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FRICTION AND WEAR IN SODIUM*

N. J. Hoffman and J. J. Droher

Liquid Metal Engineering Center** Canoga Park, California

In the design of a safe and reliable sodium-cooled reactor such as the *Fast Flux Test Facility* (FFTF), one of the more important problem areas is that of friction and wear of components immersed in liquid sodium or exposed to sodium vapor. Sodium coolant at elevated temperatures may severely affect most oxide-bearing surface layers which provide corrosion resistance and, to some extent, lubrication and surface hardness. Consequently, accelerated deterioration may be experienced on engaged-motion contact surfaces, which could result in unexpected reactor shutdown from component malfunction or failure due to galling and seizure.

In this paper, we will first present an overall view of the friction and wear phenomena encountered during oscillatory rubbing of surfaces in high-temperature, liquid-sodium environments. We shall conclude with specific data generated at the Liquid Metal Engineering Center (LMEC) on this subject.

A number of organizations and individuals other than the Liquid Metal Engineering Center staff are involved in this experimental work on friction and wear in sodium performed at LMEC. K. E. Horton of the Materials Development Branch, Reactor Research and Development Division, US AEC is the sponsor monitor while R. N. Johnson of the Hanford Engineering Development Laboratory is coordinating the friction and wear efforts in support of the Fast Flux Test Facility. Two organizations other than LMEC are involved in this overall friction program, Westinghouse ARD and Atomics International, and they are developing similar data.

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BACKGROUND

A. DEFINITIONS

Friction coefficient (f) is defined as the ratio of the measured frictional force (F) in the direction of motion to the load (L) normal to the plane of motion. For most nonsodium applications, the designer usually is interested in the static friction coefficient (which is based upon the initial friction force at the beginning of a stroke) and the dynamic friction coefficient (which is based upon the frictional force during the stroke). In sodium and other high-temperature reactive media where diffusion bonding can occur under certain time-temperature conditions, a third friction coefficient should also be considered.

This coefficient is usually called the breakaway coefficient of friction because the diffusion bonds must be broken away before motion can start. Hence, the breakaway coefficient of friction may be considered to be the initial static coefficient of friction measured after a significant dwell period of surfaces in contact. If the breakaway coefficient does not differ from the static coefficient, it is conventional to state that no breakaway was observed, although in reality the "usual" friction force to initiate motion was still present.

Wear in FFTF work, is expressed as the depth of flat surface worn away per unit distance traveled per unit of contact pressure. This expression is identical to the concept of volume of flat surface worn away per unit distance traveled per unit contact load:

$$(\text{cm}/\text{cm})/(\text{kg}/\text{cm}^2) = (\text{cm}^3/\text{cm})/\text{kg}$$

or

$$(\text{in.}/\text{in.})/\text{psi} = (\text{in.}^3/\text{in.})/\text{lb.}$$

In many cases, the numerical values of wear coefficient (K) will be expressed as a number times 10^{-11} (in./in.)/psi, with the load noted, as wear may be a function of load as well as contact pressure (to convert from these English wear values to the Metric wear values, multiply the former wear values by 14.19). The reader is cautioned against the indiscriminate comparison of wear coefficients reported by different investigators without first checking for dimensional consistency.[1,2,3] For example, some investigators report a dimensionless wear coefficient by dividing by "p", the indentation hardness or yield pressure of the softer material involved. Other investigators utilize a "K" defined as the probability that a sheared asperity will be lost from a surface. A wear coefficient so defined differs from ours by the factor of "3p". Since 3p is on the order of 10^5 psi, reported values of wear coefficient can usually be distinguished as to type of units and their order of magnitude. A wear coefficient expressed as a unitless number times 10^{-6} has a p or 3p term factored out. While the use of the wear coefficient with the 3p factored out has the advantage of a dimensionless coefficient with a physical meaning, there is often a substantial disadvantage in that "p" is often not readily available to the designer to calculate wear. Since K and "p" are functions of temperature and previous processing history, predicting wear from room temperature "p" data is not recommended for high temperature applications. In such attempts, a knowledgeable metallurgist can guess a reasonable "p" value but probably not a reasonable K value. An experimentally derived wear coefficient at the temperature of interest on the material of interest is the value the designer should use to predict wear.

Two main types of wear are considered in this report: abrasive wear and adhesive wear. In general, abrasive wear is observable in scanning electron microscopy as grooved lines on the wear surface (Figure 1). Adhesive wear often exhibits a smeared, "cold butter" appearance (Figure 2), indicating that metal has plastically flowed. Other types of wear are occasionally noticed, such as brittle intergranular fracture (Figure 3), and localized, plowed surfaces (Figure 4). Corrosive wear can also occur when sliding takes place in a corrosive environment. Most structural materials selected for applications involving liquid sodium exhibit negligible corrosive effects if reasonable purity levels are maintained. However, as will be explained later in this paper in more detail, the effect of the media upon formation and dissolution of surface films can be of vital importance.

B. ENGINEERING CONSIDERATIONS

Friction forces are those forces which resist the movement of one body relative to another contacting body. A fairly definite force is required to start a body moving and it must be equal and opposite to the static friction force; a different-sized force is required to keep the body moving at a constant speed and it must be equal and opposite to the dynamic friction force. Moreover, in high-temperature sodium under certain conditions, diffusion bonding (or self-welding) of materials can occur at contacting regions under certain conditions and these bonded junctions must be broken before one body can move relative to another contacting body; in this case, the breakaway friction force must be overcome, which is composed of both the static friction force and the force necessary to break the diffusion bonds.

In a typical moving device, there is a driving mechanism (engine or motor) which can generate any required amount of force up to some limiting value, then a sliding mechanism, which transforms the force into usable form by employing cams, gears, etc. and at the same time dissipates some of the energy as friction, while finally, there is an output mechanism which uses up the rest of the available energy. In order to size the driving mechanism, the designer should know the maximum friction values which may be encountered to initiate motion and to maintain motion. In other instances, where the forces are being imposed upon thin-wall or relatively fragile members, the designer must make sure that forces imposed will not exceed those causing damage to the structure. As a very rough rule of thumb, friction values which do not exceed 0.5 are generally considered good for sliding surfaces at elevated temperatures. Values above 0.5 generally portend significant surface damage, and values above 1.0 are generally considered unacceptable. Individual cases must be considered on the basis of all factors involved and the designer may decide to adjust these criteria values downward, or possibly to adjust them upward.

The variation of friction with temperature, time. rubbing distances, etc. is also of considerable interest. Sudden changes in friction from a high-friction regime to a low-friction regime, or the converse, can be important. For example, fuel assemblies in a reactor are separated by duct pads but are clamped together to form a rather compact core. Sudden changes in friction between contacting duct pads could affect the degree of core compaction and cause sudden, undesirable changes in core reactivity. For this reason, the frictional behavior of candidate duct pad materials have been explored under a wide variety of conditions.

The wear process is generally thought of as a harmful one, and, indeed in the majority of practical situations, this is the case. Wear may be classified by the wear mechanism involved, e.g., adhesive wear or abrasive wear, or quantified by a wear coefficient. Wear may be judged by its engineering consequences; "light or beneficial" wear if it helps the surfaces to run in properly, "severe" wear if it is too rapid, "galling" if the surface becomes very rough and irregular, and "seizing" if the engine or motor driving the system stalls or a protective clutch slips.

In addition, in many applications (for example, in a sodium-cooled reactor) there is also concern about the quantity and size distribution of the particulate matter generated as wear debris. Particulate matter is of engineering concern because of four potentially undesirable effects.

(1) Wear debris particles can wedge between close-fitting moving surfaces and cause sealing problems, damage, or even seizing.

(2) Wear debris particles can cause erosion when entrained in rapidly moving fluid.

(3) Wear debris particles can plug fluid access holes into hydrostatic bearings or other critical small passageways.

(4) Wear debris particles can serve as unwanted nucleation sites in crystallization processes.

In addition, within nuclear reactors, circulating debris particles can become activated and then cause radiation problems in their deposition sites.

Total allowable wear can be a difficult criterion to apply, especially when the allowable wear value is a small number. In some cases of adhesive wear, wear debris particles are transferred back and forth between contacting surfaces and there may appear to be very small dimensional or weight changes even though a significant amount of material near the surface may have been disturbed and transformed into a crypto-crystalline state. Wear measurements based upon weight change (converted to volumetric change by dividing by density, and to depth of wear by dividing the volume by the contact area of the test specimens) are further complicated by the presence of sodium; i.e., absorption of sodium into a porous coating or even corrosive effects may tend to mask or obscure small weight changes due to wear.

C. THEORETICAL CONSIDERATION

In the classic theory of friction accredited to Amontons (1699), frictional force is assumed to be independent of the apparent area of contact, and the coefficient of friction then becomes independent of the applied load. For our purposes, we will find it convenient to think of the force required to move a slider in a direction parallel to the surface as composed of three terms: a shearing frictional force; a plowing force; and a diffusion bond separation force.

The shearing friction force obeys the classic theory. When a load is applied, the asperities on each surface sink into each other until the actual area of contact is sufficient to support the applied load. This eventual actual area is equal to the load divided by the yield pressure of the softer surface. When the surfaces slide over each other, the force required to shear this actual area is the shearing frictional force.

