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Engine Seal Technology Requirements to Meet NASA's Advanced Subsonic Technology Program Goals

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Cycle studies have shown the benefits of increasing engine pressure ratios and cycle temperatures to decrease engine weight and improve the performance of commercial turbine engines. NASA and the industry have defined technology requirements of advanced engines and engine technology to meet the goals of NASA's Advanced Subsonic Technology (AST) initiative. A number of new technologies are being developed that will allow next-generation engines to operate at higher pressures and temperatures to meet engine efficiency and performance goals. Improving seal performance, reducing leakage and increasing service life while operating under more demanding conditions, will play an important role in meeting overall program goals. This article provides an overview of the AST program, discusses the motivation for advanced seal development, and highlights seal technology requirements to meet future engine performance goals.

Introduction

NASA has begun the Advanced Subsonic Technology (AST) program to improve both engine and vehicle performances and lower direct operating costs (DOC), working closely with the aircraft industry. Using engines being certified today as the baseline, general program goals include the following:

1) Reduce next-generation commercial aircraft direct operating costs including interest by 3% (large engines) and 5% (regional engines).

2) Reduce engine fuel burn by up to 10%.

3) Reduce engine oxides of nitrogen (NO_x) emissions by more than 50%.

4) Reduce airport noise by 7 dB (or about three-quarters reduction in acoustic energy).

Meeting these aggressive goals for engines to be certified by 2005–2006 requires significant advancements in the fans, compressors, combustors, and turbines, and also the subcomponents including engine seals. Airline customers have become increasingly cost-conscious prompting the NASA/industry team to pursue technologies that show promise of high-performance benefit-to-cost ratios. Technologies are being pursued that will increase engine and vehicle performance, lower acquisition and lifetime costs, and reduce engine maintenance.

Seals have repeatedly shown high-performance benefit-to-cost ratios in recent studies[1] as a result of their high-performance payoff and their relatively low development costs. Advanced engine seals show promise of reducing engine losses and maintaining these performance benefits over engine service intervals. New seals coupled with improved design codes give the designer better control of engine secondary flows, critical in extracting the maximum useful work out of these high-power density engines.

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AST Program Goals

NASA's AST program is pursuing technology developments to boost engine efficiency and reduce costs for both large and regional class engines.

Specific Fuel Consumption

NASA is targeting a reduction in specific fuel consumption (SFC) of 8% for large engines (>20,000-lb thrust) and 10% for regional engines. Reducing engine-specific fuel consumption helps airlines in several ways. Starting with a clean sheet aircraft/engine design, reducing SFC reduces engine and airframe weights. Reducing airplane weight and size reduces acquisition costs including interest, key to today's airlines. For reference, costs to operate a 747 aircraft are broken down as a percentage of total DOC in Fig. 1, showing that engine and airframe acquisition and maintenance costs are about half of the total costs.[2] Reduced fuel burn also translates into lower airline fuel bills. However, with fuel prices at current historic lows (about 65 cents per gallon; 1994 reference), reduced fuel burn is less of a cost driver.

SFC has continued to decrease over the course of turbine engine history, as shown in Fig. 2. In this chart a number of turbojet and turbofan engine SFCs are shown vs engine certification date. Reducing SFC by 8% from current baseline engines will result in engines with SFC values for large engines of about 0.48 lb/h/lb. In addition to the fundamental improvements sought in the combustion process, reduced fuel

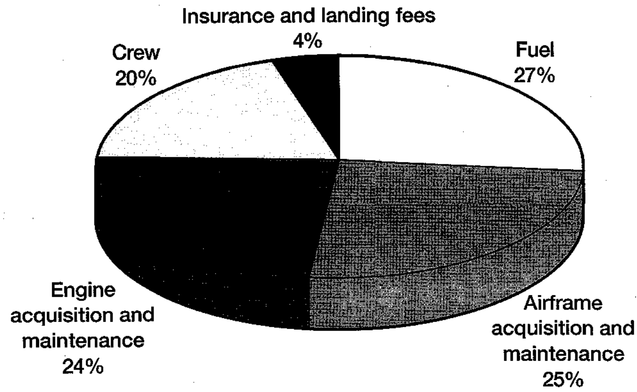


Fig. 1 Direct operating cost breakdown for 747 jetliner, fuel price of 65 cents per gallon, 5000 nm range.[2]

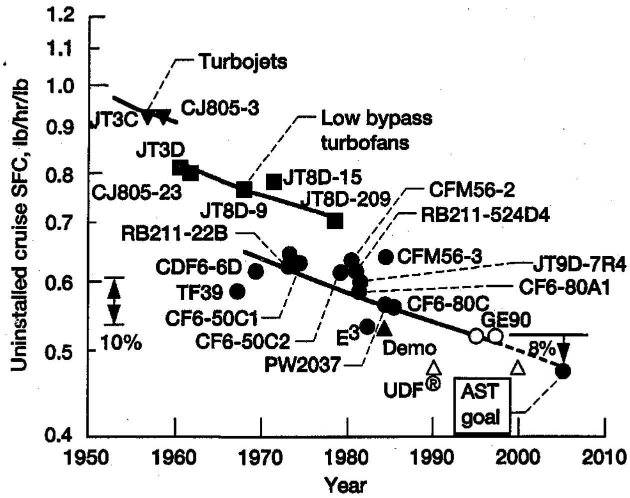


Fig. 2 Subsonic engine historical trend and program goal specific fuel consumption.

