# SELF-LUBRICATING COATINGS FOR HIGH-TEMPERATURE APPLICATIONS

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ABSTRACT

Some present-day aeropropulsion systems already impose severe demands on the thermal and oxidative stability of lubricant, bearing, and seal materials. These demands will be much more severe for systems planned to be operational around the turn of the century. The complex gas turbine engines in modern aircraft contain many variable-geometry components with load-bearing surfaces that must be self-lubricating at high temperatures and high gas pressures. In hypersonic aircraft of the future the propulsion systems will also incorporate variable-angle air inlet ramps that will need seal surfaces having the ability to slide with low friction and wear at very high temperatures. In addition, the airframe control surface bearings may see high temperatures and certainly will need to be protected by sliding-contact control surface seals that will be the first line of defense against the temperatures generated by aerodynamic heating at hypersonic velocities.

Solid lubricants with maximum temperature capabilities of about 1100 °C are known. Unfortunately, none of the solid lubricants with the highest temperature capabilities are effective below approximately 400 °C. However, research at Lewis shows that silver and stable fluorides such as calcium and barium fluoride act synergistically to provide lubrication from below room temperature to approximately 900 °C.

This talk describes plasma-sprayed, self-lubricating composite coatings that have been developed at Lewis. Background information is given on coatings, designated as PS100 and PS101, that contain the solid lubricants in a Nichrome matrix. These coatings have low friction coefficients over a wide temperature range, but they have inadequate wear resistance for some long-duration applications. Wear resistance was dramatically improved in a recently developed coating, PS200, by replacing the Nichrome matrix material with metal-bonded chromium carbide containing dispersed silver and calcium fluoride/barium fluoride eutectic ($CaF_2/BaF_2$). The lubricants control friction and the carbide matrix provides excellent wear resistance. Successful tests of these coatings as backup lubricants for compliant gas bearings in turbomachinery and as self-lubricating cylinder liners in a four-cylinder Stirling engine are discussed.

WHY HIGH-TEMPERATURE SOLID LUBRICANTS?

High temperatures in many advanced aerospace and terrestrial applications preclude the use of conventional liquid lubricants on many of the bearing and seal surfaces. This table illustrates some of these applications and the typical temperatures of the surfaces that require lubrication.

## WHY HIGH-TEMPERATURE SOLID LUBRICANTS?

| CURRENT AND FUTURE NEEDS FOR HIGH-TEMPERATURE SOLID LUBRICANTS | TEMPERATURE, °C |
|---|---|
| • AIRCRAFT GAS TURBINE ENGINES | |
| VARIABLE STATOR-VANE BUSHINGS | |
| COMPRESSORS—CURRENT | 350 |
| TURBINES—NEAR FUTURE | 1000 |
| THRUST-REVERSAL BEARINGS | 800 |
| • SUPERSONIC AIRCRAFT (MACH 3-5) | |
| CONTROL-SURFACE BEARINGS | 350 |
| CONTROL-SURFACE RUB SEALS | 650 |
| • HYPERSONIC AIRCRAFT | |
| CONTROL-SURFACE RUB SEALS | 500-2000 |
| • ROTARY ENGINES FOR GENERAL AVIATION | |
| APEX SEALS | 300-650 |
| • ADIABATIC DIESEL CYLINDER LINERS | 600-1100 |
| • STIRLING ENGINES | 760-1100 |
| • AUTOMOTIVE GAS TURBINE ENGINES | |
| REGENERATOR WEAR FACE SEALS | 260-1100 |
| FOIL BEARINGS (MAIN SHAFT) | 650 |