The plowing force is that force required to cause macroscopic flow of metal. This flowing metal can be in material in front of a slider or be material which is part of a generated debris particle.[4] In the former case, the plowing force is equal to the cross-section of the resultant wear groove times the mean pressure required to move the material in the surface being grooved by the slider.[1] In the latter case, a generated debris particle is forced to flow and then adhere to one or both sides of the rubbing couple, forming a new and wavier surface. For a given load, quasi-flat surfaces which are partially submerged into mating surfaces at various points will require smaller plowing forces with increasing number of points of contact.[1] Hence, the plowing force required to flow metal is sensitive to surface waviness, which would decrease the number of points of indentation. Further, the greater the apparent contact area for a given load (i.e., the smaller the apparent contact pressure), the greater the number of points of contact. Thus, a low contact pressure on flat surfaces will give a lower plowing force. Finally, ductile materials have higher plowing force terms than hard, brittle materials because work hardening of ductile materials will cause the shear plane to be shifted below asperity peaks to a shear surface of greater area.

The diffusion bond separation force involves bonding forces that are more dependent on time, temperature, and surface film formation than on applied load. If the surfaces in contact are lapped and clean, the diffusion bond separation force will be a strong function of apparent contact area and independent of contact pressure.[5]

Since the shearing force is directly proportional to load, the coefficient of friction concept is valid for those cases where shearing friction force is the only significant component of force required for one surface to slide over another. When the plowing force and diffusion bond separation force are significant, dividing the summed required forces by the normal load results in friction coefficients that are not independent of load. Specifically for a given contact pressure, light loads would result in higher apparent coefficients of friction than high loads. For given loads, an increase in contact area can raise, lower or have no effect on the apparent coefficient of friction as has been discussed above.

D. RELATIONSHIP BETWEEN FRICTION AND WEAR

The relationship between friction and wear can be stated simply: there is no relationship. A high friction sliding combination can show high or low wear. A low friction combination can also exhibit high or low wear. In general, pure adhesive wear involves flow of metal along with the transfer of wear debris particles back and forth between surfaces and thus results in high friction and low measured wear. Pure abrasive wear does not involve the forces required to flow metal but material worn away is lost to both surfaces. Thus, this type of wear often shows lower friction and higher wear.

Either friction or wear may lead to failure through seizing. Seizing is a phenomenon that may involve excessive shearing forces in the case of friction seizing or involve excessive plowing forces in the case of galling seizing.[4] Wear can generate debris particles that must be smeared between two moving surfaces, leading to galling seizing. The wear debris particles can cause galling far downstream from the point they were generated.

E. DIFFERENCE BETWEEN SODIUM AND OTHER ENVIRONMENTS

A liquid sodium environment around rubbing surfaces creates three new conditions that can affect the friction picture.

(1) Either a lubricative surface film or an ultraclean, bare metal may be the thermodynamically stable surface phase, depending on the temperature and oxygen level of the sodium.

(2) The chemistry of the material surface can change with time due to mass transfer, particularly in ΔT systems.

(3) The question of whether wetting of rubbing surfaces by liquid sodium has occurred must always be considered in systems operating under 700°F.

The first condition listed above means that the measured coefficient of friction for a rubbing couple can be greater or less than it would have been in air or in an inert atmosphere, depending on the liquid sodium temperature and purity. When bare metal is the stable surface phase, the surfaces tend to bond together. Wear debris particles probably have less chance of escaping from contacting, sliding surfaces, thus increasing the required plowing force term. The diffusion bonding separation force becomes an important consideration when minutes have passed with surfaces in static contact at temperatures above 1000°F when bare metal is the stable phase. The breakaway friction coefficient can become high. The kinetics of film formation at certain temperatures can be such that exposure time under isothermal temperature conditions will affect the friction results.

The second condition means that materials that show acceptable friction and wear properties in short-term tests also must be exposed for long times in a ΔT loop to see if any catastrophic surface effects occur on either of the contacting materials.

The third condition involves the phenomenon of wetting in liquid metals. Depending somewhat on time, sodium purity, component material, and upon the condition (films and cleanliness) of component surfaces prior to immersion in the sodium, there is a temperature at which wetting of the solid surface will occur. For most structural materials, this temperature falls somewhere between 500 and 700°F. Below 500°F, generally wetting will not occur except after relatively long periods of immersion. Between 500 and 700°F, significant periods of time may be required for sodium to wet the surface and tests inadvertently could be performed on unwetted surfaces. Unwetted surfaces immersed in liquid sodium have been observed to exhibit extremely low friction, probably due to droplets of liquid sodium being trapped between the rubbing surfaces. If solid surfaces are pressed together before being immersed in sodium, the non-wetting liquid will not penetrate between the surfaces, resulting in friction values not characteristic of surfaces in sodium. Heating to well above the wetting temperature (750 to 900°F range), prior to initiating rubbing under sodium will eliminate either of the above conditions. However, pretest heating should not be done when it will not simulate the actual application where rubbing in sodium will commence prior to wetting.

F. OXYGEN CONSIDERATIONS INVOLVED IN METAL-TO-METAL SLIDING CONTACT IN LIQUID SODIUM

For years, the technical community involved with friction testing in liquid sodium has known that oxygen content of the sodium is a critical parameter. Lubricative layers of $Na_xCr_yO_z$ were assumed to form on metal surfaces that contained chromium. The accepted stoichiometry for this sodium-chromium-oxygen compound is now $NaCrO_2$. The oxygen content and temperature regimes where this lubricative layer is stable under equilibrium conditions is theoretically predictable from thermodynamic equilibria data. If this layer is present, the coefficient of friction is low. The kinetics of formation of the lubricating layer are critical as to whether equilibrium conditions are achieved. The method of determining the oxygen content turns out to be extremely important in evaluating friction data since each method can give different results. The above three topics, i.e., thermodynamic equilibria, kinetics, and effect of the method for determining oxygen on evaluating friction data, are discussed in the following text.

1. Thermodynamic Equilibria Calculation

The equations dealt with are:

$$NaCrO_2 \rightarrow 2\ (\text{O dissolved in Na to the point of saturation}) + \text{Na} + \text{pure Cr} \quad (1)$$

$$NaCrO_2 \rightleftharpoons 2\ (\text{O dissolved in Na}) + \text{Na} + \text{Cr in stainless steel} \quad (2)$$

According to Gross, et al.,[6] the change in free energy for Equation 1 is

$$\Delta F_0 = 8300 + 19.6T \quad (3)$$

In units of calories/2 g-atoms of oxygen.

The free energy for Equation 2 would be:

$$\Delta F = \Delta F_o + RT \ \ln \frac{a_0^2 a_{Cr} a_{Na}}{a_{NaCrO_2}} = 0, \qquad (4)$$

where:

$$a_0 = \frac{C_{0 \text{ in Na}}}{C_{0 \text{ in Na at sat.}}}$$

$$a_{Cr} = \frac{C_{Cr \text{ in austenitic stainless steel (SS)}}}{C_{Cr \text{ in SS in equilibrium with pure Cr}}}$$

$$a_{Na} = 1.0$$

$$a_{NaCrO_2} = 1.0$$

$$\Delta F_o = 8300 + 19.6T$$

Thus:

$$RT \left[2.\ln (C_{0 \text{ in Na}}/C_{0 \text{ in Na at sat.}}) + \ln a_{Cr}\right] = -8300 - 19.6T \qquad (5)$$

Dividing through by 2 RT, changing ln to log, and solving for log C_0 in Na yields

$$\log C_{0 \text{ in Na}} = \log C_{0 \text{ in Na at sat.}} - 1/2 \log a_{Cr} - 907/T - 2.142 \qquad (6)$$

There are various equations for log C_0 in Na at sat. In 1970, Gross, et al., used the relationship:

$$\log C_0 \text{ in Na at sat.} = 5.21 - 1777/T, \qquad (7)$$

which combines with Equation 6 to give:

$$\log C_0 \text{ in Na} = 3.07 - 2684/T - 1/2 \log a_{Cr} \qquad (8)$$

However, as of the end of 1972, the oxygen saturation equation for sodium recommended by Argonne National Laboratory is:

$$\log C_0 \text{ in Na at sat} = 7.023 - 2828/T, \qquad (9)$$

which combines with Equation 6 to give

$$\log C_0 \text{ in Na} = 4.881 - 3735/T - 1/2 \log a_{Cr}, \qquad (10)$$

where T is in degrees Kelvin and C is in parts per million by weight.

The activity of chromium in stainless steel (a_{Cr}) is neither known nor constant. For example, if the atomic percent chromium in 18-8 SS is taken as a rough approximation (~ 20%), then an initial chromium activity of 0.2 can be used. Other rationalizations can be used to choose another slightly different activity value.