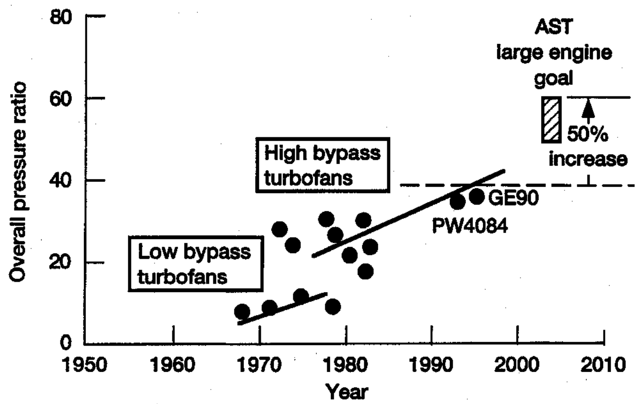


Fig. 3 Historical trend and program goal overall pressure ratio.

burn also helps lower missionized emissions, for a cleaner environment.

Engine Pressure Ratio

For both engine classes, the goal is to increase pressure ratio up to 50% from engines currently being certified for flight. Pressure ratios for large engines are targeted to increase to 50 or 60, as shown in Fig. 3, along with a historical trend line. For reference, the PW4084 now certified for the Boeing 777 has an overall pressure ratio of just under 40. Regional aircraft engines pressure ratios are expected to climb from 35 to 45. Engines decrease in size with increasing pressure ratios. Reducing engine size again reduces weight and acquisition costs. However, as engine pressure ratios increase and the engine becomes more compact, blade tip clearances do not scale proportionately. Therefore blade tip clearances must be addressed, or some of the performance benefits sought with the increased pressure ratios will be lost (see the New Sealing Approaches Under Development section later in this article).

As a result of increasing the compression ratio, engine compressor discharge temperatures that are typically ≤1200°F, are expected to reach 1300°F and higher, requiring compressor materials with 1450°F operating temperatures (considering margin requirements). Turbine inlet temperatures that are typically ≤2600°F are expected to increase several hundred degrees requiring improved cooling approaches, high-temperature materials, and thermal barrier coatings in the turbine hot section. Seal material temperatures will increase in proportion to the compressor and turbine material temperatures.

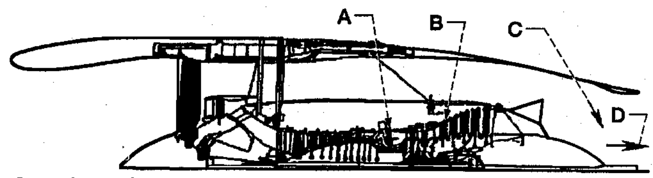
NASA/industry studies[1] have projected that improving engine performance and reducing operating costs will result in airline economies over the life of the engine fleet 20 times the total development cost, a strong motivation for implementing advanced technologies that are cost effective.

Motivation for Advanced Seal Development

Source of Engine Efficiency Gains

Overall engine efficiency, the useful work produced by the engine divided by the fuel energy content, can be determined by the product of the three efficiencies[3] illustrated in Fig. 4. Plotting the historical trends of core efficiency vs the product of transmission and propulsive efficiencies (Fig. 5), one sees that relatively more progress has been made recently in advancing the propulsive (e.g., fan), and low-pressure turbine efficiencies than has been made in the core. This is illustrated by the historical trend line. To obtain the low SFC desired for the advanced engines, more progress must be made in increasing core efficiencies, as illustrated by the future trend line, since under current economic conditions airlines are not interested in open rotor (e.g., unducted fan) engines. Comparing the slopes of these two lines, reaching the SFC goal requires proportional, or balanced, increases in core and the product of propulsive and transmission efficiencies.

Increasing core efficiencies will be obtained by high-cycle pressure ratio, and compressor exit temperature, high-turbine inlet temperature, and improved component efficiencies including reducing engine losses. Improved engine seals will dramatically reduce engine losses (as will be shown herein) and will enable engine designers to better manage the increasingly important secondary airflows.



Core thermal efficiency = Energy at the LP turbine entry (B) / Energy of fuel (A)

Transmission efficiency = Energy at the nozzle (C) / Energy at the LP turbine entry (B)

Propulsive efficiency = Useful work produced by engine (D) / Energy at the nozzle (C)

Overall efficiency = Core thermal x transmission x propulsive efficiency

Fig. 4 Breakdown of engine efficiencies.[3]

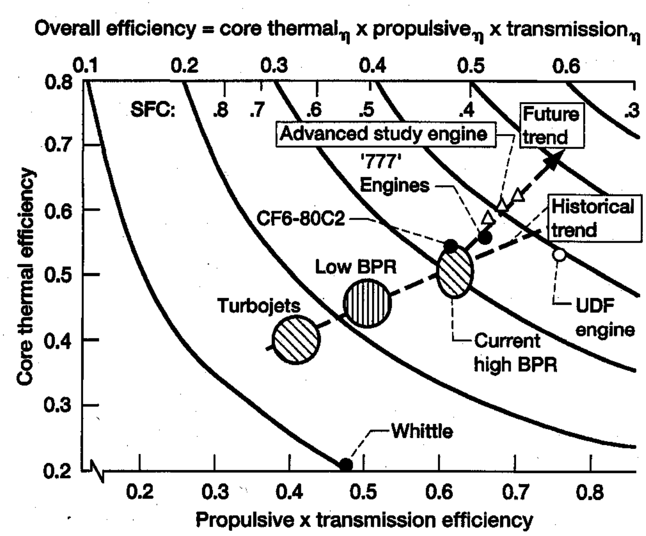


Fig. 5 Historical turbine engine overall efficiency as a function of core thermal efficiency and propulsive x transmission efficiency showing required improvements in core efficiency.[3]

