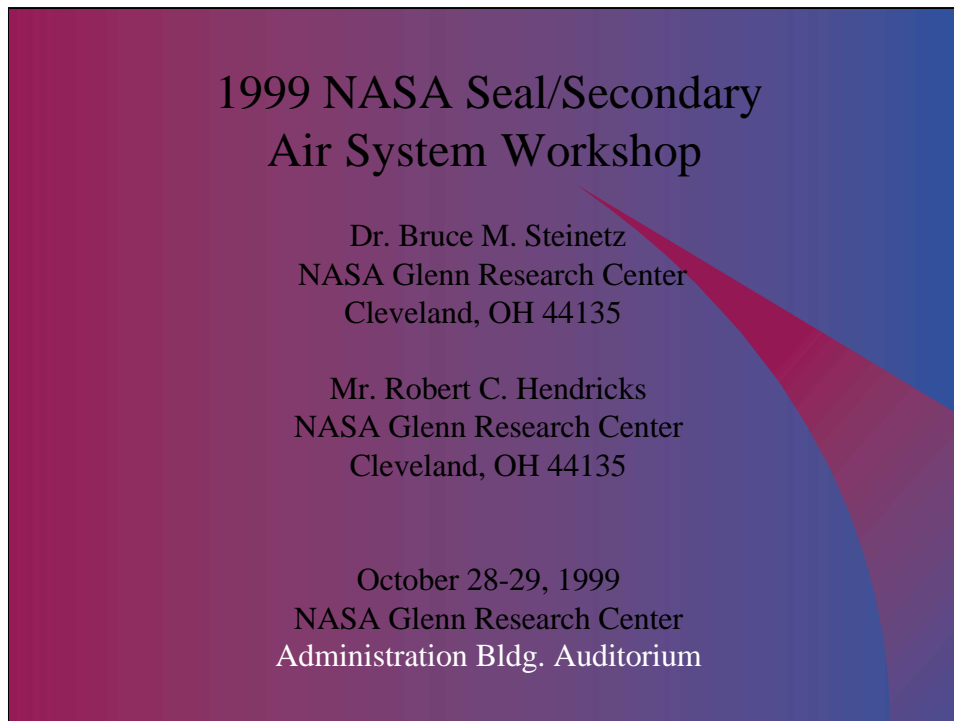


1999 NASA SEAL/SECONDARY AIR SYSTEM WORKSHOP

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Glenn Research Center
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NASA Glenn hosted the Seals/Secondary Air System Workshop on October 28-29, 1999. Each year NASA and our industry and university partners share their respective seal technology development. We use these workshops as a technical forum to exchange recent advancements and “lessons-learned” in advancing seal technology and solving problems of common interest. As in the past we are publishing two volumes. Volume 1 will be publicly available and will be made available on-line through the web page address listed at the end of this chapter. Volume 2 will be restricted under International Traffic and Arms Regulations (I.T.A.R.)

In this conference participants gained an appreciation of NASA’s new Ultra Efficient Engine Technology (UEET) program and how this program will be partnering with ongoing DOE –industrial power production and DOD- military aircraft engine programs. In addition to gaining a deeper understanding into sealing advancements and challenges that lie ahead, participants gained new working and personal relationships with the attendees.

When the seals and secondary fluid management program was initiated, the emphasis was on rocket engines with spinoffs to gas turbines. Today, the opposite is true and we are, again building our involvement in the rocket engine and space vehicle demonstration programs.

AST Program Goals

- **Reduce commercial aircraft direct operating costs including interest (DOC+I) by:**
 - 3% (large engines) and 5% (regional engines)
- **Reduce engine fuel burn up by:**
 - 8% (large engines) and 10% (regional engines)
- **Reduce engine oxides of nitrogen (NO_x) emissions by greater 50%**
- **Reduce airport noise by 7 dB, or about three-quarters reduction in acoustic energy**
- **Entry into service: 2005 - 2006**

Recognizing the need to reduce aircraft operation costs, NASA established several programs to improve both engine and vehicle performances and lower direct operating costs (DOC). The Advanced Subsonic Technology Program (1995-1999) targeted the goals shown in the chart (Steinetz and Hendricks, 1998).

