A Review of Engine Seal Performance and Requirements for Current and Future Army Engine Platforms

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Abstract

Sand ingestion continues to impact combat ground and air vehicles in military operations in the Middle East. The T-700 engine used in Apache and Blackhawk helicopters has been subjected to increased overhauls due to sand and dust ingestion during desert operations. Engine component wear includes compressor and turbine blades/vanes resulting in decreased engine power and efficiency. Engine labyrinth seals have also been subjected to sand and dust erosion resulting in tooth tip wear, increased clearances, and loss in efficiency. For the current investigation, a brief overview is given of the history of the T-700 engine development with respect to sand and dust ingestion requirements. The operational condition of labyrinth seals taken out of service from 4 different locations of the T-700 engine during engine overhauls are examined. Collaborative efforts between the Army and NASA to improve turbine engine seal leakage and life capability are currently focused on noncontacting, low leakage, compliant designs. These new concepts should be evaluated for their tolerance to sand laden air. Future R&D efforts to improve seal erosion resistance and operation in desert environments are recommended.

Introduction

Extended military operations in Afghanistan and Iraq continue to tax Army helicopter engines such as the T700-701C, used in the U.S. Army's UH-60L Blackhawk, due to sand and dust ingestion erosion (ref. 1) resulting in decreased engine power and increased engine overhauls due to shortened component lives. Additionally, operational tempos in Afghanistan and in Iraq for the Blackhawk are roughly 3 times their normal mission levels. Through 2004, Blackhawk operations in Afghanistan totaled roughly 6000 flight hours and in Iraq totaled 73,000 flight hours (ref. 2). Reliance on inlet particle separators (IPS) and filter systems is necessary to maintain engine operational readiness. Results from the field indicate that improvements are needed in labyrinth seals found in the Blackhawk helicopter.

An overview is given of the sand and dust ingestion requirements of the T-700 engine followed by observations of how sand has affected engine components and performance in the field. The sand flow path is discussed with respect to the #3 labyrinth seal, the compressor discharge pressure seal, the inner balance piston seal, and the labyrinth seal located on the 1st stage cooling plates. General observations are made with actual components from the field along with a short discussion of their inspection criteria and options for repair. These discussions are specific to operations at Corpus Christi Army Depot (CCAD) where the T-700 engine is currently overhauled. Finally, a summary is presented of noncontacting seal development efforts by the government along with suggestions for future seal development.

History of the T-700 Engine Development With Respect to Sand and Dust Ingestion

During the Vietnam War, in which the UH-1 Huey was used extensively for combat operations, search and rescue and medical evacuation, many engine maintenance problems surfaced including sand ingestion. Issues included primitive maintenance conditions, low service life, high spare parts requirements, high fuel consumption, frequent maintenance, as well as vulnerability to ground fire (ref. 3). Moreover, approximately 60 percent of unscheduled engine removals were a result of foreign object damage (FOD) or sand ingestion (refs. 3 and 4). Sand and dust particles could become airborne during a Nap-of-the-Earth (NOE) operation and then be ingested by the engine (ref. 5). It was clear that a need existed for more reliable, maintainable, and survivable helicopter engines with better fuel consumption.

Due, in part, to these experiences in Vietnam, the Army began to look at the next generation utility helicopter. A replacement for the UH-1 would come in the form of the Utility Tactical Transport Aircraft System (UTTAS) program. Requirements included twin engines with the ability to fly with one engine operating and the ability to lift a crew of 3 with a unit of 11 combat-equipped troops at a 4000 ft-altitude on a 95 °F day (ref. 3). The 4000 ft, 95 °F specification is a minimum requirement concluded from studies of areas of the world likely needing helicopter support (ref. 5). Additional requirements were 1500 shaft horsepower, 20 to 30 percent reduced fuel consumption, an integral particle separator, reduced logistic support, improved survivability, and 37 to 50 percent reduced maintenance man-hours. The design life of the engine was targeted for 5000 hr with 15,000 hr on low-cycle fatigue life and 1500 hr mean time between failure requiring overhaul (ref. 4). Missions for the UTTAS helicopter included tactical troop transport, transport of equipment and supplies combat assault and extraction, medical evacuation, administrative/command troop transport, and transport of maintenance/medical personnel/supplies/ equipment (ref. 6). The helicopter would need to perform multiple take-off/landings, hover, and NOE operations (ref. 5). General Electric's GE-12 engine fit the Army's UTTAS requirements and was eventually selected and redesignated T700-GE-700 (ref. 4). Army engine sand and dust ingestion test specifications for the Utility Tactical Transport Aircraft System (UTTAS) program were originally developed from Air Force jet engine test specification MIL-E-8593. The requirements included 10 hr of operation, using sand particles ranging from 0 to 200 μm, at a concentration of 53 mg/m^3, and no more than a 5 percent shaft horsepower (SHP) loss and a 5 percent specific fuel consumption (SFC) increase (ref. 5). The Air Force revised this specification to MIL-E-5007 revision C in the 1960s by increasing the particle distribution to 0 to 1000 μm, known as C-spec sand. Sand sampled from Saudi Arabia has a composition similar to that of C-spec sand. For qualifying the T700-GE-700 these specifications were revised to 50 hr of testing, using C-spec sand at the same concentration level above. SHP losses were limited to 10 percent and SFC increases were limited to 15 percent (ref. 5).

Observations of the Effects of Sand and Dust Ingestion on Engine Performance

General Description

Early on the Army experienced excessive engine erosion due to the lack of an inlet particle separator during training exercises in 1963 and 1964 at Fort Benning, Georgia. The Army's 11th Air Assault Division observed that helicopter engines were removed with only 300 hr of service due to sand erosion. It was found that helicopters flown in tight formations tend to increase the concentration of sand in the air which is then ingested by the engine. It was also found that the sand at Fort Benning was made of 98 percent quartz with 50 to 60 percent in the 210 to 420 μm size range (ref. 7).

In 1980 and 1981 the Army deployed a fleet of Blackhawks, Chinooks, and Cobras to the Egyptian desert to evaluate desert operations in what is known as Bright Star I and II. Blackhawk helicopters were

equipped with integral particle separators (IPS) on the T700-GE-700. No engines were removed due to loss of performance from the 15 Blackhawk helicopters over the course of over 1200 engine flight hours and 2000 sand landings (ref. 8). Upon inspection after Bright Star II operations, the T-700 engines exhibited 1st stage leading edge peening with some roll-over at the compressor with tip rounding on further stages, axial and air seal clearance increases, and also plugging of the combustor and turbine cooling air passages with sand particles (ref. 5). Although significant engine improvements were made in terms of engine reliability and durability, specifically with the IPS, the Army felt that extended operations in severe environments merited further improvements.

