members chosen with essentially equal representation from government, industry, and engineering sectors of academia. In accordance with their charter, the committee estimated what they viewed as the proper tribological ingredients in courses given at all academic and practitioner levels. These efforts presumably would result in an increased acceptance of tribology as a necessary part of technological knowledge: MSc courses in tribology were established at Leeds, Reading, and Swansea (a total of 75 degrees granted as of the end of the tenure of the Committee); the Council for National Academic Awards (CNAA) amended its regulations to allow educational establishments to offer diploma courses in tribology under its aegis; the Joint Committee for Higher National Certificate in Engineering accepted the subject as appropriate for offer by colleges; and the Engineering Industry Training Board recommended that training schemes be adopted for a "Tribology Technician Engineer." In addition, a wide variety of short courses were fashioned and delivered, and among the documents created in these efforts was the publication of the Iron and Steel Industrial Training Board titled, "Guide Syllabus for Training in Tribology at Craft Apprentice Level." A "Basic Tribology Module" was identified as "representing a minimum coverage of tribology which should be present in the education of all mechanical engineers," and is reproduced in Appendix A of this report.

The ETC also conducted a variety of studies to determine the existing state of tribological education and to estimate the gap between what was, and what should have been. In a 1971 survey of 68 universities and polytechnics, 43 of whom responded to the questionnaires, it was found that tribology topics were contained in over 200 courses. It is interesting

to note, however, that of this number, about two-thirds of the course subjects were not listed as tribology, as such, but they were courses in the usual areas of fluids, materials, mechanics, etc.

In presenting its conclusions relative to education and training, the Committee on Tribology was concerned about the interdisciplinary nature of the subject and the fact that "education itself may have to become more inter-disciplinary." They suggested that activities such as theirs might appropriately stimulate changes in education requirements and in pattern of education in other fields of endeavor.

(b) Research and Liaison Committee

As laid down by the main Committee, the mission of the Tribology Research and Liaison Committee (RLC) was to (1) consult with appropriate industry, education, and research activities to define research requirements, identify problems, propose "frameworks" for their solution, and to identify long-term trends of "technological implications of future development in tribology," (2) to advise and assist with the promotion and coordination of research, and (3) annually to advise the Minister of Technology on research supported by him in the field of tribology.

The RLC group acted as a major reviewing body for the main Committee, covering a number of industrial sectors, and aiming at establishing the pattern of tribological problems, their causes, and costs. The product of their review was to be an ability to estimate the economic benefits to be realized in proposed tribological research projects.

A major result of these activities was the establishment of the RLC as a review body for the evaluation of research proposals in tribology. The Committee reviewed proposals addressing a wide variety of problems, including: abrasiveness of magnetic tapes, the study of lubricants of avoid staining of copper during rolling, diesel engine lubrication with non-distillate fuels, wear of unlubricated steels at elevated temperatures, corrosive wear, bearing instability, wear research connected with IC engine scuffing, early warning of tribological failure, fatigue in liquid lubricated concentrated contacts, plasma deposited wear-resistant coatings, and turbulent flow in large journal bearings.

In its liaison operations, the RLC found that a major deficiency existed in the utilization by industry of existing information (this was also a conclusion of the DES Working Group). Here reference is found to The Gap (our capitals) between research workers and designers which is so-often cited in discussions on science and technology in the UK. (This is in no way meant to infer that The Gap was invented in or is exclusive to the UK.) To tackle the problem, two approaches were taken consisting of an "awareness" campaign (later carried on by the Information and Publicity Committee), and the preparation and restricted distribution, mainly

to regional government staffs, of a Tribological Directory. The Directory listed over a hundred experts as recommended sources of tribological assistance. Liaison was also conducted with the Tribology Group of the Institution of Mechanical Engineers.

In their conclusions, the RLC saw one of their most important and successful functions as that of proposal evaluation. On the related problem--that of identifying research priorities--the Committee was less enthusiastic, citing needs for a closer relationship with government bodies, and for better access to information on government policies and resources.

(c) Information and Publicity Committee

The Committee on Information and Publicity (CIP) was charged with the dissemination of information about the virtues of tribology and news concerning the activities of the main Committee and its sub-groups. In addition, the CIP was to promote and assist in the collection, digestion, and dissemination of technical information; and to stimulate and record feedback from tribological users. As with the other sub-Committees, "awareness" appeared as a key issue with the CIP.

As a result of the March 1969 meeting titled, "Tribology in the Process Industries," (co-sponsored by the Ministry of Technology and the IMechE), the CIP became concerned about the "awareness" of the upper levels of management and the members of small firms. A "two-pronged" approach was adopted in which the economic aspects of tribology would be presented to management and marketing officials, and these presentations would be followed by technical sessions held on tribological subjects related to design and cost. Within a period of one year, (beginning in October 1969) a series of four such meetings, titled "Profit from Tribology," were held in Cardiff, Manchester, Sheffield, and Glasgow. The contents of these meetings appear to have emphasized the first of the two prongs: high-ranking government officials were invited hosts, the film titled "No More Problems" was featured, care was taken to ensure a full measure of media coverage, and delegates were furnished with leaflets containing a "light-hearted explanation of tribology" in terms related to the Pullmans on which they travelled to the "Awareness Meetings. There is every reason to believe the statement that "...through these events...substantial progress was made in increasing understanding of the commercial and other benefits to be obtained by proper application of good tribological design and practice."

An effort that met with limited progress was that related to the compilation of tribological case studies. Here the CIP met with several difficulties: (1) the commercial security that tends to surround tribological successes and failures; (2) the inability of industrial activities to recognize a tribological problem as such, and (3) the difficulty in phrasing actual tribological events in a form (desirable for case studies)

that either shows a principle which is capable of being re-applied or a practice capable of being repeated. Nevertheless, casebooks were compiled and distributed, mainly to attendees of the regional awareness meetings described above.

A large amount of promotional material was produced and disseminated by the CIP. This included various brochures, a catalogue of films, course descriptions, an *International Calendar on Tribology Events*, speaker's kits (for use by the Panel of Tribology Speakers), and a Tribology Symbol.

(d) The Tribology Handbook

The Tribology Handbook Exploratory Committee was established in 1967 under the chairmanship of Mr. M. J. Neale. The culmination of the efforts of this group was the publication in 1973 of the *Tribology Handbook* (Butterworths, London) with Neale as the editor of the contributions from more than 100 authors. Although our review of this document has been cursory, the Handbook is clearly valuable in its timeliness as a compilation of information on a "new" technology, and as a very tangible output of the Committee on Tribology.

The style of the Handbook is somewhat unique in its positive practical flavor--a sort of "this is the way it is" approach--which, though courageous, is perhaps misleading concerning the state of the tribological art. There is a notable lack of reference to the literature on tribology, which can leave the user of the Handbook at something of a technological dead-end. (Some recourse is provided in the references to pertinent ISO and BSS standards.) Reflective of the complexities of tribology itself, there are selections in which data are given on situations of little relevance to practical applications (and no guidance for extrapolation thereto), and other portions of the Handbook give very detailed information on very specific industrial applications with no indication as to how these might be applied to guide the design of new equipment. These deficiencies are cited by Parker (see Appendix B) as evidence of a more-general confusion in tribological definitions and classifications. Despite these drawbacks, the Handbook now exists in a technological environment where once there was a vacuum--those involved are to be congratulated on their considerable effort, and they should be encouraged to expand and refine their "baseline" document.