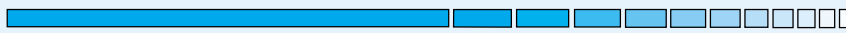
Cycle studies have shown the benefits of increasing engine pressure ratios and cycle temperatures to decrease engine weight and improve performance in next generation turbine engines. Advanced seals have been identified as critical in meeting engine goals for specific fuel consumption, thrust-to-weight, emissions, durability and operating costs. NASA and the industry are identifying and developing engine and sealing technologies that will result in dramatic improvements and address each of the goals for engines entering service in the 2005-2006 time frame.

Engine Study Results: Expected Seal Technology Payoffs

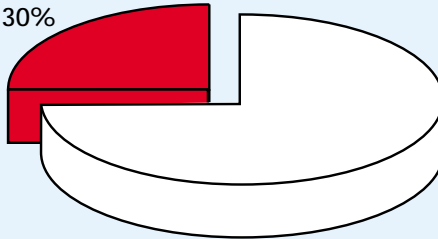
Seal Technology	Study Engine	Company	System Level Benefits
Large Diameter Aspirating Seals (Multiple Locations)	GE90/Transport	GE	-1.86% SFC -0.69% DOC+I
Interstage Seals (Multiple Locations)	GE90/Transport	GE	-1.25% SFC -0.36% DOC+I
Film Riding Seals (Turbine Inter-stage seals)	AST Regional/AE3007	Allison	> -0.9% SFC > -0.89% DOC+I
Advanced Finger Seals	AST Regional	AlliedSignal	-1.4% SFC -0.7% DOC+I

General Electric, Allison and AlliedSignal Engines all performed detailed engine system studies to assess the potential benefits of implementing advanced seals. The study results were compelling. Implementing advanced seals into modern turbine engines will net large reductions in both specific fuel consumption (SFC) and direct operating costs including interest (DOC+I) as shown in the chart (Steinetz et al, 1998).

Seal Contribution to Meeting AST SFC Goals



Seals
20-30%



Goal - Reduce SFC by 10%
Seal Contribution: 2 - 3% SFC Reduction

Advanced Seal Technology: An Important Player

CD-94-64764

Applying the seals proposed in the previous slide to just several engine locations would reduce SFC 2 to 3% . This represents a significant (20-30%) contribution toward meeting the overall goals of the AST program.

AST Descoped Seal Program



General Electric

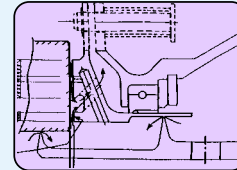
Large Diameter Seal Development

#1 Aspirating Seal -

G.E. C.R.D. Rig Tests. CFD Analysis, Engine Test (Option)

#2 Low Hysteresis Brush Seal Development

Rig Tests, Engine Test

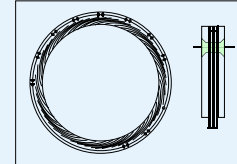


Allied Signal

Low-Hysteresis Finger Seal Development

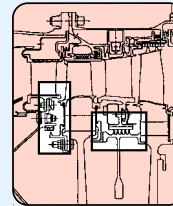
Rig Tests (NASA LeRC) - Baseline & Low Hysteresis Designs

- Performance & Endurance Tests



Allison Engine Company

Seal - Secondary Air System Design



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NASA partnered with several companies to evaluate respective advanced sealing technologies as explained on these two charts.