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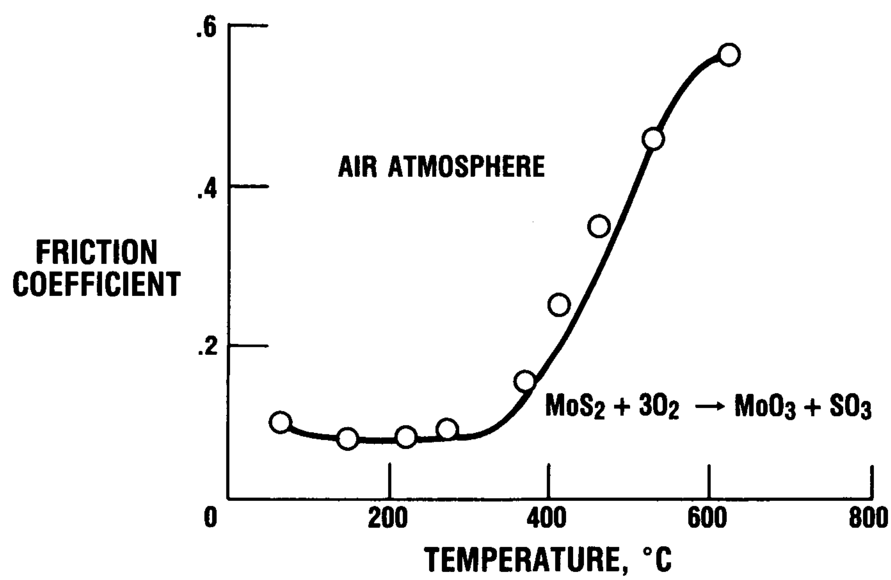
EFFECT OF OXIDATION ON LUBRICATION WITH MOLYBDENUM DISULFIDE

Conventional solid lubricants such as molybdenum disulfide and graphite have limited high-temperature capability because they oxidize in air at temperatures below 500 °C. The sharp rise in the friction coefficient of molybdenum disulfide as the temperature is increased above approximately 350 °C is caused by oxidation of the solid lubricant to solid molybdenum trioxide and gaseous sulfur oxides.

# EFFECT OF OXIDATION ON LUBRICATION WITH MOLYBDENUM DISULFIDE

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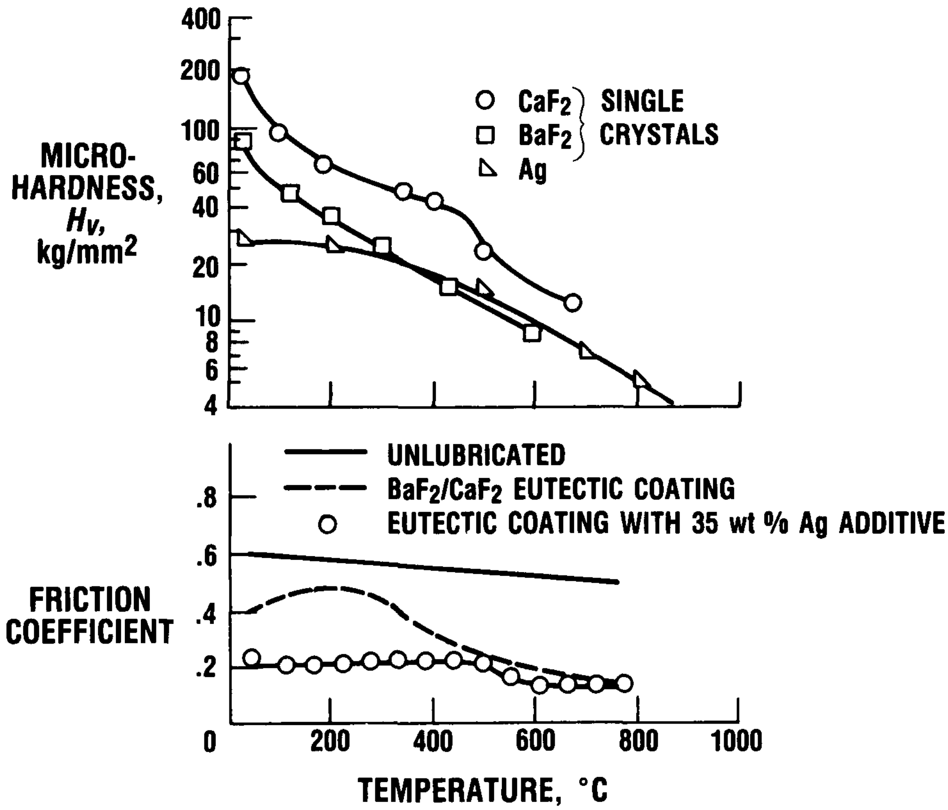
## EFFECT OF TEMPERATURE ON MICROHARDNESS AND FRICTION COEFFICIENTS OF COATING MATERIALS

There appears to be a correlation of the hardness and frictional properties of stable fluorides and silver. Silver is very soft at room temperature and is a good thin-film solid lubricant from room temperature to approximately 500 °C, but it becomes too soft to lubricate at higher temperatures. Calcium fluoride and barium fluoride do not lubricate below approximately 400 °C but provide lubrication at higher temperatures. Silver and the fluorides therefore act synergistically in PS200 to provide wide-temperature-spectrum lubrication.