In Figure 5, a plot of the parts per million of dissolved oxygen in equilibrium with $NaCrO_2$ vs temperature is given for various assumed a_{Cr} values. The appropriate chromium activity curve indicates a division between the regime of low friction lubricated sliding and the regime of unlubricated sliding. After long-time exposure in sodium, the activity of chromium in metal surfaces probably drops as all the surfaces in the sodium start to move toward a high iron, ferrite composition. The effect with 1160°F sodium of a gradual lowering of the chromium activity in the rubbing surfaces on the dissolved oxygen level in equilibrium with sodium chromite is shown in Figure 6. This figure indicates that a high friction regime can be encountered with time, possibly in a sudden manner rather than as a gradual increase in friction.

2. Kinetics

Equilibrium conditions are not necessarily attained if the temperature of the sodium is low enough. Friction tests at 900°F on stainless steel rubbing against itself have indicated that an 15-hour hold time is required to change from a high friction regime to a low friction regime. If the old rule-of-thumb approximation in chemical kinetics holds true that the reaction rate doubles every 20°F, then the relationship so labeled in Figure 7 may approximate the actual reaction time for sodium chromite formation on 18-8 SS. Figure 7 also estimates the reaction time if the rule-of-thumb is off by a factor of two. The resultant spread in the kinetic estimates shows that below 825°F the lubricative layer will probably take more than 2 days to form, while at 1160°F this layer would form in less than 15 minutes and possibly in less than 1 second.

3. Effect of the Method of Determining Oxygen on Evaluating Friction Data

In the period 1970 - 1973, there were six main methods being used by the technical community for determining oxygen in sodium: (1) extrusion amalgamation, (2) total consumption amalgamation, (3) vanadium-wire equilibrium, (4) oxygen meter, (5) plugging meter, and (6) assumption of cold-trap-temperature control. The two amalgamation techniques involve bypass tubes with sodium at main-vessel temperature flowing through these tubes, which should be crimped or valved off at this temperature. The vanadium-wire technique involves heating the sodium passing by a vanadium wire to 1382 ± 9°F and allowing the oxygen to distribute between the vanadium, sodium, and structural metal for a time period sufficient that equal activities of oxygen are achieved in the three materials, or between just sodium and vanadium if the structural metal is not heated high enough for equilibria to occur. The oxygen meter involves emf measurements using a solid, ceramic electrolyte, with the sodium usually at either 600°F or 900°F.* Both of the latter two methods measure oxygen activity rather than oxygen content. The plugging meter measures the temperature at which precipitates start to plug a small opening at low temperature.

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* These temperatures are selected based in part upon consideration of ceramic electrolyte life.

These precipitates are usually phases predictable from the oxygen-hydrogen-sodium phase diagram and come out at distinct temperatures which are a function of the hydrogen and oxygen contents of the sodium. The first phase to precipitate is probably NaH, followed at some lower temperature by precipitation of a NaH + Na_2O mixture. The precipitation temperatures are good indicators of the effective cold-trap temperature. Knowing the effective cold-trap temperature allows a good estimate of the oxygen content. The last method, which directly measures the cold-trap temperature, would give a good estimate of the oxygen content if the system is indeed under cold-trap control.

Shifts in the sodium chromite equilibrium with temperature may affect the validity of the oxygen analyses in nonisothermal systems. This occurs when the sodium is hot enough so that the chromite reaction can move toward equilibria in the time it takes the sodium to cool from test vessel temperature to a lower temperature at the point of sampling.

When using the flow-through sample tubes, relatively long times are involved from the time of crimping to solidification, and sodium chromite can precipitate on the walls of the tube. The extrusion amalgamation technique eliminates this precipitate (as well as other precipitates) and would thus be an invalid analysis method in that it does not account for some portion of the compounds involving sodium and oxygen.

The oxygen meter method analyzes the activity which can be used to establish the dissolved oxygen content. Since an oxygen meter is usually operated well below 1100°F, the sodium in any system operating above this temperature must be cooled down through a temperature range where reactions occur in fractions of a minute (Figure 7). The sodium will lose dissolved oxygen by chromite deposition as it circulates into the cooler regions of the oxygen meter circuit if the original oxygen content is high. If the chromium activity of the structural metal is known, Figure 6 may be usable to predict the maximum reading the oxygen meter will show, independent of how much higher the dissolved oxygen content was at test temperature. At system temperatures below 900°F, higher dissolved oxygen contents than equilibrium conditions can be shown, as the chromite reaction rate is very slow compared to sodium flowrates out of hot regions in a sodium system.

Oxygen analyses conducted with the plugging meter can be affected by the sodium chromite reaction. With high-temperature, high-oxygen sodium the sodium chromite itself may cause plugging in the plugging meter, though the temperature of this plugging should be far higher than the usual sodium hydride-sodium oxide plugging temperatures. Identical plugging temperatures for the sodium hydride - sodium oxide precipitates do not necessarily mean the oxygen contents of the two systems are identical as there are an infinite number of concentrations that will precipitate out a single phase at a fixed temperature in a ternary system.

The oxygen analyses used or planned to be used for reporting the actual oxygen values in friction tests at LMEC are the total consumption amalgamation technique or the vanadium-wire technique. The total consumption amalgamation technique measures all residue from sodium in a previously sealed-off flow-through sample tube after the sodium has been dissolved in mercury. All the residue is considered to be Na_2O and the sodium content of the residue is measured. Multiplying the sodium content by 16/46 gives the oxygen content if indeed all the residue is Na_2O. Oxygen tied up as $NaCrO_2$ would thus be undervalued by a factor of four. If the only species in the residue were Na_2O and $NaCrO_2$, it could be assumed that the oxygen dissolved in sodium at high temperature eventually would end up as both Na_2O and $NaCrO_2$ while the $NaCrO_2$ originally present on the tube walls at high temperature would remain $NaCrO_2$. This method is thus not specific for dissolved oxygen in sodium but measures a distorted total amount of oxygen.

The vanadium-wire technique measures dissolved oxygen only and does not require that sodium be cooled before analysis. The sodium is heated, in fact, which does not affect the results since any $NaCrO_2$ is present almost certainly on the walls, not in the sodium flowing into the vanadium-wire module. Thus, the vanadium-wire device is a valid measure of dissolved oxygen which is normally the only oxygen species of interest.

The tests performed at LMEC in the friction and wear program in support of FFTF were done in sodium that measured less than 5-ppm oxygen by the total amalgamation method, or considerably less than 5-ppm oxygen by the vanadium-wire method.

LMEC FRICTION AND WEAR TESTS AND RESULTS

A. FACILITY DESCRIPTION

The friction and wear tests at the LMEC are performed in vessels, each of which is equipped with a flow-through, thermal convection cold trap attached to the vessel wall itself, and with a parallel flow-through sample line. The driving force through the sample line is by an electromagnetic (EM) pump. The test specimens are immersed in 25 to 50 gal of sodium. The sodium flows out of the vessel, through a 1/2-gal cold trap, and back into the vessel at $<$ 0.1 gpm. In general, the cold trap runs continuously during testing at all temperatures and times except during sampling.

The friction apparatus itself involves a weighted, driven plate supported by three rubbing surfaces equally spaced from the center of rotation and 120 degrees apart. Friction and wear tests are being performed using very short, reciprocating sliding contact, prototypical of certain FFTF component operations. This type of motion is achieved by using the concept of a bell crank (see Figures 8 and 9) to convert unidirectional rotation of a drive motor shaft to rotation of a few degrees back and forth. The extent of the rotation can be set anywhere from 3 to 13.5 degrees by means of a screw adjustment external to the apparatus. Slack was designed into the drive plate to provide a "quasi-universal" joint. Because of this slack, an indicating device was included to show the actual angle of rotation of the moving wear surface immersed in sodium.

E. FACILITY CAPABILITIES AND LIMITATIONS

1. Specimen Configuration

The apparatus was designed to take any thickness or configuration of wear surface up to 5 in. in any direction. Most tests were performed using a plate rotating back and forth over three flat-faced pins, (Figure 10). Other tests involved the flat faces of three tabs rotating back and forth over three other flat-faced tabs (Figure 11).

2. Material Interactions

The number of friction and wear devices inserted into each test vessel was limited to three. This limitation was imposed so that materials would not be tested in the same vessel simultaneously with another material where interactions were expected.

3. Stroke Length and Velocity

The length of stroke could be controlled from 0.005 in. to 0.500 in. LMEC has expressed the stroke lengths in terms of pin diameters. The stroke starts out from the rest position at one end of the stroke, not from the middle of the stroke. Thus, a stroke of d (the pin diameter) or greater is required to move virgin plate material over 100% of the pin. All stroke lengths less than d involve rubbing by some percent of the pin area only on the plate area originally in contact with the pin, i.e., never on virgin plate surface. In Figure 12, the percentage of pin surface that never sees virgin plate surface is given as a function of stroke length expressed in terms of pin diameter.

During each stroke, the relative velocity of the rubbing surfaces builds up to a maximum velocity, dies away to zero velocity, and then is motionless for 1 sec or less prior to stroke reversal (Figure 13). The average velocity can be varied between 0.001 in./sec and 1.0 in./sec, but the average velocity has ranged between 0.03 in./sec and 0.1 in./sec in the tests performed to date.

