AEROSPACE INFORMATION REPORT

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Lubricating Characteristics and Typical Properties of Lubricants Used in Aviation Propulsion and Drive Systems

INTRODUCTION

This Aerospace Information Report (AIR) is intended as a guide toward standard practice, but may be subject to frequent change to keep pace with experience and technical advances. Hence, its use where flexibility of revision is impractical is not recommended.

The information contained herein is an attempt to establish sets of guidelines for the selection of properties governing the lubricating characteristics of lubricants to be used in current and future aviation propulsion and drive systems. It is the intent of the SAE Committee E-34 on Propulsion Lubricants, that this document reflects currently accepted thinking in the industry and government agencies concerned with the lubrication of components in aviation primary propulsion systems, and associated power transfer gearboxes and transmissions.

The content of this AIR is the result of communication among lubricant manufacturers, hardware manufacturers, lubricant specialists, tribologists, lubricant specifiers and lubricant users. Continued communication will be encouraged to maintain the information contained herein as current as possible. Users are advised that they can contribute to subsequent changes and additions to this document by their comments, suggestions and criticism.

Although a lubricant serves multiple functions in a system (e.g., coolant, debris scavenger and diagnostic medium in addition to lubricating), this document deals with the lubricant in its "lubricating" function only.

Unfortunately, in present standards, some properties of importance in determining lubricating ability and the methods to quantify these properties tend to be ignored and in some cases there are no standardized test methods. Because these properties are important to designers, they are included in this document even if methods are not specified or standardized. In these cases, typical values obtained by particular methods are presented. It is intended that by including these data, focus will be brought on the deficiencies in this area and data from improved and/or standardized methods will be presented in future editions of this document.

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It must also be recognized that the selection of properties relevant to lubricating characteristics must be made in the light of the other characteristics necessary or desirable in the lubricant. This document is not intended to specify the properties of fluids optimized for lubricating ability but it is intended to provide the guidance to be considered, along with the other requirements for the application, in determining the values to be specified for each property. Trade-off in the selection of limits for various properties must be made based on the relative impact of these properties on each other and on the system.

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1. SCOPE:

This AIR establishes guidance for the specification of formulated lubricant properties which contribute to the lubricating function in bearings, gears, clutches and seals of aviation propulsion and drive systems.

2. REFERENCES:

2.1 Applicable Documents:

1. Glossary of Terms and Definitions in the Field of Friction, Wear and Lubrication - Tribology, Research Group on Wear Engineering Materials, Organization for Economic Cooperation Development, Paris, 1969.

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3. Dowson, D., "Elastohydrodynamics," Proc. Inst. Mech. Engrs., 1967-68, Vol. 182, Part 3A, paper No. 10.

4. Cameron, A., "Principles of Lubrication", Longmans, London, 1966, p. 31.

5. Jones, W.R, Johnson, R.L., Winer, W.O. and Sanborn, D.M., "Pressure-Viscosity Measurements for Several Lubricants to 5.5 X 10^8 N/m^2 (8 X 10^4 psi) and 149 C (300 F)," ASLE Trans. Vol. 18, No. 4, October 1975, pp. 249-262

2.2 Definitions and Terminology:

The following terms are defined according to the definitions given in 2.1(1.) and according to the customary engineering descriptions used in the aerospace community.

Fatigue - Removal of particles detached by fatigue arising from cyclic stress variation. (1) Spalling is removal of material by fatigue resulting from the global contact stress. It can be surface or subsurface initiated; (2) Pitting is removal of material by fatigue resulting from local stress within the contact. It is surface or near surface initiated. Fatigue pits are smaller scale than fatigue spall; (3) Micropitting (Peeling, Frosting) – This type of fatigue is characterized by subsurface shallow spalling in the order of 0.0002 to 0.0005 inch in depth which occurs where the surface finishes have many asperities greater than the lubricant film thickness. Normally micropitting is only a slight distress to the contact surface and appears to be nothing more than a frosted appearance.

Fretting - A wear phenomena occurring between two surfaces having oscillatory relative motion of small amplitude.

Scratching - The formation of fine scratches in the direction of sliding. Scratching may be due to asperities on the harder surface, hard particles between the surfaces or embedded in one of the surfaces. Scratching is considered to be less damaging than scoring (scuffing).

2.2 (Continued):

Scoring (Scuffing) - The formation of severe scratches in the direction of sliding. (1) Scoring may be due to local solid phase welding or to abrasion. (2) In the USA the term scuffing is sometimes used as a synonym for scoring. (3) In the U.K. scuffing implies local solid-phase welding only. (4) Minor damage should be called scratching rather than scoring (scuffing).

Glazing - The formation of a glazed or polished surface due to localized plastic flow.

Smearing - Plastic flow and removal of material from a surface and redeposition as a thin layer on one or both surfaces.

Corrosion - Reaction at surfaces due to electrochemical or direct chemical attack resulting in discoloration and/or pitting of the surface. Can occur on functional and nonfunctional surfaces.

Corrosive Wear (Tribochemical Wear) - A wear process in which chemical or electrochemical reaction with the environment predominates. (1) Usually, corrosive wear is a mild form of wear, but it may become very serious, especially at high temperatures or in moist environments. (2) In some instances, chemical reaction takes place first, followed by the removal of corrosion products by mechanical action; in other instances, mechanical action takes place first, characterized by the formation of very small debris which subsequently is chemically transformed; the phenomena may be mutually enhancing. A form of corrosive wear is oxidative wear.

Fretting Corrosion - A form of fretting in which chemical reaction predominates. (1) Fretting corrosion is often characterized by the removal of particles and subsequent formation of oxides, which are often abrasive and so increases wear. (2) Fretting corrosion can involve other chemical reaction products, which may not be abrasive.

Wear - The progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface. (1) Wear is usually detrimental, but in mild form it may be beneficial, e.g., during running in. (2) A body may become unserviceable as a result of major plastic deformation. Small-scale plastic deformation occurs in almost all wear processes.

2.3 Symbols and Abbreviations:

AIR	Aerospace Information Report
ASTM	American Society for Testing and Materials
EHD	Elastohydrodynamic
EP	Extreme Pressure
F	Shear Force
m	Slope
N	Normal Load
PFPE	Perfluoroalkylpolyether
PPE	Polyplenyl ether
R	Entraining Velocity
S	Sliding Velocity
T	Total Temperature

2.3 (Continued):

Tb	Bulk Temperature
Tf	“Flash” Temperature
TCP	Tricresyl Phosphate
µm	Micro-meter
h/µ	Lambda Ratio

3. FUNDAMENTALS OF LUBRICATION AND LUBRICANT PROPERTIES:

3.1 Lubricant Function:

In any lubricated contact, the lubricant generally must perform two primary functions. These functions are surface separation for the reduction of wear and heat removal. While the primary purpose of a lubricant is to extend component life by reduction or elimination of wear and various unacceptable types of surface distress, only a small portion of the lubricant which is generally supplied to a component is required for this purpose. In components like rolling element bearings and gears with high load Hertzian contacts, less than 10% of the lubricant supplied is required for surface separation or protection. The remaining 90% is supplied to provide adequate cooling to control and stabilize component temperatures at an acceptable level.

The physical, surface interactive and chemical properties of a lubricant determine how well it performs these two functions. The primary properties that determine the lubricating and wear reduction performance of a lubricant include the viscosity and pressure viscosity coefficient (which determine how thick a film a lubricant can form at a given set of conditions including geometry, load, surface speed and temperature). In addition to these two physical properties, the type and quantity of surface active boundary lubricating additives that may be present play an important role in a lubricant’s surface protection/wear reduction role. Boundary lubricating additives are particularly important at low speeds and/or high loads where the films generated by Elastohydrodynamic effects are particularly thin.

The primary characteristics, which determine a lubricant’s ability to remove heat from a component, are heat capacity, thermal conductivity and thermal stability. These characteristics determine how well the lubricant can absorb heat from the mechanical component and how well it can stand up to the thermal environment it is subjected to. Frequently, antioxidant additives are used to increase the thermal stability of a lubricant basestock to permit it to be used at higher temperatures.

While not primarily a lubricating function in the strict sense of the word, corrosion protection is a third major performance requirement for many lubricants. Corrosion preventive additives are frequently used to improve the corrosion protection of a given lubricant. Corrosion protection can be provided by a combination of effects including chemically adherent surface film formation, acid neutralization and moisture elimination or control. The effectiveness of anticorrosion additives is very much controlled by their detailed chemical properties.

3.2 Lubrication and Failure Mechanisms:

3.2.1 Introduction: The topic of lubrication and the failure of lubricated surfaces are quite complex. The performance of the lubricant, with its physical and chemical properties, in most cases cannot be formulated into simple and reliable equations to predict the role of lubricant properties in the failure process. Failure in the form of wear, for example, is not an intrinsic property of a bearing or gear material. Also, the performance of an oil or grease is not an intrinsic property of the lubricant alone, but it is the result of the physical and chemical interactions within an entire lubricated contact system. Consequently, the design or selection of a lubricant is both science and experience based. The rationale is derived from both lubrication and failure mechanisms and their interactions within a lubricated contact system.

The lubricant prevents failure through the formation of lubricating films by hydrodynamic lubrication, Elastohydrodynamic (EHD) lubrication and boundary lubrication. The criteria for failure are judged by the user. If the deterioration of the surfaces or level of friction has progressed to the degree that it threatens the essential function of the component, it can be considered to have failed.

Through experience the engineer recognizes distinct classes of failure (see section entitled 2.2 Definitions). These failures are defined without presupposing the exact mechanism by which they occur. They are defined in engineering terms based on a description of observations. The observations and their classifications reflect the remaining evidence of a complicated sequence of events involving many physical and chemical processes that preceded it. Associated with the physical and chemical interactions on the surfaces are several mechanistic wear processes which generally fall under the basic mechanisms of:

Adhesion
Chemical reaction
Plastic flow
Fatigue

During the service life of a component, the lubricant must provide the lubrication mechanisms required to prevent or control these basic wear processes. The role of the lubricant and its design and selection rationale can be understood by considering the structural elements of a lubricated contact.

3.2.2 Structural Elements of a Lubricated Contact: Engine and transmission systems have a very wide range of lubricated contacts within their basic components of bearings, gears, seals, clutches and splines. The lubricated contacts cover a wide range of contact stresses and rolling/sliding motion.