(e) The Centres of Tribology

The 1966 DES Working Group saw the creation of Centres of Tribology as a means of spanning The Gap. Universities did not always relate their work to the needs of industry, and in addition, the results of research work in universities and other establishments were often phrased in such a way as to be unintelligible to potential users. (In the US and elsewhere, these problems were emerging to form part of what has since been referred to as the field of "Technology Transfer.") Extracting from

paragraph 91 of the DES report[1], "Industry has a great need for very close relationship to, and ready communication with, the centres of research in tribology so that engineers and designers on the one hand, and scientists on the other, can speak of industry's problems in a common language. Until this is acknowledged, industry's need in this sphere will never be fully met."

The Committee on Tribology endorsed the concept of Centres of Tribology and, in November 1967, recommended the establishment of Centres at the University of Leeds, the University College of Swansea, and the Reactor Engineering laboratory of the UK Atomic Energy Authority (UKAEA), at Risley. Each Centre was to give general tribological service to industry within its locale, and nationwide services in areas of specialization: Leeds for "bearing design," Swansea for "metallurgical industries," and Risley for "hostile environments."

Without delay, the Minister of Technology implemented the recommendation of the Committee, including the granting of funds in the amounts of £75,000 for Leeds and £40,000 for Swansea to assist during the first two years of operation. The Risley operation was separately established and funded through the UKAEA. Further government funds have been provided through the first four-to-five years of existence of the Centres: a noteworthy feature of their birth was that each Centre should become self-sufficient during this period. A Management Advisory Committee, with representatives of the Committee on Tribology, was set up by each Centre, and the Centres were expected to maintain "close liaison" within the constraints imposed by the confidentiality of their commercial work.

Finally, it should be noted that the National Engineering Laboratory (NEL) at East Kilbride (near Glasgow) was included as a kind of *ex officio* member of the triumvirate, having long been a major contributor to UK programs of industry-oriented tribological research.

Today these Centres, together with the *Tribology Handbook*, are among the most-prominent monuments to the work of the Committee on Tribology. As we have noted previously, they have been major sources of information for our look at tribology in the UK, and further description of their activities is deferred to the subsequent section devoted to this purpose.

3. General

Although further comment on the Committee on Tribology will be found in the conclusions of this report, it is appropriate to mention here some of the general impressions gained from our study of its activities. One of these is that the Committee and its sub-Committees were largely concerned with promotional matters*. This is not surprising given the

*In ESN 22-7:196, R. A. Burton writes "...[tribologists] may be both scientist and engineer at once--or possibly they may be neither. Whatever they are, they are public relations conscious."

perceived nature of the problem in 1966 and the apparent absence then of any technological entity in the UK for the focus of attention on such problems. The DES Working Group, and the Committee on Tribology, appear to have been given strong government support in the beginning, and this "flying start" was more than enough to ensure a sustained flurry of activity from the enthusiastic and thoroughly-committed members of the various groups involved.

If the fanfare appears to have had an element of bravado in it, or if the potential rewards were perhaps exaggerated or, at least, unprovable, much of this can be justified by the axiom that when dealing with business, academic, and socio-political entities, sometimes a four-by-four is needed just to get their attention. One danger in emphasizing the promotional aspects of a "new technology" is that enthusiasm, rather than necessity, can become the mother of invention. In our concluding remarks, we attempt, at least, to identify such subjective observations. Here, it is sufficient to reemphasize that in the UK, and to some extent throughout the world, technical communities think more about problems in friction, lubrication, and wear, and when doing so they often think tribology.

In reviewing the final report we have been impressed with its almost overwhelming air of success. The UK government apparently accepted this attitude since, citing the activities of the Committee on Tribology as a case in point, it decided in 1970-71 to expand its involvement in the support of industrial technologies. To this end, Committees on Corrosion and on Terotechnology* and Materials Handling joined the Committee on Tribology under the auspices of the new Committee for Industrial Technology.

*Terotechnology is defined as, "...the management of physical resources...", etc. It is our "feeling" that the term refers to activities of plant management engineering, or, perhaps, aspects of "maintenance." There has been created a National Terotechnology Centre to deal with these "matters." The Centre has, in fact, "...launched the first of its series of Tero-link meetings - 'seminars' (sic) which bring together engineers and representatives of one other terotechnology discipline...for an informal interchange of views intended to give each group a better understanding of the thinking, working practices and problems of the other."

III. UK TRIBOLOGY CENTRES

As discussed above, three centres of tribology were established in 1968*. The goals of the Centres were clearly to bridge The Gap and to make a genuine contribution to solving the problems of industry through the unified approach of tribology. The steps taken by government in this venture were indeed dramatic, and the investment was made with an unusual degree of optimism and aggressiveness. We thus felt particularly interested in visiting the Centres and examining their progress after about eight years of operation.

The three Centres were visited and in each case we were hosted by the respective directors. Without exception, we were greeted with enthusiasm and candor. Problems as well as plans were openly discussed, and we were uniformly impressed by the dedication shown by staffs of the three activities.

1. The National Centre of Tribology (NCT), Warrington, Lancs.

This Centre, like the other two, was established in January, 1968. Unlike the centers at Leeds and Swansea, NCT, with the designation of "National," has had something of an advantage due to the apparent special governmental blessing and affiliation implied by the title. In fact, NCT is on the grounds of the UK Atomic Energy Authority (UKAEA) Reactor Centre at Risley and as such, probably has a less difficult time paying the incidental expenses.

Dr. W. H. Roberts is the manager of the Centre, and it was he who met with us and graciously spent some time showing us the Centre and discussing the problems faced by the Centres in general. The work at NCT is divided among UKAEA, the European Space Program, and Consultancy (comprised of government and industry). Relative to consultancy, Roberts explained that only 10-30% is government support, and this is not in the form of grants but rather, directly funded research and development programs. Currently, the total turnover is £500,000, divided evenly among the above three activities.

It is clear that industrial consultancy was the main goal in establishing the three Centres. NCT, Roberts explained, recognizes this, but such support is difficult to achieve. In his critically important area of industrially-funded programs and consultancy, the numerous contracts are generally small, ranging from £1,000 to £2,000.

When NCT started (with governmental funding guaranteed for five years), there were five professional staff members: Now there are 20 and the unit is self-supporting. To maintain this situation requires constant work

*Some of the early events at the Centres are described by R. A. Burton in ESN 21-12:259 (1967).

and demands that both short- and long-term industrial contracts be obtained. One measure of success of NCT is that "small customers" are returning after initial jobs.

NCT is very well equipped to perform a wide range of applied research and testing studies. We found the following laboratories to be particularly interesting:

The European Space Tribology Laboratory (ESTL) is a sub-group engaged in research and testing for the European Space Agency. The facilities include a "state-of-the-art-equipped" clean room for mechanical and thermal testing of special bearings and seals for use in space. There is an effort underway on electrical slip rings for vacuum use. And in the area of lubrication, they are studying and developing anti-creep barriers through chemically controlled viscosity. In aiming of precision devices, such as telescopes and antenna pointing systems, it is essential to avoid torque fluctuations in bearings, and this problem is being investigated here under a continuing program. In the area of solid lubrication for space applications, NCT is using Pb thin films (of submicron thickness) on ball bearings. This approach, they hope, can be used to avoid seizing of steel against steel.

