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Volume I

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and Progress Reports

Mechanical Elements Operating in Sodium and Other Alkali Metals

Volume I

Literature Survey

By
J.K. Balkwill

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ABSTRACT

A search was made of literature reporting information published since 1950 on mechanical devices with rubbing surfaces operating in alkali metals. Sodium environments are emphasized, with data also included from potassium, NaK and lithium experiments. The characteristics of potentially useful materials that are important in liquid metal applications are discussed. Material compatibility and friction/wear testing programs conducted since 1950 are described. Experimental and operating experience with full-size components is presented.

I. INTRODUCTION

Liquid sodium is an attractive heat-transfer fluid for use in liquid-metal-cooled nuclear reactors because of its large liquidus range, its desirable viscosity, heat capacity and thermal conductivity properties, and its reasonable cost. It is currently the reference coolant in the design of the Liquid Metal Cooled Fast Breeder Reactor (LMFBR). Other alkali metals are being considered for use as heat-transfer fluids in the higher-temperature nuclear power generation systems for space vehicles. NaK-77 has been used successfully at temperatures up to 1300°F in SNAP reactors; non-nuclear heat transfer test loops have operated with potassium, lithium and rubidium at temperatures as high as 2000°F.

The problems of lubrication in liquid metal systems require departure from standard lubrication practice. The use of an organic lubricant for rubbing surfaces operating in a liquid metal system adds the complication of providing seals to prevent contact between the lubricant and liquid metal. Mechanical devices such as fuel handling equipment and control rod drives may be awkwardly designed to remove bearing surfaces from high-temperature locations in liquid metal to low-temperature locations in the cover gas environment. The use of the liquid metal coolant (and of the liquid metal working fluid in space power systems) as the only lubricant for rubbing surfaces in liquid metal systems thus has the advantages of reduced design complexity and greatly simplified seal problems.

However, such use of a liquid metal as a lubricant, with its high chemical reactivity and low viscosity, causes problems not normally encountered in conventionally lubricated bearings. Where conventional lubricants provide boundary lubrication during transients such as startups when metal-to-metal contact is likely, the liquid metals dissolve or reduce protective surface films and permit metal-to-metal contact. Bearing materials must be completely compatible with the liquid metal lubricant and with other materials in the system to prevent any surface damage by corrosion or mass transfer that would accelerate failure rates; compatibility is seldom a problem with conventional lubricants. Liquid metal viscosities are very low when compared with those of conventional lubricants, so that the dynamic lubricating film thickness that can be obtained with liquid metals is very thin, making metal-to-metal contact much more probable.

The low viscosities also mean relatively lower load-carrying capacities for bearings lubricated with liquid metal, emphasizing the need for careful design and selection of the best possible material.

The particular features of the liquid metal environment that most affect the design of mechanical elements lubricated by the environment are summed up as the following:

- 1) Operating temperatures will be high, assumed as 1200°F in the LMFBR.
- 2) Operating environments will have high chemical reactivity.
- 3) Metal-to-metal contact is much more probable than in conventional systems.
- 4) Allowable unit loading of bearings is low.

A final requirement may be added: the mechanical element must operate with exceptionally high reliability because of its critical role in operation of the reactor system, and because of the prohibitive difficulty of repair or replacement in a reactor system.

It is apparent that an interdisciplinary approach combining the best possible mechanical designs and operating parameters with selection of the optimum materials will be required in procuring satisfactory mechanical elements.

This literature survey, which is Volume I of the report, "Mechanical Elements Operating in Sodium and other Alkali Metals," reports on the more significant mechanical element development and experimental programs that have been conducted since 1950, grouping the data under material selection, or under element performance. Volume II of the report will contain the experience survey, which will be a listing of all mechanical elements that have operated in a sodium environment in four liquid-metal-cooled reactors: the Sodium Reactor Experiment (SRE), the Hallam Nuclear Power Facility (HNPF), the Experimental Breeder Reactor (EBR-II), and the Enrico Fermi Atomic Power Plant (EFAPP); their design data and operating performance are included. Volume II will be published later in 1968.

Many structural materials are available which have good compatibility in liquid metal systems, but the material must also have good bearing characteristics. In Section III.A the characteristics of potentially useful materials that are important in liquid metal applications are listed and discussed. The many materials that have been investigated for use in liquid-metal-lubricated mechanical elements are grouped in classes by their chemistry or reactivity in Section III.B. Finally, the many material compatibility programs that have been conducted since 1950 are discussed, grouping the data by material classes in Section III.C.

In Section IV.A the types of mechanical elements and bearings that may be used in liquid metal systems are described with their particular advantages and disadvantages when liquid metal lubrication is required. Experimental and operating experience of full-size components is presented in Section IV.B.

Where liquid metals other than sodium have been used in tests described in this report, the relevance of the data to a comparable sodium system should be considered. In simple corrosion tests, NaK and potassium may be considered to be of the same degree of corrosiveness as sodium; if the same oxide level is maintained, lithium is generally shown to be more corrosive than sodium. Where results of corrosion tests are given in comparative terms, the rankings of materials in NaK and potassium are not expected to change in sodium. Sliding friction data from friction-and-wear tests should be comparable for these alkali liquid metals, but wear data taken in lithium will tend to be more severe because of the higher chemical aggressiveness of lithium. In any case, because earlier studies reported data qualitatively, and because there has been little uniformity in reporting test parameters, extrapolation of results of one test to conditions of another test cannot be made with any assurance of reliability.

For engineering properties of sodium and NaK that may be required in designing or testing mechanical elements operating in liquid metals, the Sodium-NaK Engineering Handbook will serve as the definitive reference. The Liquid Metal Engineering Center published a draft revision of the 1955 edition of this handbook in June 1967. Information pertinent to operation of mechanical elements in sodium may be found in:

- Chapter 1. Physical Properties
- Chapter 2. Chemistry
- Chapter 3. Effects on Materials
- Chapter 6. Purification
- Chapter 15. Bearings and Seals
- Chapter 16. Auxiliary Equipment and System Accessories.

II. SUMMARY

A search was made of literature reporting information published since 1950 on mechanical devices with rubbing surfaces operating in alkali metals. The commonly used term liquid metal as used in this report includes only sodium, potassium, the several NaK compositions, and lithium. Six hundred references were obtained from searches of pertinent categories in the Liquid Metal Information Center (LMIC) system; of these, some 300 documents were selected for detailed evaluation. Information from 77 sources is referenced in the body of the report. The characteristics of potentially useful materials that are important in liquid metal applications are discussed; material compatibility and friction/wear testing programs conducted since 1950 are described; and experimental and operating experience with full-size components is presented.

Two basic friction/wear testing units have been used, the pin-on-plate (or cylinder) and the twin-opposed-shoes on rotating cylinder, but the many variations within these two basic types make quantitative comparison of test results very difficult. Also, earlier friction/wear studies reported wear data qualitatively; later studies have used a material removal rate, cm^3 removed per cm of travel per unit load, as a quantitative measure of wear. Perhaps because of the variation in equipment, test conditions, and specimens, there has been little uniformity in reporting test parameters, particularly the chemistry of the liquid metal. In the experiments presented here, a test's results can be judged only within the framework of that test's parameters; extrapolation beyond the parameters cannot be made with any assurance of reliability.

Review of friction/wear testing reported shows that most work has been done at temperatures no higher than 1000°F ; only three test series at 1200°F or higher were found. Three simple corrosion tests of materials potentially useful for high temperature bearings have reported data at temperatures as high as 1600°F .

The end uses for liquid-metal-lubricated mechanical devices were found to fall into three categories: radial bearings for large centrifugal pumps; devices for guiding or supporting such reactor components as control rods, process tube spacers and seals, core hold-down devices, and fuel handling mechanisms; and

finally, small fluid-film hydrodynamic bearings operating at ultra-high speeds for the power conversion machinery of space nuclear reactor systems. Bearings for large centrifugal sodium pumps have been manufactured and used successfully at temperatures up to 1000°F and for periods up to 25,000 hr. These bearings were made by hard-facing or surface-coating the desired bearing material on a base alloy. The design was usually self-pressurized hydrostatic. The sizes were significantly smaller than those being considered for LMFBR applications.

For rubbing of mating surfaces in liquid metals under boundary lubrication conditions that exist in control rods, for example, careful selection of wear-resistant materials has resulted in generally successful operation of such devices in liquid-metal-cooled reactors built to date. However, operating temperatures of these reactors were 1000°F or less, and test times were short in terms of LMFBR requirements. For operation in this boundary lubrication region, coefficients of sliding friction of 0.3 to 0.4 were commonly reported. No relationship has been demonstrated between friction coefficient and wear.

For small space power systems, development of successful high-speed bearings is recognized to be one of the major problems of the power conversion machinery. Materials selection is subordinate to design problems, as the application demands performance in a regime where the reasons for bearing instabilities are not completely understood.

III. SELECTION OF MATERIALS

A. REQUIRED MATERIAL CHARACTERISTICS

The friction and wear behavior of materials sliding on one another depends in a complex way on a number of physical and chemical characteristics of the wearing materials. Other characteristics important to the final element design, such as cost and fabricability, must be considered in selecting the material. When the requirement of operation with a high-temperature alkali metal environment as the lubricant is superimposed on the design, the relative importance of the characteristics may be changed significantly from their importance in conventionally lubricated elements.

The many characteristics commonly considered in selection of bearing materials are discussed in this section under specific headings, with special emphasis on the effect of the alkali metal environment on the importance of each characteristic. The listing is alphabetical; no attempt is made to determine the order of importance to the final element design, since this order may vary with each application. The characteristics are:

1) Alloying tendency of couples	10) Fabricability
2) Coefficient of friction	11) Fatigue strength
3) Compressive strength	12) Hardness
4) Conformability	13) Melting point
5) Corrosion resistance	14) Radiation damage
6) Cost	15) Thermal conductivity
7) Dimensional stability	16) Thermal expansion coefficient
8) Ductility and impact strength	17) Transmutation to a radioactive source
9) Elastic modulus	

1. Alloying Tendency of Couples

A brief discussion of the theories of Bowden and Tabor⁽¹⁾ on the sliding contact of solids is appropriate to explain why rubbing surfaces in liquid metal environments should be made of materials with no tendency to alloy with each other.

Bowden showed that friction in metals is basically an adhesion or welding problem. On a microscopic scale a metal surface is rough, consisting of peaks (or asperities) and valleys. Surfaces in contact are supported only by a few of these asperities so that the real area of contact is very small and the stress in the asperity is very high. As the load is increased, plastic deformation occurs. When sliding occurs, high temperatures can exist at the contact points, and as a result of the high stresses and high temperatures the asperities can weld together. For sliding to continue the weld must be broken, and it is the work required to shear these welds and deform the asperities that determines the friction of the system. Surface damage to the sliding parts results when the break occurs in the base metal of the asperity rather than at the weld and metal is transferred from one surface to another.

Coffin⁽²⁾ developed the adhesion theory further by suggesting that the alloying tendency between metals sliding in a couple was the principal factor in determining whether welding of asperities and the resulting wear and surface damage would occur. If a solid solution is formed at the weld, the bond will be stronger than the base materials and shearing will occur in the base metal of the asperity. If there is no solubility between the metals but an intermetallic compound is formed, the bond will in general be brittle and weak, shear will take place at the weld and surface damage will be slight. If no solid solution or intermetallic compound is formed, the bond will be largely mechanical and the weaker asperity will shear at the bond, again with comparatively slight surface damage. To avoid formation of solid solutions or intermetallics, mating materials with differing crystal structures, large differences in lattice parameters, or differing electrochemical potentials are most attractive.

When a load-carrying continuous fluid film is not present, as at startup or shutdown of a bearing, or in an application where relative motion is too slow to generate a hydrodynamic film, metal-to-metal contact and asperity welding are probable. Wear is reduced in conventionally lubricated systems if the metal surface is covered with an adsorbed film of lubricant or a chemical reaction film (commonly oxide) that prevents clean metal-to-metal contact and asperity welding to some degree. With low-viscosity, highly reactive liquid metals, no adsorbed lubricant film is present and any protective (oxide) film on the metal surface is reduced or dissolved, so that metal-to-metal contact is actually

promoted. It is, therefore, very desirable to have no alloying tendency in metal couples chosen for rubbing surfaces in liquid metals.

2. Coefficient of Friction

A low friction coefficient is not in itself as important to rubbing surfaces in liquid metals as resistance to wear. It has been demonstrated⁽³⁾ that high friction in a sliding system does not necessarily result in high wear, and that a low-friction system may show excessive wear. High resistance to wear will be preferred over a low coefficient of friction in selecting a bearing couple for liquid metal service. The only criterion that might be required is that the coefficient of friction be reasonably low during the period of operation in the boundary lubrication regime so that the starting torque from a driving motor may be minimized.

Work with tungsten, tantalum, molybdenum, copper, and carbides of tungsten and titanium has demonstrated^(3,4,5) that sliding friction and wear can be less in a sodium environment than in vacuum or air. The improved friction behavior is attributed to the lubricating properties of a complex film formed at the rubbing surface, and assumed to be a reaction product of sodium, oxygen and the metal. Recent work⁽⁶⁾ with fluoride coatings on surfaces rubbing in sodium also showed improved friction and wear characteristics compared with similar uncoated surfaces tested. (These reports are discussed fully in Section III.C.) Caution must be used in extrapolating these results to the practical engineering applications required in operating reactor systems; the data were obtained at lower temperature, lower velocities or very short exposure times. Formation and maintenance of such films in an engineering system could be very difficult.

3. Compressive Strength

When a steadily-applied load is considered, the load-carrying capacity of a bearing is a direct function of its compressive strength, and of the viscosity of the lubricant that determines the film-bearing capacity. The low viscosity of liquid metals results in a low film-bearing capacity relative to conventional lubricants, so that an increase in bearing area or a reduction in bearing clearance or both is required over that of a conventionally lubricated design to maintain the same bearing load-carrying capacity. Where the film-bearing capacity

is not controlling, the liquid-metal-lubricated bearing tends to become very large, and it is important to have a material with as high a compressive strength as possible to keep the size reasonable.

4. Conformability

Conformability, the ability of a bearing couple to change configuration to compensate for misalignment and geometric inaccuracies (wearing-in), is an important property of bearing materials in conventionally-lubricated systems. Good conformability generally results from low hardness and low modulus of elasticity, but the classes of materials that have good corrosion resistance in liquid metals generally have high hardness and high modulus of elasticity. Other considerations may also dictate a high hardness and high elastic modulus requirement in a liquid metal bearing, so that conformability is usually not possible.

The high temperatures associated with liquid-metal systems make the alignment problem particularly severe. It follows that extreme precision in design, fabrication and installation of rubbing surfaces in liquid metals is required to compensate for the lack of conformability. The lubricating fluid must then be kept exceptionally clean, because the danger of damage from a particle passing through such a nonconforming bearing is much greater.

5. Corrosion Resistance

Where corrosion resistance seldom influences material selection in conventionally lubricated systems, it is the first characteristic considered in liquid metal systems and one of the most important. The bearing material must be completely compatible with the liquid metal environment at the operating temperature, over the life of the bearing. Intergranular corrosion or selective attack along certain crystallographic planes can roughen the surface finish enough to cause failure. The strength or hardness of the material surface can be affected detrimentally by selective leaching of alloying elements, leading to early fatigue failure of the surface and then the element. Finally, material compatibility with the liquid metal system as a whole must be established; where a bearing material may have excellent corrosion resistance in a static liquid metal test, it may show mass transfer behavior in a dynamic system when the liquid metal contacts another (construction) material. This could

result in rapid loss of an alloying element from the bearing material by selective leaching, and failure of the element. The actual amount of material leached from a bearing will be small, but it may still present a problem if it is highly radioactive, and this factor should be considered in evaluating the corrosion rate of a bearing material.

6. Cost

Unlike conventionally lubricated mechanical devices, cost does not play an important part in the selection of materials for liquid-metal-lubricated devices. Difficulty of access to the bearing in a nuclear system may prevent scheduled frequent replacement, and the resulting long lifetime and high reliability requirements demand the use of the best design and materials available. The original installed cost of a liquid metal bearing loses significance when compared with the cost of repairing a failed unit.

7. Dimensional Stability

Because the load-carrying capacity of a bearing is proportional to the viscosity of the lubricant, bearings lubricated with liquid metals must be designed with increased bearing area or reduced film thickness, or both, compared with conventionally lubricated bearings. The film thickness is generally reduced as far as manufacturing capabilities permit, and it is essential, therefore, that dimensional changes caused by metallurgical instability be negligible in order to maintain the proper design clearances during the life of the bearing.

8. Ductility and Impact Strength

Some degree of ductility and impact strength is desirable in all bearing material applications to prevent damage or failure from shock loading and to provide good "embeddability," the ability to absorb foreign particles coming through the bearing without suffering scoring or wear. However, hard materials, such as bonded carbides that have performed well in liquid metals, have very poor embeddability. When these materials are used in applications with close clearances, the system should also be designed for extremely good wear resistance to prevent wear debris from damaging the surfaces. The entire liquid metal inventory must also be kept clean and free from debris, such as insoluble corrosion products from structural materials, that could damage the bearing in passing through.

9. Elastic Modulus

A high elastic modulus at the operating temperature will permit high loading without plastic deformation and with minimum elastic deformation. This is necessary to maintain the dimensional stability of the small clearance design required in liquid-metal bearings. The high elastic modulus is not desirable in that it means the material will have poor embeddability. When grit is expected to pass through conventional bearings, with much greater clearances, a low elastic modulus will permit its passage with minimum scoring, and if the proportional limit has not been exceeded the bearing will return to its original shape after the particle has passed through it. Such operation is not possible when a high-modulus material is used with the small clearance design of liquid-metal bearings, and bearing surface damage may be expected when grit is present in the lubricant of such bearings.

10. Fabricability

Fabricability has not been a problem with the comparatively small sizes of liquid metal bearings produced to date. Alloys and carbides have been supplied as solid pieces, cast, wrought, or sintered, but solid construction is not practical for a 20-in.-diameter bearing, for example. Hard facing, flame spraying, plasma spraying and surface alloying bearing materials on structural base metals are all possible techniques for producing the large units that will be required for an application such as a 30,000-gpm sodium pump. Bearing materials being considered for use in such large units must therefore be amenable to satisfactory application and finishing techniques. Extensive development work would seem to be indicated to determine the best base metal, application technique and final finishing operations for these large units, and to demonstrate the long-time integrity of the bond between bearing material and base metal.

An important requirement of any fabrication process is that uniformity of product properties, both physical and chemical, from one unit to the next is absolutely essential if the high reliability required of liquid metal bearings is to be achieved. Changes in material chemistry or processing procedures that affect the dimensional stability, strength, hardness, or surface properties could have a serious effect on the performance of the final element. The bearing material must, therefore, be amenable to suitable quality control procedures.

11. Fatigue Strength

A high fatigue strength is essential in any bearing material to prevent fatigue cracking of the surface, spalling and eventual failure. Fatigue failures in bearings are common where cyclic conditions of load and temperature are encountered. The liquid metal environment may prove beneficial in fatigue-inducing situations when its excellent thermal conductivity and heat capacity will act to prevent large temperature differences from developing from point to point in the bearing surface.

12. Hardness

Generally, a material with a high room temperature hardness can be given a higher surface finish that results in a more uniform contact area, less tendency to have asperities welding, and therefore less wear. The hot hardness of a material at its service temperature, however, is a more important measure of its serviceability than is the room temperature hardness; a high hot hardness will tend to keep load-carrying capacity from decreasing, and wear rates from increasing, at service temperatures.

13. Melting Point

The mechanical properties of metallic materials deteriorate, in general, as the melting point is approached, so that the high melting point is desirable in high-temperature applications simply to maintain the mechanical properties of the material that influence the load-carrying capacity of the bearing. The melting point should be high to prevent incipient fusion from frictional heating at the highly stressed points of contact. A high melting point also means lower atomic mobility at the service temperature and, therefore, lower diffusion rates and less tendency to bond at the contact points. The higher melting point thus reduces the alloying tendency of the bearing couple, a very desirable feature in liquid-metal applications.

14. Radiation Damage

Bearings intended to operate in a strong radiation field should not include materials known to be susceptible to radiation damage. Two common effects of radiation damage, swelling and embrittlement, would act to hasten failure of the bearing. Boron compounds, valuable for the hardness they impart to a

bearing material, would be an example of an undesirable material if they are to be exposed to a neutron flux that would cause the boron-to-helium transformation.

15. Thermal Conductivity

A high thermal conductivity will dissipate frictional heat more rapidly, minimizing the alloying tendency at points of interfacial contact and preventing mechanical damage from local overheating. Liquid metal lubricants can help to make up for a low thermal conductivity in an otherwise desirable bearing material by their excellent heat transfer characteristics.

16. Thermal Expansion Coefficient

The thermal expansion characteristics of the complete mechanical element assembly must be carefully considered if the small clearance designs required with low-viscosity liquid metal lubricants are to be successful. The element must have proper fit and clearance both at room temperature and at the selected operating temperature. Care must be taken if the element is operated above its design temperature that a proper clearance still exists. Use of only one material in a bearing couple, of course, minimizes the potential thermal expansion mismatch, but here again the bearing material must be matched carefully with the structural material of the assembly.

Thermal expansion problems increase as the size of the mechanical element increases. Use of a thin coating of bearing material on a base metal as the rubbing surface in an otherwise monometallic element minimizes this difficulty. Here the thermal expansion coefficients of coating and base must be matched to prevent loss of bonding during thermal cycling.

17. Transmutation to a Radioactive Source

Material leached from bearing surfaces will be transported throughout the system, and may deposit out of the sodium in undesirable locations. The amount of such materials will be very small in comparison with the total volume of sodium and containment metals in the system, but if it has become radioactive during its exposure in the bearing, it will transport this radioactivity in amounts that could be substantial. Cobalt, which is commonly used in bearings, is one element that might cause such a problem. If a bearing surface is to be exposed to significant radiation during its lifetime, its corrosion characteristics and the

radioactivity of its corrosion products should be evaluated to determine if a problem will exist because of radioactive material transfer.

B. MATERIAL CLASSES

1. Nonrefractory Metals and Alloys

As a broad class, the nonrefractory metals, high strength steels and super alloys have lower temperature limitations than the other material classes considered here. Within their temperature limitations, however, these materials exhibit many attractive combinations of properties. With these materials it is possible to have high strength and hardness — both very desirable for liquid-metal-lubricated rubbing surfaces — and yet retain significant ductility and ability to deform plastically without cracking. Their corrosion resistance varies with the chemistry and, of course, with temperature, but it may be rated in general as good. Mass transfer properties in particular must be considered for the overall liquid metal system. Fabrication is the simplest of any of the material classes, properties are well known and reproducible, and theoretical density (zero porosity) is attained easily.

The nickel and cobalt super alloys have the highest temperature potential; cobalt-base alloys have demonstrated superior corrosion resistance. The high strength tool steels represent the hardest materials of the metal alloys reviewed, although their use temperature must be kept below 1000°F, where corrosion resistance, dimensional stability and hot hardness are considered good. Above 1000°F one or more of these properties can be expected to deteriorate rapidly.

2. Refractory Metals and Alloys

Except for hardness, the advantages offered by the nonrefractory metals and super alloys are also found in this class of materials. While the hot hardness values of the refractory metals and alloys are lower, at nominal liquid metal system bulk temperatures of 1000 to 1200°F, than those of high strength steels or super alloys, highly localized overheating at metal-to-metal contact points could raise the temperature where wear is occurring to the point where the hot hardness and strength of the high-melting-point refractory metals would be superior.

The excellent corrosion resistance of the refractory metal alloys to alkali metal environments has been demonstrated^(7, 8, 9) at temperatures up to 2000°F. Internally gettered alloys of niobium and tantalum are used for maximum corrosion resistance and strength, and the TZM and TZC molybdenum modifications were developed for their higher strength and recrystallization temperature.