For a concentrated contact, the performance is derived from the integrity of four general regions as shown in Figure 1. Each region performs certain functions in the lubrication and failure process. The success of the lubricant depends upon how well it handles the normal stress and accommodates the tangential shear within these regions.

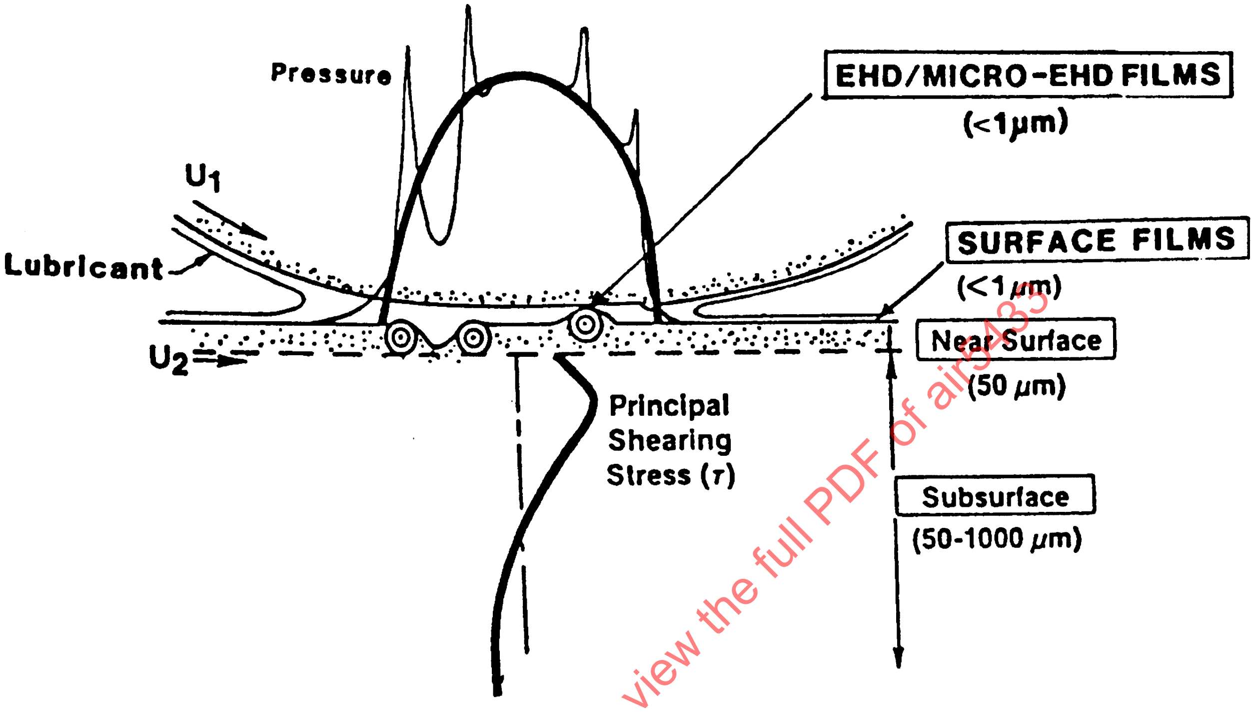


FIGURE 1 - Structural Elements of a Lubricated Contact

3.2.2 (Continued):

The EHD and micro-EHD lubricated region is created by the generation of an Elastohydrodynamic (EHD) lubricant film. On a global scale, the EHD film is derived from the hydrodynamic pressure generated in the inlet region of the contact. On a local scale, it is derived from the micro-EHD lubrication action associated with the local topography of the surfaces. The EHD/micro-EHD region is typically less than 1 μm thick.

The surface film region contains the thin outer layers of the surface. They consist of surface oxides, adsorbed films and chemical reaction films derived from the lubricant and its additives. These surface films are almost always less than 1 μm thick.

The near surface region contains the inner layers of the surface. This region may include a finely structured and highly worked or mechanically mixed layer. It may also include compacted wear debris or transferred material from a mating surface. The deformed layers, which are of a different microstructure than the material below them, may arise from surface preparation techniques such as grinding and honing. They may also be induced during operation; for example, during running in. Hardness and residual stress may vary significantly in this region. They may also be substantially different from the bulk material below. The near-surface region may be on the order of 50 μm below the surface.

3.2.2 (Continued):

For concentrated contacts, a subsurface region can be defined which may be 50 to 1000 µm below the surface. This region is not significantly affected by the mechanical processes that produce the surface or the asperity-induced changes that occur during operation. Its microstructure and hardness may still be different from the bulk material below it, and significant residual stresses may still be present. These stresses and microstructures, however, are the result of macro processes such as heat treatment, surface hardening and forging. For typical Hertzian contact pressures, the maximum shear stress is located within the subsurface region (see Figure 1). In other words, the detrimental global contact stresses are communicated to the subsurface region where subsurface-initiated fatigue commences.

One can also define a "quiescent zone" which is located between the near-surface region and the subsurface region. The "quiescent zone" resides at a depth below the surface in which the local asperity and surface defect stresses are not significant and the stress field from the macroscopic Hertzian contact stress is not yet appreciable. This zone is quiescent from the point of view of stress and the accumulation of plastic flow and fatigue damage. The existence of the quiescent zone is important with regard to rolling contact fatigue. It inhibits the propagation of cracks between the stress field in the near-surface region and the stress field in the subsurface region.

3.2.3 Lubrication Mechanisms: The physical and chemical properties of the lubricant work within the structural elements of the contact through the mechanisms of hydrodynamic (or Elastohydrodynamic) lubrication and boundary lubrication.

Elastohydrodynamic Lubrication: The formation of a hydrodynamic or EHD lubricant film contributes to lubrication by reducing the local stresses between the surfaces and by creating a lubricant film easy to shear. For a concentrated contact like that in Figure 1 the pressure and elastic deformation are very similar to the Hertzian contact condition of dry contact. This results in three functional regions along the direction of surface motion as shown schematically in Figure 2.

The formation of an EHD lubricant film is derived from the hydrodynamic pressure generated in the inlet region. EHD lubrication is on excellent quantitative grounds. This allows the lubricant film thickness to be predicted from the viscous properties of the lubricant, the geometry of the contact system and their kinematic operating conditions. EHD theory has proven to be a very useful design tool for predicting the lubrication regime for various applications. However, it is not sufficient to predict failure. This is partly because EHD lubrication is primarily an inlet phenomenon; that is, its major role occurs in a region removed from the Hertzian region where the more local events involved in failure initiation take place. The EHD lubrication process can significantly influence the severity of these local events. The nominal thickness of an EHD film determines the degree of asperity interaction between the surfaces. Thus, the hydrodynamic or EHD lubrication mechanism is viewed as a method for the role that lubricant properties (particularly physical properties) have on their ability to separate surfaces with a lubricant film. The prediction of failure must incorporate several less quantifiable processes.

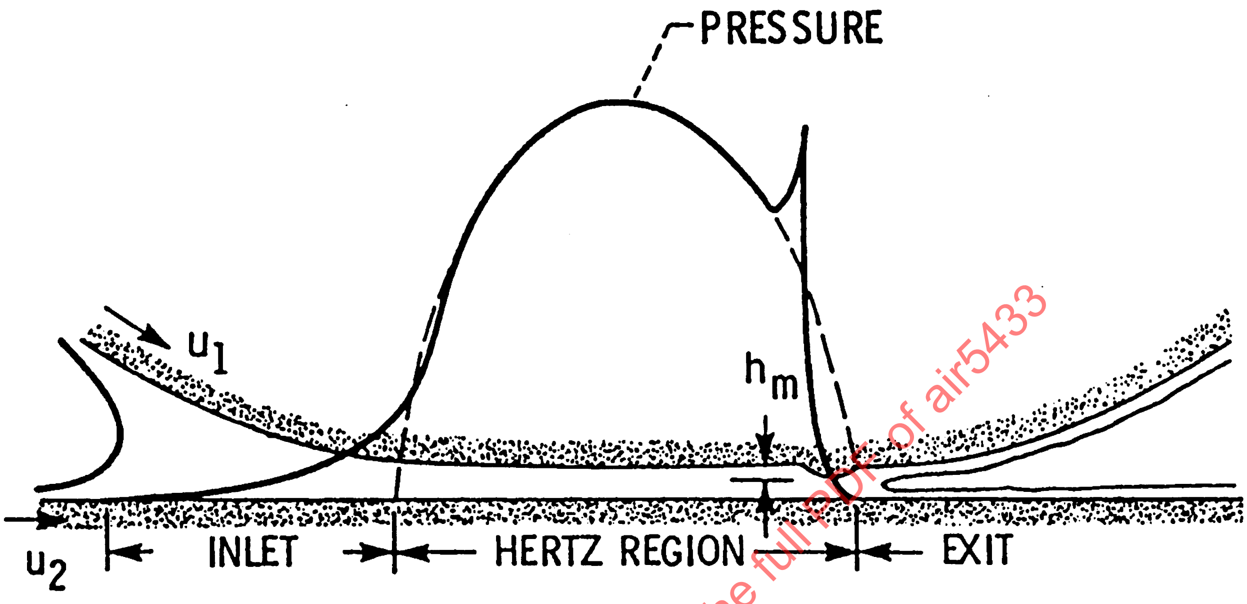


FIGURE 2 - EHD Lubrication

3.2.3 (Continued):

Surface Temperature: Surface temperature is not a lubrication process but a key link between lubrication and failure. Temperature significantly influences the viscous properties of the lubricant that control the thickness of a hydrodynamically generated lubricant film. It is also a major driving force in the formation of chemical reaction films. It influences the rate of lubricant degradation. It influences the strength of surface films as well as the flow properties of the material in the near-surface region. Consequently, it is not surprising that the total temperature level is a frequently used criterion for failure, such as scuffing (or scoring).

From a simplistic point of view the total temperature (T) is the sum of a bulk temperature (T_b) of the component and the "flash" temperature (T_f) associated with the instantaneous temperature rise derived from the friction within the lubricated contact. Flash temperature may arise from the traction of the lubricant film as well as from the energy dissipated from the adhesion, plastic flow of surface films, and deformation of the material within the near-surface region. The magnitude of T_f can be predicted if simplifying assumptions about the coefficient of friction and convection heat transfer is made.