Table 1 Advanced regional engine (20,000-lb thrust) performance benefits

Location	Seal	ΔSFC, %	ΔThrust/wt %
(a) Using brush and film riding seal technology[5]			
Turbine rim 1st/2nd, forward	Brush	−1.14	3.41
Compressor discharge	FRFS[a]	−0.33	0.61
Preswirl (aft sump)	FRFS	−0.49	0.91
Net engine benefit	——	−1.96%	4.93%
(b) Using film riding seal technology[5]			
Turbine rim 1st/2nd, forward	FRCS[b]	−1.80	5.43
Compressor discharge	FRFS	−0.33	0.61
Preswirl (aft sump)	FRFS	−0.49	0.91
Net engine benefit	——	−2.62%	6.95%

[a]Film riding face seals.
[b]Film riding circumferential seals.

In addition to the case made for improving core efficiencies by reducing leakages and managing secondary airflow systems more efficiently, there are several other compelling reasons to advance seal technology to meet advanced engine goals. There is a strong correlation between the percentage reduction in seal leakage and either the percentage decrease in SFC or percentage increase in thrust, all other things held constant. Also, advancements in seal technology generally are made with investments much smaller than those required for a compressor or turbine stage redesign and qualification. Studies performed by Stocker[4] and corroborated by Smith[1] estimated that making the same performance improvements with compressors or turbines would cost a minimum of four to five times more than the cost of fielding new seal technology for the same efficiency gains. With the limited technology development budgets the country is faced with, NASA and the engine community are pursuing technologies such as seals with a high return on technology-dollar invested.

Engine Study Results

NASA and the U.S. Army commissioned a study (Allison Engine Company) to examine two modern engines and identify performance benefits possible through implementing advanced engine seals. The study[5] examined a turbofan engine (AE3007) slated for growth to meet the 20,000-lb thrust requirement of the AST regional aircraft, and a turboshaft engine (T-800 study basis) examined for potential growth to meet the military Integrated High Performance Turbine Engine Technology (IHPTET) Phase 2 goals.

In the study, performance benefits of applying advanced seal technology were objectively determined relative to the advanced engine with conventional seal technology. A summary of the advanced regional engine results is shown in Table 1 and the advanced turboshaft engine results are shown in Table 2.

In each engine two levels of turbine rim seal technology were examined, namely brush seals and film riding circumferential seals currently under development. In the advanced regional engine, pressure conditions require film riding face seal technology at the compressor discharge and preswirl (aft-sump) location. In the study,[5] implementing the brush seals at the first- and second-stage forward turbine rim locations and the seals mentioned resulted in a 1.96% reduction in SFC and a 4.93% increase in thrust-to-weight (Table 1a). Substituting film riding circumferential seals for the brush seals resulted in a 2.62% reduction in SFC and a 6.95% increase in thrust-to-weight (Table 1b). Even greater efficiency gains were found when including the tip clearance control among others, see Ref. 5.

In the advanced turboshaft engine study, two carbon intershaft seals were used. In addition, either brush or the film riding circumferential seals were used for two turbine rim seal locations. Implementing the brush rim seals resulted in a 4.44% reduction in SFC and a 10.86% increase in horsepower (Table 2a). Substituting film riding circumferential seals for the brush seals resulted in a 5.28% reduction in SFC and an 11.26% increase in horsepower (Table 2b).

Table 2 Advanced turboshaft performance benefits

Location	Seal	ΔSFC, %	ΔHP, %
(a) Using brush seal technology[5]			
Turbine rim 1st/2nd, aft	Brush	−4.16	10.30
Intershaft (2 each)	Carbon seal	−0.28	0.56
Net engine benefit	——	−4.44%	10.86%
(b) Using film riding seal technology[5]			
Turbine rim 1st/2nd, aft	FRCS[a]	−5.00	10.70
Intershaft (2 each)	Carbon seal	−0.28	0.56
Net engine benefit	——	−5.28%	11.26%

[a]Film riding circumferential seals.

Large improvements such as these are possible by reducing airflow through the turbine rim seals to only that which is required for cooling and to prevent hot gas ingestion. Airflow savings were up to 2.5% of core flow for the regional and over 3% for the turboshaft engine. It is recognized that the new rim seal technology must be proven under engine operating conditions. However, to meet stated program goals, improvements such as these cannot be overlooked since there are few if any other locations where gains of this magnitude can be realized.

Seal Technology: Current and Advanced Requirements

In examining seal requirements for advanced engines it is instructive to review current engine seal capabilities. Table 3 provides an overview of current engine seal capabilities in terms of pressures, speeds, temperatures, and materials. Table 4 summarizes expected seal operating requirements for next-generation turbine engines including some military applications. Seals will be expected to operate hotter, seal higher pressures (to accommodate higher pressure ratios), and operate with higher surface speeds.