Molybdenum and tungsten are also important in liquid-metal-lubricated mechanical devices for a unique property first described by Kissel et al.⁽⁴⁾ In low-speed sliding tests at temperatures up to 1300°F, it was demonstrated that molybdenum showed considerably lower friction and surface damage when sodium was used as a lubricant at the rubbing surface than when the test was made in argon. It was shown that a complex sodium-molybdenum oxide had formed an adherent surface film at the rubbing interface and had provided excellent boundary lubrication. The lubricating ability of molybdate films prompted interest in tungsten, and it was determined⁽⁵⁾ that the frictional behavior of sodium-lubricated tungsten was quite similar to that of molybdenum. Collaborative information on the lubricating ability of complex oxide compounds was reported by Peterson.⁽¹⁰⁾ Potassium molybdate and sodium tungstate were shown to be effective lubricants in an Inconel system sliding in air at 1300°F.

Balchin⁽³⁾ further demonstrated, in low temperature tests (below 400°F), that the frictional behavior of metals sliding under liquid sodium depended on whether the sodium simply dissolved the surface oxide (in which case the friction and wear were higher than when the surface oxide was acting as a lubricant) or whether it could react with the oxide and the metal to form a complex oxide that acted as a lubricant.

On the basis of these findings, the refractory metals would appear to have great potential in low-sliding-speed or intermittent-contact applications in high-temperature mechanisms operating in sodium. Success of extrapolating the results to high-speed, continuous contact applications is less certain. The formation of the complex oxide film requires oxygen or oxide, and while such a film may be formed when a system begins operation, maintenance of the film as it wears away must come from oxide in the sodium; in a practical system this may be difficult.

A further result of this discovery of the complex oxide lubricant is the attempt to improve friction and wear characteristics of other bearing materials such as Stellites, tool steels and bonded carbides by adding nominal amounts of molybdenum or tungsten. These experiments are discussed under the material class concerned.

3. Carbides

The carbides of the IV-A, V-A, and VI-A transition metals have many of the properties considered desirable in bearing materials. Their thermal conductivity properties are similar to those of pure metals. They have high hardnesses, high compressive strengths, and high elastic moduli. Their melting points are the highest of any of the material classes. Their resistance to alkali metal corrosion is satisfactory, although it may be affected by fabrication processes that introduce impurities or porosities; intergranular impurity leaching may then lead to mechanical damage.

The primary concern with carbides is their brittleness, susceptibility to impact loading damage, and extreme abrasiveness of any debris produced by such damage. From a fabrication standpoint, the problem is the inability to achieve high densities (close to theoretical), which results in a (comparatively) rough surface. It is argued that such a porous surface may have some value in its ability to absorb or embed debris particles that otherwise would cause scoring, but this has not been demonstrated empirically.

As a class, the binderless carbides have less appeal than the well-developed bonded carbides. However, progress of recent attempts to produce a thin carbide bearing surface in situ on the shaft or journal by surface treatment⁽¹¹⁾ offers some hope of realizing the desirable properties of the carbides without the undesirable features present in monolithic specimens.

4. Bonded Carbides

The commercially produced bonded carbides used commonly in cutting tools are designed to overcome the two serious faults of pure carbides, brittleness and porosity. They retain the high compressive strength, hardness, elastic modulus and thermal conductivity of the carbides and add the desirable feature of excellent commercial status. Good corrosion resistance to liquid metal environments has been demonstrated, but this property will vary with the bonding agent.

Iron, nickel, and cobalt are the metals most commonly used as bonding agents; carbides of tungsten, titanium, tantalum, chromium, and niobium are used alone or in combination. According to Kieffer⁽¹²⁾ the action of the bonding agent is to form an alloy network between the hard crystals of carbide. The success of the iron group as bonding agents stems from the fact that there is some solubility of the carbide in these bonding agents at the sintering temperatures used to prepare the materials; alloying of the bonding agent and carbide occurs to form a eutectic liquid phase that solidifies to a tough matrix. Liquid-phase sintering also provides the theoretical density so difficult to achieve with pure carbides. Sykes⁽¹³⁾ has further shown that the metallographic structure of cobalt-bonded tungsten carbide is changed significantly when titanium carbide is added; a reaction between the carbides and the cobalt produces a new phase that ties up much more of the bonding agent in solution or as a complex intermetallic compound. Coffin⁽¹⁴⁾ correlated this change in character of the bonding matrix with the observed improved performance when cutting steel of cutting tools made of the mixed carbides over tools of tungsten carbide. He further observed that the wear resistance of the mixed carbide material used as a bearing surface in sodium was better than that of the material containing only tungsten carbide. He concluded that bearing wear was caused by alloying of the bonding agent in the bonded carbide with the metal of the other rubbing surface, and that wear would be decreased by: (1) reducing the amount of free bonding agent, as by tying it up with titanium carbide additions, and (2) selecting a metal for the surface rubbing on the carbide that had a low solubility in the bonding agent.

Because the major limitation in the use of bonded carbides in high-temperature liquid metals was expected to be the corrosion resistance of the bonding agent,⁽¹⁵⁾ the natural extrapolation was to replace the iron group bonding agents with refractory metals. Tantalum, tungsten, molybdenum, and niobium have all been used successfully in experimental formulations. These materials proved to have increased resistance to corrosion and mass transfer in liquid metal systems and higher temperature capabilities than carbides bonded with cobalt, iron, or nickel. Wallace⁽¹¹⁾ concluded that refractory-metal bonded carbides probably have the best potential as materials for alkali-metal-lubricated journal bearings. The greatest drawback to these materials is the limited data available on fabrication techniques and mechanical properties.

Use of molybdenum and tantalum also provides an opportunity for improved boundary lubrication characteristics by formation of the complex sodium-metal-oxide surface film reported by Kissel.⁽⁴⁾ It is not yet clear whether the chemistry of the refractory metal in its role as a bonding agent in bonded carbides will allow formation of the complex oxide.

5. Other Materials

a. Oxides

Ceramic oxides have high hardnesses, high compressive strengths, high elastic moduli and satisfactory corrosion resistance in alkali metals. High densities, close to theoretical, are easily achieved. Beryllium oxide has good thermal conductivity but a higher chemical reactivity than alumina. The greatest drawback to successful operation of oxide rubbing surfaces is, like carbides, their brittleness.

b. Borides

The general observations on carbides also apply to borides. Much less information on properties and experimental behavior is available for borides.

c. Nitrides

As a class, the nitrides are less promising than carbides or borides because of their high vapor pressures, lower hardnesses and producibility problems. Neither borides nor nitrides show the potential for any exceptional advantage over carbides that might warrant a development program to bring them to the same state of knowledge as carbides.

d. Surface Treatments

Treatments used to apply a thin coating of bearing material on the surface of nonbearing-material substrate will be considered as a separate class. While the corrosion, friction and wear properties of the material will be the same as for bulk specimens, the thermal properties of the composite, and the fabrication processes to form the composite, are different enough to put the composite in a separate class. Flame spraying or plasma spraying is commonly used to apply refractory metals, carbides, bonded carbides, and oxides to an almost unlimited range of substrate alloys. Carburization and nitriding produce cases of essentially pure carbides or nitrides on selected substrate alloys. By using surface

coatings, the material for the mechanical device may be chosen for its strength, toughness, thermal expansion characteristics, or fabricability; the desired friction and wear properties are then produced by adding a coating of bearing material with the correct bearing properties for the design environment.

While surface treatments seem to offer the best features of wear resistance and base metal ductility, they are beset with problems peculiar to the class that have kept them in a developmental stage, behind the state of knowledge of the parent bearing materials. The problem of producing a satisfactory permanent bond holding its integrity through thermal and mechanical shocks is paramount. Achieving the full density required for satisfactory performance of any bearing material is often difficult. Maintaining the chemistry of the parent material during the surfacing operation is essential to success of the composite, and yet is not accomplished easily. Finally, reproducibility of the surfacing process must be raised to the same level as that of the fabrication of monolithic pieces before reliable performance can be obtained.

Because the difficulty of building bearings from monolithic blocks of bearing materials increases greatly as the size of the bearing increases, it is probable that the very large bearings contemplated for LMFBR pumps will be surface-coated. Successful commercialization of the process would also provide improved performance in smaller bearings where thermal expansion mismatches between bearings and structures have caused design problems.

C. EXPERIMENTAL AND OPERATING EXPERIENCE

1. Nonrefractory Metals and Alloys

a. Copper and Copper Alloys

(1) Item No. 1

The earliest materials investigation reported was a broadly based low-temperature NaK screening of several dozen materials judged to be potentially useful as bearing materials in liquid metals. Vail^(16,17) tested several combinations of materials that were under consideration for sodium bearing applications. Tests were made under boundary lubrication conditions at 350 to 950°F. Only a qualitative, comparative evaluation of performance was made in which each combination was rated from Group 1 (best) through Group 5 (worst):

Group 1 — negligible wear, no apparent material transfer, both specimens polished

Group 2 — smooth wear of fixed pin, polishing of rotating sleeve, no apparent material transfer

Group 3 — smooth wear of either specimen, minor material transfer

Group 4 — excessive wear, or surface roughening, or material transfer

Group 5 — failed to complete the test.

The test parameters used were as follows:

Type of Test: Fixed loaded pin (0.312 in. diameter) held against rotating sleeve

Environment: NaK (56%K) liquid

Temperature: 350 to 950°F

Sliding Speed: 450 ft/min

Load: 34 lb/pin, equivalent to 15,000 psi as test starts with line contact, decreasing as wear increases the contact area

Time: 205 min.

Copper and its alloys appeared in combinations that gave the best performance of any but bonded carbides at 600 and 850°F. Copper against Carboloy-779, chrome plate, SAE-52100 steel and Kentanium (K-138) showed Class 2 performance at these temperatures. Aluminum-bronze against 18-4-1 HSTS was also placed in Class 2 at 600°F, and in Class 3 against Stellite-98M2 at 850°F. The tests showed generally lower friction coefficients than other metal vs bonded-carbide combinations, but also showed high wear.

The apparent advantages of copper as a bearing material must be balanced against its high solubility in sodium at elevated temperatures. Its usefulness is limited, therefore, to systems of moderate temperature and short lifetime, and, most important, where dissolved copper in the liquid metal will not adversely affect the rest of the system. Within these limitations, copper alloys have found significant usefulness.

(2) Item No. 2

Vail reports tests⁽¹⁸⁾ of copper vs tungsten-carbide journal bearings lubricated with NaK. Satisfactory results were achieved; the bearings operated in the hydrodynamic region as designed and did not show excessive wear when operated with only boundary lubrication.

The test parameters used were as follows:

Type of Test: Hydrodynamic journal bearing, 2-3/8-in. diameter

Environment: NaK

Temperature: 100 to 500°F

Sliding Speed: 750 to 1050 ft/min

Load: 0 to 175 psi

Time: 1500 hr.

At the end of the test, an abnormally high copper content was found in the system NaK. This emphasized the corrosion problem that exists if copper bearings are operated in liquid metals.

(3) Item No. 3

Coffin⁽²⁾ investigated the performance of thrust bearings using copper turning on bonded tungsten carbide. The success of the combination at temperatures up to 650°F was attributed to the lack of solubility of copper in the bonded carbide so that no tendency to alloy existed in the combination. Coffin later⁽¹⁹⁾ used this same combination to demonstrate the achievement of hydrodynamic behavior in a bearing through the phenomenon of wear-in.

The test parameters used were as follows:

Type of Test: Loaded pad rotating on fixed disc

Environment: NaK (77% K)

Temperature: 500 to 750°F

Sliding Speed: 2 to 800 ft/min

Load: 0 to 200 psi

Time: Up to 24 days.

Some 25 tests were made on the copper running on bonded carbide combination with times up to 24 days without incident. The wear-in phenomenon was described as follows: a bearing surface operating with a high coefficient of friction, perhaps 0.2, would gradually develop a lower coefficient, perhaps 0.01, although no changes in load or speed had been made. The bearing was assumed to be operating hydrodynamically. An increase in loading produced a higher friction, which again gradually decreased with time. It was assumed that the two surfaces meshed together in a fashion similar to screw threads, with a clearance measured in microinches.

A sharp increase in temperature caused a sharp increase in friction because of the mismatch in thermal expansion coefficients; the mating, meshing surfaces interfered at the higher temperature, as they had when the load was increased, and the wear-in process had to begin again.

The short-time compatibility of copper with tungsten carbide provided a useful bearing for this experiment, as suggested by Vail⁽¹⁸⁾ in Test No. 2 preceding.

(4) Item No. 4

A high speed (24,000 rpm) journal bearing test rig was operated to investigate bearing torque, lubricant flow rate and stability limits for bearings in high temperature potassium.⁽²⁰⁾ Bearing design rather than material testing was the main emphasis. All tests were made using an aluminum-bronze bearing sleeve material on a chrome-plated stainless steel shaft. No corrosive or erosive action was observed during the normal test program, most of which was carried out in water. About 10 hr of testing in 400°F potassium were accomplished before a leak in the liquid metal system ended the testing.

Static corrosion testing, 900 hr in 1200°F potassium, showed uniform surface attack on the aluminum-bronze; the conclusion recommends against the exposure of aluminum-bronze to dynamic potassium for more than 1000 hr.

This is another example of the copper-base alloy making a valuable contribution where long-time liquid metal exposure was not needed.

b. Steels

(1) Item No. 1

According to Vail's tests^(16,17) the excellent compatibility of 18-4-1HSTS at 350°F fell off with increasing temperature, so that at 850°F excessive welding or friction was noted between 18-4-1HSTS and bonded carbides Carboloy 779 and K-138, K-138A, Stellite-J and several other miscellaneous materials. The prospects for use in high-temperature couples were not promising. Test parameters used were as follows:

Type of Test: Fixed loaded pin (0.312 in. diameter) held against rotating sleeve

Environment: NaK (56% K) liquid

Temperature: 350 to 950°F

Sliding Speed: 450 ft/min

Load: 34 lb/pin, equivalent to 15,000 psi as test starts with line contact, decreasing as wear increases the contact area

Time: 205 min.

(2) Item No. 2

A similar screening experiment by Elliott et al.,⁽²¹⁾ confirmed the excellent low-temperature (250°F) performance of tool steels against bonded carbides. In the qualitative evaluation of the results, six combinations of J-34HSTS and a bonded carbide were given top rating.

The test parameters used were as follows:

Type of Test: Loaded pad, 3/8-in. square, rotating on fixed disc

Environment: Sodium

Temperature: ~250°F

Sliding Speed: ~3 ft/min

Load: 35 psi

Time: 600 min.

(3) Item No. 3

More extensive testing of tool steels was conducted by Roberts.⁽²²⁾ A low-chromium tool steel, C92, was reported to have very low wear rates when rubbed against itself in sodium at temperatures up to 1000°F; wear scars were polished and only minute scoring effects were observed.

The test parameters used were as follows:

Type of Test: Fixed loaded pin with cylindrical rubbing surface held against rotating sleeve.

Environment: Sodium

Temperature: 300 to 1000°F

Sliding Speed: 6 ft/min

Load: 2.4 kg on pin, equivalent to about 5000 psi at end of test, as determined from area of wear scar

Time: 10 hr.

Wear was calculated from the dimensions of the elliptical wear scar on the pin as the volume of metal removed. Wear rates increased sharply with temperature, going from 5×10^{-12} cm³/cm/kg at 550°F to 7×10^{-10} cm³/cm/kg at 950°F. The friction was unusually high, about 0.8, during the test.

(4) Item No. 4

Further friction and wear testing of tool steels alloyed with molybdenum, tungsten, and chromium was reported by Roberts.⁽²³⁾ Test parameters were the same as noted for the previous Test (No. 3) with the additional provision that oxygen in the sodium was held to an estimated level of 5 ppm by cold trapping.

Four low-alloy steels (max Cr, 3%) were tested first; after 100 hr at 950°F their initial hardnesses had decreased sharply and surface damage and wear were considerable. These steels are not recommended for use in high-temperature sodium. Three tool steels were then tested in various combinations with two Stellites. Specific wear rates for the SM18 and C92 tool steels sliding on Stellite-1 increased sharply above 750°F. Wear regions were generally

polished at 550°F, but less polished at 850°F and 950°F, and it appeared that surface plastic flow had occurred. The order-of-magnitude wear rates and friction coefficients for these tool steels were the same as quoted for the previous experiment.

Similar experiments were run in argon containing sodium vapor, and results were compared with tests run in gaseous environments of helium and argon. Friction and wear were generally lower in sodium environments than in the gaseous environments. Roberts suggests that the low wear rates and friction coefficients observed with these Mo-W-Cr steels in environments of high-purity sodium were the result of effective boundary lubrication by the complex oxide film formed by reaction of the molybdenum, tungsten, and chromium constituents of the alloys with oxygen and sodium. This is the same reaction first proposed by Kissel^(4,5) in his work with molybdenum and tungsten metals. Roberts continues by questioning the ability of these complex oxides to provide effective long-time boundary lubrication films with self healing properties, without a continuing source of oxygen. The possibility of forming sodium-chromium complexes (without oxygen) that could act as boundary lubricants is suggested.

(5) Item No. 5

Freede⁽²⁴⁾ conducted an extensive series of screening tests to develop comparative friction and wear data on several material classes.

The test parameters used were as follows:

Type of Test: Fixed pins bearing on loaded rotating plate

Environment: Sodium, liquid and vapor

Temperature: 800°F and 1200°F

Sliding Speed: 5 to 16 ft/min

Load: 123 psi

Time: ~200 hr.

Test results for combinations including one or two steels are given in Table 1. Both wear rates and friction coefficients were low in the 800°F sodium vapor environment and, with one exception, they were similarly low in the 800°F liquid sodium environment. Tool steels would seem to be acceptable for 800°F

TABLE 1
COMPARATIVE FRICTION AND WEAR DATA ⁽²⁴⁾

Test No.	Pin Material	Plate Material	Coefficient of Sliding Friction	Specific Wear x 10 ¹¹ on Pins, Average (cm ³ /cm/kg)
At 800°F, in sodium vapor				
E-1	AISI-M3, Type 2	AISI-M4	0.33	2.2
E-2	AISI-M4	AISI-M43	0.36	2.9
E-3	AISI-M43	AISI-M3, Type 2	0.33	1.4
At 800°F, in liquid sodium				
C-1	AISI-M3, Type 2	AISI-M4	0.31	4.9
C-2	AISI-M4	AISI-M43	0.29	2.5
C-3	AISI-M43	AISI-M3, Type 2	0.45	7.1
30	AISI-M43	AISI-M3, Type 2	0.33	1.0
At 1200°F, in liquid sodium				
B-1	AISI-M2	AISI-M1	1.07	Welded
B-2	AISI-T15	AISI-T1	0.94	Welded
H-1	Rex 49	Rex 49	-	Welded
8	Stellite-6B	AISI-M1	0.95	Welded
B-3	Type 17-4 PH SS	AISI-M15	1.07	Welded
H-3	Rex 49	Hastelloy-C	0.38	38.7
11	AISI-T1	Hastelloy-C	0.47	6.7

service, from these results. At 1200°F, all pin materials tested welded to the tool steel plate, showing friction coefficients of about 1.0. One tool steel pin, AISI-T1, on Hastelloy-C plate gave acceptable performance.

c. Super Alloys

(1) Item No. 1

After testing several super alloy combinations in NaK at 350 to 950°F, Vail concluded^(16,17) that nickel or nickel alloys, with the possible exception of Colmonoy-6, did not have good compatibility characteristics at high temperatures; and that the cobalt-tungsten-chromium alloys that showed fair characteristics at temperatures up to 600°F did not have good characteristics at higher temperatures. This pattern of excellent compatibility at low temperatures which decreased as temperature increased was common to all the super alloy classes tested.

The test parameters used were as follows:

Type of Test: Fixed loaded pin (0.312 in. diameter) held against rotating sleeve

Environment: NaK (56% K) liquid

Temperature: 350 to 950°F

Sliding Speed: 450 ft/min

Load: 34 lb/pin, equivalent to 15,000 psi as test starts with line contact, decreasing as wear increases the contact area

Time: 205 min.

Nickel-manganese brazing alloy showed high friction and severe welding to cobalt-bonded tungsten carbide at 850°F.

Nickel-chromium Colmonoy-6 showed excessive welding at 850°F when tested against 18-4-1 HSTS on Tantung-G, but gave fairly good compatibility results when tested against itself or bonded carbides. It appeared to be more resistant to galling than other hard-facing alloys tested.

Chromium-nickel-iron alloys 2T-12, 2T-14, and 2T-15 showed high wear rate and plastic deformation in 850°F tests in spite of room temperature hardnesses as high as 68R_C. The alloys welded to bonded carbides, Stellites and chrome plating in the 850°F tests.

Chromium-tungsten-cobalt alloys (two grades of Stoodly alloys) were tested as hard-faced specimens; the samples were porous, which may have accounted for their poor performance. The alloy showed welding in 850°F tests with bonded carbides, Stellite-J and 18-4-1HSTS; none of the materials tested in combination with the Stoodly alloys showed promise for high-temperature bearings in liquid metals.

Tantung-G with Carboloy-779 showed excellent performance at 350°F (Class 1) but the compatibility decreased and friction coefficient increased rapidly with rising temperature; at 800°F the performance was Class 4, excessive wear or friction. Use at relatively low (600°F) operating temperatures was recommended.

The Stellites performed similarly to Tantung-G; they were most compatible with bonded carbides and copper alloys. Stellite-98M2 appeared to be slightly superior to Stellite-J for a diminished tendency to weld to other alloys at 600°F, but at 850°F severe welding and scoring was observed when it was tested against bonded carbides, 18-4-1HSTS and copper alloys. Stellite-J with Carboloy 779 showed excellent performance at 350°F (Class 1), satisfactory performance at 600°F (Class 3) and excessive wear (Class 4) at 800°F. Excessive welding occurred when Stellite 3 or Stellite 6 was tested at 600°F against 18-4-1HSTS, chrome plate, and SAE-52100 steel.

(2) Item No. 2

A similar screening experiment by Elliott et al.,⁽²¹⁾ confirmed the excellent low-temperature (250°F) performance of super alloys against bonded carbides. In the qualitative evaluation of the results, ten combinations of Stellites against a diversity of materials were given top rating. Stainless steel, bonded carbides and tool steels were among the materials tested successfully against Stellite-1 and -100.

The test parameters used were as follows:

Type of Test: Loaded pad, 3/8-in. square, rotating on fixed disc

Environment: Sodium

Temperature: ~250°F

Sliding Speed: ~3 ft/min

Load: 35 psi

Time: 600 min.

(3) Item No. 3

Sarnecki⁽²⁵⁾ reports a test of gears and sleeve-type bearings in 1200°F sodium. Meshing gears and journal bearings turned on the same shaft at very slow speeds (about 1-1/2 ft/min) for times up to 3000 hr, with total exposure to 1200°F sodium reaching 5000 hr. The gear and bearing were loaded up to 75 lb but no estimate of unit loading was made. Complete test results are given in Tables 2 and 3. The best bearing combination was Hastelloy-C turning on molybdenum; some galling and scoring occurred, but it was concluded that performance was not significantly affected. Combinations of gears tested indicated that Hastelloy-C was the most durable material, showing little wear when mated with Type 316 SS (plain and aluminized), Timken 16-25-6 and Incoloy, while all the mating gears except Incoloy were badly worn.

TABLE 2
GEAR TEST RESULTS⁽²⁵⁾

Gear Combinations	Total Time in Sodium (hr)	Total Time Rotated (hr)			Condition of Gear
		No Load	9 to 75 lb Load	75 lb Load	
AISI 316 SS	555	126	48	39	Badly worn
Hastelloy-C, SN-1					Good
Aluminized 316 SS	540	104	169	30	Badly worn
Hastelloy-C, SN-2					Good
Incoloy	2817	139	62	977	†
Hastelloy-C, SN-2*	3357	243	231	1023	
Timken 16-25-6 alloy	1071	154	208	0	Badly worn
Hastelloy-C, SN-3					Good
Hastelloy-C, SN-4	3403	0	128	2628	†
Hastelloy-C, SN-3*	4474	154	336	2628	

*Gear was used on previous test; total times include previous test.

†Both gears appeared in good condition; buildup of material (unknown) occurring on back side of gear teeth.