The current ESTL contract is scheduled to run until the end of 1979. As satellites become more important to ESTL (such as weather satellite systems), so will problems of tribology. NCT feels that they can play a central role in keeping such systems functioning. Through an aggressive testing and development program NCT has indeed shown that it has the capabilities to do this.

A major aspect of NCT's initial charge and still current work is tribological factors of environment. The principal aspect of this work, considering the UKAEA landlords, has been the problem of liquid sodium in contact with alloys and various compounds. In those experiments, liquid sodium at 700°C is circulated through a test rig. A range of complex tests is run, including wear, fretting and reciprocating motion. The amount of oxygen contained within the liquid sodium is controllable, since oxide films formed by reaction of the alloys with the liquid sodium may provide some boundary lubrication.

The General Laboratory is a large room containing a number of active experiments and equipment used for trouble-shooting for industry. There are a number of instruments for testing bearings, and an interesting polymer test rig, developed for noting wear transitions during loading. Roberts showed us an interesting biomedical laboratory, in which is displayed NCT's role in the development of prosthetic devices for a knee joint.

The NCT operation is, to a first approximation, doing what it was appointed to carry out: Acting as a consultancy for industry and treating

tribology in an interdisciplinary manner. NCT also gives workshops and appears to play a vital role in the European Space Program. It does appear, however, that NCT is generally not creating new programs and new approaches. It has little time or resources to do this. In our view, they are not actually developing forward-looking research studies. In addition, their teaching efforts are minimal. NCT is in fact working hard just to survive, and they cannot - even by their own admission - be viewed as being totally independent of government. While it is true that the government grants have stopped, a fair proportion of the program is supported by Ministry of Defence money.

2. The Leeds Tribology Centre

Dr. R. J. Wakelin, Director of the Leeds Unit, notes that oil was discovered in Oklahoma in 1831, the same year that Leeds University was founded by the clothmen of Leeds. This, he feels, is a prophetic coincidence because 1831 can be considered to be the start of modern industry and of the need to service that industry - tribology. The Leeds operation is smaller than NCT, both in numbers of people and in turnover. Furthermore, it is attached in some tenuous way to the University which exacts its pound for electricity and other services, so that Wakelin's headaches begin with paying the most elemental bills - not to mention meeting the payroll. Through very hard work, however, enough small (and some big) contracts are obtained to maintain the operation.

When Wakelin, whose recent review[4] provides a useful introduction to tribology, took over some five years ago from Prof. D. Dowson (of Mechanical Engineering at Leeds), government support had ended. But with help from Dowson and others, and by beating the industrial bushes across Britain, Wakelin feels now that the Leeds Unit is viable. They currently employ 15 staff, of which five are senior professionals. In addition, Wakelin has developed a "membership" of 320 companies who, for £55/year, get a newsletter, limited free consultation and an abstracting service. He is attempting to generate a cash surplus and, currently, the Centre is marginally in the black, turning over about £80,000 per year. Wakelin feels that he is still in a position where the charges are too low, but that when they are raised, the financial picture will improve.

The Centre is very image-conscious and has developed some ongoing public relations and programs: they have an annual "International Exhibition" on tribology; there are three "Open Days" for industry; and there are one-day (and longer) conferences.

The laboratories are well equipped and, especially important, there is a good relation with the Mechanical Engineering Department, so that capabilities are greatly extended. (The ME Department has an excellent metrology laboratory, with extensive instrumentation for surface characterization.)

A lubrication testing service has been instituted, with capabilities for both physical and chemical tests. Friction and wear testing in metals, ceramics and polymers represents no problem and, together with a "Computerized National Bearing Design Service," make the Centre ideal for the solution of industrial bearing problems. Jointly with the "University Bio-Engineering Group for Study of Human Joints" the Unit is examining tribological aspects of the performance of natural and artificial joints. One success involving an industrial contract in which the Unit was involved was the development of the Dunlop Denovo tire. Here, on failure due to a blowout, a lubricant is released within the tire. This lubricant gives what is known as internal aquaplaning, plugs the puncture and, due to a constituent with a high vapor pressure, reinflates the tire. This tire, an example of good tribological design, is for sale, and, incidently, is on the Centre's automobile.

Wakelin's basic philosophy is that the Centre must be made to survive. This, he feels, will demonstrate that an interdisciplinary approach to lubrication and wear is not only essential but possible. Moreover, one has the impression that Wakelin and co-workers are not particularly concerned with semantics. Rather, they want to perform a service and are trying hard to do so.

3. The Swansea Tribology Centre

This Centre is based at the University College of Swansea, one of four main campuses within the Welsh university system. The director, Dr. A. R. Lansdown, is a virtual jack-of-all-trades, being one of the three technical staff members--the group is half its original size. The pattern at Swansea appears in many respects to be a scaled-down version of that at Leeds. Relationships with the University administrative offices appear to be fragile and sometimes strained, with a level of University commitment somewhat akin to that between landlord and tenant. The annual salary budget is on the order of £24,000, and the past four years of independent operation have resulted in a bank balance of about £10,000--a situation that precludes a great deal of long-term planning.

Lansdown is quite sanguine about the situation, seeing it not so much as a measure of interest in tribology but more as a natural result of past and current economic trends in the UK (and, to some extent, worldwide). There is "plenty of work" to be had and, although fairly constant vigilance is required, funding is maintainable at the present level. This level, as we interpret Lansdown's view, is something like a proper "interim steady state," given the existing and near-future economic environment.

Again, the relationships between the Centre and the University departments, particularly Mechanical Engineering, are completely unofficial, but cordial and cooperative. In the ME Department (Chairman, Prof. F. T. Barwell) Dr. B. J. Roylance and Mr. M. H. Jones are actively pursuing

a program of investigation into various failure monitoring techniques in which ferrography (see Appendix C), among other methods, plays a prominent role. Roylance, incidentally, is a former employee of the Centre.

The Centre laboratory is small, but equipped with a quantity and quality of equipment appropriate to the size of the operation (Lansdown has readily exploited the economies associated with the use of surplus equipment). The Centre performs various standard tests for industry and provides some more-specialized services such as failure analysis. An especially interesting capability is that of rating bearings for further service. Lansdown reported good results so far (it's much too early for a final judgement) with a system that involves the cleaning, inspection, and rating of bearings that have been removed from machinery during preventative maintenance periods.

The major project underway in the lab appeared to be the testing of non-skid surfaces for shipboard use. Here the need is for surfaces that perform at relative speeds of less than 30 kts, and this is the lower limit for most existing data on such surfaces. Under the sponsorship of the Royal Navy, Lansdown's group is experimentally determining the non-skid characteristics of a variety of surface formulations with different liquid films (like seawater) and contaminants (like jet fuel). Having once almost skidded over the side of an aircraft carrier, one of us found it especially easy to groove with this project.

