



# Advanced High Temperature Structural Seals

Charles W. Newquist, Juris Verzemnieks, Peter C. Keller, Michael Rorabaugh,  
and Mark W. Shorey  
The Boeing Company, Seattle, Washington

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## 1 SUMMARY

This program addresses the development of high temperature structural seals for control surfaces for a new generation of small reusable launch vehicles. Successful development will contribute significantly to the mission goal of reducing launch cost for small, 200 to 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. Longer sealing life will allow use for many missions before replacement, contributing to the reduction of hardware, operation and launch costs.

During this phase of the program the following tasks were successfully accomplished:

- (1) Sealing concepts were developed and fabricated
- (2) The aerothermal environment for a high temperature seal design for an X-38 vehicle environment was analyzed
- (3) An articulating arc-jet test fixture for evaluating seal concepts was fabricated to simulate an elevon structure
- (4) 8 seal specimens were exposed to arc jet conditions in a total of 10 separate model runs

In summary, fibrous ceramic bulb seals were demonstrated to dramatically decrease the temperature in a gap below the seal compared to an unsealed gap. With surface temperatures in excess of 2200 °F above the seal, the gap temperatures below the seal position were about 200 to 450 °F with a single seal installed rather than 2100 °F with no seal.

Seal fabrication and design issues – particularly attachment ideas – were identified and addressed during concept development and also during fabrication of the test seals. The original seals from the supplier needed to be modified by Boeing Phantom Works because of a late change in the test fixture design and lessons-learned from the very first arc-jet run. The necessity for modification led to development of a new approach to closing the ends of the bulb seals and to a more thorough understanding of ceramic textiles for seal applications, including:

- (1) Damage to the outer seal surface that was in contact with the movable elevon nose
- (2) Potential benefits of a CMC coating/impregnant for the ceramic fiber seal-surfaces
- (3) Use of a rigid, 100%-ceramic attachment

## 2 INTRODUCTION

NASA is considering developing a number of new vehicles for space missions that return to the earth. These include vehicles such as the Spaceliner 100 and X-38 emergency crew return vehicle (CRV). These newer vehicles are much smaller than the Space Shuttle and require different designs and technology for sealing gaps between structures and movable control surfaces to prevent ingestion of hot gas or plasma into critical areas. The Shuttle is large enough that the actual sealing elements for the elevons can be placed deep enough into the structure to be able to use relatively low temperature limit materials. However, seals in newer, smaller vehicles will be located closer to hot gases passing over the surface of the vehicle. The resultant higher temperatures will require the use of high temperature materials in the seals.

The goal of this program was to design and fabricate high temperature seals for these newer vehicles and test them in an arc-jet environment at the NASA Ames facility. The first part of this effort has been described<sup>1</sup> and included the selection of the X-38 as the source of the aerodynamic data around which to analyze the thermal environment and determine the constraints around which to develop seal concepts. The lessons learned from the Shuttle experience and X-38 and X-37 design projects were incorporated into the development of seal concepts for this project.

Because the X-38 program had generated extensive aerodynamic data this study used that X-38 data and an elevon seal design based on their vehicle design for baseline purposes. In a previous study for the X-38 program, Dunlap et al.<sup>2</sup> performed a series of experiments to measure flow rates, resiliency, and unit loads for candidate seals for the rudder/fin seal location on bulb seal constructions (a further study was also reported by Dunlap et al.<sup>3</sup>). These bulb seal configurations are used to seal the main landing gear door, the orbiter external tank umbilical door, and the payload bay door vents on the Space Shuttle. Because this configuration was extensively studied it was selected as the baseline configuration for this study.

The specific objectives of the current study were to:

- 1) Perform a thermal analysis of the seal design configuration using X-38 data.
- 2) Develop designs for the seal test items and the seal test fixture
- 3) Fabricate the seals and the seal test fixture
- 4) Experimentally determine anticipated seal temperatures for representative, external flow boundary conditions under arc-jet test conditions simulating vehicle re-entry.

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<sup>1</sup> Newquist, C.W., Verzemnieks, J., Keller, P.C., and Shorey, M.W., "Advanced High Temperature Structural Seals," NASA CR-210522, November 2000

<sup>2</sup> Dunlap, P.H., Steinetz, B.M., and Curry, D.M., "Rudder/Fin Seal Investigations for the X-38 Re-Entry Vehicle," NASA TM-210338/Rev 1, November 2000

<sup>3</sup> Dunlap, P.H., Steinetz, B.M., Curry, D.M., and Newquist, C.W., "Further Investigations of Control Surface Seals for the X-38 Re-Entry Vehicle," NASA TM-210980, July 2001

The specific arc-jet test objectives were to:

- 1) Validate thermal model at two gap sizes (*0.25 and 0.375 inch – 0.625 diameter seal*)
- 2) Evaluate arc-jet performance of:
  - Baseline Shuttle Seals** with Nextel 312 (2 layers of braid cover), Inconel spring tube, and 6 and 9 lb/ft<sup>3</sup> Saffil core fill
  - Advanced Seals** with Nextel 440 (2 layers braid cover), Inconel spring tube, and 6 and 9 lb/ft<sup>3</sup> Saffil core fill

**Next Generation Seal Designs** of concentric braided-sleeving of Nextel 440

- 3) Evaluate wear resistance at RT of candidate seals against TUF-RCG coated TPS tiles

The following sections will describe the arc-jet test model fixture, the seal construction and test matrix, the test facility, and the results of the testing.

### 3 DESCRIPTION OF TEST FIXTURE

The test fixture consists of a water-cooled copper box containing a stainless steel movable elevon section that is covered with AETB tiles. Figure 1 shows a cross-section drawing of the fixture indicating the tiles with shaded blocks. The two photographs of Figure 2 are of (a) the mock-up article that was made for fit-up trials and b) the mock-up article in the arc-jet facility.

Figure 3 is a dimensioned drawing of the fixture, and Figures 4 and 5 are the upper and lower brackets that were modified at NASA ARC after a late design change. This design change was needed to accommodate the adjustable seal gap as well as elongated holes for the stainless steel pressure tap tubes and thermocouple wires. Figure 6 is a more detailed view of the area in which the test seals are installed. The seal cross-section is actually compressed (*not circular as shown in the drawing*) into the gap against the curved nose of the movable elevon. The seal compression for all of the runs for the standard 0.25-inch gap was designed to be a nominal 20% diametrically. The compression for the 0.375-inch gap was to be slight contact.

The seal test elements are cylindrical in cross section and have a rigid tail running the full length of the seal. The cylindrical portion of the seal nests into a groove in the tile just ahead of the elevon gap and the tail is trapped between the upper and lower seal holders as shown in Figure 6 for a mechanical attachment design.

Figure 7 shows the AETB tiles that were machined for the flat areas of the fixture. Note the interlocking edges for sealing. The surface AETB material was installed as multi-piece tiles on all surfaces due to the constraints of AETB manufacture and to account for differential thermal expansion between the tiles and the metal structure. Figure 8 illustrates the machining of one of the elevon nose-sections using a process that was identical for all the tiles, including the sections for the cove (not shown). These tile elements were then coated with a Toughened Unit-Piece Fibrous Insulation (TUF-RCG) coating followed by a reaction cured glass (RCG) coating. Those surfaces of the

nose tiles that were going to be in contact with the test seals were lightly sanded to remove surface asperities.

The actual test fixture with construction details is shown in Figures 9 through 11. Please note the metallic structure, cooling tubes, actuation arm, thermocouple feeds, and pressure port fittings. Figures 10 and 11 also include the finished installation of the coated AETB tiles.

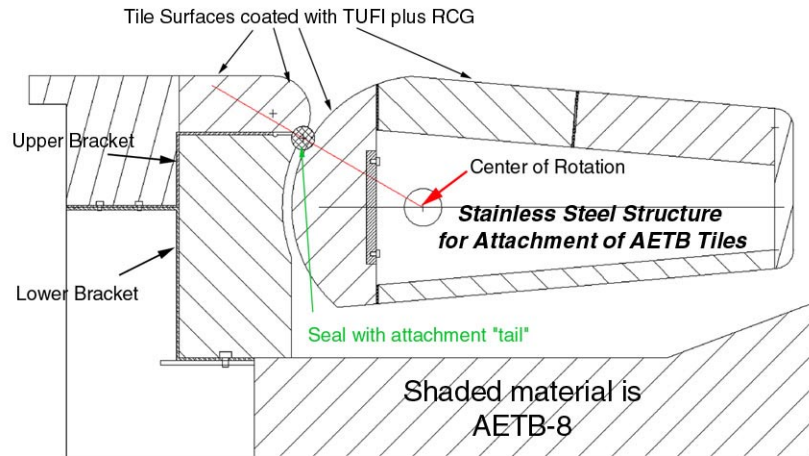
Figure 12 shows photographs of the upper surface of the test fixture (*prior to test*) with installed insulation tiles, including installation of test seal #1. From right-to-left the components are (1) Silfrax block; (2) Cove tiles; (3) seal—*white in appearance*; (4) nose tiles; (5) upper surface tiles—*beginning with a radiused leading edge*. Gaps between each of the nose tiles, and between the nose tiles and the upper surface tiles, have been stuffed with Saffil batting.

Figure 13 shows the same upper surface at a zero degree elevation angle before the test, and at an elevation of 5 degrees after arc-jet run #98–01.

Raising and lowering of the moveable elevon section was done by turning a flexible shaft connected to the test fixture (Figures 9 and 10) and routed through a vacuum seal in the bottom of the vacuum chamber. The number of turns of the crank on the flexible shaft per degree of elevon motion was calibrated before the tests began (2 turns per degree of inclination). Elevon positioning (raising and lowering) is accomplished by rotating the manual crank a predetermined number of turns, which is specified and documented prior to each test run. After the first couple of runs, the angles were marked on the cover plate on the test box.

The flexible cable required 3 iterations to develop a robust design. The main cause was greater than expected friction between the sides of the movable elevon and the blanket insulation adjacent to the copper sidewalls. Commonly available shafts from Dremel and Sears were not sufficiently rugged for bi-directional rotation. An industrial-grade, bi-directional flexible shaft (from S.S. White Technologies, Inc., Piscataway, NJ) was the final, successful iteration.

Thirty-one thermocouples were used to monitor temperatures, and 7 pressure taps were installed as described in Table 1. The ARC Ceramics Lab performed the installation of this instrumentation with assistance from Boeing Phantom Works.