# EFFECT OF TEMPERATURE ON MICROHARDNESS AND FRICTION COEFFICIENTS OF COATING MATERIALS

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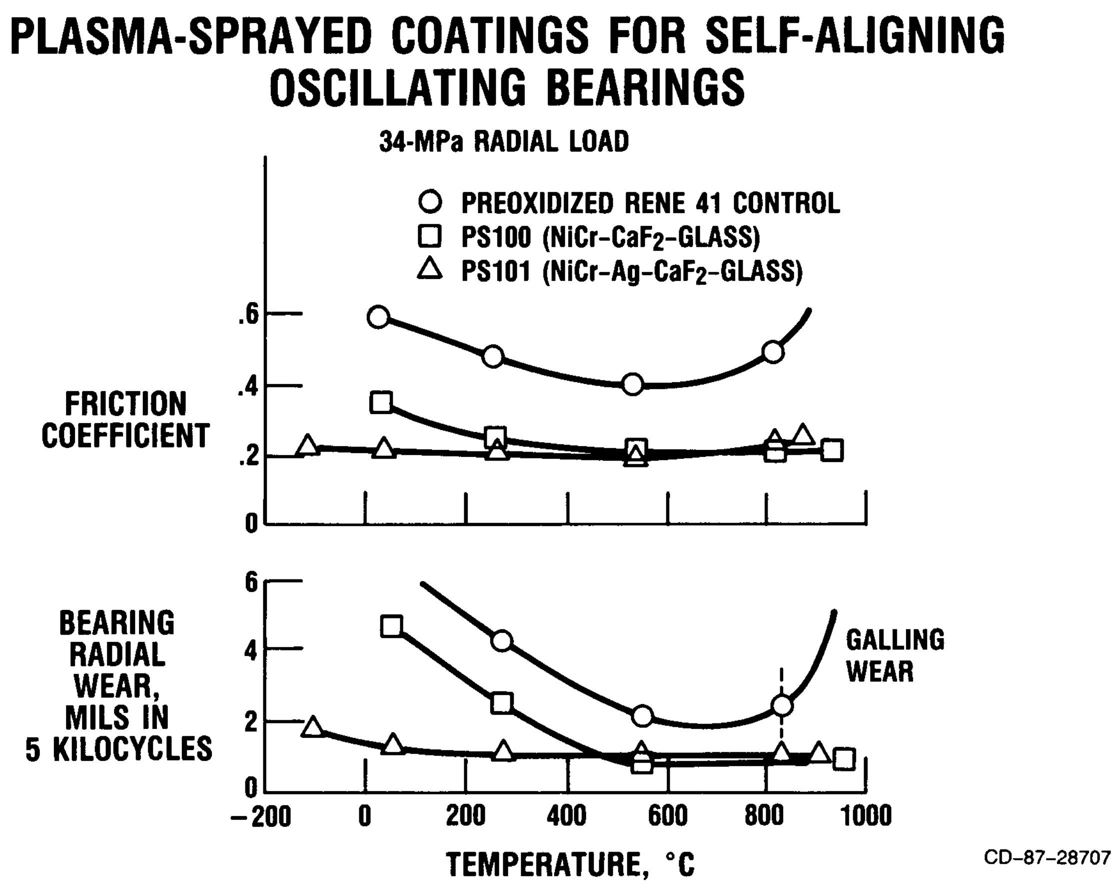
PLASMA-SPRAYED COATINGS FOR SELF-ALIGNING OSCILLATING BEARINGS

The effect of temperature on the friction and wear properties of Nichrome-based, plasma spray coatings containing solid lubricants was determined. The PS100 composition, which contained calcium fluoride as the only lubricant, lubricated above approximately 400 °C, but not at lower temperatures. The transition from high to low friction and wear corresponded to the brittle-to-ductile transition temperature of calcium fluoride at high shear rates. Adding silver as the second lubricant in PS101 resulted in a coating with good lubricating properties from -60 to 900 °C. The Nichrome-based coatings exhibited moderate ductility. This property and their good lubricating properties have led to their application in high-temperature, lightly loaded shaft seals, where some degree of compliance is desirable in the seal material.