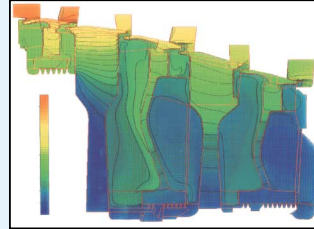
GE investigated large diameter aspirating seals and brush seals for the balance piston location in the low-pressure turbine. AlliedSignal investigated a new, low-hysteresis finger seal design. AlliedSignal and NASA performed rig performance and limited endurance tests in NASA's Turbine Seal test Rig. Allison Engine performed a detailed seal/secondary air system design to evaluate benefits of advanced seals throughout their AE3007 engine (Munson, 1999).

AST Descoped Seal Program (cont'd)



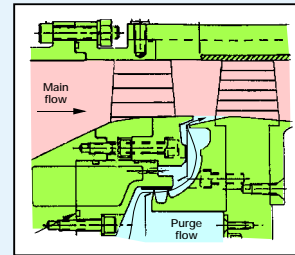
CFD - Research Center

Develop coupled secondary air (SCISEAL)/main flow path (TURBO) solution technique to predict complex cavity/main flow path interactions



UTRC

- Measure steady/unsteady turbine rim seal/cavity flows for baseline rim seal geometry
- Develop optimized (reduced flow) rim seal



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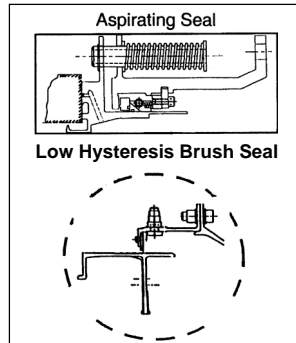
NASA contracted CFDRC to develop a coupled secondary air/main flow path solver to investigate complex turbine cavity/rim seal/main flow phenomenon. CFDRC coupled the CFDRC/NASA code SCISEAL to the Mississippi State Univ. code TURBO to perform these unsteady calculations.

NASA also contracted with UTRC to measure the steady/unsteady turbine rim seal/cavity flows to assess the performance of both baseline turbine rim seal and optimized (reduced flow) rim seal geometries.

Highlights of AST Seal Program Accomplishments: GE

General Electric

- Successfully demonstrated 36" Aspirating seal
 - Leakage <1/5th labyrinth seal
 - Operates without contact under severe conditions:
 - 10 mil TIR
 - 0.25°/0.8 sec. Tilt Maneuver loads (0.08" deflection!)
- Successfully demonstrated 36" Low Hysteresis Brush seal in GE90 demonstrator
 - 30% leakage reduction over previous 2-stage brush seal
 - Leakage <1/2 labyrinth seal
 - Survived punishing GE90 HCF durability test



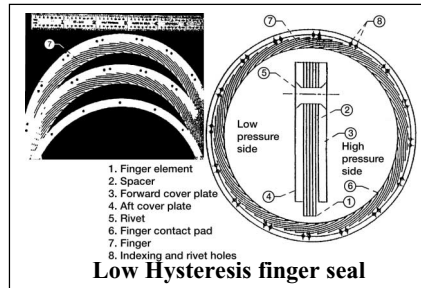
Aspirating Seal: General Electric is developing a low leakage aspirating face seal for a number of locations within modern turbine applications. This seal shows promise both for compressor discharge and balance piston locations. The seal consists of an axially translating mechanical face that seals the face of a high speed rotor. The face rides on a hydrostatic cushion of air generated by air supplied through ports on the seal face supplied by air from the high pressure side of the seal. The small clearance (0.001-0.002 in.) between the seal and rotor results in low leakage (1/5th that of new labyrinth seals) and applied to 3 locations in a GE90 engine can lead to >1.8% SFC reduction. GE Corporate Research and Development tested the seal under a number of conditions to demonstrate the seal's rotor tracking ability. The seal was able to follow a 0.010 in. rotor face total indicator run-out (TIR) and could dynamically follow a 0.25° tilt maneuver (simulating a hard maneuver load) all without face seal contact (see also Turnquist in the current Seal Workshop Proceedings for further details). GE and NASA are seeking to demonstrate this seal on a demonstrator engine under a future program.