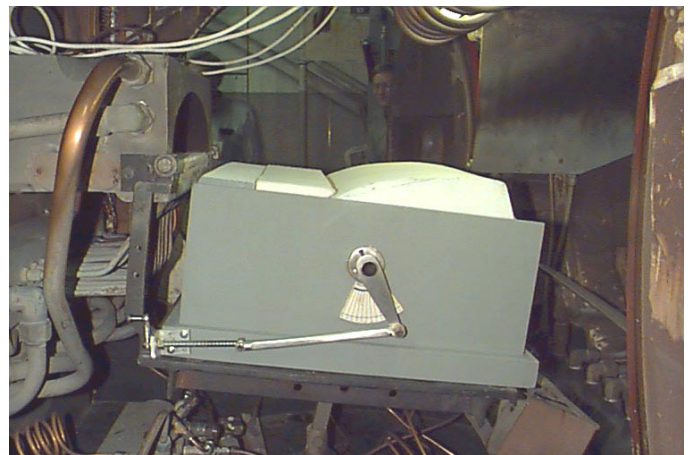


*This Entire Assembly Fits Into A Water-Cooled Copper Box*

**Figure 1.—Cross Section of Arc-Jet Test Fixture Highlighting AETB Tile.**

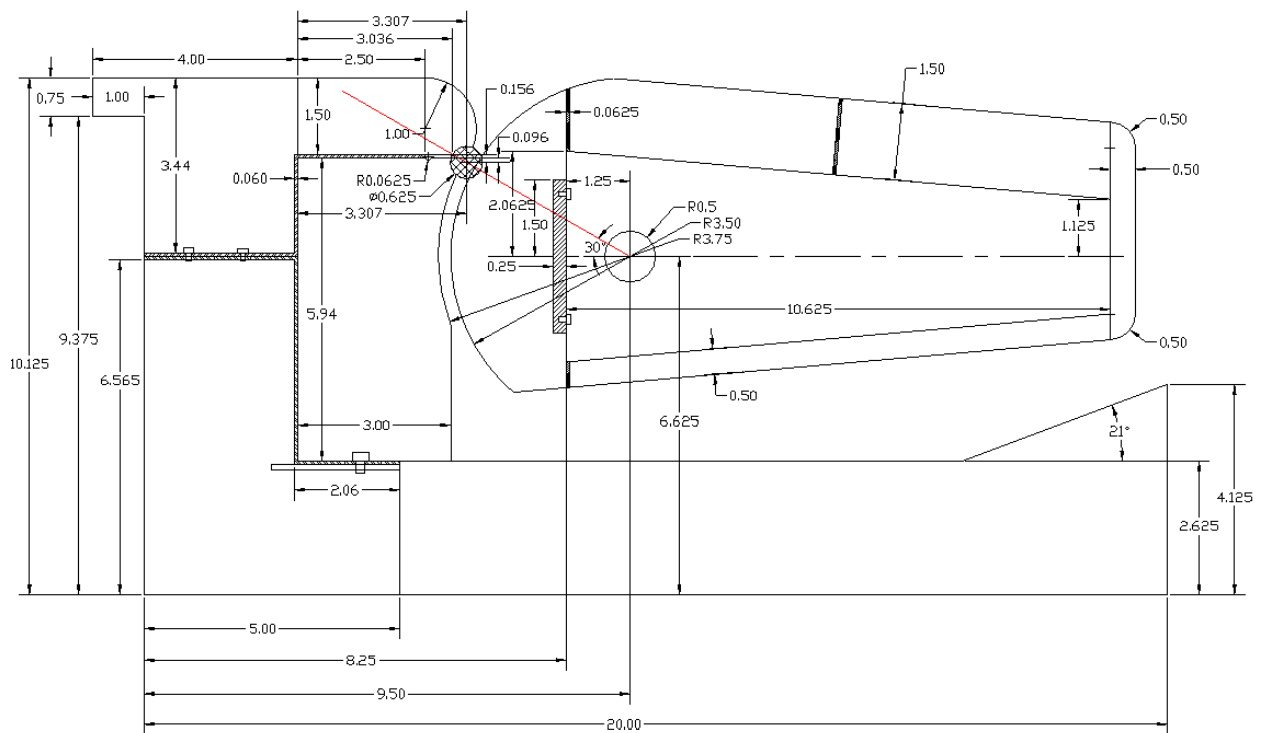


(a)

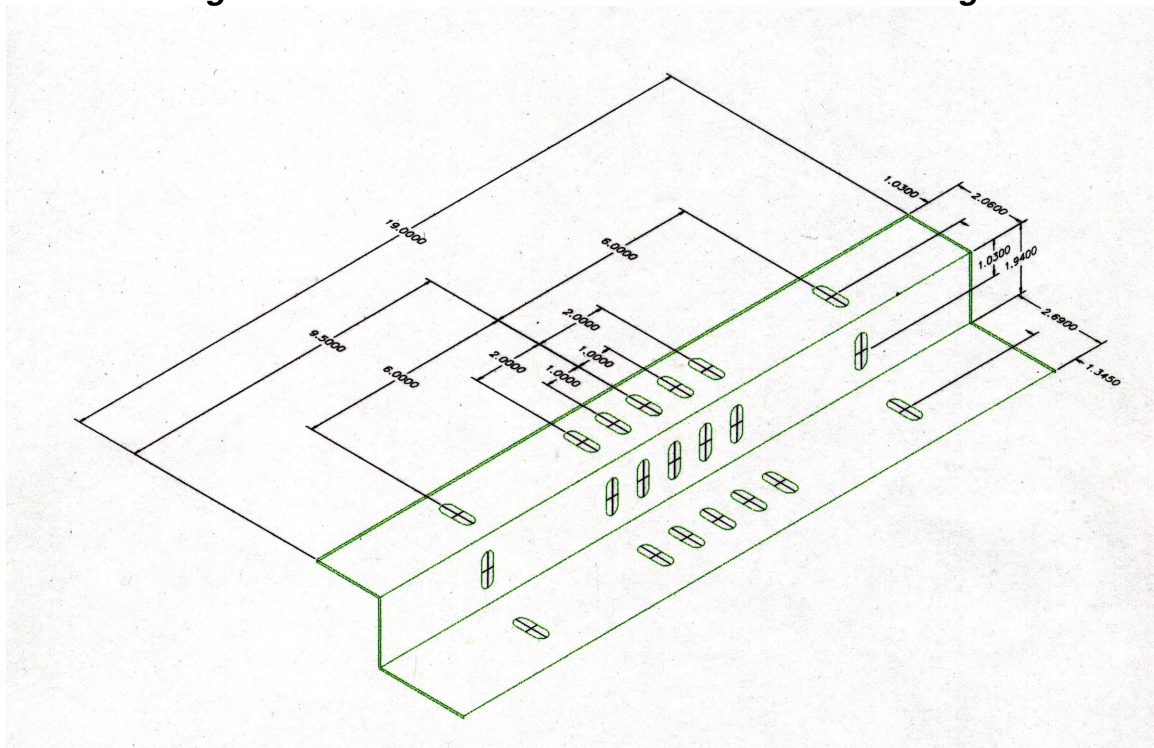


(b)

**Figure 2.—Mock-Up of Arc-Jet Test Fixture Used for Fit Up Check in the Arc-Jet Facility at NASA ARC.**



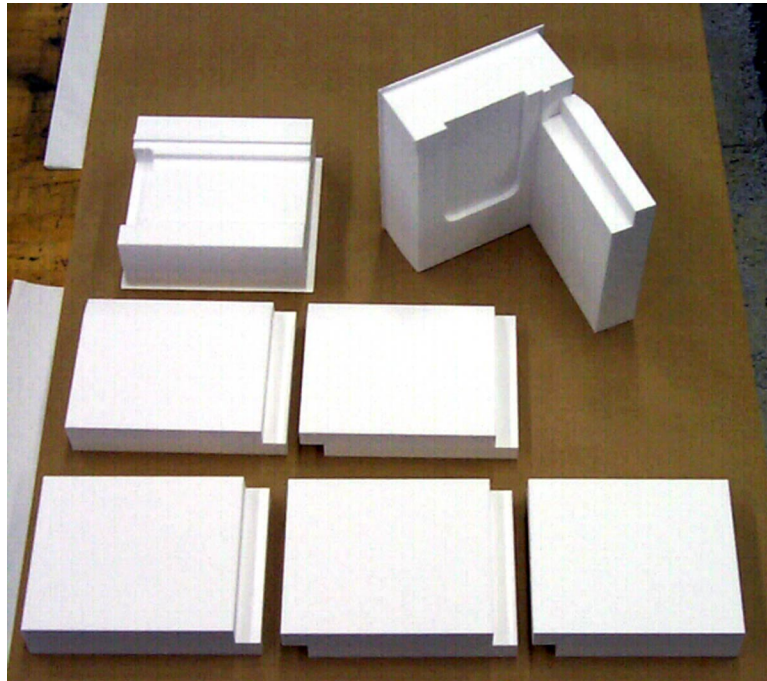
**Figure 3.—Arc-Jet Test Fixture Dimensional Drawing.**



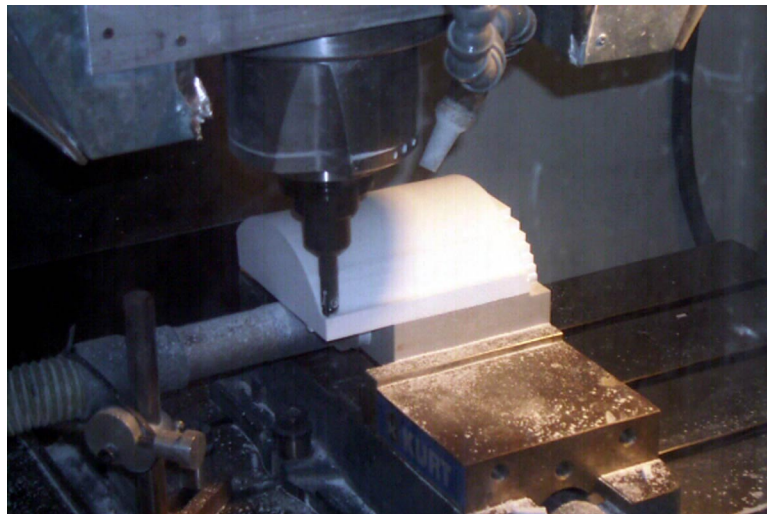
**Figure 4.—Arc-Jet Test Fixture Dimensional Drawing. Modified upper bracket.**





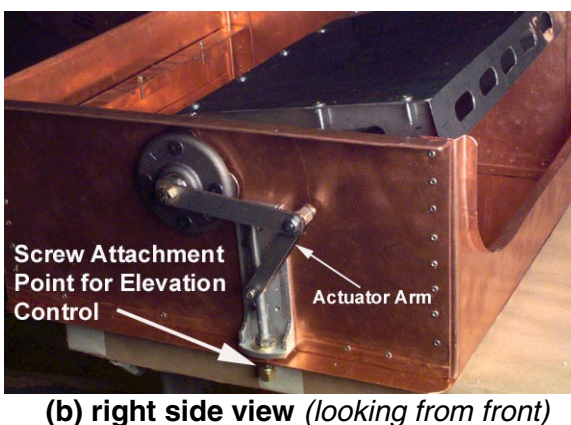
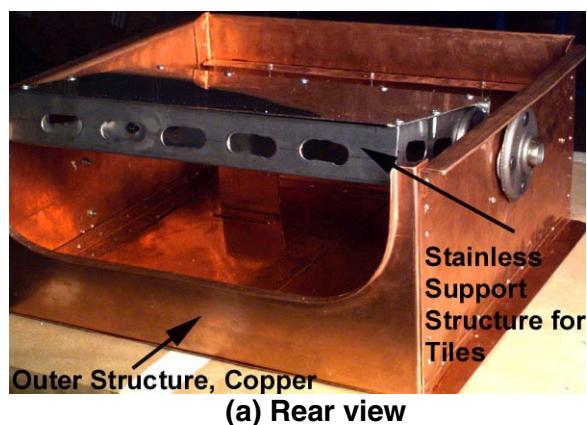