Boundary Lubrication: It is well known that surface films are important to boundary lubrication because they prevent adhesion and provide a film that is easy to shear. These films may be in the form of oxides, adsorbed films from surfactants and chemical reaction films from other additives or the bulk fluid. These surface films are schematically shown in Figure 3.

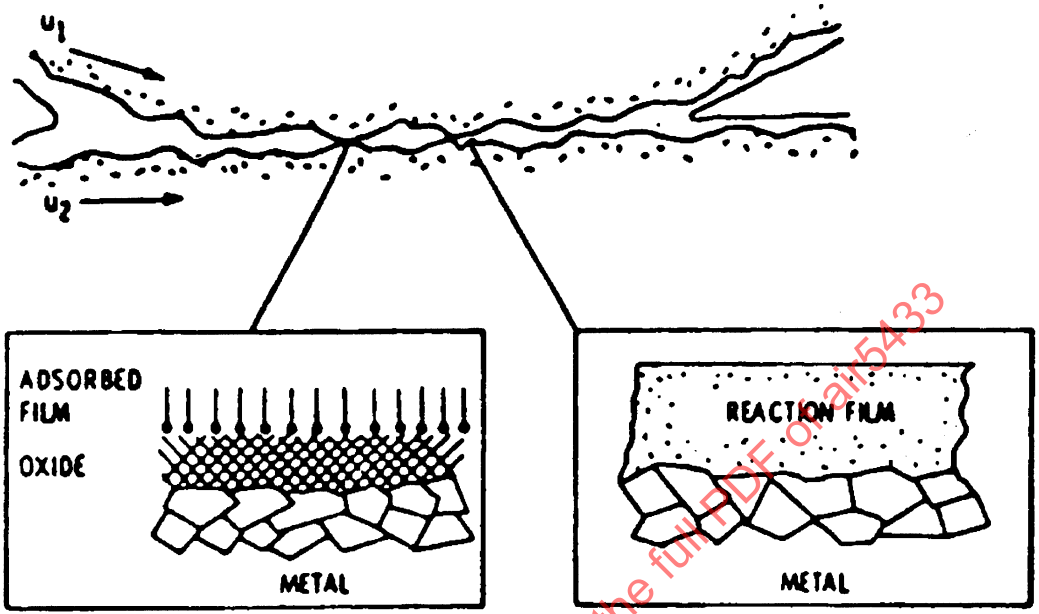


FIGURE 3 - Surface Films From Boundary Lubrication Mechanisms

3.2.3 (Continued):

The interactions of surface films are very complex. Most studies on the subject have focused on the chemical identification or phenomenological effect of surface films, but little is known about the mechanism of protection, the means of removal, or the rate of reformation. At high temperatures the oxidation of the base fluid can contribute to surface film formation. There have been many studies on the catalytic effect of metals on the bulk oxidation of lubricants. Similar oxidative processes can occur under the thermal stress environment in the contact region where intermediate oxidation species can react with the surface or organo-metallic material that may be present. These reactions can influence boundary lubrication in several ways; such as by corrosive wear, by competition with other additives, or by forming polymeric material - that is, a friction polymer.

The contribution of surface films in preventing wear is complex. The time and spatial distribution of the various surface films within the contact seem to be important, particularly with regard to the accumulation of material (including debris of all sorts) in surface depressions and the formation of films at asperity sites. In view of the complexity of surface films, one wonders what the real lubricating "juice" is in a real system. Its properties may be much different from the original lubricant applied.

3.2.3 (Continued):

Mixed Film Lubrication: The lambda ratio, h/µ, a very useful engineering quantity, is the ratio of the hydrodynamic or EHD lubricant film thickness (h) to the average combined roughness height (µ) of the interacting surfaces. It is a simple way of describing the degree of asperity interaction. Thus, when lambda is >3, spalling fatigue life is much greater than for lower lambda, because local asperity stresses have been significantly reduced. Its connection with surface-initiated fatigue seems to be more obvious than failure modes associated with wear or scuffing. The latter failure modes generally appear at low lambda, less than 1, where the concept of lambda loses much of its meaning.

When µ is the same order of magnitude as h, the surface topography becomes intimately involved in the lubrication process itself in the form of micro-EHD lubrication. Local hydrodynamic or EHD pressures can be generated at asperity sites or topographical features associated with surface finishing process or wear processes. Micro-EHD lubrication can be confused with boundary lubrication.

3.2.4 Failure Processes:

3.2.4.1 Surface Interactions: Perhaps the most important quantity in connection with failure is the deformation attributes of the near-surface region. It is unfortunate that there is little understanding of near-surface mechanical properties or the attributes needed to complement the various lubricating mechanisms to prevent failure. To maintain surface integrity, the near-surface region must prevent microfracture and maintain a viable surface finish even in the presence of plastic flow.

The interaction of the tribological processes in an asperity encounter is shown schematically in Figure 4.

The severity of interaction is reflected in the normal load N, which is influenced by the thickness of hydrodynamically generated film, h. The shear force F is influenced by the various surface films and micro-EHD lubricant films along with the flow properties in the near-surface region. The exact mechanism whereby shear stress is applied to the near-surface region is not known. This could come about through metal-to-metal adhesion, but it is also possible to have sufficient compressive and shear stresses applied locally through a thin lubricant film.

In any case, the severity of interaction is important to the initiation and propagation of the events toward failure. The severity of interaction will determine whether the result is (1) a benign elastic encounter, (2) a further accumulation of plastic fracture sites that can lead to the generation of wear particles (e.g., microspalling, mild mechanical wear, and delamination), (3) oxidative or corrosive wear, or (4) the advancing of adhesive transfer, which can lead to smearing or scuffing.

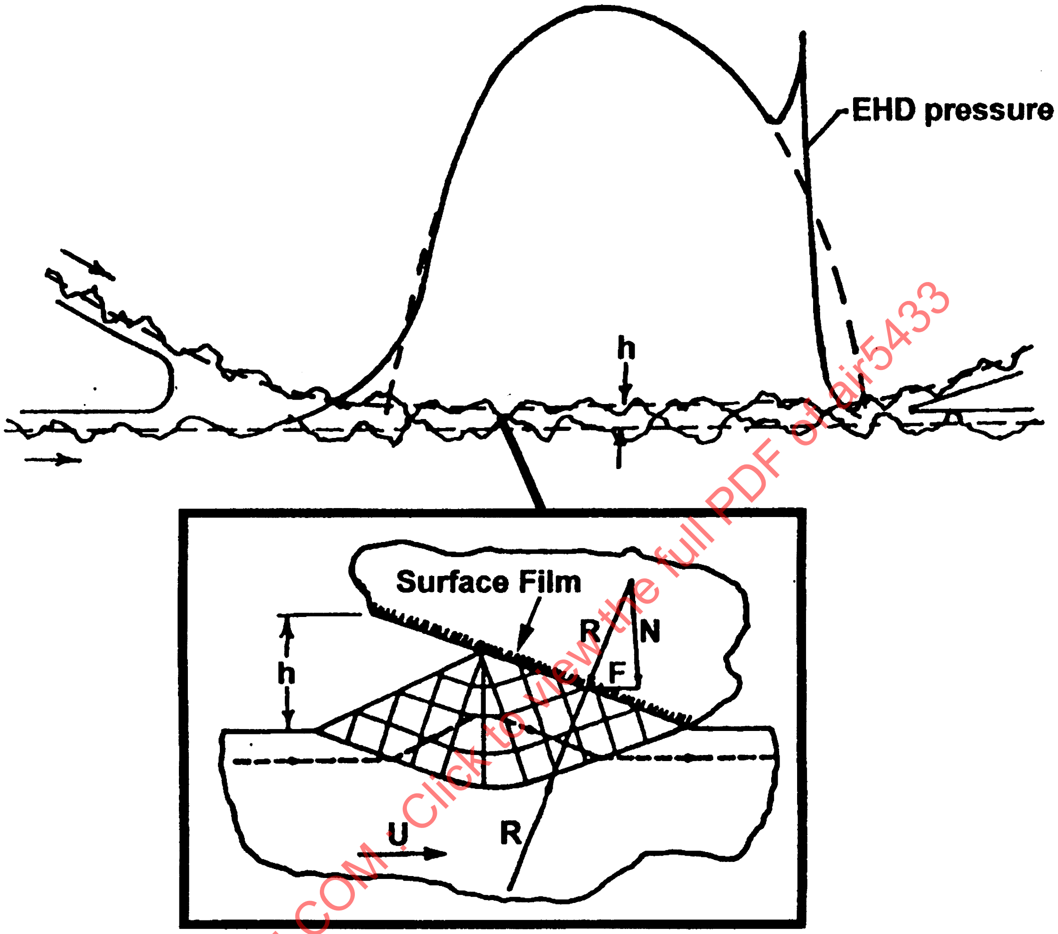


FIGURE 4 - Interaction at Asperity Site

3.2.4.1 (Continued):

Failure can occur through four basic processes of adhesion, plastic deformation, fatigue and chemical reactions. The recognized failure descriptions in bearings and gears, such as smearing, pitting, spalling and scuffing, are not singly connected to these basic processes but are associated with the interaction of the processes both simultaneously and sequentially. The importance of connecting these basic processes with the commonly accepted failure modes is associated with engineering decisions required to extend the onset of failure through improved lubricant properties, material selection, design or allowable operating conditions.

3.2.4.2 Local Film Removal: Under high normal and tangential stresses, boundary films trapped between contacting asperities can be stretched until they rupture. This allows the formation of metal-to-metal contact on an atomic scale, which results in strong adhesive or welded junctions.

With relative motion between the contacting asperities, junction growth occurs by plastic deformation. Fracture ultimately takes place, and it can occur at a location different from the original interface resulting in material transfer from surface to surface. The formation and rupture of adhesive junctions is accompanied by very high local temperatures that can form reaction films on the newly formed surface and change the mechanical properties of the underlying material. "Adhesive wear" occurs when the adhesive transfer of material is the important or controlling mechanism.