In more recent military operations in Iraq, "it became immediately evident that the previous desert exercises and commercial operations had failed to predict the severity of Desert Shield/Storm conditions." (ref. 5) Engine hardware exhibited similar erosion from deployments in Egypt but to a greater degree (ref. 5). Tabakoff and Hamed note that helicopter operations in these sandy conditions were limited to 50 to 250 hr (ref. 9).

Results of helicopter operations in a desert environment have shown erosion of compressor blades, stators, and shrouds. In the turbine section cooling air exit holes have been "glassed" over. Also fine particles have been impacted on internal passageways and turbine nozzles. These effects have resulted in decreased power, increased SFC, and decreased surge margin (ref. 5). In general, sand erosion was found to be more prevalent in the compressor than the turbine (ref. 3). Edwards and Rouse (ref. 5) specifically address the following performance losses due to a 1 percent loss in compressor efficiency:

1. At constant turbine temperature, a 1 percent loss in compressor efficiency results in a 3 percent drop in power.
2. At constant power, a 1 percent loss in compressor efficiency results in a 1 percent increase in turbine temperature.
3. At constant SHP, a 1 percent loss in compressor efficiency results in a 1 percent increase in SFC.

It is clear that these performance losses impact military operations such as available contingency power, engine component life, and decreased mission range.

The following sections of the paper focus on the sand pathway through the T-700 engine and its impact on four labyrinth seals: the #3 labyrinth seal, the compressor discharge pressure seal, the inner balance piston seal, and the cooling plate seals.

Sand and Dust Flowpath Through the T-700 Engine

The inlet particle separator (IPS), figure 1, on the T-700 is composed of the swirl frame, front frame, and main frame. The swirl frame, at the front of the engine, contains angled swirl vanes which forces the air into a rotational motion. Sand and other debris are separated from the air through inertia. The particles move to the outer diameter of the main frame, into a scroll case, and out of the engine through a blower. The "clean" air in the swirl frame is re-oriented to the compressor inlet via the front frame deswirl vanes (ref. 10). The IPS is designed to provide 90 percent protection from FOD (i.e., stones, ice, metal particles, sticks, leaves, etc.) and separates 85 to 95 percent of sand and dust particles (ref. 4).

Effect of Wear on Labyrinth Seals

Labyrinth seal teeth are designed to be thin with sharp corners. Thin teeth limit any heat generation to the rotor which is integral to most labyrinth teeth designs. Sharp corners result in a lower discharge coefficient which lowers the air leakage across the labyrinth teeth.

Studies by Hamed and Tabakoff have shown that erosion of engine components is dependent on the particle material, geometry, its kinetic energy, and impingement angle on the component. Erosion is also dependent on the component geometry and material (ref. 11). The rate of erosion is found to increase with particle velocity and temperature. Geometrically angular and sharp particles such as aluminum-oxide
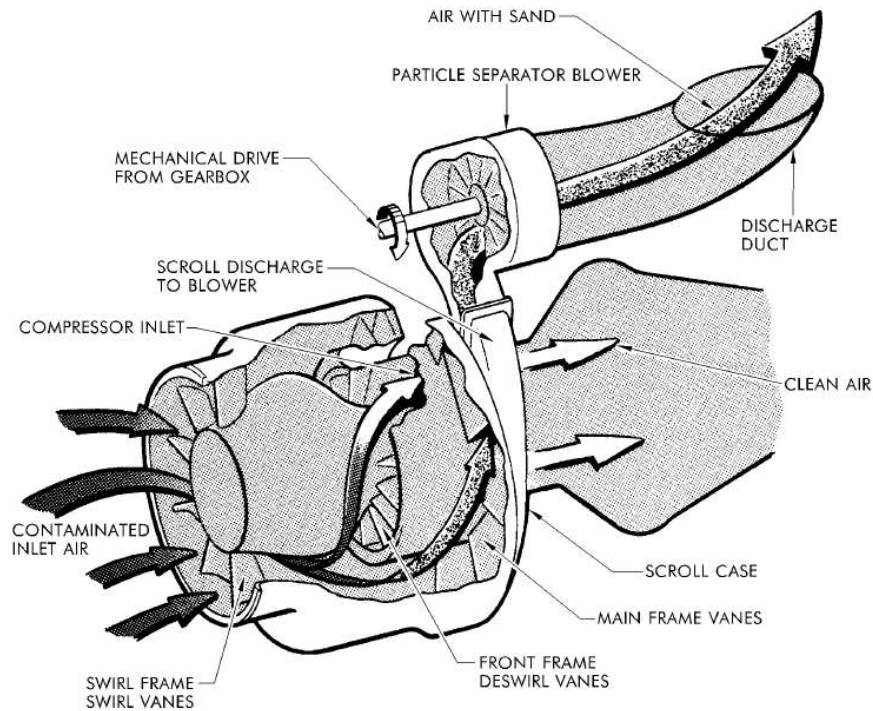
Figure 1.—Inlet particle separator.

were found to be more erosive than silica sand and fly ash. Material erosion rate also varies by the materials' ductile or brittle characteristics. According to Hamed et al. ductile materials erode more quickly at lower incidence angles (e.g. 15° to 30°), while brittle materials erode more quickly at higher incidence angles (e.g., > 60°) (ref. 11). The incidence angle is defined by Hamed et al. as the angle of impact of the particle with respect to the surface with 90° being perfectly perpendicular to the surface.

With this criteria, labyrinth seal wear can be characterized by eroded clearances, blunted knife edges, worn surfaces, and impacted sand on surfaces. Increased clearances and blunted or rounded knife edges contribute to loss in sealing efficiency and increased leakage while worn surfaces may impact the labyrinth seal integrity. In the following sections, sample labyrinth seals removed from T-700 engine overhauls will be compared against these seal wear characteristics.

Engine Overhaul Operations at CCAD

A short description is given of the current T-700 overhaul process at Corpus Christi Army Depot (CCAD). The Reliability Improvement thru Failure Identification and Reporting (RIMFIRE) program and the Recapitalization (RECAP) program are described.