***Figure 7.—Typical AETB Machined Tiles for Flat Surfaces of Arc-Jet Test Fixture***

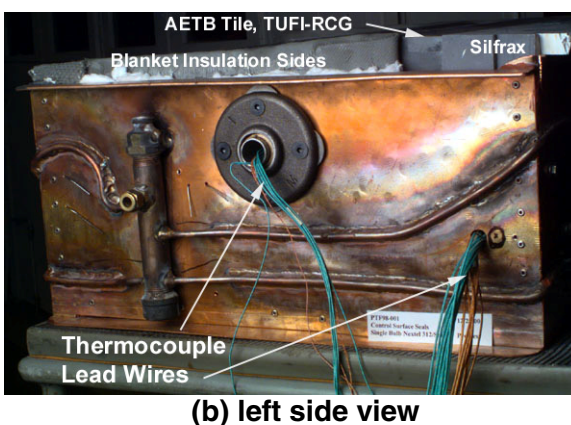
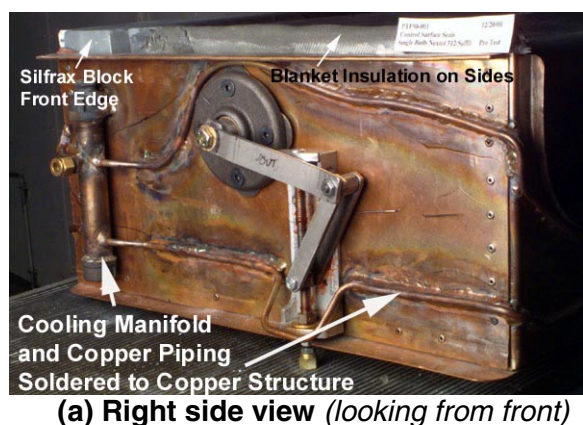


***Figure 8.—Machining the Leading Edge Tiles for the Arc-Jet Test Fixture***

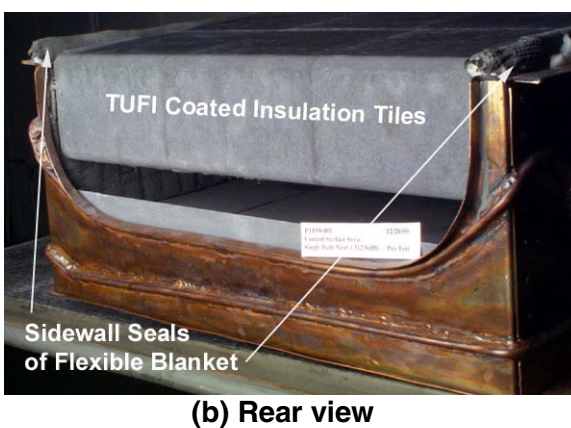
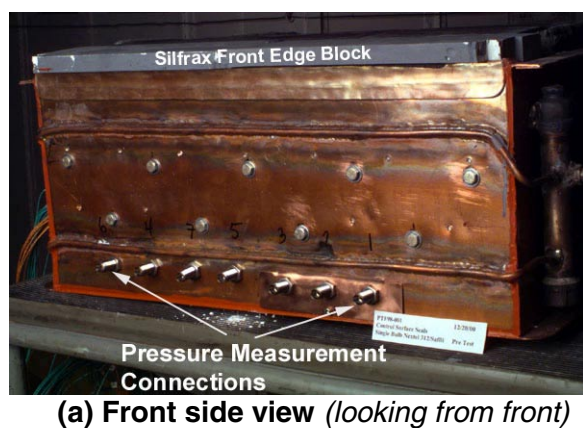




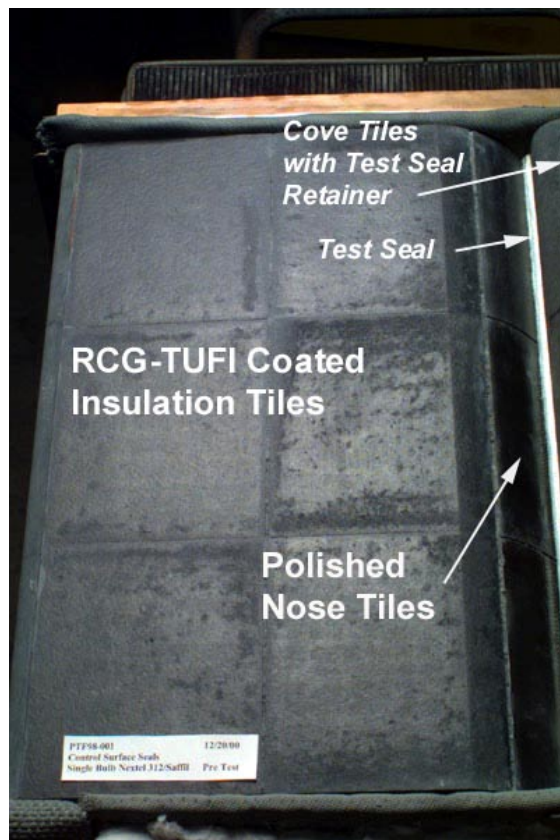
**Figure 9.—Metal Structure for Arc-Jet Test Fixture.**



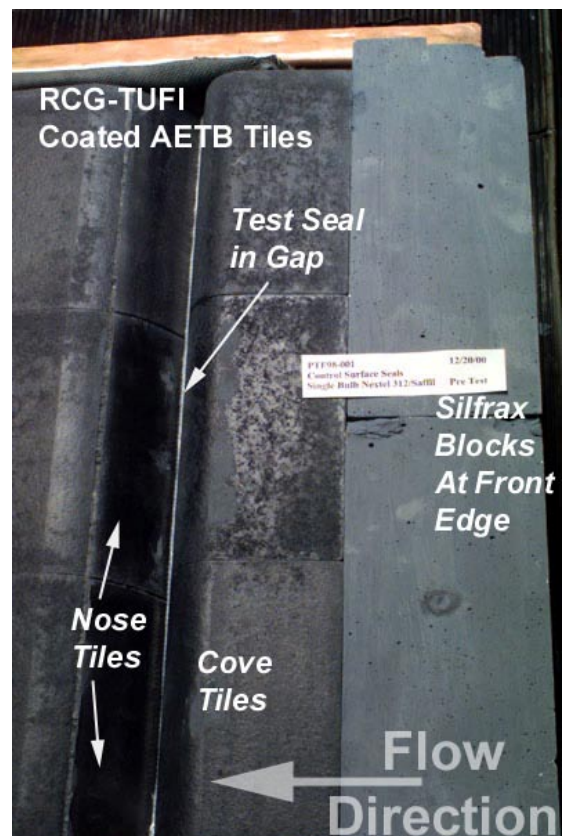
**Figure 10.—Side Views of the Arc-Jet Test Fixture.** Cooling Coils, Installed AETB Tiles, Leads from Thermocouples, and the Actuator Arm for Adjusting Angle of Elevon.



**Figure 11.—Arc-Jet Test Fixture.** (a) Front View with Pressure Tap Ports and the Upper Edge of the Silfrax Block and (b) the Rear Side Showing TUF-RCG Coated AETB Tiles.

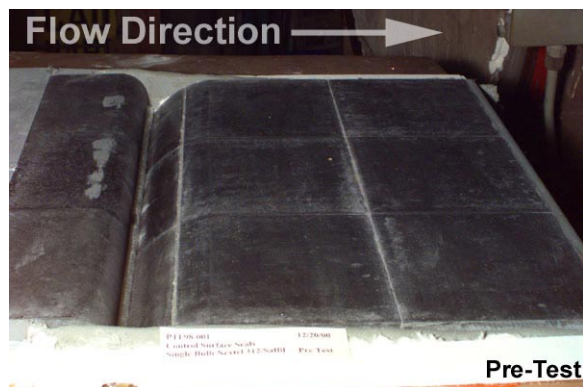


(a)

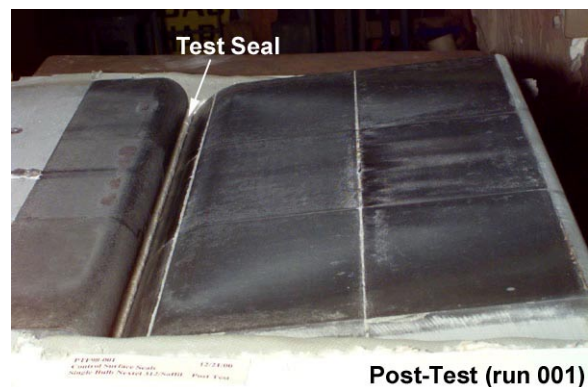


(b)

**Figure 12.—Test Fixture. Views of Upper Surface with Installed TUFI/RCG Coated AETB Tiles.**



(a)



(b)

**Figure 13.—Test Fixture. Views of Upper Surface:(a) Zero Degree Elevation and (b) 5 Degree Elevation.**



**Table 1.—Thermocouple/Pressure-Tap Locations**

TC ID No.	TC Type	T/C Location Description
1	R	Upper surface, 6" left of centerline, , 6.5" from nozzle lip
2	R	Upper surface, 2" left of centerline, , 6.5" from nozzle lip
3	R	Upper surface, 1" left of centerline, , 6.5" from nozzle lip
4*	R	Upper surface, 1" right of centerline, , 6.5" from nozzle lip
5	R	Upper surface, 2" right of centerline, , 6.5" from nozzle lip
6	R	Upper surface, 6" right of centerline, , 6.5" from nozzle lip
7	R	Cove entrance surface, 6" left of centerline, , 0.5" above seal
8	R	Cove entrance surface, 2" left of centerline, , 0.5" above seal
9	R	Cove entrance surface, 1" left of centerline, , 0.5" above seal
10*	R	Cove entrance surface, 1" right of centerline, , 0.5" above seal
11	R	Cove entrance surface, 2" right of centerline, , 0.5" above seal
12	R	Cove entrance surface, 6" right of centerline, , 0.5" above seal
13	K	Cove gap surface, 6" left of centerline, 0.5" below seal
14	K	Cove gap surface, 2" left of centerline, 0.5" below seal
15	K	Cove gap surface, 1" left of centerline, 0.5" below seal
16*	K	Cove gap surface, 1" right of centerline, 0.5" below seal
17	K	Cove gap surface, 2" right of centerline, 0.5" below seal
18	K	Cove gap surface, 6" right of centerline, 0.5" below seal
19	K	Cove gap surface, 1" right of centerline, 1.5" below seal
20*	K	Cove plenum surface, 1" right of centerline, 5.5" below seal
21	R	Elevon nose surface, left hand gap, 45 deg above zero
22	R	Elevon nose surface, 2" left of centerline, 45 deg above zero
23*	R	Elevon nose surface, on centerline, 45 deg above zero
24	R	Elevon nose surface, 2" right of centerline, 45 deg above zero
25	R	Elevon nose surface, right hand gap, 45 deg above zero
26	K	Elevon nose surface, left hand gap, 25 deg above zero
27	K	Elevon nose surface, 2" left of centerline, 25 deg above zero
28	K	Elevon nose surface, on centerline, 25 deg above zero
29	K	Elevon nose surface, 2" right of centerline, 25 deg above zero
30	K	Elevon nose surface, right hand gap, 25 deg above zero
32*	K	Elevon nose tile / aluminum plate bond line, on centerline
PT-1		Upper surface, on centerline, 6.5" from nozzle lip
PT-2		Cove entrance surface, on centerline, 0.5" above seal
PT-3		Cove entrance surface, 4.5" right of centerline, 0.5" above seal
PT-4		Cove gap surface, on centerline, 0.5" below seal
PT-5		Cove gap surface, 4.5" right of centerline, 0.5" below seal
PT-6		Cove gap surface, on centerline, 1.5" below seal
PT-7		Cove plenum surface, on centerline, 5.5" below seal

\* Indicates thermocouples monitored in real time

TC #31 was not used. The PT designation is for pressure tap.

