CONTROL SURFACE SEAL DEVELOPMENT FOR FUTURE RE-ENTRY VEHICLES

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Control Surface Seal Development for Future Re-Entry Vehicles

presented at

NASA Seal/Secondary Air Delivery Workshop
NASA Glenn Research Center
26 October 2000

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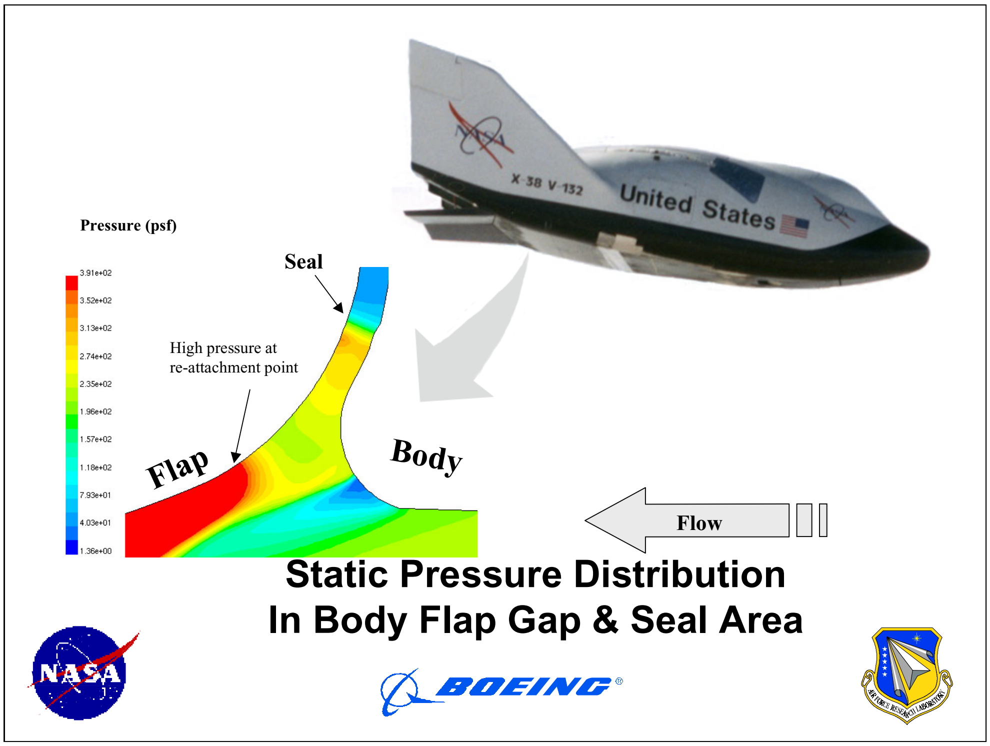


Phase 1 of this project was presented at this workshop last year. This chart is taken from that presentation and illustrates our modeling analysis. The flow environment was from X-38 re-entry conditions and the physical dimensions were adapted from the X-38 preliminary designs. Thethermal modeling was accomplished using FLUENT, a commercially available CFD software package.

We focused on the seal area and two seal conditions: (1) an impermeable seal, and (2) a permeable seal -- permeability, k= 1 x 10^{-7} ft^2

Seal Surface Condition (20° flap δ)	Impermeable	Permeable Permeable Seal ($k = 1 \times 10^{-7}$ ft^2)
Radiation Equilibrium Heat Flux (Btu/sq ft-hr)	7000 to 9000	15000 to 30000
	Seal permeablility significantly increases seal heating.	
Radiation Equilibrium Temperatures (°F)	2000 to 2200	~~2500 to 3000~~ 2300
	High seal permeablility significantly increases seal temperatures *Note: These radiation equilibrium temperatures are only a rough estimate of actual material temperatures. A transient structural thermal analysis is required to accurately predict seal temperatures.*	

The phase one thermal analysis results for radiation equilibrium temperatures is shown in this chart, with an overstrike for the permeable seal case-- a revised estimate for temperatures.