Low Hysteresis Brush Seal: A single stage low-hysteresis brush seal was developed for modern engine applications under the NASA AST program. This program showed that a single stage low-hysteresis seal was an improvement over the existing two-stage brush seal in the GE90 engine. Sub-scale (8 9/16" diameter) single-stage seals were used to pre-screen different seal design and material combinations. Lessons learned from these tests were subsequently used to design/fabricate 36" brush seals that were installed and tested on a GE90 demonstrator ground-based engine. The single stage brush seal performed well under very aggressive high cycle fatigue tests in the GE90. The single stage seal (with advanced design features) leakage flow was 30% less than the previous 2-stage brush seal and was less than half that of a competing new labyrinth seal. The single stage low-hysteresis brush seal survived the punishing GE90 HCF durability test. (see also presentation by Tseng in the current Seal Workshop Proceedings for further details).

Highlights of AST Seal Program Accomplishments: AlliedSignal

AlliedSignal

- Developed low-hysteresis finger seal for turbine applications
- Low cost photo-etching process demonstrated resulting in seal costs a fraction of brush seals
- Pressure balanced design demonstrated very low hysteresis in repeated NASA Glenn seal rig testing
- Leakage 20-70% less than typical four-knife labyrinth seal (0.005" clearance)
- Extensive analytical work and rig testing has resulted in finger seal ready for consideration for future engine testing. (ref AS900 Engine)



AlliedSignal AS900

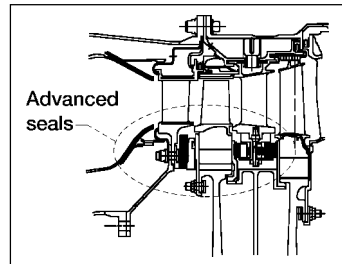
Under the AST program, AlliedSignal and NASA have developed a low-hysteresis finger seal for turbine applications (Arora et al, 1999). The finger seal is similar in general configuration to a brush seal, but functions in a very different manner. Instead of a random array of fine wires, the finger seal uses a stack of precision machined sheet stock laminates. Each laminate is machined to create a series of fingers around the inner diameter that follows shaft growth or movement during engine operation. Successive laminates are indexed to cover the finger spaces in the previous laminate layer.

The finger seal exhibits low-leakage (20-70% less than a 4 tooth labyrinth seal with a tight 0.005" clearance). Laminates made using low cost photo-etching technique results in a seal that costs a fraction that of brush seals. The AST finger seal program developed a balanced pressure finger seal design that essentially eliminates hysteresis or frictional drag between the radially moving laminates and the downstream backing plates that had caused unacceptably high leakage in previous finger seal designs. This frictional drag had prevented the laminates from moving radially inward to follow the shaft after a transient event or during rotor slow-down conditions (see also presentation by Arora and Proctor in the 1999 Seal Workshop Proceedings for further details).

Highlights of AST Seal Program Accomplishments: Allison

Allison Engines

- Conducted realistic study of gas turbine engine to determine effect of advanced seals on the total system
- Determined advanced seal requirements
- Determined cost/benefit of advanced seals



Benefits:

- Constant rotor inlet temperature (RIT) (rubber airframe/fixed engine):
 - +1.9% Thrust-to-weight
 - -0.7 % Mission Fuel Burn
- Constant Thrust
 - Reduces RIT by approximately 20°F - increases blade life by more than 50%
 - Reduces fuel burn by approximately 0.7%
 - Reduces emissions of CO and unburned hydrocarbons
 - Results in DOC reduction of approximately 0.9%: 18% of NASA AST goal for regional engine applications.