The Centre also provides resident courses for practicing engineers, designers, and manufacturers. The latest three-day offering (for £115) is the tenth in a series covering the practical applications of tribological know-how concerning such things as lubricants and additives, bearings, wear, material selection, and filtration. The lecturers are selected from industry, the University, and the Centre.

Lansdown would agree with Wakelin concerning the difficulties inherent in managing contracts that tend to be of the one-shot low-profit type. These, he feels, are especially pernicious because the benefits accrued from the consulting service are far in excess of the costs to the customer, and yet these long-term benefits are almost impossible to quantify. Almost like education itself, anyone can calculate what tribology costs, but no one knows what it's worth. The difficulty is related to the problem of getting industry to think of tribology as a long-term investment. Until this happens, the Center at Swansea is likely to remain a modest operation.

IV. OTHER UK ACTIVITIES

We hope that it is obvious by now that there is a great deal underway in the UK in the tribology area. Some of it is mundane and some is the "new" tribology at all, but rather a practice in name-changing with the traditional approach to lubrication and wear. Many of these activities (with pre- and post-1966 tribology) are widely known, but many others are submerged within large university departments or government laboratories. Some industrial activities, obviously, are not visible at all. So to gauge the work of the tribologist and the results of the work of the various committees is no easy task.

We recognize the inherent limitations in attempting to "cover it all," and also know that such comprehensive coverage is not possible in a limited time frame. By speaking with a number of key individuals and visiting a fair proportion of the institutions which have tribological programs, we were able, we believe, to cover a reasonable cross section of UK activities in this field. Short reviews of some of these contacts are given below. In addition, the reader is referred to Appendix B which is a brief review of the convention titled "Tribology 1976." Here we heard some rather unexpected comments from eminent UK Tribologists.

1. Government Laboratories

(a) The Admiralty Materials Laboratory (AML)

This organization is involved with a number of topics in lubrication and wear. The Laboratory is located in Holton Heath, Poole, Dorset and was established in 1947 to assist the Royal Navy in their many and diverse materials problems. As such, the laboratory is by its nature "interdisciplinary," and, in our view, very successfully so.

Relative to lubrication and wear, a central problem faced with high performance sea-going systems is the maintenance of engines. This problem is obviously not limited to naval systems, but will involve good practice anywhere. The sea, however, represents special problems (the same can, of course, be said for aircraft). Thus "Engine Health Maintenance" (EHM) has become the battle cry of a number of UK and US defense agencies (not to mention industries).

The basic philosophy used by AML, as well as by the US Navy and at a number of UK and US institutions, is to monitor the lubricant for tell-tale signs of chemical contamination or structural debris which indicates engine wear. The trick of course is to be able to use these as indicators of impending failure; e.g., bearing fatigue and piston ring scuffing. AML employs a variety of experimental techniques in their EHM program. Dr. G. Pocock is using x-ray fluorescence to analyze for iron in lubricating oil. A wear device is lubricated by oil which is pumped through the

system and this oil is continuously subjected to x-ray fluorescence. Dr. C. A. Parker is concurrently performing visible fluorescence measurements on the same oil.

Another aspect of EHM under study at AML is ferrography. This currently fast-developing technique, described in Appendix C, involves the analysis of wear debris which is magnetically separated from lubricating oil. The EHM work mentioned here represents only a small part of the lubrication studies underway at AML.

(b) The National Engineering Laboratory (NEL)

D. Scott is the head of the Creep and Tribology Division of NEL. He has assisted in pioneering the ferrographic approach and has published widely in the field of wear (he is the editor of the journal, *Wear*). Scott has done a considerable amount of work on the metallurgical aspects of wear, and has an "engineer's sense" about problems of tribology. He believes that the research work in lubrication and wear is today to a great extent not relevant to industrial need. It is Scott's belief that many problems can be solved by the correct use of available information, and that new machines are not in reality being designed with this sufficiently in mind. Thus, machine designers tend to "start from scratch," and it is into this situation where "tribological research" has presumably found its place.

2. The "Lube Lab" at Imperial College--A Case In Point

Tribology is now established in the vocabulary of curriculum committees of British colleges of engineering. There are a variety of courses throughout the country, and with the introduction of the Basic Tribology Module (Appendix A), it is clear that tribology teaching has received a boost. As stated previously, it was not really possible for us to speak with many academics who have developed programs both at the undergraduate and graduate levels. Accepting the risks involved, we have chosen to discuss in some detail the operation of one university laboratory in which tribology is flourishing.

An eminently suitable example is, in our view, the Lubrication Laboratory of Imperial College. The founder of the Lab, and professor of Lubrication Engineering, is Dr. A. Cameron. While embracing the concept of an interdisciplinary approach, Cameron avoids the use of the word "tribology," and views many of the activities stemming from the Jost Report as "gimmicky." The operation, referred to by the staff as the "Lube Lab," is indeed a joint attack on lubrication and wear problems by chemists (of which Cameron is one), mechanical engineers, and metallurgists.

The goals of the Lube Lab are best appreciated by quoting from a recent report[3]: "...to understand the basic phenomena in lubrication

and apply them to as wide a range of problems in industry as possible...to teach students the art of research and...see how their work can best be related to the real world "

Cameron is an extremely active individual with the energy and enthusiasm to develop a well-supported teaching/research operation comprised of over 30 students working for their PhD degrees. The research of these students is divided into seven areas:

Optical Elastohydrodynamics - Here visible and infrared light is employed to study the properties of lubricants at contact points (e.g., gears or bearings). Film thickness measurements, using optical techniques, can relate much about time-dependent viscosity and fluid elasticity. Infrared techniques are being developed to determine lubrication and surface temperature.

Properties of Metals - The metallurgical problems and possibilities of tribology are vast and are in need of more attention. Surface fatigue in rolling contact is an important problem, especially due to current interest in friction drives. New approaches are being taken by Lube Lab towards this. Fretting corrosion and wear resistance of conversion coatings are being studied. Dr. A. Roberts, an Imperial College metallurgist, and currently on the staff of Lube Lab, has been studying the segregation of minor alloying elements towards worn surfaces. A new wear test machine is currently under construction and will be used together with ESCA and Auger spectroscopy. There are at least eight on-going programs centered around properties of metals related to wear.

Engine Performance - This active program is principally aimed at understanding and avoiding the scuffing of piston rings in diesel engines. A diesel engine and a variety of test rigs are being employed to determine the effect of additives on scuffing. Cameron believes that this essentially chemistry approach to the problem is unique.

Surface Topography - Optical interference methods are being used by a group of four researchers to characterize surface roughness and to determine how roughness affects crankshaft behavior. Porous coatings are being studied as well to determine how effective they are when applied to bearings.

Chemistry - Generally, and perhaps too simply, it may be said that lubricants are used to separate moving surfaces from one another. The field of the chemistry of lubrication is indeed complex, and nine researchers, mainly chemists, are concentrating their efforts in studies of adsorption and desorption of surface active agents, chemisorption of chemical additives, and the mechanisms of the formation of the so-called "friction polymers." The chemical and physical properties of fluids close to the metal surface are also being investigated. There is a strong indication that the viscosity will change near such a surface, and this phenomenon is being investigated. Dr. H. Spikes, a Cambridge graduate in chemistry, is playing a central role in these studies.

