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GAS-PATH SEAL TECHNOLOGY

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SUMMARY

Improved gas-path seals are needed for better fuel economy, longer performance retention, and lower maintenance, particularly in advanced, high-performance gas turbine engines. Problems encountered in gas-path sealing are described, as well as new blade-tip sealing approaches for high-pressure compressors and turbines. These include a lubricant coating for conventional, porous-metal, rub-strip materials used in compressors. An improved hot-press metal alloy shows promise to increase the operating surface temperatures of high-pressure-turbine, blade-tip seals to 1450 K (2150° F). Three ceramic seal materials are also described that have the potential to allow much higher gas-path surface operating temperatures than are possible with metal systems.

INTRODUCTION

Seals present fundamental and continuing problems in gas turbine engines. Many seals are used in these engines. A large gas turbine engine, such as that shown in figure 1, has over 100 major seals and several hundred minor seals. Seals not only restrict gas leakage, but also provide thrust balancing, meter cooling gas flow, and protect bearing compartments and other mechanical components. Thus, the cumulative effect of sealing practice is appreciable. Our present concern for fuel conservation and need for much better performance retention call for improved seals. Also advanced engines will operate at higher pressures, temperatures, and speeds than current engines. These engines will have to be run "tighter" than current engines. Hence, even better seals will be required. The Lewis Research Center is working in most of the major sealing areas and has an extensive shaft sealing program that has resulted in a very successful lift-pad sealing concept. This concept is excluded from this presentation but is addressed in reference 1 and is briefly described in the sump-fire program presentation (ref. 2).

This presentation addresses the primary-gas-path seals. The main function of these seals is to keep the working fluid in the designed flow path. Thus, the working fluid can contribute to the useful work energy of the engine rather than be added to the wasted energy of leakage.

Primary-gas-path seals can be classified as either outer or inner air seals. The inner air seals are usually labyrinth seals and are the interstage or end seals (fig. 2). These seals are composed of rotating knife edges interfacing with a stationary sleeve of a rub-tolerant and erosion-resistant material. The outer air seals are blade-tip seals (fig. 2) and are located in the gaps between the blade tips and the casing shroud. The casing shroud also contains a rub-tolerant and erosion-resistant material. Of all the seals, the primary-gas-path seals have the greatest effect on performance, particularly on fuel economy.

As an example, compressor efficiency, one measure of performance, is greatly affected by the blade-tip clearance. The compressor efficiency penalty as the ratio of blade-tip clearance to blade height is increased is shown in figure 3. These data were obtained from operational and research compressors (ref. 3). Usually, the high-pressure stages of high-performance compressors have short span heights. Hence, the compressor efficiency is very sensitive to blade-tip clearance. Note in figure 3 that doubling the clearance can mean a 2-percent penalty in efficiency. In addition, stall/surge margins also depend greatly on clearance.

GAS-PATH SEALING PROBLEMS

Operating seal clearances depend on both operating conditions and installation. Operating conditions include maneuver and landing "g"-load deflections, aerodynamic surge and pressure-induced stator deflections, rotor dynamic response to rotor unbalance, thermal transient mismatch between rotating and static seal components, centrifugal growth, and engine-case distortion (ovalization) caused by engine mounting. The first two conditions depend on the operating history of the specific engine. Closer-clearance operation can be attained by using rub-strip liners with initially tight clearances and permitting the interaction of blade tips to wear in the required operating clearances. The remaining conditions are common to all engines of the same model and require basic structural and design modifications to achieve significant reductions in running clearance. We are working on such design concepts, including active clearance control.

Generally, the gas-path seal clearances change with each engine condition, such as idle, takeoff, and cruise. Dimensional changes in the seal support structure are large relative to the seal clearances. The trend toward higher engine pressures and temperatures will tend to increase both seal displacements and erosion.

Although nominally rub-tolerant materials are used today, problems arise during close-clearance operation when severe rub situations are encountered. In these situations the blade tips can wear severely.

Figure 4 shows the surface of a conventional shroud seal material after a severe rub. There are two distinct regions in the wear pattern. On the far right, acceptable rubbing has occurred; on the left, the blade-tip material has been "smeared" or transferred. This smearing is undesirable because the blade tip has worn, resulting in a larger leakage path. However, an almost equally undesirable situation occurs when the shroud material transfers to the blade tip and results in a full 360° rub groove caused by this effective increase in blade height.