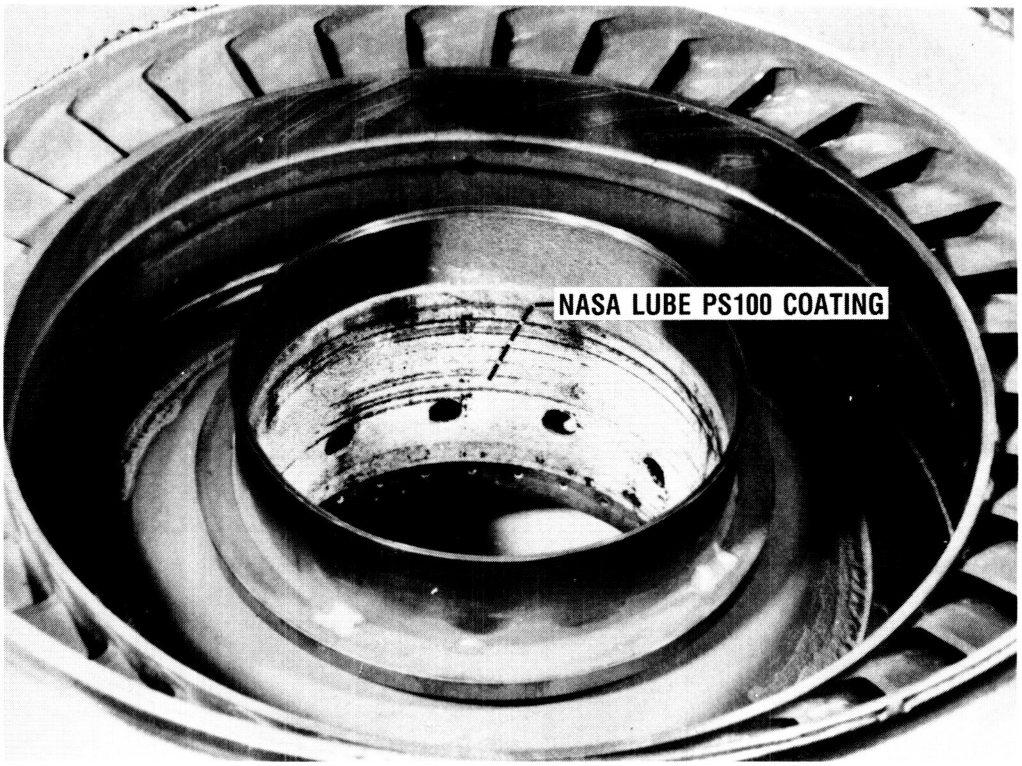


COMPRESSOR/TURBINE SHAFT SEAL OPERATES AT 650 °C

A knife-edge shaft seal from a gas turbine engine was coated with PS100 because PS100 is nongalling in sliding contact with the nickel alloy shaft material and is sufficiently compliant to be plastically deformed by circumferential knife edges on the rotating shaft. Further advantages of this coating, when compared with a porous abradable seal material, are superior erosion resistance and the virtual elimination of secondary leakage. Both of these advantages can be attributed to the absence of the continuous pore structure that is characteristic of abradable seal materials.



## COMPRESSOR/TURBINE SHAFT SEAL OPERATES AT 650 °C

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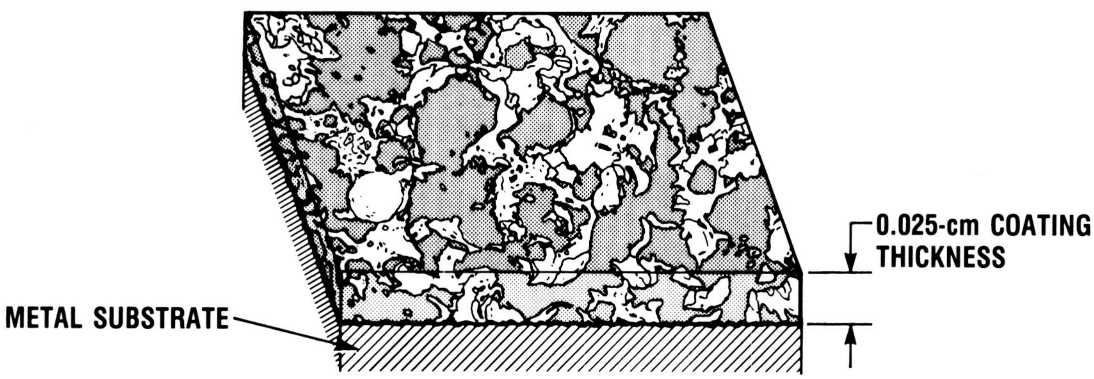
## THE CONCEPT

This figure illustrates the concept of a very wear-resistant, self-lubricating composite coating material (PS200) that was developed at NASA Lewis. The composition is applied by plasma spraying a blend of chromium carbide, silver, and a $CaF_2/BaF_2$ eutectic. The function of each component is summarized in the figure. PS200 lubricates from room temperature to 900 °C in oxidizing or reducing atmospheres.