General Description

T-700 engines are inducted into CCAD for overhaul or repair through the Defense Logistics Agency (DLA). A team of technicians can usually disassemble the T-700 in a day. The T-700 engine overhaul process is time-critical. The main focus or goal is to overhaul the engine as quickly and as safely as possible so that the engine can be returned to the field. Inspections on various parts are performed in the most cost-effective manner possible. For example, seal inspections contain visual and quantitative criteria where measurements may be necessary. If a crack is found through visual inspection, the part is automatically scrapped and the remaining quantitative criteria is not performed. Parts that are repairable are reworked. The Storage, Analysis, Failure Evaluation and Reclamation (SAFR) program at CCAD

stores both scrapped and repairable parts. Scrapped parts are set aside for further analysis, while repairable parts are stored until needed.

Engine part inspections at CCAD for the T-700 follow guidelines found in Army DMWR 1-2840-248-1 (ref. 10) volume 1, Depot Maintenance Work Requirement for Engine, Aircraft, Turboshaft. Inspection criteria are given for each part. For example, inspection criteria for the compressor discharge rotating seal include usable limits, and repairable limits with corrective actions. Also, the teeth are inspected for cracks, nicks, gouges, and dents. Finally, tooth wear is quantified by measuring the seal diameter and comparing them to minimum diametral limits with corresponding repair guidelines.

RIMFIRE and RECAP

Previous engine documentation standards included the Electronic Deficiency Report System (EDRS) and the DA Form 2410, Component Removal and Repair/Overhaul Record. Both databases provided a preliminary assessment of engine problems. Further detailed investigations were not conducted which limited corrective actions to recurring engine problems.

RIMFIRE is a reporting system used by the U.S. Army to qualitatively identify part failures and removals in the T-700 engine. Initiated in September 2003, experienced inspectors have documented part failures and removals at the T-700 overhaul facility at CCAD using pictures with descriptions. Then, the information is stored in a web-accessible database for further analysis.

The RIMFIRE database has been used to determine what components have caused the majority of engine removals and the common component failure mode. Recent engineering review board results indicate that low power or torque was the number one reason for engine removals. The top three causes for this were stage 1 blisk erosion, gas generator stator 1st stage shroud spalling, and 1st stage turbine blade oxidation.

The inspector's handbook documents T-700 engine inspection criteria for the Electrical system, Accessory Module, Cold Section Module, Hot Section Module, and the Power Turbine Module. The inspection criteria is used to qualitatively grade the condition of a part based on pre-defined wear standards (e.g., light, moderate, or severe wear). For example, erosion on blisk airfoils can be graded as heavy, moderate, or light. Heavy erosion is characterized by an extremely rough surface with the airfoil missing metal, having indentations, and showing a rolled over appearance. Moderate erosion is characterized by a rough surface with the airfoil showing some distress and raised metal surfaces. No metal rollover is present. Light erosion is defined with a mildly distressed surface with the airfoil having a rough texture but not raised metal surfaces or rollover. The criteria for grading was developed by the engineering community.

The compressor discharge pressure (CDP), inner-balance piston (IBP), and #3 labyrinth seals are not currently inspected through RIMFIRE. The cooling plate seals on the Stage 1 forward and aft cooling plates are inspected for coating loss. Light coating loss is defined as 10 to 15 percent loss. Moderate coating loss is between 15 to 40 percent and severe coating loss is greater than 40 percent. The part number, serial number, number of hours, picture, and other identification are saved in a database for further analysis (ref. 12).

RECAP is a DOD-wide initiative to maintain readiness of the military's combat systems, one of which is the T-700. Recapitalization seeks to either upgrade or rebuild current systems to a "zero time/zero mile" standard. For example, T-700 engines in Blackhawks would either be rebuilt to "as new" or upgraded to the current T700-GE-701D (ref. 13). Rebuilding may involve repairing or replacing wear/life items such as rotor blisks, gas generator blades, and seals. Air seals include the inner balance piston seal and the compressor discharge pressure seal. RECAP also tightens inspection criteria on the T-700. For example, no rub grooves are allowed on the sealing surface of the outer balance piston seal. No wear is allowed on carbon seals, and seal teeth on the cooling plates are not permitted to wear below blueprint limits.

Throughput Operations and Cost

The cost to overhaul the T-700 is in the range of several hundred thousands of dollars. T-700 engine overhaul at CCAD is completed within 80 and 90 days. Approximately 100 engines are overhauled at CCAD in a month. This number varies from month-to-month and year-to-year (ref. 14).

Sample T-700 Labyrinth Seals

Labyrinth Seal Location, Purpose, and Cost

Data from 4 labyrinth seals taken from the T-700 overhaul facility at CCAD are discussed. They are the #3 labyrinth seal, the CDP seal, the IBP seal, and the labyrinth seals on the gas generator cooling plates, (fig. 2).

The #3 labyrinth seal (fig. 3), composed of 2 sets of 4-knife labyrinth teeth, is located forward and radially inward from the 1st stage compressor. The forward labyrinth teeth seal the aft end of the forward or A-sump. Purge air is bleed from the fourth stage compressor to a space between the 2 sets of teeth to separate the air and oil cavities. Air leakage through the rear labyrinth teeth is fed back into the compressor.

The CDP seal (figs. 4 and 5) is composed of 3 sets of labyrinth teeth. CDP seal air leakage from the forward 7-knife labyrinth comes from impeller tip leakage and is ported to the turbine 4th stage shrouds. Fourth stage compressor bleed air feeds the cavity between the middle and rear CDP seal labyrinth teeth. This provides a positive air pressure to seal the forward end of the middle or B-sump. Air leakage from the middle labyrinth teeth is fed to the turbine 4th stage shrouds.

The inner balance piston (IBP) seal (fig. 6) is a 5-knife labyrinth. A portion of the cooling air from around the combustor is re-directed by the inner balance piston seal to the 3rd stage turbine flowpath.

Cooling plates (fig. 7) with 4-knife labyrinth teeth are located on the aft and rear of the 1st stage turbine disk. The seals serve to direct cooling air to the 1st and 2nd stage turbine blades. Also, together with the outer balance piston seal they prevent cooling air from escaping to the main gas stream.

Unit part costs for these labyrinth seals range from a few hundred to over $5000.

Inspection and Repair Criteria

Detailed seal inspection criteria and repair guidelines are found in Army DMWR 1-2840-248-1 (ref. 10). The discussion below is limited to the #3 labyrinth, CDP, IBP, and cooling plate seal.