In addition to performance loss, poor gas-path seals cause many associated problems. Increased clearance due to rubbing or lack of erosion resistance decreases the stall/surge margin in the compressor. Severe rubbing of blade tips can initiate cracks in the blades and greatly reduce the blade life. Seal wear debris may deposit downstream and affect other components' performance. The most serious consequence of poor rub tolerance is, of course, self-destruction.

The Lewis sealing programs are fully integrated with the Department of Defense's programs on gas-path sealing.

HIGH-PRESSURE-COMPRESSOR TIP SEALS

Prior to the current jumbo jets, compressor tip seal surfaces in civilian engines were not treated with a rub-tolerant material. Because of their relatively low stage pressure ratios and more-rigid structures than current jumbo jet engines, the operating seal clearances in these older engines were set so rubs would never occur. Also fuel prices were relatively low when these engines were designed. Current jumbo jet engine designs, however, could not afford this operating penalty, and rub-tolerant surface materials had to be used. It is estimated that as much as a 4-percent increase in compressor efficiency was obtained by using rub-tolerant surface treatments.

Two classes of rub-tolerant materials are widely used today. One class includes porous metal, cermet, and composite materials. These are generally thermally sprayed or sintered, fine metal particles or metal fibers with low cohesive strength due to their porosity (fig. 5). In principle the particles or fibers are sheared off by bond fracture during a rub. A trade-off must be made between rub tolerance and erosion resistance.

As a result, present shroud seal materials may have either poor rub tolerance or poor gas erosion resistance (fig. 6). Fortunately, both good rub tolerance and good erosion resistance can be obtained through more careful control of the material-processing variables than is presently used, but much work remains to be done in this area.

In figure 6, an NASA experimental material is compared with two conventional shroud seal materials - porous metal and porous cermet. The porous metal material shows very low friction, which indicates good rub tolerance, but is badly eroded by hot gas. The loss of shroud material by erosion is, of course, detrimental to performance. On the other hand, the cermet material had good erosion resistance but poor rub tolerance. Because of its high friction, the cermet blade-tip material would transfer to the shroud material. Obviously, a trade-off must be made between rub tolerance and erosion resistance.

The NASA experimental material, however, shows reasonable friction and excellent erosion resistance (fig. 6). These qualities are achieved by using a plasma-sprayed, solid lubricant coating on the conventional porous metal material. In addition, this lubricant coating is formulated to provide oxidation resistance; and further, it will reduce leakage flow through the porous structure. The photomicrograph in figure 7 is a magnified cross-sectional view of this shroud seal material, showing the plasma-sprayed, solid lubricant surface coating on the porous metal substrate.

Figure 8 shows the same view after a knife-edge rub. Knife-edge rubs are similar to blade-tip rubs. The groove indicates a clean rub, with no metal transfer from or to the knife edge. The knife edge showed no measurable wear. The coating provided a glassy phase, on the rub surface, that acted as a high-temperature solid lubricant. The preliminary results with this lubricant coating material are promising. However, further studies and additional testing, simulating a complete engine environment and operating cycle, are necessary before this material concept can be used in an engine. This work is described in references 4 and 5. A continuing Lewis in-house program is under way to study this approach further.

The other class of material is the plastically deformable surface materials. These materials are almost fully dense and are characterized by their low yield strength. During a rub these materials flow plastically and at the same time offer good erosion resistance (fig. 9). They are generally applied by thermal spray processes. One of the most serious problems with currently used materials is that the debris is not innocuous. A program (Contract NAS3-20054) has recently been started to very fundamentally investigate plastically deformable materials. The goal is to find a better substitute for the currently used materials and at the same time learn how to make more-rub-tolerant, gas-path seal materials.

HIGH-PRESSURE-TURBINE TIP SEALS

In high-pressure turbines, the currently used engine tip seals are segmented shroud seals, which are limited to gas-path surface temperatures less than 1366 K (2000° F). Because of the more severe environment in high-pressure turbines, oxidation and corrosion resistance and the ability to withstand thermal cycling are additional requirements.

