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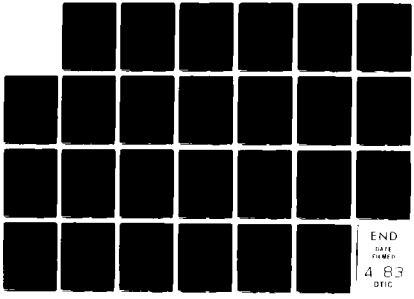

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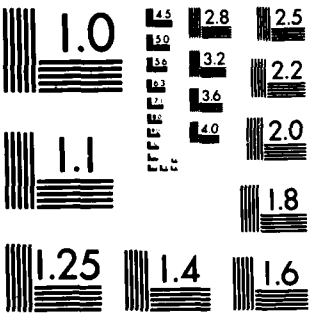
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FINAL REPORT

FUNDAMENTAL RESEARCH ON TRIBOLOGY

Frederick F. Ling
William Howard Hart Professor

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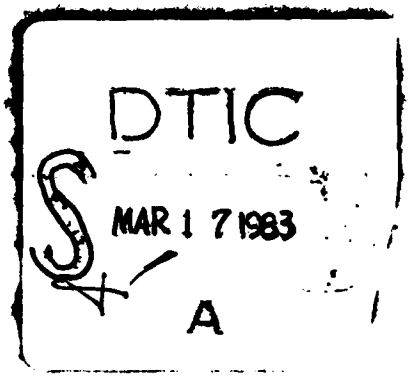

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Troy, New York 12181

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FINAL REPORT

FUNDAMENTAL RESEARCH ON TRIBOLOGY

Frederick F. Ling
William Howard Hart Professor

to

The U.S. Army Research Office
Research Triangle Park
North Carolina 27709

under

Contract Number DAAG29-79-C-0204

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January 1983

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FUNDAMENTAL RESEARCH ON TRIBOLOGY		5. TYPE OF REPORT & PERIOD COVERED Final Report September 1979-August 1982 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Frederick F. Ling		8. CONTRACT OR GRANT NUMBER(s) DAAG29-79-C-0204
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering, Aeronautical Engineering & Mechanics Rensselaer Polytechnic Institute Troy, New York 12181		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office Post Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE January 1983 13. NUMBER OF PAGES 43
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Tribology, friction, lubrication, wear, surface studies

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Final report of a three-year project pertaining to fundamental research on tribology. Topics investigated by an interdisciplinary team were: surface mechanics--smooth surfaces; surface mechanics--nonsmooth surfaces; observations of surface deformation and deterioration during sliding; the role of particulates on rolling contact lubrication in the mixed film regime; surface analysis by infrared emission microspectroscopy, laser speckle interferometry and phased-locked interference microscopy; foaming of lubricants due to

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additives/contaminants; surface reaction kinetics related to wear processes; transport processes in the contact line region; viscoelastic properties of low molecular weight polystyrene solutions; thermal effects in lubricating fluid film; coupled heating and distortion of hydrodynamic films; wear characteristics of composites; wear characteristics of water-lubricated Al_2O_3-metal sliding couples; fluid motion about a translating particle in a slider bearing.

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1. INTRODUCTION

The U.S. Army Research Office undertook to fund the interdisciplinary program in 1979, under Contract DAAG29-79C-0204, FUNDAMENTAL RESEARCH ON TRIBOLOGY. During 1980 the Advisory Panel, comprising of the Chairman, Dr. Frederick W. Schmiedeshoff, Dr. Philip A. Parrish, Dr. David R. Squire, and Dr. Edward A. Saibel, was instrumental in helping the Rensselaer research team to sharpen its goals. That is, the importance of the fundamental areas of research were reassessed while keeping in mind the areas' technical relevance.

This final report covers research conducted between September 1979 through August 1982. Section 2 discusses briefly the research area and achievements. Reprints and preprints are grouped in an appended folder. Section 3 gives an account of the research team and interdisciplinary collaboration. In the space below an examination of the need for tribology is made. It is axiomatic that the generic technology of tribology must be underpinned by fundamental research.

Tribology, the science and technology of friction-lubrication-wear, is vital to the design, manufacture and utilization of virtually every system with moving parts [1,2]. Its purpose is to optimize the energy efficiency, product durability and reliability of machines and systems.

It has been estimated by the National Commission on Materials Policy [3] that wear costs the U.S. economy 15 billion dollars a year in materials costs alone in 1973. In addition, a recent report "Strategy for Energy Conservation Through Tribology" [4] shows that up to an 11% saving in national energy consumption is possible from the direct or indirect benefits of an R & D plan consisting of some 40 specific projects dealing with friction, lubrication and wear of machine components.

Japan, France, Germany, the UK, the USSR, among others have redoubled their respective tribology research efforts since the beginning of the Army Research Office tribology project at Rensselaer. During 1981, a German report estimated the benefit to the USA to be $23,000,000,000 annually if tribology is vigorously pursued. Of course, this saving is possible only with some investment; the cost-benefit ratio in specific cases has been shown to be attractive indeed.

The wear control and friction problems in mechanical components generally determine energy efficiency, product durability and reliability of machinery, both simple and complex. These problems are usually of fundamental origin and research on them can have lasting impact on both technology and manpower preparation. The machines in which wear control is needed are of immediate importance to the effectiveness of our nation's defense missions as well as to our industrial community in general. Thus, the findings of this research project may solve immediate field problems associated with performance effectiveness, equipment availability (readiness), and reliability, while also providing an effective advance in our fundamental technology base. It is also very clear that advances in tribology can mitigate our national concerns for conservation of energy and materials of machine construction.

Rensselaer Polytechnic Institute is a recognized center for advanced research, development and education in tribology; it is the only university in the United States offering a degree program in tribology. That multifaceted interdisciplinary technology requires a diversity and intensity of expertise not usually found in a single organization but which is available in the Institute for Wear Control Research (IWCR) functional laboratories and affiliated laboratories to be detailed later.