## 4 DESCRIPTION OF SEAL CONSTRUCTION AND TEST MATRIX

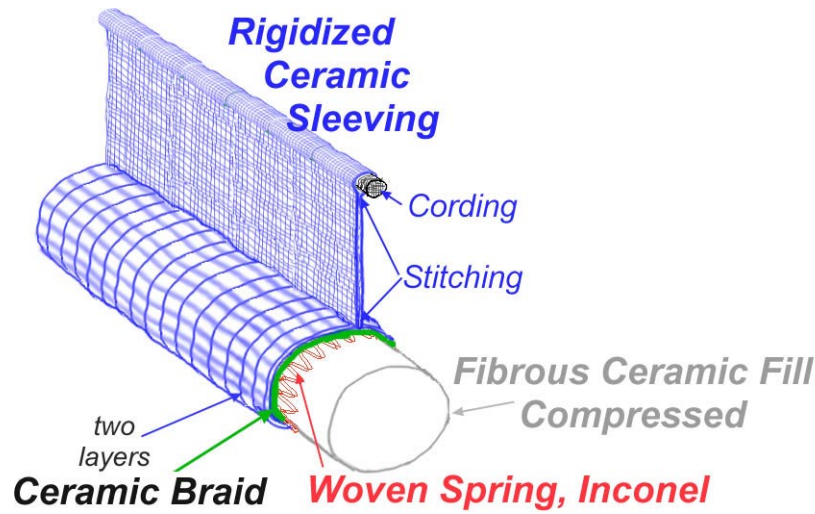
The seal test elements are made from Nextel 312 and 440 fabric and braid. Most of the test seals contain compressed Saffil batting, Inconel springs, and Nextel 440 sewing thread.

Baseline seals were 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 1600 °F as learned from Shuttle experience. For capability to temperatures of 2000 to 2200 °F ceramic fiber products such as Nextel 440 material are necessary.

The standard spring device (again based on 1600 °F performance) has been Inconel X-750 wire (multi-stranded) that is woven into a spring. Steinetz and Dunlap<sup>2</sup> investigated bulb seal resilience to temperatures of 1900 °F and found that the standard bulb seal construction with the Inconel spring permanently deforms at this temperature. The construction designs of the Steinetz and Dunlap<sup>2,3</sup> studies were baselined because of their extensive data for flow and compression testing.

The advanced bulb seal configuration that was tested used a design that was introduced during the development of X-38. This design uses a core fill of concentric layers of Nextel 440 sleeving to form a resilient seal that shows promise at temperatures to over 2200 °F.

Attachment of bulb seals to the thermal protection system structure is very important. A method of attachment that is 100% ceramic was selected. This method 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. This construction is shown in the drawing of Figure 14.



**Figure 14.—Single Bulb Seal Construction Details.**

#### **4.1 Seal Attachment**



A Nextel 440 braided sleeve (1/2 inch nominal diameter) was used for the attachment “tail” into which a stretched Nextel 440 1/8 inch diameter sleeve was sewn into one side. This flattened sleeving was attached to the bulb seal (locating the joint with a tool having the fixture contour – see Figure 15) by sewing — again with Nextel 440 thread. The seal and attachment fixture was then heat treated to remove the sizing before placing into the molding tool for densification and rigidization of only the “tail.”

Metallic attachment, silicone bonding, and ceramic cements were considered and rejected 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.


#### **4.2 Seal Configuration**


Table 2 lists the parameters describing the eight seal configurations for the first 12 arc-jet test runs. Nextel 440 material was tested as the exterior covering and compared to the standard Nextel 312 braided sleeving.

**Table 2.—Fabricated Seals and Details of Construction**

Seal #	Seal Type / Mfg	Seal Construction Fill / Spring / Braid	Seal Dia (Inch)	Saffil Fill Density (lbs/ft <sup>3</sup> )
1	Bulb / HiTemp <sup>#</sup>	Saffil / Inconel / 312 / 312	0.625	9
2	Bulb / HiTemp	Saffil / Inconel / 312 / 312 	0.625	6
3	Bulb / HiTemp & Boeing	Saffil / Inconel / 312 / 440	0.625	6
4	Bulb / HiTemp & Boeing	Saffil / Inconel / 312 / 440	0.625	6
5	Concentric / Boeing	Nextel 440 sleeve, 1/8, 1/4, 1/4, 1/2, 1/2, 1/2, 1/2	0.540	N/A
6	Concentric / Boeing	Nextel 440 sleeve, 1/4, 1/4, 1/2, 1/2, 1/2 	0.570	N/A
7	Bulb / HiTemp & Boeing	Saffil / Inconel / 312 / 440	0.625	6
8	Bulb / HiTemp & Boeing	Saffil / Inconel / 312 / 440	0.625	9
None	None	None	None	None

<sup>#</sup> Hi Temp Insulation, Camarillo, California

 The Hi-Temp end closures were modified by Boeing because of difficulties with seal #1 . We used this design modification on the remaining seals.

 The diameters are given in order, from the center outwards -- in fractions of an inch .

#### 4.3 Baseline and Advanced Seal Fabrication. Bulb Seals.

Hi-Temp Insulation, Inc. of Camarillo, California fabricated the initial baseline seal bulbs (without the “tail”). They were made to the original design length of 18 inches. Before testing was to begin the design was changed to 19.25 inches, and this necessitated modifying the original seals by splicing a section from one of the extra bulbs to increase the length. The splice on Test Seal#1 was made by splicing the exterior Nextel 312 layers by sewing with Nextel 440 thread and using the end closures that were made by Hi-Temp. It turned out that during installation of the seals into the test fixture at NASA ARC the end closures on this seal were stiffer and slightly larger than the 0.625-inch diameter of the design. The test fixture at ARC was modified (by removing material in the cove seal-retention groove) to accommodate this seal, but the end closure design for the remaining seals was also modified. A continuous Nextel layer was used on the exterior – unlike the spliced exterior layer of the first seal.

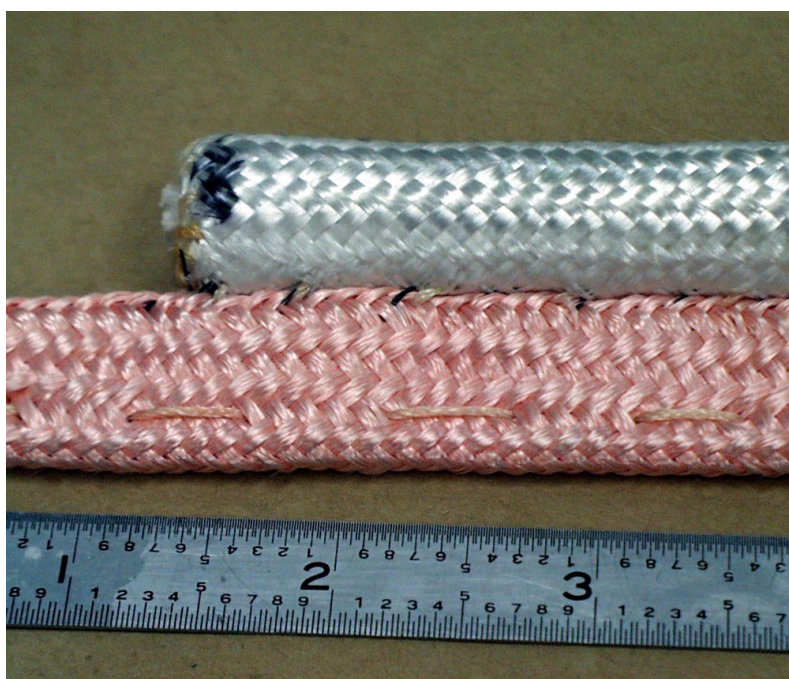
The end closures used braided sleeving sections that were inverted so that one end showed only the folds from the inversion. Sleeving of ¼ inch diameter was used and one inverted sleeve was inserted into another. A ¾ inch plug was made from this concentric, 4-layer sleeving “plug” that was to be inserted into the end closure. The end closure for the bulb was made by removing the Saffil for a length of ¾ inch, folding both exterior Nextel layers into the center cavity and inserting the “plug” described earlier. The plug was then sewed with Nextel 440 thread to hold it in place. The plug required a hollow center that was filled with Saffil batting (Fig 15).

The stitching used to secure the attachment tail to the bulb seal can barely be seen in Figure 15. The ends of the attachment sleeving (the pink material) will be trimmed to the proper length after the rigidization process is complete. Figure 16 shows another end view of the seal assembly. The

black thread in the figure is cotton and was used as a temporary fabrication aid. It disappears during the sizing removal process. The photo in Figure 16 also shows a black marking of ink from the fabrication sequence.

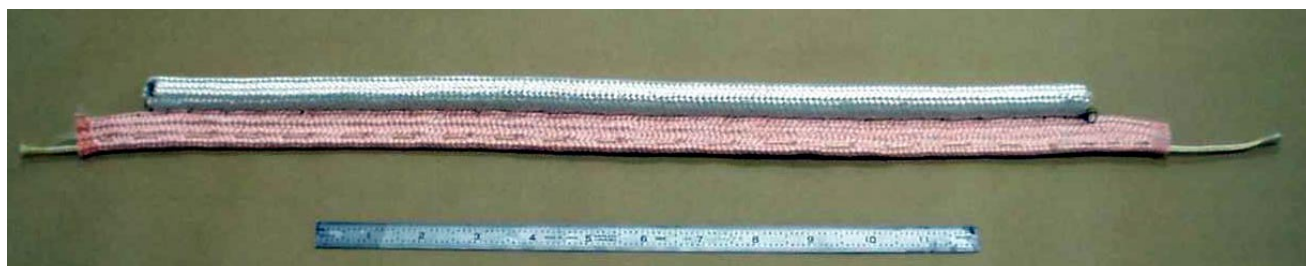


**Figure 15.—End View of Seal Assembly Showing End Closure and Attachment “Tail” Prior to Sizing Burnout.**



**Figure 16.—Another End View of Seal Assembly Showing End Closure and Attachment “Tail” Prior to Sizing Removal.**

Figure 17 shows the entire seal assembly prior to being placed into a furnace for the removal of the sizing. The temporary cotton basting thread and Scotch™ cellophane tape fabrication-aids are also shown.