Aerothermal analysis was performed during the first phase of this program using X-38 data and FLUENT, a commercial CFD code. The seal aerothermal environment was estimated with a steady state flowfield solution. Steady state flow solution assumes constant energy flow into the cove sufficient to balance heat flux into seal and structure. An effective seal prevents high flow rates into the cove. However, there was a problem with including porosity as a property of the seal, and resulted in estimated porous-seal temperatures that appeared to be high. Attempts were made to overcome the porosity issue, but temperature estimates as the porosity was decreased to negligible values did result in convergence (at very low porosity) to temperatures that were estimated with an impermeable seal. The thermal analyst's solution is outlined below:

- Determine equivalent mass leakage ratio of permeable bodyflap seal
- Apply Shuttle Orbiter elevon-seal-leakage correlation factors to determine bodyflap thermal environment.
- Apply aerothermal environment to thermal structural model of seal
- Seal-heating prediction methods used on the Shuttle Orbiter were developed in terms of leakage rates. To apply these to a permeable seal, an equivalent leakage rate must be determined.

Leakage rates on our seal designs were determined and resulted in seal temperatures that are estimated now to be in the range of 2300°F. Previous analysis had resulted in seal temperatures on the order of 2650°F

THERMAL ANALYSIS -- Approximate Methods

2-D Analysis with FLUENT

Arcjet Conditions
1. Conduct 2D integrated CFD/structural thermal analysis on test fixture at test conditions
2. Compare predicted pressure and temperatures with test data
3. Adjust analysis parameters to improve correlation with data

Flight Conditions
1. Conduct FLUENT analysis with method resulting in best agreement with test data at flight conditions

Limitations and Assumptions
1. FLUENT contains no real gas model, seal temperature analysis conducted by matching flow total temperature
2. Analysis parameters and assumptions which resulted in agreement with test data are assumed to work well for flight conditions

Advantages
1. Relatively fast CFD analysis Integrated flow field and structural heat transfer analysis

Apply Correlations of Test Data

Arcjet Conditions
1. Predict heating and pressure at reference locations on test fixture surface using established 2D boundary layer method
2. Correlate seal and cove temperature data to reference values with relationships developed on previous studies
3. Evaluate applicability of previously developed correlations to current conditions
4. Evaluate assumption of equivalence of leakage and flow through a porous seal

Flight Conditions
1. Predict heating and pressure at reference locations on test fixture surface using established 2D boundary layer method
2. Use correlations of test data to predict seal and surrounding structure aerothermal environments
3. Conduct transient finite element analysis of seal region during reentry to determine seal temperatures

Limitations and Assumptions
1. Correlations developed from test data are assumed to be valid at flight conditions as well

Advantages
1. Rapid analysis method
2. Used successfully before CFD available

The next few charts are about thermal analysis and issues of relating analysis of the arc-jet conditions to those of flight. There are three basic methods for analysis -- these are listed in **bold** type and discussed below.

For all the methods, since there is no data at actual flight conditions, it is assumed that 1) the important parameters in the flow are modeled and 2) that if the method matches data at the test conditions it will also be valid at flight conditions. For the three methods we're looking at those assumptions range from bad to good.

Since **FLUENT** has no real gas model, flows with total temperatures greater than 3000 R will not be modeled correctly. That includes both the arcjet and flight environments. So, this violates assumption (1) above. But it is able to analyze complex flow fields relatively quickly and I think can give us good indications of the trends due to seal porosity and other parameters.

Correlations of the arcjet data will inherently include the real gas effects in the arcjet. So this should be an improvement over the FLUENT predictions. But it still assumes the real gas and chemistry effects in the arcjet can be extrapolated to flight. This violates assumption (2) to some degree.

The Ames CFD work will use a sophisticated model of the air chemistry which I expect is based on a lot of theory and high temperature chemical data. The important aspects of the flow field are certainly modeled and the assumption that the methods will also be valid at flight conditions has probably been shown for Shuttle and other flight data. So I think we can claim a high amount of confidence in flight predictions made with this method.