Mechanical Face Seals

Self-acting mechanical face seals play a vital role in sealing bearing locations in turbine engines. Carbon face seals have low leakage and can seal pressures up to 150 psid. They can operate at moderate surface speeds (up to 475 ft/s) with acceptable friction and wear rates.[6] These seals operate reliably with low leakage and cost less than labyrinth seals and therefore will continue to play a role in advanced aircraft engines.

Even more will be asked of mechanical face seals in future engines. Carbon face seal speeds will be up to 600 ft/s for advanced engines. Where mechanical face seals are required to seal counter-rotating shaft locations, surface speeds will approach 1000 ft/s. Conventional face seals will continue to be

Table 3 Summary of current turbine engine seal technology

Seal	ΔP, psid	Temperature, °F	Surface speed, ft/s	Materials
Face	150	1000	475	Carbon
Labyrinth	250–400	1300	1500	Ni superalloy teeth + abradable
Brush	80–100/stage	1300	1000	Cobalt superalloy
Outer air seals:				Abrasive tipped blades vs:
Compressor	Stage	1200	1200	Felt metal
HP turbine	ΔP	2000+	1500	Graded ceramic

Table 4 Summary of advanced turbine engine seal technology

Seal	ΔP, psid	Temperature, °F	Surface speed, ft/s	Materials
Face:				
Single rotation	150	1000	600	Carbon
Counter-rotation	60	1000	1000	Carbon
Film riding seal	800	1500	900	Ceramic
Labyrinth	250–400	1300	1650	Ni superalloy teeth w/abrasive tips + abradable
Brush	140/stage	1500	1650	Ni superalloy or ceramic
Outer air seals:				Abrasive-tipped blades vs:
Compressor	Stage	1300	1200	Sprayed abradable
HP Turbine	ΔP	2200+	1650	Graded ceramic

limited to temperatures of 1000°F or less because of the oxidation of the carbon seal ring.

Labyrinth Seals

Perhaps the single most common flow path seal used over turbine-engine history is the labyrinth seal. The labyrinth seal consists of multiple knife edges (typically five) run in close clearance to the rotor (0.010–0.020 in.), depending on location. Labyrinth seal pressures in current engines can be as high as 400 psi depending on location. Seal temperatures are generally 1300°F or less. Labyrinth seals are used for surface speeds up to 1500 ft/s. Labyrinth seals are clearance seals and therefore have high leakage rates. Labyrinth seals are used as shaft seals and as inner air seals, sealing the vane-to-drum interstage locations.

Advanced engines will continue to use labyrinth seals, but to a lesser degree. Advanced designs will incorporate labyrinth knives coated with an abrasive to maintain sharp knife edges and retain relatively good pressure drop characteristics even after a rub. Abrasive tipped seals will be run against either honeycomb or sprayed-abradable lands. Clearances will be maintained at levels as tight as is prudent. In shrinking labyrinth clearances, however, designers must be careful to preclude shaft vibrations that can be caused under small clearance conditions.[7]

Brush Seals

Brush seals consist of a dense pack of bristles sandwiched between a face plate and a backing plate. The bristles are oriented to the shaft at a lay angle (generally 45–55 deg) that points in the direction of rotation. A primary attribute of the brush seal is its ability to accommodate transient shaft excursions with little if any wear unlike labyrinth seals that wear to the full radial excursion opening large leakage paths. Brush seals are designed initially with a small radial interference ≤0.004 in. to accommodate seal-to-shaft centerline manufacturing variations. Leakage rates on initial run can be as little as 10–20% of comparable labyrinth seals. Experience has shown that during engine operation, brush seal flow rates do increase because of wear. After extended operation, brush seals will wear to a clearance opening at a small radial gap at part-power conditions. However, brush seal performance is generally better than the best performing labyrinth seals. Brush seals are used in multiple stages for pressure differential above 80 psi, to prevent bristle packing and deflection under the backing plate causing excessive wear. Cobalt-based alloys such as Haynes 25 are generally used for bristle materials running against rotors coated with chrome-carbide, or aluminum-oxide. Currently, seal temperatures are generally 1300°F or less and surface speeds are generally 1000 ft/s or less.

Brush seals will continue to evolve to meet the evermore demanding conditions they are subjected to. In advanced engines surface speeds are expected to reach 1650 ft/s with temperatures reaching 1500°F. Long-term durability at these extreme conditions is the primary concern and is receiving attention through military sponsorship.[8] Higher temperature materials will be required for the bristles and for the wear-resistant shaft coatings. It is envisioned that cobalt-based superalloy bristles may be replaced in the high-temperature (up to 1500°F) locations. Nickel-based superalloys, such as Haynes 214, form a more stable, tenacious oxide, with lower friction at higher temperatures.[9]

Under these extreme conditions, designs that would significantly limit the irrecoverable bristle wear are highly desirable. Researchers are investigating whether the small bristle lift forces generated during operation can aid in reducing wear.[8] Other proprietary designs to reduce pressure-induced closure are also being investigated. Ceramic brush seals are being investigated by a number of researchers.[10–12] Though not yet proven, hard ceramic bristles may be more wear resistant and may offer longer term wear lives.