# THE CONCEPT

### PS200—A PLASMA-SPRAYED COMPOSITE SOLID LUBRICANT COATING




| COMPOSITION | FUNCTION |
| --- | --- |
| 32% Ni ALLOY<br>48% $Cr_3C_2$ | WEAR AND OXIDATION RESISTANCE |
| 10% Ag | LOW-TEMPERATURE LUBRICATION |
| 10% $BaF_2/CaF_2$ EUTECTIC | HIGH-TEMPERATURE LUBRICATION |

- LUBRICATES IN AIR, HELIUM, OR HYDROGEN TO 900 °C

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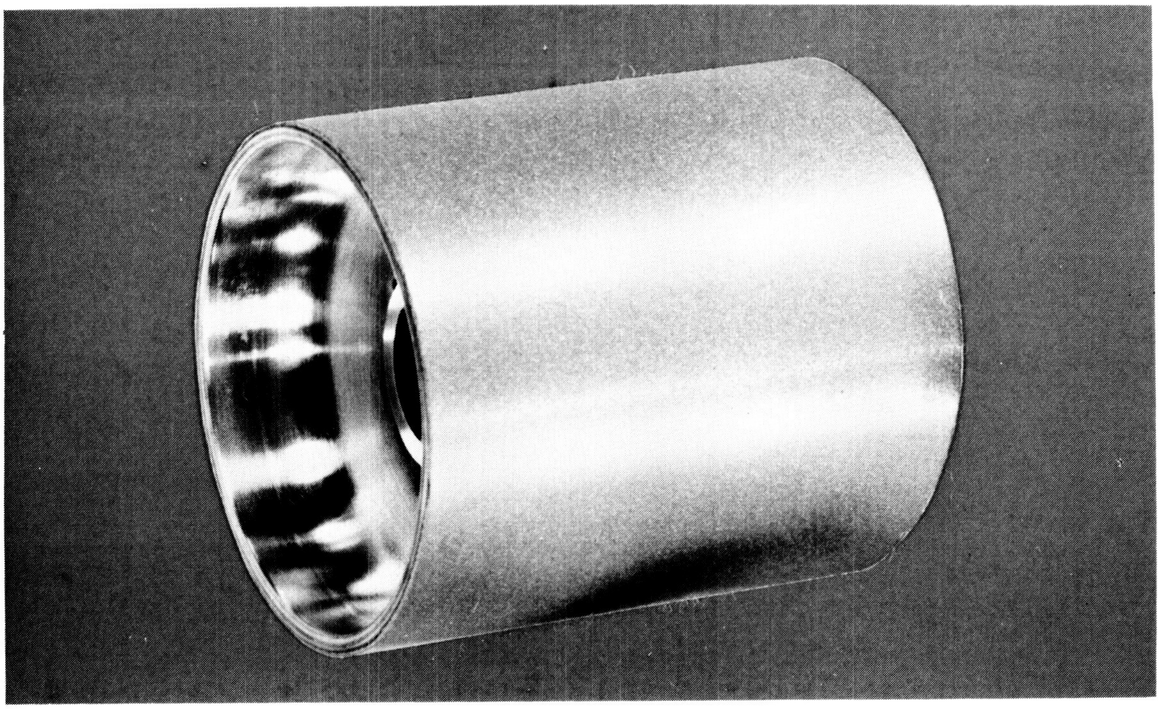
GAS BEARING JOURNAL COATED WITH PS200 AND FINISHED BY DIAMOND GRINDING

A 64-mm-diameter gas bearing journal was coated with PS200. The coating was diamond ground after the plasma-sprayed coating was applied. Even without optical magnification the composite nature of the coating is apparent. (Bright speckles of silver are uniformly distributed throughout the coating.)