THERMAL ANALYSIS -- Higher Order Method

Non-Equilbrium Air 3D CFD Analysis
(NASA ARC Reacting Flow Environments Branch)

Arcjet Conditions
1. Conduct 3D non-equilbrium CFD analysis for test geometry and conditions drawing on experience of modeling arcjet flows
2. Validate method with measured pressure, temperature and LIF data

Flight Conditions
1. Conduct 3D non-equilibrium CFD analysis of vehicle geometry at flight conditions using identical air chemistry model as used for test conditions
2. Apply CFD aerothermal environment to finite element model of vehicle seal region to determine reentry temperature histories

Limitations and Assumptions
1. Requires significant time, effort and experience

Advantages
1. Highest fidelity analysis
2. Benefits from Reacting Flows Branch experience in modeling arcjet flows

(continued)

Collaboration with NASA-Ames Research Center RFE Branch has resulted in suggested Aerothermal Analysis Tasks of Benefit to Advanced High Temperature Seals program. The object is to use the most sophisticated anlaysis of the arc-jet flow field in order to be able to make the best extrapolation of arc-jet test data to flight conditions. The following tasks are being discussed:

1)Investigate relationship between boundary layer enthalpy profile and thickness forward of control surface gap and enthalpy of flow entering gap at test conditions

2)Investigate relationship between control surface deflection angle, Mach number, control surface pressure and pressure at seal at test and flight conditions

3)Produce high fidelity CFD solution at test conditions for comparison to test data and approximate methods

4)Predict seal and cove aerothermal reentry environments with methodology validated at arcjet conditions

THERMAL ANALYSIS -- Summary

Analysis assumes that: 1) the important parameters in the flow are modeled.
2) that if the method matches data at the test conditions it will also be valid at flight conditions.

How Do the Methods of Analysis Compare ?

FLUENT

- FLUENT has no real-gas model
- However, it can quickly analyze complex flow fields and give us good indication of trends due to porosity, etc.

Correlations of Arc-Jet Data

- Will inherently include real-gas effects.
- However, it still assumes that real-gas and chemistry effects can be extrapolated to flight.

NASA-Ames CFD

- Uses sophisticated model of gas chemistry
- Can claim a high degree of confidence in flight predictions.

SEAL DESIGN

Baseline Seals -- Orbiter, X-33, X-38

Standard Bulb	**Nextel™ 312 & 440** for the braid/fabric over the metal spring and the fiber fill. **Inconel™** metal alloy spring -- woven multi-wire **Saffil™** fiber for the fill material -- vary bulk density
Advanced Bulb Seal	**Nextel™ 440** for the braid/fabric over concentric layers of Nextel™ 440 sleeving
Next Generation Seals	**TBD** -- based in part on arc-jet test results

Baseline seals have been selected from the experience of Shuttle Orbiter and numerous design programs for small re-entry vehicles such as X-38, X-33, and X-37.

Nextel 312 materials are capable of long-term service only to temperatures of around 1600F. For capability to temperatures of 2000 to 2200F ceramic fiber products using Nextel 440 material are included.

The standard spring device (again based on 1600F performance) has been Inconel wire (multi stranded) that is woven into a spring. Steinetz and Dunlap in the study for the previous presentation in this workshop investigated bulb seal resilence to temperatures of 1900F and found that the standard bulb seal construction with the Inconel spring permanently deforms at temperatures of 1800 to 1900F. We have baselined the construction designs of the Steinetz and Dunlap study because of the extensive flow and compression testing performed in that study.

The advanced bulb seal configuration that we will test uses a design that was introduced during the development of X-38. This design uses a core fill of concentric Nextel sleeving to form a resilient seal that shows promise at elevated temperatures.

Next generation seals will consider other features such as refractory metal foils or springs and ceramic composite elements to retain resiliency and lower the permeability. Of course these designs will be based in part on the results of arc-jet testing.