Rensselaer has been associated for a quarter of a century with the field now covered by tribology. During that period, there have been many significant advances to the field attributable to activities here. Recently, under the formal structure of IWCR, significant problems solved include: for the MAB Metal Processing Equipment Program (MPEP), a major contribution won the French Joseph Marie Jacquard Medal, Groupement pour l'Advancement de la Mechanique Industrielle for Professor Ling; the DOT sponsored Coast Guard icebreaker hull coating study has resulted in an RPI certified coating which has demonstrated a dramatic increase in abrasion life over conventional coatings and has also shown considerable reduction of ship drag losses; the Caterpillar Tractor Company sponsored effort on cavitation erosion of bearing materials in the D-10 tractor diesel engine has broken new ground in understanding premature failures of new bearing materials; the NASA sponsored aircraft brake program has resulted in new materials and/or new designs for high energy brakes for the future.

2. RESEARCH ACHIEVEMENTS

2.1 Long-Term Goal

To improve the quantitative and fundamental understanding of wear processes relevant to mechanical components which represent advancement as to improved mechanical reliability, energy efficiency and critical material substitutability.

2.2 Near-Term Goal

To conduct research on tribology on broad fronts which are relevant to the quantitative and fundamental understanding of wear in boundary and micro-elastohydrodynamic lubricated systems, and with boundary lubricated material parts which are primarily composite systems.

2.3 Research Achievements

2.3.1 Surface Mechanics--Smooth Surfaces. Surface mechanics as an area of endeavor was coined over a decade ago to stress the importance of modeling surface related phenomena and to provide the ingredients for contact problem formulation [5] in what is now known as the field of tribology [3].

History has shown that contact mechanics in general have been the subject of inquiry since the last century. But a subset, which is of contemporary technical relevance, has only been treated in the literature more recently. The subset is characterized by moving references, the use of transform techniques, single layered media and generic solutions whenever possible. It should be noted that the singleness of layer is not limiting in light of the availability of numerical inversion via transform algorithms [6]. Examples are surface temperatures under moving heat sources: under the high speed approximation of the relevant heat conduction different equation, cases studied were the cases of a layered half space, a layered circular cylinder and a layered sphere [7]. Next is a pair of problems with surface load on a layered half space in the case of elastic layer [8] and in the case of viscoelastic layer exhibiting standard linear model [9]. Moreover, human joint cartilage has been modelled as a layered media [10]. Within the definition of surface mechanics under the smooth surface assumption, Professor Ling, various graduate students and colleagues have been examining the effects of several field interactions, of nonlinearities, of anisotropy, of environments on surfaces and of its role in tribosystem failure [11]. In the space below, the work of doctoral student Joseph Pitkin, under Professor Ling's direction, will be discussed in some detail. Dr. Pitkin is now employed by the General Electric Company.

A study was made of the governing equations of the nonlinear thermoelastic theory [12], with consideration given to both large deformations temperature dependence of material parameters. The main objective is to ascertain the importance of certain coupling terms usually neglected, with a view toward eliminating discrepancies between theory and experiment and aiding the interpretation of experimental results.

Particular attention is given to high-speed sliding contact situations, for which high temperatures can become localized near the contact surface, thus contributing to the significance of the coupling terms in this region [13].

An analysis of the characteristic surfaces for the applicable field equations discloses that a boundary layer of thermal origin can be developed for practical sliding contact speeds, low compared with elastic wave speeds but, nevertheless, leading to large values of a dimensionless parameter termed the Peclet number P_o. The boundary layer development is related to the reduction of the heat equation from elliptic to parabolic type [14] as $P_o \to \infty$.

An iterative finite difference scheme has been developed guided by the aforementioned considerations and incorporating the known features of the boundary layer. A typical contact situation has been analyzed, utilizing a rectangular finite difference grid with variable grid line spacing and 340 grid points. The results of direct searches for the 1020 temperatures and displacements are part of a paper presented at the Ninth U.S. National Congress of Applied Mechanics [15]. Suffice to say here that it was found that the retention of the nonlinear coupling terms in the thermoelastic equations can significantly affect the solution of these equations.

2.3.2. Surface Mechanics--Nonsmooth Surfaces. Surfaces are made to interact in a great variety of manners. Examples are: static thermal contact; static mechanical contact which is inferred in the thermal contact category; static electric contact which also implies mechanical contact simultaneously; sliding contact in contradistinction to the above which in general may also be dynamic contacts. Roughness plays an important role in mechanical contact [16], especially in the presence of foreign particles such as dust or wear particles. A host of interaction phenomena involving deformable medi have been and can be modelled. Suffice to note two examples: when the bulk material pair in contact are squeezed together under high pressure as in the case of metalworking [17]; when the apparent area of contact (normal load divided by yield pressure of the softer material engaged in contact) is much larger [18] than the real area of contact (sub-areas in actual physical contact).

While the examples given above are deterministic models, these may be used in conjunction with the statistical characteristics of surfaces when either the smooth surface assumption is not valid or the degree of detail to which the surface to be modelled is so high that a deterministic modelling of the surface is rendered unfeasible. In other words, when the details required are complex, the deterministic model of a single "encounter" together with the statistics of the surface have been proven to be fruitful in many situations.

In recent years, with the aid of high-speed computers, topographical information has been accrued by stylus profilometry. It should be noted that profile information by non-contact method such as the optical method pursued by Professor Lauer in 2.3.5 have yet to be brought up to the quantitative status. A computer has the ability to store, compare and reproduce

profile traces and can combine a series of parallel traces to form a three-dimensional picture of an area of a surface [19,20]. Perhaps of even greater importance, the computer can perform any desired calculation with the digitized profile. In particular, the distributions of heights, peak heights, slopes and peak curvatures and any desired moments of these distributions can be found.

Plots of cumulative height distribution versus height showed that certain surfaces have near Gaussian height distribution and others have non-Gaussian distribution [21]. A three point analysis is used [22] for defining a peak; that is, a peak is said to be occurring where one reading is higher than its neighboring readings in a height sampling given the same sampling interval. It has been shown that if the height distribution is Gaussian, then the peak height distribution is also approximately Gaussian for all sampling intervals. The peak curvature distribution is a function of peak height. Theory and experiment show that the peak curvature distribution exhibits a general tendency to be skewed towards zero curvature.