4. Testing Environment

In general, the vessels being used for friction and wear tests at LMEC are capable of holding sodium at 1200°F, although one vessel is capable of containing 1350°F sodium. The sodium in these vessels is always cold trapped at test temperature and thus is capable of being purified to very low oxygen and hydrogen contents. The mercury amalgamation, total consumption method has been used to analyze for "total alkali as oxygen" and values of 5 ppm or less have been achieved prior to each test. No rigorous correlation between the amalgamation method results and oxygen content estimated by oxygen activity measurements (vanadium-wire or oxygen-meter) are possible; but since the LMEC systems are cold trapped to below 240°F, the oxygen content as estimated from activity measurements would probably be below 1 ppm.

The sodium in the LMEC systems for the friction tests was neither entirely under isothermal conditions nor entirely under a ΔT condition. A small percent, < 5%, of the isothermal sodium in the test vessel was subjected to a ΔT condition to induce convective flow through the cold-trap circuit. The sodium in the vicinity of the rubbing surfaces was relatively isothermal and relatively quiescent.

Flat-faced rubbing surfaces were in full planar contact during dead-weight loading while immersed in sodium, and during all changes in test temperature. Standard operating procedures required that the sodium be initially brought to > 700°F to achieve wetting before testing began. Testing usually was started at 450°F (expected temperature for fuel change in FFTF) with the bulk of the testing at 1160°F (maximum bulk temperature expected in hot leg of FFTF system).

5. Tests Involving Carbide Coatings

Friction tests of carbide coatings at LMEC have shown that carbides are the only family of materials among those tested that consistently give the lowest coefficient of friction in liquid sodium. Since chromium was a desired constituent of sliding surfaces exposed to sodium, a matrix material that contained chromium was desired for codeposition with the carbide. Chromium carbide was selected as a most prominent carbide candidate for two reasons: (1) chromium carbide would have the least complicated chemical stability relationships with both the chromium in the matrix and the stainless steel structures involved in sodium systems; and (2) chromium carbide has a coefficient of thermal expansion nearer to candidate substrate materials than other common carbides.

Initial tests were with a chromium carbide plus nickel matrix applied by a spark-discharge method (the Mech-Electron process). Although the coatings applied by this process were not continuous and were very thin, sufficient promise was indicated that intensive testing with this coating began.

The chromium carbide in a Nichrome matrix was then applied by a detonation-gun method (the Union Carbide D-gun process). This chromium carbide had excellent dynamic friction properties in sodium and appeared as the most promising candidate for FFTF duct wear-pad surfaces (Table 1, 2, 3, and 4).

Extensive testing showed that the method of surface finishing the chromium carbide coating after deposition was important. Nondimensional finishes (brush finishes) gave better dynamic friction results than lapped finishes. Three methods of nondimensional finishing were tested; these finishing processes are called old dry brush, wet brush, and new dry brush in this report. The wet-brush finish proved inferior to either of the dry-brush techniques in terms of dynamic friction properties. The dry-brush finish gave dynamic friction coefficients around 0.4 at 1160°F. Friction results from 85% Cr - 15% Nichrome (80% Ni - 20% Cr) with the new dry-brush finish are shown in detail in Figure 14. Friction from a typical individual, short stroke is shown in each curve segment as a function of distance. The stroke distance is expressed in terms of pin diameters. The cumulative rubbing distance (in inches) for each stroke plotted, is given below each curve segment.

The breakaway friction properties (static friction after a dwel', also sometimes referred to as the self-welding coefficient) of the chromium carbide plus Nichrome proved, on occasion, to be higher than desired as values around unity were occasionally encountered. Possible solutions to this problem involve changing the type of matrix material, changing the relative proportions of carbide and matrix, and changing the parameters of applying the coating or, indeed, the method of coating itself.

Titanium carbide with various binders was also tested. The titanium carbide with Nichrome binder had excellent coefficients of dynamic friction, but again, poor breakaway friction coefficients. Substituting molybdenum for Nichrome as the matrix material eliminated self welding tendencies, as measured by a breakaway coefficient of friction, but the dynamic friction values were high. Further friction testing of titanium carbide was terminated when chemical stability tests of carbides in sodium at Westinghouse ARD eliminated titanium carbide with either matrix as a candidate. Chromium carbide plus Nichrome proved to be stable in these tests.

In addition to defining and solving the problem of high breakaway friction values associated with chromium carbide plus Nichrome, quality control techniques for the D-gun process of applying this promising coating need to be adapted to volume production methods. Although the quality of these coatings is known to vary considerably at present, the main problem appears to be a lack of quantitative method of inspecting the coated part. The Hanford Engineering Development Laboratory is planning to develop such techniques.

Finally, the designer must become familiar with the characteristics of utilizing carbide coatings. Coating over sharp corners, neglecting to feather the carbide at the edge of the coating when required, or forgetting that both rubbing surfaces should be coated can all lead to unsatisfactory performance and even to failure of the coating.

6. Tests Involving Inconel 718

The rather severe seizing and galling in sodium often encountered when one or both of the rubbing surfaces is a Type 300 SS has created interest in alternative structural materials for sliding contact applications. Inconel 718 is an alloy often considered as a candidate for such applications. Tests at 1160°F showed that galling is still present when this alloy is used under low contact pressures. High contact pressure tests, at 2000 psi, gave much better friction results than tests at 200 psi or 1000 psi. The load to achieve the 1000 and 2000 psi was identical (Tables 5, 6 and 7). Chromizing Inconel 718 was examined as a method of eliminating the high friction values encountered at pressures under 2000 psi and appears promising. Friction curves of chromized Inconel 718 are shown in Figure 15.

7. Tests Involving Wire-Wrap/Fuel Cladding

In CY 1971, three tests had been performed on fuel cladding in 1160°F sodium; during 1972 these three tests were repeated except that the sodium temperature was increased from 1160°F to 1350°F, while the number of rubbing strokes was decreased from 10,000 to 2,000. Both series of the wire-wrap/fuel cladding wear tests involved identical material planned for use in the FFTF. The wire was 20% CW Type 316 SS wire, 0.0560-in. diameter. The fuel cladding was 0.230-in. diameter tubing from the Hanford Engineering Development Laboratory (HEDL) of the type planned for FFTF fuel cladding. The cladding had a close-fitting rod inserted in it to represent swelled fuel pressing against the cladding.

A plate holding three segments of wire wrap was mounted over a plate holding three cladding specimens. Each of the three wire-wrap segments rested on the crest of a cladding tube, resulting in three-point support between the two plates. The cladding specimens were mounted on the bottom plate tangentially to a 1-in. radius and spaced 120 degrees apart (Figure 16). Wire-wrap segments were mounted on the upper plate at angles of 12, 20.5, and 29.5 degrees from tangency (Figure 17). This upper plate was driven through a rotation of ~ 13 degrees, then rotated back, until slightly more than 2000 strokes of sliding contact between wire wrap and cladding were accumulated. The stroke motion is thus an arc movement roughly parallel to the tube and between 0.1 - to 0.2-in. length of relative movement. The inches of sliding contact experienced by any point on the cladding does not correspond to the total inches of relative motion since each point on the cladding is rubbed only when the wire is actually passing over it (Figure 18).

The wire-wrap/cladding wear test results for ~ 10^4 strokes at 1160°F sodium and ~ 2×10^3 strokes at 1350°F are given in Table 3.

The actual wire cladding will have an angle of 4 degrees between it and the tube axis. Line-up difficulties precluded using any angle below 12 degrees in these test series.

Preliminary tests at 90 degrees and at smaller angles indicated that the depth worn away was sensitive to angle, with 90 degrees being the most severe case. The three angles chosen were selected on the basis that 3, 5, and 7 times the sine of 4 degrees equaled the sines of these angles. It was hoped that this would allow extrapolation back to 4 degrees. In the actual test, depth of cladding worn away proved to be unrelatable to angle in the 12 to 30 degree range.

The depth of wear experienced indicated that a contact load of 20 lb caused intolerably severe wear, while a load of 1.5 lb caused an acceptable extent of wear if provided for in the design.

The effect of temperature in these tests, or the measured sawing force, is shown in Figure 19, where the ratio of sawing force to applied load is plotted as a function of temperature. These data are from the 20-lb load test and were measured after completion of 10,000 strokes at 1160°F.