TABLE 3
SLEEVE BEARINGS TEST RESULTS⁽²⁵⁾

Sleeve Bearing Combinations 1. Inner 2. Outer	Total Time In Sodium (hr)	Total Time Rotated (hr)			Reason Test Stopped	Condition of Sleeve Bearings
		No Load	9 to 75 lb Load	75 lb Load		
1. Molybdenum } 2 2. Molybdenum } sets	61	1	0	0	Assembly seized	One set seized, both sets badly galled
1. Molybdenum 2. Molybdenum	170	*	0	0	Increased friction and binding in the assembly	Mo-to-Mo badly galled Hastelloy-C to Mo good
1. Hastelloy-C 2. Molybdenum	324	125	48	39	Increased friction in the assembly	Molybdenum galled Hastelloy-C scored, picked up some Mo
1.† Hastelloy-C 2.† Molybdenum	494	126	48	39		
1. Hastelloy-C } 2 2. Molybdenum } sets	1	§	0	0	Assembly seized	Both sets of bearings seized and badly galled
1. Hastelloy-C } 2 2. Molybdenum } sets	2566	243	231	1023	Binding occurred	Both sets, excessive galling Material (probably Hastelloy-C) deposited on Mo
1. Hastelloy-C } 2 2. TZM } sets	1071	154	208	0	Increased friction	Both sets, excessive galling. Material (probably Hastelloy-C) deposited on TZM
1. Hastelloy-C } 2 2. Molybdenum } sets	2908	0	81	2294	Excessive friction	Both sets, some scoring and galling. Material (probably Hastelloy-C) deposited on Mo
1. TZM } 2 2. TZM } sets	791	0	0	0	Assembly seized	**
1. Hastelloy-C } 2 2. Hastelloy-C } sets	1220	0	47	334	Test program discontinued	One set, very satisfactory; other set, good

*Rotated (manually) only when torque measurements were being made.

†Set of bearings used in previously listed combination; total times include previous test.

§Rotated 2 min. Bearings apparently failed due to improper preconditioning.

**Two rotations made at no load; assembly seized after one rotation at a 25 lb load. One set seized; seizure caused by localized galling at the extreme upper end of the outer alcove bearing. Remainder of the mating surfaces were virtually unharmed (same as other set).

The author comments that a soaking period of up to 100 hr in 1200°F sodium was required before dynamic operation, and that immediate seizure resulted in several tests when preliminary soaking was omitted. He concludes that the soaking time was necessary to form the complex metal-sodium-oxide film that provided some degree of boundary lubrication (after Kissel).^(4,5) It was also noted qualitatively that when the oxide level in the sodium was lowered by cold trapping, bearing friction increased, although no quantitative means of determining the actual oxide concentration was available.

The experiment would indicate that once formed, the lubricating film of sodium-metal-oxide can be maintained up to 2000 hr by system oxides.

No comparison of super alloy performance with bonded carbides was made in the program.

(4) Item No. 4

Friction and wear testing of Stellite super alloys was reported by Roberts.⁽²³⁾ The test parameters used were as follows:

Type of Test: Fixed loaded pin with cylindrical rubbing surface held against rotating sleeve.

Environment: Sodium

Temperature: 300 to 1200°F

Sliding Speed: 6 ft/min

Load: 2.4 kg on pin, equivalent to about 5000 psi at end of test, as determined from area of wear scar

Time: 10 hr.

Wear was calculated from the dimensions of the elliptical wear scar on the pin as the volume of metal removed.

Stellite-1 and -6 showed almost a complete lack of scoring in liquid sodium and in sodium vapor. For Stellite-6 sliding on the harder Stellite-1, wear rates rose from about 7×10^{-12} cm³/cm/kg at 400°F to 3×10^{-10} at 950°F; friction coefficients increased from about 0.4 to 0.5.

Tests were also run in argon, helium, carbon dioxide and sodium vapor; a wide range in wear rates in the different environments was obtained with only a small spread in friction coefficients. At 400°F, the friction coefficients in the different environments all fell within the narrow range of 0.35 to 0.50, but corresponding specific wear rates covered four orders of magnitude from 10^{-12} to 10^{-8} cm³/cm/kg. This is an indication that wear rates cannot be correlated with friction coefficients.

(5) Item No. 5

Frank⁽⁷⁾ reports successful static corrosion testing of STAR-J Stellite alloy in potassium liquid and vapor. After 1000 hr at 1600°F, no significant surface attack was found in metallurgical examination of the specimens. However, a morphological change caused by thermal aging that caused measurable dimensional growth was noted; no significant dimensional changes were found in similar specimens exposed at 1200°F and 800°F.

(6) Item No. 6

Test data on coefficients of sliding friction in sodium were reported for Stellite-19B wear blocks riding on a Carboloy-98B shaft.⁽²⁶⁾

The parameters used were as follows:

Type of Test: Modified Falex, fixed loaded wear blocks riding on rotating shaft

Environment: Sodium

Temperature: 450 to 1000°F

Sliding Speed: Not given, probably less than 15 ft/min

Load: 75 lb, no conversion to unit loading given

Time: Not given.

Average friction coefficients were compared with previous values obtained in the inert gas:

Temperature (°F)	Coefficient of Sliding Friction	
	Inert Gas	Sodium
77	0.950	-
445	-	0.172
572	0.860	0.440
842	0.552	0.500
1022	0.312	0.602

The coefficient in sodium increased when the temperature was raised to 572°F, presumably from delubrication of the metal surface as the sodium began wetting the surface. Oxide formation is given as the reason for the decrease in the inert gas coefficient, the higher the temperature the greater the rate of oxide formation and the more lubrication from the resulting oxide layer.

(7) Item No. 7

Freede⁽²⁴⁾ conducted an extensive series of screening tests to develop comparative friction and wear data on several material classes. The test parameters used were as follows:

Type of Test: Fixed pins bearing on loaded rotating plate
 Environment: Sodium, liquid and vapor
 Temperature: 1200°F
 Sliding Speed: 5 to 16 ft/min
 Load: 123 psi
 Time: ~200 hr.

Three pins of different diameters, each of the same material, were held in a vertical position in a triangular lattice 120 deg apart, below the test plate; they were located at three different radial distances from the center of the plate so that each pin's velocity relative to the plate was different. Loading was applied through a flexible joint that permitted equal pressure to be applied to each pin sliding surface which was flat. Results were reported in terms of specific wear of the pins, where material was removed, in cm³/cm of travel per kilogram of load; the specific wear number reported is the average of the three pins, each of which traveled a different distance, at a different velocity.

Super alloys were one material, or both, of 67 tests in 1200°F cold-trapped sodium liquid as reported in Table 4. Three tests in 1000°F liquid sodium and two in 1200°F sodium vapor are also included in Table 4. General conclusions that may be drawn from the data are:

- 1) The hard-facing Colmonoy alloys as plates caused extremely high wear on all pins tested except the high-tungsten Stellite-3. Colmonoy hard-faced pins showed very high wear when tested on plates of K-95 (bonded tungsten carbide) and Stellite-6B.
- 2) Hastelloy-C as a plate showed some of the best performances of any combinations tested; Stellite hard-faced pins on Hastelloy-C plates gave the lowest wear rates of any combinations tested when the sliding velocity was reduced.
- 3) Friction coefficients in the range of 0.3 to 0.4 were easily obtainable; no correlation between friction coefficient and specific wear was found.
- 4) Inconel-718 as a plate showed high wear rates with all pins tested except molybdenum pins; Inconel-718 pins tested on a TZM plate showed comparably good performance. Inconel-718 pins, in fact, showed low wear on plates of Stellite-6B, Stellite-6H(HF), K-95, and a high wear rate only on a Hastelloy plate.
- 5) Stellite Star-J pins showed low wear on plates of Stellite-6B, tungsten, molybdenum, and Hastelloy-C, but high wear on a K-95 plate.
- 6) K-95 (cobalt-bonded tungsten carbide), as a plate showed low wear only with pins of Hastelloy-C, Inconel-718, and Stellite-6B.

In cases where "material buildup" is indicated instead of a wear rate, the length of the pins increased during the test, because of a welded type of deposit built up on the pin, presumably of wear debris.

2. Refractory Metals and Alloys

Although molybdenum has been shown to form complex oxide films in sodium that provide good boundary lubrication, the metal and its alloys have shown a tendency to wear and gall significantly in friction and wear experiments. If such galling can be accepted as not seriously detrimental to long-term service, the excellent corrosion resistance of molybdenum can make it a useful material

TABLE 4
SPECIFIC WEAR OF SUPER ALLOY COMBINATIONS
IN SLIDING CONTACT IN 1200 °F SODIUM⁽²⁴⁾
(Sheet 1 of 2)

Contact pressure: 8.65 kg/cm² (123 psi).
Length of test: ~200 hr (unless stopped sooner by galling).
Environment: 1200 °F liquid sodium, except *1200 °F sodium vapor, †1000 °F liquid sodium.
HF: hard-facing. TS: tool steel.

Test No.	Material		Pin Sliding Velocities (cm/sec)	Coefficient of Sliding Resistance at Test Temperature		Average Specific Wear on Pins (cm ³ /cm ² -kg x 10 ⁻¹¹)
	Pin	Plate		Initial	Final	
2	304 SST (CRES)	Stellite-6B	5.3, 6.7, 8.0	0.40	0.57	259
3	Hastelloy-C	Stellite-6B	5.3, 6.7, 8.0	0.53	0.66	10.5
4	17-4 PH	Stellite-6B	5.3, 6.7, 8.0	0.53	-	15.9
5	17-7 PH	Stellite-6B	5.3, 6.7, 8.0	0.84	-	288
6	Stellite-6B	Stellite-6B	5.3, 6.7, 8.0	0.68	0.84	20.0
14	Stellite-6B	Stellite-6B	5.3, 6.7, 8.0	0.40	0.67	9.4
22	Molybdenum	Stellite-6B	5.3, 6.7, 8.0	0.32	-	3.6
37	TZM	Stellite-6B	5.3, 6.7, 8.0	0.59	0.90	Material Buildup
46	Tungsten	Stellite-6B	2.3, 3.0, 3.5	0.33	0.33	5.15
50	Stellite-3	Stellite-6B	2.3, 3.0, 3.5	0.31	0.35	5.73
56	Stellite-273(HF)	Stellite-6B	3.1, 3.9, 4.7	0.31	0.24	14.0
62	Stellite-1(HF)	Stellite-6B	3.1, 3.9, 4.7	0.36	0.50	5.73
68	Colmonoy-4(HF)	Stellite-6B	3.1, 3.9, 4.7	0.30	0.40	125.6
72	Inconel-718	Stellite-6B	3.1, 3.9, 4.7	0.18	0.26	3.87
81†	Rex-49 (TS)	Stellite-6B	3.1, 3.9, 4.7	0.51	2.07	Material Buildup
90	Stellite Star-J	Stellite-6B	3.1, 3.9, 4.7	0.20	0.21	4.80
57	Stellite-273(HF)	Stellite-1(HF)	3.1, 3.9, 4.7	0.30	0.28	6.79
58	Stellite-6H(HF)	Stellite-6H(HF)	3.1, 3.9, 4.7	0.42	0.40	9.74
59	Stellite-273(HF)	Stellite-273(HF)	3.1, 3.9, 4.7	0.36	0.29	32.5
75	Hastelloy-C	Stellite-6H(HF)	3.1, 3.9, 4.7	0.36	0.82	116.1
86	Stellite-1016(HF)	Stellite-273(HF)	3.1, 3.9, 4.7	0.31	0.33	14.20
87	Tungsten	Stellite-1(HF)	3.1, 3.9, 4.7	0.37	0.41	Material Buildup
88	Stellite-3	Stellite-6H(HF)	3.1, 3.9, 4.7	0.50	0.35	4.58
92	TZM	Stellite-273(HF)	3.1, 3.9, 4.7	0.15	0.31	Material Buildup
93	Inconel-718	Stellite-6H(HF)	3.1, 3.9, 4.7	0.15	0.31	3.46
28*	Stellite-6B	Stellite-6B	5.3, 6.7, 8.0	0.36	-	12.8
7	Hastelloy-C	Hastelloy-C	5.3, 6.7, 8.0	0.58	0.65	Material Buildup
9	Stellite-6B	Hastelloy-C	5.3, 6.7, 8.0	0.23	0.46	2.2
10	Molybdenum	Hastelloy-C	5.3, 6.7, 8.0	0.36	0.41	Material Buildup
11	AISI-TI(TS)	Hastelloy-C	5.3, 6.7, 8.0	0.48	0.53	6.7
23	Tungsten	Hastelloy-C	5.3, 6.7, 8.0	0.25	-	4.7
36	Rex-49(TS)	Hastelloy-C	5.3, 6.7, 8.0	0.34	0.32	38.7
38	Stellite-3	Hastelloy-C	5.3, 6.7, 8.0	0.37	0.32	7.15
41	Tungsten	Hastelloy-C	5.3, 6.7, 8.0	0.29	0.42	2.88
51	TZM	Hastelloy-C	2.3, 3.0, 3.5	0.27	0.34	2.98
52	17-4(PH)	Hastelloy-C	2.3, 3.0, 3.5	0.29	0.37	401.0
63	Inconel-718	Hastelloy-C	3.1, 3.9, 4.7	0.27	0.33	25.25

TABLE 4
SPECIFIC WEAR OF SUPER ALLOY COMBINATIONS
IN SLIDING CONTACT IN 1200 °F SODIUM
(Sheet 2 of 2)

Test No.	Material		Pin Sliding Velocities (cm/sec)	Coefficient of Sliding Resistance at Test Temperature		Average Specific Wear on Pins (cm ³ /cm ² -kg x 10 ⁻¹¹)
	Pin	Plate		Initial	Final	
65	Stellite-273(HF)	Hastelloy-C	3.1, 3.9, 4.7	0.35	0.40	Material Buildup 1.28 0.43 1.07 50.4
78	Stellite-1016(HF)	Hastelloy-C	3.1, 3.9, 4.7	0.33	0.33	
79	Stellite-6B(HF)	Hastelloy-C	3.1, 3.9, 4.7	0.29	0.36	
80	Stellite Star-J	Hastelloy-C	3.1, 3.9, 4.7	0.29	0.30	
29*	Hastelloy-C	Hastelloy-C	5.3, 6.7, 8.0	0.43	-	
42	Stellite-3	Colmonoy-75(HF)	5.3, 6.7, 8.0	0.48	0.39	4.40
43	Hastelloy-C	Colmonoy-5(HF)	5.3, 6.7, 8.0	0.38	0.56	37.6
44	Stellite-6B	Colmonoy-6(HF)	5.3, 6.7, 8.0	0.32	0.44	Material Buildup
45	17-4(PH)	Colmonoy-70(HF)	5.3, 6.7, 8.0	0.33	0.41	Material Buildup
49	Colmonoy-4(HF)	Colmonoy-5(HF)	2.3, 3.0, 3.5	0.37	0.63	25.8
53	Colmonoy-4(HF)	Colmonoy-75(HF)	2.3, 3.0, 3.5	-	0.35	80.5
61	Colmonoy-6(HF)	Colmonoy-75(HF)	3.1, 3.9, 4.7	0.37	0.28	39.2
60	Inconel-718	Inconel-718	3.1, 3.9, 4.7	0.29	0.25	7.95
64	Hastelloy-C	Inconel-718	3.1, 3.9, 4.7	0.25	0.45	18.56
73†	Rex-49(TS)	Inconel-718	3.1, 3.9, 4.7	0.31	0.83	21.25
74	Molybdenum	Inconel-718	3.1, 3.9, 4.7	0.95	-	Galled
82	TZM	Inconel-718	3.1, 3.9, 4.7	0.25	0.36	2.19
91	Stellite-1016(HF)	Inconel-718	3.1, 3.9, 4.7	0.27	0.36	7.25
95	Tungsten	Inconel-718	3.1, 3.9, 4.7	0.31	0.31	16.08
21	Stellite-3	K-162B	5.3, 6.7, 8.0	0.32	0.36	Material Buildup 2.9 7.30 75.4 19.8 34.0 2.76 6.55 10.03 3.69 10.40
24	Hastelloy-C	K-95	5.3, 6.7, 8.0	0.57	0.47	
47	Stellite-6B	K-95	2.3, 3.0, 3.5	0.46	0.89	
48	Colmonoy-6(HF)	K-95	2.3, 3.0, 3.5	0.61	0.83	
54	Stellite-1(HF)	K-95	3.1, 3.9, 4.7	0.50	0.53	
55	Stellite-6H(HF)	K-95	3.1, 3.9, 4.7	0.50	0.61	
70	Inconel-718	K-95	3.1, 3.9, 4.7	0.49	1.50	
71	Stellite-1016(HF)	K-95	3.1, 3.9, 4.7	0.44	1.34	
84	Stellite Star-J	K-95	3.1, 3.9, 4.7	-	0.74	
85†	Stellite-6B	K-95	3.1, 3.9, 4.7	0.40	0.28	
94	Stellite-3	K-95	3.1, 3.9, 4.7	0.31	0.56	
96	Stellite Star-J	Tungsten	3.1, 3.9, 4.7	0.61	0.41	2.81
89	Stellite Star-J	Molybdenum	3.1, 3.9, 4.7	0.94	0.66	3.27
97	Stellite-6B	TZM	3.1, 3.9, 4.7	0.34	0.32	20.80
83	Inconel-718	TZM	3.1, 3.9, 4.7	0.33	0.49	4.02
8	Stellite-6B	AISI-M1(TS)	5.3, 6.7, 8.0	0.43	-	Galled & welded

in high temperature sodium. It appears that its more important use will be as the preferred bonding agent for high-temperature bonded carbides.

Tungsten, on the other hand, shows consistently good friction and wear performance if the mating material is chosen to be very hard and wear resistant. Within its fabrication limitations, tungsten may be used successfully for a great many combinations of temperature, load and sliding speed.

a. Item No. 1

Vail's⁽¹⁷⁾ early testing of potential bearing materials included only molybdenum from the refractory metal group. No estimate of the chemistry of the sample used was given. He found fairly satisfactory compatibility when tested at 350°F with cobalt-bonded tungsten carbide, but some surface wear was apparent. At 600°F and 850°F and higher loads, the friction, wear and surface damage increased rapidly.

b. Item No. 2

The frictional behavior between sliding-contact specimens was studied by Kissel et al.,^(4,5) in argon and with molten sodium at the interface using molybdenum, tungsten and carbides. With molybdenum sliding on molybdenum, it was observed that friction was generally lower and surface damage much less severe when sodium was present, compared with dry sliding.

The test parameters used were as follows:

Type of Test:	Fixed loaded ball bearing riding on flat plate moving linearly back and forth
Environment:	Sodium
Temperature:	500 to 1200°F
Sliding Speed:	0.04 ft/min
Load:	80,000 psi
Time:	Not given.

The observed behavior suggested that strongly adsorbed surface films were influencing frictional behavior significantly. Thermodynamic considerations indicated that the formation of a sodium-molybdate film on molybdenum (granting

the presence of oxygen) was likely, and that the film would be stable over a wide temperature range.

The lubricating ability of molybdate films prompted interest in tungsten, and the frictional behavior of sodium-lubricated tungsten was found to be quite similar to that exhibited by molybdenum.

The concept of lubrication by molybdenum and tungsten complex oxide films in sodium has been extended to the investigation of alloys containing these two metals. The expectation is that such alloying will improve the friction and wear characteristics in sodium of a material with other desirable bearing characteristics.

c. Item No. 3

Sarnecki⁽²⁵⁾ reports a test of gears and sleeve-type bearings in 1200°F sodium. Meshing gears and journal bearings turned on the same shaft at very slow speeds (about 1-1/2 ft/min) for times up to 3000 hr, with total exposure to 1200°F sodium reaching 5000 hr. The gear and bearing were loaded up to 75 lb but no estimate of unit loading was made. Complete tests results are given in Tables 2 and 3.

The best bearing combination tested was Hastelloy-C turning on molybdenum; some galling and scoring was noted at the end of testing but it was concluded that performance had not been adversely affected by this damage. Total operating time was 2300 hr. Later work reported by Amateau⁽²⁷⁾ showed that Hastelloy-C also exhibited reduced damage in sliding in sodium compared with argon. Sarnecki comments that without a preoperational soaking period of up to 100 hr in 1200°F sodium, immediate seizure resulted in several tests.

The results indicate that the complex oxide needs a finite time to form in such a system, and that once formed it is effective for significant operating times.

TZM alloy tested by Sarnecki was not as successful as the unalloyed molybdenum; no opinion is hazarded as to the reason for this.

d. Item No. 4

In developing a high-pressure, high-temperature 10-stage centrifugal pump for NaK, friction and wear studies were made of several bonded carbides judged

to have the best potential. One test of a bonded carbide running on a molybdenum-1/2 titanium alloy was reported⁽²⁸⁾ in this series. This combination (Kenna-metal K-84 rotating on Mo-0.5Ti) showed both lower wear and a lower friction coefficient (0.094) than the pairs of bonded carbides tested. No further reporting on the combination in this program was found.

The test parameters used were as follows:

Type of Test: Modified Falex, fixed, loaded, opposed, full-conforming blocks held against rotating cylinder.

Environment: NaK (77% K)

Temperature: 1200°F nominal

Sliding Speed: 262 ft/min, time: 300 min

Load: 600 psi initial; 130 to 220 psi at end of test, as determined from area of wear scar.

e. Item No. 5

In a program directed at evaluating materials for potassium-lubricated bearings operating up to 1600°F, unalloyed tungsten and TZM (Mo-0.5Ti-0.08Zr-0.02C), both arc-cast/stress relieved, were tested in static corrosion capsules of Nb-1Zr alloy for 1000 hr at 800, 1200, and 1600°F.^(7,8) Metallographic examination of all specimens revealed no significant changes in microstructure as a result of the exposure to potassium liquid or vapor. No corrosion was found by weight measurements. Excellent corrosion resistance to liquid metals, perhaps the best of all material classes considered here, is one of the most significant advantages of the refractory metal.

f. Item No. 6

Freed⁽²⁴⁾ conducted an extensive series of screening tests to develop comparative friction and wear data on several material classes. Test parameters used were as follows:

Type of Test: Fixed pins bearing on loaded rotating plate

Environment: Sodium

Temperature: 1200°F

Sliding Speed: 5 to 16 ft/min

Load: 123 psi

Time: ~200 hr.

The test data on couples with one or more refractory metals or alloys in liquid sodium at 1200°F are given in Table 5. Molybdenum and TZM pins showed extremely heavy wear on tungsten plates and performed erratically on super alloy plates. Molybdenum pins on Stellite-6B plate gave very good performance, but TZM pins on the same plate and on Stellite-273(HF) plate performed badly. Molybdenum pins on Hastelloy-C, Inconel-718, and tool steel plates performed badly, but TZM pins on the same plates performed very well.

3. Carbides

The ready commercial availability and improved resistance to brittle failure of bonded carbides over pure carbides has reduced interest in and need for development of pure carbide bearing materials. In an early screening test^(29,30) carbides of titanium, zirconium, and chromium showed no attack after exposure to 1500°F static sodium for 100 hr. The materials were similarly resistant to 1500°F static lithium. In a General Electric program to develop materials for potassium-lubricated bearings,⁽⁷⁾ carbides of titanium, zirconium, and tantalum were carried only through the first static corrosion screening test, with the expected excellent results. They were not selected for further testing in corrosion couples or friction/wear tests.

4. Bonded Carbides

The earliest materials investigation reported⁽¹⁶⁾ was a broadly based low-temperature-NaK screening of several dozen materials judged to be potentially useful as bearing materials in liquid metals. Qualitative evaluation of the results showed that the material with the widest degree of compatibility with itself and other materials was Carboloy (tungsten carbide with a cobalt binder). Fourteen years later, in surveying materials for 1000°F service in lithium, it was noted⁽¹¹⁾ that refractory-metal-bonded carbides probably held the best potential as materials for alkali metal lubricated journal bearings. The resulting experimental program reported⁽¹¹⁾ that the best compatibility and wear characteristics were exhibited by high-density, molybdenum-bonded tungsten carbides. Discussion of these and other test results follows.