For many years the roughness of a surface has been characterized by an asperity height parameter such as the arithmetic mean height or the root-mean-square (rms) height about the centerline. Since surfaces may have identical rms heights and yet have quite different textures it is necessary to consider some means of quantifying a horizontal characteristic length such as a wavelength or slope. Random process theory has been applied to surface geometry study and brings correlation techniques and frequency domain analysis to the surface science field. In particular the autocorrelation function provides a measure of wavelength characteristics.

The use of autocorrelation functions to characterize surface profiles [23] was introduced in 1959. Correlation techniques were applied to all

kinds of surfaces [24] and autocorrelation functions and dispersion spectra were used to establish the required reference lengths for surface roughness measurements [25]. Later, additional numbers were proposed to characterize surfaces. These are the first and second derivatives of surface profiles and their ratio [26]. These were intended to give the directional properties of surfaces as they are measured.

When rough surfaces are modeled as two-dimensional, isotropic Gaussian random processes, and analyzed with techniques of random process theory, the distributions of heights of surface maxima and mean gradients are found to differ seriously from line profile peaks and mean gradients [27]. Therefore, to relate the profile properties to surface properties an assumption must be made about the nature of the surface. If a surface is known or assumed to be random, then a profilometric representation along a straight line is sufficient to characterize the surface [28].

While the complete characterization of surface roughness requires the autocorrelation function of surface profiles be known, a simpler measure may be found in a pair of numbers which are theoretically sound [29] and may be computed from surface profiles. Results have been verified by the experiment. This is true for stationary random processes. The two numbers are the standard deviation of the slope and the mean thickness of the surface profile. The former contains the behavior of the autocorrelation function of a surface profile.

Within the context of this research project there are at least three reasons why the characterization of surface texture is important. By surface texture is meant the geometrical and other surface characteristics such as deformation.

First, characterization of a surface is necessary to the understanding of the basic mechanics of friction and wear. Second, by thus relating the texture of the surface to its function, an optimal design of the surface would be possible. Finally, a characterization of surface texture independent of manufacturing processes would allow flexibility in manufacturing operation and challenge manufacturing research to introduce more efficient production of these optimized surfaces. The important link between function and texture has been under much study [30,31,32], yet no definite results have been obtained. The success of surface texture design is determined by its ability to "run-in" and serve a useful life [33].

Doctoral candidate Mary C. Dawson has been concerned with the area since January 1981. Much has been accomplished in what has been termed here as computer-aided-profilometry (CAP) with the accompanying analysis. An experimental program designed to relate run-in with certain surface roughness characterization is in progress. The emphasis is on the role of surface topography on lubrication in the mix film regime [34].

By using only one material, a consistent surface finishing technique and a single well-defined lubricant, the geometric effects can be isolated [32]. Through the use of the CAP, statistical properties of the surface can be determined and compared with experimental results. In this manner the important geometric properties of a sliding surface can be identified and compared to theoretical predictions.

Theoretical work to date has produced simple models (single asperity interactions, homogeneous material properties, Gaussian distribution of asperities, etc.) [22,27,31]. After comparison of these models with the results of the experiments, new models can be developed and tested. New research should consider more sophisticated models (anisotropic materials,

non-Gaussian distributions of asperities, traction, lubricants, etc.) [35, 36,37]. The pin-on-disc test machine can easily handle different materials and lubricants as needed to verify more advanced models.

There currently exists little experimental evidence relating the texture of a surface to its performance as part of a sliding system. This experimental work with the pin-on-disc machine and CAP coupled with analysis should provide new insights into the influence of surface features on tribological applications.

2.3.3 Observations of Surface Deformation and Deterioration During Sliding. In the pursuit of basic understanding of the friction and wear processes, much careful work has been done, see, for example, the summary of Bowden and Tabor [38,39]. Other examples include those carried out on single crystals [40,41]; this type of activity was accelerated with the and impetus of the prime U.S. space era. For machinery and mechanical systems which operate in the earth's atmosphere, the ever presence of surface oxides or man-made coatings cry out for better understanding. In Section 2.3.2, surface texture was used; it is understood to be the geometry as well as the material on and near the surface.

Earlier research and analysis was discussed. On the observation side, the scanning electron microscope (SEM), because of its large depth of field, has proven to be a powerful tool indeed for studying surfaces. A logical consequence of the recent availability of large chamber in SEM systems is the incorporation of friction/wear experiments within the chamber. Devices for such experiments have been designed [42], but the emphasis so far has been on the design and performance of the test rig itself. Only a limited number of experimental observations have been reported.

Messrs. Calabrese and Murray and students have designed and operated such a test rig. The primary motive for building this device was to evaluate the effect of the metallurgical microstructures of engineering alloys on sliding performance. Thus far, both surface deformation effects and surface deterioration have been studied.

Essentially, the test consists of a rotating cylinder, mounted on the stage of the SEM, with a spring-loaded pin sliding against the periphery of the cylinder. The entire assembly was tilted off of the vertical axis so that the electron beam would impinge on the sliding contact area. A slow speed synchronous motor was used to rotate the cylinder. Video tape recordings were made during each test for later reference and study. At various intervals, the test was stopped so that the interface could be photographed at high magnification.

The test alloys used for the cylinder and the slider pin were selected because they contained the various phases and typical microstructures found in different types of steel. These included: austenite, ferrite, martensite, and carbide precipitants.

All of the cylinders were polished and very lightly etched to highlight the grain structures. Surface roughness values, after etching, were below 0.05 μm.

The results obtained to date have significantly expanded the understanding of the wear process. Thus far, the major conclusions are as follows:

- What would normally be considered as "mild wear," based on observations with an optical microscope, was often found to be a cataclysmic event when viewed at very high magnifications in the SEM.