## GAS BEARING JOURNAL COATED WITH PS200 AND FINISHED BY DIAMOND GRINDING



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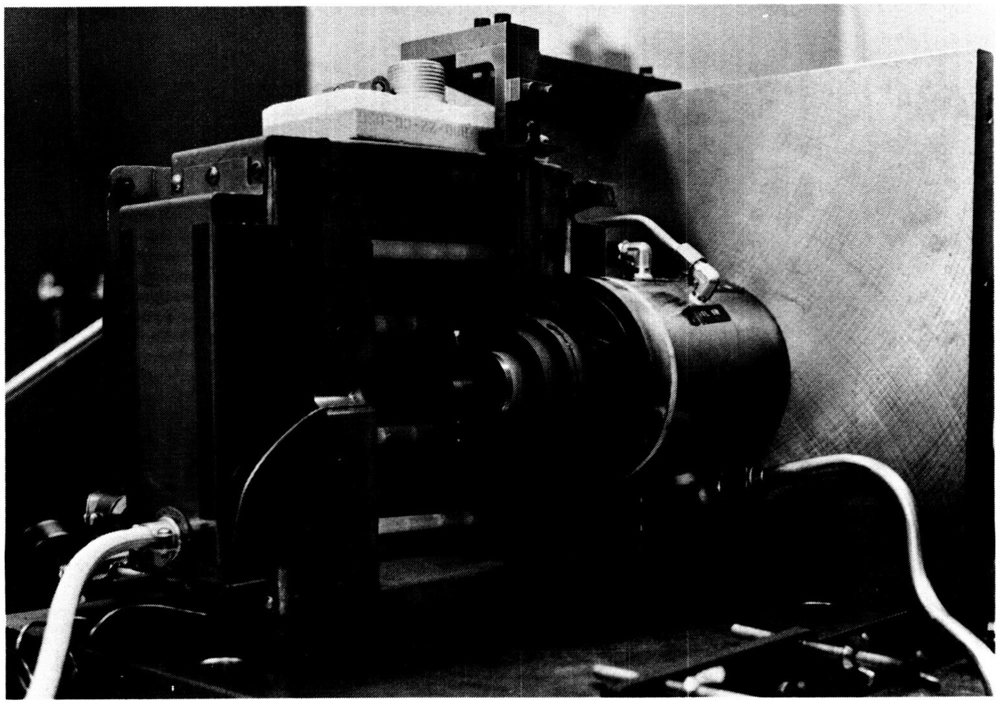
FOIL BEARING UNDER TEST AT 700 °C

One-half of the furnace surrounding the test bearing housing was removed to show a foil bearing under test at 700 °C. Bearing/journal assemblies lubricated with PS200 coatings on the journal have successfully completed over 10 000 start/stop cycles (20 000 rubs) in tests of this type.



# FOIL BEARING UNDER TEST AT 700 °C



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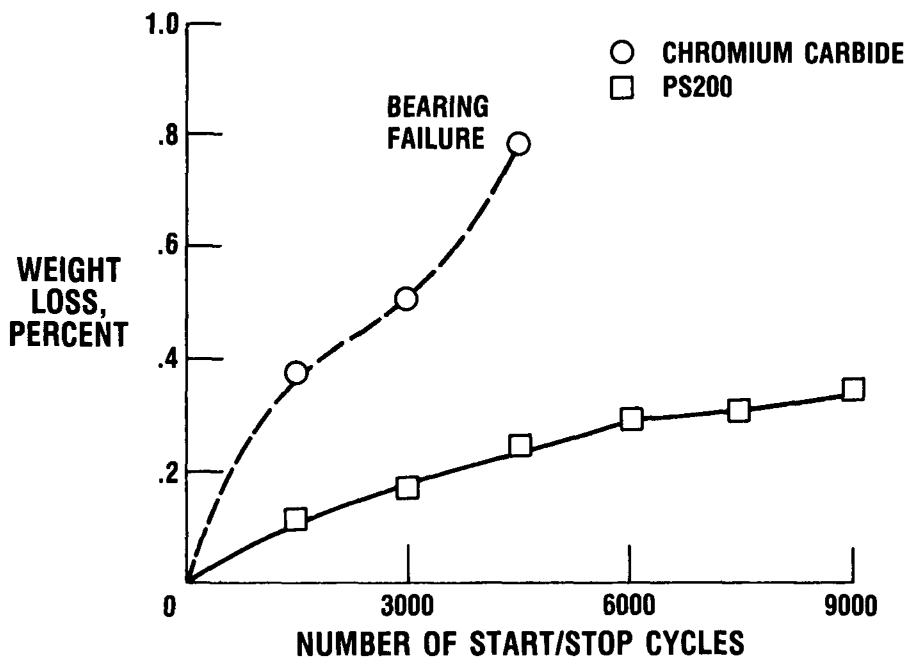
WEAR PROFILES OF PREOXIDIZED INCONEL X-750 FOIL BEARINGS RUN AGAINST JOURNALS LUBRICATED WITH PLASMA-SPRAYED CHROMIUM CARBIDE OR PS200