Outer Air Seals

Outer air seals provide a small clearance, rub-tolerant seal at compressor and turbine blade tip locations. Outer air seals take various configurations depending on application. In the compressor, where temperatures are 1200°F or less, the seals consist of felt metal pads bonded to the compressor case. In some applications debonding has occurred and the industry is investigating more durable sprayed-abradable approaches for advanced applications. In the high-pressure turbine section, graded ceramic abradable seals are sprayed onto turbine-case insert rings to provide good abradable characteristics.[12] Graded ceramic seals are used to minimize the thermal strains between the high-expansion rate metal-ring substrate and the low-expansion rate ceramic (alumina or partially stabilized zirconia) seal surface. Sustained seal temperatures of 2000°F and above are common. In both the compressor and the turbine, blades are tipped with an abrasive tip material to prevent blade wear and isolate wear in the rub surface. Isolating wear in the rub material results in material removal in a limited distance around the circumference, limiting engine performance degradation.

Blade Tip Clearance Control

Better management of blade tip leakage improves engine designs in several ways. Reduced compressor blade tip leakage improves compressor efficiency and improves stall/surge margins, improving engine operability (see also shape memory alloy seal discussion later). Maintaining tighter clearances over the life of the engine addresses a key observation that 80–90% of engine performance degradation is caused by blade tip clearance increase.[6] In a limited number of commercial engines, blade tip clearance control is used. Blade tip clearance control is performed today by preferentially cooling the turbine case during cruise operation. This has been successful in greatly reducing turbine blade clearances in the PW4000 series of engines and has resulted in handsome turbine efficiency gains.[6]

Currently the industry does not use active feedback control. Adding feedback control by sensing average blade tip clearances and regulating case coolant will provide extra benefits, including allowing the use of clearance control for other than the cruise-only condition, as is the case today. Mechanical control techniques are also being examined. Allison has demonstrated[13] centrifugal compressor efficiency gains up to 1% using an experimental electromagnetic actuator to control compressor clearances. For both active feedback control techniques, a pacing technical issue that is being worked is the development of reliable, high temperature sensors.

Loss of design clearances results in a loss of thrust, requiring an increased throttle setting to achieve the same engine performance. The increased throttle setting, however, increases the exhaust gas temperature (EGT) and reduces the life of the hot turbine components. When the EGT exceeds a Federal Aviation Administration (FAA) certified limit, engine overhaul is required, costing typically over $1 million (1993 dollars). Engine manufacturers will continue to develop techniques to combat this performance degradation to serve their cost-conscious airline customers.

New Sealing Approaches Under Development

Film Riding Seals

Film riding seals are designed to operate without contact. Eliminating contact except for periodic transient conditions greatly increases seal life. Film riding face seals can be designed to operate at the high pressures and temperatures anticipated for compressor discharge and sump-aft locations of next-generation gas turbine engines. Seal leakage rates are a small fraction of competing brush and labyrinth seals. Most film riding seals have been designed to operate as a face seal, but new designs under development[5] are proposed to operate as circumferential seals for turbine rim seal applications. By design, the seal operates without contact greatly reducing wear and provides more stable performance over its life.

Though these seals have not yet entered engine service, they have shown promise in several recent tests. Gamble[14] examined the feasibility of self-acting face seals for a high thrust-to-weight ratio military gas turbine engine. The lift pad seal was tested in a counter-rotating shaft location between the high-pressure and low-pressure shafts. The seal operating speed was 800 ft/s and utilized spiral groove geometry providing a running film during operation. The seal's leakage rates were less than a third of a competing labyrinth seal. Munson[15] successfully demonstrated a single-rotation film riding face seal at temperatures up to 800°F, surface speeds over 500 ft/s, and pressures up to 400 psid in a seal test fixture. Leakage

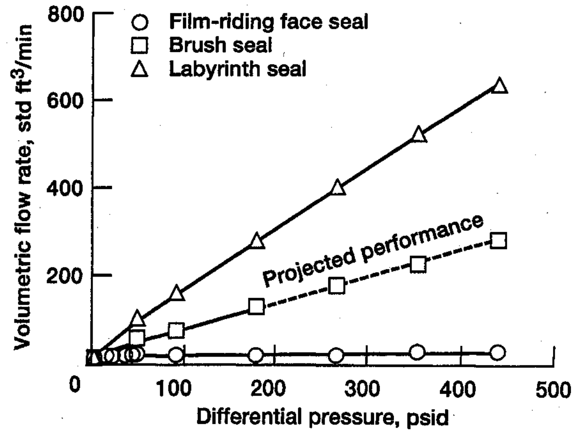


Fig. 6 Comparison of seal leakage rates as a function of differential pressure. Seal diameter, 148 mm (5.84 in.).[15]

rates were less than one-tenth those of labyrinth seals and less than one-fifth those of brush seals (Fig. 6).

There are several issues that must be resolved for implementing these low-clearance (≤0.001-in.) seals into engine service including minimizing the effects of potential dust ingestion and gracefully accommodating aircraft maneuvering loads. Solutions to these issues are being pursued under the AST program.

Compliant Seals

There are a number of new seal concepts that are being developed to address sealing problems of advanced engines. Two new seals are the compliant hydrodynamic shaft seal[16] and the laminated finger seal[17] shown in Fig. 7. In the compliant shaft seal, shingled-sealing elements float on a hydrodynamic film virtually eliminating seal wear, operating within design displacement limits (≤0.015 in.). New generations of this seal that may have higher displacement capability are being evaluated.