- o During sliding, microcracks are formed and progress through the surfaces in directions which appear to be determined by the way the load is distributed through the steel matrix. Grain boundaries do not appear to be involved in the process because the progression of the microcracks is both inter and transgranular.
- o The wear particles are produced in the form of platelets by shear forces that essentially delaminate the metal structure.
- o The wear process is dominated by the breakdown of the matrix. Hard, dispersed particles in the matrix (e.g., carbides in heat-treated steel) had no discernible influence on the results except for a change in the direction in which the microcracks formed.

A paper describing the results of this first phase of the study has been presented [43] and is being reviewed published.

2.3.4 The Role of Particulates on Rolling Contact Lubrication in the Mixed Film Regime. Until very recently, little attention has been given to the effect of abrasive contaminants on rolling contact bearing life. However, advances in elastohydrodynamic lubrication have focussed attention on the importance of surface defects, such as dents or scratches, which could be caused by the presence of hard debris.

A number of failure modes have been identified for rolling bearings [44]. These include: fatigue, excessive loading (brinnelling), lubricant starvation, electrical pitting, corrosive wear, and surface damage or wear by abrasive particle. When a hard particle is trapped between the rolling element and the opposing surface, it creates a three-body abrasive wear condition which can result in damage in the form of dents, furrows or sharp-edged scratches. Metals, bulged around the damaged

area, form shoulders that would cause stress concentrations which in turn help to initiate fatigue. The flaws can also promote asperity interactions with the abrasive or with the opposing surface, thus accelerating wear.

During the past ten years, a number of papers have been published on this subject. Of these, three experimental studies of the effect of abrasive contaminants on the fatigue and wear of lubricated rolling contact bearings are of particular interest [45,46,47]. Also see other discussions [48,49].

The third study [47] was work done at Rensselaer. Unlike the other studies, emphasis in that work was the effect of abrasive particle size on bearing performance, rather than wear or fatigue. Electrical contact resistance measurements were used to determine when metal-to-metal contacts were occurring through the elastohydrodynamic film. Effects of speed, abrasive particle size and concentration on percent of contact resistance were studied experimentally. Both mild steel and molded nylon retainers were evaluated.

With steel retainers, the percent contact was linear with respect to the natural log of the particle size. A much more complex relationship was observed for the nylon retainer. Moreover, damage is proportional to concentration. Contact resistance drops precipitously for a particle size of 0.3 μm.

One observation, common to all tests, was the fact that the contact resistance reached a peak as soon as the particles entered the bearing. From then on, the percent contact tended to drop. Bearings exposed to particles larger than the elastohydrodynamic film (0.3 μm) would not run back in (or recover), even when the contaminated oil was replaced with

clean oil. With particles smaller than 0.3 μm, the bearings recovered in less than a day, even if they were run with contaminated oil. In other words, the particles are crushed as they pass through the bearing and thereafter, they no longer affect performance.

Together with earlier studies [45 46], the work [47] showed the importance of particle size and concentration on bearing wear, fatigue life and performance. Particle hardness has also been seen to be an important factor. Brittle abrasives, such as silica, are fragmented as they pass through the bearing. Apparently, the resulting debris is too small to affect bearing wear or performance although some surface damage can still be seen under the microscope.

Studies of the effect of abrasive particles on bearing performance and wear in the EHD region of lubrication are being continued. An on-line Ferrograph wear particle analyzer, Model 958PF, has been loaned to RPI by Foxboro. This instrument is being used to monitor wear continuously during the tests. Periodically, the bearing is also being removed from test, cleaned and weighed on an analytical balance to determine weight loss. The gravimetric weight loss is then compared with the wear particle concentration readings to establish correlation. These wear measurements, coupled with electrical contact resistance values, provide a more complete picture of how the bearing responds to particulate contamination [50].

2.3.5 Surface Analysis by Infrared Emission Microspectroscopy, Laser Speckle Interferometry and Phase-Locked Interference Microscopy. Professor Lauer, during the current contract period, has continued his lifetime work on infrared spectroscopy. In the application to elasto-hydrodynamic lubrication his recent work has resulted in infrared emission microspectrophotometry (IEM) [51,52,53,54]. Recent work has shown that lubricants become aligned in a contact and that additives or impurities may fall out of solution under certain operating conditions. As a result viscosities and traction coefficients can drop, causing increased wear. Preliminary spectral data with titanium nitride-coated bearing balls are consistent with excellent lifetimes, no scuffing under our most severe conditions, but a tendency for corrosion. The coatings, though chemically inert, were sufficiently porous to permit attack of the underlying metal. Molecular alignment in the contact was greater with the coated balls than with uncoated balls. The coated balls produced a lower flash temperature (difference between the maximum temperature in the contact and the temperature in the inlet to the contact) than the uncoated balls even though the heat conductivity of the coating is less than that of the ball metal itself. Almost all of the work was carried out with just polyphenyl ether (5P4E) and one additive, 1.1,2-trichloroethane, although chemical effects, primarily friction polymers, were observed for a traction fluid with tricresylphosphate and some other single experiments were made.

Perhaps the most significant results were obtained when IEM was combined with scanning electron microscopy (SEM). Through these means the porosity of some of the bearing coatings and their relation to corrosion reactions under high stress were established. The expected

availability of a scanning Auger spectrometer will enable the determination of elemental composition on wear scars.

Professor Lauer has been developing phase-locked interference microscopy and laser speckle interferometry for surface analysis. Phase-locked interference microscopy is capable of a depth resolution of 30Å at this time. Laser speckle interferometry is less sensitive, but is simpler to use and can cover a larger field of view. Results so far showed that scuffed or scored bearing regions reacted, i.e., changed profile, by two orders of magnitude faster than other areas when exposed to dilute hydrochloric acid as a probe. Interestingly enough when the same metal was just heated locally, the extent of surface change at ambient temperature increased with the maximum temperature of preheating according to an Arrhenius relationship. This technique is therefore very sensitive as a probe for determining stresses.

In summary, in terms of instrumentation, Professor Lauer has expanded his earlier capability of surface analysis by infrared emission microspectroscopy (IEM) to include laser speckle interferometry (LSI) and phase-locked interference microscopy (PLIM). Some of his latest results have just been published [55,56].