Inconel X-750 foil bearings wore less rapidly sliding against PS200 than against a baseline chromium carbide coating without solid lubricant additions. Foil bearings sliding against PS200 repeatedly survived the specified 9000 start/stop cycles at programmed temperatures to 650 °C and were in very good condition at the completion of those tests. On the other hand, foil bearings sliding against the baseline coating were excessively worn after 3000 start/stop cycles.

## WEAR PROFILES OF PREOXIDIZED INCONEL X-750 FOIL BEARINGS RUN AGAINST JOURNALS LUBRICATED WITH PLASMA-SPRAYED CHROMIUM CARBIDE OR PS200

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APPLICATION EXAMPLE: STIRLING ENGINE HOT PISTON RING TESTS

The Stirling engine is an externally heated engine. The working fluid in the thermodynamic cycle is typically gaseous hydrogen. Oil lubrication is not used in the piston/cylinder region of the engine. Conventionally, glass-reinforced polytetrafluoroethylene (PTFE) seal rings are located near the bottom of the pistons in the cooler region of the cylinders (<280 °C) because of the temperature limitations of PTFE. The use of PS200 as a cylinder liner material allowed the metal piston ring to be placed at the top of the piston, where the top ring reversal temperature is 760 °C.

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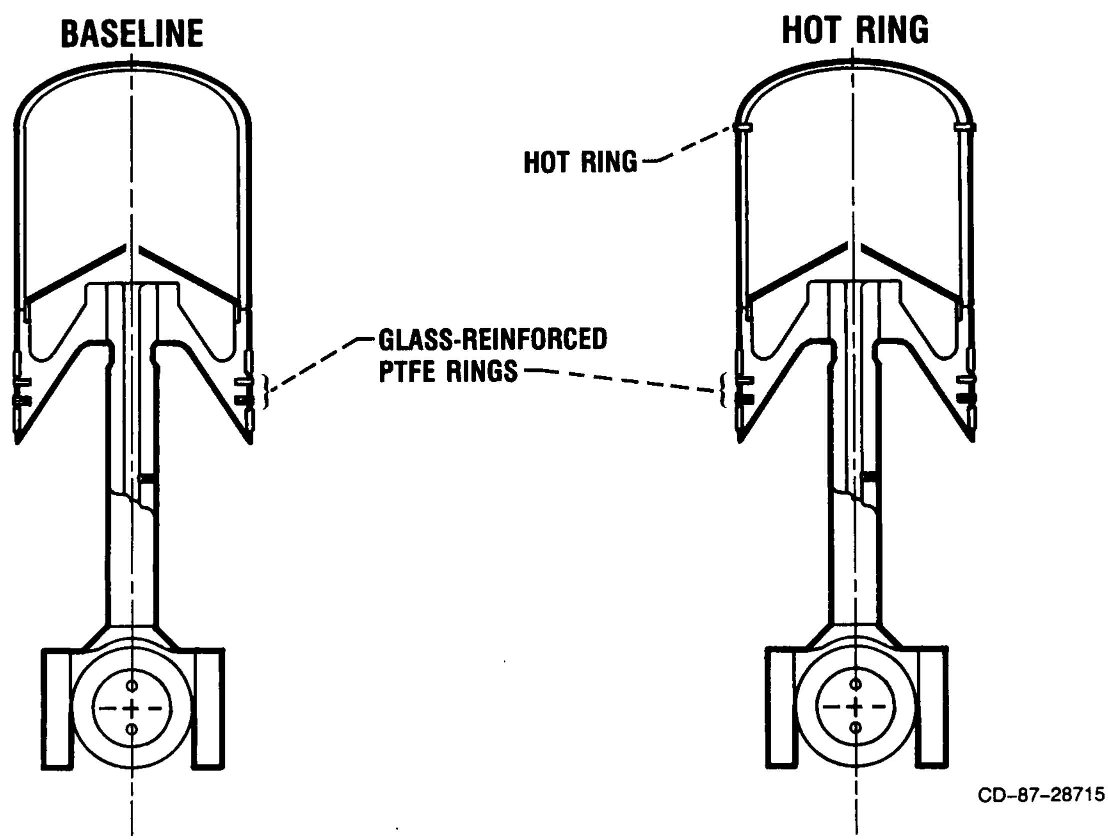
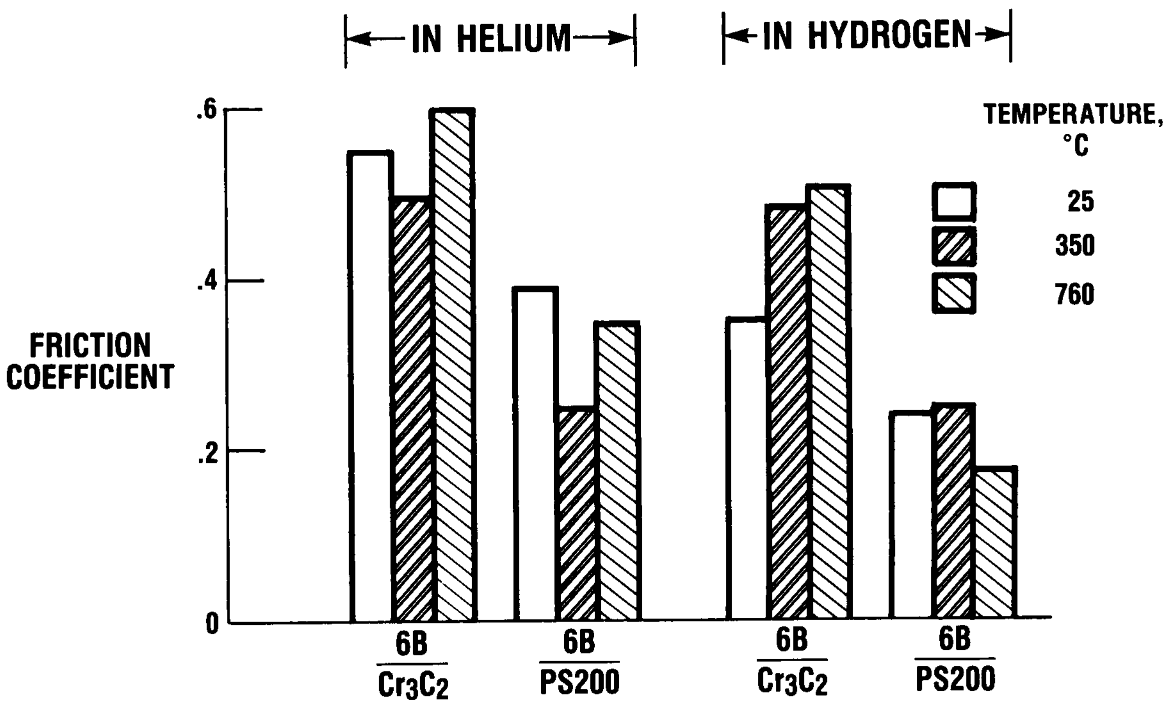


BONDED CHROMIUM CARBIDE AND PS200 IN STIRLING ENGINE ATMOSPHERES

Stellite 6B sliding on PS200 in helium or in hydrogen at 25, 350, and 760 °C demonstrated good frictional properties and excellent wear resistance in laboratory bench tests. These results led to the selection of this material combination for the piston rings and cylinder liner coating in a four-cylinder Stirling engine.

## BONDED CHROMIUM CARBIDE AND PS200 IN STIRLING ENGINE ATMOSPHERES

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## RESULTS OF HOT PISTON RING TESTS

Using a metallic top piston ring sliding against a PS200 piston liner provided a 7 percent increase in net engine efficiency as compared with a baseline engine equipped only with glass-reinforced PTFE rings near the bottom of the piston. The efficiency increase has been attributed to a closing of the clearance gap between the piston and the cylinder wall (appendix gap), which reduced heat loss to the cylinder walls. The 7 percent gain in efficiency correlates well with a theoretical computation that predicted up to a 10 percent efficiency gain if the appendix gap losses could be eliminated.