In general any cracks present in the seal hardware automatically results in scrapping the component. Any wear causing a raised metal surface are blended to remove stress concentrations. For all seals, usability limits are in place in terms of size, depth, and coverage for nicks, dents and gouges. Additional criteria specific to each seal are given in the following paragraphs.

The #3 labyrinth seal is replaced if diametral wear limits on the labyrinth teeth are exceeded. The wear limits only apply to the labyrinth teeth directly adjacent to the bleed air inlet ports as shown in figure 3.

Coated seals include the CDP, IBP, and cooling plate seals. The CDP seal can be recoated provided that the coating has not worn through the base material and the minimum average seal diameters are met, otherwise the CDP seal is scrapped. Recoating the CDP seal involves a number of operations. These encompass cleaning the part for grease, oil, and dirt, followed by clean-up machining, then grit blasting and welding seal material to the part, rough machining, visual inspection with FPI, heat treatment, followed by abrasive grit blasting, final machining, fluorescent penetrant inspection (FPI), and final identification.

As with the CDP seal, if usable wear limits on the IBP are exceeded, the seal can be recoated provided that minimum diametral wear limits are met and that the coating has not worn through to the base material. Recoating involves the same operations as the CDP seal.
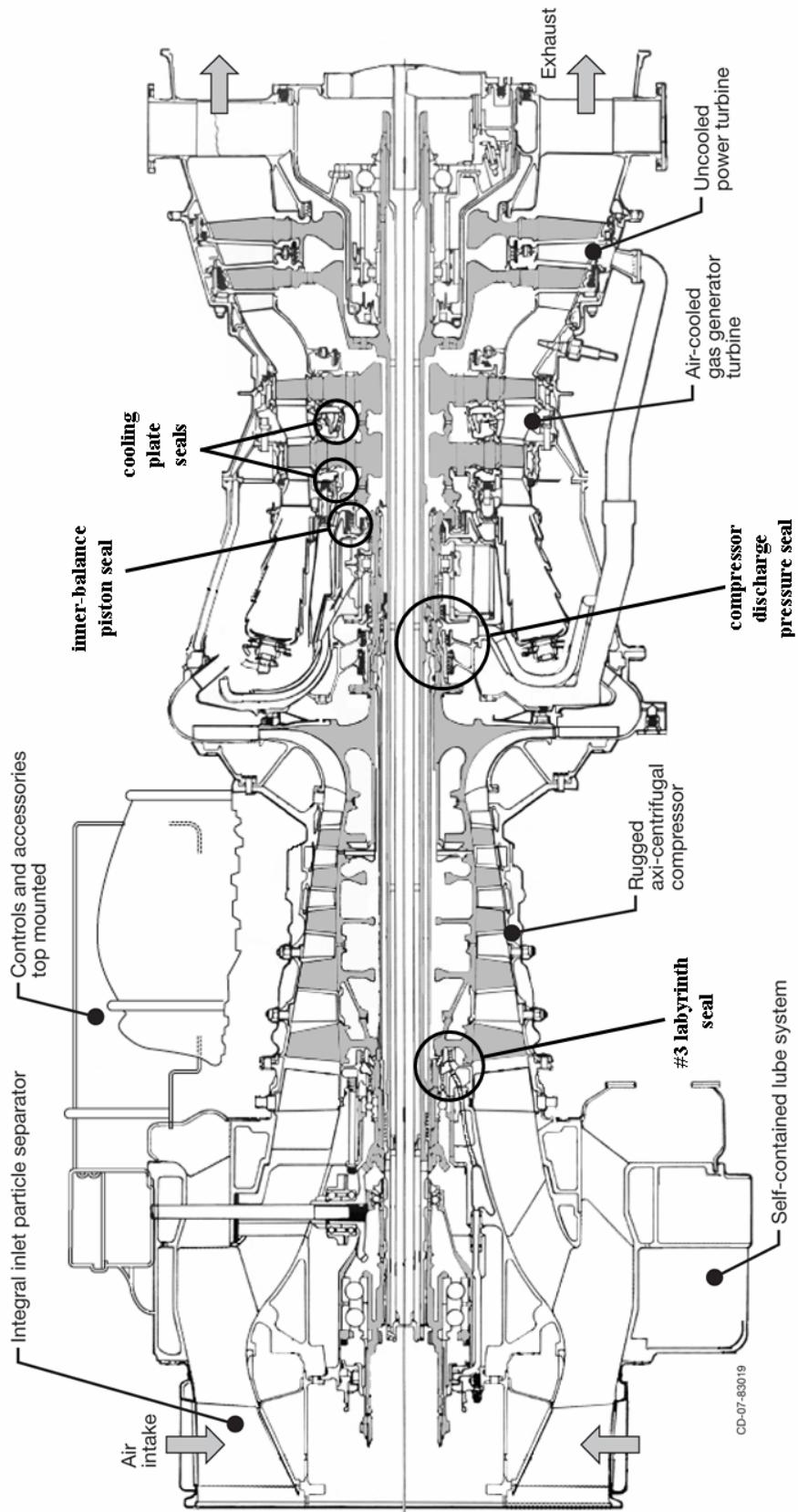
Figure 2.—T-700 Engine schematic showing locations of various labyrinth seals.
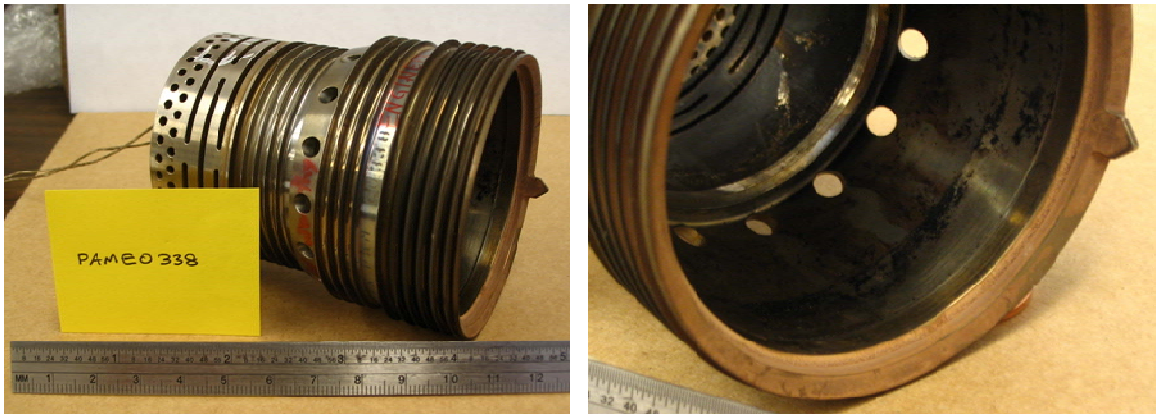
Figure 3.—No. 3 labyrinth seal.