TEST OBJECTIVES:

- **Validate thermal model at two gap sizes** *(0.25 and 0.375 inch -- 0.625 dia. seal)*
- **Evaluate Arc-Jet performance of:**
  - **Baseline** Shuttle seals with Nextel 312 (2 layers of braid cover), Inconel spring tube, and 6 & 9 lb/ft^3 Saffil core fill
  - **Advanced Seals** with Nextel 440 (2 layers braid cover + 1 layer braid with 5HS cover), Inconel spring tube, and 6 and/or 9 lb/ft^3 Saffil core fill
  - **Next Generation** Seal Designs
- **Evaluate wear resistance at RT of candidate seals against TUFI-RCG coated TPS Tiles; and, Where Possible, perform high temperature wear resistance cyclic testing.**

The test objectives are presented in this chart. They are to validate the thermal modeling, evaluate performance of the baseline and advance seal materials discussed in the previous chart, and to evaluate wear resistance at room temperature against TUFI-RCG coated tiles. Because of the articulation of the test fixture we will gain some idea of high temperature wear behavior -- we will perform cyclic movements where appropriate.

High Temperature Structural Seals

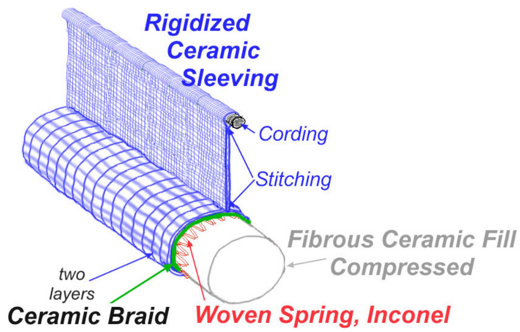
Test Matrix Components

Seal Configuration	DESCRIPTOR #1 Material Fabric/Braid	#2 weave	#3 Knitted wire Spring	#4 Mat'l Fill	#5 Fill (lb/ft3)	#6 Attachment to fixture	CMC Augr	Arc-Jet Tests: Run #	Arc-Jet Tests: Temp/Press	Arc-Jet Tests: Hi Temp Cyclic Wear	Lab Environment T: RT Wear in Arc-Jet Fixture	Lab Environment T: Flow Resistance @ GRC (RT)
	Braid is two layers, unless stated other						Check-Out Run		Establish operating envelope; Determine angle limits of this fixture in Arc-Jet facility; Measure cove pressures and T's as function of elevon			
Baseline -- Single	Nextel 312	Braided sleeving	Inconel -- 0.53 inch diam.	Saffil	6	CMC stiffened "tail" attached by sewing; held in fixture with small-corded-bulb.		1	Measure elevon surface temperatures as function of el			
BULB 0.625 inch dia. **SEAL GAP** = 0.25 inch **COMPRESSION** = 20% Diametrally	Nextel 312	Braided sleeving		Saffil	6			2	X		X	
	Nextel 312	Braided sleeving		Saffil	9			3	X		X	
	Nextel 440	Braided sleeving		Saffil	9			4	X		X	X
	Nextel 440	Braided sleeving		Saffil	9			5	X	X		
Baseline -- Double	Nextel 312	Braided sleeving		Saffil	6			6	X		X	
	Nextel 440	Braided sleeving		Saffil	9			7	X		X	X
	Nextel 312	Braided sleeving		Saffil	6			8	X		X	
		LARGER GAP -- 0.375 inch -- Run #8										
Concentric Braid Fill single	Nextel 440	5HS fabric over concentric 1/8, 1/4, 1/2 inch diameter braid sleeving	N/A	N/A	N/A	Overwrap fabric forms tail, with cording at interior side of cross-section; stiffen with CMC matrix.		9			X	X
	Nextel 440	440 Braided sleeving over concentric 1/8, 1/4,1/2 inch diameter braid sleeving	N/A	N/A	N/A	Tail formed fromOne inch diam. Braid with cording at interior side; stiffen with CMC matrix.		10			X	X

END of BASELINE & ADVANCED SEAL TESTS

This table lists the parameters describing the seal configuration for the first 10 arc-jet test runs. We plan to begin with the single bulb seal configuration and also include the double seal configuration. We will conclude this series with the Nextel 440 concentric sleeving core design. The variables to be tested will be the exterior covering -- compared will be 5 Harness satin fabric to the standard braided sleeving. As described later we will use the fabric so that we have an exposed face where the majority of yarns are parallel to the sliding direction.