Allison performed a detailed secondary air system study to identify potential locations where the greatest performance improvements could be made implementing advanced seals. This study examined in great detail the benefits of applying advanced seals in the high pressure turbine region of the engine. Low leakage film-riding seals cut in half the estimated 4% cycle air currently used to purge the high pressure turbine cavities in the AE3007 regional jet engine. These savings can be applied in one of several ways. Holding rotor inlet temperature (RIT) constant the engine mission fuel burn can be reduced 0.7%, or thrust-to-weight could be increased 1.9%. Alternatively, RIT could be lowered 20°F resulting in a 50% increase in turbine blade life reducing overall regional aircraft maintenance and fuel burn direct operating costs 0.9% for a 600 nautical mile mission. Thermal, structural, secondary-air systems, safety (seal failure and effect), and emissions analyses were also performed showing that the proposed design was feasible (Munson, 1999).

Other Turbine Seal Accomplishments

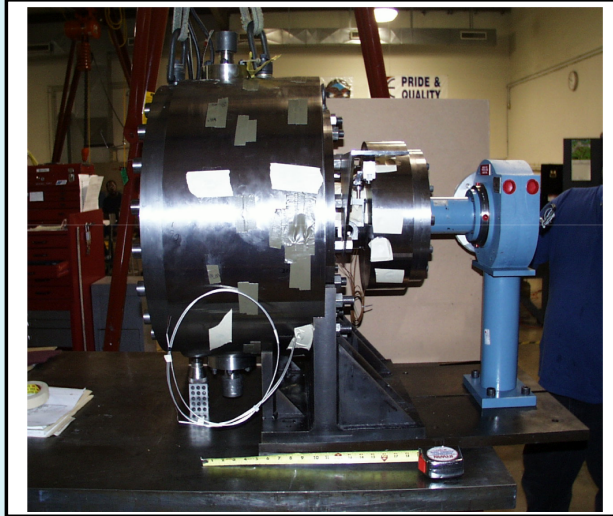
- Completed fabrication/received delivery of state-of-the-art turbine seal test rig capable of testing seals under all anticipated IHPTET/VAATE/NASA speed and temperature (1500 °F) conditions.
- Completed coupling of TURBO (main-flow path solver) to SCISEAL (Seal/secondary air system solver) to investigate turbine/rim seal flow interactions and aid in the design of more robust rim seal systems.
- Awarded SBIR Phase I to Mohawk Innovative Technology to investigate film-riding compliant foil seal (derivative of foil bearing technology) with potential for very low leakage and non-contacting operation.

The high temperature, high speed turbine seal rig fabrication has been completed. Installation of this state-of-the-art test rig is underway.

CFD- Research Corporation has completed the coupling of TURBO and SCISEAL for analyzing the complex main stream (TURBO) and secondary air stream (SCISEAL) interactions, including the effects of vane/blade wake interactions. The package can analyze flows from the engine centerline through the turbine rim seal location and through main flow path.

NASA has awarded to Mohawk Innovative Technology an SBIR Phase I to investigate film-riding compliant foil seals (see presentation by Salehi and Heshmat in the current 1999 Seal Workshop Proceedings). Foil seals are derived from foil bearing technology and block flow between high and low pressure cavities through very narrow gaps between the shaft and the foil. The hydrodynamic lift between the seal and the shaft prevents rotor-seal contact during operation. High temperature solid film lubricants applied to the shaft prevent wear during start-up and shut-down when limited contact occurs (see presentation by DellaCorte in the current 1999 Seal Workshop Proceedings).

High Temperature Seal Rig Fabrication Complete



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The high temperature, high speed turbine seal rig is shown after fabrication and assembly were completed at the vendor.

Why is Seal Development Key for UEET?

Increase Efficiency:

- **Minimum parasitic leakage is required to meet efficiency/fuel burn goals**

Increase Stage Loading:

- **Minimum blade tip loss, interstage leakage critical to meeting stage loading goals**

Reduced Emissions:

- **Minimum parasitic leakage translates into minimum fuel burn which translates into minimum emissions across the board:**
 - » **NO_x**
 - » **CO**
 - » **CO₂**
 - » **Water vapor**

NASA has begun in FY00 a new program entitled Ultra Efficient Engine Technology (UEET) program whose goal is to dramatically improve engine efficiency and reduce emissions through advanced turbomachinery concepts.