TABLE 5
SPECIFIC WEAR TEST RESULTS FOR REFRACTORY METALS⁽²⁴⁾

Test No.	Pin Material	Plate Material	Coefficient of Sliding Friction	Specific Wear On Pins, Average (cm ³ /cm/kg x 10 ⁻¹¹)
35	Molybdenum	Rex 49(TS)	-	Galled and welded
10	Molybdenum	Hastelloy-C	0.35	Material buildup
22	Molybdenum	Stellite-6B	0.32	3.6
33	Molybdenum	Tungsten(PS)	0.45	213
39	Molybdenum	Tungsten	0.54	1088
74	Molybdenum	Inconel-718	0.95	Galled
40	TZM	Tungsten	0.65	936
32	TZM	Tungsten(PS)	0.34	215
51	TZM	Hastelloy-C	0.32	2.98
37	TZM	Stellite-6B	0.63	Material buildup
77*	TZM	Rex-49(TS)	0.44	6.37
82	TZM	Inconel-718	0.36	2.19
92	TZM	Stellite-273(HF)	0.31	Material buildup
46	Tungsten	Stellite-6B	0.36	5.15
23	Tungsten	Hastelloy-C	0.29	4.7
41	Tungsten	Hastelloy-C	0.33	2.9
87	Tungsten	Stellite-1(HF)	0.41	Material buildup
95	Tungsten	Inconel-718	0.31	16.1

*This test at 1000°F.

TS = tool steel, HF = hard faced, PS = plasma sprayed

a. Item No. 1

Vail⁽¹⁶⁾ tested about 90 different combinations of materials being considered for sodium-lubricated bearing applications under boundary lubrication conditions. He concluded that at 350°F the combinations containing Carboloy and another very hard material performed best. He later extended the work to include many more material combinations and higher test temperatures, up to 950°F.⁽¹⁷⁾ He again concluded that the bonded tungsten carbides and titanium carbides gave the best results. In all, some 13 combinations of tungsten and titanium carbides, with varying amounts of cobalt and nickel binder, were found to have negligible wear or material transfer at 850°F in NaK.

The test parameters used were as follows:

Type of Test:	Fixed loaded pin (0.312-in. dia) held against rotating sleeve
Environment:	NaK (56% K) liquid
Temperature:	350 to 950°F
Sliding Speed:	450 ft/min
Load:	34 lb/pin, equivalent to 15,000 psi as test starts with line contact, decreasing as wear increases the contact area
Time:	205 min.

To evaluate the results, the final surface finish of both specimens was measured, and the total wear of both specimens was checked by a micrometer or dial gage. A qualitative, comparative evaluation of the performance was made by dividing the material combinations into five groups.

Group 1 — negligible wear, no apparent material transfer, both specimens polished

Group 2 — smooth wear of fixed pin, polishing of rotating sleeve, no apparent material transfer

Group 3 — smooth wear of either specimen, minor material transfer

Group 4 — excessive wear, or surface roughening, or material transfer

Group 5 — failed to complete the test.

Vail's comments on the performance of the general bonded carbide classes follow.

Cobalt-bonded porous tungsten carbide indicated Group 1 or 3 performance, with a lower friction coefficient against bonded titanium carbide; recommended for oscillating-motion bearings where porosity might allow embedding of wear products.

Cobalt-bonded tungsten carbides showed excellent performance in the 350°F tests, but the compatibility of the Carboloy-55A — Carboloy-779 pair decreased as temperature increased going from Class 1 at 350°F to Class 5 at 950°F. Decreasing the amount of cobalt binder tended to improve the 850°F performance, and the testing of the high-cobalt-content Carboloy-190 showed comparatively high friction, wear and material transfer. Thus, the lower the amount of cobalt binder, the less the tendency for superficial damage.

At about the same time, Coffin⁽¹⁴⁾ suggested that the wear resistance of a cobalt- or nickel-bonded tungsten carbide bearing surface depended on the solubility of the material rubbing against it in the carbide and in the bonding agent. The higher the solubility the higher the damage was expected to be; and since materials were generally more soluble in the bonding agent than in the tungsten carbide, higher wear was to be expected as the amount of bonding agent was increased. The superior performance of mixed titanium carbide-tungsten carbide-cobalt bonded cutting tools was explained by showing that less free cobalt was present in the mixed carbide product than in the tungsten carbide product.

Cobalt-bonded tungsten-tantalum carbide (Carboloy-907, -77B) showed excellent compatibility properties, particularly with the high-cobalt Kennametal-K-12.

Cobalt-bonded tungsten-tantalum-titanium carbides, when tested with similar or tungsten carbide cermets, showed good wear resistance but with high friction coefficients.

Cobalt-bonded titanium carbides tended to spall or pick up material when run against a similar material, but gave excellent results in combination with low-cobalt tungsten carbide cermets.

Iron-bonded titanium carbides gave excellent results against Carboloy-779.

Nickel-bonded titanium carbides, in combination with tungsten carbide cermets, gave highly satisfactory results.

Nickel-bonded titanium-molybdenum carbide gave best results against itself or a nickel-bonded titanium carbide, or a tungsten-tantalum-titanium carbide.

Cobalt-bonded chromium carbide was the only class not to show promising behavior in these tests. All of the combinations fell into Group 4 or 5, showing galling and wear.

The material pairs including at least one bonded carbide that showed Group 1 performance are listed in Table 6 with temperature as a parameter. It is to be emphasized that at 600°F and above, the only combinations in the whole test program exhibiting Group 1 performance were pairs of bonded carbides. Average coefficients of sliding friction are given for some combinations.

b. Item No. 2

The corrosion resistance of bonded titanium carbides was determined⁽³¹⁾ in 930°F sodium.

The test parameters used were as follows:

Type of Test:	Static and dynamic corrosion
Environment:	Sodium
Temperature:	930°F
Sliding Speed:	Not applicable
Load:	Not applicable
Time:	1 mo.

Pin specimens of four bonded titanium carbides, Kennametal K-138A, K-151A, K-161B, and K-162B were tested. There was no change in surface appearance and metallographic examination showed that no pitting or intergranular attack had occurred. The corrosion rates (0.05 static, 0.3 dynamic, mg/cm²/mo) were of the same order of magnitude as those determined previously for Carboloy-55A and 779.

TABLE 6
MATERIAL PAIRS WITH CLASS 1 PERFORMANCE^(16,17)

Fixed (Pin) Specimen	Rotating (Sleeve) Specimen	Temperature (°F)	Average Coefficient of Friction
Carboloy-55A	Carboloy-779	350	-
6-6-2 HSTS	Carboloy-779	350	-
17/4 PHSS	Carboloy-779	350	-
18-4-1 HSTS	Carboloy-779	350	-
Stellite-J	Carboloy-779	350	-
Kentanium-20 Fe/80 TiC	Carboloy-779	600	-
Kentanium K-138	Carboloy-779	600	-
Kentanium K-138	Kentanium K-138	600	-
Kentanium K-138A	Carboloy-779	800	-
Carboloy-44A	Carboloy-44A	850	0.36
Carboloy-X304OD	Carboloy-44A	850	0.46
Carboloy-907	Carboloy-907	850	0.36
Carboloy-44A	Sintercast WF-87	850	0.29
Kentanium 20 Fe/80 TiC	Carboloy-779	850	-
Kentanium K-151	Carboloy-779	850	-
Carboloy-907	Sintercast WF-87	850	0.44
Carboloy-831	Firthite HT-77	850	0.20
Kentanium-K-151	Firthite HT-77	850	-
Kentanium-K-12	Carboloy-77B	850	0.25
Carboloy-X304OD	Carboloy-X304OD	850	0.45
Kentanium K-138	Carboloy-X304OD	850	0.29
Kentanium K-152B	Kentanium K-138A	850	-
Kentanium K-138	Carboloy-779	900	-

c. Item No. 3

The corrosion resistance of bonded carbides of titanium, tungsten, and silicon was determined^(29,30) in screening tests at 1500° F in sodium and in lithium.

The test parameters used were as follows:

Type of Test:	Static and tilting-capsule corrosion
Environment:	Sodium
Temperature:	1500° F
Sliding Speed:	Not applicable
Load:	Not applicable
Time:	100 hr.

The extent and nature of corrosion was determined by weight and dimensional changes, and metallographic examinations; the latter was usually the most important phase of the overall evaluation. The results are summarized in the following figure. Silicon carbide impregnated with silicon showed heavy attack because of removal of the silicon; the silicon carbide grains were not attacked. The bonded tungsten carbides were not attacked. The nickel-bonded titanium carbides were slightly attacked, predominately by solution of the nickel phase. The one chromium carbide cermet tested was not attacked.

d. Item No. 4

A series of rubbing friction tests was conducted⁽²¹⁾ to determine the most suitable materials for bearings in a 50-hp sodium pump. The test parameters were chosen to simulate boundary lubrication conditions. The performance was evaluated by measuring surface finish before and after each test, by recording the coefficient of friction during the test, and by photographing the specimens at 10X.

The test parameters used were as follows:

Type of Test:	Loaded pad, 3/8-in. square, rotating on fixed disc
Environment:	Sodium
Temperature:	~250° F
Sliding Speed:	~3 ft/min
Load:	35 psi
Time:	600 min.

The results of the test were graded as very good, good, fair or bad. Of the 300-plus combinations of materials tested, 33 were judged to be very good,

DESIGNATION	MATERIAL	CORROSION RESISTANCE			
		BAD	POOR	FAIR	GOOD
DURHY*	SiC-Si
4107-22-7 †	SiC-Si
KENTANIUM† K150A	80% TiC-10 Nb TaTiC ₃ -10 Ni
KENTANIUM† K151A	70% TiC-10 NbTaTiC ₃ -20% Ni
KENTANIUM† K152B	64% TiC-6 NbTaTiC ₃ -30% Ni
KENTANIUM† K162B	64% TiC-6 NbTaTiC ₃ -25% Ni-5% Mo
CARBOLOY* 779	91% WC-9% Co
CARBOLOY* 55A	87% WC-13% Co
CARBOLOY* 907	74% WC-20% TaC-6% Co
CARBOLOY* 608	83% Cr ₃ C ₂ -2% WC-15% Ni

*STATIC TEST
†SEESAW TEST

TYPE OF DATA	ARBITRARY CORROSION RATINGS AND DATA RANGE BASES			
	BAD	POOR	FAIR	GOOD
DEPTH OF ATTACK (mils*)	3	2	1	0
WEIGHT CHANGE (%)†	6	4	2	0
DIMENSIONAL CHANGE (%)	3	2	1	0
*MEASURED IN METALLOGRAPHIC EXAMINATIONS. †DETERMINED BY DIRECT MEASUREMENT AND/OR BY CALCULATIONS BASED ON THE MATERIAL(S) FOUND IN THE TEST MEDIUM BY CHEMICAL ANALYSES.				

6-6-68 UNCL

7694-4730

Corrosion Resistance of Bonded Carbides Tested in
1500°F Sodium for 100 hr^(29,30)

and 24 of these included a bonded carbide as one material. The marked superiority of this class, even under the mild environment of the tests, is apparent.

Exact compositions of all the bonded carbides were not given, apparently because at the time the materials were proprietary. Tungsten carbides bonded with less than 10% cobalt and less than 20% cobalt were used, some with additions of titanium carbide. Several compositions of nickel-bonded titanium carbide modified with niobium carbide and chromium carbide were also tested. The second material in the successful pair ranged from tool steel and stainless steel through Stellites to bonded carbides. Stainless steels, notorious for self-welding behavior in sodium, can apparently be used in the boundary lubrication devices under the moderate conditions of this test if the mating material is a bonded carbide.

e. Item No. 5

In conducting a program to develop NaK-77 as a high-temperature power transmission fluid for aircraft, it was necessary to build a high-temperature, high-pressure pump to handle NaK-77 at 1000° F and 3000 psi. Depending heavily on data developed by Vail,⁽¹⁷⁾ tungsten and tantalum carbides were chosen for the pump bearings and rotating assembly. Friction and wear studies conducted at 1000 and 1200° F⁽³²⁾ confirmed the capability of these materials to operate at the higher temperature, but it was emphasized that reliable liquid-metal-lubricated bearings operating above 1000° F were still in the development stage.

Ten material combinations were tested initially in NaK at 1000° F to determine operating characteristics of the test machine.⁽³²⁾ The ten combinations used 7 materials, Carboloy-44A, Carboloy-120, Carboloy-799, Kentanium-138, Kentanium-138A, Kentanium-151A, and Firthite HT-77. The test results were inconclusive primarily because each test lasted only 5 min. One of the best combinations appeared to be Carboloy-779 running on Kentanium-138A, but the large difference in thermal expansion coefficients made this pair impractical for the required bearing designs.

The test parameters used were as follows:

Type of Test: Modified Falex, fixed, loaded, opposed V-blocks held
against rotating cylinder

Environment: NaK (77% K)

Temperature: 1000° F

Sliding Speed: ~150 ft/min

Load: 5,000 to 11,000 psi (at end of test, as determined from
area of wear scar)

Time: 5 min.

The combination of Carboloy-779/Kennametal-138A was selected for further testing in the same equipment, together with two new combinations chosen from a materials review, Kennametals K-91 and K-84 running on Kentanium K-138A.

The test parameters used were as follows:

Type of Test: Modified Falex, fixed, loaded, opposed V-blocks held against rotating cylinder

Environment: NaK (77% K)

Temperature: 1000°F

Sliding Speed: ~150 ft/min

Load: 1100 to 1700 psi (at end of test, as determined from area of wear scar)

Time: 360 min.

The results of four tests⁽³³⁾ are given in Table 7.

TABLE 7
FRICTION/WEAR TESTING OF BONDED CARBIDES⁽³³⁾

Run	Fixed Specimen	Rotating Specimen	Load (lb)	Coefficient of Sliding Friction	Wear Scar Area on One V-Block (in. ²)	Final Bearing Load (psi)
M-11	Kentanium-138A	Carboloy 779	96.5	0.229	0.056	1215
M-12	Kentanium-138A	Carboloy 779	96.5	-	0.055	1240
M-13	Kentanium-138A	Kennametal K-91	96.5	0.129	0.062	1090
M-14	Kentanium-138A	Kennametal K-84	96.5	0.165	0.039	1735

The material pair judged to have the best combination of wear scar finish, load-carrying capability and coefficient of sliding friction was K-84 running on K-138A. These materials were recommended for use in the pump gears, shafts and bearings. It was noted that each of these tests produced some material flow, causing a feathered surface to be raised on the trailing edge of the wear scar on each V-block. The feather was found to be almost entirely cobalt,

assumed to have been "wiped" from the bearing surface, with large traces of iron from an unexplained source, perhaps system mass transfer. Such severe material flow raised the question of how well these materials could perform if long-time service were required; at this temperature reduced loading would undoubtedly be necessary.

Further consideration was given to the problem of fabricating complex parts of bonded carbides with thermal expansion coefficients so much lower than conventional structural materials such as stainless steels. It was decided⁽²⁸⁾ to test flame-sprayed bonded carbides on René-41 as the rotating member in the modified Falex test.

The test parameters used were as follows:

Type of Test:	Modified Falex, fixed, loaded, opposed, full-conforming blocks held against rotating cylinder
Environment:	NaK (77% K)
Temperature:	1200°F nominal
Sliding Speed:	262 ft/min
Load:	600 psi initial; 130 to 220 psi at end of test, as determined from area of wear scar
Time:	300 min.

The test results are summarized in Table 8. It was concluded that flame-plated carbides were not entirely satisfactory in this application; all specimens exhibited considerable scoring and material transfer. Further analysis indicated that less-than-adequate precautions had been taken in preparing the substrate metal, applying the coating, and grinding the coating to final dimensions. Mechanical damage may have been responsible for the coatings' poor performance, rather than friction and wear. This emphasizes the importance that proper fabrication and design practices will have in procuring a satisfactory liquid metal bearing using bonded carbide applied to a substrate metal.

One other test was run in this series, Kennametal K-84 running on molybdenum - 0.5% titanium alloy. This combination showed both the lowest wear area and the lowest friction coefficient in this test series. Both specimens

TABLE 8
WEAR TESTS OF FLAME-SPRAYED BONDED CARBIDES⁽²⁸⁾

Fixed Specimen	Rotating Specimen	Coefficient of Sliding Friction	Average Wear Scar Area (in. ²)	Final Bearing Load (psi)	Temperature (°F)
Haynes-25	Linde LW-5*	0.189	0.327	130	1000 to 1240
Haynes-25	Linde LW-1*	0.195	0.262	163	1190 to 1260
Ferro-TiC J	Linde LW-5*	0.316	0.196	217	1035 to 1250
Kennametal K-138	Linde LW-1*	0.335	0.299	143	1080 to 1160
Mo-0.5 Ti	Kennametal K-84	0.094	0.140	304	1080 to 1175

*Flame sprayed coating on René-41

had a plated appearance with definite material transfer. This promising test indicated further work with molybdenum alloys could be rewarding.

f. Item No. 6

In a program directed at evaluating materials for potassium-lubricated bearings operating over a 400 to 1600°F range, 14 materials were selected.⁽³⁴⁾ Seven of these materials were bonded carbides, as follows: Carboloy-907 and -999, Kennametal K-601, and four unnamed proprietary materials, TiC + 5%W, TiC + 10%Nb, TiC + 10%Mo, and Grade 7178. Corrosion testing of these materials in potassium, in Nb-1Zr alloy capsules, was reported.^(7,8,35)

The test parameters used were as follows:

Type of Test:	Static Corrosion
Environment:	Potassium
Temperature:	800, 1200, and 1600°F
Sliding Speed:	Not applicable
Load:	Not applicable
Time:	1000 hr.

The bonded carbides all showed excellent resistance to static potassium. The Nb-1Zr alloys that contained the Carboloy-907, Carboloy-999 and Grade 7178 specimens in the 1600°F test all showed a significant increase in carbon content. Niobium carbide was detected on the capsule surface, complex cobalt-tungsten carbides and free tungsten were found on the specimen surface. Thermodynamically, tungsten carbide is less stable than niobium carbide and mass transfer of carbon through the potassium to the capsule was not unexpected. Some carbon transfer was found in tests of these materials at 1200°F but the amount was significantly less. Essentially, no transfer of carbon was observed to have occurred at 800°F.

Visual and metallographic examination of the seven bonded carbides is summarized as follows:

- 1) TiC + 10% Mo; TiC + 10% Nb; TiC + 5% W: no change in microstructure or surface at any of the three test temperatures.
- 2) K-601: no change in microstructure or surfaces at 800 or 1200°F; some surface roughening at 1600°F.
- 3) Grade 7178: no change in microstructure at 800 or 1200°F; some carbon transfer at 1200°F, significant carbon transfer at 1600°F; no corrosion reactions at any temperature.
- 4) Carboloy-907, Carboloy-999: no change in microstructure at 800 or 1200°F; some carbon transfer at 1200°F, significant carbon transfer at 1600°F; slight surface roughening at 1200°F, slight surface attack to depth of less than 0.001 in. at 1600°F.

Apparently the bonded titanium carbides are superior to the bonded tungsten carbides in long time stability in a system where a potential carbon sink (the niobium alloy capsule wall) and transfer medium (liquid metal) exist. This stability should be considered for such applications at and above 1200°F; bearing surfaces are small compared with containment alloy surfaces in liquid metal systems, and decarburization by mass transfer could be quickly detrimental to bearing surfaces.

Seven combinations of these bonded carbides with TZM and with each other were selected⁽³⁶⁾ for proposed friction and wear testing in high-temperature

potassium. The decision to place considerable emphasis on the refractory-metal-bonded carbides was based on their excellent high temperature stability. Rubbing combinations of hard vs soft and hard vs hard materials were chosen to compare the performance of the two combinations. Preliminary results of this test program have been published.⁽³⁷⁾ One significant finding was that friction/wear tests in 400°F potassium showed much lower coefficients of friction than comparable tests in high vacuum; the average coefficient for TiC + 10% Nb against itself at 400°F was calculated as 0.07.

g. Item No. 7

The compatibility and wear characteristics of selected bearing materials were investigated⁽¹¹⁾ for use in lithium and NaK systems in support of the SNAP 50/SPUR pump development program. Twenty-two bonded carbides were corrosion tested in 1100°F lithium in tilting capsules for times up to 7000 hr. The wear behavior of 12 of these materials (both rubbing surfaces were the same material) was then investigated in 32 tests at varying loads, speeds and temperatures (600 to 1000°F) in lithium and NaK (78% K).

The conclusions were summarized as follows:

- 1) Molybdenum-bonded carbides of tungsten, niobium and titanium showed excellent compatibility with 1100°F lithium.
- 2) Cobalt-bonded tungsten carbides were compatible with 1100°F lithium if their cobalt content was 3 to 5%, but were subject to significant solution corrosion if their cobalt content was 8 to 25%.
- 3) Nickel-bonded carbides of tungsten and titanium showed poor compatibility with 1100°F lithium because of solution corrosion for specimens containing 4 to 25% nickel.
- 4) Nickel-bonded carbides showed satisfactory wear resistance in NaK, but were unsatisfactory in lithium, as was expected from the lithium compatibility tests. Molybdenum-bonded and cobalt-bonded carbides showed excellent wear resistance in lithium and NaK.

The compatibility test parameters used were as follows:

Type of Test: Tilting-capsule corrosion
Environment: Lithium
Temperature: 1100°F
Sliding Speed: Not applicable
Load: Not applicable
Time: 700 hr (samples also examined at 500 and 2000 hr).

Complete results of the compatibility tests are reproduced in Table 9. The refractory bonded tungsten carbides showed detectable weight changes that increased with increasing time. Metallographic analysis (Table 10) did not detect any lithium attack, and the weight loss was attributed to carbon mass transfer to the Nb-1Zr alloy capsule. Since no free tungsten was detected at the specimen surface, it was concluded that this amount of carbon transfer would not affect bearing performance. The molybdenum-bonded carbides of niobium and titanium did not exhibit carbon transfer.

For cobalt-bonded tungsten carbides with cobalt concentrations below 5.55%, no lithium corrosion was detected metallographically. Lithium attack, with decrease in surface hardness, was displayed in higher cobalt content materials. None of the nickel-bonded carbides was completely corrosion resistant, although the degree of attack may not have been serious.

The wear and friction test parameters used were as follows:

Type of Test: Modified Falex, fixed, loaded, opposed shoes (either flat or fully conforming) held against rotating disc
Environment: NaK (78% K) or lithium
Temperature: 600, 700, or 1000°F
Sliding Speed: 36 to 268 ft/min
Load: up to 41,000 psi with flat shoe, up to 3500 psi with fully-conforming shoe
Time: ~20 hr.