The laminated finger seal is constructed of a stack of laminations, with each lamination consisting of multiple fingers or flexure elements (Fig. 7b). The fingers allow the seal to follow radial movements of the rotor. Layers are indexed such that axial openings between fingers are covered by the succeeding layer. With the larger load carrying area of the fingers, this seal may have a considerably longer wear life than a wire brush seal, but still needs to be demonstrated.

Shape Memory Alloy Seals

Under contract (Memry Technologies and AlliedSignal), NASA is examining the feasibility of using a low-temperature, compressor-case compensator ring made of shape memory alloy (SMA) material to minimize compressor blade tip clearances during engine operation.[18] The compensator ring (Fig. 8) is fabricated of a copper–aluminum–nickel SMA. The two-piece compensator ring achieves a near-zero net coefficient of thermal expansion (CTE) by balancing the competing effects of normal thermal growth with a pretrained contraction that occurs as the material goes through its martensite to austenite transition temperature. Tailoring the net CTE of the system in this manner provides a thermally activated system that reduces radial tip clearances from 0.017 in. (using the standard steel ring in the magnesium case) down to 0.005 in. with the SMA compensator ring. Upon cooldown the previous process reverses, ensuring that adequate tip clearances are maintained over the temperature range.

In Phase I, researchers fabricated a full-scale compensator and demonstrated the feasibility of training the SMA ring to exhibit the proper shape change properties. In Phase II compressor efficiency gains will be measured on a T-55 compresser implementing four compensator rings. Calculations[19] have shown that implementing compensator rings in the first four

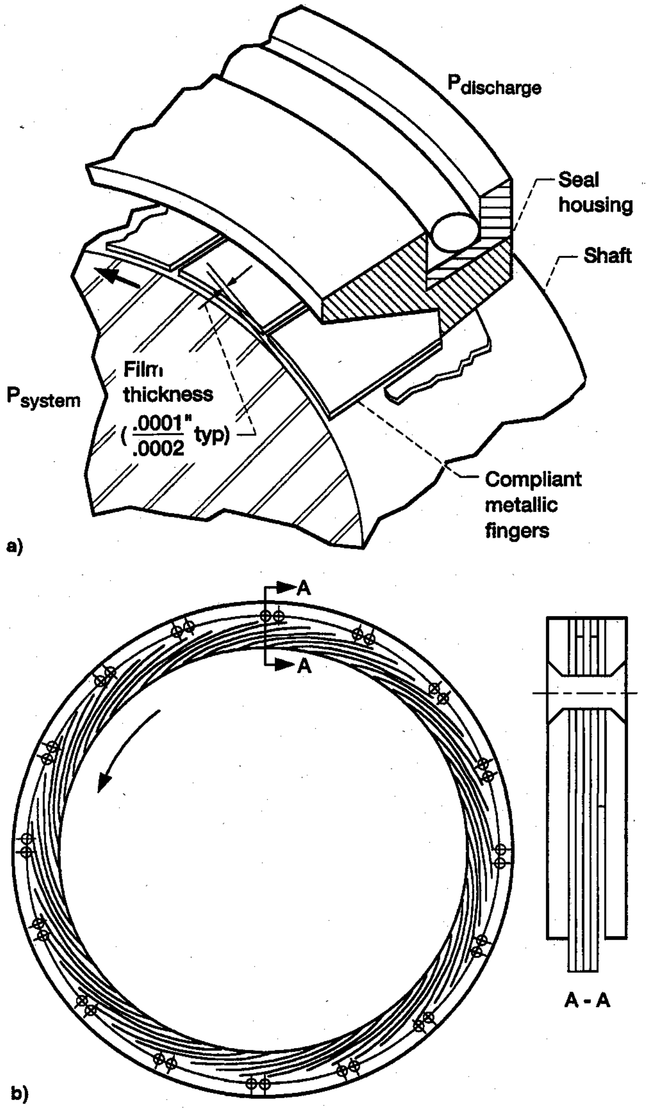


Fig. 7 New seal concepts: a) compliant metallic hydrodynamic shaft seal[16] and b) laminated finger seal.[17]

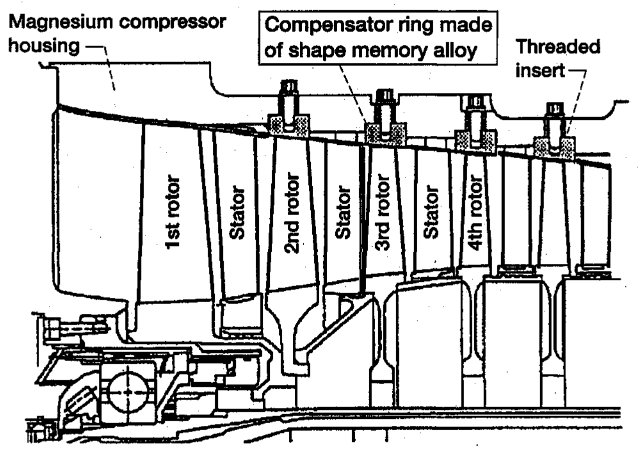


Fig. 8 Shape memory alloy compressor shroud seal shown in compressor cross section.[18]

stages would increase axial compressor efficiency by 0.5% and axial compressor surge margin by about 3%. Full compressor (axial plus centrifugal) efficiency would increase by 0.3% and could potentially increase compressor surge margin. Calculations have also shown that controlling blade tip clearances throughout the axial compressor (stages 1–7) to 0.005 in. would increase full compressor efficiency 0.7%, but would require some additional SMA development for the higher temperatures.