Former doctoral candidate and postdoctoral associate Vincent King has joined the 3M Company and Dr. Leonhard Keller has returned to Switzerland.

2.3.6 Foaming of Lubricants Due to Additives/Contaminants. Professor Ross, during the current contract period since 1980, has been investigating the foaming of lubricants due to additives. Foaminess may also

occur by accidental contamination introduced earlier by chemical degradation of the lubricant itself during use or degradation of materials, such as gaskets, with which it is in contact. This work has shown that surface activity is closely related to the phase diagram of a multicomponent system.

In liquids of very low conductivity, such as hydrocarbons, there are far too few ions to adsorb and so confer an electric charge on dispersed particles, such as those that arise normally in lubricants as a result of use. Nevertheless, zeta potentials of 25 to 125 millivolts have been observed for various types of particles dispersed in nonaqueous media of low conductivity.

Separation of electric charge in non-ionizing solvents of low dielectric constant depends on the pressence of materials capable of donating or accepting electrons or protons. These materials may be dissolved species such as molecules, polymers, or micelles; or they may be the interfaces of dispersed particles or even the surfaces of container walls. The transfer of charge may occur internally, as in the transfer of a proton between a Lewis acid and a Lewis base.

Electrodeposition studies with carbon black suspended in hydrocarbon solutions of a variety of solutes demonstrate that acidic dispersants tend to produce positively charged particles and basic dispersants tend to produce negatively charged particles. The better dispersants are either micelle- substances or oil-soluble polymers having the ability to accept or donate protons. Proton transfer rules their effectiveness, so that the relative acidity or basicity of surfaces and dissolved polar solutes determine the sign and to some extent the magnitudes of electric conductivity, electrodeposition, electrophoresis, and streaming or sedimentation potentials.

An apparatus has been constructed to measure surface potentials of adsorbed solute (lubricant additive) at the metal-oil interface, using the vibrating-plate technique. This is now complete and preliminary data is being gathered.

2.3.7 Surface Reaction Kinetics Related to Wear Processes. Professor Hudson and doctoral student Lassig, during the present contract period since 1980, have carried out studies on the interaction of hydrocarbon molecules of varying complexity with iron surfaces in the manner of earlier work on Ni [57,58,59,60,61]. The rates of the initial decomposition reaction between the hydrocarbon and the surface and the subsequent uptake and migration of carbon and hydrogen into the bulk are being measured using a variety of surface physics techniques.

The second currently active area of research involves the measurement of the amount and kind of material taken up into the bulk of a sample while it is being subjected to wear. To date, samples of high purity iron have been prepared and run in a standard sphere-on-plate wear test configuration. The samples are cleaned after testing to remove traces of lubricant from the free surface, then they are examined by Auger electron spectroscopy, combined with ion bombardment etching, to determine whether components of the lubricant used are taken up into the bulk of the sample during the wear test. Initial measurements made with a conventional Auger spectrometer indicated significant uptake. The poor lateral spatial resolution of this instrument, however, leaves some ambiguity as to whether the uptake is limited to the wear scar, and to whether the occlusion of lubricant in pores or cracks is involved [62]. A scanning Auger microprobe is currently being checked out for operation

in the Surface Studies Laboratory at Rensselaer in the Summer of 1982. Once this instrument is available, further measurements of the uptake of lubricant components can be made with sufficient lateral spatial resolution to resolve the current ambiguities.

2.3.8 Transport Processes in the Contact Line Region. Professor Wayner and doctoral student Tung, during the present contract period since 1980, have been studying experimentally and theoretically heat, mass and momentum transfer in the contact line region (junction of a thin liquid film, vapor and substrate). Theoretical results concerning a general equation for the contact line boundary conditions (curvature, apparent contact angle and/or thickness) for fluid flow and heat transfer that account for temperature, superheat and surface forces have been formalized and submitted for publication. Single component systems are analyzed in these studies. The results are used to describe the interfacial profile, adsorption, rewetting and heat transfer at the contact line. Experimentally, the initial results of a study of evaporation and wetting in the contact line region of a mixture of decane and 2% tetradecane were submitted for publication. Multicomponent systems are extremely important since lubricants are complex mixtures formulated from many components. Small changes in composition have a significant effect on performance. Since preliminary studies using fatty acids/decane and isodecyl pelargonate/additives demonstrated that these systems are extremely difficult to study and analyze, a relatively simple system of decane/2% tetradecane was studied first. Even with this simple system, the transport processes were significantly altered by the addition of a small percentage of a second component. Dr. Tung has joined the General Motors Research Laboratories.

An understanding of physicochemical processes (wetting and transport processes) in ultra-thin films ($\delta < 10^{-5}$m) and in the contact line region ($\delta \to 0$) is important to good lubrication. These processes should be optimized to promote heat transfer and to minimize frictional losses. The processes are controlled by a gradient in the chemical potential which is a function of temperature, composition and film thickness. In these thin film systems, interfacial effects are magnified and a small amount of a second component can cause dramatic changes in wetting and fluid flow. Experimental results have demonstrated that these changes also have a dramatic effect on lubrication. Therefore, a systematic study of the effect of changes in the bulk composition on wetting and transport processes in non-isothermal ultra-thin films is proposed. Since lubrication is a non-isothermal process, controlled heat transfer experiments are used such that the effects of temperature gradients are present.

It has been proposed that since the chemical potential of a curved film is a function of the film profile, considerable information concerning the physicochemical processes in a thin film could be obtained by studying the effect of evaporation on the profile of a stationary evaporating film [63,64]. To demonstrate the validity of this hypothesis, a heat transfer cell with a scanning microphotometer capable of studying evapo- rating ultra-thin films was developed and tested at Rensselaer [65,66]. The results of these studies demonstrated that the experimental equipment was capable of generating extensive detailed information on wetting and the transport processes occurring in the film thickness region $\delta < 10^{-5}$m. Briefly, a series of experiments using decane and decane/2% tetradecane demonstrated that a stationary evaporating film is

stabilized by multicomponent adsorption, a curvature gradient and surface shear stresses that are a function of the evaporation rate. Comparison of the single component results with those obtained using a mixture demonstrated that the addition of a small amount of a second component with a lower vapor pressure gave a significant increase in stability at the same total evaporation rate. In order to enhance the understanding of the contact line region, it was found that a complementary thermodynamic study of the equilibrium thickness profile of a single component sessile drop was necessary [67,68,69,70].