TABLE 9
COMPATIBILITY DATA: BONDED CARBIDES IN LITHIUM AT 1100°F⁽¹¹⁾
(Sheet 1 of 2)

Material	Source	Test Medium	500 hr				2000 hr				7000 hr			
			Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)	Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)	Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)
Mo-CbC	CANEL	argon lithium*	+0.025	+0.016	Nil	-	-0.012	Nil	-0.046	13	+0.037	Nil	-0.368	5
			-0.074	Nil	Nil	-	-0.037	+0.046	+0.069	5	Nil	Nil	-0.160	5.5
WC-Mo-CbC	CANEL	argon lithium	-0.016	Nil	-0.022	1.5	-0.016	Nil	Nil	1.1	-0.016	+0.041	-0.089	0.6
			-0.032	-0.020	Nil	1.4	+0.063	-0.176	-0.043	2	-0.586	+0.041	+0.086	1.4
K-7178	Kennametal	argon lithium	-0.023	Nil	Nil	6	-0.011	Nil	Nil	3	-0.067	+0.157	Nil	5
			-0.067	Nil	Nil	5	-0.302	+0.013	+0.030	5	-0.481	+0.039	+0.148	4
K-601	Kennametal	argon lithium	+0.022	+0.026	+0.030	3	-0.034	-0.025	-0.089	2	+0.112	Nil	Nil	3
			+0.045	-0.026	+0.027	3.5	-0.078	-0.039	-0.059	1.5	-0.19	+0.026	Nil	3
TiC-10 Mo	Kennametal	argon lithium	-0.011	-0.053	-0.089	2	-0.011	+0.027	+0.030	3	-0.034	-0.040	+0.149	4
			-0.034	-0.040	-0.059	2	-0.023	+0.053	+0.089	4	-0.045	+0.011	-0.119	2.5
K-11	Kennametal	argon lithium	Nil	-0.026	-0.030	2.5	+0.079	-0.013	Nil	5	-0.045	+0.039	+0.089	4
			-0.146	-0.026	-0.030	2	-0.135	-0.065	-0.059	5	-0.535	+0.091	+0.119	3
Carboloy-999	G.E.	argon lithium	-0.011	Nil	Nil	7	Nil	Nil	-0.296	9	-0.091	Program terminated		
			-0.160	Nil	Nil	5	-0.331	-0.780	-0.590	12	-0.570			
K-8	Kennametal	argon lithium	-0.080	+0.039	Nil	6	-0.103	-	-	3	-0.080	Program terminated at 5773 hr		
			-0.275	-0.080	-0.150	5	-0.332	-	-	5	-0.470			
Carboloy-905	G.E.	argon lithium	-0.024	-0.040	-0.119	10	-0.024	-0.013	-0.24	10	-0.125	Program terminated		
			-0.238	-0.080	-0.150	9	-0.226	-0.119	+0.18	8	-0.580			
K-96	Kennametal	argon lithium	-	-	-	-	-	-	-	-	+0.112	Nil	+0.060	2.5
			-0.175	-0.027	-0.089	2.3	-0.238	Nil	Nil	2	-0.325	-0.013	+0.030	2
Carboloy-44A	G.E.	argon	+0.056	Nil	Nil	9	-0.124	+0.026	+0.089	8	+0.147	-0.026	-0.030	Program terminated at 5910 hr
			-0.192	Nil	-0.030	9	-0.350	+0.066	+0.060	9	-0.980	+0.013	+0.030	
Carboloy-907	G.E.	argon	-0.023	-0.013	Nil	5.5	+0.045	-0.026	Nil	12	-0.114	+0.026	-0.119	Program terminated at 5886 hr
			-0.226	-0.026	Nil	10	-0.273	+0.013	+0.059	8	-1.27	+0.026	-0.119	

TABLE 9
COMPATIBILITY DATA: BONDED CARBIDES IN LITHIUM AT 1100 °F
(Sheet 2 of 2)

Material	Source	Test Medium	500 hr				2000 hr				7000 hr			
			Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)	Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)	Weight Change (mg/cm ²)	Length Change (%)	Width Change (%)	Surface Finish (μin./in.)
Carboloy-78	G. E.	argon	-0.089	-0.013	Nil	10	-0.011	-0.130	+0.059	10	-0.101	-0.039	Nil	8
		lithium	-0.448	-0.026	-0.059	10	-0.515	-0.130	+0.089	8	-0.895	-0.117	Nil	9
K-86	Kennametal	argon	-	-	-	-	Nil	Nil	Nil	6	-0.011	+0.053	Nil	Program terminated at 5404 hr
		lithium	-	-	-	-	-2.38	Nil	Nil	6	-3.25	Nil	Nil	
K-701	Kennametal	argon	+0.022	+0.026	+0.030	2.5	Nil	Nil	-0.089	2	+0.090	+0.040	+0.030	2.5
		lithium	+0.034	+0.238	+0.030	5.0	-0.224	-0.040	-0.089	2.5	-0.326	+0.067	+0.030	3
K-94	Kennametal	argon	-0.09	+0.039	-0.150	6.5	Incompatible	-	-	-	-	-	-	-
		lithium	-0.390	-0.052	-0.270	8.5	-	-	-	-	-	-	-	-
Carboloy-190	G. E.	argon	-0.068	+0.013	+0.030	9	Incompatible	-	-	-	-	-	-	-
		lithium	-0.756	-0.131	-0.030	10	-	-	-	-	-	-	-	-
K-801	Kennametal	argon	-0.022	+0.013	+0.059	4	Nil	-0.026	-0.059	4	Incompatible	-	-	-
		lithium	-0.555	+0.130	+0.269	3	+0.778	+0.375	+0.655	6	-	-	-	-
							Incomplete decontamination							
Carboloy-330	G. E.	argon	+0.011	Nil	-0.090	3	Incompatible	-	-	-	-	-	-	-
		lithium	-0.555	-0.013	-0.090	3.5	-	-	-	-	-	-	-	-
SP-112	Kennametal	argon	+0.034	Nil	-0.030	2	Nil	Nil	-0.060	3	Incompatible	-	-	-
		lithium	-1.15	+0.254	+0.030	-	-3.39	+0.215	+0.387	-	Cracks	-	-	-
K-151A	Kennametal	argon	-0.022	Nil	-0.060	1.0	Incompatible	-	-	-	-	-	-	-
		lithium	+1.47	+1.64	+0.92	-	Cracks	-	-	-	-	-	-	-
K-162B	Kennametal	argon	Nil	Nil	+0.087	1.3	Incompatible	-	-	-	-	-	-	-
		lithium	-14.1	+0.027	-0.060	3	-	-	-	-	-	-	-	-

*Maximum change of two lithium-exposed specimens in all materials

TABLE 10
METALLOGRAPHY OF COMPATIBILITY SPECIMENS:
BONDED CARBIDES IN LITHIUM AT 1100°F(11)
(Sheet 1 of 3)

Material	Source	Duration (hr)	Environ- ment	Phase Change in General Structure	Maximum Lithium Attack (mils)	Hardness*		Remarks
						Surface VHN	Center VHN	
Mo-CbC	CANEL		Pretest	Mo, Mo ₂ C-CbC, Mo ₂ -Cb ₂ C †		817	766	Compatible
		500	argon	None	nil	841	927	
			lithium			849	929	
		2000	argon		nil	874	883	
			lithium			707	767	
		5000	argon		nil	-	-	
			lithium			726	746	
WC-Mo-CbC	CANEL	7000	argon	Homogenizing of the (Mo-Cb)C phase which increased the porosity from 1% to 7% after 7000 hr	nil	752	825	Structurally unstable; lith- ium penetration into porosity
			lithium			810	781	
		500	argon		nil	1605	1740	
			lithium			1648	1648	
		2000	argon		nil	1265	1548	
			lithium			1524	1524	
K-7178	Kennametal	7000	argon	None	nil	1454	1438	Compatible
			lithium			1564	1693	
		500	argon		nil	1062	1564	
			lithium			1892	1839	
		2000	argon		nil	1892	1789	
			lithium			1892	1840	
K-601	Kennametal	7000	argon	None	nil	1839	1839	Compatible
			lithium			1892	1866	
		500	argon		nil	1892	1892	
			lithium			1892	1892	
		2000	argon		nil	2005	1947	
			lithium			1947	2005	
TiC-10 Mo	Kennametal	7000	argon	None	nil	2005	2005	Compatible
			lithium			2150	2150	
		500	argon		nil	2175	2125	
			lithium			2225	2225	
		2000	argon		nil	2200	2175	
			lithium			-	-	
K-11	Kennametal	7000	argon	None	nil	-	-	Compatible
			lithium			-	-	
		500	argon		nil	1971	2000	
			lithium			1995	1981	
		2000	argon		nil	1990	1970	
			lithium			1985	194	
Carboloy-999	G.E.	7000	argon	Program terminated	nil	1839	1839	Compatible
			lithium			1789	1839	
		500	argon		nil	1790	1839	
			lithium			1892	1892	
		2000	argon		nil	1896	1875	
			lithium			1839	1839	
Carboloy-999	G.E.	7000	argon	Program terminated	nil	1870	1844	Compatible
			lithium			1892	1892	
		500	argon		nil	1940	1940	
			lithium			1866	1866	
		2000	argon		nil	1839	1892	
			lithium			1814	1814	

*5-kg load unless otherwise stated

†Identified by X-ray diffraction

TABLE 10
METALLOGRAPHY OF COMPATIBILITY SPECIMENS:
BONDED CARBIDES IN LITHIUM AT 1100 °F
(Sheet 2 of 3)

Material	Source	Duration (hr)	Environ- ment	Phase Change in General Structure	Maximum Lithium Attack (mils)	Hardness*		Remarks
						Surface VHN	Center VHN	
K-8	Kennametal		Pretest			1839	1839	
		500	argon	None	nil	1892	1839	Compatible
		2000	lithium			1866	1839	
		7000	argon lithium argon lithium	Program terminated	nil	1892 1790	1789 1814	
Carboloy-905	G.E.		Pretest			1839	1897	
		500	argon	None	nil	1740	1339	Compatible
		2000	lithium			1814	1789	
		7000	argon lithium argon lithium	Program terminated	nil	1789 1693	1740 1693	
K-96	Kennametal		Pretest			1622	1606	
		500	argon	None	nil	-	-	Compatible
		2000	lithium			1579	1649	
		7000	argon lithium argon lithium		nil	1605 1605 1346	1648 1605 1605	Incompatible
Carboloy-44A	G.E.		Pretest			1564	1648	
		500	argon	None	nil	1605	1605	Compatible
		2000	lithium			1621	1648	
		7000	argon lithium argon lithium	Program terminated	nil	1524 1468	1564 1505	
Carboloy-907	G.E.		Pretest			1839	1839	
		500	argon	None	nil	1892	1839	Compatible
		2000	lithium			1866	1866	
		7000	argon lithium argon lithium	Program terminated	nil	1789 1870	1789 1892	
Carboloy-78	G.E.		Pretest			1648	1648	
		500	argon	None	nil	1648	1648	Compatible
		2000	lithium			1671	1648	
		7000	argon lithium argon lithium	Program terminated	nil	1564 1657	1605 1606	
K-86	Kennametal		Pretest			-	-	
		500	argon	None	1.4	1413	1524	Incompatible
		7000	lithium argon lithium	Program terminated		1158	1468	

*5-kg load unless otherwise stated

TABLE 10
METALLOGRAPHY OF COMPATIBILITY SPECIMENS:
BONDED CARBIDES IN LITHIUM AT 1100 °F
(Sheet 3 of 3)

Material	Source	Duration (hr)	Environ- ment	Phase Change in General Structure	Maximum Lithium Attack (mils)	Hardness*		Remarks
						Surface VHN	Center VHN	
K-701	Kennametal	500	Pretest	None	nil	-	-	Compatible
		2000	argon lithium			1605	1693	
		2000	argon lithium			1564	1524	Incompatible
		7000	argon lithium			1682	1740	
K-94	Kennametal	500	Pretest	None	2.1	1379	1379	Incompatible
		500	argon lithium			1314	1413	
		500	argon lithium			1225	1363	
		500	argon lithium			841	891	
K-801	Kennametal	500	Pretest	None	7	874	857	Incompatible
		2000	argon lithium			725	866	
		2000	argon lithium			1145	1283	
		2000	argon lithium			1171	1197	
Carboloy-330	G.E.	500	Pretest	None	5.8	1178	1239	Incompatible
		500	argon lithium			966	1314	
		500	argon lithium			774	1145	
		500	argon lithium			1486	1564	
SP-112	Kennametal	500	Pretest	None	10 fracturing	1564	1564	Incompatible
		2000	argon lithium			641	1564	
		2000	argon lithium			1644	1780	
		2000	argon lithium			1693	1789	
K-151A	Kennametal	500	Pretest	None	fracturing	1704	1717	Compatible
		500	argon lithium			1839	1839	
		500	argon lithium			965	1814	
		500	argon lithium			1006	966	
K-162B	Kennametal	500	Pretest	None	3.2	986	966	Incompatible
		500	argon lithium			966	958	
		500	argon lithium			1120	1253	
		500	argon lithium			1120	1253	
K-162B	Kennametal	500	Pretest	None	3.2	709	1259	Incompatible
		500	argon lithium					
		500	argon lithium					
		500	argon lithium					

*5-kg load unless otherwise stated

Test parameters were chosen to simulate boundary lubrication conditions. Restarts were included in several of the tests. Wear depth measurements and surface finish changes were evaluated, and a comparative rating of 1 (best) through 6 (worst) was established as listed:

<u>Rating</u>	<u>Wear (mils/ft sliding contact)</u>	<u>Post-Test Surface Finish (μin./in.)</u>
1	$<3 \times 10^{-6}$	<10
2	$<3 \times 10^{-6}$	10 to 40
3	3 to 50×10^{-6}	10 to 40
4	3 to 50×10^{-6}	>40
5	$>50 \times 10^{-6}$	10 to 40
6	$>50 \times 10^{-6}$	>40

Complete results of the wear and friction tests are reproduced in Table 11. Some tests in argon were performed to demonstrate that liquid metals did provide some manner of lubrication, and did reduce wear and friction. All discs of the bonded carbides, except K-151A in 700°F lithium, showed wear resistance of Class 1, the best, under the following test conditions:

- 1) In lithium or NaK
- 2) At 600, 700, or 1000°F
- 3) At sliding speeds of 36 to 268 ft/min
- 4) With 0 to 20 restarts
- 5) For loads of 1150 to 41,000 psi.

The nickel-bonded titanium carbide K-151A that displayed poor wear resistance in 700°F lithium showed excellent wear resistance in 600°F NaK, emphasizing the compatibility results that determined that nickel-bonded carbides lacked lithium corrosion resistance. Several other wear ratings of Class 3 are attributed to loss of lithium from the wear tester at some time during the test.

TABLE 11
FRICTION AND WEAR BEHAVIOR OF BONDED CARBIDES IN LITHIUM AND NaK⁽¹¹⁾
(Sheet 1 of 3)

Test No.	Material		Shoe† Config- uration	Load (lb)	Temp (°F)	Media	Disk Sliding Velocity (ft/min)	Sliding Distance (ft x 10 ³)	No. of Restarts	Coef. of Friction (start)	Wear (mils)	Weight Loss (mg)	Surface Finish (μin./in.)		Sliding Wear (mils/ft x 10 ⁶)	Rating§
	Disk	Shoes*											Pretest	Post-test		
7	K-7178	S	F	30	700	Argon	36	13.0	11	0.5	D 2.25 S 1.25-1.59	369 2.1-2.8	10 6-5	8 15-15	171 122	5 5
8	K-7178	S	C	15-45	700	Lithium	268	109.0	3		D nil S nil-nil	- -	10 10-10	4.5 1.0-1.5	0 0	1 1
9	K-7178	S	C	20	700	Lithium	268	403	0	-	D 0.05 S ---	- -	10 10-10	2.5 6-5	0.12 -	1 -
10	K-7178	S	F	20	1000	Lithium	268	364	20	0.26	D nil S nil-0.25	3.9 Chipped	10 10-10	8 8-1.0	0 0.7	1 1
11	K-7178	S	F	20	1000	Lithium	268	113	3	0.2	D 0.156 S ---	1.4 -0.3-+0.7	10 10-10	3 2-1	1.4 -	1 -
12	K-7178	S	F	20	600	NaK-78	268	366	20	0.37	D nil S 0.3-0.3	8.6 2.3-5.4	10 10-10	1.0 1.5-1.0	0 0.8	1 1
13	K-7178	S	F	20	1000	NaK-78	268	39.4	0	0.2	D nil S 0.12-0.08	Chipped nil-1.7	10 10-10	3.5 11-4.5	0 3	1 2
14	K-601	S	F	30	700	Argon	36	12.7	10	0.57	D 1.05(est) S ---	281.6 0.4-0	5 6-6	- -	82.5(est) -	6 -
15	K-601	S	F	20	1000	Lithium	268	366	20		D 0.025 S 0.28-0.21	9.9 0.5-4.2	5 6-7	3 5-5	0.07 0.8	1 1
16	TiC- 10 Mo	S	C	20	700-800	Lithium	268	357	3		D 0.25 S 0.275-0.275	Chipped	10 10-10	30 7-9	0.70 0.8	2 1
17	TiC- 10 Mo	S	F	20	1000	Lithium	268	37.4	0	0.22	D --- S ---	Broke apart	10 10-10	- -	- -	- -
18	K-11	S	F	30	1000	Lithium	36 69 107 143 178 214 268	2.15 4.03 6.26 8.32 10.29 12.75 36.02 79.82	2 2 2 2 1 3 2 14	0.25	D 0.025 S 0.85-0.85	11.5 5.8-2.9	5 10-7	6 9-8	0.31 11	1 3 Lost lithium
19	K-11	S	F	30	700	Lithium	36 107 268 268	2.14 3.93 206 31.36 243.43	2 2 4 1 9	-	D --- S ---	2.2 1.9-1.5	4 5-7	- -	- -	- -

*S means same material as disk

†F = flat shoes, C = conforming shoes

§See page

TABLE 11
FRICTION AND WEAR BEHAVIOR OF BONDED CARBIDES IN LITHIUM AND NaK
(Sheet 2 of 3)

Test No.	Material		Shoe† Config- uration	Load (lb)	Temp (°F)	Media	Disk Sliding Velocity (ft/min)	Sliding Distance (ft x 10³)	No. of Restarts	Coef. of Friction (start)	Wear (mils)	Weight Loss (mg)	Surface Finish (μin./in.)		Sliding Wear (mils/ft x 10⁶)	Rating§
	Disk	Shoes*											Pretest	Post-test		
20	Carboloy-999	S	F	30	1000	Lithium	36 69 107 143 178 268 268	2.10 4.21 6.16 8.32 9.91 15.88 38.68	2 2 2 2 2 2 4	0.12	D 0.26 S -0.55 -0.66 +0.6 +0.5	32 0.7-0.9	8 3-3	10 15-10	3.0 7.7	1 3 Lost lithium
Cooled, heated and restarted							268	85.26	16							
21	Carboloy-999	S	F	20	600	NaK-78	268	35.3	0	0.29	D nil S 0.23-0.23	2.3 0.1-0.4	7 8-3	3.5-6 1.5-1.5	0 6.5	1 2
22	Carboloy-999	S	F	20	600	NaK-78	268	370	20	0.13	D 0.025 S 0.135-0.135	2.4 1.2-1.1	7 3-5	4-6 1.3-1.5	0.07 0.4	1 1
23	K-8	S	F	30	700	Lithium	36 107 268	2.08 6.49 332.3 341.47	2 2 9 13	-	D --- S ---	1.6 1.7-2.3	2 8-8	- -	- -	- -
24	K-8	S	F	30	1000	Lithium	36 69 107 143 178 268	2.16 3.84 6.23 8.35 10.32 15.82 46.72	2 2 2 2 2 1 11	-	D --- S ---	0.9 +4.6 -0.4	5 8-7	- -	- -	- -
25	K-8	S	F	30	1000	Lithium	36 268	2.15 80.99 83.14	2 - 2	-	D --- S ---	+0.1 -0.5 -0.3	5 8-8	- -	- -	- -
26	Carboloy-905	S	F	30	1000	Lithium	36 69 107	2.11 4.22 6.40 12.73	2 2 2 6	0.23	D 0.038 S 0.35-0.34	6.1 2.3-3.5	8 4-5	7 4-5	3.0 27.6	1 1 Lost lithium
27	Carboloy-905	S	F	30	1000	Lithium	36 69 107 178 214 268	2.18 4.18 6.22 8.22 10.39 16.00 47.19	2 2 2 2 2 1 11	0.26	D 0.063 S 0.65-0.9	8.2 2.1-2.8	7 5-6	5 4-4	1.34 19	1 3 Lost lithium

*S means same material as disk

†F = flat shoes, C = conforming shoes

§See page

TABLE 11
FRICTION AND WEAR BEHAVIOR OF BONDED CARBIDES IN LITHIUM AND NaK
(Sheet 3 of 3)

Test No.	Material		Shoe† Configuration	Load (lb)	Temp (°F)	Media	Disk Sliding Velocity (ft/min)	Sliding Distance (ft x 10 ³)	No. of Restarts	Coef. of Friction (start)	Wear (mils)	Weight Loss (mg)	Surface Finish (μin./in.)		Sliding Wear (mils/ft x 10 ⁶)	Rating§
	Disk	Shoes*											Pretest	Post-test		
28	K-96	S	C	15-45	700	Lithium	268	367	0	-	D nil S nil-nil		10 10-10	1.5 3-3	0 0	1 1
29	K-96	S	F	20	1000	Lithium	268	364	0	-	D nil S 0.05-0.1	1.9 Nil-+0.3	10 10-10	2.0 3-1.5	0 0.3	1 1
30	K-96	S	F	20	600	NaK-78	268	321	0	0.22	D nil S 0.2-0.04	+0.1 +0.2 -+0.4	10 10-10	2.5 3-3.5	0 0.6	1 1
31	K-96	S	F	20	600	NaK-78	268	363	20	0.22	D nil S 0.08-0.08	Chipped Chipped	10 10-10	2 2.5-2.5	0 0.2	1 1
32	Carboloy-78	S	C	20	700	Lithium	268	326	3	0.34	D 0.138 S nil-nil	2.1 3.2-5.2	10 10-10	13 13-6	0.4 0	2 2
33	Carboloy-78	S	F	20	1000	Lithium	268	353	3	0.26	D nil S nil-nil	0.8 0.05-0.2	10 10-10	3 1.5-3	0 0	1 1
34	K-94	S	F	20	600	NaK-78	268	307	0	0.29	D nil S 0.08-0.03	1.6 0.4-0	6 9-8	2.5-4 3.2.5	0 0.3	1 1
35	K-94	S	F	20	600	NaK-78	268	293	20	0.18	D nil S 0.08-0.1	1.1 1.1-0.7	3 8-8	2-3 0.6-0.7	0 0.3	1 1
36	K-151-A	S	C	15-45	700	Lithium	268	5.36	0		D 10.5(est) S ---	1067.1 23.9-99.5	10 10-10	- -	1950(est) -	6 -
37	K-151-A	S	F	20	600	NaK-78	268	345	0	0.13	D nil S 0.62-0.5	3.6 2.3-1.1	4 3-3	2.5 4.5-3	0 1.8	1 1
38	K-151-A	S	F	20	600	NaK-78	268	370	20	0.28	D nil S 0.7-0.7	1.3 1.4-0.5	3 3-3	3 3-3	0 1.9	1 1
39	K-162-B	S	F	20	600	NaK-78	268	376	0		D nil S 0.15-0.2	0.9 0.5-0.2	3.5 5-5	2 1.5-1.5	0 0.5	1 1
40	K-162-B	S	F	20	600	NaK-78	268	362	20		D nil S 0.2-0.15	3 0.6-1	3.5 5-5	2 4-2.5	0 0.55	1 1

*S means same material as disk

†F = flat shoes, C = conforming shoes

§See page

One final phase of this test program will be discussed. Recognizing that the use of bonded carbide sleeve or insert bearings complicates the mechanical design of the bearing because of the mismatch of thermal expansion coefficients and the need for larger journal diameters, the application of a thin coat of bearing materials by plasma spray on the shaft and housing was attempted. Some coatings of cobalt-bonded tungsten carbide and molybdenum-bonded niobium carbide were tested and displayed promising wear behavior in NaK. However, difficulties with adhesion, porosity, and impurities suggested that improved process control was required for acceptable performance in lithium. A vigorous development effort was recommended to define a standard coating procedure that would ensure reliable bearing surfaces.

Availability of such a process would appear to be desirable, if not essential, for fabrication of bonded carbide bearing surfaces in the very large sizes being considered for LMFBR pumps.

h. Item No. 8

Freed⁽²⁴⁾ conducted an extensive series of screening tests to develop comparative friction and wear data on several material classes.

The test parameters used were as follows:

Type of Test:	Fixed pins bearing on loaded rotating plate
Environment:	Sodium
Temperature:	1200°F
Sliding Speed:	5 to 16 ft/min
Load:	123 psi
Time:	~200 hr.

The test data on eleven couples containing one or two bonded carbides in liquid sodium at 1200°F are given in Table 12. The Colmonoy pin showed severe wear on the K-95 (WC-9 Co) plate. Three combinations showed about the best wear of any in the test series, including one bonded carbide-on-bonded carbide combination. When the combination was reversed, however, the WC-Mo pin rubbing on the TiC₂C-Ni plate showed imbedding, and very poor performance.

TABLE 12
SPECIFIC WEAR OF BONDED CARBIDES⁽²⁴⁾

Test No.	Pin Material	Plate Material	Coefficient of Sliding Friction		Specific Wear x 10 ¹¹ on Pins Average (cm ³ /cm/kg)
			Start	Finish	
13	K-162B	K-95	0.24	0.72	2.5
24	Hastelloy-C	K-95	0.57	0.47	2.9
47	Stellite-6B	K-95	0.49	0.89	7.3
48	Colmonoy-6 (HF)	K-95	0.63	0.83	75.4
12	K-95	K-162B	0.27	0.95	Material Buildup
21	Stellite-3	K-162B	0.32	0.36	Material Buildup
70	Inconel-718	K-95	0.49	1.50	2.76
71	Stellite-1016 (HF)	K-95	0.44	1.34	6.55
84	Stellite-Star J	K-95	-	0.74	10.03
85*	Stellite-6B	K-95	0.40	0.28	3.69
94	Stellite-3	K-95	0.31	0.56	10.40

*This test at 1000°F.