Single Bulb Seal Configuration



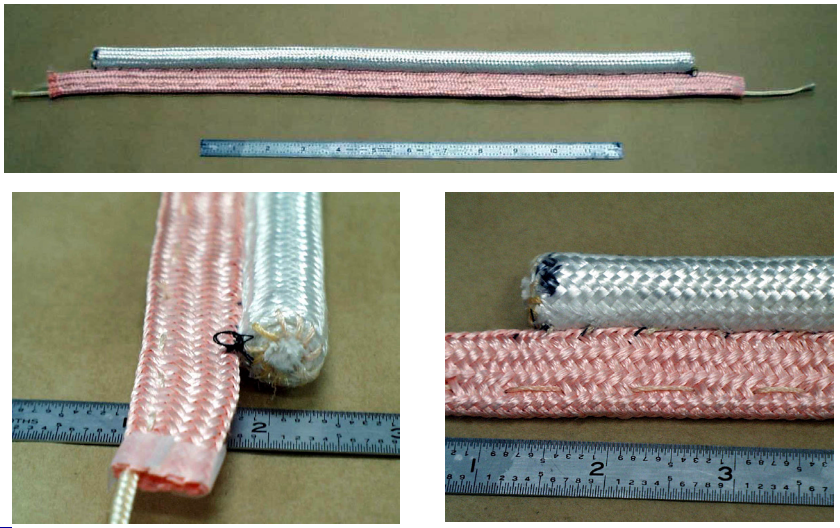
Attachment of bulb seals to the thermal protection system structure is very important. We selected a method of attachment that is all ceramic and uses the basic bulb seal element combined with braided fiber products; then finished with a selective rigidization using a proprietary Boeing ceramic coating/matrix material.

We used a 1/2 inch Nextel 440 braided sleeve into which we sewed a stretched Nextel 440 1/8 inch diameter sleeve into one side. This flattened sleeving was attached to the bulb seal (locating the joint with a tool having the fixture contour) by sewing with Nextel 440 thread. The seal and attachment fixture is then heat treated to remove the sizing before placing into the molding tool for densification and rigidization.

We considered metallic attachment, silicone bonding, ceramic cements and rejected them because of service temperature limitations, and the desire to have an easily replaced unit. The same concept works as well for a fabric over-wrapped bulb seal.

SEAL FABRICATION

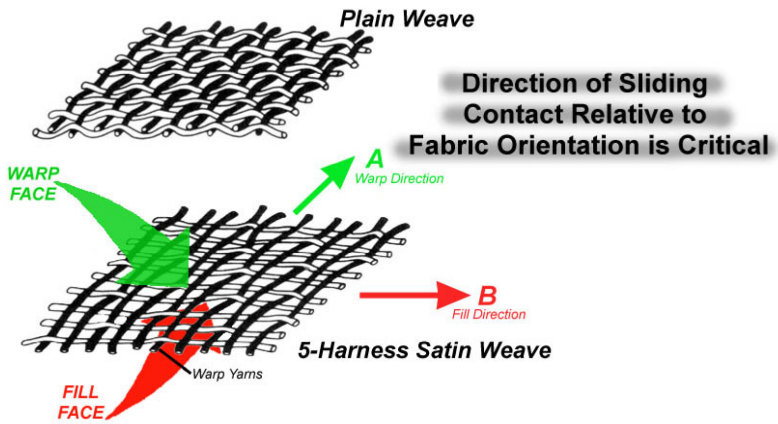
Ready for Sizing Burn-Out & Tail Rigidization



The first test article seal (Nextel 312 braid, Inconel spring, and 9 lb/ft^3 core Saffil) with the attachment sleeve. This unit includes the stitching which is barely visible against the bulb seal in the photo at the lower right. The ends of the attachment sleeving will be trimmed to the proper length after the rigidization process is complete.