3.2.4.3 Gross Surface Failure: Adhesive wear on a large scale (scuffing or scoring) occurs between gear surfaces under high sliding velocity. A similar mechanism in rolling element bearings is called "smearing." The precise mechanism of scuffing is not well understood, but it does involve the gross failure of the surface and is generally accompanied by a rapid increase in friction and contact temperature. A current view of scuffing is that under conditions yet to be defined it is a gradual breakdown in the lubrication of interacting asperities, the nature of which may be boundary, micro-EHD, or a mixture of the two. Although the final scuffing mode may represent the gross breakdown of various lubrication films and the near-surface region, it may be triggered by the deterioration in surface topography as a result of adhesive wear or local plastic flow. The result is catastrophic and the "EP" properties of a lubricant to prevent this failure mode are a key factor in performance.

3.2.4.4 Chemical Reaction: The mechanistic processes associated with fatigue and plastic flow are the result of material deformation caused by stress. A significant part of wear and its control involves chemical reaction processes with the environment. The environment is defined, as that portion of the contact system that is not an intrinsic part of the surfaces. The environment includes the surrounding atmosphere as well as the lubricating films.

Pure chemical reactions should be distinguished from "tribochemical" reactions, which are a consequence of the tribological interactions between the contacting surfaces. "Corrosion" results from reaction of the surfaces with the ambient environment under the prevailing ambient conditions; tribochemical behavior is activated by mechanical interaction of the contacting surfaces. Corrosion often occurs on surfaces because of improper handling or storage resulting from the absence or removal of a protective film.

3.2.4.4 (Continued):

The prevention of adhesive wear is accomplished by forming tribochemical films. These films may be formed from oxygen in the atmosphere or from antiwear or extreme pressure additives. "Tribochemical wear" generally involves a continuous process of surface film formation and removal. The formation process involves chemical reaction or adsorption of chemical species on the surface. The removal process results from mechanically induced crack formation and abrasion of the reaction products in the contact. The process introduces "clean," that is, activated, local areas where new tribochemical films can be formed and subsequently removed. The tribochemical process introduces thermal and mechanical activation of the near-surface region, which can cause (1) greater chemical reactivity as a result of increased asperity temperature and (2) changes in the microstructure and mechanical properties of the near-surface layer due to high local temperatures and mechanical working.

Under favorable operating conditions, tribochemical reactions may be associated with "mild wear." Mild wear is characterized by low wear rates and smooth surfaces frequently caused by oxidation of the surfaces and subsequent removal of the oxide. Unfavorable operating conditions can result in "severe wear," where the surfaces are extensively disturbed by gross adhesion and plastic flow rather than oxidative wear. Severe wear can be prevented by increasing the rate of chemical reactions to form protective surface films at the same rate as clean activated local areas are generated. In this way, a balance can be obtained between adhesive wear and "chemical wear." "Corrosive wear" is a term used when chemical wear dominates the adhesive wear mode by a wide margin. Additive composition and concentration control the rate of chemical wear. An optimum additive formulation is achieved when there is a balance between adhesive and chemical wear for a given degree of contact severity.

3.2.4.5 Plastic Deformation: Depending on the contact geometry, relative hardness and load, the shape of a contacting surface can be permanently deformed on both a macroscopic and microscopic scale as a result of plastic deformation. On a macroscopic scale the overload of rolling elements of a bearing can cause "Brinell marks" or distortion of the entire rolling track.

Almost all wear processes involve plastic flow on a microscopic scale. The plastic deformation that occurs from overrunning of hard particles, such as contaminants and wear debris, is "denting."

"Plowing" occurs when there is displacement of material by a hard particle under the presence of sliding or combined rolling/sliding conditions.

"Abrasive wear" occurs when the plastic deformation leads to material removal and wear debris.

General plastic deformation of asperities and ridges on rolling contact surfaces such as bearings is referred to as "surface distress" or at least the initial stages of surface distress. The final stages of surface distress involve the loss of material through microfracture and pitting.

3.2.4.6 Fatigue Processes: Fatigue is caused by cyclically repeated stresses on the contact surface, which eventually introduce permanent damage within the material. Damage begins as a crack. After repeated stress cycles, cracks can propagate and eventually lead to loss of surface material. Fatigue may initiate and propagate from the macrostresses induced in the subsurface region. This results in "spalling" characterized by relatively large craters. Fatigue can also be initiated in the near-surface region as a result of microstresses from asperities or surface defects, such as dents, grooves, nicks and scratches. If the combined micro and macro stress fields propagate cracks through the quiescent zone and into the subsurface region, surface-initiated fatigue spalling can occur. "Pitting" and "delamination" occur when crack propagation is confined to the near-surface region. These processes are associated with the final stages of surface distress discussed above. The role of the lubricant is to reduce the local stresses at and near the surface to prevent the initiation of fatigue cracks. In addition, the lubricant cannot "weaken" the surface with respect to crack initiation due to surface energy modifications at the surface.

3.2.5 Summary Comments: A lubricated contact is viewed as four structural elements to understand the mechanisms associated with the role of the lubricant in the generation of lubricant films and the failure of these films which leads to commonly accepted failure modes. The physical properties of a lubricant, particularly viscosity, serve to reduce local stresses and provide a separating film of low shear strength. This hydrodynamic process is predictable and basic lubricant properties are used to predict performance. There is a somewhat rational basis for the selection of current values and desired values for future aircraft systems.

The chemical attributes of a lubricant serve to form protective films on the surface, which prevent local adhesion and disruption of the surface. The formation, removal and performance of these films are complex and very application dependent. The lubricants that produce these films are frequently classified as "anti-wear" or "EP" depending upon how well they function toward reducing wear or preventing scuffing at high loads.

The connection between the testing of the chemical attributes of a lubricant and its performance in an aircraft system is not very good. Measurements from bench tests are not directly related to hardware performance. Most tests strive only to provide some sort of relative ranking of lubricants. Extrapolation of test results to other operating conditions is difficult.

In almost all cases, the physical properties and chemical attributes of a lubricant work together. It is difficult to separate the contribution of selected properties. The overall performance level for a particular system is judged ultimately by the user. The connections between typical observations made by the user and the tribological features are summarized in Table 1.

TABLE 1 - Wear Processes and Tribological Implication

Observed Wear Behavior	Primary Mechanistic Wear Process	Primary Structural Elements	Tribological Implication
Mild mechanical wear Adhesive wear Smearing	Adhesion	Surface films Near-surface	Interacting surfaces that are not sufficiently protected by lubricating films (surface films or EHD/micro-EHD films) frequently result in adhesive transfer or removal of near surface material. Surface integrity can be maintained by proper selection of material pairs and lubrication to provide protective surface and EHD/micro-EHD films.
Corrosion Tribochemical wear	Chemical reaction	Surface films Near-surface EHD/micro-EHD films	Tribochemical behavior is activated by mechanical interactions of the contacting surfaces producing activated surface sites and local high temperatures for chemical reactions. Tribochemical wear involves a continuous process of surface film formation and removal. Correct balance is required between chemical wear and adhesive wear, requiring appropriate lubricant/additive aggressiveness.
Surface indentation Surface distress Abrasive wear	Plastic flow	Near-surface	Most observed wear behavior involves plastic deformation as a result of displacement of material under sliding conditions (plowing, smearing) or material removal (abrasive, adhesive wear). Overrunning of hard particles produces debris denting, giving rise to surface-initiated fatigue spalling. EHD/micro-EHD films reduce or eliminate local surface plastic flow.
Pitting Fatigue spalling	Fatigue	Near-surface Subsurface	EHD/micro-EHD films redistribute surface pressure, thereby modifying the magnitude and location of critical stresses. The induced subsurface shear stress is important with respect to the critical shear stress of the material in the subsurface region. The EHD film/surface roughness ratio influences fatigue life due to high local stress at surface defect sites (asperities, dents, and material inconsistencies).

3.3 Properties:

Customary lubricant properties are listed below under two headings of physical and chemical:

PHYSICAL PROPERTIES

Kinematic Viscosity
Temperature-Viscosity Coefficient
Pressure-Viscosity Coefficient
Traction Coefficient
Surface Tension
Specific Heat
Thermal Conductivity
Density
Volatility
Pour point
Foaming
Bulk Modulus
Vapor Pressure
Miscibility
Cone Penetration (greases)
Dropping Point (greases)

CHEMICAL PROPERTIES

Oxidative and Thermal Stability
Anti-Wear Performance
"EP" Performance
Corrosion

Some of the above properties are directly related to lubrication functions involving viscosity, anti-wear and EP performance. Others are indirectly related. Specific heat is a design consideration since the lubricant is used to remove heat as well as provide lubrication. Surface tension and density influence the supply and distribution of the lubricant within the mechanical components. Decomposition properties influence the ability of the lubricant to operate within a thermal environment as well as lubricate the components within that environment. Pour point is connected to low temperature starting ability. The lubricant serves several functions, including the removal of wear debris. The focus of this document is primarily on the properties directly related to the lubricating function.

3.4 Properties Significance:

The significance of lubricant properties can be exposed by observing their influence in a lubricated contact over a wide range of conditions such as load, speed and temperature. Additional insight can be obtained by observing the influence of lubricant properties as a function of film thickness. This approach helps to separate the role of the physical and chemical properties.

3.4.1 Properties in Hydrodynamic Lubrication: Hydrodynamic lubrication is the generation of a load supporting pressure by the motion of two surfaces, which pumps the lubricant into a convergent space. The theory for pressure generation, film thickness and lubricant flow is derived from Reynolds Equation where viscosity is the most important fluid property. The role of viscosity is easily seen in an Equation 1 for film thickness assuming rigid cylinders and a viscosity independent of temperature or pressure.

$$\frac{h_o}{R} = 4.896 \frac{U\mu_o}{W} \qquad \text{(Eq. 1)}$$

where:

h_o = film thickness on the line of centers
R = equivalent radius of curvature
U = one-half the sum of the surface speeds
μ_o = viscosity
W = load

Since viscosity is directly related to film thickness, the level of viscosity can be selected for a given application to provide sufficient film thickness for complete surface separation. Since most applications are not constant speed, or constant load devices, lubricant decisions are made to select an appropriate level of viscosity. In many cases design decisions are made to obtain the geometry, surface finish, material and load to allow a customer selected lubricant to operate successfully.

The process of generating a hydrodynamic film results in power consumption and a temperature rise of the lubricant film. Both internal and external thermal effects can decrease the viscosity substantially. The rate of change of viscosity with temperature can be significant. The thermal effect on viscosity also varies with lubricant type.