**Figure 17.—Typical Seal Assembly Ready for Sizing Removal.**

#### **4.4 Next Generation Seal Fabrication. Concentric-Braided-Sleeving.**

Seal fabrication for the concentric braid bulbs was entirely done at Boeing Phantom Works using Nextel 440 braided sleeving. Development of the final configurations was predicated on the diameters and resiliencies that were possible with various combinations of  $\frac{1}{8}$ ,  $\frac{1}{4}$ , and  $\frac{1}{2}$  inch nominal diameters of braided sleeving. Because of this a smaller diameter was used for these seals than the 0.625-inch that was used for the other test seals. Depending on the stiffness of the concentric braid, bulb diameters of nominally 0.54 and 0.57 inch were selected. The smaller diameter was selected for the stiffer bulb and 0.57 inches was chosen for a less stiff version.

Nextel 440 braided sleeveings can be stretched to decrease their diameter, or compressed axially to produce larger diameters. Test seal #5 was a stiffer seal because it contained more braid and was stretched during the fabrication procedure to produce a stiffer, tighter bulb. Test seal #6 was produced at a larger diameter of 0.57 inches by axially compressing the concentric braid uniformly to achieve the desired diameter at the desired stiffness level.

For both of the concentric-braid configurations a sufficient quantity of Scotch™ brand cellophane tape was used as a fabrication aid. Without the tape as a temporary aid it would have been nearly impossible to achieve relatively uniform diameters through the entire fabrication process—especially during the attachment of the “tail” section.

#### **4.5 Process for Tail Rigidization**

The rigidization of the “tail” piece was accomplished with dedicated tooling using a Boeing proprietary ceramic slurry.



The seal rigidization process was accomplished using single cycles of impregnation with a modified version of a water-based alumina coating system. The slurry was composed of various grades of alumina powder from 0.2 to 5 micrometers in particle size combined with alumina sol as a binder. A wetting agent was also part of the slurry to enhance wicking into the fabric of the “tail” section.

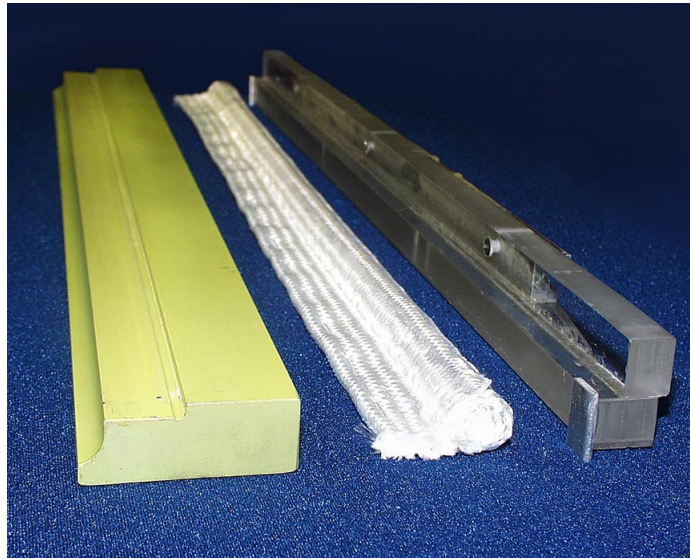
The specific composition is proprietary. It includes enhancements to the coating system described in US Patent 5,958,583 (issued 1999). It differs from the coating system primarily in that it: (1) does not include high-emittance additives normally used for heat radiation, and (2) has more large particles as filler material for the relatively open fabric.

The process is simple and is illustrated in Figures 18 through 22.

Figure 18 shows the end of a typical seal and the trimmed attachment “tail.” Figure 19 is a collection of the seal assembly and the two tooling articles used for forming the tail and keeping the bulb and the “tail” properly aligned.



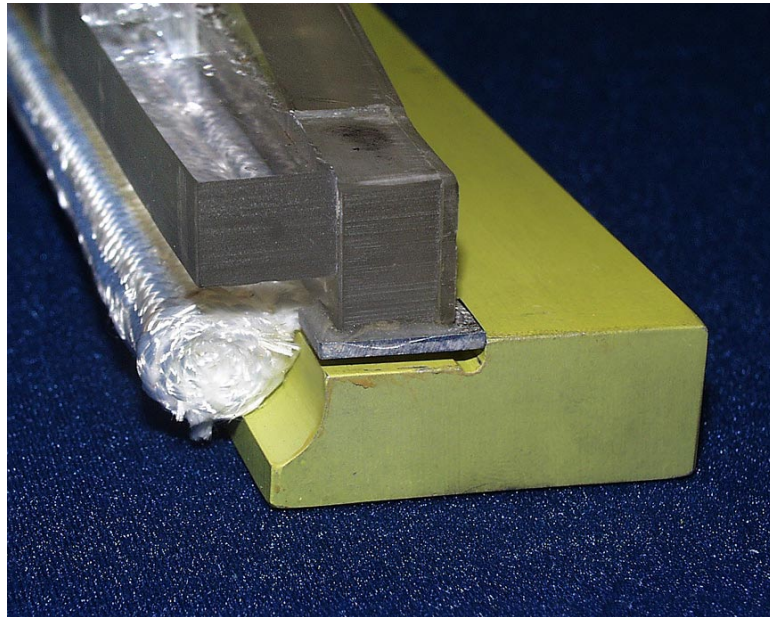
***Figure 18.—End View of a Typical Seal Assembly After Sizing Removal,  
But Prior to Rigidization of the “Tail.”***



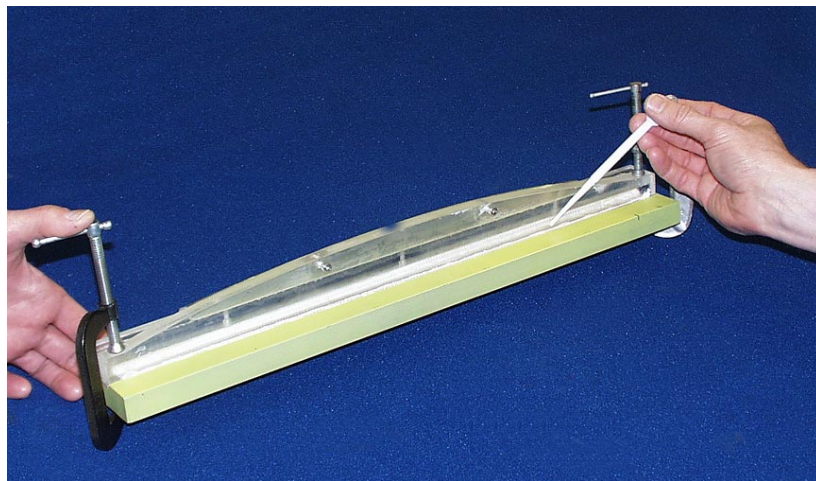
***Figure 19.—Typical Seal Assembly and Fabrication Tooling.  
Ready for “Tail” Rigidization.***

Figure 20 is a photograph of the end of the tooling article. The metal pad under the acrylic piece is a spacer that defines the thickness of the attachment “tail.” The ends of the acrylic section are clamped to the painted aluminum base to compress the tail as seen in Figure 21. The close-up photo of Figure 22 is a more detailed view of the slurry infiltration process. The acrylic was used so that we could see how far the slurry had wicked into the tail section. Slight wicking into the bulb exterior was allowed. However, on one seal the slurry wicked into the exterior braid of the bulb over approximately 1/3 of the seal length (test seal #3).

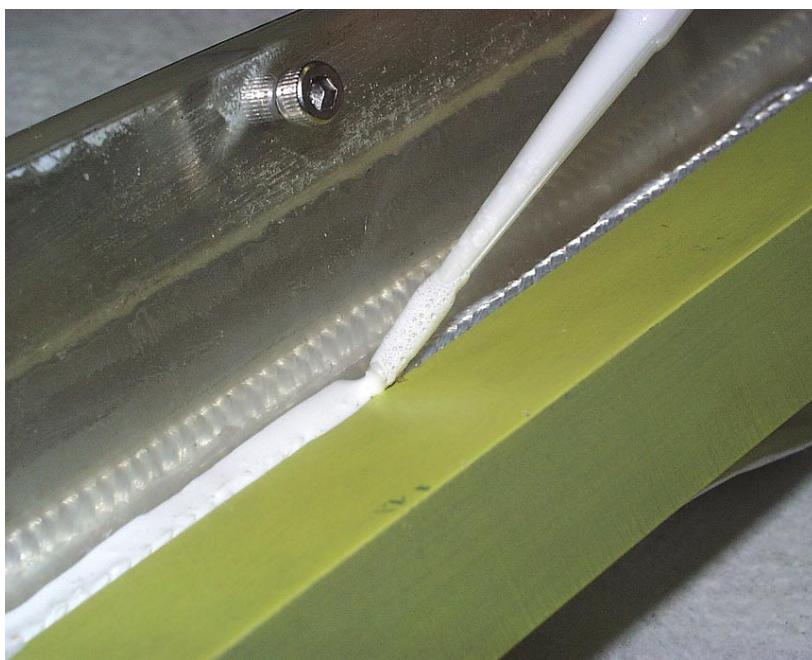
The entire assembly was placed into an oven for a drying period of at least 6 hours at 120 °F.



***Figure 20.—End View of a Seal Assembly Placed onto the Tooling for Rigidization.***



***Figure 21.—Typical Seal Assembly in Tooling for Rigidization.  
Showing Application of the Slurry.***



**Figure 22.—Close-Up Photo Showing Application of the Slurry.**

## **5 DESCRIPTION OF PANEL TEST FACILITY (PTF)**

The following description is based on the Ames report on PTF98.<sup>4</sup>

### **5.1 Introduction**

The Arc Jet Complex at ARC has nine available test bays located in two separate laboratory buildings. Figure 23 shows a schematic representation of the location of these test bays. Presently, four bays contain operational arc jet units of differing configurations. The operating characteristics of these operational units are summarized in Table 3.