Hydrodynamics - Dr. C.M.M. Ettles, a staff member, is directing a number of studies on the thermal and elastic effects which predominate in the operation of large hydrodynamic bearings. These effects give rise to variations in viscosity and also to contortion of metal surfaces. Nine research programs, over an impressive range of topics (from non-linearities of journal bearings to theoretical studies of thermohydrodynamic behavior...) populate the lab and form a strong group in fluid mechanics as applied to tribological problems.

Gearing-Related Research - This effort, according to Cameron, is the key-stone of the lab. Every aspect of the group's expertise seems to concentrate here, from large experimental programs to theory. The Transmission Laboratory is doing both basic and applied work in machine design, culminating now in improved designs for helicopter gear boxes. Computer-aided design is used here extensively.

From lubrication studies to surface metallurgy, chemistry, hydrodynamics, etc., Cameron's group is clearly operating an interdisciplinary theme. And it works. Together with five post-doctoral researchers and a cadre of enthusiastic graduate research students, Cameron has, as of late 1975, developed a program with an operating budget of £313,800--all outside funds.

Present here is an environment of excitement where the staff and students believe that they are doing something which is unique. And, indeed, they are. Cameron believes that his approach is the right one, and feels strongly that it should be picked up by others, especially the US. As if to demonstrate his ideas, he, together with others at Imperial College have, through a labor of love, created a radically new scull for boat racing incorporating the principals of naval architecture, materials science, lubrication, etc. The boat has won ably.

V. SUMMARY AND CONCLUSIONS

As it is with so many inquiries of a similar nature, we have raised more questions than we are able to answer. We have found that the issue of tribology is complex and difficult to define even when considered in a more-or-less restricted technical sense. In the UK, however, no such restriction is strictly applicable, for the beginnings of tribology and, to some extent, its present form, are overlayed with influences that stem from a particular political and economic environment. In previous sections of this report we have attempted, with some difficulty, to limit our remarks to factual information that is, at worst, the hearsay evidence of very qualified individuals. In this section we shall attempt to summarize this information and we shall allow ourselves to interject our own interpretation of the issues and even, perhaps, a few answers. If this is something of a liberty, we hope that previously expressed apologies are sufficient. The interested reader is encouraged to consult the vast quantity of literature on the subject, an introduction to which is available from the references of this report.

1. The Problem

The motive force that spawned tribology in the UK was, according to the Jost Report, a significant loss of industrial resources due to plant and machinery breakdowns caused by friction, wear, and allied phenomena. In 1966 the problem had presumably grown to a magnitude sufficient to stimulate direct government intervention, the results of which we have described herein. Although there is no refuting that problems stemming from friction and wear are of paramount importance within the larger domains of machinery design and maintenance, it is an over simplification to imply that these alone gave birth to tribology. Many other influences were undoubtedly at work. The concern for the state of UK industry, which was laboring under the weight of many economic difficulties in addition to worldwide inflationary trends, led to pressure for government intervention which, in the UK, has long been viewed by many as a viable corrective measure.* In addition, the nature of the activities of the DES Working Group and subsequent committees has been promotional to an extent that we are led to believe that the creation of a new technology was an end in itself. We point to these factors, not as criticism, but in the interest of problem definition. If in the US a similar movement is to be

*In an editorial article titled "Tribology: A moral tale about government aid," (*London Times*, 8 March 1976) Hugh Stephenson defends the activity as a laudable example of governmental procedure. He writes, "In short, the whole little story seems to be a model of effective government intervention in the industrial sphere, producing high returns for modest outlays and regenerating the productivity of British industry by increasing its competitiveness."

sponsored, we believe that it is vitally important to acknowledge factors such as these, at the outset.

Supporters of tribology point to economic gains far in excess of the annual \$515 million predicted in the DES report. Critics claim that this prediction was a vast exaggeration. We have tried to avoid this popular arguing point because, in our view, neither side is proveable. It is probably unwise to base a "new industrial technology," on such premises, but if such predictions are to be made in the US, we urge that they be carefully documented and, in order to avoid extended post-mortems, that the design of such an economic experiment include a basis for evaluating the results. The remarks of Summer-Smith(5) will provide useful warnings to forecasters of technological economic benefits. We feel that the chief virtue of predicting enormous savings is to get the attention of potential sponsors who, we admit, are often unimpressed with proposals that do not attach a dollar-value to advances in science and technology. We further admit, however, that it is difficult for us to visualize an industry that is unable to see or, having seen, is unable to act upon a design/maintenance problem that is costing them 1.5% of the GNP.

As a cause of the "problem," the DES Working Group did identify two factors that are as real today as they were in 1966. They cited the interdisciplinary nature of tribology and, partly as a result of institutional inability to cope with such things, the inadequate communications--what we have termed "The Gap"--between the searchers for new principles and methods (largely in academia) and the practitioners (largely in industry) for whose benefit the searches, in theory, are conducted. Because of our academic backgrounds, we are not unfamiliar with this problem and have often witnessed less-than-successful swims up tradition-bound academic streams in search of its solution. We recognize industrial technologies, such as tribology, as a somewhat different approach to bridging The Gap, and shall have more to say in this regard in subsequent paragraphs.

Whereas we have spent several months observing the UK situation, we find ourselves less informed regarding friction and wear problems in the US. There are many industrial, university, and (perhaps to a lesser extent) government laboratories in the US that are conducting research into such problems. Although we see a need for a classification and coordination of such work, and perhaps even some central unifying agency, we are not aware of a need for a new industrial technology and its associated organizational framework. There is The Gap, however, and this is a proper cause celebre for a broad spectrum of existing institutions and technical disciplines.

2. The UK Approach

(a) Awareness

The terms of reference of the Committee on Tribology, previously enumerated, were largely to advise, report, and make recommendations on matters associated with tribology. To the apparent extreme satisfaction of the parties concerned[2], however, the responses of the Committee and its various offspring appear to have extended well beyond the rather modest framework laid down by the Minister of Technology. Much of this activity can be lumped under the heading of "Awareness." The coining of the term "tribology" can itself be seen as an effective semantic shortcut to be used in a nationwide campaign to intensify interest in problems associated with wear and lubrication.

The awareness motif manifests itself in every aspect of the Committee's activities--education, training, industrial management, the Centres, the Handbook--and is illustrated by such themes as "Profit from Tribology," and "No More Problems." For these efforts we give full marks, and we do indeed commend the intensity of the work and the enthusiasm of those involved; and we recommend the experiences of the UK tribology effort as a case history in effective technological public relations.

(b) The UK Tribology Centres

The UK Tribology Centres were thrust into The Gap to "form and maintain a two-way bridge with industry and to undertake research on a commercial basis." That this is a precarious position, we readily acknowledge. As discussed below, industrial/academic communications and interdisciplinary activity are two areas of endeavor that continue to pose difficult problems everywhere. We view the result of the formation of the Centres as a qualified success.