The approach taken to viscosity-temperature correlation has been mostly empirical. The standard viscosity-temperature relation is the Walther Equation 2 from which the ASTM viscosity-temperature chart was formed

$$\log \log (\mu_o + 0.6) = m \log T + C \qquad \text{(Eq. 2)}$$

where:

T = absolute temperature
M = slope of ASTM viscosity-temperature chart

3.4.1 (Continued):

While many lubricants give reasonably straight lines on the ASTM chart, the extrapolation capability at the extreme ends of temperature are not very accurate.

The slope m is an important lubricant property. The performance of a lubricant will improve, or at least be more predictable, if the sensitivity between viscosity and temperature were diminished. A common approach to the viscosity-temperature characterization of lubricants is the viscosity index (VI). VI is based on a comparison with two families of lubricants having widely different viscosity-temperature behavior. One is designated zero and the other is designated 100.

3.4.2 Properties in Elastohydrodynamic Lubrication: High loads or non-conforming geometries introduce elastic deformation into the hydrodynamic problem. A more important feature is the tremendous change in viscosity that results from the high pressures that are developed. The result is the rather remarkable load carrying mechanism of EHD lubrication. The lubricating film thickness formula derived from the Reynolds Equation for EHD conditions includes both elastic and viscosity-pressure parameters. One version of this Equation 3 for a line contact is:

$$\frac{h_m}{R} = 2.65 {\frac{U\mu_o}{E'R}}^{0.7} (aE')^{0.54} {\frac{w}{E'R}}^{-0.13} \qquad \text{(Eq. 3)}$$

where:

h_m = minimum film thickness
R = equivalent radius of curvature
U = entraining velocity
$F0_o$ = atmospheric viscosity
A = pressure viscosity coefficient
E' = equivalent elastic modulus
w = load per unit width
μ_o = viscosity at atmospheric pressure

In contrast to the hydrodynamic problem where film thickness is directly proportional to viscosity, we see that under EHD conditions the film thickness is proportional to the lubricant properties of viscosity and pressure-viscosity raised to the power of 0.7 and 0.54, respectively. The above equation indicates that film thickness is not very sensitive to load.

The interaction between pressure and lubricant viscosity is important to the success of an EHD lubricating film. While this physical characteristic is important, it is generally absent from existing specifications. Measurements of viscosity under high pressures are difficult to make. Pressure-viscosity data for many lubricants are not always available. In addition, the correlation of the results in a simple form for many different types of fluids has not been entirely satisfactory.

3.4.2 (Continued):

The variation of viscosity with pressure is usually described by an exponential relation proposed by Barus Equation 4

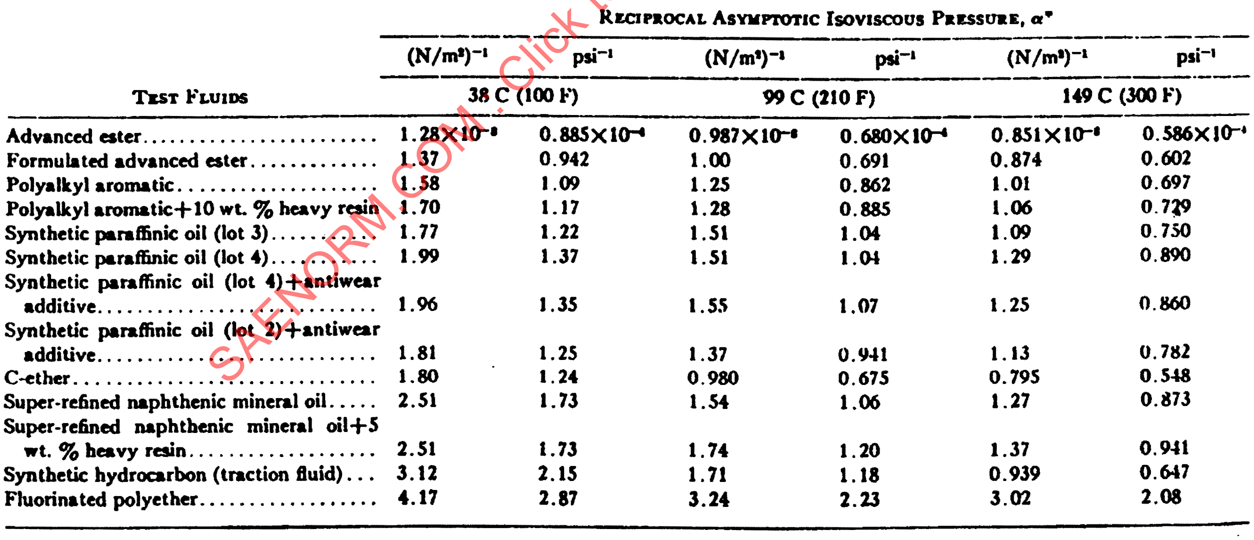
$$u = u_o e^{ap} \qquad \text{(Eq. 4)}$$

where:

μ = viscosity at pressure, p
μ_o = viscosity at atmospheric pressure
a = pressure-viscosity coefficient
p = pressure

This equation works reasonable well for predicting film thickness provided that the variation in the pressure-viscosity coefficient with temperature is taken into account. The pressure-viscosity coefficients for a range of aircraft fluid types have been measured and are given in Table 2. The pressure-viscosity coefficients are reasonably similar for many classes of fluids with some notable exceptions. Perfluoroalkylpolyether (PFPE) and polyphenyl ether (PPE) have exceptionally high pressure-viscosity coefficients. These fluids are very good EHD film formers.

TABLE 2 - Pressure-Viscosity Coefficients for Test Fluids



	Reciprocal Asymptotic Isoviscous Pressure, α*					
	$(N/m^2)^{-1}$	psi^{-1}	$(N/m^2)^{-1}$	psi^{-1}	$(N/m^2)^{-1}$	psi^{-1}
Test Fluids	38 C (100 F)		99 C (210 F)		149 C (300 F)	
Advanced ester	1.28×10^{-8}	0.885×10^{-4}	0.987×10^{-8}	0.680×10^{-4}	0.851×10^{-8}	0.586×10^{-4}
Formulated advanced ester	1.37	0.942	1.00	0.691	0.874	0.602
Polyalkyl aromatic	1.58	1.09	1.25	0.862	1.01	0.697
Polyalkyl aromatic+10 wt. % heavy resin	1.70	1.17	1.28	0.885	1.06	0.729
Synthetic paraffinic oil (lot 3)	1.77	1.22	1.51	1.04	1.09	0.750
Synthetic paraffinic oil (lot 4)	1.99	1.37	1.51	1.04	1.29	0.890
Synthetic paraffinic oil (lot 4)+antiwear additive	1.96	1.35	1.55	1.07	1.25	0.860
Synthetic paraffinic oil (lot 2)+antiwear additive	1.81	1.25	1.37	0.941	1.13	0.782
C-ether	1.80	1.24	0.980	0.675	0.795	0.548
Super-refined naphthenic mineral oil	2.51	1.73	1.54	1.06	1.27	0.873
Super-refined naphthenic mineral oil+5 wt. % heavy resin	2.51	1.73	1.74	1.20	1.37	0.941
Synthetic hydrocarbon (traction fluid)	3.12	2.15	1.71	1.18	0.939	0.647
Fluorinated polyether	4.17	2.87	3.24	2.23	3.02	2.08

There is a general trend that fluids with high pressure-viscosity coefficients also have high viscosity-temperature slopes (low VI). Thus, a lubricant with a positive pressure-viscosity attribute may be offset by a negative viscosity-temperature attribute. To put this into perspective, it is helpful to consider the product of viscosity and pressure-viscosity (μ_{oa}) as a function of temperature. This is shown in Figure 5. Since both μ_o and a appear in the EHD film thickness equation, their product, and its variation with temperature, can be considered as a single lubricant property for EHD film formation.

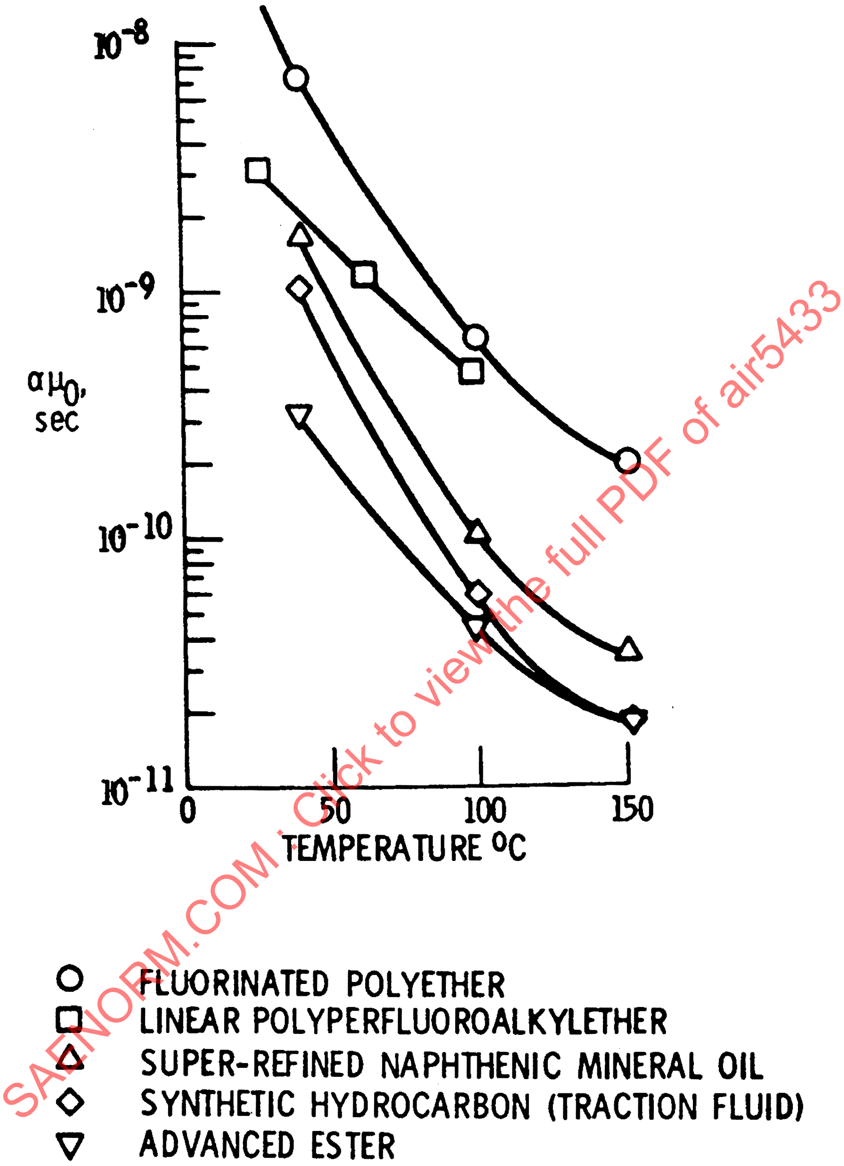


FIGURE 5 - EHD Film Forming Capacity as Function of Temperature

3.4.2 (Continued):

The significance of the lubricant property μ_{oa} can be shown by calculating the film thickness to surface roughness ratio (lambda ratio) over a temperature range. This is shown in Figure 6 for two aircraft engine lubricants. The reduction in film thickness with temperature is quite significant in the low temperature region. At elevated temperatures, the viscous properties of the two lubricants are much less sensitive to temperature.