2.3.9 Viscoelastic Properties of Low Molecular Weight Polystyrene Solutions. Professor Birnboim, during the first two years of the current contract period, has been concerned with the viscoelastic properties of low molecular weight polystyrene solutions in the high frequency regime. At high frequencies, beyond the backbone relaxation, the dynamic viscosity $\eta(\infty)$ of dilute polymer solutions remained in excess of $\eta_s(0)$. This excess, $\eta(\infty) - \eta_s(0)$, has been attributed in some cases to "internal viscosity" as in the theories of Cerf and Peterlin; or in other cases (circa 10 MHz) delay line apparatus suitable for low viscosity solutions has been developed in order to investigate this high frequency behavior. Solutions of low MW polystyrene (2200) were selected for study. It was found that the primary effect of the solute is to influence the characteristic relaxation time, τ_{solv}, of the solvent. In this case τ_{solv} is shifted to longer times, and thereby the solvent contribution in the presence of polymer $\eta_{sp}(0)$ is enhanced and becomes $\eta(\infty)$. A free volume argument is invoked to support this interpretation. The τ_{solv} is sensitive to a change (decrease) in free volume of the solvent, whereas the

polymer backbone relaxation times τ_p, are sensitive to $\eta_{sp}(0)$ but not directly to free volume. By contrast, in high MW concentrated solutions the terminal relaxation times are sensitive to free volume changes introduced by the dilutent. Analysis on the basis of concentration and temperature superposition of all the data is shown to be consistent with the shift in solvent relaxation hypothesis. The implication of these results to intrinsic viscosity and to the role of polymer additives in lubricants are discussed [71]. Further pursuit of the role of additives requires direct measurement of the solvent relaxation time in the absence and presence of the additive. The optical techniques of Brillouin and Mountain light scattering will be used. Measuring Brillouin shift under pressure in the diamond anvil cell has been successful [72]. However, in order to measure line width the contrast must be improved. Towards this end, triple pass Fabry-Perot geometry and a computer-aided feedback stabilization loop have been implemented. For line width beyond the Fabry-Perot resolution the above system permits the locking in on the Brillouin (or Rayleigh) line and then determine line width by the autocorrelation method. It has been necessary to extend the correlation time scale limit to shorter times: to 100 μs from the earlier limit of 12 μs. A burst recording method was developed for this purpose; and the technique of moments of probability distribution as developed by Pike was also implemented. Some rudimentary results have been obtained with these newly implemented techniques.

This effort, per se, is not proposed for extension. The methodology may be applied to related studies in the future.

2.3.10 Thermal Effects in Lubricating Fluid Film. During the first two years of the current contract period, Professor Richard N. Smith, with the collaboration of Professor John A. Tichy during the first year, has studied thermal effects in lubricating fluid films [73,74].

An analytical solution for the full thermal field in a journal bearing under isoviscous conditions was found [73]. The results were for adiabatic bearing surfaces and for isothermal bearing surfaces, with an isothermal shaft in all cases. The effects of convection and of dissipation in the film were found to be governed by a single dimensionless parameter, $Pe = \rho c_p \omega c^2/k$, under the assumption that pressure gradient effects do not influence the thermal field. Results for bulk temperature, heat transfer to bearing surfaces, and for temperature profiles across the film were calculated. For small values of Pe, the thermal field was found to be fully developed, while for large values, dissipation dominates the temperature field and was found to be the primary heat transfer source.

Under the joint direction of Professor Smith and Professor Roger Wright of the Materials Engineering Department, doctoral candidate Don A. Lucca has been concerned with the heating effects in the drawing of wire and strip under hydrodynamic lubrication conditions [75]. Both theory and experiments were conducted. Results elucidated the important governing parameters in the determination of heating effects in the drawing of wire and strip under hydrodynamic conditions. Dr. Lucca has joined the Luke Tool and Engineering Company.

2.3.11 Coupled Heating and Distortion of Hydrodynamic Films. Professor Ettles, during the present contract period in 1980, has been engaged in the study of coupled heating and distortion in hydrodynamic films. A computational method was developed to find the overall temperature distortion in a converging film and the bounding solids. This model viewed the film in elevation and in the direction of sliding, and was extended to compute transient effects [76,77]. The model is being further developed to the axisymmetric case (the face seal configuration) and to the full three-dimensional case. Two new features have been introduced. Firstly, several components and films of arbitrary shapes can be considered in the axisymmetric case so that realistic face seal configurations can eventually be analyzed. Secondly, the entire system of films and solids is solved as a set of elliptic equations in contradistinction to a mixed set of parabolic and elliptical equations. This improves stability and convergence.

2.3.12 Wear Characteristics of Composites. During the first year of this current contract period, postdoctoral associate Jack C. Roberts and Professor Ling worked on certain wear characteristics of composites.