Putting an island into a river does not constitute a bridge, but, on the contrary, creates two unspanned streams where once there was one. We feel that there is yet much work to be done at both ends. On the industrial side, the awareness campaign has played a major role in sensitizing industry to the existence of tribological needs. In addition, largely due to enormous personal involvements of the Centre personnel, many industrial problems have been referred to the Centres for solution. Perhaps the central problem yet remaining, at the interface with industry, is the fact that even after ten years of hard-sell, industry still does not think of tribology in terms of long-term investment and gains. As a result, the Centre projects are small, on the average, and are of the trouble-shooting variety. Some of the attendant difficulties are: a shortage of funds for growth and future planning, a lack of support for exploratory programs, and the variety of managerial and personnel problems that accompany a month-to-month existence. We feel that these

problems, and particularly their industrial source, are linked to the suitability of tribology as a "new industrial technology."

On the academic side of The Gap the Centres, particularly those at Leeds and Swansea, are in touch with adjacent academic departments, but these alliances are maintained because of the mutual interests of the involved individuals and have no apparent official or financial bindings. A particularly important problem, we feel, is the lack of research, even on a "commercial basis," within the Centres. In the presence of this absence, the Centres tend to look like industry from the academic point of view. In the somewhat repugnant frame of reference in which research is thought of as "high" and applications as "low," the lack of viable research programs within the Centres can lead to the up and down divisions that now separate industry from academia. The involvement of academia with the Centres must, we feel, balance the industry involvement. Thus while the Centres are putting out industrial brushfires, and getting paid for it, they must maintain their ties with research at a university level. These ties, that is research programs within the Centre (by either Centre or University personnel), might be more easily established and maintained if the long-term industrial commitments could be stimulated.

There are other more-specific problems that are worth illuminating for their value as lessons. In their current "financially independent" status, the Centres do not work together as originally envisioned. This lack of togetherness is aggravated by the "special" status of the National Centre at Risley, and by the absence of any central leadership and coordination for the three. Which Centre does what work is not determined by geography or special qualifications, as originally planned, but essentially by marketing factors and by vigorous salesmanship. While we salute the free-enterprise flavor of the situation, we wonder about the long-term stability of the institutional participants in this competition. It appears reasonable to consider a merger under some form of centralized management.

The UK Tribology Centres have been, and continue to be of assistance in the solution of industrial problems. Their personnel are, in general, well-qualified and enthusiastic. The extent to which their internal activities are interdisciplinary is difficult to assess, partly because of the trouble-shooting nature of their work. As we view it, "interdisciplinary" is a term that is difficult to relate to industrial "fixes" where the particular discipline invoked is dictated by the nature of the problem. There is a need for continued vigilance regarding the bridging of The Gap, and as mentioned above, in-house research programs are needed and might be stimulated by an industrial commitment that transcends immediate problems. With these observations, and given that tribology is itself a sufficient *raison d'être*, we can see a meaningful if modest future for such institutions in the UK.

3. The Concept of Industrial Technologies

If there is some distance between the research front line and the assembly line, there is an instinct among research directors (for example) which calls for this distance to be reduced. It is into The Gap that many "industrial technologies" (IT) will enter and, in so doing, presumably fill it. An IT is thus an activity created for the purpose of assisting in the effective economic operation of a given industry (our definition). It should be "interdisciplinary," simply because the exercise of closing The Gap is "inter" to at least two elements, one of which is the "real world" that cannot be disciplined.

The question which we should like to address is how a tribological-like view will work in the practice of design in the US. The very act of engineering design, of course, ought to be and always should have been interdisciplinary. The engineer must appreciate the limitations and utility of the materials with which he is dealing. If a system must be lubricated, it is obvious that wear and lubrication will be central features of the problem, and chemical expertise will be needed in one form or the other. And so it is with engineering education. A design engineering course needs an amount of traditional subject matter sufficient to get across concepts and rules which are fundamental precepts, and then a liberal dose of exercises in which these are applied to simulated or actual real-world design problems.

There are those[3], however, who would ask us to take up a different approach to the concept of engineering design, both in the teaching and in the practice. It is the suggestion, for example, of the Committee on Tribology that an interdisciplinary approach be taken to one aspect of the design, operation and maintenance of machinery. They feel that the solution of friction problems in the design of machinery, due to the wide range of operating chemicals, materials and mechanics, will require a new technology. The goal is commendable, but to achieve it, is it appropriate to restructure the academic and industrial system of traditional expertise?

As we have noted, an IT approach, in attempting to bridge the gap between theory and practice, in actuality can leave new gaps between the two sides. Where previously, the designer found himself dealing with, say, a lubrication problem, now the same man need no longer deal with that problem because the new expert has been brought into the design stage. (One nice thing about an activity that makes a claim at being interdisciplinary is that virtually anybody can unabashedly claim the self-contradictory quality of interdisciplinary expertise. This, in a way, doth make experts of us all.) The designer (or maintainer) has presumably less to do--at least less to be concerned with. A real problem, we believe, is that the introduction of still other elements of expertise can constitute an impediment to the interactions between disciplines that

are vital to a creative design process. A good design engineer should, for example, feel compelled to appreciate the materials aspects of his system. Whether or not this responsibility is (or ever has been) felt by a majority of designers, there is some reason to doubt that the growth of a new field, materials science, has always been conducive to improved materials practices in the design process. In any case, an emphasis on a certain element of design should be accomplished with a minimum of artificial barriers such as those that attend the creation of a new technology with its entourage of experts and jargon.

The problem will be aggravated if the new technology is conceived by the technocrat and scientific entrepreneur who, though fathering a concept, and even in fact supporting it after birth, is left with the difficulty of making it legitimate. The justifications for the creation of bridging-The-Gap fields must be based on need, rather than on hot desire. This is a vital point, if only to avoid the proliferation of new technologies. We have already seen the birth of terotechnology, but why stop here? What about temperature intensive systems (thermology), combustion systems (pyrology), rotating systems (turbology), etc.? (Thus we have the problem of gas turbine lubrication: turbothermopyrotribology.)

Tribology, to us, shows that IT's can be created, but their effectiveness in the scientific and industrial arenas can be limited. Lube Lab at Imperial College stands in contradistinction to this. It has succeeded in the use of a formula whereby specialists in traditional fields are put under an administrative umbrella and without undo orchestration seem to resonate in a way which spells success. We have all seen active groups like this evolve either due to strengths inherent in a personality, the pressures of natural technological needs, or by simple luck. If these elements are present, the fanfare is less essential and the work can go sliding along on a well-greased high plane.

4. Conclusions

If the reader has turned to this section of the report for a simple list of tribological do's and don't's, we are sorry to disappoint him. We are also somewhat dismayed that the subject of our inquiry has led us in politico-economic directions that have inevitably diverted us from a more scientifically-pleasing description of current projects and future challenges in the arcas of friction, lubrication, and wear. This latter development is not without its happy side since it excuses us (we hope the reader will agree) for making some subjective observations and, of course, revealing some of our own suppressed frustrations.

We admit to having begun this study with a "we're from Missouri" attitude about tribology. The name-thing had stimulated our skepticism, and we had a need to be shown some tangible evidence of the fruits of this approach. This attitude was further fueled by the evangelistic nature

of several tribologists, especially those who advocated rather sweeping changes in industry and academia, with tribology as the prototype.