Figure 4.—Compressor discharge pressure seal with impacted sand.

Figure 5.—Modified compressor discharge pressure
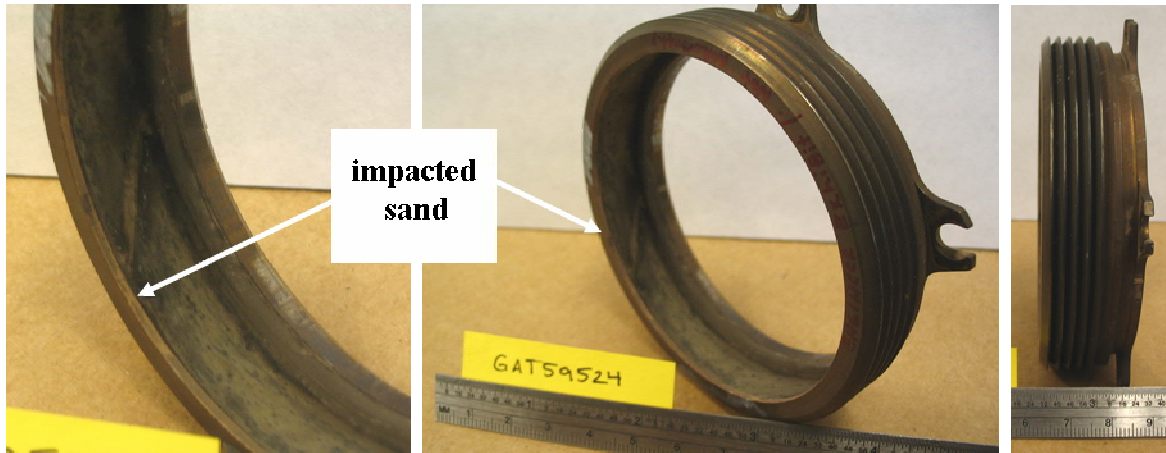seal with impacted sand.

Figure 6.—Inner-balance piston seal.

Figure 7.—Forward cooling plate with impacted sand.

In addition to usable coating wear limits, the cooling plate labyrinth seals have percent chipped limits before the part is recoated. Recoating involves cleaning, grit blasting, recoating, inspecting the coating for flaws, and final machining the coating to specifications.

Description of Labyrinth Seals Taken out of Service (Wear Observations, Sand Impaction, and Pictures)

Recall that the labyrinth seals described in the following section were taken out of service from T-700 overhaul operations at CCAD. The descriptions given below are a combination of CCAD inspections and additional visual observations of sand impaction from the authors with respect to labyrinth seal wear criteria.

Three #3 labyrinth seals received from CCAD showed no visible signs of sand impaction. Operational hours varied from nearly 2000 to over 6000 hr and all three were marked "undersized". Two of the three labyrinth seals exhibited labyrinth seal tooth tip roll-over on the first two teeth to the right of the air inlet ports as shown in figure 3.

Three CDP seals were received from CCAD with operational hours ranging from 1600 to nearly 5000 hr. Evidence of impacted sand on the inner surface of the part is shown in figure 4 and in a modified CDP seal shown in figure 5. Sand was also observed in between the labyrinth teeth on the largest diameter of the CDP and modified CDP. It is most likely the sand was present in the air leakage from the centrifugal compressor tip since the labyrinth teeth adjacent to the inlet ports fed by the fourth stage compressor bleed air showed no signs of sand impaction. Micrographs shown in figures 8 and 9 give a rough indication of the size of sand particles taken from the CDP seals in figure 5. The CDP seal labyrinth teeth closest to the impacted sand exhibited some discoloration possibly due to heat exposure, but are otherwise smooth. Some of the remaining teeth on the CDP have nicks possibly due to handling. The modified CDP labyrinth teeth closest to the location of impacted sand are black and rough to the touch. Two of the teeth are slightly rolled-over at the tip.
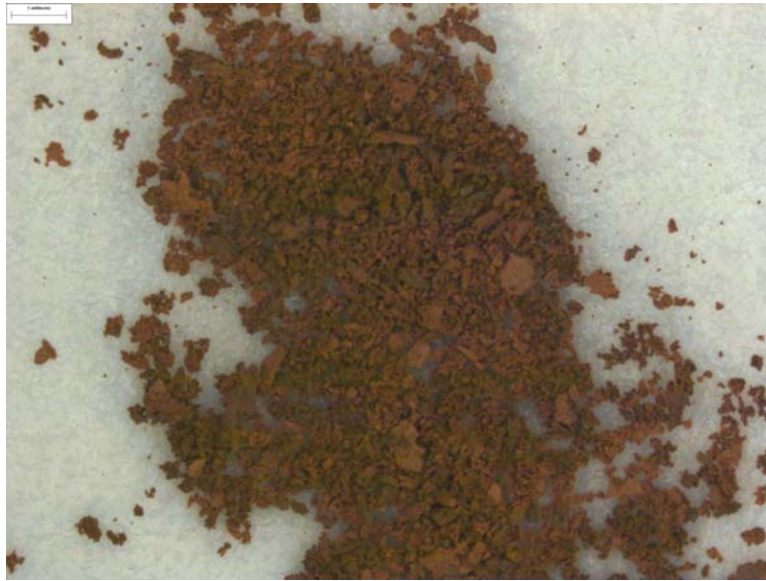

Figure 8.—Micrograph of sand particles from modified CDP seal in figure 5.

Figure 9.—Close-up micrograph of sand particles from modified CDP seal in figure 5.

All three IBP seals were determined to be "undersized" per CCAD with operational hours ranging from 800 to 2000. Some impacted sand was found on the forward lip of one IBP seal as shown in figure 6. A black, oily, soot-like substance was also observed on the inner surface of the IBP. The likely source of the impacted sand is from the cooling air flows past the combustor of the T-700. No sand was observed on or in between the labyrinth teeth.