5. Surface Coatings

Vail⁽¹⁷⁾ reported that tungsten carbide applied to a stainless steel base material by the use of Tung Tube hard facing did not have satisfactory friction and wear characteristics; it did not perform as well as cobalt-bonded tungsten carbide when tested against other bonded carbides or tool steels. No explanation was given for the unsatisfactory results. The Stoddy high-chromium hard-facing alloys tested by Vail showed severe surface damage in most combinations, and did not give promising results; it was noted that the coatings applied were porous. Colmonoy-6 appeared to be more resistant to galling than any of the other hard-facing materials tested.

Ten years later, Kumpitsch⁽²⁸⁾ tested flame-sprayed bonded carbides on René-41 as the rotating member in a modified Falex test. Although low friction coefficients in the range of 0.2 to 0.3 were obtained, considerable scoring and material transfer occurred; the performance was not as good as similar bonded carbides had shown when tested as monolithic specimens. It was concluded that flame-plated carbides were not entirely satisfactory in this application. Further

analysis indicated that less than adequate precautions had been taken in preparing the substrate, applying the coating, and final grinding the coating, and that the material's performance probably had been adversely affected by less-than-optimum fabrication procedures.

An extensive survey of plasma-sprayed coatings was reported by Wallace,⁽¹¹⁾ who tested the compatibility and wear characteristics of materials in high temperature lithium and NaK. Specimens of Nb-1Zr alloy and Hastelloy-X were plasma sprayed with coatings of carbides of tungsten, titanium and zirconium and with bonded carbides. The lithium-tested coatings, Mo-25NbC, WC and WC-3Mo displayed poor wear resistances, including spalling. This was attributed to reaction of lithium with an aluminum oxide residue left from grit blasting the substrate surface. The same materials gave satisfactory performance when tested in NaK that did not attack the oxide residue. This again points out the need for the extra care needed in the fabrication processes if surface coatings are to show comparable performance to monolithic specimens.

The titanium carbide and zirconium carbide coatings displayed poor wear resistance while the tungsten carbide coatings showed good wear resistance. This was attributed to the high oxygen contamination of the tungsten carbide coatings which is assumed to have led to the formation of the complex sodium-tungsten oxide that provided some boundary lubrication. Although the coating displayed good wear resistance, the surface finish deteriorated. The increase in surface roughness was attributed to the porosity in the as-applied coating.

Murray⁽³⁸⁾ tested flame-sprayed coatings of chrome oxide with and without an undercoat of molybdenum, aluminum oxide, and tungsten carbide bonded with cobalt and nickel on Type 410 SS. The screening study consisted of a series of 50-hr tests in static 600°F NaK. The chrome oxide coatings disintegrated during the first test. After five cycles, the aluminum oxide coating was much roughened, but intact; this coating was judged to be unsuitable. The nickel-bonded tungsten carbide coating was selected as best of the group.

Nb-1Zr alloy was surface treated by five different methods of carburization that produced a carbide case from 0.1 to 1.2 mils thick, depending on the process.⁽¹¹⁾ All the carburization methods that were wear tested with flat rub shoes showed instantaneous failure. When the stress was reduced by a factor

of 12 by using conforming shoes, all tests with one particular process were successful in 700 and 1100°F lithium, with numerous restarts. Performance was judged to be nearly equivalent to that of the bonded carbides. This carburizing method was recommended for full-scale testing.

The advantages of carburized case bearing surfaces on the pump shaft were considered important enough to recommend that carburized Nb-1Zr alloy be used as the journal in the final design.

Roberts⁽²²⁾ reported high wear rates on nitrided steel running on nitrided steel in 750 and 950°F sodium. Although the initial surface hardness was given as 700 to 800 VPN before the test, hardness measurements after the 100-hr high-temperature runs showed a pronounced drop to about 200 VPN. It was concluded that the loss of the nitrided case was probably the result of a chemical reaction with the sodium. It would seem that the use of nitrided cases to raise the surface hardness of steels to reduce their tendency to self-weld in sodium should be limited to temperatures below 750°F. A study of the kinetics of nitriding/denitriding might establish a useful lifetime for some low-temperature applications.

Wallace⁽¹¹⁾ reported essentially instantaneous failure of a nitride coating on Nb-1Zr alloy when wear tested in 700°F lithium. The coating of about 0.1 mil may not have been thick enough to escape mechanical failure; nitride cases on steels commonly are several mils thick.

A program conducted to determine the feasibility of solid film lubrication in liquid sodium showed (6) favorable lubricating properties and resistance to 1000°F sodium corrosion for calcium-barium-fluoride coatings fired on a nickel-chromium alloy.

The test parameters used were as follows:

Type of Test:	Fixed, hemispherical tip, loaded button riding on rotating disc
Environment:	Sodium
Temperature:	1000°F
Sliding Speed:	2000 ft/min

Load: 120,000 psi at start, to 500 psi at end as calculated
from area of wear scar.

Time: 1 hr at no load + 1 hr with load.

The thin coatings, 1 to 2 mils thick, effectively lubricated the nickel-chromium sliding couple in sodium. Calcium fluoride-barium fluoride coatings showed no evidence of attack by sodium after 2 or 3 hr. Lithium fluoride and sodium fluoride were dissolved out when they were present in the coating. Friction coefficients below 0.2 were obtained.

The test load was higher than would be designed for in a bearing or seal to give an accelerated test. Coating life at reduced loads would undoubtedly be satisfactory if only wear from load were considered, but long-time compatibility testing in dynamic sodium should be successfully accomplished before further tests of bearing capabilities are made.

IV. PERFORMANCE OF MECHANICAL ELEMENTS

For the LMFBR program it is assumed that mechanical devices, such as pump bearings, fuel handling equipment and control rod drives, will be required to operate in a sodium environment at temperatures up to 1200°F for extended lifetimes. Operation may be continuous or intermittent, but in either case must be highly reliable. The use of sodium as a lubricant causes several problems that are not normally encountered in conventionally lubricated bearings. Liquid metal viscosities are very low, compared with those of conventional lubricants, so that the all-important lubricating film thickness that can be obtained with liquid metals is very small, making surface-to-surface contact much more probable. Since the load-carrying capacity of a bearing is dependent on the viscosity of the lubricant, bearings lubricated with low-viscosity liquid metal must be carefully designed to keep the loading low. Where conventional lubricants may provide boundary lubrication by forming an adsorbed or chemical reaction film on the metal surface, sodium prevents boundary lubrication by reacting with and dissolving protective surface films and promoting metal-to-metal contact. Where conventional lubricants have been replaced by surface coatings or simple surface films such as oxides that give satisfactory high-temperature lubrication, sodium not only will remove such a coating but will prevent its reformation, again promoting metal-to-metal contact. The materials used must be completely compatible with the sodium, because any corrosion or dissolution by the sodium will cause surface damage that will have the same effect as mechanical wear, acceleration of wear rates and early failure.

The several types of bearings in general use are discussed in this section, with the influence that the sodium environment has on their operating characteristics. Experimental and operating experience reported in the literature for full-size components is presented.

A. TYPES OF MECHANICAL ELEMENTS

1. Hydrodynamic Bearing

In the hydrodynamic fluid film bearing, a continuous film separates the sliding surfaces during operation; the pressure required to support the load is

generated within the bearing itself, and the only external pressure is that required to feed enough lubricant into the bearing to maintain a full fluid film. Conventionally lubricated hydrodynamic bearings can tolerate some wear if surface damage is not extensive. However, with liquid metal as a lubricant, its low viscosity demands bearings designed with a very small clearance, and the tolerance for wear decreases to the vanishing point.

Some disadvantages of the plain hydrodynamic bearing are its inherent instabilities under light load conditions, its nonaligning characteristics, and the small flow of lubricant that may not remove friction-generated heat from bearing surfaces fast enough. Rotor shaft systems can exhibit several forms of dynamic instabilities: shaft whirl, shaft whip, and resonant vibration. These all have a basic pattern in which the shaft center tends to rotate in an orbit within the bearing clearance. If the amplitude of this orbit becomes large enough, equal to the radial clearance in the bearing, solid contact is made between shaft and bearing, and failure results. Once again liquid-metal-lubricated bearings are at a severe disadvantage when compared with conventionally lubricated designs; the bearing clearance is so small in liquid metal designs that essentially no instability can be tolerated if the journal and bearing are to be kept from touching at high speeds.

These instabilities have been analyzed and controlled for fluid-film bearings operating with laminar flow in the clearance space. Plain journal bearings have been modified into variations, such as the Rayleigh-step, elliptical-journal, pocket-journal, tilting-pad and floating-ring designs, that can be self-aligning and that do overcome the inherent instability problem to some degree. However, different analytical and design techniques must be used when turbulent conditions prevail in the lubricant films. With high-speed operation and low-viscosity liquid metal lubricants, turbulent flow in fluid-film bearings presents a new set of problems. The load-carrying capacity of a bearing increases when the change from laminar to turbulent flow in the lubricant film occurs, but the bearing power consumption (friction) rises even more sharply. Recorded bearing torques in the turbulent region have been 4 to 40 times as great as predicted by laminar theory.⁽²⁰⁾ Since the lubricant flow rate also decreases in the turbulent region, the problem of frictional heat removal is aggravated. Two reports^(39,40) dealing with the

development of a theory of turbulent lubrication in small high-speed mercury-lubricated bearings have been published by Arwas.

A third report⁽⁴¹⁾ by Elrod et al. , presents a theory for turbulent lubrication and for rotor-bearing dynamics of flexible high-speed rotors supported in turbulent-flow bearings lubricated with low kinematic viscosity fluids. These theories may be reviewed for their applicability to small, very high speed bearings lubricated with alkali metals, such as are required in the rotating converter units of nuclear electric power systems in space.

Another serious disadvantage of the hydrodynamic bearing is its poor load-carrying ability at low speeds. A conventional bearing depends on boundary lubrication to protect the bearing surfaces at startup and while the shaft is coming up to design speed. Liquid metal lubricants have no boundary lubrication properties, and the bearing materials must be extremely wear-resistant if they are not to be severely damaged during startup and low-speed operations.

2. Hydrostatic Bearing

In the hydrostatic fluid film bearing, complete separation of the surfaces in relative motion is maintained by a continuous fluid film, but the load-supporting pressures are supplied from an external pressure source, and may be as high as needed for optimum bearing design. The hydrostatic bearing offers relative freedom from the instabilities inherent in hydrodynamic bearings; it has a load capacity independent of lubricant viscosity, and it has a high load-carrying capacity at no rotation, startup and low-speed operation. Wear of bearing surfaces is thus minimized.

However, the high load capacity is achieved at the expense of providing a separate external pressure source that complicates the system design considerably. A flow restrictor is also required in the feed line between bearing and pressure source if the bearing is to function properly, and these restrictors are sensitive to both plugging and erosion. Lubricant flow through the bearing is higher than in a hydrodynamic bearing, causing a higher parasitic power loss, but also providing improved temperature control.

When the hydrostatic bearing is to be used in a sodium pump, one compromise that can be made to avoid the complication of a separate pressure

source is to use the pump's own discharge to pressurize the bearing. The advantage of high load capacity is still operative at design speeds, and a smaller bearing area may be used. But the load capacity falls off rapidly as pump speed decreases, and the bearing surfaces will come into contact at low speeds and at start-stop operation, just as in the hydrodynamic bearing. The pump system must be carefully designed, then, to keep the bearing load at start-stop and at low speeds to an absolute minimum.

The parasitic flow required to pressurize such a bearing for an LMFBR pump has been estimated at 7% of the total pump discharge.⁽⁴²⁾ If the bearing is designed with larger clearances to prevent contact at the lowest operating speed, the size of the bearing becomes larger and the parasitic flow increases sharply. Design parameters for such a unit must be carefully traded off if the optimum bearing performance is to be achieved.

Recently, the use of a hydrostatic self-aligning bearing has been proposed⁽⁴³⁾ to minimize the radial clearance necessary in hydrostatic bearings, and thereby to decrease the power loss due to bearing flow requirements to an estimated 1-1/2% of full pump flow. The required bearing diameter is also significantly smaller.

3. Rolling-Element Bearings

For a rolling-element bearing to function properly, there must be no wear or surface degradation of the rolling element or races. Surface damage of any kind results in rough operation which further accelerates wear and leads to complete failure. The combination of high-pressure contact between rolling element and race (because of the small contact area) and the poor conformity of these contacting surfaces discourages the formation of a hydrodynamic film of lubricant. Such a film would prevent the intimate contact of these surfaces that results in surface welding of contacting asperities, material transfer from one surface to another, wear, and ultimately bearing failure.

Successful operation of rolling-element bearings has been achieved in applications for conventional environments where conventional lubricants may be used. Theories for formation and maintenance of an elastohydrodynamic lubricant film have been developed and correlated with observed wear patterns. One such experimental and mathematical study⁽⁴⁴⁾ of elastohydrodynamic film formation in

a rolling-ball test apparatus showed that significant wear occurred only when the film was interrupted, and that wear became progressively more rapid as the severity of asperity contacts increased. This emphasizes the importance of maintaining an unbroken lubricant film to prevent wear in rolling contact.

For the LMFBR program it is assumed that mechanical devices, such as fuel handling equipment and control rod drives, will be required to operate in an environment of liquid sodium, or sodium vapor plus an inert cover gas, at temperatures up to 1200°F for extended lifetimes. Operation may be continuous or intermittent, but in either case must be highly reliable.

The special problems caused by sodium environments are especially severe in rolling-element bearings, where high pressures exist in the contacts between rolling elements and races even under light loads. Low viscosity and high chemical reactivity of the lubricating sodium tend to keep the film bearing capacity low, so that the bearing must be carefully designed to keep the unit loading low. Corrosion damage to a bearing surface is more likely to cause trouble than in a journal bearing because the area of contact is smaller. Because of the severity of these problems, early workers recommended⁽⁴⁵⁾ that rolling element bearings not be considered for high-load continuous service, although they were still considered useful in intermittent-use, light-load applications.

4. Boundary Lubrication of Surfaces

Where surfaces in relative motion move too slowly to build up an hydrodynamic lubricant film between them, and where no external pressure source is used to supply a lubricant film, the two surfaces will be forced into contact by the applied load and will suffer wear. The accepted theory of adhesive wear is described in Section III.A.1. With conventional lubricants, an adsorbed lubricant film may cling to the rubbing surface, or a chemical reaction film (usually oxide) may have formed on the rubbing surface; any such film will tend to prevent the clean metal contacts that weld, then break, causing wear. Special lubricating films may be applied to rubbing surfaces to perform the same service. With alkali metals, no such contaminating films are possible; the liquid metal either dissolves or reduces any surface film that may be present, and fails to provide an adsorbed film of beneficial thickness because of its low viscosity.

Liquid metals, then, actually promote metal-to-metal contact and severe wear of rubbing surfaces. Mechanical elements that must be used in liquid metals in the boundary lubrication regime should be designed with the following tenets in mind to minimize wear:

- 1) The bearing surfaces should be as large as practical to keep bearing loads low.
- 2) Materials in a rubbing couple should be chosen to have no alloying tendency in each other.
- 3) Clearances should be as large as possible without impairing the mechanical function of the element.
- 4) Surface finishes of the rubbing surfaces should be as high as possible to distribute the load over as much of the surface as possible.

B. EXPERIMENTAL AND OPERATING EXPERIENCE WITH MECHANICAL ELEMENTS

Development of mechanical elements and bearings lubricated by liquid metals has been conducted with three groups of end products in mind:

- 1) Small radial and thrust bearings operating at high speeds and high temperatures continuously for 1 year or more are needed for nuclear electric power systems in space. Typical here is a 1/2-in.-diameter bearing turning at 35,000 rpm with a sliding speed of 5500 ft/min, at 1200°F. Experimentation is directed to developing and proving bearing design theories in the unfamiliar high-speed region; research in high-temperature materials is carried out concurrently.
- 2) Intermediate, large, and very large radial and thrust bearings are needed for coolant pumps for liquid-metal-cooled reactors and for liquid metal heat transfer systems. In these cases, bearing design theory is more established and the emphasis is on extending successful operation to the higher temperatures, and on finding materials that will be satisfactory at the higher temperatures of an LMFBR. A bearing for a 30,000-gpm sodium pump could be 2 ft in diameter; turning at 1000 rpm, a sliding speed of more than 6000 ft/min is produced. Such a bearing will be expected to operate at 1200°F for

1 year without inspection or servicing, with frequent start-stop operations during that year, and with an eventual lifetime of many years.

- 3) Intermittent operation is required of devices such as control rod bearings, fuel handling mechanisms, gears and latches. Sliding speeds are low in these applications, and high wear rates are expected if only boundary lubrication by liquid metals is present. Self-welding during the dwell times must also be prevented.

Most of the experimental work on friction and wear in liquid metals is conducted in the boundary lubrication area because greatest wear occurs during times of boundary lubrication in any class of bearings. It is hoped that by understanding the mechanisms of wear in liquid metals under boundary lubrication conditions, wear in full-size elements can be prevented. Screening tests of material couples in a friction-and-wear apparatus also provide an empirical evaluation of what materials show the least wear in boundary lubrication situations.

1. Hydrodynamic Bearings

Low friction journal and thrust bearings which are lubricated with a hydrodynamic film of liquid metal have been designed from well established bearing theory and operated successfully for thousands of hours. As the new requirements of space nuclear reactors brought ultra-high speed operation into prominence, it was found that bearing performance was not completely understood in the region of turbulent flow in the bearing clearance. In the turbulent region, lubricant flow was lower, friction losses were higher, but load-carrying capacities also increased sharply. Experimentation with theory and equipment has produced some understanding of the problem, but much remains to be done. Typical of the studies of the problem are the low-viscosity bearing stability investigation by General Electric;⁽⁴⁶⁾ a fundamental investigation of liquid-metal-lubricated journal bearings by the Southwest Research Institute;⁽⁴⁷⁾ a study of the lubrication behavior of liquid metals at North Carolina State College;⁽⁴⁸⁾ and a program to develop the theory of turbulent lubrication with low kinematic-viscosity fluids, at Mechanical Technology Incorporated.^(39,40,49) These studies were performed with low-viscosity lubricants other than liquid metals in an attempt to develop a theoretical understanding of bearing performance.

a. Item No. 1

In the earliest reported tests of bearings in liquid metals, Apkarian⁽⁵⁰⁾ investigated the feasibility of using liquid metals such as NaK as bearing lubricants, and found that properly designed bearings lubricated by liquid metal supported practical loads through a wide range of temperatures and speeds.

Bearing Type:	Tapered-land thrust	Journal
Bearing Size:	40 in. ²	2.375 in. x 2.4 in.
Bearing Material:	Carboloy, 18-4-1 tool steel	18-4-1 tool steel bearings on journals of Stellite-J, Stellite-1, and 18-4-1 TS
Load:	400 to 2000 lb	400 to 1800 lb
Environment:	NaK (50% Na)	NaK (50% Na)
Temperature:	150 to 850°F	75 to 300°F
Speed:	175 to 1150 rpm	900 to 1750 rpm
Time:	Not given	Not given

The materials used in the tests were satisfactory in regions of full-film lubrication, although the length of the test runs was not given. Only Carboloy was satisfactory under heavy unit loads in the region of boundary lubrication. The NaK was found to behave in accordance with established hydrodynamic principles. It was noted that bearing operation was considerably improved, with increased load-carrying capacity and reduced friction, after the liquid metal had wetted the bearing, at a temperature of 200 to 250°F.

b. Item No. 2

Vail⁽⁵¹⁾ reported a life test of 2700 hr on a Carboloy tapered-land thrust bearing.

The test parameters used were as follows:

Bearing Type:	Tapered-land thrust
Bearing Size:	40 in. ²
Bearing Material:	Carboloy

Load: 500 lb
Environment: NaK (58% K)
Temperature: 300 to 750°F
Speed: 900 rpm
Time: 2700 hr operational
3300 hr in NaK.

At the end of the test there was no evidence of depreciation in the load-carrying capacity of the hydrodynamic lubricating film of liquid metal. At no point in the test was hydrodynamic lubrication impaired by the hard particles of Stellite-6 accidentally introduced into the NaK by failure of a guide bearing. Bearing surface finish changed from 1 to 3 during the test. About 250 stops and startups were made during the run.

c. Item No. 3

Vail further reports ^(18,52) on journal bearing tests of two 2-3/8-in. - diameter hydrodynamic journal bearings with NaK as the lubricant.

The test parameters used were as follows:

Bearing Type: Journal
Bearing Size: Not given
Bearing Material: Copper or tungsten carbide bearing, tungsten carbide journal
Load: 200 to 1800 lb
Environment: NaK and sodium
Temperature: 100 to 500°F
Speed: 1200 and 1700 rpm
Time: 1500 hr.

The tests proved that the performance of the bearing over the limited range of test conditions was predicted adequately by the then-existing theoretical and empirical concepts for a full journal bearing. The calculated minimum film thicknesses were also shown to be as empirically postulated.

d. Item No. 4

Coffin⁽¹⁹⁾ investigated the copper/carbide combination in the form of thrust bearings in NaK at temperatures up to 750°F. Postulating that with low-viscosity fluids, such as liquid metals, the theoretical boundary lubrication film thickness could become small enough to reach the same order of magnitude as the surface roughness, he found that loading the test bearing produced a friction coefficient typical of boundary lubrication, but that the friction dropped steadily as the test continued under load. This wearing-in process produced a bearing with a calculated extremely small clearance, in the order of a fraction of a microinch. The wearing-in was achieved only with the two combinations of copper on tungsten, and copper on cobalt-bonded tungsten carbide, and was undoubtedly due to the excellent conformability of the copper. With this extremely small clearance, hydrodynamic performance was achieved that permitted extremely high load-carrying capacities.

The test parameters used were as follows:

Bearing type:	Loaded pad rotating on fixed disc, simulating thrust bearing
Bearing Material:	Copper on tungsten, copper on cobalt-bonded tungsten carbide
Load:	0 to 200 psi
Environment:	NaK (77% K)
Temperature:	500 to 750°F
Speed:	2 to 800 ft/min
Time:	Up to 24 days.

e. Item No. 5

Tests of lightly loaded water- and potassium-lubricated bearings in a high speed journal bearing rig were compared⁽²⁰⁾ with theoretical predictions based on laminar bearing theory. Conventional hydrodynamic theory accurately predicted the bearing performance in the laminar flow regime. The transition from laminar flow (of lubricant in the bearing clearance area) to turbulent flow occurred at higher speeds than predicted. Recorded bearing torques in the non-laminar regions were 4 to 40 times as great as predicted by laminar theory.

The test parameters used were as follows:

Bearing Type:	Journal, plain
Bearing Size:	1-in.-diameter x 2 in. long
Bearing Material:	Aluminum-bronze bearing, chrome-plated Type 316 SS shaft
Load:	0 to 50 lb
Environment:	Potassium
Temperature:	400°F
Speed:	0 to 24,000 rpm
Time:	Not given.

This test demonstrated that existing theory did not predict bearing operation above the transition speed, and that successful operation was possible in the turbulent region. The lightly loaded unmodified bearing was not subject to hydrodynamic instabilities.

f. Item No. 6

Successful testing of a liquid metal hydrodynamic journal bearing at a shaft speed of 8000 rpm, intermediate between the very early designs and the ultra-high-speed space power units, was reported by Richards.⁽⁵³⁾ The bearing operated over 10,000 hr in 625°F lithium with no problems. The hydrodynamic design had evolved from results of combinations of water tests, previous liquid metal experiments, and testing of proposed bearing materials.

The test parameters used were:

Bearing Type:	Hydrodynamic journal
Bearing Size:	2.5-in.-diameter x 2.5 in. long
Bearing Material:	Bonded carbide, proprietary formula (Mo-22Nb-4C)
Load:	11.3 lb maximum
Environment:	Lithium
Temperature:	650°F

Speed: 8500 rpm nominal; maximum journal surface speed reached 5700 ft/min

Time: 10,031 hr.

Wear measurements showed the bearing to have worn 0.1 to 0.4 mils; the journal was cracked during disassembly and accurate measurements were not possible, but the surface finish was unchanged from the pretest condition.

g. Item No. 7

A series of hydrodynamic journal bearing experiments in sodium was conducted⁽⁵⁴⁾ to investigate the stability characteristics of four different geometries, and the wear properties of several material combinations.