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TABLE 1 Summary Table of Friction in Sodium — Pebbly Chrome Carbide @ 300 Psi

Test			Test Conditions							Friction Results					
No.	Materials		Temperature (°F)	Load/Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (pin diameter)	Total Strokes/Distance† (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate*								Avg Init.	Max Obs.	Avg Final	Avg Init.	Max Obs.	Avg Final
LP	CrC + (20% Cr - 80% Ni) binder vs itself. Substrate - Inconel 718 coated by Linde D-Gun. Finish - nondimensional, pebbly, old dry brush.		450	13.4/300	0.08	0.80	36/6.9	-	-	0.24	-	-	0.24	0.24	-
↓	↓		500	↓	↓	↓	40/7.7	-	-	0.10	-	-	0.20	0.30	-
			600				44/8.4	-	-	0.20	-	-	0.23	0.30	-
			700				48/9.2	-	-	0.04	-	-	0.04	0.28	-
			800				52/10.0	-	-	0.32	-	-	0.32	0.36	-
			900				56/10.8	-	-	0.38	-	-	0.38	0.40	-
			1000				60/11.5	-	-	0.46	-	-	0.40	0.46	-
			1100				64/12.3	-	-	0.40	-	-	0.40	0.44	-
			1150				[illegible]	216	None observed	0.40	0.52	0.48	0.46	0.52	0.48
			1160				7254/1000	72	None observed	0.40	0.46	0.40	0.34	0.50	0.34
			1000				7268/>1000	-	-	0.42	-	-	0.42	0.50	-
			900				7280/>1000	-	-	0.30	-	-	0.38	0.46	-
			900				7284/>1000	72	None observed	0.26	-	-	0.30	0.37	-
			800				7288/>1000	-	-	0.44	-	-	0.38	0.46	-
			700				7292/>1000	-	-	0.36	-	-	0.38	0.40	-
			600				7296/>1000	-	-	0.36	-	-	0.38	0.38	-

*Unless specifically noted, plate material is same as pin.
†Strokes and distance are cumulative values from beginning of test.

TABLE 2 Summary Table of Friction in Sodium -- Lapped Chrome Carbide @ 300 Psi

Test			Test Conditions							Friction Results					
No.	Materials		Temperature (°F)	Load/ Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (pin diameter)	Total Strokes/ Distance† (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate*								Avg Init.	Max Obs.	Avg Final	Avg Init.	Max Obs.	Avg Final
LG	CrC + (20% Cr - 60% Ni) binder vs itself. *Substrate* - Inconel 718 coated by Linde D-Gun. Lapped finish with 320 grit SiC to 16 rms.		450	13.6/300	0.08	0.80	34/6.5	-	-	0.22	-	-	0.22	0.50	-
			500				42/8.0	-	-	0.20	-	-	0.22	0.48	-
			600				46/8.8	-	-	0.20	-	-	0.22	0.52	-
			700				50/9.6	-	-	0.30	-	-	0.30	0.30	-
			800				54/10.4	-	-	0.36	-	-	0.36	0.50	-
			900				58/11.1	-	-	0.37	-	-	0.36	0.50	-
			1000				62/11.9	-	-	0.40	-	-	0.40	0.50	-
			1160				2702/500	216	None observed	0.38	0.86	0.48	0.48	0.86	0.48
			1160				5298/1000	72	None observed	0.56	0.58	0.56	0.52	0.70	0.52
			1000				5310/>1000	-	-	0.44	-	-	0.48	0.62	-
			900				5322/>1000	-	-	0.36	-	-	0.44	0.56	-
			900				5326/>1000	72	None observed	0.56	-	-	0.58	0.60	-
			800				5332/>1000	-	-	0.40	-	-	0.50	0.64	-
			700				5336/>1000	-	-	0.55	-	-	0.52	0.64	-
			600				5340/>1000	-	-	0.52	-	-	0.48	0.56	-

*Unless specifically noted, plate material is same as pin.

†Strokes and distance are cumulative values from beginning of test.

TABLE 3 Summary Table of Friction in Sodium -- Dry-Brush Chrome Carbide @ 1000 Psi

Test			Test Conditions						Friction Results						
Number	Materials		Temperature (°F)	Load/ Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (Pin diameter)	Rubbing Experienced Number of Strokes/ Distance (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate								Average Initial	Maximum Observed	Average Final	Average Initial	Maximum Observed	Average Final
6-2C	Chromium Carbide – 15 Vol.% Nichrome Substrate 316 SS D-gun applied, (cooler gun condition) "New dry brush" finish Carbide size < 5μ Nichrome size < 20μ HEDL Coating No. CN-1b Union Carbide Process LC-1C		450	16.7/1000		0.86	4/.48	–	None Observed	0.29	–	–	0.26	0.29	–
			450				4/.48	–	–	0.11	–	–	0.16	0.19	–
			500				10/1.2	–	–	0.12	–	–	0.11	0.12	–
			600				16/1.9	–	–	0.06	–	–	0.16	0.21	–
			700				22/2.7	–	–	0.26	–	–	0.28	0.30	–
			700				4/3.1	–	–	0.24	–	–	0.24	0.26	–
			700				46/8.2	–	–	0.30	–	–	0.29	0.32	–
			700				88/13.3	–	–	0.31	–	–	0.30	0.32	–
								–	–	–	–	–	–	–	–
			700			0.28	4/13.2	–	–	0.24	–	–	0.29	0.34	–
			800				10/13.5	–	–	0.24	–	–	0.30	0.36	–
			900				16/13.7	–	–	0.17	–	–	0.28	0.41	–
			1000				22/13.9	–	–	0.17	–	–	0.20	0.25	–
			1100				28/14.2	–	–	0.13	–	–	0.26	0.37	–
			1160				12504/503	144	1.01	0.30	0.62	0.20	0.38	0.88	0.36
			1160				25004/993	108	0.72	0.41	0.56	0.41	0.33	0.66	0.48
								–	–	–	–	–	–	–	–
			450			0.86	4/994	480	None Observed	0.23	–	–	0.16	0.23	–
			450				46/999	–	–	0.26	–	–	0.20	0.26	–
			450				88/1004	–	–	0.25	–	–	0.15	0.25	–
			700				4/1005	–	–	0.24	–	–	0.21	0.24	–
			700				46/1010	–	–	0.21	–	–	0.26	0.32	–
			700				88/1015	–	–	0.31	–	–	0.27	0.31	–

TABLE 4 Summary Table of Friction in Sodium -- Dry-Brush Chrome Carbide @ 500 Psi

Test			Test Conditions						Friction Results						
Number	Materials		Temperature (°F)	Load/Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (Pin diameter)	Rubbing Experienced Number of Strokes/Distance (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate								Average Initial	Maximum Observed	Average Final	Average Initial	Maximum Observed	Average Final
6-4C	Chromium Carbide – 15 Vol.% Nichrome Substrate 316 SS D-gun applied, (cooler gun condition) "New dry brush" finish Carbide size <5μ Nichrome size <20μ HEDL Coating No. CN-1b Union Carbide Process LC-1C		450	23.7/500		0.66	4/.63	–	None Observed	0.26	–	–	0.22	0.26	–
			450				4/.63	–	–	0.28	–	–	0.16	0.10	–
			500				10/1.6	–	–	0.19	–	–	0.18	0.19	–
			600				16/2.5	–	–	0.20	–	–	0.20	0.22	–
			700				22/3.5	–	–	0.29	–	–	0.26	0.29	–
			700				4/4.1	–	–	0.25	–	–	0.28	0.30	–
			700				30/7.9	–	–	0.21	–	–	0.24	0.26	–
			700				54/11.7	–	–	0.29	–	–	0.33	0.36	–
								–	–	–	–	–	–	–	–
			700			0.18	4/11.9	–	–	0.24	–	–	0.26	0.31	–
			800				10/1.8	–	–	0.22	–	–	0.26	0.30	–
			900				16/12.4	–	–	0.28	–	–	0.30	0.33	–
			1000				22/12.7	–	–	0.22	–	–	0.25	0.31	–
			1100				28/12.9	–	–	0.26	–	–	0.29	0.34	–
			1160				6244/282	144	1.06	0.36	0.82	0.40	0.37	0.86	0.36
			1160				12504/552	108	0.64	0.34	0.46	0.39	0.30	0.46	0.36
								–	–	–	–	–	–	–	–
			450			0.66	4/553	480	None Observed	0.25	–	–	0.24	0.25	–
			450				30/557	–	–	0.22	–	–	0.21	0.22	–
			450				54/560	–	–	0.26	–	–	0.22	0.20	–
			700				4/561	–	–	0.24	–	–	0.22	0.28	–
			700				30/565	–	–	0.28	–	–	0.28	0.32	–
			700				54/569	–	–	0.28	–	–	0.28	0.32	–

TABLE 5 Summary Table of Friction in Sodium -- Inconel 718 @ 2000 Psi

Test			Test Conditions							Friction Results					
No.	Materials		Temperature (°F)	Load/Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (pin diameter)	Total Strokes/Distance† (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate*								Avg Init.	Max Obs.	Avg Final	Avg Init.	Max Obs.	Avg Final
12	Inconel 718 vs itself		1160	15.7/2000	[illegible]	0.80	[illegible]	2[illegible]	None observed	0.62	-	-	0.60	0.68	-
			1160				12694/[illegible]	1[illegible]	None observed	0.56	-	-	0.50	0.56	-
			1100				12722/10[illegible]	-	-	0.56	-	-	0.48	0.56	-
			1000				12772/10[illegible]	-	-	0.50	-	-	0.50	0.60	-
			900				127[illegible]/10[illegible]	72	None observed	0.50	-	-	0.48	0.50	-
			800				12835/1014	-	-	0.52	1.46	1.48	0.50	0.50	0.40
			700				12858/1016	-	-	0.50	1.46	1.46	0.30	0.50	0.20
			600				12892/1018	-	-	0.60	-	-	0.50	0.60	-
			550				1291[illegible]/102[illegible]	-	-	0.42	-	-	0.32	0.40	-
			500				12940/1022	-	-	0.50	-	-	0.40	0.50	-
			450				12964/1024	-	-	0.50	-	-	0.42	0.50	-
			400				1299[illegible]/1026	-	-	0.56	-	-	0.42	0.56	-

*Unless specifically noted, plate material is same as pin.
†Strokes and distance are cumulative values from beginning of test.