Three forward cooling plates were received from CCAD with operation hours ranging from 2000 to 3000 hr. Labyrinth teeth on one cooling plate were blackened and rough to the touch. Coating was chipped on most of the teeth. Another cooling plate, figure 7, showed impacted sand on both the inner surface and backside. Micrographs of the sand taken from this part are shown in figures 10 and 11. The source of the sand is likely from the cooling air flows around the combustor of the T-700.
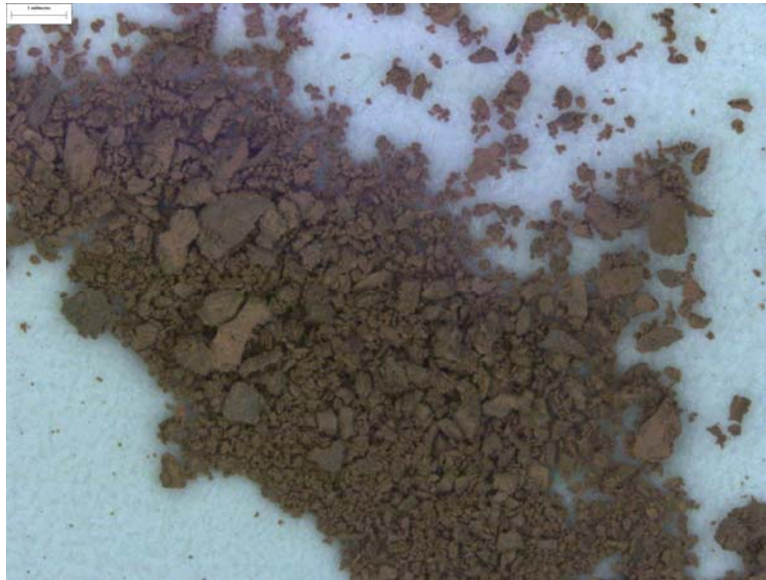

Figure 10.—Micrograph of sand particles from cooling plate, figure 7.

Figure 11.—Close-up micrograph sand particles from cooling plate, figure 7.

Cost/Benefit of Seals and Government Efforts
on Noncontacting Seal Development

The Army and NASA have been working collaboratively to improve turbine engine seal leakage performance and life capability through analysis, testing, and investigation of innovative seal concepts. The cost benefits, highlights of past successes, and efforts to develop noncontacting low leakage seals are discussed.

Cost Benefits

Cycle studies have shown that increasing engine pressure ratios and cycle temperatures can reduce engine weight and improve the performance of next generation turbine engines. Advanced seals are critical to meeting engine goals for specific fuel consumption (SFC), thrust-to-weight ratio, emissions, durability, and operating costs. Three engine manufacturers each performed detailed engine systems studies and found that applying advanced seals to just several engine locations would yield a 2 to 3 percent reduction in SFC. They also projected a reduction in direct operating costs of nearly 1 percent (refs. 15 and 16). These gains are achieved through reduced seal leakage and increased seal durability.

Past Successes

To gain the benefits of reduced seal leakage, brush and finger seals have been studied and developed for use in gas turbine engines. These contacting compliant seals have leakage rates about half that of labyrinth seals. In 1994, Hendricks et al. reported that YT-700 engine tests with a dual-brush seal had specific fuel consumption 3 percent better than with the BOM labyrinth seal at high pressure and 5 percent better at lower pressure (ref. 17). These tests were characterized by surface speeds of 160 m/s (530 ft/s), pressures to 1 MPa (145 psi), and temperatures to 680 K (765 °F). In 1997 Arora and Proctor reported brush seal test results obtained at NASA Lewis at speeds up to 809 ft/s, pressure differentials up to 145 psid, and inlet air temperatures up to 1100 °F, which indicated brush seals were a viable candidate for the JTAGG II engine, an advanced gas generator (ref. 18). In 1999, Arora et al. reported that a low hysteresis finger seal design had been developed and tested at the NASA Glenn Research Center (GRC), which had leakage considerably lower than a labyrinth seal, costs considerably less to manufacture than a brush seal, and was ready for engine testing (ref. 19). A larger, 8.5 in. diameter finger seal was tested in NASA's High Temperature, High Speed Turbine Seal Rig at operating conditions up to 366 m/s, 517 kPa, and 922 K (1200 ft/s, 75 psid, and 1200 °F), which simulated advanced-engine rate power conditions and met leakage performance goals during the endurance test (ref. 20).

Noncontacting Seal Development Efforts

Increased temperatures and speeds required for advanced gas turbine engines limit the life capability of low leakage contacting seals such as brush seals and finger seals. To address the need for low leakage, long life seals NASA has developed a High Temperature, High Speed Turbine Seal Test Facility and is currently conducting foundational research in the area of noncontacting, low leakage seals.

The High Temperature, High Speed Turbine Seal Test Rig (fig. 12) is designed to measure the leakage performance and power loss of circumferential seals at pressure differentials from 0 to 250 psid, surface speeds in excess of 1200 ft/s and inlet air temperatures from 70 to 1500 °F. The overhung 215.9 mm diameter seal test disk is mounted on a shaft supported by two oil-lubricated bearings and driven by an air turbine. A torque meter is used to measure seal power loss. A more detailed description of the test rig and facility capabilities can be found in reference 21. Comparisons of leakage performance and power loss of brush, finger, and labyrinth seals tested in this facility can be found in papers by Proctor et al. (ref. 22) and Delgado et al. (ref. 23). Generally speaking, brush seals and finger seals have
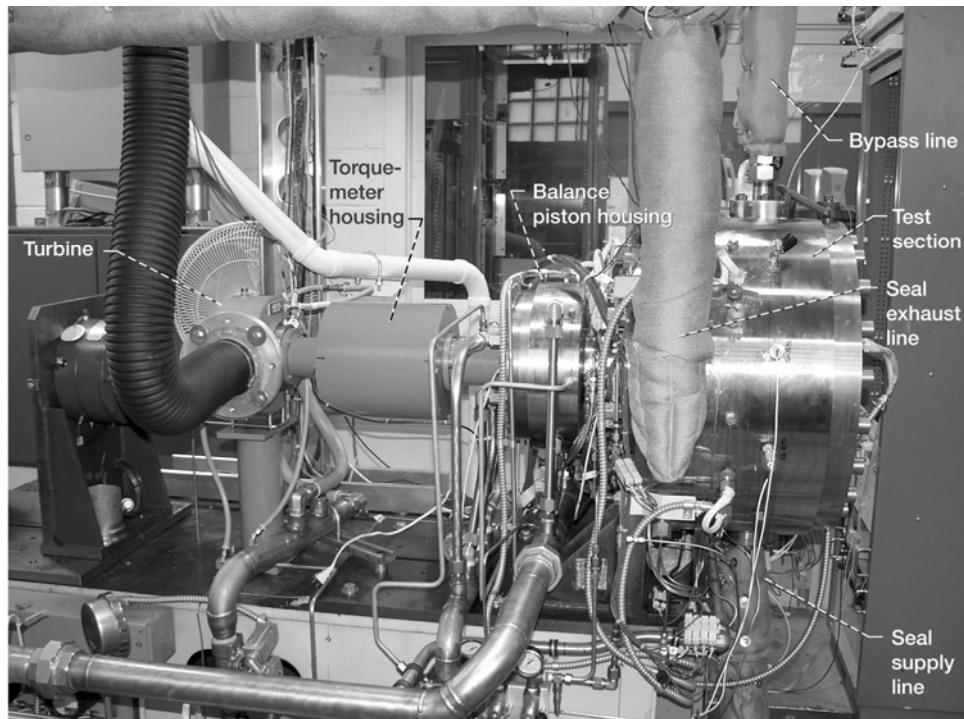
Figure 12.—NASA High Temperature, High Speed Turbine Seal Test Rig.