Advanced Design and Analysis Techniques

Implementation of the low leakage seals under development will be done in a systematic fashion to reap the performance improvements without unbalancing the secondary airflow systems. Modern turbine engines are finely tuned thermally and implementing advanced low-leakage seals such as the film riding circumferential rim seals will cause a redistribution of the secondary airflow. Provisions must be made such that adequate cooling flow reaches disks and blade attachments to keep these critical components within their temperature allowables and to preclude hot gas ingestion.

To ensure successful application of advanced seals, new analytical approaches are required. Under NASA sponsorship and with industry participation, a variety of computational codes are being developed to design the basic seal structures, assist in managing the critical secondary airflow and power streams, and finally to assess the seal's impact on engine dynamics.

Computer codes have been developed by Shapiro and Athavale[20] enabling designers to predict seal leakage and dynamic performance prior to costly fabrication and testing. These codes have been successfully used by the industry in designing film riding face seals.[5] Code extensions are required to analyze and predict the performance of the new film riding circumferential seals.

Turbine rim seals, though simple in nature, are critical seal interfaces in the engine. Adequate purge must always be provided to prevent the ingestion of hot (>2500°F) combustion gases into the high-speed disk cavities. Codes being developed[21] will now enable the engine designer to design and better manage the highly coupled secondary to power stream inter-

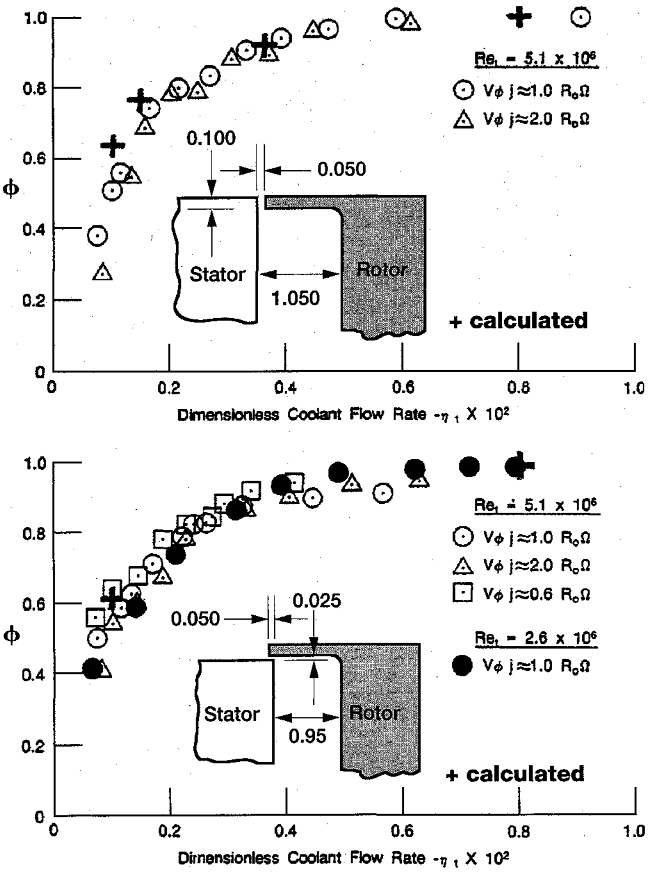


Fig. 9 Comparison of calculated[21] and experimental[22] cooling effectiveness parameter ϕ (using the CO_2 concentration method) as a function of purge flow rates η_t.

action at this location. This computer code (SCISEAL) was recently anchored with experimental data[22] measuring the effects of purge flow and rim seal geometry on the ingestion of main flow gas into the turbine disk cavity. In these studies, several turbine rim seal geometries illustrated in Fig. 9 were examined and the cooling effectiveness parameter ϕ was predicted. Good correlation was observed between the measured and predicted cooling effectiveness parameters over a broad range of flow rates providing confidence in the technique. Extensions are now underway to couple SCISEAL to leading codes[23–25] such as ADPAC that treat the time-averaged flow that exists in the multiple rows of stationary and rotating blades upstream and downstream of the rim seals.

Another reason the turbine rim seal is critical is the considerable percentage of core flow (2–3%) going through the rim seal, above that required for cooling. Munson and Steinetz[5] have shown that large engine performance benefits are possible replacing the rim seals with either brush seals or new film riding technology. Validated design codes as discussed will play a critical role in successfully implementing these low leakage seals to ensure the engine does not suffer hot gas ingestion under any possible power or transient conditions.

Modern Examples of Engines Employing Advanced Seals

Designers are replacing conventional labyrinth seals with advanced seals wherever it is practical, to improve performance during flight service including both steady-state and transient conditions. To demonstrate performance benefits possible with advanced seals several brush seal examples will be cited.

There are significant performance improvements possible with brush seals. Hendricks et al.[26] investigated performance improvements possible by implementing brush seals in the compressor discharge location of a T700 helicopter test stand engine (Fig. 10). When a compressor discharge labyrinth seal was replaced with a brush seal, seal leakage decreased, pressure increased, and specific fuel consumption decreased more than a full percentage point.