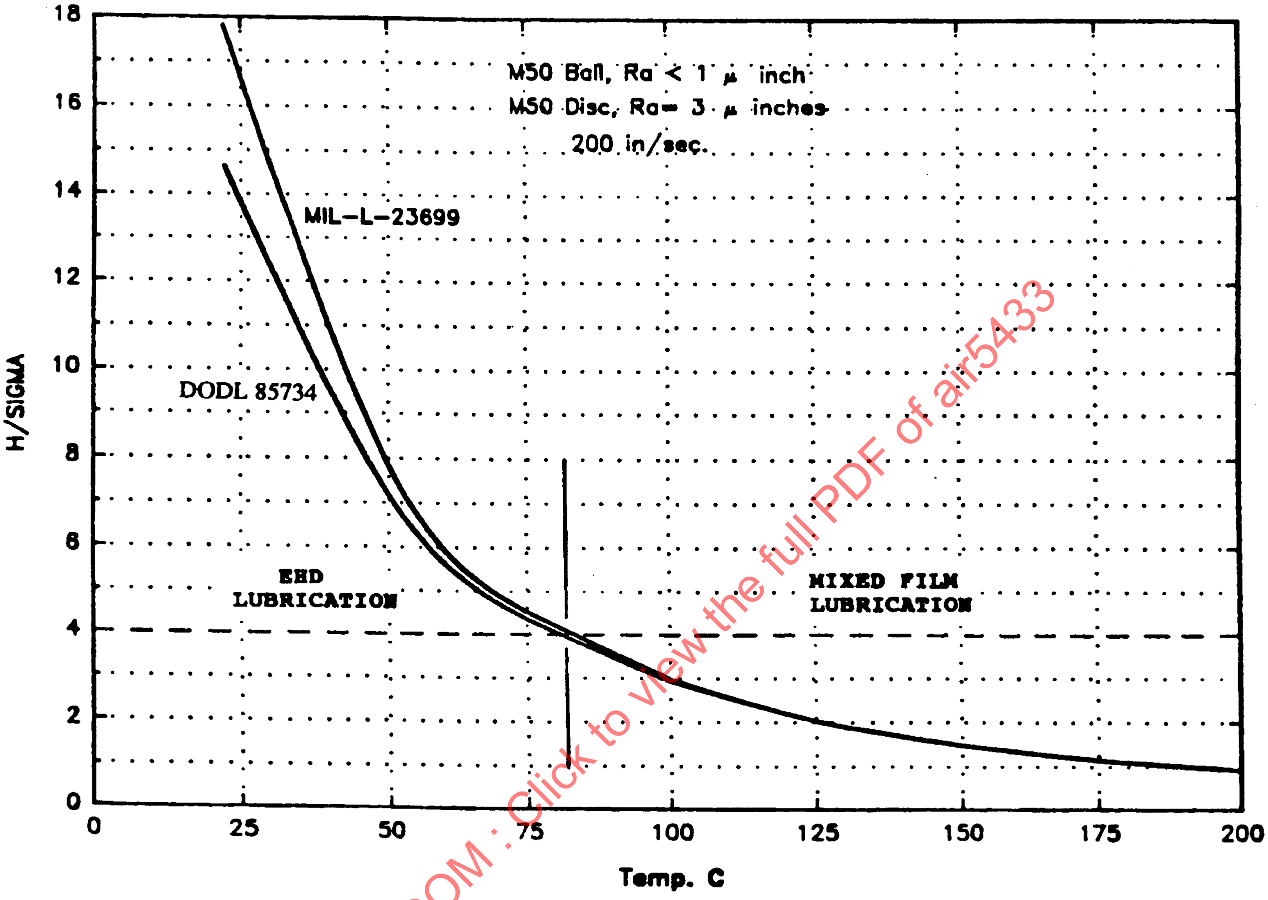


FIGURE 6 - Film Thickness to Surface Roughness Ratio Versus Temperature

3.4.2 (Continued):

There are several lubricant related factors that can cause the film thickness predicted by the EHD equation to be less than predicted. The inlet region to the contact (see Figure 2) does not require very much lubricant, but the inlet boundary must be sufficiently upstream of the contact to avoid starvation. The location of this inlet boundary is influenced by surface tension and density of the lubricant. Starvation results in a thinner film thickness. The reduction of film thickness depends on the location of the inlet boundary.

The fluid molecules see a great deal of shear in the inlet region due to the converging geometry. The maximum shear stress occurs at a location within the inlet region where the film thickness is approximately $2h_o$. This is close to the "heart" of the film generating area. Thus, any non-Newtonian fluid behavior will surely influence film thickness. Finally, the viscous flow, and backflow, in the inlet region can cause heat generation within the lubricant film. This thermal effect is sufficient to reduce the film thickness, particularly at high speeds.

3.4.3 Properties for EHD Traction: Under EHD conditions, the inlet region is primarily responsible for the generation of film thickness. The Hertzian region (see Figure 2) is primarily responsible for the friction, or traction, of the lubricated contact. The high pressure in the Hertzian contact causes the lubricant to become pseudo-solid. If there is relative motion between the surfaces, the solid-like lubricating material must accommodate shear between the surfaces. Under incipient sliding conditions, where the slip velocity between the surfaces is very small compared to the rolling velocity, the lubricant behaves like an elastic solid. As the sliding velocity is increased, the lubricant will shear like a plastic solid. This causes the traction between the surfaces to reach a maximum. The maximum traction, or traction coefficient (load/traction force), is usually on the order of 0.07. The traction coefficient reflects the limiting shear strength of the lubricant. The traction within the contact is a major cause of heat generation in bearings and gears. Traction coefficients can be considered as a property of a fluid.

Traction coefficients vary with molecular structure. PFPE's have a traction coefficient about 0.11 at 23 °C. "Traction fluids" have even higher traction coefficients.

The traction coefficient also varies with temperature. Figure 7 shows the variation of traction coefficient with temperature for two aviation lubricants. The reduction of traction coefficient from 0.06 to 0.03 when the temperature is increased from 23 to 125 °C indicates that the lubricants become more "efficient" at elevated temperatures with regard to power consumption.

3.4.4 Properties for Boundary Lubrication: Lubrication films generated by hydrodynamic mechanisms can totally separate surfaces to prevent wear and control friction. Boundary lubrication occurs under conditions where there is significant surface interaction. It is characterized by the following:

(1) The lubrication mechanisms are highly complex involving metallurgical effects, surface topography, physical and chemical adsorption, corrosion, catalysis and reaction kinetics.

(2) The primary function of boundary lubrication is the formation of surface films to minimize wear and surface damage.

(3) The formation of surface films is controlled not only by lubricant chemistry, but its interaction with the surfaces, wear debris and the environment.

(4) While the formation of surface films are very chemical in nature their performance is determined by mostly unknown physical properties such as shear strength, thickness, surface adhesion, film cohesion, melting point or decomposition temperature and solubility.

The fundamental physical and chemical properties of boundary lubricating films are really too complex to be of practical value to the user for design and selection. In any case, they cannot be measured. The user, supplier and specifier rely on empirical boundary film properties that reflect their general performance for reducing wear and preventing catastrophic failure, i.e., anti-wear and EP performance. Anti-wear and EP performance is evaluated by test methods, which are difficult to relate to the user's hardware. The user is the ultimate judge of the boundary film properties.