very similar leakage rates and power losses. Both brush and finger seals have leakage rates substantially less (~50 percent) than labyrinth seals, but wear due to contacting operation. If properly designed for a given application the wear rate of these seal types is sufficiently low to merit using them in an engine to gain the efficiency of the lower leakage rate. The higher temperatures and speeds of some advanced gas turbine engines are sufficient to cause bristle tip melting and excessive wear, which is the motivation for pursuing low leakage, noncontacting seal concepts.

The foil seal is one type of noncontacting seal concept that has been investigated (refs. 24 and 25). This circumferential seal is based on journal foil bearing technology in which a top foil anchored at a single circumferential location on the inner diameter of the seal housing wraps around the ID to the anchor point. Corrugated bump foils between the top foil and bearing housing provide stiffness and support to the top foil keeping it close to the rotor, but allowing for rotor growth and dynamic motion. During rotation hydrodynamic forces push the top foil away allowing the rotor to ride on a thin film of air. A foil seal is formed by using two layers of top foils, each with slots on one edge so that it may be formed to block axial flow through the bump foils. The top foils are clocked so that the tabs of one block the flow through the slots of the other. The 8.5 in. diameter seal shown in figure 13 was tested in the NASA facility and was successfully operated up to 25,000 rpm. It's leakage flow factor was about twice that of brush or finger seals. Since this is counter to previous findings with smaller diameter seals it was concluded that there are some scaling issues that need to be addressed (ref. 26).

The noncontacting finger seal combines the compliant features of the finger seal, which accommodate geometry changes due to thermal and dynamic conditions, with hydrodynamic and/or hydrostatic lift pads, which ride on a thin film of air and prevent contact during rotation. Early noncontacting finger seals had lift pads extending from the fingers in both the upstream and downstream directions (ref. 27). The NASA-patented noncontacting finger seal, shown in figure 14, eliminates the lift pads extending in the upstream direction to reduce hydrostatic closing forces on the upstream finger element (ref. 28). This seal is comprised of a high pressure finger element adjacent to a low pressure finger element with lift pads sandwiched between a forward spacer and cover plate and an aft spacer and cover plate. The high pressure and low pressure finger element are oriented so that the fingers of one cover the slots between
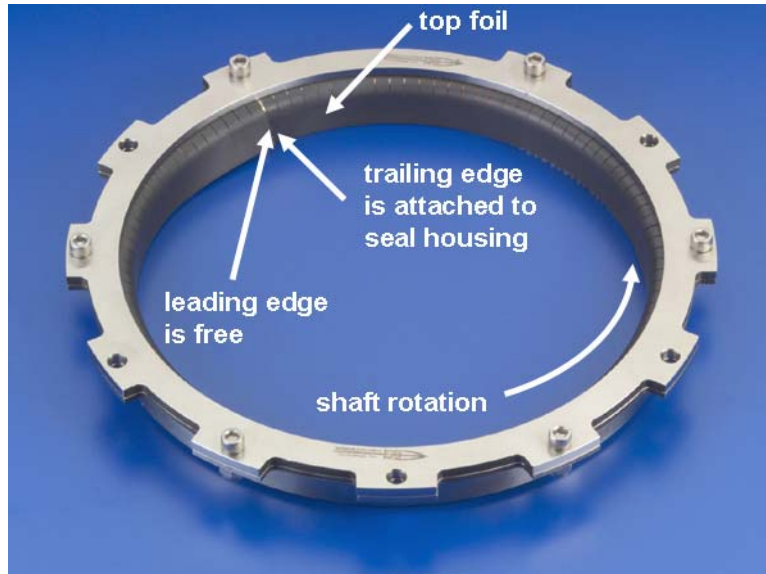
Figure 13.—Mohawk Innovative Technology Inc. foil seal.
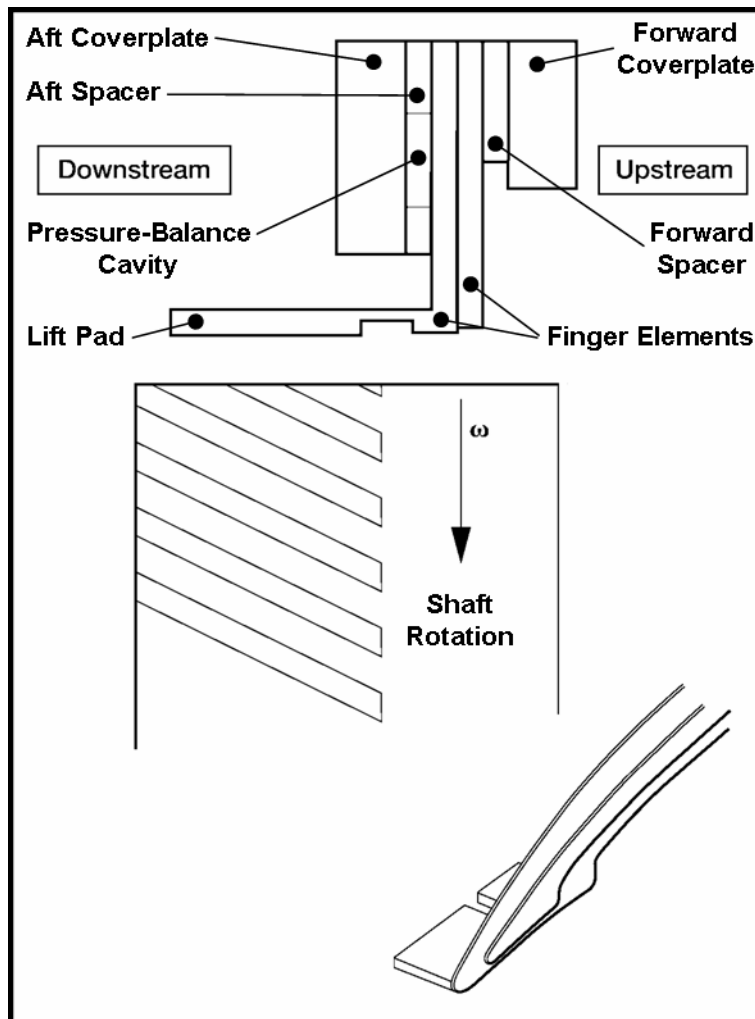