The NASA UEET program goals include an 8-15% reduction in fuel burn, a 15% reduction in CO₂, a 70% reduction in NO_x, CO and unburned hydrocarbons, and a 30 dB noise reduction, relative to program baselines. Under the UEET program, NASA has contracted with General Electric to perform a GE90 engine test to demonstrate the aspirating seal developed and laboratory-tested in the AST program. NASA has contracted with PW/Stein Seal to develop advanced carbon seals. Other seal development programs are under discussion with program officials.

Turbine Engine Seal Summary

- **NASA and industry partners are pursuing engine performance advancements to reduce fuel burn, reduce operating costs, and ensure industry competitiveness into the next century and beyond.**
- **Advancements in seal technology will play an important role in achieving performance goals.**
- **Significant reductions in SFC are possible through implementing advanced seal technology. Engine studies show that over 2.5% reduction in SFC is possible applying advanced seals to a few locations.**
- **Costs of developing advanced engine seals are a small fraction of re-designing & re-qualifying complete compressor or turbine components with comparable performance improvements.**

Engine designers are re-evaluating all aspects of turbine engines to meet the efficiency, performance and operating cost goals set for next generation turbine engines. A comprehensive survey was made of cycle losses in terms of leakages in modern jet engines such as the Allison Engine AE3007 (Munson, 1999), the GE90 (Tseng, in the current NASA Seal Workshop Proceedings) and an AlliedSignal business engine (Arora, 1999). The survey showed that large performance gains were possible in applying advanced seals in several key locations in the engine.

Structural Seal Accomplishments

Thermal Barrier Development

- Proved feasibility of NASA Glenn developed Thermal Barrier in a 1/5th Scale Reusable Solid Rocket Motor Firing. Blocked hot gas and soot from reaching the Viton O-ring. Viton O-ring and thermal barrier in “like-new” condition after the test.

Space Vehicle Control Surface Seal Development

- Completed design/began fabrication of control surface seal test apparatus to evaluate seal thermal resistance to re-entry level heating rates in Ames Arcjet Tunnel for BANTAM/Spaceliner-100, X-38 (Station emergency escape vehicle demonstrator), X-37 (Space operations vehicle).

NASA Glenn is also developing structural seals for demanding aero- and space applications.

The NASA Glenn developed braided carbon fiber thermal barrier is the primary candidate being considered by NASA and Thiokol for the redesign of the Space Shuttle RSRM nozzle-to-case joint and for nozzle joint 2 to prevent Viton O-ring damage. Incorporation of the NASA Glenn developed braided carbon fiber thermal barrier into the nozzle joints of the Space Shuttle RSRMs would eliminate hot gas penetration to nozzle joint O-rings and prevent extensive reviews that delay shuttle launches. On August 10, a NASA Glenn developed braided carbon fiber thermal barrier was successfully evaluated in an MNASA reusable solid rocket motor (RSRM) at NASA Marshall. The MNASA RSRM is a 1/5th-scale version of the full-scale RSRMs used to launch the space shuttle. Tested in a redesigned nozzle-to-case joint, an intentional flaw in the nozzle insulation allowed hot combustion gases to reach the thermal barrier. Soot was observed on hardware upstream of the thermal barrier, but none was seen on the downstream side. Post-test inspection revealed no damage or erosion to either the thermal barrier or to downstream O-rings that the thermal barrier is designed to protect. (see presentation by Steinetz and Dunlap in the current 1999 Seal Workshop Proceedings for further details).