The black thread (photo lower left) is cotton and was used as a temporary fabrication aid. It disappears during the sizing removal process. The lower right photo also shows a black marking of ink from the fabrication sequence.

Direction of Sliding Contact Relative to Fabric Orientation



The direction of sliding contact with a ceramic fabric is critical. Experience indicates that sliding contact on a fabric face in the parallel direction of the floating yarns results in less damage than perpendicular to them.

This chart illustrates some of the definitions involved with this discussion -- such as warp and fill faces of a 5-harness satin weave fabric.

Arc-Jet Testing & Fixture

- **Arc-Jet testing of seals in a unique, articulating fixture.**
- **Use NASA-Ames PTF** *(Panel Test Facility)*

  20 MW

  Pressure of 20 torr (approximately 80,000 ft of altitude)

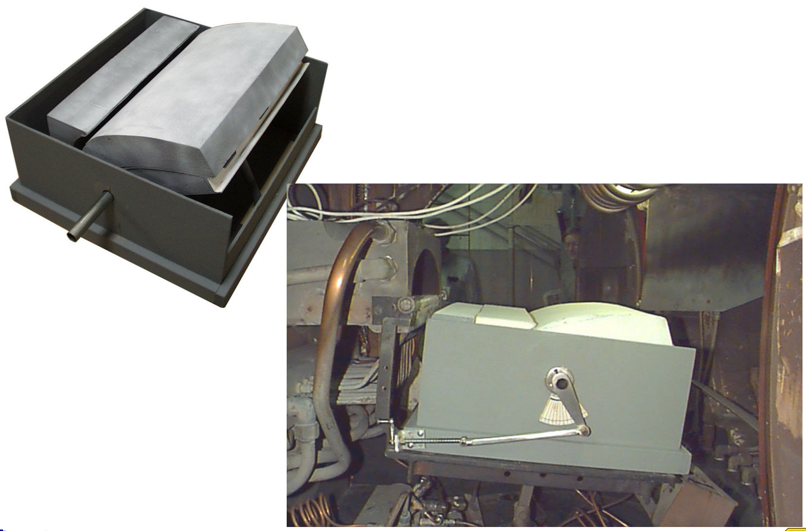
  Convective heating rate = 0.5 to 75 Btu/ft^2-sec

  Mach No. 5.5

The program team designed a unique, articulating control surface element as an Arc-Jet test fixture for the NASA-ARC PTF .

The pressure of 20 torr is the chamber pressure -- the dynamic pressure on the control surface element and seal will be higher and a function of the deflection angle.

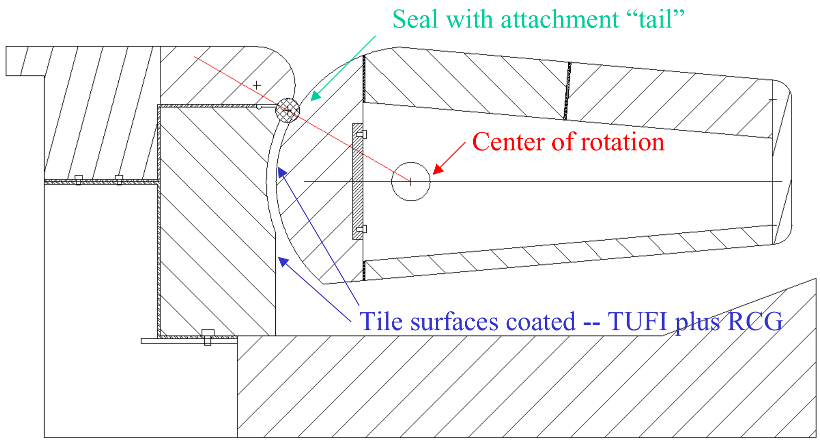
Mock-Up of Arc-Jet Test Fixture



This chart shows the mock-up of the test fixture that was fabricated for the first phase of this project. It was a model for design check-out in the arc-jet, and to work out the fine details including actuator location and alignment of fixture with arc-jet fittings. It turned out to be an invaluable tool for the design process and elicited significant suggestions and enthusiasm from the staff of the facility.