The test parameters used were as follows:

Bearing Type:	Hydrodynamic journal, four modifications
Bearings Size:	1.5-in.-diameter x 1.5 in. long
Bearing Material:	Combinations of Inconel, Hastelloy-X, Stellite Star-J, Titanium Carbide, Molybdenum-1/2 Titanium
Load:	0 to 70 psi
Environment:	Sodium
Temperature:	500 or 800°F
Speed:	2,000 to 12,000 rpm
Time:	200 to 1000 min per test.

Four different bearing configurations were tested: cylindrical bearings with two and three axial grooves, plain cylindrical bearings with herringbone groove journals, and tilting-pad bearings with three pads.

The tilting-pad bearings were the most stable. Actual bearing torques for these bearings agreed favorably with turbulent flow theory, indicating that turbulent flow conditions prevailed. Critical transition speed from laminar to turbulent flow occurred at a higher speed than theory predicted. Surface damage of the tilting-pad bearing pivots was observed in some tests, even after very short runs at light pivot loads.

Stellite Star-J mated with any of the other materials, except the molybdenum-1/2 titanium alloy tested, gave the best performance. Four combinations including the molybdenum alloy seized, possible from severe overloading by instabilities. The only bearing using a Hastelloy-X - Inconel pair (both high nickel content) seized. Variations in bearing loading conditions make material performance difficult to assess.

Preference for the pivoted-pad design was also expressed in the description of another liquid metal bearing test rig⁽⁵⁵⁾ being readied for operation. The test bearing used four segmented pads retained by spherical pins and balanced so that their centers of gravity coincided with the pivot contact points. The configuration was preferred because of its resistance to partial frequency whirl and because of its ability to self-adjust to misalignments or structural distortions. Disadvantages of the design were its complexity and its tendency to fretting or seizing of pivot points.

h. Item No. 8

The longest operating time reported for a hydrodynamic journal bearing was for those bearings used on the sodium pumps for the 2000-kw sodium test facility at the Los Alamos Scientific Laboratory.⁽⁵⁶⁾ These were multistage centrifugal pumps, each with three sodium-lubricated shaft bearings and two oil-lubricated mechanical face seals.

The operating conditions were as follows:

Bearing Type:	Hydrodynamic journal
Bearing Size:	About 2 in. diameter x 5 in. long
Bearing Material:	Colmonoy No. 6 sleeve on Type 304 SS shaft, rotating in corresponding Colmonoy insert in Type 304 SS housing.
Load:	Radial only, magnitude not given.
Environment:	Sodium
Temperature:	850°F for primary pump, 550°F for secondary pump
Speed:	1675 rpm
Time:	11,920 hr for primary pump, 13,375 hr for secondary pump.

The lower bearing was in the inlet bowl below the first pumping stage, the center bearing was just above the discharge from the last pumping stage, and the upper bearing was at the level of the discharge nozzle. During operation of the sodium loops for the times noted in the preceding paragraph, no trouble was experienced with any of the sodium-lubricated bearings. Post-operational examination of bearings from the secondary pump showed that the upper and lower bearings had suffered only very minor scoring, with original grinding marks clearly visible over nearly all of both stationary and rotating surfaces. The center bearing was scored more heavily, uniformly on the rotating surface but on one side only on the stationary surface. The scoring was believed to be the result of shaft misalignment, although the pump performance had not been affected. The entire pumping assembly was judged to be suitable for future service for an indefinite period.

i. Item No. 9

A technology program to develop the theory and design data needed for design of liquid-metal-lubricated bearings operating in the turbulent flow regime has been reported.^(57,58) A comprehensive set of design data is presented⁽⁵⁷⁾ that covers operation of tilting-pad journal bearings in both the laminar and the turbulent flow regimes. All the fluid-dynamic bearing characteristics are tabulated as functions of bearing geometry and operating conditions. The data are presented in normalized form and cover the full range of generally used bearings, with L/D ratios from 0.25 to 1 for Reynolds numbers up to 30,000.

The parallel experimental investigation conducted to assess the validity of this bearing design data used NaK-78 at 110 to 120°F. The test bearing was a four-pad tilting pad type, 2 in. diameter and 2 in. long. The speed range tested was 3,000 to 28,000 rpm, yielding a range of Reynolds numbers of 1,250 to 11,700. The test data are presented and compared with the corresponding calculated data derived from the design data tables. The steady-state load capacity of the NaK-lubricated bearings was determined, as well as the stiffness and damping properties of the liquid metal lubricant films.

In general, good agreement of the experimental data with the calculated design data was found, particularly when the tests were conducted with the bearing pads assembled with a preload coefficient of 0.5.

2. Hydrostatic Bearings

The largest sodium pumps built to date have used a hydrostatic bearing pressurized by the pump discharge. Used first on the Fermi pump, which was designed for a flow rate of 11,800 gpm of 850°F sodium and tested at 1000°F, the bearings were 12 in. diameter and 14 in. long. The same bearings were installed in the Hallam pump, designed for 7200 gpm of 950°F sodium, and in the EBR-II pump, designed for 5500 gpm of 800°F sodium. Bearing performance has been satisfactory in all cases, and this type of bearing will be one of the reference designs⁽⁵⁹⁾ for the 60,000 to 120,000 gpm pumps now being considered for the LMFBR.

The Hallam pump is described in Reference 60. The bearing housing supported in the pump diffuser casting contained four pressure-pad chambers which were supplied with sodium from the impeller discharge during pump operation. The journal was formed as an extension of the inlet eye of the impeller. The load-carrying capacity of the bearing depended on the pump discharge pressure; when the pump was started up or stopped, rubbing was to be expected. At these times, however, there was no load on the bearing (pump shaft was vertical) other than that from assembly misalignment, and the rubbing wear was expected to be minimal. The rubbing surfaces were faced with Colmonoy-5 (journal) and Colmonoy-6 (bearing) to resist wear.

Each of the 6 Hallam pumps accumulated about 20,000 hr of operating time, for a total of 117,000 hr for all 6 pumps.⁽⁶¹⁾ No bearing problems were experienced in all that time, which speaks well of the design reliability. Extrapolation to LMFBR environment however, must be made with care. The Colmonoy hardfacing, for example, will not resist sodium attack or rubbing wear satisfactorily at the LMFBR temperature of 1200°F, so that a new bearing surface material must be qualified. A bearing diameter of 2 ft is not out of the question, which, with the same shaft speed as Hallam (1100 rpm), will give a sliding speed (and wear per day) at the bearing surface twice that of the Hallam bearing. Bearing design must incorporate high efficiency; where the Hallam bearings used about 4% of the pump discharge as parasitic flow to pressurize the bearing pads, it has been estimated⁽⁴²⁾ that bearing losses in a 60,000 gpm pump may run as high as 7%.

Pumps for the Prototype Fast Reactor (PFR) at Dounreay⁽⁶²⁾ will have a hydrostatic journal bearing using the delivery pressure of the pump to feed the bearing jets through filters. Design conditions for the pumps are 21,000 gal (U.S.)/min at 400°C (750°F); the pumps are in the cold legs of both primary and secondary circuits. The bearing for the primary pumps will be 12 in. diameter by 12 in. long, manufactured from austenitic stainless steel with Stellite hard facing deposited on both shaft and bearing. Sodium flow through the bearing is expected to be a little more than 1% of total maximum pump flow. A similar 9-inch-square bearing will be used on the secondary pumps.

The PFR pump design was based on information gathered from a 7200 gal (U.S.)/min prototype pump⁽⁶³⁾ that operated satisfactorily at temperatures up to 750°F for 7000 hr, and stopped and started 300 times. The main bearing for this vertical centrifugal pump was a sodium-lubricated hydrostatic type fed from the pump delivery; it was 200 mm diameter by 200 mm long, with a radial clearance of 0.28 mm. Fabrication was of stainless steel, with spray-fused Stellite-6 deposited on both the bearing and shaft. The maximum sodium flow through this bearing was 1%.

3. Rolling-Element Bearings

Because of the severity of problems peculiar to rolling-element bearings operating in a liquid metal environment, most experimenters have neglected development of such bearings. No experience applicable to LMFBR temperature of 1200°F was found; some successful operations have been reported at lower temperatures and always with light loading. The normal failure mode of rolling-element bearings in conventional lubricants is surface fatigue leading to cracking and mechanical damage, and the loading problem becomes more severe in low-viscosity liquid metals.

One test of a commercial needle bearing has been reported.⁽⁶⁴⁾ Needle bearings of high-speed tool steel (18W-4Cr-1V) were oscillated in 850°F sodium through a 5 deg arc at a frequency of 120 cpm, for a total of 2 million cycles. The applied load was 200 lb. The test was to simulate operation of a universal joint in sodium. Results reported are qualitative: the bearing operated quietly and satisfactorily, was still serviceable at the end of test, and showed no visual evidence of corrosion. However, the short time required to run the test, less

than 300 hr, detracts from the usefulness of the data for long lifetime uses. Also, microscopic examination of the races revealed that traces of materials were picked up from some of the contact area; the appearance is likened to fretting corrosion occurring in other anti-friction bearing applications. Decreasing the radial clearance of the bearing is suggested to minimize this effect. The potential seriousness of this problem is brought out by the ball bearing failures described in Reference 65 where material transferred from retainer to balls and races, causing the stress concentrations and consequent failure by cracking.

Work on liquid-metal-lubricated rolling-element bearings was reported⁽⁶⁶⁾ by the U.S. Naval Engineering Experiment Station from a program intended to find the cause of, and remedy for, the unsatisfactory performance of conventional anti-friction bearings exposed to NaK. The rolling-contact experiments were made with toroid rolling elements; materials tested were high-speed tool steels T-1 (18W-4 Cr-1V) and T-15 (12W-5 Cr-5 Mo-5V), high-carbon stainless steel (440C) and SAE52100 bearing-quality steel. The environments for the tests were NaK-78 and a lubricating oil at temperatures from ambient to 700°F. The results indicated that at 250°F in NaK the load-carrying capacities of all the materials tested were about equal and were about half of the capacity in oil at room temperature. Indeed, the load-carrying capacity of T-1 steel in NaK at 250°F was lower than in oil at 500°F. A further severe drop in rolling capacity in NaK was apparent when the temperature was raised from 250 to 500°F.

At the conclusion of the test, the radial production anti-friction bearings used to support the rolling elements during the test were dismantled and examined. The T-1 bearings experienced no failures in 500°F NaK during the short life and low loads of the test, but definite deterioration of the bearing surfaces was observed, primarily at the point of rolling contact. A significant reduction in bearing life expectancy was induced from these observations.

The reason for the failure of conventional anti-friction bearings in NaK was concluded⁽⁴⁵⁾ to be metal-to-metal contact between the various elements of the bearing. The solution suggested was to provide some means of continually separating the contact surfaces, but no way of doing this was proposed. The overall results of the program were discouraging enough to conclude that

the use of anti-friction (rolling-element) bearings in NaK or sodium to support continuously rotating components for long times should be abandoned.

Similar work⁽⁶⁵⁾ found bearing failures to be traceable to retainer failures. Experiments were conducted with ball bearings of 50 to 140 mm bore size run at 850 rpm, at thrust loads of 400 to 4300 lb, in NaK or sodium at 250°F. Seven metal alloys tested as retainers failed by wear against the load-carrying members (which were made of hardened SAE52100 bearing steel). Material (the wear particles) transferred from the retainers to the balls and races; the transferred material formed high spots on the normally smooth surfaces, causing stress concentrations and consequent failure by cracking. The low-viscosity lubricant then promoted the cracking which finally progressed to shattering and complete failure. When a phenolic-cloth-laminated material was used as the retainer, no evidence of material transfer was found and the bearing life was much longer than with any metallic retainer; it approached the rated life with normal lubrication. Such a system is not feasible, of course, above the temperature limit in NaK or sodium of the laminate, which has been placed at 275°F.⁽⁴⁵⁾

It can be noted here that these tests were inspired by a successful 5000-hr test⁽⁶⁵⁾ of a small commercial ball bearing in 250°F NaK, operated at 1750 rpm with very low loads, 30 lb radial and 30 lb thrust. It is indicated that lightly loaded commercial ball bearings can be operated in 250°F NaK for satisfactory lifetimes.

Retainer problems were noted in tests reported by Argonne National Laboratory.⁽⁶⁷⁾ In a commercial bearing with Stellite-3 balls and races and a Berylco-255 retainer, operated 450 hr in 300°F sodium, copper smears were found on the balls and races. Similar bearings without retainers operated for 1850 hr in 300°F sodium, and for 950 hr in 900°F sodium, under a thrust load of 240 lb without apparent damage. However, a similar bearing tested at Atomics International under heavier load for 385 hr in 1000°F sodium was reported⁽⁶⁸⁾ to be unsatisfactory. The outer race was Haynes-25, the inner race was cast Stellite-19, and the balls were cast Stellite-3. Operating conditions for the bearing were 85 rpm and 870 lb axial load. Roughness of both balls and races increased during the test, from 8 μ in. rms to 300 for the races and 60 for the balls. The bearing was judged unsatisfactory for the intended use.

Reference 69 briefly describes the only full-size ball-bearing application found in this literature search. A Byron Jackson canned-rotor pump moving 3625 gpm of 900°F sodium in a development test was said to have unsatisfactory bearing life for the sodium-lubricated ball bearings, which are not described.

A shaft-bearing system design and development program for hermetically sealed liquid metal pumps was conducted at the Pratt & Whitney CANEL Laboratories from 1962 to 1965.⁽⁷⁰⁾ Only one ball-bearing test in lithium is reported; the rest of the work was with journal bearings. The test ball bearing was of a 40-mm bore design with a 12-deg angular contact. Inner and outer races, and the balls, were M-2 tool steel; the one-piece retainer was AMS-6415 low-alloy steel. The test was made in 600°F lithium, starting at 500 rpm and a 5-lb radial load, and increasing over the first 100 hr to 2600 rpm and a 40-lb radial load. After only 102 hr the test was terminated because of high vibration. The retainer was found broken into 10 identical sections, with failures across the minimum cross-section of the ball pockets. Misalignment between inner and outer races of the bearing was suggested⁽⁷¹⁾ as the cause of the retainer failure.

In EBR-II, the Mark I oscillator rod drive bearing assembly operated in an atmosphere of sodium vapor and argon at about 150°F. The assembly included a ball bushing that failed after about 5800 hr of exposure. This failure allowed the balls to work down the shaft, out the sodium vent holes into the adjacent control rod drive shaft labyrinth seals. This resulted in the failure of two control rods to drop during a scram. Both the oscillator rod and drive were subsequently discarded, and a new drive was designed without ball bearings.

4. Boundary Lubrication of Surfaces

Friction and wear testing has been reported on a great many combinations of materials and environments. The tests, in general, are intended to provide an estimate of long-time, low-load performance of a device operating in liquid metal by accelerating the time (continuous operation, higher sliding speed) and increasing the unit loading. The tests usually serve to screen out material combinations that are obviously unsatisfactory because of galling, seizing or high wear rates, but they leave unanswered the question of how well the surviving combinations will perform in the real liquid metal environment. At the

least, friction and wear tests should be augmented by long term dynamic corrosion testing in liquid metal.

Another factor that makes wider use of the friction and wear tests difficult is the lack of uniformity in test equipment and test parameters reported. Many of the tests were highly specialized in application and neglect to record such items as sodium purity and surface preparation of specimens. The friction and wear tests reported in Section III of this report are listed in Table 13.

TABLE 13
LIST OF FRICTION/WEAR TESTS

Reference	Author	Date	Liquid Metal	Temperature (°F)
16	Vail	1951	NaK	350
17	Vail	1954	NaK	350 to 950
21	Elliott	1954	Sodium	250
19	Coffin	1958	NaK	500 to 750
33	Kumpitsch	1958	NaK	1000
4	Kissel	1960	Sodium	500 to 1200
5	Kissel	1962	Sodium	500 to 1200
22	Roberts	1962	Sodium	300 to 1000
25	Sarnecki	1963	Sodium	1200
6	Sliney	1964	Sodium	1000
28	Kumpitsch	1964	NaK	1200
23	Roberts	1965	Sodium	300 to 1000
11	Wallace	1965	Lithium or NaK	600, 700, 1000
26	Adams	1967	Sodium	450 to 1000
24	Freede	1967	Sodium	800, 1000, 1200

Tests on components are reported in the following text.

a. Item No. 1

Jamrog and Stella⁽⁶⁷⁾ evaluated the performance in sodium of gears and bearings proposed for use in EBR-II fuel-handling mechanisms, at temperatures,

loads and speeds characteristic of the fuel-handling equipment operation. Successful operation at times up to 1800 hr was achieved with certain combinations. Complete results are given in Tables 14, 15, and 16. Summarizing, good tests (no wear) in 900°F sodium were reported for gears of Tantung-G (425 hr) and chrome-plated HSTS (950 hr); commercial ball bearings with balls and races of Stellite-3 and with no retainers (950 hr); and journal bearings with chrome-plated HSTS running on the same material or on Stellite-3 (425 and 950 hr).

One unsatisfactory test noted was that of a journal bearing with a chrome-plated HSTS shaft running in a copper-plated HSTS bearing. After 200 hr in 900°F sodium, under a 63.5 psi load, the copper plating had worn to the point of galling in 4 of the 6 tests. Later tests with a chrome-plated HSTS shaft running in a chrome-plated HSTS bearing that was fitted with copper pin inserts instead of copper plating were all satisfactory; the principle of using inserts instead of the continuous coating apparently provided enough copper to give the desired wear-in smearing effect without the undesirable galling.

b. Item No. 2

Laboratory tests to determine the degree of adhesion and self-welding of various bearing material couples were conducted^(72,73) in sodium at temperatures ranging from 500 to 1000°F with static loads that were increased in steps from 1000 psi to a maximum of 10,000 psi, or until self-welding occurred. Two types of tests were made, a simple static load, and a static load with intermittent twisting (torque) of one sample on the other added. Complete results are given in Table 17. In the simple static load tests, the load was applied for 50 min and the force needed to separate the couple was measured. None of the bearing couples showed any appreciable tendency for direct adhesion during these static load tests, even at the most severe operating conditions of 1000°F and 10,000 psi load.

The torque test was more severe. It was carried out on a bearing couple after the simple static load test was complete. One sample was turned 90 degrees on the other half of the material couple by means of a torque wrench at the beginning and end of the 50-min static loading. The increase in torque required to turn the sample was measured as the severity of the operating environment was increased. In these tests, several of the softer samples showed galling and welding; rougher surfaces appeared to increase the tendency to galling.

TABLE 14
SUMMARY OF BALL BEARING TEST IN LIQUID SODIUM AND SODIUM VAPOR⁽⁶⁷⁾

Bearing Description	Material				Test Temper- ature (°F)	Thrust Load (lb)	Radial [*] Load (lb)	Test Time (hr)	Race Displacement [†] (in.)		Appearance
	Races and Balls	R _C	Retainer	R _C					Before	After	
Angular Contact; New Departure #20208-#5A; 1.5748-in. bore; 3.1496 in. OD; 11 balls, 15/32-in. dia	Stellite-3	56	Berylco-255	44	300	90	14	445	0.002	0.008	Copper smear on balls and races
		56		43	300	90	14	445	0.002	0.009	
Angular Contact; New Departure #20208-#5A; 1.5748-in. bore; 3.1496-in. OD; 15 balls, 15.32-in. dia	Stellite-3	57	None		400	240	42.5	2.5	0.0025	0.0025	No evidence of bearing wear Slight tarnish No evidence of bearing wear Slight tarnish Dark tarnish Dark tarnish
		57	None		300	240	28	1852	0.0025	0.0035	
		57	None		400	240	42.5	2.5	0.0025	0.0025	
		57	None		300	240	28	1852	0.0025	0.0035	
		54	None		900	240	21	956	0.0015	0.0063	
		57	None		900	240	21	956	0.0015	0.0053	
Angular Contact;§ New Departure #20208-#5A; 1.5748-in. bore; 3.1496-in. OD; 15 balls, 15/32-in. dia	Stellite-3	57	None		900	Misa- ligned during test. No load	>200	956	0.0035	-0.0032	Coated with Na and NaO; No apparent damage

*Calculated load based on friction coefficient of 0.8 at journal bearings.

†Measure of overall wear for angular contact bearing.

§Tested in sodium vapor.

TABLE 15
SUMMARY OF TEST ON VARIOUS JOURNAL BEARING - SHAFT COMBINATIONS IN LIQUID SODIUM⁽⁶⁷⁾
(Sheet 1 of 2)

Material Combination* and Test Conditions	Bearing No.	Clearance (in.)		Wear (in.)	Rockwell C Hardness				Appearance
		Initial	Final		Bearing		Shaft		
					Before	After	Before	After	
Bearing: Berylco-25S Shaft: SST 416, (CP) Test Temperature: 300°F Radial Unit Bearing Press.: 63.5 psi Total Revolutions: 211, 461 No. of Starts: 105,730 Test Time: 444 hr	J-1 J-2 J-3 J-6	0.0012 0.0012 0.0012 0.0012	0.001 0.0011 0.001 0.0012	+0.0002 +0.0001 +0.0002 0.0	44 43 43 43	44 43 43 43	37 37 37 37	37 37 37 37	Copper smear on shaft Copper smear on shaft Copper smear on shaft Copper smear on shaft
Bearing: Berylco-10 Shaft: SST 416 (CP) Test Temperature: 400°F Radial Unit Bearing Press.: 190.6 psi Total Revolutions: 950 No. of Starts: 480 Test Time: 2.5 hr	J-9 J-10 J-11 J-12	0.0024 0.0026 0.0026 0.0026	- - - -	- - - -	24 23 23 24	24 24 23 24	40 41 40 41	40 41 40 41	Bearing galled badly Good Bearing galled badly Bearing galled and seized
Bearing: High-Speed Tool Steel, (CuP) Shaft: High-Speed Tool Steel, 18-4-1, (CP) Test Temperature: 900°F Radial Unit Bearing Press.: 63.5 psi Total Revolutions: 75,500 No. of Starts: 47,750 Test Time: 208 hr	J-13 J-14 J-15 J-16 J-17 J-18	0.0018 0.0009 0.0008 0.00084 0.0004 0.0007	0.0008 0.0008 0.0012 0.0015 0.0010 0.0013	+0.001 +0.0001 -0.0004 -0.00065 -0.0006 -0.0006	61 63 64 64 64 62	62 63.5 63 63.5 64 57	61 61 60 60 60 60	62 62 63 63 63 63	Bearing galled and seized Copper plating worn away in loaded region Copper plating continuous; no wear marks Copper plating worn away; bearing had begun to gall Copper plating worn off slightly Galling at wear areas Bearing galled and seized
Bearing: Berylco-25S Shaft: SST 416, (CP) Test Temperature: 300°F Radial Unit Bearing Press.: 127 psi Total Revolutions: 851,000 No. of Starts: 425,500 Test Time: 1852 Hr	J-5 J-3 J-20 J-19	0.0032 0.0032 0.0031 0.0030	0.0045 0.0008 0.0014 0.0036 0.0029 0.0046 0.0055 0.0093	+0.0013 -0.0024 +0.0004 -0.0018 +0.0002 -0.0015 -0.0025 -0.0063	44 45 25 24	44 45 23 24	40 40 40 40	41 41 41 41	Copper smear on shaft Copper smear on shaft Copper smear on shaft Copper smear on shaft

TABLE 15

SUMMARY OF TEST ON VARIOUS JOURNAL BEARING - SHAFT COMBINATIONS IN LIQUID SODIUM
(Sheet 2 of 2)

Material Combination* and Test Conditions	Bearing No.	Clearance (in.)		Wear (in.)	Rockwell C Hardness				Appearance
		Initial	Final		Bearing		Shaft		
					Before	After	Before	After	
Bearing: High-Speed Tool Steel (CP)	J-21	0.0023	0.0015	+0.0008	64	64	55	56	Satisfactory
Shaft: High-Speed Tool Steel, (CP) Test Temperature: 900°F Radial Unit Bearing Press.: 95.3 psi Total Revolutions: 195,278 No. of Starts: 97,639 Test Time: 426 hr	J-22	0.0023	0.0018	+0.0005	63	61	56	56	Satisfactory
	J-23	0.0021	0.00045	+0.0018	61	59			
	J-24	0.0021	0.0021	0.0	63	60	37	37	Satisfactory
	J-24	0.0006	+0.0015	62	61				
	J-24	0.00193	0.0004	+0.0003	64	64	43	42	Satisfactory
			0.0019	+0.00153					
Bearing: HSTS, (CP); Radial Copper Pins	J-37	0.00195	0.0015	+0.00043	57	60	57	57	Satisfactory
Shaft: High-Speed Tool Steel, (CP)	J-38	0.0018	0.0009	+0.00105					
Test Temperature: 900°F			0.0012	+0.0006	60	60	57	57	Satisfactory
Radial Unit Bearing Press.: 115 psi			0.00185	+0.00005					
Total Revolutions: 195,278									
No. of Starts: 97,639									
Test Time: 426 hr									
Bearings: HSTS, (CP); Longitudinal Copper Pins	J-39	0.0023	0.0006	+0.0017	60	57	54	56	Satisfactory
Shaft: High-Speed Tool Steel, (CP)	J-40	0.002	0.0017	+0.0006			57		
Test Temperature: 900°F			0.0055	-0.0035	62	62	54	57	Satisfactory
Radial Unit Bearing Press: 190.6 psi			0.0067	-0.0047			57		
Total Revolutions: 438,230									
No. of Starts: 169,115									
Test Time: 956 hr									
Bearing: Stellite-3	J-1	0.0026	0.0025	+0.0001	61	56	54	59	Satisfactory
Shaft: High-Speed Tool Steel, (CP)	J-2		0.0019	+0.0007			57		
Test Temperature: 900°F			0.0056	-0.0024	57.5	56	54	56	Satisfactory
Radial Unit Bearing Press.: 95.3 psi			0.0041	-0.0017			57		
Total Revolutions: 438,230									
No. of Starts: 169,115									
Test Time: 956 hr									

*(CP) = Chrome Plated
(CuP) = Copper Plated

TABLE 16
SUMMARY OF GEAR TEST IN LIQUID SODIUM^{*(67)}
(Gear Speed: 8.6 rpm)

Gear Description		Hard- ness (R _C)	Test Temper- ature (°F)	(A) [†] Oil Lube Load Rating (lb)	(B) Applied Test Load (lb)	B/A (x100)	Test Time (hr)	Total Revolu- tions	Total Starts
Type	Material								
American Standard 20-deg Stub Tooth; 12-in. diametral pitch, 36 teeth; 1-in. face	SAE 4640 (CP) [§]	52	300	1110	28	2.5	445	211,461	105,730
		400		1110	85	7.6	2	950	480
		300		1110	56	5.0	1852	851,000	425,500
American Standard 14.5-deg full depth; 10-in. diametral pitch, 30 teeth; 1-in. face	SST 440C (CP)	48	900	1000	28	2.8	208	75,000	47,750
		56							
	Tantung-G	57	900	1000	42.5	3.8	426	195,000	97,639
		55							
American Standard 20-deg Stub Tooth; 12-in. diametral pitch, 36 teeth; 1-in. face	High Speed Tool Steel (CP)	54	900	1110	42.5	3.8	956	438,230	169,115
		54							

*Overall evaluation: No visible wear.