TABLE 6 Summary Table of Friction in Sodium -- Inconel 718 @ 1000 Psi

Test			Test Conditions							Friction Results					
	Materials									Static Friction			Dynamic Friction		
No.	Pin	Plate*	Temperature (°F)	Load/Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (pin diameter)	Total Strokes/Distance† (in.)	Dwell (hr)	Break-away Friction	Avg Init.	Max Obs.	Avg Final	Avg Init.	Max Obs.	Avg Final
14	Inconel 718 vs itself		450	15.6/1000	0.06	1.1	164/25	-	-	0.66	-	-	0.92	1.28	-
			500				168/26	-	-	0.70	-	-	0.88	1.28	-
			600				172/2[illegible]	-	-	0.72	-	-	1.00	1.50	-
			700				176/27	-	-	0.74	-	-	1.00	1.50	-
			800				180/28	-	-	0.76	-	-	1.04	1.50	-
			900				184/29	-	-	0.80	-	-	1.12	1.50	-
			1000				188/29	-	-	0.88		-	1.18	1.50	-
			1100				19[illegible]	-	-	0.93	-	-	1.12	1.50	-
			1160				54[illegible]	288	None observed	1.4	1.62	1.48	1.40	2.00	1.60
			1160				[illegible]	168	1.16	1.80	1.80	1.76	1.08	2.00	1.10
			1100				[illegible]/1055	-	-	1.65	-	-	1.06	1.68	-
			1000				664[illegible]	-		1.70	-	-	1.20	1.70	-
			900				[illegible]	72	None observed	1.48	-	-	0.98	1.40	-
			800				6730/1050	-	-	1.38	-	-	1.20	1.50	-
			700				6762/105[illegible]	-	-	1.38	-	-	1.08	1.50	-
			600				678[illegible]/10[illegible]	-	-	1.42	-	-	1.16	1.48	-
			550				6818/1064		-	1.64	-	-	1.28	1.64	-
			500				6848/1068	-	-	1.66	-	-	1.30	2.00	-
			450				6874/1072	-	-	1.90	-	-	1.46	1.98	-
			450				6902/1077	-	-	2.00	-	-	1.46	2.00	-

*Unless specifically noted, plate material is same as pin.
†Strokes and distance are cumulative values from beginning of test.

TABLE 7 Summary Table of Friction in Sodium -- Inconel 718 @ 200 Psi

Test			Test Conditions							Friction Results					
No.	Materials		Temperature (°F)	Load/ Pressure (lb)/(psi)	Average Velocity (in./sec)	Stroke Length (pin diameter)	Total Strokes/ Distance† (in.)	Dwell (hr)	Break-away Friction	Static Friction			Dynamic Friction		
	Pin	Plate*								Avg Init.	Max Obs.	Avg Final	Avg Init.	Max Obs.	Avg Final
16	Inconel 718 vs itself		1100	9.1/200	0.07	0.63	3414/500	288	None observed	1.96	1.56	1.90	1.36	2.02	1.36
↓	↓		1100	↓	↓	↓	6610/1000	168	None observed	1.50	1.50	1.36	1.38	1.76	1.34
			1100				6640/1009	-	-	1.50	-	-	1.16	1.50	-
			1000				6660/1013	-	-	1.36	-	-	1.00	1.36	-
			900				6694/1017	72	None observed	1.26	-	-	0.96	1.26	-
			800				6724/1022	-	-	1.84	-	-	1.14	1.84	-
			700				6766/1028	-	-	1.54	-		1.16	1.54	-
			600				6796/1032	-	-	1.50	-	-	1.24	1.50	-
			550				6822/1036	-	-	1.96	-	-	1.50	1.96	-
			500				6850/1041	-	-	1.46	-	-	1.30	1.60	-
			450				6878/1045	-	-	1.82	-	-	1.36	1.82	-
			400				6906/1050	-	-	1.42	-	-	1.32	1.42	-

*Unless specifically noted, plate material is same as pin

†Strokes and distance are cumulative values from beginning of test.

TABLE 8 Wire Wrap/Cladding Results

Load on Wire Wrap/Cladding Combination* (lb)	No. of Strokes†	Temperature (°F)	Oxygen Content§ (ppm)	Wire and Tube Axis Angle (deg)	Wear Depth** (mils)	Wear Depth** (mils/lb)
1.5	10,000	1160	<5	12 ± 6.5	0.4	~0.3
				20.5 ± 6.5	0.3	
				29.5 ± 6.5	0.5	
	2,000	1350	8	12 ± 6.5	0.6	~0.3
				20.5 ± 6.5	0.65	
				29.5 ± 6.5	0.2	
5	10,000	1160	<5	12 ± 6.5	2.0	~0.4
				20.5 ± 6.5	2.4	
				29.5 ± 6.5	1.1	
	2,000	1350	8	12 ± 6.5	0.9	~0.2
				20.5 ± 6.5	0.9	
				29.5 ± 6.5	0.8	
20	10,000	1160	<5	12 ± 6.5	4.0	~0.2
				20.5 ± 6.5	3.8	
				29.5 ± 6.5	2.5	
	2,000	1350	8	12 ± 6.5	2.2	~0.1
				20.5 ± 6.5	1.8	
				29.5 ± 6.5	2.6	

*Wire Diameter was 0.0560 in.

† Each stroke was an arc movement roughly parallel to the tube axis with a 15-deg arc length on a 1-in. radius.

§ Oxygen content measured by total consumption amalgamation method.

**Extensive material transfer between wire and cladding; buildup as common as wear depth.

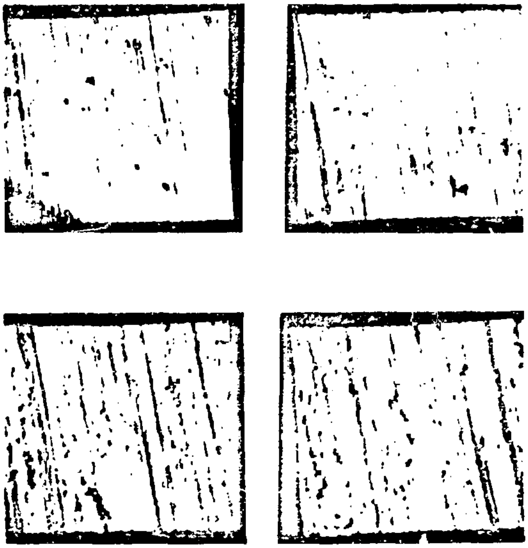


Figure 1 Abrasive Wear: Scanning Electron Microscope Photographs - TZM Molybdenum Alloy Pin after Sliding Contact Against Tungsten Plate at 130 psi in 1200°F Liquid Sodium

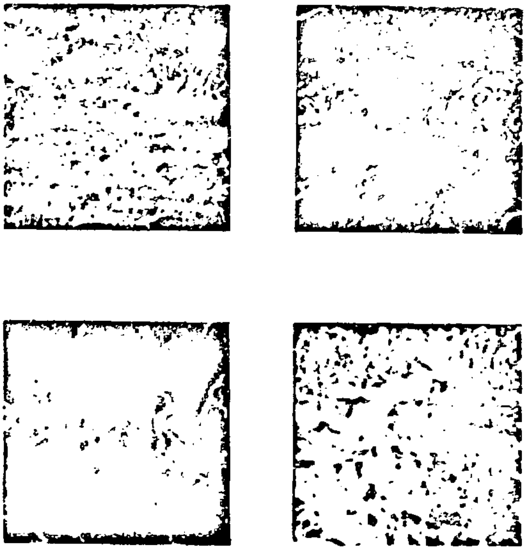


Figure 2 Adhesive Wear: SEM Photographs - Inconel 718 Pin after Sliding Contact Against Udimet 630 Plate at 53 psi in 1200°F Liquid Sodium

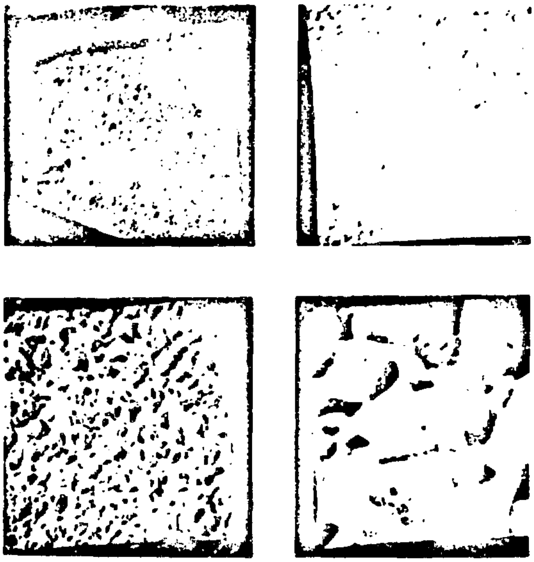


Figure 3 Wear Showing Brittle Intergranular Fracture: SEM Photographs - Tungsten Pin after Sliding Contact Against Hastelloy C Plate at 119 psi above 1200°F He