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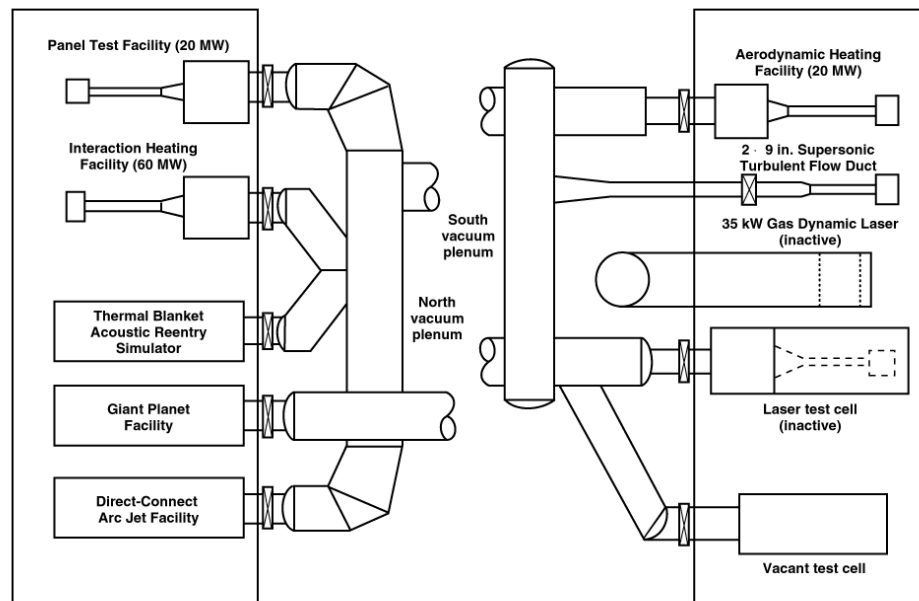
<sup>4</sup> Terrazas-Salinas, I, Rendon, D., and Hartman, J., “PTF 98, Spaceliner 100 Control Surface Seal Evaluation,” NASA ARC, ASF Test Report A-08-R-04-0018, 2001

**Table 3.—Operating Characteristics of the Arc-Jet Facilities at NASA ARC**

	Aerodynamic Heating Facility		2- by 9-in. Supersonic Turbulent Flow Duct	Panel Test Facility	Interaction Heating Facility	
Nozzle configuration	Conical		2-dimensional	Semielliptical	Semielliptical	Conical
Gas	Air, nitrogen		Air, nitrogen	Air	Air	Air
Input power, (MW)	20		12	20	75	75
Nozzle exit dimension (in.)	12, 18, 24, 30, 36 (diameter)		2 × 9	4 × 17	8 × 32	6, 13, 21, 30, 41 (diameter)
Mach number	4–12		3.5	5.5	5.5	<7.5
Bulk enthalpy (Btu/lb <sub>m</sub> )	5000 to 14,000		1500 to 4000	2000 to 14,000	3000 to 20,000	3000 to 20,000
Type of test article	Stagnation point	Wedge	Flat plate	Wedge	Wedge	Wedge stagnation point
Sample size (in.)	8 (diameter)	26 × 26	8 × 10 8 × 20	14 × 14	24 × 24	18 (diameter)
Surface pressure (atm)	0.005 to 0.125	0.001	0.02 to 0.15	0.0005 to 0.05	0.0001 to 0.02	0.010 to 1.2
Convective heating rate (Btu/ft <sup>2</sup> sec)	20 to 225	0.05 to 22	2 to 60	0.5 to 75	0.5 to 45	50 to 660
Radiative heating rate (Btu/ft <sup>2</sup> sec)	0		0	0	0 to 5	0 to 20

The 20-MW Panel Test Facility (PTF, upper left in Figure 23) was the facility chosen for the Spaceliner 100 Control Surface Seal Evaluation test program. This arc jet test is part of a test program to evaluate control surface seals concepts for 3<sup>rd</sup> Generation reusable launch vehicles.





**Figure 23.—The Test Bays in the Arc-Jet Complex.**

The purpose of this test was to measure the temperatures and pressures in the vicinity of a compressible and permeable sliding control surface seal. The data will be used to validate aerothermal models of flow in similar geometries in order to enable prediction of the thermal behavior of this type of seal in reentry conditions.

## 5.2 Panel Test Facility

The PTF consists of a 20-MW segmented arc heater coupled to a semi-elliptical nozzle. The nozzle discharges in a semi-free jet within a  $4 \times 4 \times 4$ -foot test cabin where the panel test fixture attaches at the nozzle exit (Figure 24 shows a typical installation in the PTF). The test stream is suitable for the simulation of boundary layer heating environments on flat-panel samples of approximately 14 by 14 inches. The panels can be inclined to the flow direction at angles of  $-4^\circ$  to  $+15^\circ$ , although  $+6^\circ$  is the practical maximum.

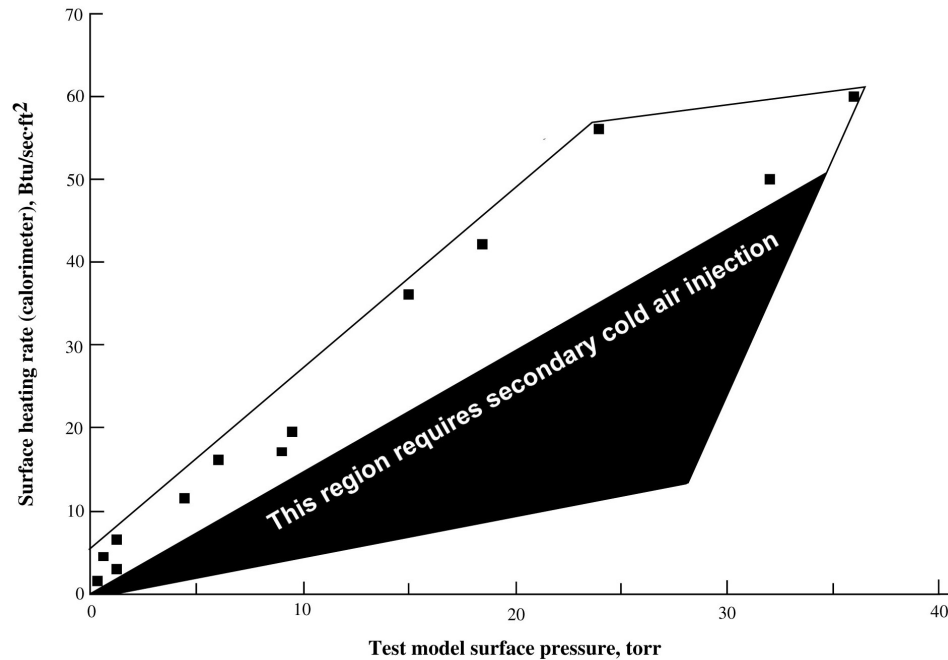


**Figure 24.—Installation, typical in the PTF.**

Surface conditions on flat-plate test articles can be varied in two ways: inclination angle of the tilt table and selection of the arc operating parameters (current and mass flow rate). Optical access through both doors and the roof of the test cabin allow imaging of the flow and the test article. Flow is evacuated from the test chamber by the steam-ejector vacuum system, providing static pressures in the range of 0.1 to 10 torr. Water cooling manifolds are available inside the test chamber for cooling of test article components.

The heater operates at pressures from 1 to 10 atmospheres and enthalpy levels from 2000 to 14,000 Btu/lbm (air). The lower enthalpy range is achieved by mixing cold air with the test stream in the plenum or downstream electrode package. The PTF simulates some of the conditions experienced by the Space Shuttle heat shield tiles, such as heat flux, surface pressure, and gap flow, and has been used extensively in Space Shuttle heat shield development and certification.

Recent test programs in the PTF have focused on testing flexible thermal protection blankets for next-generation reusable launch vehicles. The envelope of surface conditions on the test article for the PTF is shown in Figure 25, and the physical parameters are listed in Table 3. Run durations as long as 30 minutes are possible with a 45-minute cool down between runs.



**Figure 25.—Operating Envelope of the PTF at NASA ARC.**

NASA ARC assisted in installing the test article into the test fixture and in installing the test fixture into the PTF. NASA ARC Ceramics Lab with the assistance of Boeing Phantom Works, also cooperated to install the thermocouples, pressure taps, and the surface insulation on, in, and surrounding the test article.

The arc jet testing was performed with test model surface temperatures of approximately 2200 °F for up to 10 minutes during each run. Surface temperatures were monitored optically; the control surface gap temperatures were monitored using thermocouples; and pressures in the control surface gap were monitored using pressure transducers.

The tests were conducted with the moveable elevon section at zero degrees (parallel to the flow) and at up to 16 degrees into the flow. The purpose of the higher elevon angle was to increase the pressure and temperature in the seal area. Since the seals were permeable, measuring pressures and temperatures on both sides of the seal allowed evaluation of the effectiveness of the seals in blocking flow into the gap. The downstream side of the seal was open to the aft end of the test model to permit the possibility of gas flow through the control surface gap.



### 5.3 Matrix of Test Articles to be Tested

The test articles were the elevon gap seal elements; there was one seal for each test. Table 4 lists the seal elements and the tests originally planned.

**Table 4.—Arc-Jet Test Seal Description and Selected Test Parameters**

<b>Test #</b>	<b>Seal Type</b>	<b>Seal Gap</b>	<b>Table Angle</b>	<b>Elevon Angle</b>	<b>Surface Temp</b>	<b>Duration</b>
1	Single Bulb Nextel 312/Saffil	0.25 inch	4 degrees	0-7 deg	2200 F	~5 min
2	Single Bulb Nextel 312/Saffil	0.25 inch	4 degrees	0-10 deg	2200 F	~5 min
3	Single Bulb Nextel 312/Saffil	0.25 inch	6 degrees	0-10 deg	2200 F	~5 min
4	Single Bulb Nextel 440/Saffil	0.25 inch	6 degrees 8 degrees	0-10 deg	2200 F	~5 min
5	Single Bulb Nextel 440/Saffil	0.25 inch	6 degrees	0-10 deg	2200 F	~5 min
6	Single Bulb Concentric Braid Nextel 440/Saffil	0.25 inch	6 degrees	0-10 deg	2200 F	~5 min
7	Single Bulb Concentric Braid Nextel 440/Saffil	0.25 inch	6 degrees	0-10 deg	2200 F	~5 min
8	Single Bulb Nextel 440/Saffil	0.375 inch	6 degrees	0-10 deg	2200 F	~5 min
9	Single Bulb Nextel 440	0.375 inch	6 degrees	0-10 deg	2200 F	~5 min
10	No Seal	0.25 inch	6 degrees	0-10 deg	2200 F	~5 min

## 5.4 Test Parameters

The test article was subjected to convective heating in accordance to the parameters set forth in Table 5.