[†]Using Lewis Formula: $W = F_{syc}/P_d$ (s = stress; assumed 300,000 psi for heat-treated gear steel).

[§](CP) = chrome-plated.

TABLE 17

ADHESION AND SELF -WELDING TESTS (STATIC LOAD WITH INTERMITTENT TORQUE)^(72,73)
(Sheet 1 of 3)

Test Combination No.	Material	Acceptability*	Pretest Hardness	Max Temp (°F)	Max Torque (lbs)	Max Load (psi)	Post-Test Surface Condition
1	347 SST Cap 347 SST Table	C	85-86Rb 85-86Rb	700	Welded	10,000	Galled and welded
2 (In nitrogen atm)	347 SST Cap 347 SST Table	C	24Rc 22Rc	700	Welded	10,000	Galled and welded
3	Armco Stellite-6 (1)†	C	45-50Rb 55-65R30N	500	Welded	10,000	Galled and welded
4	Inconel-X Cap Inconel-X (Annealed) Table	A	36Rc 27-28Rc	1000	340	10,000	High spots polished High spots polished
5	Ampco No. 18 Cap Stellite-1 Table (1)	C	97-97.5Rb 48-52Rc	1000	160	2,500	Welded plastic deformation 1/4 in. deep High spots polished
6	347 SST Cap Inconel-X (Hardened) Table	B	85-86Rb 36-38Rc	900	260	10,000	Scored lightly and worn Scored lightly
7	347 SST (Chrome-Plated) 347 SST (Chrome-Plated)	C	48Rc 48Rc	1000	300	10,000	Galled and worn slightly Galled, plastic deformation, metal pickup
8	420 SST (Hardened) Cap SAE 52100 Table	C	56.2-71.5R30N 6.5-10Rc	600	Erroneous	2,500	Worn and flaked Scored, plastic deformation, metal pickup
9	Stellite-6 Cap (1) Colmonoy-6 Table (1)	A	55.5-65R30N 49-54Rc	1000	200	10,000	Polished Pitted, smooth
10	304 SST (Chrome-Plated) 304 SST	C	22.5-24R30N 34.5-36R30N	1000	Erroneous	10,000	Galled (erroneous due to apparatus seizure) Galled
11	410 SST (Hardened) 304 SST	C	40.5-42.5R30N 34.5-36R30N	900	250	10,000	Heavy gall Heavy gall, metal pickup
12	431 SST (Hardened) 304 SST	C	51-63R30N 33.2-34R30N	800	180	10,000	Galled Galled, metal pickup
13	446 SST Cap 304 SST Table	C	24.2-28R30N 34.5-35R30N	700	160	10,000	Spalled and torn Scored, metal pickup
14-A §	Malcomized 347 SST Cap (2) 304 SST Table	A	82-88R15N 53.5-56Ra	1000	50	10,000	Smooth Smooth
14-B	Malcomized 347 SST Cap (2) 304 SST Table	A	77-73R15N 51.5-53Ra	1000	120	10,000	Fairly smooth Smooth

TABLE 17
ADHESION AND SELF-WELDING TESTS (STATIC LOAD WITH INTERMITTENT TORQUE)
(Sheet 2 of 3)

Test Combination No.	Material	Acceptability	Pretest Hardness	Max Temp (°F)	Max Torque (lbs)	Max Load (psi)	Post-Test Surface Condition
15-A (In nitrogen atm)	Stellite-6 Cap (1) 304 SST Table	C	60.5-69Ra 52-53Ra	1000	240	2,500	Galled with some exchange of metal at and near the circumference Slightly galled at and near the circumference
15-B	Stellite-6 Cap (1) 304 SST Table	B	60.5-70.5Ra 52-53Ra	1000	300	10,000	Smooth in center, slightly worn near circumference Fairly smooth
16	Stellite-6 Cap (1) Stellite-6 Table (1)	A	64.5-70Ra 77Ra	1000	170	10,000	Smooth, slightly polished around circumference and center Smooth
17	Stellite-6 Cap (1) 347 SST (Chrome-Plated)	B	67-72Ra 62-66Ra	1000	190	10,000	Slightly worn at circumference Slightly worn near circumference
18	"S" Inconel Cap "S" Inconel Table	B	62.5-66Ra 64-65.5Ra	1000	130	10,000	Smooth to pitted in several spots Smooth to pitted in several spots
19	Nitrided 304 SS Cap (3) 304 SST Table	B	94R15N 50Ra	1000	160	10,000	Fairly smooth Fairly smooth
20 (In argon atm)	BN in Nickel Matrix on 304 (4) 304 SST Table	C	2-2.5MoH 50Ra	900	440	1,000	Slightly galled, exchange of metal Worn and slightly galled, exchange of Metal
21-A (In argon atm)	BN in Nickel Matrix on 304 (5) 304 SST Table	A-	3.5Rb 60Ra	1000	105	1,000	Fairly smooth Fairly smooth
21-B (In argon atm)	Bn in Nickel Matrix on 304 (5) 304 SST Table	C	3.5Rb 60Ra	1000	120	2,500	Slightly galled, exchange of metal Worn and galled, exchange of metal
22-A	SAE B1112 Cap 347 SST Table	B	83-86Ra 77-78Ra	1000	50	1,000	Slightly galled Buildup from B1112 steel
22-B	SAE B1112 Cap 347 SST Table	A		1000	70	2,500	Polished, no additional galling Polished, fairly smooth
22-C	SAE B1112 Cap 347 SST Table	A		1000	90	5,000	Polished, no additional galling Polished, fairly smooth
22-D	SAE B1112 Cap 347 SST Table	A		1000	130	10,000	Polished, slight spherical deformation Polished, slight convex deformation
23 (In argon atm)	BN in Nickel Matrix on 304 (6) BN in Nickel Matrix on 304 (7)	C		800	400	1,000	Galled Galled
24	347 SST Cap Post-heat-treated Nitride 347 SST Table (8)	A-	51Ra 46Ra	1000	130	10,000	Smooth, superficial grooving Unchanged

TABLE 17

ADHESION AND SELF-WELDING TESTS (STATIC LOAD WITH INTERMITTENT TORQUE)
(Sheet 3 of 3)

Test Combination No.	Material	Acceptability	Pretest Hardness	Max Temp (°F)	Max Torque (lbs)	Max Load (psi)	Post Test Surface Condition
25	Post-heat-treated Nitrided 347 SST Cap (8)	A	65Ra	1000	120	10,000	Unchanged
	Post-heat-treated Nitrided 347 SST Table (8)		46Ra				Unchanged
26	347 SST Cap	B+	51Ra	1000	240	10,000	Smooth, one groove approx 1 mil deep
	Post-heat-treated Nitreded 347 SST Table (Lapped to 32 rms Finish) (8)		50Ra				Smooth
27	Post-heat-treated Nitrided 347 SST Cap (Lapped to 32 rms Finish)	B+	63Ra	1000	90	10,000	Smooth, center slightly grooved
	Post-heat-treated Nitrided 347 SST Table (Lapped to 32 rms Finish) (8)		49Ra				Smooth, center slightly grooved

*Acceptability:

- A. Acceptable under conditions similar to test.
- B. Limited acceptability under similar conditions (some surface damage).
- C. Unacceptable.

†Notes:

- (1) Stellite-1, Stellite-6, and Colmonoy-6 were welded onto Type 304 stainless-steel specimens.
- (2) Malcomizing is a furnace nitriding process patented by V. T. Malcol of the Chapman Valve Mfg. Co. Nitride case depths were approximately 6 mils.
- (3) Nitrided by the A. F. Holden Co. (salt bath process); 6-mil case depth.
- (4) Coating applied to specimen from a dispersion of NiO and BN in isopropyl alcohol and nitromethane prepared to yield a 20-80 volume ratio of boron nitride to nickel matrix. The "as-deposited" coating was dried under infra-red lamps and then subjected to a reduction step in hydrogen at 500°C. The reduced coating was isostatically pressed at 25 psi. The coating was then sintered in purified hydrogen at 950°C for 1/2 hr and allowed to cool slowly for 2 hr. Final coating thickness was approximately 2 mils. (Vitro Laboratories, West Orange, New Jersey)
- (5) 50-50 volume ratio of boron nitride to nickel matrix. Coating thickness approximately 3-4 mils.
- (6) 10-90 volume ratio of boron nitride to nickel matrix. Coating thickness approximately 6 mils.
- (7) 20-80 volume ratio of boron nitride to nickel matrix. Coating thickness approximately 2 mils.
- (8) Specimens were malcomized at 1050°F for 48 hr and post-heat-treated at 1200°F for 4 hr.

§Two mils ground from cap and table faces of combination No. 14-A.

c. Item No. 3

Tests on prototype components and mechanisms that were expected to operate in sodium in the Fermi reactor were carried out at temperatures ranging from 500 to 1100°F, and reported in References 72 and 73. The harder material combinations generally showed better wear and resistance to self-welding than did the softer materials. Stellite-6 and nitrided stainless steel both performed exceptionally well. Stellite-6 appeared to be best suited for repetitive wear applications, while the relatively thin nitride case on stainless appeared best suited for stainless-steel applications requiring resistance to self-welding and wear resulting from nonrepetitive or infrequent cyclic operation. It should be pointed out that the duration of the tests (except for the gripper) was measured in hours, and that longer exposure time in sodium, on the order of several months, are required to confirm the results of these short-time tests.

Tests on these prototypes are summarized as follows:

Valve:

Mechanism: Stellite-6 cylinder sliding in Type 347 SS valve body
with 6-mil clearance

Environment: Sodium at 500 to 1000°F

Work: 800 cycles in 220 hr; immersed for 700 hr

Results: No sticking or seizure; light rub marks.

Quick Release Pin:

Mechanism: AISI 4130 steel pin (body 35R_C plunger 59R_C)
Type 440C SS, 59R_C load-carrying balls
Chromium carbide 70R_C pin guide

Environment: Sodium at 570°F

Work 1000 cycles, load and release

Results: No wear on pin, balls scored slightly by pin guide

Reciprocating Shaft Seal and Bellows Seal:

Mechanism: Type 440C SS chrome-plated shaft, Stellite-3 and
K-Monel sliding rings, K-Monel fixed rings
Type 347 SS expansion bellows

Environment: NaK at 500°F

Work: 10,000 cycles (6-in. stroke) at 1/2 to 2 cpm

Results: Seal operated very well; no evidence of wear, galling or grabbing; shaft was polished. Bellows failed abruptly after 9990 cycles by complete separation of the top convolution from the welded base plate.

Fuel Subassembly Gripper:

Mechanism: Type 304 SS fabrication throughout, except that cam surfaces were chrome-plated, internal wear ring was weld-coated with Stellite-6, fingers were solid (cast) Stellite-6.

Environment: Sodium at 500 to 1100°F

Work: 3160 gripping cycles over 319 days of sodium exposure.

Results: Wear was insignificant except that the chrome plating on the cams was rubbed off at the finger contact points.

Operation of a similar gripper which has made 900 successful fuel transfers in and out of the EBR-II core is described in Reference 74. The jaw actuator is Type 304 SS, chrome plated, bearing against four Stellite inserts in the jaw-and-funnel support piece. The gripper jaws and funnel are Type 420 SS, chrome-plated. The jaw cams are Stellite, rubbing on the gripper jaws. The jaw pivots are 18-4-1 HSTS hardened and chrome plated.

Core Subassembly Nozzle and Support Plates:

Mechanism: Type 304 SS nozzle assembly (inner cylinder rubbing on outer cylinder) sliding in hole in Type 347 SS support plate, with 6-mil clearance.

Environment: Sodium at 750°F

Work: 2-1/2-in. stroke, 62 cycles

Results:

- 1) Test terminated because of severe chattering; severe uniform galling found between inner and outer cylinder and between outer cylinder and support plate.
- 2) Test repeated with contacting surfaces of nozzle and support plate surface hardened by nitriding and lapped to 32 rms finish; 1000 cycles were completed in 2 hr with evidence of slight rubbing but no wear, then another 5000 cycles were completed in 7 hr with evidence of increased rubbing but no wear, galling, or seizure.

d. Item No. 4

Two identical 4-1/2-in. diameter piston ring seal assemblies were evaluated⁽⁷⁵⁾ for suitability as the Hallam process tube/grid plate seal. The seal between the outside of the process tube and the grid plate opening was to be piston rings on the tube, which would allow the required linear motion between tube and grid plate to take place without losing the seal.

The test results are summarized as follows:

Mechanism:	Four-1/2-in diameter Type 17-4PH SS piston rings in two grooves in a Type 304 SS piston, sliding in a Type 304 SS bore. No special surface treatments were used.
Environment:	Sodium at 625°F
Work:	10,034 cycles over a 3-in. stroke, in 560 hr
Results:	Leak rate tests made with 180°F water showed 0.08% before test, 0.14% after test. Some vertical scoring of rings and bore was found, damage 1 mil deep.

The mechanism was then exposed to an additional 25 cycles in 30 min in 1000°F sodium; the leak rate after this test was 0.07%. The improvement in leak rate was attributed to healing some of the surface damage during the 1000°F test, thus reducing the area for leakage between ring and bore. No estimate of leak test accuracy was made.

e. Item No. 5

Tests were performed⁽²⁵⁾ with gears and sleeve type bearings in 1200°F sodium under loading conditions that duplicated the operation of a proposed control rod design. Meshing gears and journal bearings turned on the same shaft at very slow speeds (about 1-1/2 ft/min) for times up to 3000 hr with total exposure to 1200°F sodium reaching 5000 hr. The gear and bearing were loaded up to 75 lb but no estimate of unit loading was made. Complete tests results are given in Tables 2 and 3.

Five sets of sleeve bearings with molybdenum or TZM rubbing against the same material showed severe galling, even seizure. Ten sets of Hastelloy-C shafts turning on molybdenum bearings showed some galling, but the wear was judged not severe enough to affect performance. Hastelloy-C on Hastelloy-C gave the best wear performance in the bearing tests and in the gear tests. One molybdenum bearing was reported to have a high surface concentration of molybdenum carbide, which probably formed during operation, but no description of the wear suffered by this bearing is given.

f. Item No. 6

Performance of the Fermi oscillator rod bearings in short-time sodium tests was excellent.⁽⁷⁶⁾

The test results are summarized as follows:

Mechanism:	1) Inverted pivot bearing; Kennametal K-138A spherical socket 2-in. diameter, Kennametal K-95 pivot with lubricant grooves 2) Four sleeve bearings; hard facing of Colmonoy-70 or Stellite-6B on aluminum-bronze bearings, Colmonoy-4 or -5 hard facing on shaft
Environment:	Sodium at 500 and 750°F
Work:	75 hr at 300 to 600 rpm and 10 hr at 0.06 rpm
Results:	All bearings in excellent condition; no galling or scoring; hair line cracks in two Colmonoy-5 journals but no spalling.

A second test was run on bearings from the high-power oscillator rod:

Mechanism: 1) Inverted pivot bearing identical with previous test

 2) Two sleeve bearings; Colmonoy-4 hard faced
 Type 304 SS bearings, Stellite-6 hard facing on shaft

Environment: Sodium at 600°F

Work: 96 hr at speeds of 6 to 600 rpm

Results: All bearings in excellent condition; pivot bearing surfaces polished, sleeve bearings burnished.

Fabrication specifications for the safety rod drive unit for the APDA full-scale test facility⁽⁷⁷⁾ recommended Stellite-6 for all wearing parts in contact with sodium or sodium vapor; and Stellite-6 vs Stellite -1 or -3 where the possibility existed of sodium causing self-welding.

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APPENDIX

TABLE A-1
NOMINAL COMPOSITIONS OF BONDED CARBIDES
(Sheet 1 of 3)

Manufacturer Designation	WC	TiC	TaC	NbC	NbTaTiC	Co	Ni	Ta	Mo	Other
Adamas —										
Grade A	94					6				
Grade AA	97					3				
Grade GG	60		28			12				
Canel —										
Mo-NbC				26					74	
WC-Mo-NbC	90			2					8	
Carboloy —										
44A	94					6				
55A	87					13				
77B	57		27			16				
78	76	12	4			8				
78C	85	4	1			10				
120	88					12				
190	70					25		5		
330	56-1/2	20	9-1/2			2	12			
779	91					9				
831	51	32	10			7				
905	92-1/2					4		3-1/2		
907	74		20			6				
999	97					3				
X304OD	88					12				
X3344	2					15				83 CrC
X3345	2					30				68 CrC
X3346	2					45				53 CrC
Firthite HT-77		62-72					30-23			8-5 MoC
Grade 7178	91								7	2 Nb
Kennametal —										
K-8	96-1/2					3-1/2				
K-11	97					3				

TABLE A-1
NOMINAL COMPOSITIONS OF BONDED CARBIDES
(Sheet 2 of 3)

Manufacturer Designation	WC	TiC	TaC	NbC	NbTaTiC	Co	Ni	Ta	Mo	Other
Kennametal (cont'd)										
K-12	87					13				90 TiWC
K-84						10				
K-86	72				20	8				
K-91	80					20				
K-94	86					12		2		
K-96	93					5-1/2		1-1/2		
K-138		80				20				
K-138A		65-70			15-10	20				
K-150A		80			10		10			
K-151		65			15		20			
K-151A		70		10			20			2 Nb
K-152B		64			6		30			
K-153B		54			6		40			
K-161B		73			8		16		3	
K-162B		62		8			25		5	
K-601	90							10		
K-701	87			4		9				
K-801	95-1/2						4-1/2			
K-7178	91			2					7	
K-D4675	97-1/2					2-1/2				5W
SP-112		85					7		8	
TiC-5%W	5	90								
TiC-10%Mo	4	85							10	
TiC-10%Nb	6	84								10Nb
Linde —										
LW-1	93-90					7-10				68 WCrC
LW-5	25						7			

TABLE A-1
NOMINAL COMPOSITIONS OF BONDED CARBIDES
(Sheet 3 of 3)

Manufacturer Designation	WC	TiC	TaC	NbC	NbTaTiC	Co	Ni	Ta	Mo	Other
Sintercast -										
WF-87	91					9				
No. 1		50				50				
No. 4		48				52				
No. 5		48					52			
No. 8		47					53			
No. 10		47					52			
Vascoloy -										
Grade 2A3	89					11				
Grade 2A7	95-1/2					4-1/2				
Grade EE	80	10				10				
Grade EH	54	40				6				

TABLE A-2
NOMINAL COMPOSITIONS OF TOOL STEELS

Manufacturer Designation	Cr	Mo	W	V	Mn	Si	C	Co	Fe
SAE 52100 Steel	1.4	0.3		0.2	0.3	0.2	1.0		Bal
C92	3.75	9.0	1.6	1.2			0.8		Bal
M562	4.1	5.0	6.4	1.9			0.8		Bal
SM18	4.2		18	1.1			0.7		Bal
18-4-1 HSTS	3.5-4.2		17.5-19		0.2-0.4	0.2-0.4	0.5		Bal
AISI-T1	4.1	0.7	18	1.1	0.25	0.25	0.8		Bal
AISI-M1	4	8.5	1.5	1.15	0.25	0.3	0.8		Bal
AISI-M2	4.15	5	6.3	1.85			0.8		Bal
AISI-M3, Type 3	4	6	6.1	2.4			1.0		Bal
AISI-T15	4.75	0.5	12.5	5.0			1.6	5.0	Bal
AISI-M3, Type 2	4.1	6.0	6.0	3.2			1.2		Bal
AISI-M4	4.5	4.5	5.5	4.0			1.3		Bal
AISI-M43	3.75	8.7	1.8	2.0			1.2	8.2	Bal
Rex 49 (WB49)	4.25	3.75	6.75	2.0	0.45	0.3	1.1	5.0	Bal

TABLE A-3
NOMINAL COMPOSITIONS OF SUPER ALLOYS

Manufacturer Designation	Ni	Co	Cr	Mo	W	Fe	C	Si	Mn	Others
Stellite --										
1		Bal	30		12		2-1/2			
6	3	Bal	27-31	1.5	3-1/2 - 5-1/2	3	0.9-1.4	1-1/2	1	
6B	3	Bal	28-32	1.5	3-1/2 - 5-1/2	3	0.9-1.4	2	2	
19	3	Bal	29-1/2 - 32-1/2		9-1/2 - 11-1/2	3	1.5-2.1	1	1	
Star-J	2-1/2	Bal	31-34		16-19	3	2.2-2.7	1	1	
98M2	2-5	Bal	28-32	0.8	17-20	2-1/2	1.7-2.2	1	1	V3.7-4.7
3	3	Bal	29-33		11-14	3	2-2.7	1	1	
Hastelloy-C	Bal	2.5	15.6	16	4	5	0.08			
Colmonoy --										
4	Bal		10			2-1/2	0.45	2.25		B2.0
5	Bal		11-1/2			4.25	0.65	3.75		B2.5
6	Bal		13-1/2			4.75	0.75	4.25		B3.0
75	Colmonoy 6 with TiC particles									
70	Bal		11-1/2		16	3.75	0.55	3.25		B2.5
Inconel-718	Bal		18-1/2	3		19	0.05	0.25		Ti+Al 1.5, 5.1Nb+Ta
Incoloy	34		21			Bal	0.05	0.4	0.85	
Stoody-1	Bal	6			6					
Tantung-G		Bal	27		15	2-5	2.0		1-3	Ta+Nb2-7
2T-12	40		40			20				
2T-14	60		20			20				
2T-15	70		10			20				