As far as tribology in and for the UK is concerned, we find that we must equivocate. We suspect that some of the motives leading to its birth have disappeared behind the veil of time and the enthusiasm of those who have willed it to be a success. But we are in no position to do more than speculate on these matters. Some positive things have happened. The Tribology Centres have solved a number of industrial problems, there is continuing involvement with European space programs, and there has been the beginning of classification and clarification of the morass of information on problems in lubrication and wear--the *Tribology Handbook*. Perhaps most significantly, for the UK, many technicians and professionals in industry and academia who should have been thinking about these problems, but weren't, are.

For the US, we see no need for a headlong stampede to follow the UK example. It is for us to learn rather than to emulate. From the industrial (and governmental) point of view, it is important to be realistic about the nature and magnitude of the problem. We hope that if in the UK there is a savings of 1.5% GNP to be realized, it will not require a Congressional committee to get action. In any case, if there are any mechanical design activities not now at least trying to practice good tribological habits, they had better get on with it. Where problems are identified, and are not amenable to in-house solution, the first look should be towards existing research institutes and academic centers of expertise. A good steer can be provided by the professional institutions such as the ASME and the ASLE. In the absence of satisfaction from these sources, it may then be time to think in terms of new organizational frameworks. Even at this advanced stage of inadequacy, should it be reached, we would hesitate to endorse the creation of a new technology. We would hope that there would already be an entity--professional or governmental--that could serve as a sponsor for the needed technological coverage.

We think that the name-game is of little more than promotional value and can, in fact, be counter-productive and misleading. To carry the point to the extreme, we might say that if there are tribologists, then there must be non-tribologists--those who carry out clandestine studies in lubrication and wear without a license to practice. Much more to the point, however, is the pressing question of how to get specialists in traditional fields to work together in a complementary way to formulate designs that incorporate the best features of all the relevant disciplines. We feel that the fact that tribology had to be created is, in some way, an indictment of the engineering community, and especially its academic underpinnings, for having failed to cope with this problem adequately. We did not have to read between the lines to see this as a source of frustration among the forefathers of tribology.

Why is it so hard for academia to be interdisciplinary? We have some thoughts on this, but we shall spare the reader the agony of our complete gospel on the subject. Suffice to say that The Gap plays an important role and the bridge must be built of that quality known as (pardon the expression) relevance. For what is the goal of all engineering endeavors except to support design? And what is the role of engineering design except to create imaginative and economically feasible solutions to the problems of society? And we trust that the interdisciplinary nature of the problems of society is an accepted fact. Engineers (and materials scientists and chemists) can and should pursue their special areas of expertise; but when it comes to relevant engineering design, which is by its very nature interdisciplinary, these experts must be able to work together. The key is design. This will at the same time span The Gap and be naturally interdisciplinary.

Where does the solution lie? We suspect that industrial activities that operate in the black are sensitive to the relevance issue--perhaps so much so that they are not imaginative in their long-term thinking. Academic institutions can't afford not to be imaginative and, with the abolition of a few archaic visions of what constitutes excellence, they can create an atmosphere that stimulates the pursuit of relevant design both in teaching and research. Sponsoring agencies can also assist by acknowledging the value of "research" in design and thereby provide the long-term commitment that is a strain for all but the largest of industries.

The difficulty of the problem is in proportion to its importance. We have seen, both in the UK and the US, examples of successful solutions that have been developed with relative indifference to the concept of new industrial technologies.

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5. Institution of Mechanical Engineers, *Tribology 1976 (Proceedings)*, Durham, 30 Mar-1 Apr 76, IMechE, London.
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APPENDIX A

BASIC TRIBOLOGY MODULE

The Module reproduced here was published in January 1975, under the heading of "Teaching Tribology to Undergraduate Engineers," and is an expanded version of that given in the report of the Tribology Committee[2]. The editor is A. F. Nightingale of the Polytechnic, Huddersfield. Some 16 authors contributed to the development of the Module, and 10 were responsible for the final writing. They represent a cross section of British industry and education and have produced a very useful teaching outline in about 70 pages of text and diagrams. The suggested curriculum for the course is reproduced below to give a sense of the range and depth covered. The Module is well referenced and is a comprehensive, though brief set of study notes to lubrication and wear. There is still insufficient overlap among the various fields of specialty. A rather more detailed textbook is needed with a tribological view in mind. It may be of some interest to note that D. F. Moore of University College, Dublin, has achieved this in a 1975 text entitled *Principles and Applications of Tribology* (Pergamon). In his Introduction Moore pays the expected tribute to the Jost Committee.

Another publication, though short, is useful: *Rolling Bearings* by T. S. Nisbet. This 43-page booklet published by Oxford University Press for the series, *Engineering Design Guides*, does not appear to contain the word tribology. The *Guides* are published under the auspices of the Design Council, the British Standards Institution and the Council of Engineering Institutions.

CURRICULUM

SECTION 1 : TRIBOLOGY APPLICATIONS AND DESIGN (3-4 hours)

Design Procedures
Characteristics of bearing applications
Types of bearings for varying applications and environments
Selection Procedures, data sheets 65007, 61107 economics criteria

SECTION 2 : LUBRICANTS (2 hours)

Classification of Lubricating Systems
Classification of Lubricating Materials (including gases) specifications, additives
Viscosity

SECTION 3 : MECHANISMS OF LUBRICATION (3-4 hours)

Mechanisms of Lubrication
Hydrodynamic, Elasto-hydrodynamic, Boundary, Solid or Dry lubrication
Reynolds Equation as an example of Combined Couette and Poiseuille flow. Vogelpohl method
Tilting Pad, thrust and journal bearings

SECTION 4 : SURFACE MECHANICS (3-4 hours)

Elastic Contact: Hertz equations; dimensional analysis
Plastic deformation and hardness
Concentrated Loads; surface roughness; conforming and non-conforming surfaces.
Mechanics of rolling

SECTION 5 : FRICTION AND WEAR (1-2 hours)

Application of Surface Mechanics to the laws of friction and wear
Classification of wear mechanisms

SECTION 6 : MATERIALS (1-2 hours)

Bearing Surface Materials
Wear Resistant Materials; solids, surface treatments and coatings
Friction Materials
Main Properties of Materials; Metals - compatibility of material pairs, lamellar solids, self-lubricating materials, Polymers and Ceramics

APPENDIX B

THE VIEWS OF THREE UK TRIBOLOGISTS--TRIBOLOGY '76

At the University of Durham, 10 years after the Jost Report (from 30 March to 1 April 1976), the convention titled "Tribology 1976," devoted a good deal of time to assessing the progress in the field.

In the first of three invited papers, Neale stated that, "Probably the major achievement of Tribology is that it has placed the blending of the basic disciplines within its subject area on a rational basis suitable for general recognition," and he went on to cite the "lack of matching between academic disciplines and practical problems." In his view "the really distinctive feature of Tribology is that it is a subject based upon the application of knowledge rather than the derivation of knowledge." He suggested that "if other application-based subjects could be defined it could be possible for a major part of science and technology to be re-divided in this way." The virtues of such a "new order" are demonstrated, in Neale's opinion, by the successes of tribology.