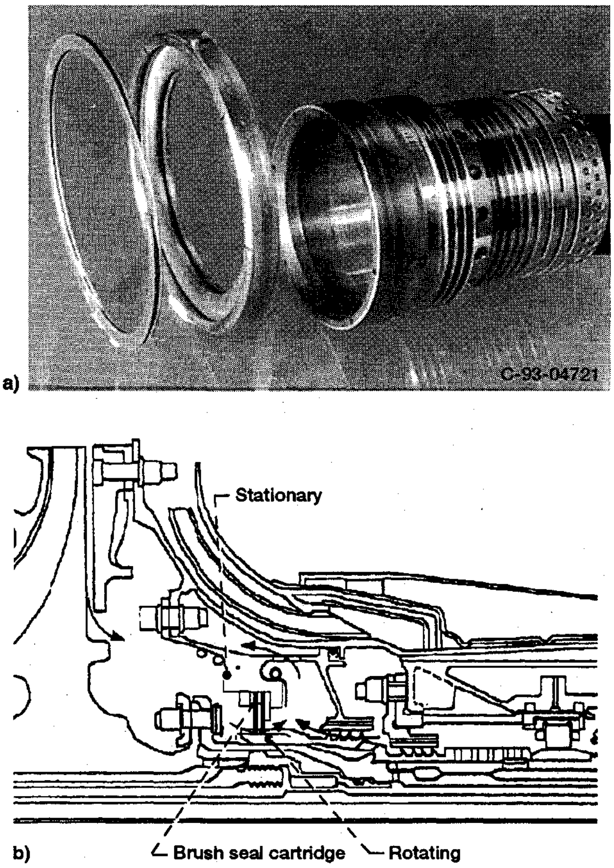


Fig. 10 T-700 helicopter brush seal test hardware and schematic[26]: a) exploded view of dual-brush compressor discharge seal system and b) brush seal package and airflow.

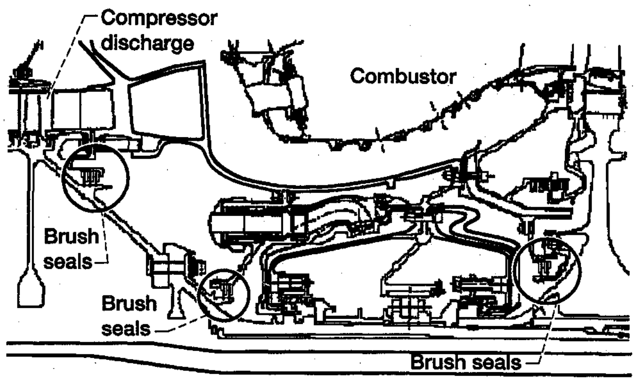


Fig. 11 Brush seals used in PW4168 engine.[27]

Engine manufacturers are embracing brush seal technology to reduce seal leakage and increase performance. The PW4168 engines use brush seals in several locations (Fig. 11). A triplex brush seal is used at the compressor discharge location. Duplex brush packs are used to reduce pressures at the mechanical face seals at the fore- and aft-ends of the bearing chamber. Improvement over conventional labyrinth seals is different for each engine design, but reductions of three-quarters of 1% of fuel burn are not uncommon. Even a partial percentage point in fuel efficiency translates into millions of dollars in savings.[27] Potential military applications include the F100-PW-229 engine for the F-15 and F-16 fighters and the advanced F-119 engine for the Advanced Tactical Fighter. The International Aircraft Engine Company V2500 commercial engine has several brush seals that have accumulated over 1 million flight hours since the 1980s.

Brush seals have been implemented on the AE-2100 engine for the SAAB2000, the T406 for the V-22 Osprey, and the AE-3007 for the Cessna Citation-X. All three engines (Allison Engine Company) share a common core and use brush seals at the compressor discharge, second stage turbine (aft), and the third stage turbine (forward) interstage locations. Though SFC improvement has been difficult to quantify, estimates range upwards of 0.25%. Brush seals are also being used on the low-pressure balance piston of the GE90, being developed to power the Boeing 777 aircraft.

Summary

NASA is working in close partnership with the aircraft industry to develop technology to reduce operating costs, reduce noise and emissions, and boost performance of next-generation commercial aircraft, under the AST program. To reach the stated goals significant improvements in engine components and subsystems are required to extract the maximum useful work from these high-power density engines. It was shown that improving engine seal technology shows great promise in assisting engine manufacturers reach the required reductions in specific fuel consumption and ultimately direct operating cost. In addition to reviewing current seal technology and highlighting seal technology advancements required, the following observations were made:

1) Significant reductions in SFC are possible by implementing advanced seal technologies. Engine studies have shown that over a 2.5% reduction in SFC for advanced regional engines is possible using advanced seals at only a few locations. Furthermore, the majority of these performance gains are possible whether or not the engine cycle is changed (i.e., higher compression ratio, higher rotor inlet temperature, etc.), as advanced seals enable designers to reduce the amount of excess cooling air used in the gasifier section.

2) Costs of developing advanced engine seals are a small fraction (one-fifth to one-fourth) that of redesigning and requalifying complete compressor or turbine components with comparable performance improvements.

3) A relatively few sealing locations contribute a large percentage to total leakage flow, allowing seal development activities to be concentrated, maximizing return on seal development resources invested.

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