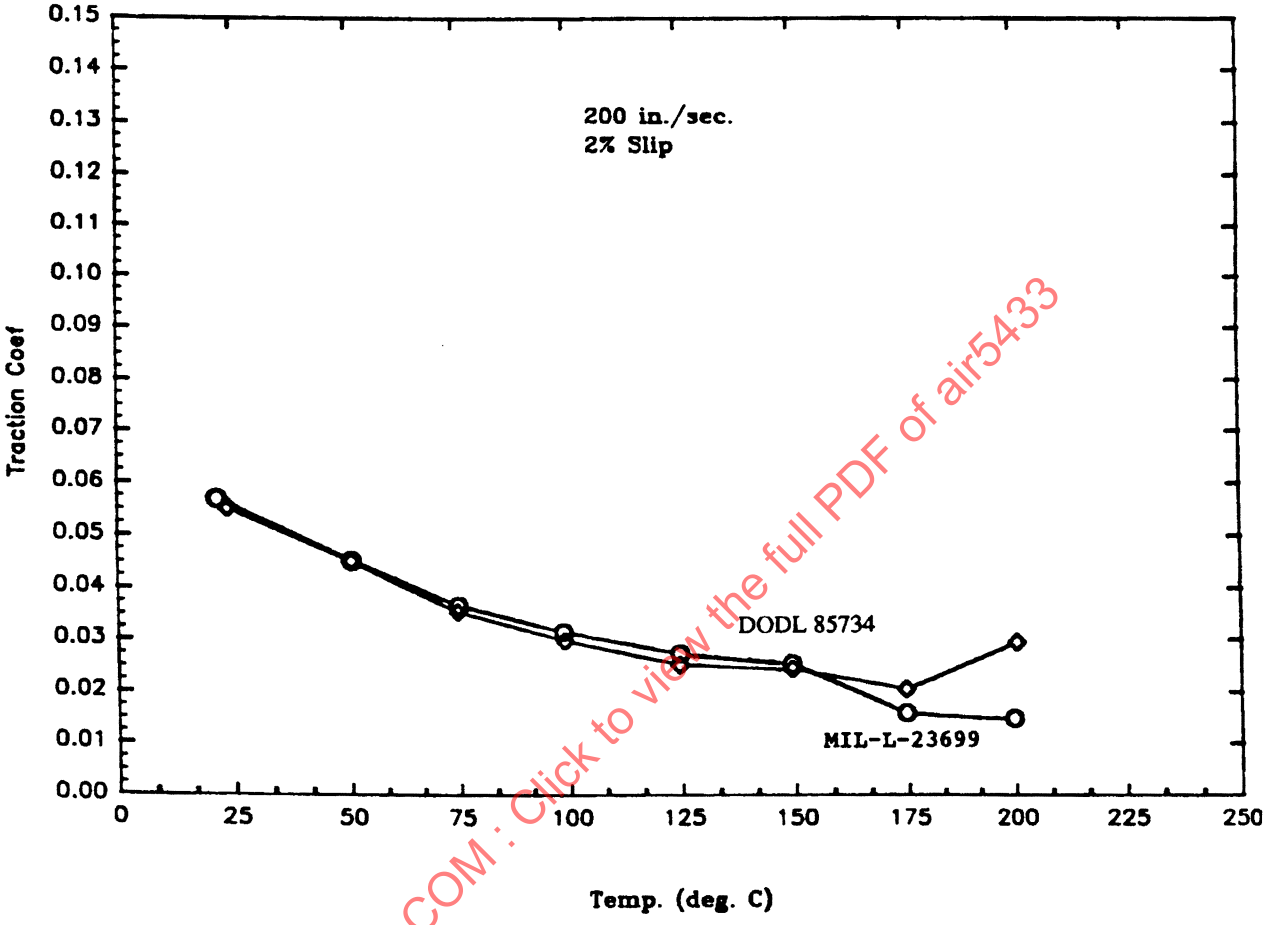


FIGURE 7 - Traction Coefficient Versus Temperature

3.4.5 Mixed Film Lubrication: There are but few applications that operate purely on hydrodynamically generated films or purely on boundary lubrication films. In most cases, hydrodynamic and EHD mechanisms operate along with boundary lubrication mechanisms. The former carries the chemistry for the latter to work, and the latter protects the surfaces so that the former can continue to operate. The joint action of the physical and chemical mechanisms seems to be a significant factor in performance. Lubricant property significance perhaps can only be judged when both types of mechanisms are allowed to operate.

An example of the interaction of both boundary and EHD mechanisms is shown in Figure 8 for an aircraft lubricant with and without an anti-wear additive (TCP). A lubricated concentrated contact is forced to transition from a full film EHD lubrication mode into mixed film lubrication by increasing the temperature. The lubricant without TCP encounters polishing wear immediately upon entering the mixed film lubrication regime. The resulting smooth surfaces allow the low shear strength EHD film to control the traction (friction). However, at 200 °C the surfaces fail because there is no boundary film to maintain the integrity of the surfaces.

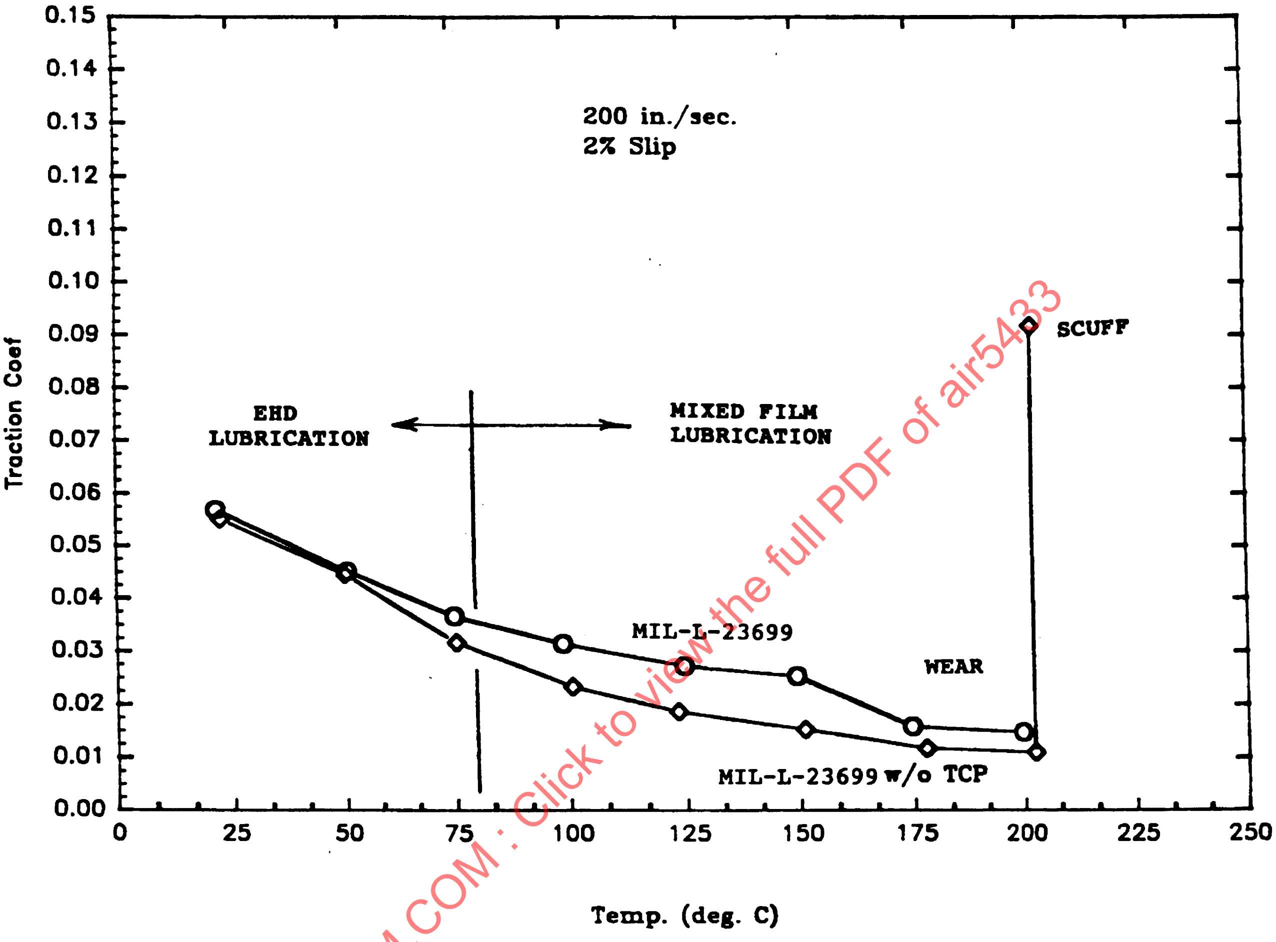


FIGURE 8 - Transition From EHD to Mixed Film Lubrication

3.4.5 (Continued):

The lubricant with the additive (MIL-L-23699) displays higher traction, but does not encounter polishing wear until it is well into the mixed film lubrication regime. The boundary films preserve the surface integrity and no failure is observed.

The role and significance of both hydrodynamic and boundary mechanism can be shown by driving a lubricated contact into the mixed lubrication regime from a number of directions. Figure 9 is a performance map obtained with an aviation lubricant (High Gear Lubricant) minus its load carrying additive (w/o LA). The performance map is defined in terms of an entraining velocity (R) and a sliding velocity (S). The entraining velocity generates an EHD film and the sliding velocity generates a thermal environment that leads the surfaces eventually toward a scuffing failure.

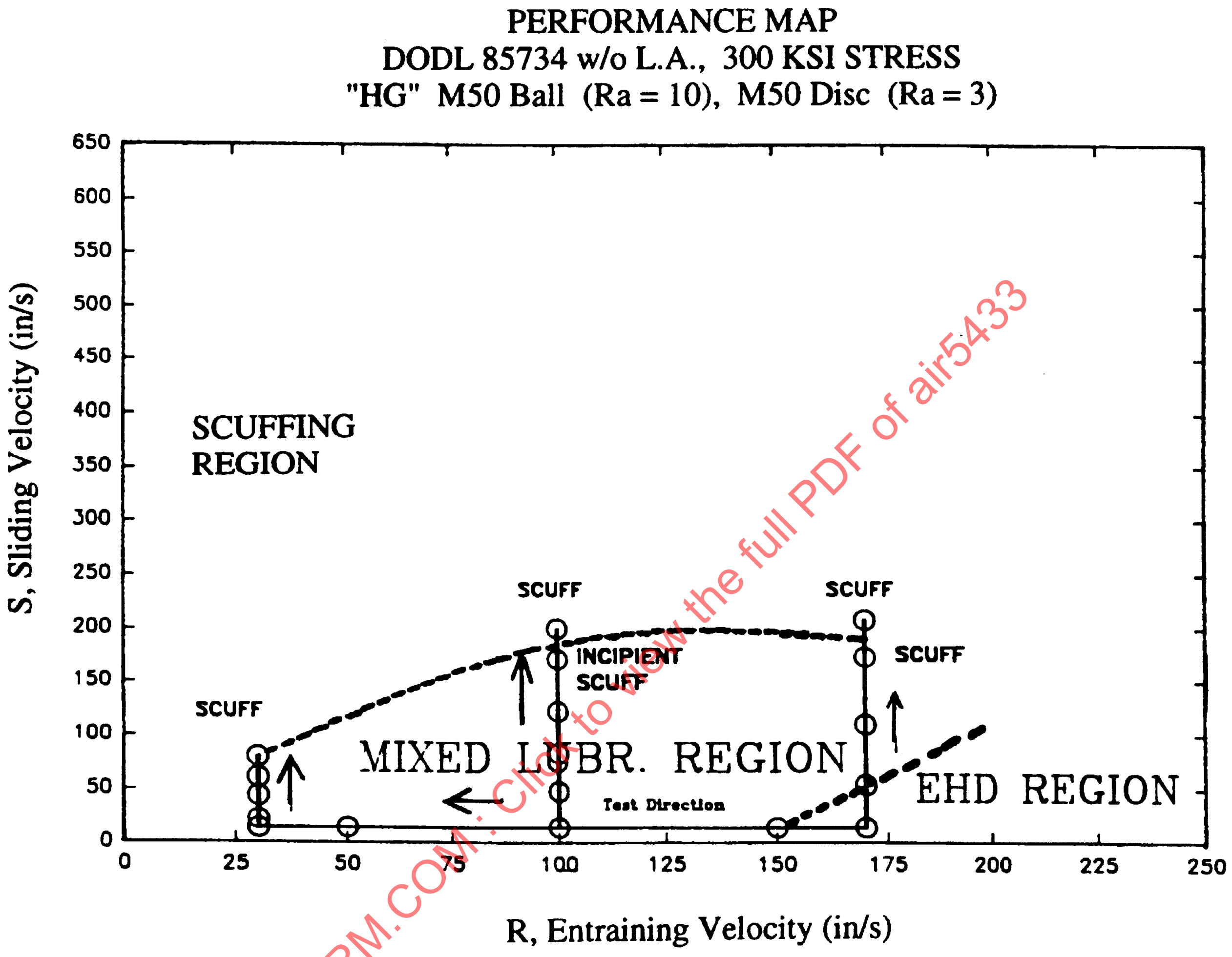


FIGURE 9 - Performrance Map Without Load Carrying Additive

3.4.5 (Continued):