As shown in figure 10, some currently used metal tip seals are merely untreated shrouds composed of a cobalt-base alloy that is softer than the blade. However, the rub tolerance is minimal and only very light rubs can be accommodated. A currently used rub-tolerant surface treatment is a direct-sintered nickel-aluminum alloy. It, however, is also limited to 1366 K (2000° F) gas-path surface temperatures. Recently, contractual work (NAS-3-18905) has led to the completion of a development effort on an improved shroud seal material, a hot-pressed, slightly porous, nickel-chromium-aluminum alloy that is yttria stabilized. This alloy meets all operating requirements and extends operation to about 1450 K (2150° F). This seal material has been successfully engine tested, and presently the laboratory fabrication process is being upgraded for larger volume production. Further engine tests are being conducted under this contract.

With current seal material technology, higher turbine-inlet-temperature c[illegible] can only be obtained by using cooling schemes on the hot-gas sur[illegible] o such schemes are shown in figure 11 - transpiration cooling and [illegible] cooling. However, the performance penalty for this additional cooling air is great, and larger clearance operation is necessary to avoid rub smearing of the cooling holes.

Currently, ceramic turbine shrouds are being developed as a means of extending uncooled-gas-path-surface operating temperatures. Three ceramic material systems are being investigated - zirconia, silicon carbide, and silicon nitride (fig. 12). The zirconia system is a graded cermet. A metal-rich composition is first directly sintered to the metal supporting shroud, and then layers of progressively more ceramic-rich materials are sintered until a surface layer of 100-percent zirconia is achieved. Finally, a porous layer is bonded for rub tolerance. This work is sponsored by the Navy. A related Lewis program (NAS3-19759) is investigating plasma spraying of this cermet system. If successful, this approach would have a large cost advantage over the direct-sintering process. Also it may be applied to existing shrouds and thus extend their life and/or operating temperatures.

Two Lewis programs are studying silicon carbide and silicon nitride systems. One, under contract NAS3-20081 is investigating density variations in and structural configurations of these systems. Another program (NAS3-20082) is investigating silicon/silicon carbide substrates coupled with a series of abradable surface layers, in order to find the most optimum combination.

In addition to improved shroud seal materials studies, work is being conducted on the mating turbine blade tips. Both treated and untreated turbine tips are being studied. Recent work has shown that turbine blade tips can wear under certain conditions. Abrasive grits such as aluminum oxide and silicon carbide bonded to the blade tips are being evaluated.

All these ceramics approaches show much promise but must overcome many problems, particularly the thermal shock resistance common to all ceramics and the attachment of the ceramic to the metal supporting structure because of differences in thermal expansion properties. Satisfactory progress is being made and we probably will see ceramic seal technology applied in the 1980's.

CONCLUDING REMARKS

Only a few of the many ongoing programs in gas-path sealing technology at the Lewis Research Center have been presented. Promising high-pressure-compressor and turbine tip seals that will make possible improved performance are being developed. Because of the necessity for conserving energy, there is a pressing need to improve and better retain engine performance in an economical, low-maintenance, and safe way. This goal can be achieved by improved seal technology, which will be even more critical in meeting the requirements of future high-performance engines.

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3. Mahler, Frederic H.: Advanced Seal Technology. PWA-4372; AFAPL-TR-72-8, Pratt & Whitney Aircraft, 1972.
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5. Shiembob, L. T.: Development of Abradable Gas Path Seals. (PWA-TM-5081, Pratt & Whitney Aircraft; NAS3-18023) NASA CR-134689, 1974.