The performance of several composite coatings sliding against ultrahigh molecular weight polyethylene was evaluated in 3-hour screening tests. The most promising coatings were then selected to run in 48-hour wear tests, both dry and in the presence of distilled water. Composite coatings containing particles of Al_2O_3 and Cu, of 18-8 stainless steel and Al_2O_3 in epoxy matrices exhibited thermal, frictional and wear characteristics similar to those seen when 316 stainless steel was run against ultrahigh molecular weight polyethylene [78]. Later, continuous

fiber woven E-glass/epoxy composite femoral shells having the same elastic properties as bone have been fabricated. This was done for total hip replacement [79]. These shells were coated with filled epoxy wear-resistant coatings consisting of 1 to 64 micron particles of: Al_2O_3, Al_2O_3 + Cu, and 18-8 stainless steel + Al_2O_3 in an epoxy matrix. The resulting femoral shells were wear tested dry against ultrahigh-molecular-weight polyethylene (UHMWPE) acetabular cups for up to 250,000 cycles on a total hip simulator. The best femoral shell tested was the one containing particles of 18-8 stainless steel + Al_2O_3 in an epoxy base. Articulation of this shell dry against UHMWPE for 250,000 cycles resulted in a friction force that was 10% lower than the current total hip prosthesis; that is, a vitallium ball articulating dry with an UHMWPE cup. An UHMWPE acetabular cup when articulating with a vitallium ball showed a weight loss of 0.0004 gram, while an UHMWPE cup when articulating with the 18-8 stainless steel + Al_2O_3 epoxy shell in the 250,000 cycle wear test showed a 0.0058 gram weight loss. Addition of graphite fibers to the UHMWPE acetabular cup and articulation with the 18-8 stainless steel + Al_2O_3 epoxy shell increased the friction force but reduced the surface damage to the UHMWPE. Dr. Roberts has joined the Bendix Research Center.

2.3.13 Wear Characteristics of Water Lubricated Al_2O_3-Metal Sliding Couples. During the course of a study of aluminum oxide sliding against low alloy steel in various lubricating media, it was noted that when water used as the lubricant very highly polished wear areas were produced [80]. Selected tests were run to evaluate the effects of parameters such as load, initial surface finish, type of Al_2O_3, and

alloy composition on the wear and frictional behavior of these combinations. The effect of sliding velocity was then determined on the best candidates.

When $A\ell_2O_3$ surface had an initial surface finish of 100-200 m center-line-average, the chemical composition of the metal surface appeared to be the dominant factor, presumably because of the formation of protective oxide film. Hardness was a secondary consideration. An alloy containing a high percentage of molybdenum was particularly effective and showed a strong tendency to develop fluid film lubrication. When rougher $A\ell_2O_3$ surfaces were evaluated, the ability of the metal to resist penetration by asperities became an important factor. The best results were obtained with fully-hardened (60 RC) martensitic stainless steel.

2.3.14 Fluid Motion About a Translating Particle in a Slider Bearing.

During the first year of the contract period, Professor John Tichy and doctoral candidate Michael Languirand examined the problem of fluid lubrication with a large particulate in it.

Most liquid lubricating systems permit contaminant particles to become entrained in the lubricant. Few, if any, systems can remove all of the particles before the lubricant enters the bearing. It is apparent, therefore, that virtually all liquid lubricated bearings are supplied with lubricants which contain contaminant particles.

Lubrication with contaminant particles has been examined theoretically by Allen and Kline [81], Prakash and Sinha [82], and others [83]. Their analysis is based on the application of "micropolar fluid" theory to various bearing geometries.

The theory of micropolar fluids may provide a first approximation to conditions where the lubricant becomes loaded with dirt or metal particles and can be considered as a fluid suspension. However, since the theory does not allow for spatially dependent fluid properties, it cannot be used for problems of discrete particles, such as the case when only a few particles are contained within the bearing fluid film. In fact, there are only a few "large" particles contained within the bearing at any time. Here "large" refers to particles whose characteristic length is at least the same order of magnitude as the minimum fluid film thickness. For example, a 25 mm (1-in) square bearing with an average film thickness of 25 μm (1000 μ in) would hold approximately $2 \times 10^{-2} cm^3$ (1×10^{-3} in^3) of oil. Particles in the 25-50 m (12-20 $\times 10^2$ μ in) length size range would typically be present in a working lubricant at concentration levels from 50-300 particles/cm^3 (8-50 $\times 10^2$ particles/in^3); hence there would only be one to six such particles present in the bearing fluid film. The typical aspect ratio (length-to-height ratio) of a dirt particle is two, the aspect ratio of many metallic user particles is much higher.

Investigators have found experimentally that these large particles have a significant effect on hydrodynamic bearing performance. Ronen et al. [84] have demonstrated that wear of hydrodynamic bearings with and without contaminant particles added to the oil supply depends on the oil film thickness. Other investigators have found similar results and all conclude that large particles have a definite effect on bearing performance. Thus there is a need to theoretically investigate the effect of large particles on hydrodynamic bearings.

A recent article by Yousif and Nacy [85] describes a relatively similar study to the present one. The forces on a rectangular profile particle are found by lubrication theory, and the free motion of the particle determined. An ensemble of particles is assumed to be arranged in laminae along the flow direction, and the bearing variables (load, friction, etc.) are determined.

An approximate solution of Stokes equations has been found to determine the pressure and velocity fields in an infinite slider bearing containing a two-dimensional high aspect ratio particle of arbitrary cross-section [86]. The particle may translate in two directions as well as rotate about its centroid. The fluid field is divided into four regions: upstream, above, below and downstream of the particle. The governing Stokes equations are applied to each region and solved through specific continuity requirements and pressure matching conditions.

For illustrative purposes, this method of analysis is applied to a plane slider bearing containing a rectangular particle which can translate in one direction. Approximate solutions are given for the pressure and velocity fields. The solution reveals a pressure drop which develops in the pressure field at the particle location. The magnitude of this drop is shown to be dependent on particle size, velocity and location. It is shown that the particle has a major effect on the bearing pressure field when it is able to significantly obstruct the flow of the lubricant.

To support the theoretical analysis experimental research is performed [87]. An experimental apparatus is used to measure the transient pressure in a slider bearing as a high aspect ratio two-dimensional rectangular particle is passed through the fluid film. The apparatus

measures pressure at a particular location in the bearing and simultaneously measures the particle's displacement with respect to its initial starting location.

Results are given to demonstrate the effect of particle velocity on the pressure field in the bearing. The experimental results presented are in good agreement with analytical results obtained from the theoretical analysis.

Dr. Languirand has joined the MIT Lincoln Laboratory.

3. THE RESEARCH TEAM AND INTERDISCIPLINARY COLLABORATION

3.1 Principal Investigator

The principal investigator is Frederick F. Ling, Director of the Institute for Wear Control Research.