Drawing -- Arc-Jet Test Fixture

Showing Tile Segments



This is the nearly final iteration of the drawing for the actual arc-jet fixture components. There is a change from this drawing of the side view -- the joints of the tile segments are now stepped.

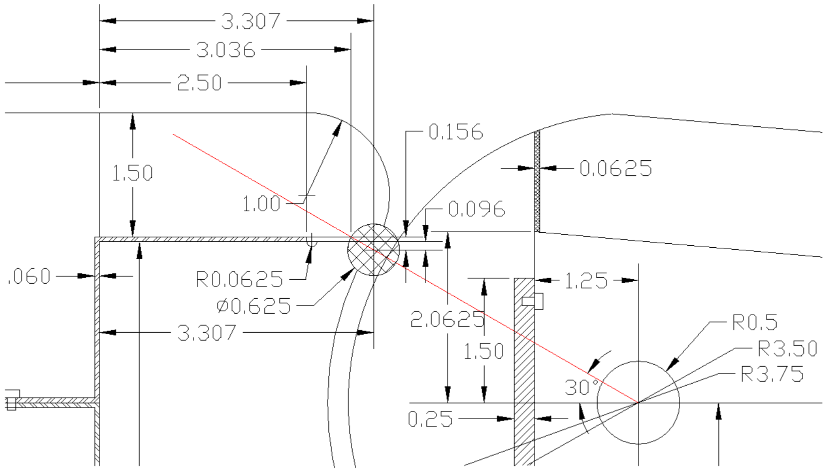
The fixture is designed so that the components can be easily disassembled *(and re-assembled),* especially the front section that holds the seal element. The front piece (Silfrax with the lip) lifts out and the metal framing can be unbolted and the seal holder lifted out -- without removing the articulating elevon section. The tested seal can then be removed and replaced with the next test article.

The tiles are mounted on metal carrier plates for ease of assembly and replacement.

The exposed tile surfaces (made of AETB-16) are coated with TUFI and overlaid with the RCG coating for a robust and smooth, glassy surface.

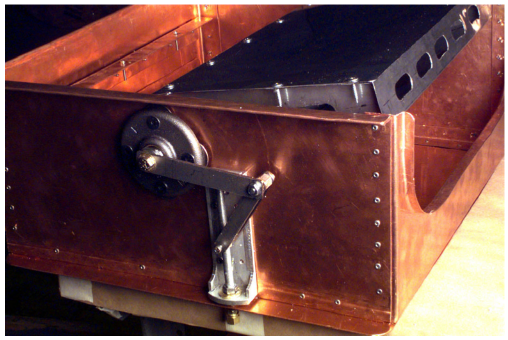
A total of 32 thermocouples will be installed for thermal data collection -- six thermocouples in potentially sensitive, critical areas will be monitored in real-time. An IR camera and optical pyrometers are also available. In addition 6 pressure transducer taps will be recording pressure data during the arc-jet runs.

Drawing -- Arc-Jet Test Fixture



The seal element is held in place mechanically. The small, corded bulb on the end of the tail is locked in by the TPS tile sections. A friction fit of the flat portion of the tail is held between the tile sections.

Arc-Jet Test Fixture -- Metallic Structure



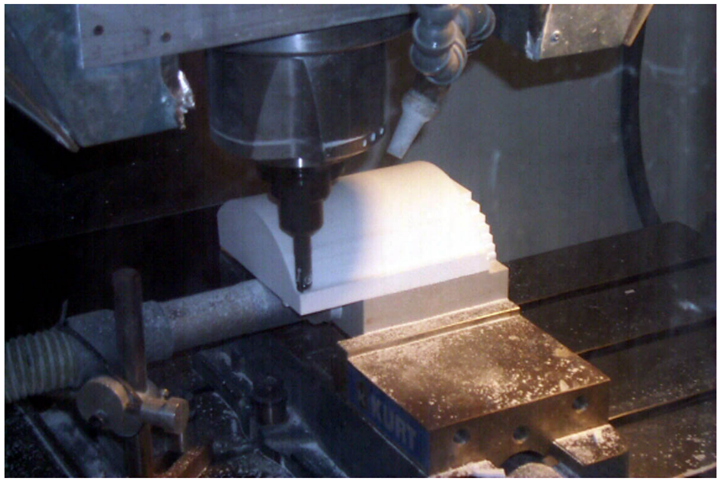
The box that holds the stationary tile assembly is made of copper sheet and will be cooled by circulating water coils on the exterior. The stainless steel metallic structure for the elevon element is clearly shown. The actuating lever will be mechanically to articulate the elevon to the required deflection angle.