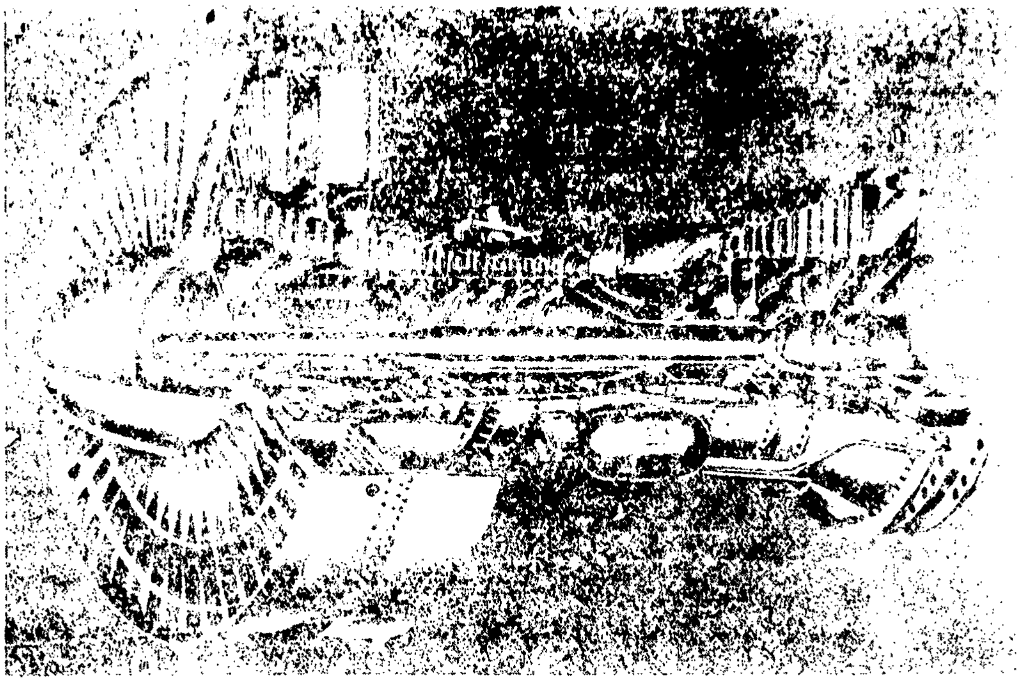


Figure 1.- Typical turbofan engine.

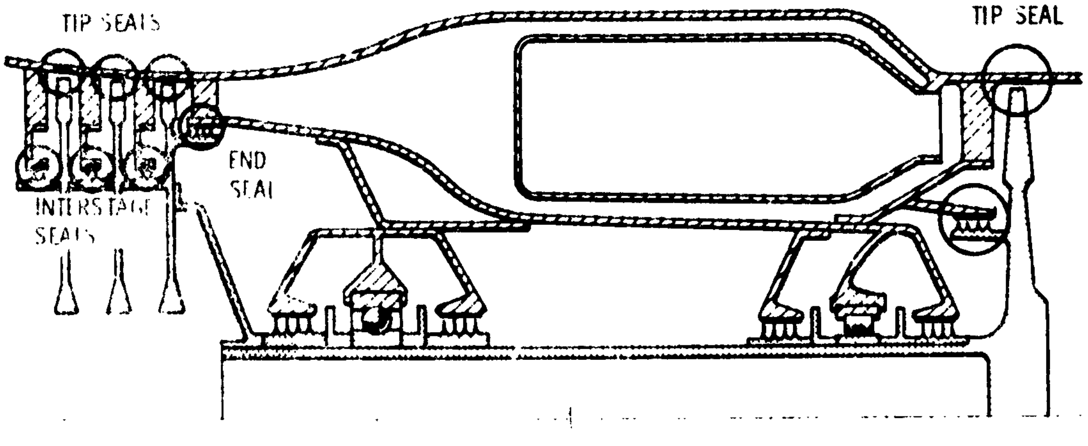


Figure 2.- Primary gas-path seals.