Figure 14.—NASA noncontacting finger seal concept.
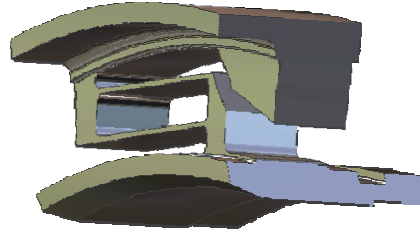
Figure 15.—Hybrid brush seal.

Figure 16.—Hydrostatic lift pad and spring housing section.

the fingers of the other. A series of slots in the forward and aft spacers and holes in the finger laminates allows high pressure air to flow into the pressure balance cavity formed by the aft spacer and cover plate and low pressure finger laminate. The balance cavity is necessary to minimize hysteresis in the seal due to friction between the fingers and the seal dam (ref. 29). Various geometries on the lift pad inner diameter and on the rotor outer diameter can be used to create an opening force between the rotor and the seal. This opening force must be in balance with the pressure closing force, which is a function of the pressure differential across the seal, finger stiffness, and friction within the seal. The opening force may be hydrodynamic in nature and require shaft rotation to be generated or it may be hydrostatically generated once a pressure differential is applied or it may be a combination of the two. Three-dimensional fluid analysis and some structural analysis has been done to gain understanding and select specific designs for testing (refs. 30 and 31). Room temperature tests of noncontacting finger seals with three different lift pad geometries (circumferential wedge, circumferential and axial wedge, and a Rayleigh step) conducted at pressure differentials up to 30 psid and speeds up to 15,000 rpm have demonstrated noncontacting operation (refs. 32 and 33). Hardware to test a noncontacting finger seal with concentric lift pads adjacent to a rotor with a herringbone groove pattern has been fabricated for testing in NASA's High Temperature, High Speed Turbine Seal Test Facility. Test data will be used to verify, develop, and refine analysis tools and design methodologies.

Hybrid brush seal technology continues to be investigated and developed. The hybrid brush seal (HBS) shown in figure 15 is a promising noncontacting, low leakage seal technology that has application to Army engines as well as commercial and advanced gas turbine engines. Hydrostatic lift pads are supported by a spring housing (fig. 16) that is radially soft and axially stiff. A brush seal is used as a secondary seal and provides damping to the hydrostatic bearing surface. Computational fluid dynamic analysis provides a means to determine the HBS functionality, such as stiffness and damping, pad pressure forces, and clearance. The HBS geometry can be modified to provide a larger or smaller operational clearance. Further, the hybrid brush seal can be installed with a larger cold clearance and maintain a smaller operational effective clearance, which means low leakage rates (ref. 34).

Conclusions

Sand ingestion in T-700 engine components, such as labyrinth seals, is a continuing issue given current military helicopter operations in the Middle East. Labyrinth seals are subjected to tooth tip blunting and surface erosion resulting in increased clearances and overall increased engine fuel consumption. Of the four different T-700 labyrinth seals inspected from Corpus Christi Army Depot, only the #3 labyrinth seal showed no signs of sand ingestion although they were judged to be undersized and thus not airworthy. Also, some sand was present at the inner lip of the inner balance piston seal. The inner balance piston seals were also judged to be undersized and thus not airworthy. Sand was present on both sides and on the inner diameter of the forward cooling plate. Finally impacted sand was present on the inner diameter and between the labyrinth teeth of the compressor discharge pressure seal. In addition,

some labyrinth teeth on both the forward cooling plate and compressor discharge pressure seal showed signs of erosive coating and surface wear as well as chipped coatings.

Future seal development efforts should focus on seal technology that is tolerant of sand particles in terms of wear and leakage performance. Continued monitoring of seals in the field, analysis of the erosive effects of sand on engine components as well as seal modeling and testing is recommended. In light of the expected exposure of seals to sand and debris it is prudent to evaluate the leakage and wear performance of noncontacting compliant seals with sand laden air. Initial tests could be conducted in a room temperature static rig to understand how well debris passed through the seal and where erosion is likely to occur. A review of possible coatings and materials to make current and future seals more wear resistant should be conducted.

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14. ABSTRACT
Sand ingestion continues to impact combat ground and air vehicles in military operations in the Middle East. The T-700 engine used in Apache and Blackhawk helicopters has been subjected to increased overhauls due to sand and dust ingestion during desert operations. Engine component wear includes compressor and turbine blades/vanes resulting in decreased engine power and efficiency. Engine labyrinth seals have also been subjected to sand and dust erosion resulting in tooth tip wear, increased clearances, and loss in efficiency. For the current investigation, a brief overview is given of the history of the T-700 engine development with respect to sand and dust ingestion requirements. The operational condition of labyrinth seals taken out of service from 4 different locations of the T-700 engine during engine overhauls are examined. Collaborative efforts between the Army and NASA to improve turbine engine seal leakage and life capability are currently focused on noncontacting, low leakage, compliant designs. These new concepts should be evaluated for their tolerance to sand laden air. Future R&D efforts to improve seal erosion resistance and operation in desert environments are recommended.

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