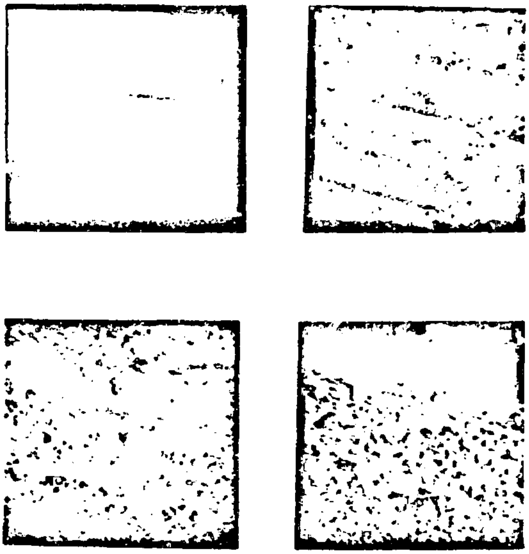


Figure 4 Localized Plowing Wear: SEM Photographs - Hastelloy C Pin after Sliding Contact Against Hastelloy C Plate at 101 psi in 1050°F Liquid Sodium

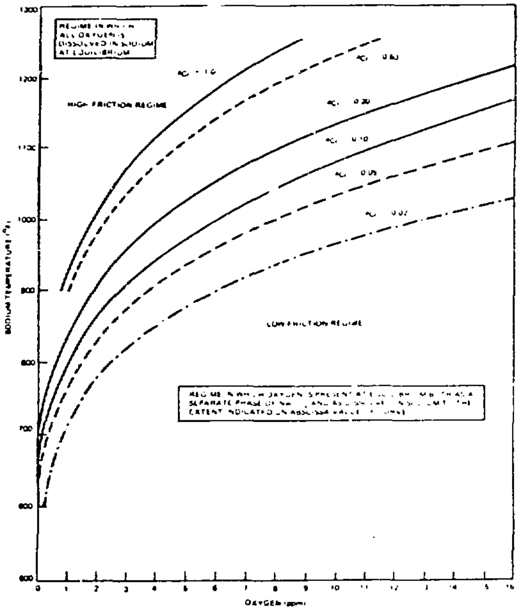


Figure 5   Oxygen Level that Sodium Attempts to Reach in 18-8 SS System

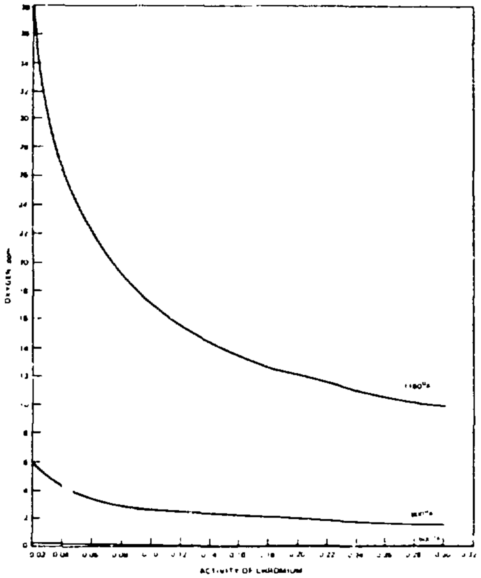


Figure 6   Equilibrium Oxygen as a Function of Chromium Activity

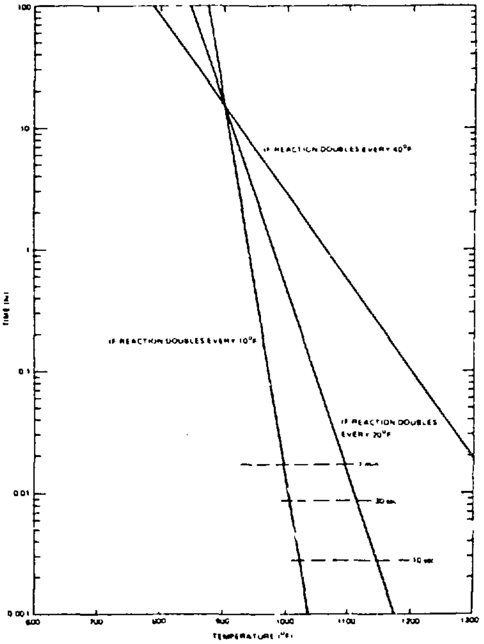


Figure 7   Rough Estimate of the Kinetics for Forming NaCrO$_2$ on Surfaces
that Contain ≈ 18% Cr