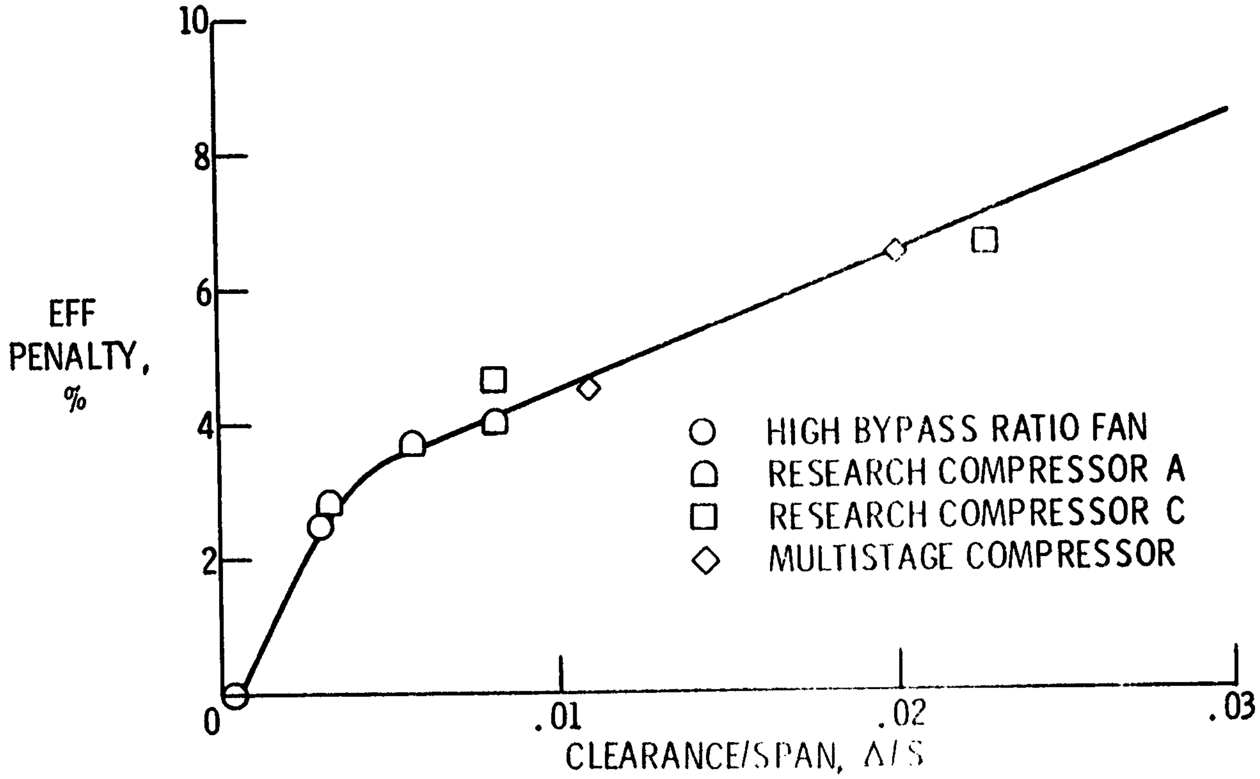
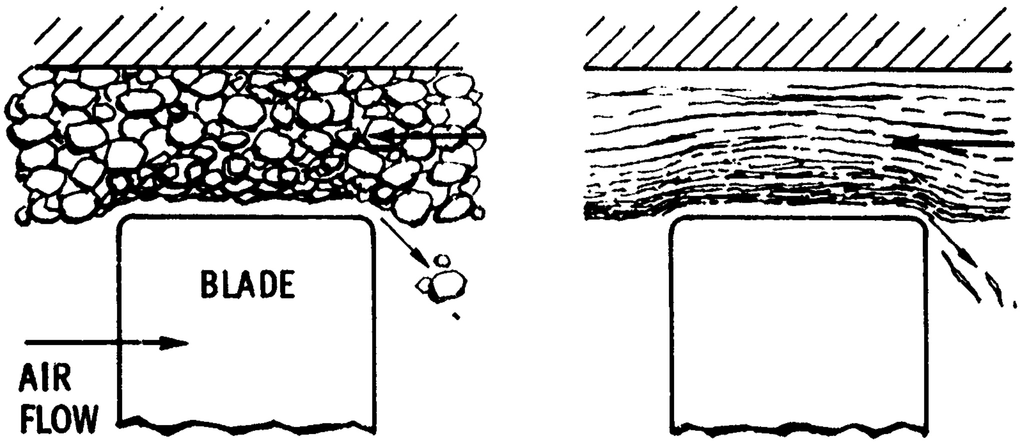


Figure 3.- Compressor performance penalty. (From ref. 3.)

Figure 4.- Shroud seal rub.



(a) Sintered metal particles. (b) Sintered metal fibers.

Figure 5.- Compressor tip seals with porous-metal surface treatments.