3.2 Senior Investigators

Senior investigators represent an interdisciplinary team as follows:

James L. Lauer	Research Professor of Mechanical Engineering and Director, Laboratory for Boundary Layer Analysis
Sydney Ross	Professor of Chemistry and Director, Colloid and Interface Science Laboratory
John B. Hudson	Professor of Materials Engineering and Director, Surface Studies Laboratory
Peter C. Wayner	Professor of Chemical Engineering and Director, Interfacial Transport Processes Laboratory

Meyer H. Birnboim	Associate Professor of Mechanics and Director, Viscoelasticity Laboratory
Christopher M.M. Ettles	Associate Professor of Mechanical Engineering
Richard N. Smith	Associate Professor of Mechanical Engineering and Director, Energy Systems Laboratory
John A. Tichy	Associate Professor of Mechanical Engineering and Director, Fluid Systems Laboratory

3.3 Research Staff and Assistants

On the staff of the Institute for Wear Control Research (IWCR) are:

S. Frank Murray	Senior Research Associate and Manager, Tribology Laboratory
Salvadore J. Calabrese	Research Specialist

Ph.D. bound graduate assistants have been selected from each discipline. Selected for their superior qualifications and supported on the full time basis are Mary C. Dawson (nee Herbert), who graduated first in her class, held two fellowships during her M.S. studies, worked at the General Electric Company before returning for her doctoral studies and Wolfgang Holzhauer who graduated near the top of his class and studied abroad during his junior year at the Swiss Federal Institute of Technology.

3.4 Monthly Tutorial/Area Specialty Seminars

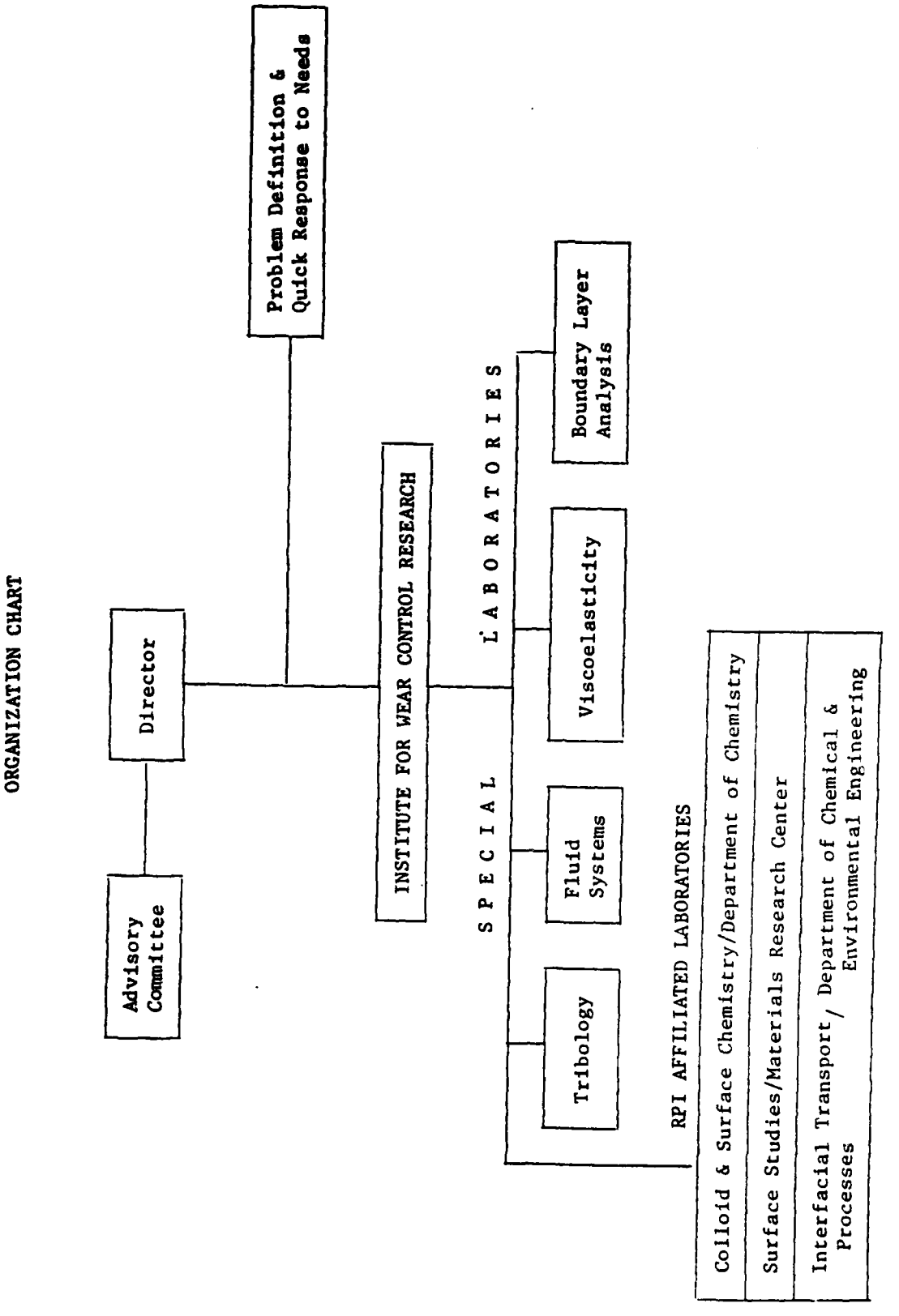
Monthly Tutorial/Area Specialty Seminars have been held. These are occasions, about two hours in duration, when members of the investigative team (faculty and/or graduate students and/or staff) survey their areas and report their latest findings. Various members do this by rotation;

occasionally a guest participant is asked to join in to enrich the discussions.

3.5 ARO Panel Review Meetings

Annual meetings have been held when the Rensselaer team would review project progress for the ARO Panel.

3.6 Institute for Wear Control Research (IWCR) and Its Functional Laboratories



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