**Table 5.—PTF98 Arc-Jet Test Conditions Including Enthalpy**

Run No.	Date of Run	Model	Exposure Duration (min)	Test Conditions						
				Table Angle (Degrees)	Arc Voltage (Volts)	Arc Current (Amps)	Chamber Pressure (psia)	Mass Flow Rates		Sonic Flow Enthalpy (Btu/lb <sub>m</sub> ) <sup>z</sup>
001	12/21/2000	Seal #1	5	4.0	4820	2000	103.1	240.0	27.7	8490
002 <sup>a</sup>	2/22/2001	Seal #2								
003 <sup>Å</sup>	2/27/2001	Seal #2								
004	2/27/2001	Seal #2	4:19	4.0	4800	1990	101.9	240.1	27.7	8260
005	2/27/2001	Seal #2	4:35	6.0	4780	1980	101.3	240.1	27.7	8140
006	2/28/2001	Seal #3	4:33	6.0, 8.0	4770	1990	101.3	240.0	27.7	8130
007	3/1/2001	Seal #4	4:14	6.0	4770	1990	101.1	240.1	27.7	8090
008	3/12/2001	Seal #5	4:34	6.0	4810	1990	102.5	240.1	27.7	8370
009	3/12/2001	Seal #6	4:09	6.0	4820	2000	102.9	240.1	27.7	8460
010	3/14/2001	Seal #7	4:15	6.0	4810	1990	102.6	240.1	27.7	8400
011	3/15/2001	Seal #8	4:05	6.1	4810	2000	102.6	240.1	27.7	8400
012	3/15/2001	No Seal	1:02	5.9	4790	2000	102.0	240.2	27.7	8270

<sup>z</sup> Total model time in the stream

<sup>a</sup> See Ref. 1

<sup>Å</sup> Facility checkout

<sup>Å</sup> Run aborted

## 5.5 Test Procedure for the PTF Arc-Jet Facility

The following is a typical procedure for an arc-jet test:

1. Establish arc
2. Establish condition
3. Raise table to desired 6° inclination to the flow
4. Hold condition while the elevon angle is raised in 2° increments from 0° to 10°. At each of these elevon angles, hold for 30 seconds before proceeding to the next indicated angle
5. Lower table
6. Normal shutdown
7. Cool down under vacuum for 10 minutes with data recording at 5-second intervals

## 5.6 Instrumentation

### 5.6.1 Model Instrumentation

The test model contained 31 thermocouples to measure temperatures at various locations and 7 pressure taps to measure various pressures in the test fixture, as indicated in Table 1.

### 5.6.2 Optical Pyrometers

Two pyrometers were used to monitor the surface temperatures of the test models. Both of these pyrometers operate under the 2-color principle. The locations that were read are given in Table 6.

**Table 6.—Location of Optical Pyrometer and Infrared Camera Readings on Upper Surfaces of the TUF/RCG Coated AETB Tiles**

Run No.	M90R2	M190R2	IR Camera
1	Over TC4	Elevon in front of TC4	Over TC4
3-12	Slightly east* of the pressure tap (P1)	Downstream of P1, 1/2-way along the curved section of the elevon	Over TC4

\* "east" is to the left side of the facility when facing in the direction of the flow stream.

#### **DAS Label: M90R2**

Manufacturer: Mikron

Model: M90-R2

Serial No. 50194

Temperature Range: 1652 °F – 5432 °F

FOV ratio: 180:1

Spectral Response: 0.78-1.06

#### **DAS Label: M190R2**

Manufacturer: Mikron

Model: M190-R2

Serial No. 5615

Temperature Range: 1652 °F – 5432 °F

FOV ratio: 180:1

Spectral Response: 0.78µm – 1.06µm

The pyrometers were located above the test chamber. They were focused as noted in Table 5.

### 5.6.3 Infrared Thermography

Infrared thermography was performed during each of the test runs with an Inframetrics 760 IR camera:

Manufacturer: FLIR (formerly Inframetrics)  
Model: 760  
Serial No. 8295  
FOV ratio: 25H : 25V  
Spectral Response: 3 $\mu$ m – 12 $\mu$ m

The camera was configured with a 25 mm lens to maximize the imaged area of the test model. The 760 IR camera was mounted outside of the test box directly above the test article. The camera looked through a 4-inch-diameter zinc selenide (ZnSe) window.

Calibration of the IR camera was performed prior to the start of the test series in the ASF calibration lab located in Building 234. The set-up of the test was duplicated during calibration, i.e. distance from model to camera and distance from window to camera.

The 760 IR camera system was calibrated using two black- bodies for different temperature ranges:

**Lower Temperature Range: 50 °C to 1200 °C (85 °F to 2190 °F)**

Manufacturer: CI Systems  
Model: SR20  
Serial No. 3SR 2042121  
22.2 mm opening

**Upper Temperature Range: approx. 1010 °C to 2871 °C (1830 °F to 5200 °F).**

Manufacturer: Thermogage  
0.625 inch opening

**The CI blackbody** includes a temperature read out and is calibrated annually by the manufacturer.

**The Thermogage blackbody** does not include temperature monitoring; its temperature is determined with a factory-calibrated (annually) transfer-standard pyrometer:

Manufacturer: Mikron  
Model: M190HTS  
Serial No. 000921  
Temperature Range: 600 – 3000 °C  
FOV ratio: 180:1  
Spectral Response: 0.78 $\mu$ m – 1.06 $\mu$ m

During calibration, optical factors are taken into consideration and recorded so that they can be used during the actual tests. These factors include target emissivity, external optics, and lens transmission factors. These parameters can be varied in the IR camera system so that the readings from the IR camera match blackbody temperatures. The values thus determined for the relevant parameters are then used as the starting point for the arc jet tests.

During the tests, several parameters may be varied. These settings are recorded on the videotape in the form of menus.

## **5.7 Facility Parameters**

Facility operations were monitored by the standard facility- monitoring instrumentation. The most relevant of these was the current, voltage, and chamber pressure. The “chamber pressure” was the pressure at the downstream end of the arc heater and was an indirect indication of the mass flow through the arc heater. The chamber pressure was used to compare present operating conditions to historical data. The mass flow through the arc heater was a controlling parameter and was also monitored and recorded. Additional data is recorded at the facility, but is rarely used by the investigators. Facility personnel use the additional data for trouble-shooting purposes, and it is provided in the data package for completeness.

## **5.8 Photography**

Standard video imaging and still pictures of the test runs were made. The standard video was shot from the top of the test box and pre- and post-test photographs were taken of the test articles. For several of the runs, video from the east port (“east” is to the left side of the facility when facing in the direction of the flow stream) was also recorded.

## **5.9 Data Report**

The data report contains all of the data collected during the runs. These data include the facility-monitoring parameters, pyrometer readings, pressure readings, and thermocouple readings. Three CD's were provided to the investigator. One contains the raw data from the test instrumentation reduced to engineering units. The files are plain tab-delimited text files. Each file contains all of the data that were collected during each run. The data columns are labeled to be self-explanatory. A second CD contains the digital pre- and post-test photographs. The third CD contains photographs taken by Ceramics Lab personnel. A copy of the videotapes of the runs and a copy of the videotape from the IR camera were also provided to the investigator. Copies of the Data CD and other relevant test data were provided to additional organizations as directed by the investigator, e.g., Glenn Research Center and the Aero-thermodynamics Branch at ARC.

## **5.10 Summary of Test Anomalies**

Anomalies encountered in this series of tests had minimal impact on the test objectives. Runs 1 through 7 suffered minor anomalies; all of the remaining runs proceeded uneventfully. During run 1, the elevon angle calibration was found to differ under “arc on” conditions. The calibration could not be confirmed, but from experience on other runs the actual angle was probably within 1 degree of the indicated angle. Additionally, during run 1, it was not possible to achieve a 10° angle on the elevon – reached only a 7° angle – because of the frictional forces generated by the seal against the elevon. Run 3 was aborted because of a faulty table-angle indicator. TC18 began to fail during

run 4. No post-test photos were taken for run 5; additionally, the M90R2 pyrometer was not turned on until after the run had begun. During run 6, the event-marker indicator was not depressed fully, so that the signal from it was not always picked up by the data system. After run 7, the flexible drive shaft required extensive rework.

The test objectives were not affected by any of these anomalies because:

1. Angle calibration effects were typically around  $\frac{1}{2}$  degree so the tolerances are certainly less than 1 degree. Even though this run was for facility checkout the lack of calibration is not significant. For all other runs calibration was performed as planned.
2. T/C 18 failed, but there are redundant thermocouples because of the symmetry of thermocouple layout.
3. The other anomalies are insignificant.

Notes for the arc-jet runs compiled by NASA-Ames personnel, and separately by Boeing Phantom Works are provided in Appendix A.

## **6 TEST RESULTS**

The analysis of test results was complicated by a number of factors – chief among them being the inherent variables in the arc-jet system and the non-steady-state conditions in the incremental steps in varying the angle of the elevon during the arc-jet runs. However, after the facility check out runs nearly all of the tests were run with comparable parameters that allow for comparison of seal types (includes baseline shuttle seals, modified baseline seals, concentric braid seals and no seal) and gap size (within the cove and also between the seal and the nose). The effect of the elevon angle obviously has a major effect, but it was not possible to realistically and directly compare incremental angles between the different runs in a rigorous fashion within the scope of this project. The reason for this is the added complexity due to the transient nature of the conditions – each angle was held for only 30 seconds – and meant that a steady-state condition was not close to being reached.

Effects of elevon angle, gap dimension within the cove, and the seal construction/materials will be discussed in sections 6.1 through 6.3.

Table 7 lists the intent of the test for each run.

**Table 7.—Summary of the TEST INTENT for PTF98 Runs**

Test #	Seal #	Test Date	Cove Gap	TEST INTENT	Time at Test Conditions (Minutes)	Seal Type / Mfg	Seal Construction Fill / Spring / Braid	Seal Dia (Inch)	Fill Density (lbs/ft <sup>3</sup> )	Fixture / Control Surface Angles
1	1	21-Dec-00	0.25	Facility Check-Out Using Shuttle Baseline Bulb Seal with 9 PCF fill; Fixture table at 4 degrees and elevon moved through a range of angles	5	Bulb / HiTemp#	Saffil / Inconel / 312 / 312	0.625	9	4° / 0,1,2,3,4,5,6,7°
2	2	Facility Check	0.25	Facility Check-Out Using Shuttle Baseline Bulb Seal with 6 PCF fill; Fixture table at -2 degrees and elevon angle at zero	2:58	Bulb / HiTemp	Saffil / Inconel / 312 / 312	0.625	6	minus 2° / 0°
3	2	Aborted run	"	Evaluate Shuttle Baseline Bulb Seal with 6 PCF fill; Fixture table at 4 degrees and elevon moved through a range of angles		"	"	"	"	minus 2° / 0°
4	2	27Feb01 - AM	"	Evaluate Shuttle Baseline Bulb Seal with 6 PCF fill; Fixture table at 4 degrees and elevon moved through a range of angles	4:19	"	"	"	"	4° / 0,2,4,6,8,10°
5	2	27Feb01 - PM	"	Evaluate Shuttle Baseline Bulb Seal with 6 PCF fill; Fixture table at 6 degrees and elevon moved through a range of angles	4:35	"	"	"	"	6° / 0,2,4,6,8,10°
6	3	28Feb01 - PM	0.25	Evaluate MODIFIED-Baseline Bulb Seal with 6 PCF fill, Fixture table at 8 degrees Initially; and then Fixture at 6 deg and elevon moved through a range of angles with 2 deg increments	4:33	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	8°, 6° / 0,2,4,6,8,10°
7	4	1Mar01 - AM	0.25	Evaluate MODIFIED-Baseline Bulb Seal with 6 PCF fill; Fixture table at 6 degrees and elevon moved through a range of angles	4:14	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	6° / 0,2,4,6,8,10°
8	5	12Mar01 - PM	0.25	Evaluate Concentric Braid Seal with Fixture table at 6 degrees and elevon moved through a range of angles	4:34	Concentric / Boeing	Nextel 440 sleeve, 1/8, 1/4, 1/4, 1/2, 1/2, 1/2, 1/2	0.540	N/A	6° / 0,2,4,6,8,10°
9	6	13Mar01 - AM	0.25	Evaluate Concentric Braid Seal with Fixture table at 6 degrees and elevon moved through a range of angles LESS STIFF THAN PREVIOUS CONCENTRIC BRAID SEAL -- BUT SLIGHTLY LARGER DIAMETER	4:09	Concentric / Boeing	Nextel 440 sleeve, 1/4, 1/4, 1/2, 1/2, 1/2	0.570	N/A	6° / 0,2,4,6,8,10°
10	7	14Mar01 - PM	0.375*	Evaluate MODIFIED-Baseline Bulb Seal with 6 PCF fill IN A LARGER GAP; Fixture table at 6 degrees and elevon moved through a range of angles	4:15	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	6° / 0,2,4,6,8,10°
11	8	15Mar01 - AM	-0.375**	Evaluate MODIFIED-Baseline Bulb Seal with 9 PCF fill IN A LARGER GAP; Fixture table at 6 degrees and elevon moved through a range of angles	4:05	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	9	6° / 0,2,4,6,8,10°
12	None	15Mar01 - PM	0.287***	Evaluate Fixture with NO SEAL in Gap	1:02	None	None	None	None	6° / 0,2°

# Hi Temp Insulation, Camarillo, California

\* Seal to control surface leading edge spacing was 0 to 0.013" at 0° control surface angle.