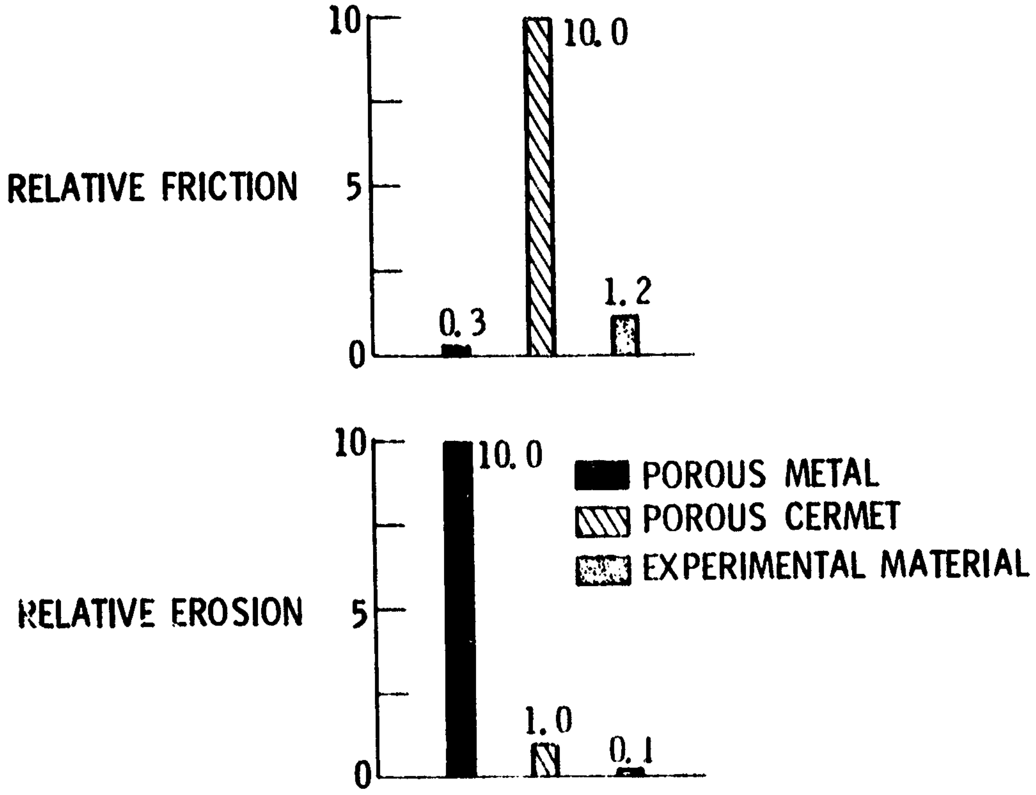


Figure 6.- Friction and erosion of shroud seal materials.

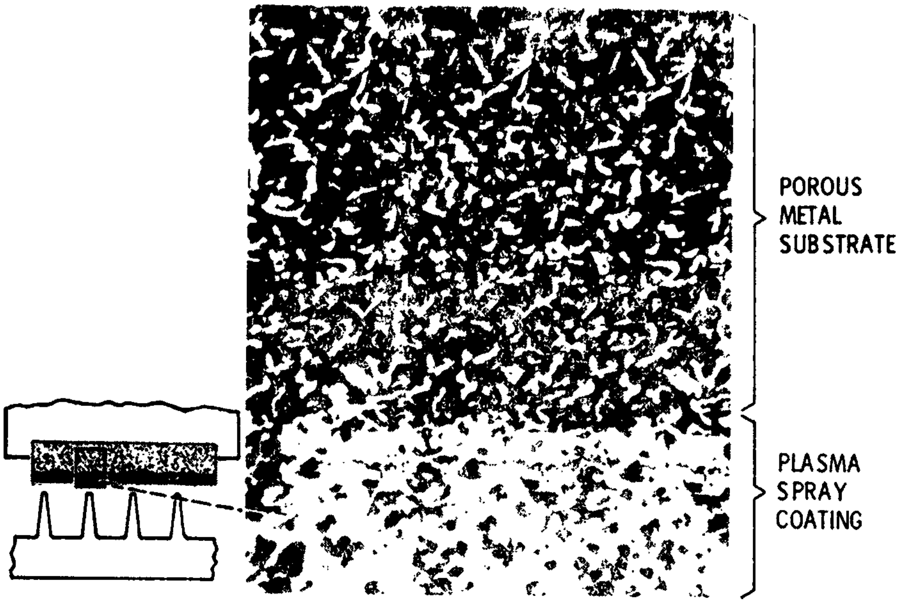


Figure 7.- Photomicrograph of NASA experimental seal material.

Figure 8.- Photomicrograph of rub groove in NASA experimental seal material.