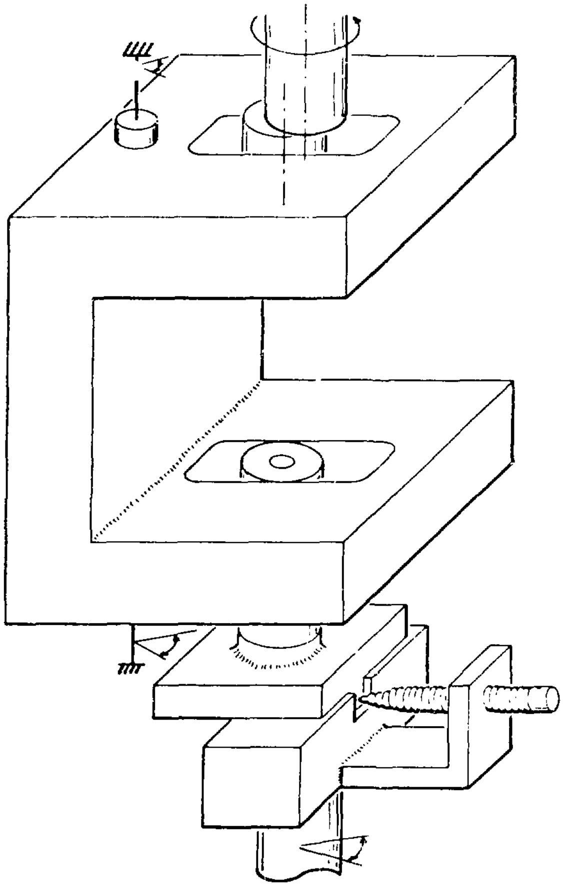


Figure 8 Schematic of Bell Crank Device

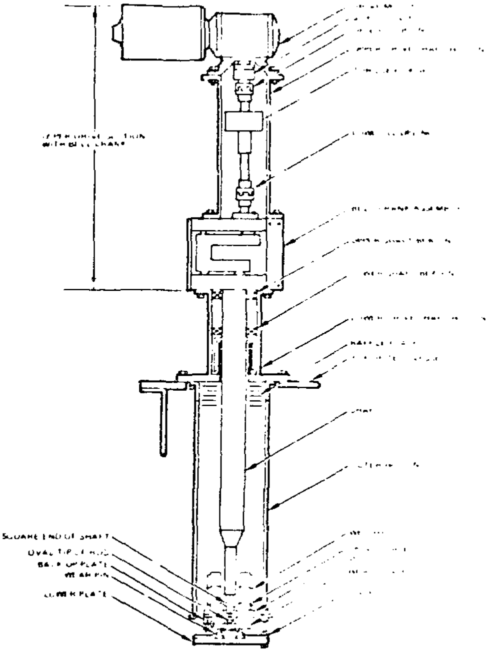


Figure 9 Schematic of Short Stroke Oscillating Wear Test Apparatus

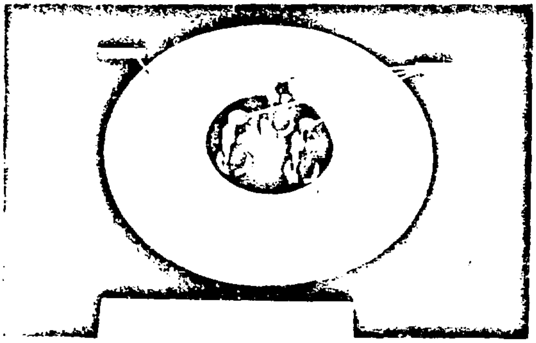


Figure 10 Typical Sliding Contact Plate and Pin Specimens

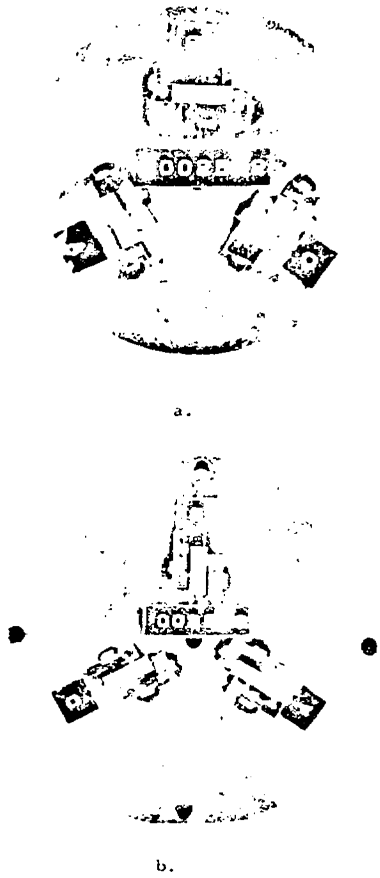


Figure 11 Typical Sliding Contact, Tab-on-Tab Specimens

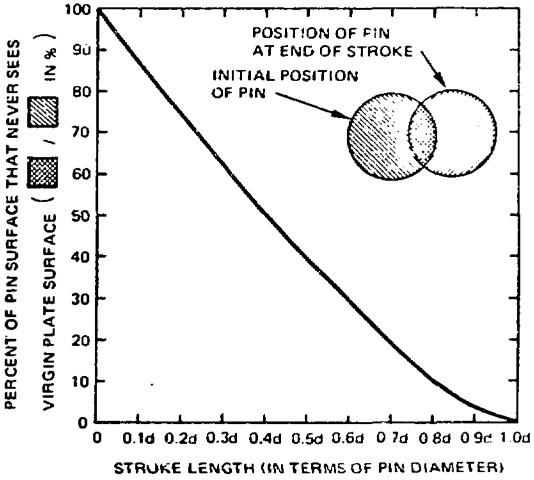


Figure 12 Percent of Pin Surface That Never Sees Virgin Plate Surface as a Function of Stroke Length

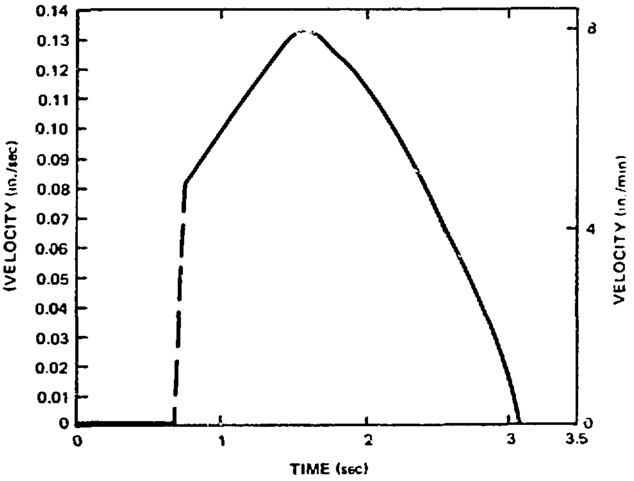
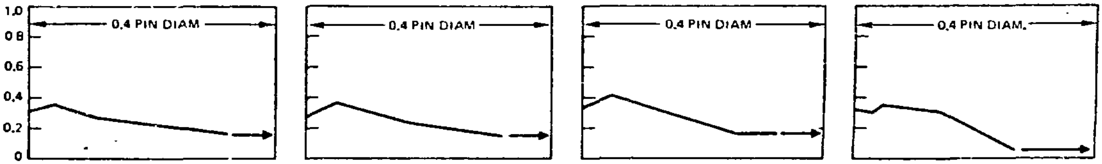


Figure 13 Relative Velocity of Rubbing Surfaces as a Function of Stroke Time

WEIGHT ON 3 PINS - 44.3 lb PIN DIAMETER - 0.24 in OXYGEN CONTENT - 5 ppm

ABSCISSA VALUE IS INTEGRATED AREA UNDER VELOCITY VS TIME CURVE, HENCE DISTANCE IN UNITS OF PIN DIAMETER OF EACH STROKE.



1160°F, 600 in., 8-24-72 STROKE 4256

1160°F, 800 in., 8-24-72 STROKE 5660

1160°F, 900 in., 8-24-72 STROKE 6266

1160°F, 1000 in., 8-24-72 STROKE 7070

Figure 14 Friction Values for Individual Strokes for Chromium Carbide and Nichrome, D-gun Applied, New Dry Brush Finish at 300 psi Contact Pressure

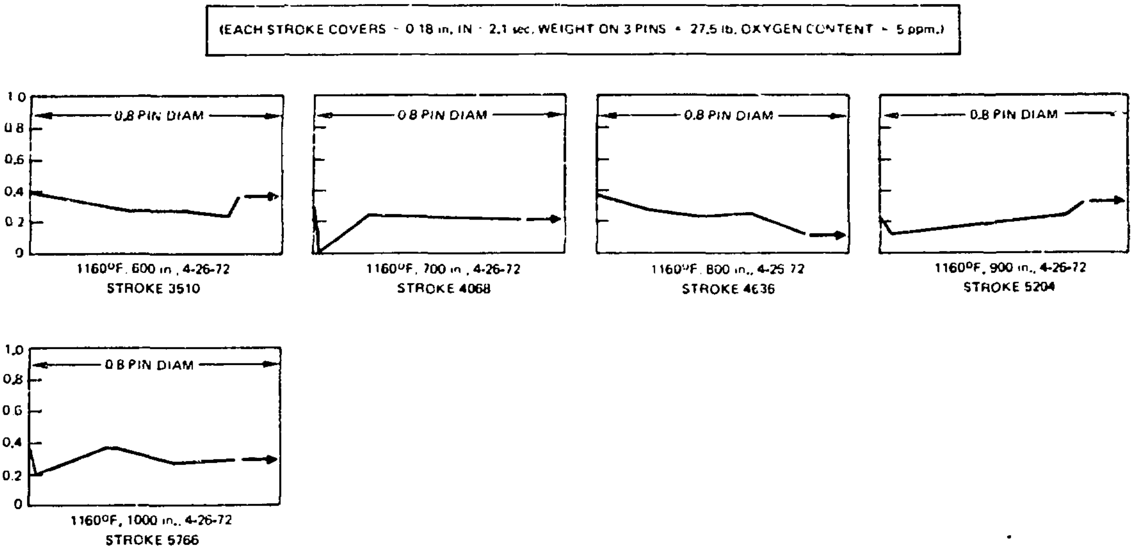


Figure 15 Friction Values for Individual Strokes for Chromized Inconel 718 vs Itself at 200 psi Contact Pressure

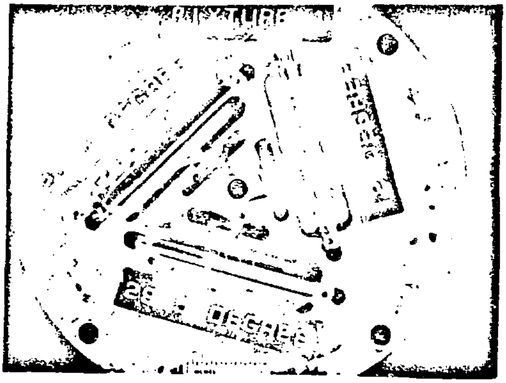


Figure 16 Cladding Specimens Mounted on Bottom Plate

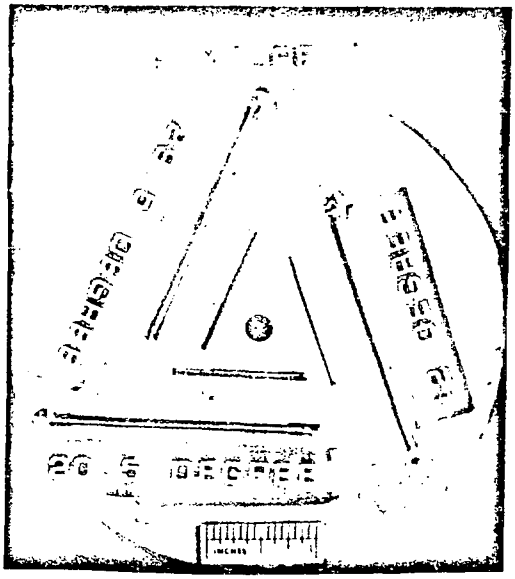


Figure 17 Wire-Wrap Specimens Mounted on Driver Plate

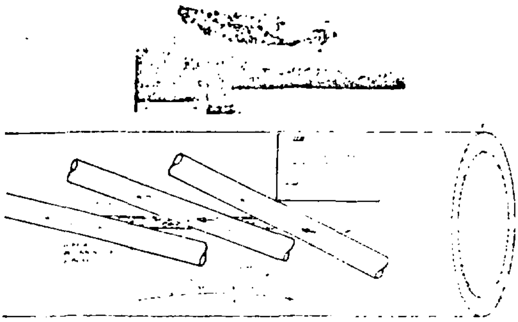


Figure 15 Length of Rubbing During Individual Stroke Experienced by Point "A" on Cladding

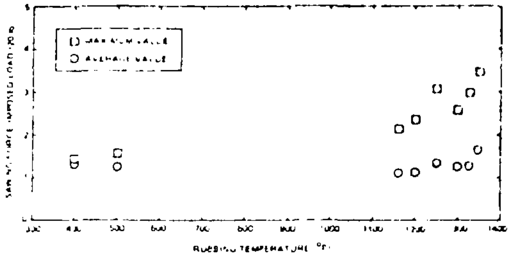


Figure 16 Effect of Temperature on Ratio of Sawing Force to Imposed Load
* Data Taken after 10,000 Strokes at 1160°F