NASA Glenn and Boeing are developing control surface seals for advanced re-entry vehicle systems. (see presentation by Verzimnieks in the current 1999 Seal Workshop Proceedings for further details)

BANTAM Advanced High Temperature Structural Seals

Objective

Advanced control surface seal concepts will be investigated and proven using appropriate high temperature test facilities

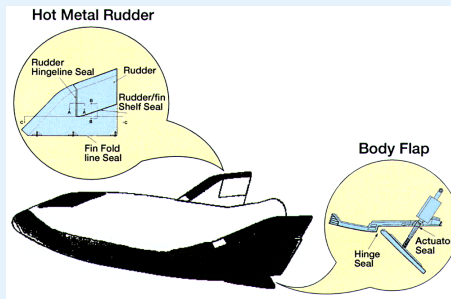
- Structural seals will be developed in concert with advanced heat-resistant composite elements being developed for advanced TPS structural concepts.

Benefits

Enabling Technology: Seals are enabling technology for advanced space launch vehicles, (e.g.: rudder; fin; body-flap; etc.)

- Weight/Performance/Cost:** High temperature seals permit lower profile TPS, more aggressive structural concepts saving weight/enhancing performance/saving payload-to-orbit costs. Eliminating the need to replace seals between missions enables Bantam to meet cost goals.
- Safety:** Robust seals increase mission safety and reliability

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Candidate Seals for Evaluation: X38 Case Study

Milestones:

- FY99 Establish seal design requirements
- FY 00 Complete fabrication/feasibility-screening of leading seal candidates
- FY01 Demonstrate technology under simulated environments: Vibro-acoustic; Arc-jet tests.

Resources:

FY	99	00	01
Budget(\$K)	242	344	344

Task Objective

This effort addresses the development of high temperature structural seals for control surfaces for the Bantam/Spaceliner-100 reusable launch vehicle. Successful development will contribute significantly to the mission goal of reducing launch cost for small, 200-300-pound payloads. Development of high temperature seals is mission enabling. For instance, ineffective control surface seals can result in high temperature (3100°F) flows in the elevon area exceeding structural material limits with a potential for loss of control surface and possibly entire vehicle. Also, longer sealing life will allow use for many missions before replacement. All of this contributes to the reduction of hardware, operation and launch costs.

Scope

This effort provides for the analysis, design, fabrication and testing of advanced structural seal concepts. Key to the success of this program will be use of emergent materials in combinations that will result in durable, feasible, and affordable seal designs. At the completion of the program, a matrix of seals and seal material combinations will have been developed for a range of aerothermal environments for a wide variety of advanced control surface applications (Spaceliner-100, X38, X37, etc). Testing will include thermal and mechanical loadings and arc-jet exposures. Aerothermal analysis methods will be applied early in the program to design the seals and will be validated by comparing the predicted and measured seal thermal responses of the validation seals in arc-jet tests (see also presentation by Verzemnieks and Newquist in the current 1999 Seal Workshop Proceedings for further details).

NASA Seals Web Sites

- **Turbine Seal Development**

<http://www.grc.nasa.gov/WWW/TurbineSeal/TurbineSeal.html>

NASA Technical Papers

Workshop Proceedings

- **Braided Rope Seal Development**

<http://www.grc.nasa.gov/WWW/structuralseal/>

NASA Technical Papers

Discussion

http://www.grc.nasa.gov/WWW/TU/InventYr/1996Inv_Yr.htm

The Seal Team maintains three web pages to disseminate publicly available information in the areas of turbine engine and structural seal development. People interested in these web sites can visit them at the addresses indicated above.

References

- Arora G.K., Proctor, M.P., Steinetz, B.M. and Delgado, I.R., 1999 " Pressure Balanced, Low Hysteresis Finger Seal Test Results," NASA TM-1999-209191, AIAA-99-2686.
- Munson, J.H., 1999, "Advanced Subsonic Transport Task 8: Advanced Seals and Secondary Airflow Systems," Final Report, Contract NAS3-27725, November, Allison EDR-18602.
- Steinetz B.M., Hendricks, R.C., and Munson, J.H., 1998 "Advanced Seal Technology Role in Meeting Next Generation Turbine Engine Goals," NASA TM-1998-206961.
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