The second invited paper was given by Dr. R. C. Parker whose 40-year involvement with friction is continuing with a variety of consulting activities during his retirement. Parker's formidable task was to document "The Contributions of Research in Tribology," and his carefully referenced paper certainly will prove to be a useful document for engineering historians. Beginning with Leonardo da Vinci's 15th century statement on the proportionality of friction and load, Parker traced a coherent advancement of the understanding of friction processes through the works of such well-known researchers as Coulomb, Westinghouse, Reynolds, Hertz, Rayleigh, Poiseuille, and Prandtl. Of the 41 references cited, three of the research contributions were published after 1966. He concluded with the observation that although the situation in lubrication is satisfactory, "The complexity of dry friction and wear has meant that most research has been descriptive rather than analytical, while current activities are mainly directed towards development aimed at solving practical problems." As noted in the main body of this report, Parker also pointed to the confusion that has resulted from an explosion in the rate of generation of publications in the field and he boldly states that "Researches in Tribology, other than in lubrication, are unlikely to have general significance until the wide range of phenomena is ordered through new, internationally agreed, definitions and classifications."

Dr. D. Summers-Smith (Imperial Chemical Industries, Ltd.) in his paper titled, "10 Years After Jost: the Effect on Industry," took what appeared to be very careful issue with the DES Working Group. According to Summers-Smith, the main claim of the Jost Report--that £515m (1.5% of the GNP)

in annual savings could be realized by application of existing tribological knowledge--was, in short, wrong. In an item-by-item critique of the report, he pointed up several mistaken assumptions and important points that were apparently not considered.

With an admitted but nevertheless skillful use of hindsight, Summers-Smith stated that while the total predicted savings might be theoretically possible (the basis of the "theory" was not contained in the Jost committee report), when such savings are proportioned over the large number of involved manufacturing units, the resources required are disproportionate with respect to the gains. The Jost report omitted large portions of the front half of a cost-benefit analysis. Summers-Smith further pointed out that tribological problems cannot be separated from other machinery difficulties. Thus, when a plant is down the opportunity is taken to carry out remedial work other than that related to the failure, and the solution of a tribological problem might preclude this opportunity. Another somewhat obscure consideration is that wear and failure are important factors in helping to recognize obsolescence and that too-effective elimination could be a deterrent to replacing out-dated equipment.

In his estimate that, at best, only 10% of the Jost report prediction of savings has been achieved, Summers-Smith was careful to point out that several benefits have resulted from the study of the committee. These are (1) the introduction of the basic principles of Tribology into the training of engineers, (2) the presentation of the results of research and experience in a form in which they can readily be applied in practical situations and, (3) the establishment of three Centres of Tribology at Leeds, Risley and Swansea. These Centres, after about seven years of activity, have become identified as sources of tribological excellence to which the industry can turn in need.

The 19 presentations following the three invited papers described above were of the usual mixed bag--there seemed to be at least 19 separate problems under investigation, thereby giving a timely demonstration of the lack of meaningful and acceptable classification lamented by Parker. The mere existence of the convention points-up the continued UK interest in tribological matters. It is probably fair to say, however, that the mood of the meeting was one in which enthusiasm was tempered by an awareness of a number of problems yet to be solved. The proceedings are available from the meeting sponsor: The Institution of Mechanical Engineers, 1 Birdcage Walk, London SW1H 9JJ.

APPENDIX C

LUBRICATION ANALYSIS

The determination of the health of a machine by taking and analyzing a sample of its lubricant is not unlike a physician looking at blood. The analogy can be extended a step further: good health habits with an occasional trip to the doctor is far preferred to a trip to the pathologist. So it is with machinery. Engine health maintenance (EHM) is the key word in many quarters these days, both in the UK and in the US. There is actually a hope--and workers are striving for this situation--that effective prognostic techniques can be developed which will enable predictions of failure sufficiently in advance of the event to remedy it, or at least to plan for it. There is some controversy associated with EHM and the various approaches to it, but the disagreement is limited to matters of examination frequency, sampling methodology and sampling techniques. This, too, it would appear is similar to the decisions faced by physicians in evaluating the health of humans.

Now to examine the life's blood of a machine would appear to be straightforward. But it's anything but that. If the oil in machinery is to be a measure of the health of the system, the analysis must in some way be diagnostic. That is, the fluid itself must carry some evidence of the problem. A central approach to EHM is the "spectrographic oil analysis procedure" (SOAP) where the oil is examined for the atomic-scale debris which may have arisen from bearings and other parts comprising the systems. It is felt that this approach, coupled with experience, can relate much of the history of the system--e.g., temperature that parts may have reached, excessive wear, unwanted impurities carried within the oil. Another more recent development looks at the "large" debris--stuff ploughed up, scraped off, or nicked off of the wearing surfaces. This technique is "ferrography" and it is considered by some to be a major breakthrough of EHM and should, they feel, be in every practitioner's black bag (see Ref. C1 and C2). There are more who believe that ferrography has yet to prove itself as a reproducible, quantifiable approach to EHM.

Ferrography in operation is straightforward. A small sample of oil is trickled down a trough in a glass microscope slide, through the poles of a magnet and, not unlike a chromatographic method, the particles become separated according to shape and mass down the length of the trough. The slide is then examined in a microscope with various types of light so that elementary color analysis can be made. The number of particles in a cc can be a measure of debris statistics and, hence, an early indication of impending fracture. Next the art of identification comes into play, and this, to be done effectively, requires experience and perhaps

some imagination. Thus, one can presumably identify oxides of iron, by both color and magnetic behavior. Of course, magnetic and more recently, non-magnetic particles are identifiable. Practitioners go a step far beyond this: they contend that debris examination with ferrography can point to the origin of the formation (both temporally and spatially) of sources of excessive wear. For example, when a population of particles changes its shape from flakes to spheres, this implies impending disaster; i.e., bearing fatigue.

In our view, though ferrography deserves much attention, there is presently too much of a sense of acceptance before all the results are in. It remains a mainly non-quantitative test, in need of a considerable amount of experience. The manufacturers of ferrographic instrumentation, we understand, are currently attempting to develop a catalog or encyclopedia of "ferrograms." Thus, a given type particle will imply a certain kind of wear, etc. But for such a complex thing as wear in the presence of a lubricant, even the most subjective observers should advise great caution. The language of ferrography as used in commercial advertisements, semi-commercial technical publications, and by the practitioners, sounds not unlike the tribological approach to lubrication and wear. They tend to classify and sub-classify, and ferrograms are then related to what are presumably acceptable wear classifications. Wear in oil lubricated systems is extremely complex, and in a fair proportion of the cases, a classification approach is difficult at best.

We have visited a number of ferrographic facilities in the UK, and were greeted by either religious fervor or by a "Wait-and-see" attitude, we subscribe to the latter.

One further point: D. Scott of NEL, who has helped pioneer ferrography and who believes very much in its future can speak intelligently about its limitations and its possibilities. He has done much in the area of ferrography, but his use of the concept for oil analysis is not divorcible from his great insight as an engineer. Scott thus brings more to ferrography than many of us are able to do and as such he can achieve important results. Ferrography, then, as a research tool in the right hands can be exciting. But in the EHM laboratory, we believe that it has a way to go.

ONRL R-7-76

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- C2. D. Scott, "Debris Examination - A Prognostic Approach to Failure Prevention," Wear 34, (1975)