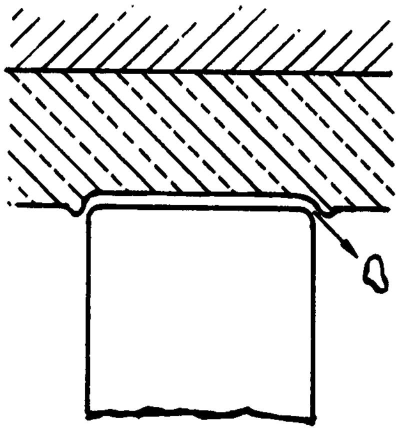
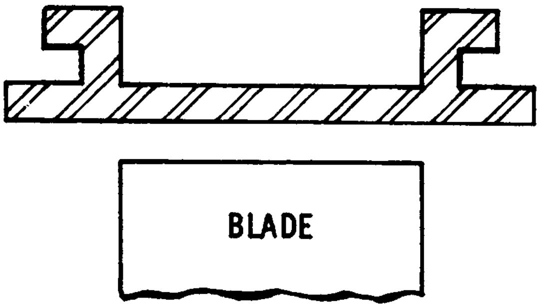
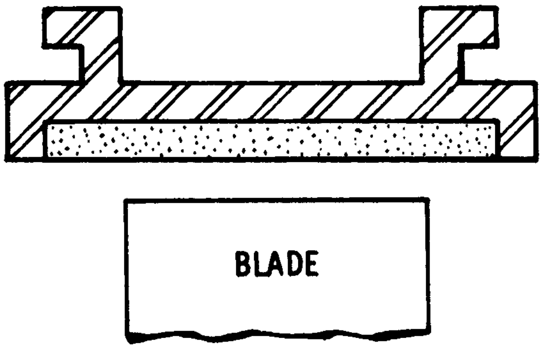


Figure 9.- Rub behavior of thermally sprayed, plastically deformable surface treatments.

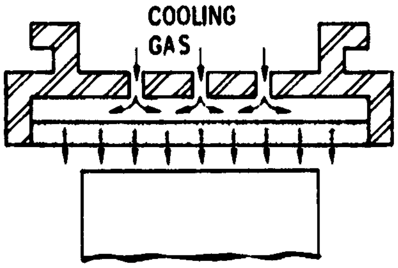


(a) Untreated cobalt-base shroud.

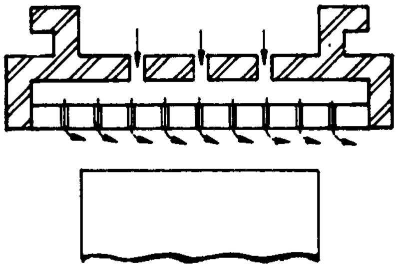


(b) Shroud with rub-tolerant surface treatment of hot-pressed Ni-Cr-Al-Y alloy or sintered NiAl alloy.

Figure 10.- Metal turbine tip seals.



(a) Transpiration cooled.



(b) Film cooled.

Figure 11.- Cooled turbine tip seals.

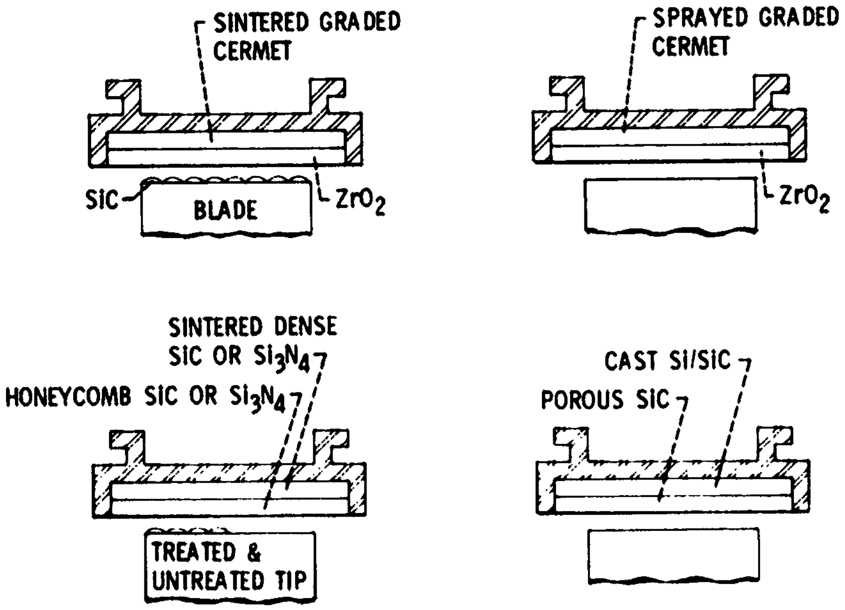


Figure 12.- Ceramic turbine tip seals.