The maximum angle of deflection may be limited by deflection of the arc-jet flow onto thermally sensitive areas of the chamber. This will be investigated during the first test run.

Arc-Jet Test Fixture -- Metallic Structure

Another view of the metallic components. This view is toward the front (the arc-jet nozzle) and shows the top of the elevon support structure.

Elevon Nose Section Machined from AETB-16
At NASA-Ames Ceramics Lab

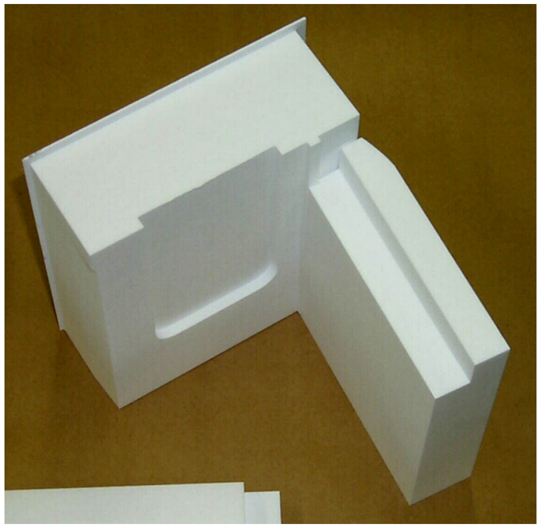


A nose section of the elevon tiles being milled for the at NASA-ARC. The front radius is being shaped.

The AETB-16 material for the tiles was supplied by Boeing, Huntington Beach with support by the Boeing X-37 program.

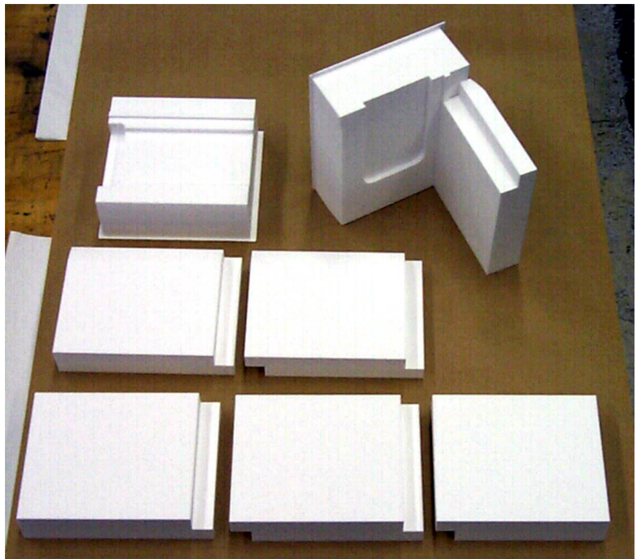
Tile Sections Machined from AETB-16

Partially finished Nose section and top surface tile



A close-up view of a finished top surface tile butted up to a partially completed nose section tile (the front radius remains to be milled). Note the stepped joints and the recessed area for the nose-tile carrier plate.

Tile Sections Machined from AETB-16



Nose section tile blanks (partially completed) along with elevon surface tiles.

All pieces are AETB-16 tile material.

SUMMARY

- Thermal analysis efforts are being coordinated with NASA-ARC in a cooperative effort for relating arc-jet environment of the seal to flight environment
- An articulating arc-jet test fixture has been designed and nearly completed
- Baseline seals have been designed and fabricated
- An all-ceramic attachment method has been designed and developed
- Arc-jet testing is scheduled for November