The performance map identifies three regions of operation: (1) EHD region where physical properties of the lubricant completely separate the surfaces, (2) a mixed film lubrication region where both the physical and chemical properties are sufficient to prevent scuffing, and (3) a scuffing region where the lubricant properties, both physical and chemical, are no longer sufficient of prevent scuffing.

Figure 10 shows a performance map obtained with the High Gear Lubricant including its load carrying additive. The transition between EHD and mixed film lubrication is essentially the same since it is a function of viscosity, which has not been changed. The scuffing boundary has been extended significantly due to the presence of the load carrying (EP) additive.

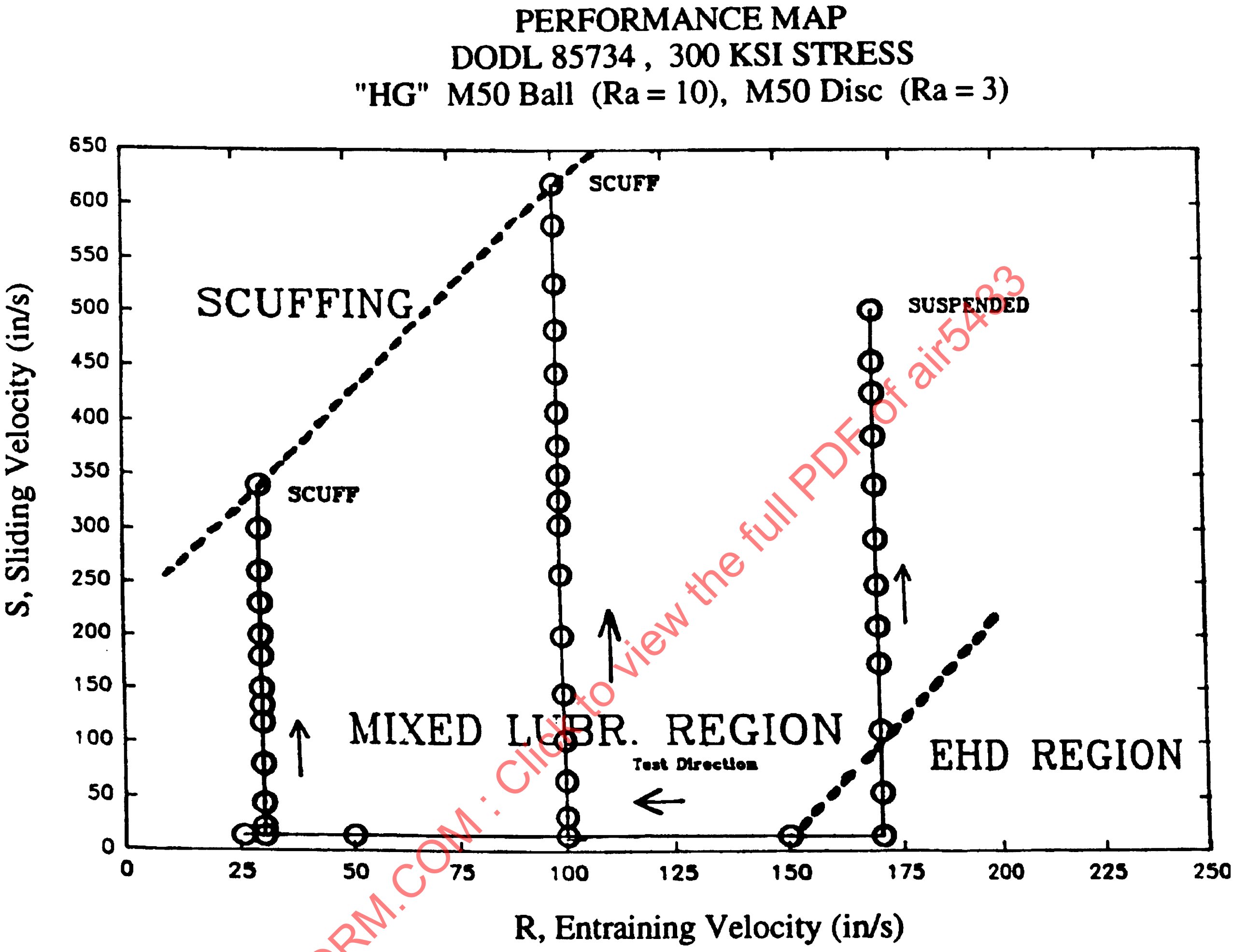


FIGURE 10 - Performrance Map With Load Carrying Additive

4. COMMONLY USED LUBRICANT PROPERTIES FOR AIRCRAFT ENGINE AND POWER TRANSMISSION SYSTEMS:

4.1 Background:

The properties presented in this section are those which are related to the lubrication function, i.e., those which directly or indirectly play a role in the performance of the fluid in the contact area of lubricated components.

Several physical properties of the basestock contribute to the formation of the film that separates surfaces in relative motion. In this respect, viscosity is the major, if not the only, specified physical property related to the lubrication function. For example, viscosity-temperature index, despite having an influence on fluid film thickness, is governed by the low temperature flow requirements of the overall system. Other physical properties which are used in determining a lubricant's film strength are not specified ideally for their contribution to lubrication but are a consequence of the need for other characteristics (e.g., thermal stability) of the basestock and the economics of producing the fluid. Although, usually not specified, these properties are not expected to vary very much for products qualified to a particular specification because the overall requirements restrict the basestock to similar chemistry. Unfortunately the methods to determine these properties tend to be ignored and in some cases there are no standard methods. Because these properties are important to designers, they are included in the tables of this section even if methods are not specified or standardized. In these cases, typical values obtained by particular methods are presented. It is intended that by including this data, focus will be brought on the deficiencies in this area and data from improved and/or standardized methods will be presented in future editions of this document.

The "chemical properties" of the lubricant are those which play a major role in establishing load carrying capacity or the performance of the lubricant in the absence of a separating film. This characteristic is very difficult to assess universally because it is not an inherent property of the lubricant itself. It is a manifestation of the interaction between the lubricant additives and the metallurgy of the contacting surfaces.

4.2 Properties and Test Methods for Lubricants Used in Aircraft Propulsion Systems:

The tables provided in this section deal with synthetic lubricants intended primarily as engine and/or gearbox lubricants for aircraft propulsion or power transfer systems.

Based upon a past survey of the SAE E-34 Aerospace Lubricants Committee members, the following tables have been generated which list the most commonly used lubricant properties and test methods that are used to determine these properties. The data presented will be divided into properties that have direct influence on the lubricant characteristics that effect the contact zone and other properties that influence the overall lubrication system design. Included in these tables is a list of lubricant specifications that were defined as being used in current aircraft propulsion systems along with typical property values. These lists are not intended to be complete but do specify the data provided during the survey. The intent of this section is to provide a list of lubricants, properties, and typical values of these properties that could be used for either the selection of a lubricant or the selection of the property value that can be used for various lubrication calculations. These tables will be updated as needed to include additional lubricants and property values as data is received.

TABLE 3 - Lubricant Property Summary for Aircraft Propulsion Systems
Kinematic Viscosity

USES:	EHL calculations, lubricant flow to lubricated components, heat generation, oil pressure drop and cage drag calculations.
TEST METHODS:	ASTM D 445/IP71 ASTM D 341

SYNTHETIC LUBRICANTS:

	Temperature °C/(°F)	Specification cSt	Typical Range cSt
MIL-PRF-7808L			
Grade 3	-51/(-60)	17 x 10^3 max	7106 - 7741
	40/(104)	11.5 min	11.6 - 12.9
	100/(212)	3.0 min	3.04 - 3.23
Grade 4	-51/(-60)	20 x 10^3 max	17,280 - 19,704
	40/(104)	17.0 min	17.61 - 17.80
	100/(212)	4.0 min	3.95 - 4.07
	204/(400)	1.1 min	1.13 - 1.23
MIL-PRF-23699F	-40/(-40)	13,000 max	7,800 - 11,500
	40/(104)	23 min	24.0 - 27.5
	100/(212)	4.9 - 5.4	5.0 - 5.3
DOD-L-85734	-40/(-40)	13,000 max	8,649 - 9,970
	37.8/(100)	25 min	27.35 - 29.50
	98.9/(210)	5.0 - 5.5	5.13 - 5.40
DEF STAN 91-100/101	-40/(-40)	13,000 max	7,532 - 11,965
	40/(104)	30 max	24.0 - 27.53
	100/(212)	4.9 - 5.4	4.97 - 5.378

REMARKS:

For calculation of hydrodynamic and elasto-hydrodynamic film thickness, the kinematic viscosity of the lubricant must be converted to dynamic viscosity by multiplying it by the specific gravity of the lubricant. Therefore, when viewing lubricants of different density for film forming ability, direct comparison of kinematic viscosity could lead to considerable error.