\*\* Seal to control surface leading edge spacing was adjusted to give 0.020" at 0° control surface angle. Spacing closed at 10° control surface angle.

\*\*\* Gap measured after run: 0° = 0.2875", 2° = 0.287", 4° = 0.2805", 6° = 0.277", 8° = 0.2695", 10° = 0.2595

Shaded cells are for runs with comparable Arc-Jet and elevon angle conditions

A summary of the pertinent temperature data -- including test and seal I.D. and description -- is presented below in Table 8.

Points of note from the data summary are as follows:

- (1) All of the seals, including several variations, performed well with no serious leakages around the seals.
- (2) Maximum  $\Delta P$ 's across the seal were 6.08 Torr for test seal #6— Concentric braid— and approximately 5.5 for the other seals at the 10-degree control surface elevation.
- (3) Maximum  $\Delta T$ 's (*as measured at the time at which the maximum temperature was reached under the seal some time after arc-off because of conduction through the AETB tiles, not necessarily through the seal*) were 1660 °F for test seal #3 and above 1495 °F for all other seals— *the only exception was seal#1 during the checkout run.*

- (4) Maximum  $\Delta T$ 's (as measured at arc-off) across the seal were 1793 °F for test seal #3 and consistently above 1570 °F for all other test seals with the exception of test seal #1 during the checkout run.
- (5) The  $\Delta T$  across the gap with no seal in place during run #12 was only 110 °F.
- (6)  $\Delta T$ 's increased only slightly by increasing the gap width from 0.25 to 0.375 inch (by allowing slight misfit-gaps between the seal and the nose tiles).

**Table 8.—Summary of the Data of PTF98 for All 12 Runs**

Test #	Seal #	Test Date	Cove Gap	Maximum Upstream Temp (deg_F)	Gap Temp Above / Below Seal (deg_F)	Delta Temp Across Seal	Maximum Delta P Across Seal (Torr)	Time at Test Conditions (Minutes)	Seal Type / Mfg	Seal Construction Fill / Spring / Braid	Seal Dia (Inch)	Fill Density (lbs/ft <sup>3</sup> )	Fixture / Control Surface Angles
					@ Arc OFF	@ Arc OFF							
1	1	21-Dec-00	0.25	2050	1580/175	1405	3.62	5	Bulb / HiTemp#	Saffil / Inconel / 312 / 312	0.625	9	4° / 0,1,2,3,4,5,6,7°
2	2	Facility Check	0.25					2:58	Bulb / HiTemp	Saffil / Inconel / 312 / 312	0.625	6	minus 2° / 0°
3	2	Aborted run	"						"	"	"	"	minus 2° / 0°
4	2	27Feb01 - AM	"	2120	1760/190	1570	4.18	4:19	"	"	"	"	4° / 0,2,4,6,8,10°
5	2	27Feb01 - PM	"	2260	1948/210	1738	5.59	4:35	"	"	"	"	6° / 0,2,4,6,8,10°
6	3	28Feb01 - PM	0.25	2290	2033/240	1793	5.36	4:33	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	8°, 6° / 0,2,4,6,8,10°
7	4	1Mar01 - AM	0.25	2250	1946/280	1666	5.37	4:14	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	6° / 0,2,4,6,8,10°
8	5	12Mar01 - PM	0.25	2270	2030/290	1740	5.8	4:34	Concentric / Boeing	Nextel 440 sleeve, 1/8, 1/4, 1/4, 1/2, 1/2, 1/2, 1/2	0.540	N/A	6° / 0,2,4,6,8,10°
9	6	13Mar01 - AM	0.25	2290	1977/255	1722	6.08	4:09	Concentric / Boeing	Nextel 440 sleeve, 1/4, 1/4, 1/2, 1/2, 1/2	0.570	N/A	6° / 0,2,4,6,8,10°
10	7	14Mar01 - PM	0.375*	2220	1980/389	1591	5.46	4:15	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	6	6° / 0,2,4,6,8,10°
11	8	15Mar01 - AM	~0.375**	2240	1970/390	1580	5.58	4:05	Bulb / HiTemp / Boeing	Saffil / Inconel / 312 / 440	0.625	9	6° / 0,2,4,6,8,10°
12	None	15Mar01 - PM	0.287***	2250	2210/2100	110	2.1	1:02	None	None	None	None	6° / 0,2°

# Hi Temp Insulation, Camarillo, California

\* Seal to control surface leading edge spacing was 0 to 0.013" at 0° control surface angle.

\*\* Seal to control surface leading edge spacing was adjusted to give 0.020" at 0° control surface angle. Spacing closed at 10° control surface angle.

\*\*\* Gap measured after run: 0° = 0.2875", 2° = 0.287", 4° = 0.2805", 6° = 0.277", 8° = 0.2695", 10° = 0.2595

⚙ PT-1 Measured 12 Torr maximum pressure. No other runs were above 9 Torr for tap PT-1

## 6.1 Elevon Angle

The effects of the angle of the elevon on seal performance could not be isolated from the test data. The short amount of time available for each test resulted in highly transient conditions as the angle was incrementally increased in 30-second intervals. However, for runs 5, 7, 8, 9, 10, and 11 the conditions were nominally equivalent and the temperatures at the arc-jet shut-off time can be reasonably compared to evaluate the other variables such as seal construction and gap size.

There are two main features in the temperature plots that illustrate the problem:

- (1) There is typically a significant amount of heating below the seal after the heating is turned off – the time at arc-off is noted on the plot of temperatures above the seal.



On figure 27 the time at arc-off is approximately 330 seconds; but figure 26 shows that heating below the seal continued for about 200 seconds after arc heating was stopped. This continued heating is due to thermal conduction through the AETB tile—and not from leakage through or around the seal.

- (2) The temperature inflections in the temperature plots due to elevon-angle changes are discernible but it is clear that conditions are not close to steady-state for each elevon angle setting.

A possible solution to the difficulty of transient conditions would be mathematical modeling by developing a thermal model that matches the arc-jet data. This was beyond the scope of this project and is included as a recommendation for future work.

## 6.2 Gap Size in Cove

Two nominal gap sizes were tested: 0.25 and 0.375 inch.

The larger gap resulted in higher temperatures being reached under the seal and similar delta pressures across the seal as compared to the other modified-baseline bulb seals. Both seals reached identical temperatures of 380 °F at shut-off as compared to 290 to 300 °F at shut off for the same type seals during comparable runs with the smaller 0.25 inch gap.

The seals in the larger 0.375-inch gap obviously were not compressed to the same degree as seals in the smaller gap. This smaller degree of compression in the gap resulted in some variable gaps in the seal-to-nose-tile area along the seal length for seal #7 in run 10 that ranged from zero to 0.013 inch at an elevon angle of zero degrees. At an elevon angle of 10 degrees the gap was non-existent. These seal-to-tile gaps were the likely reason for higher temperatures below the seal being off-center—due to slight leakage.

In run 11 with seal #8 (only difference with seal #7 was a higher Saffil density in the core fill) a gap of 0.020 inch was set at an elevon angle of zero, and this reduced to a zero gap at an elevon angle of 10 degrees. Temperature reached below the seal at arc-off was virtually identical to that of run 10.

In summary, the larger gap in the cove resulted in higher temperatures below the seal. The main factor is most likely the leakage around the seal at elevon angles below about 5 to 7 degrees.

## 6.3 Seal Construction Type

The types of seals that were tested were:

- (1) **Baseline** space shuttle bulb seals using Nextel 312 braid wrap over Inconel wire spring and filled with Saffil insulation as described earlier.
- (2) **Modified-baseline** bulb seals. Similar to baseline but with the exterior braid layer made of Nextel 440 fiber (has a higher temperature capability than 312).

- (3) **Concentric braid** seals that are made of Nextel 440 braid of different diameters and formed by placing smaller diameter braid within larger braid.
- (4) **No seal** in the gap.

Based on temperature drop across the seal at time of arc-off, and the temperature below the seal at the same time the following conclusion can be drawn: For a gap of 0.25 inch all of the seals are very close in performance except for seal #2 in run 5 that had been in the fixture for 4 runs and also had the lowest sonic enthalpy. This seal (#2) had the lowest temperature below the seal at arc-off – 210 °F. The rest of the 0.25 gap seals had temperatures below the seal of 260 to 300 °F—virtually identical.

Based on maximum pressure drop across the seal the concentric braid seals were the best (best being the highest pressure drop) at 5.8 and 6.08 Torr. All the others from the comparable runs were in the range of 5.36 to 5.59 Torr. The concentric braid seals were the smallest diameter seals, but appeared to be slightly more resistant to leakage through the seal.

Having an open gap was, as expected, the worst condition by far. The temperature drop was only 110 °F at an elevon angle of 2 degrees when the arc-jet run was halted due to high temperatures in the cove area. The maximum pressure drop was only 2.1 Torr.

The issue of wear was not separately addressed, but was indirectly addressed from seal behavior. Test seal #1 was cycled 15 to 20 times before the test resulting in a white “mist” of Nextel filament fragments on the nose tile. Figure 38 is post-test and illustrates the damaged, frayed fibers in the contact area.

One seal (a portion of test seal #3) had a negligible amount of wear. This section was the 1/3 of the length into which some of the rigidizing solution had wicked to the outer surface of the seal. This ceramic matrix appeared to dramatically reduce the seal “wear.” This is in keeping with experience on coated ceramic fabrics in general. By preventing the movement of filaments within fiber bundles damage in sliding contact or in acoustic environments can be greatly reduced. Seal #3 also had the highest  $\Delta T$  across the seal (*as measured at arc-off*).

## 6.4 Arc-Jet Facility Parameters

Notable arc-jet facility parameters are tabulated in Table 4 and plotted in Appendix B. Table 9 lists a summary of the surface temperature readings, for reference. These data were averaged over the time frame at which stable facility operations were attained; they do not account for variations due to elevon angle deflection.

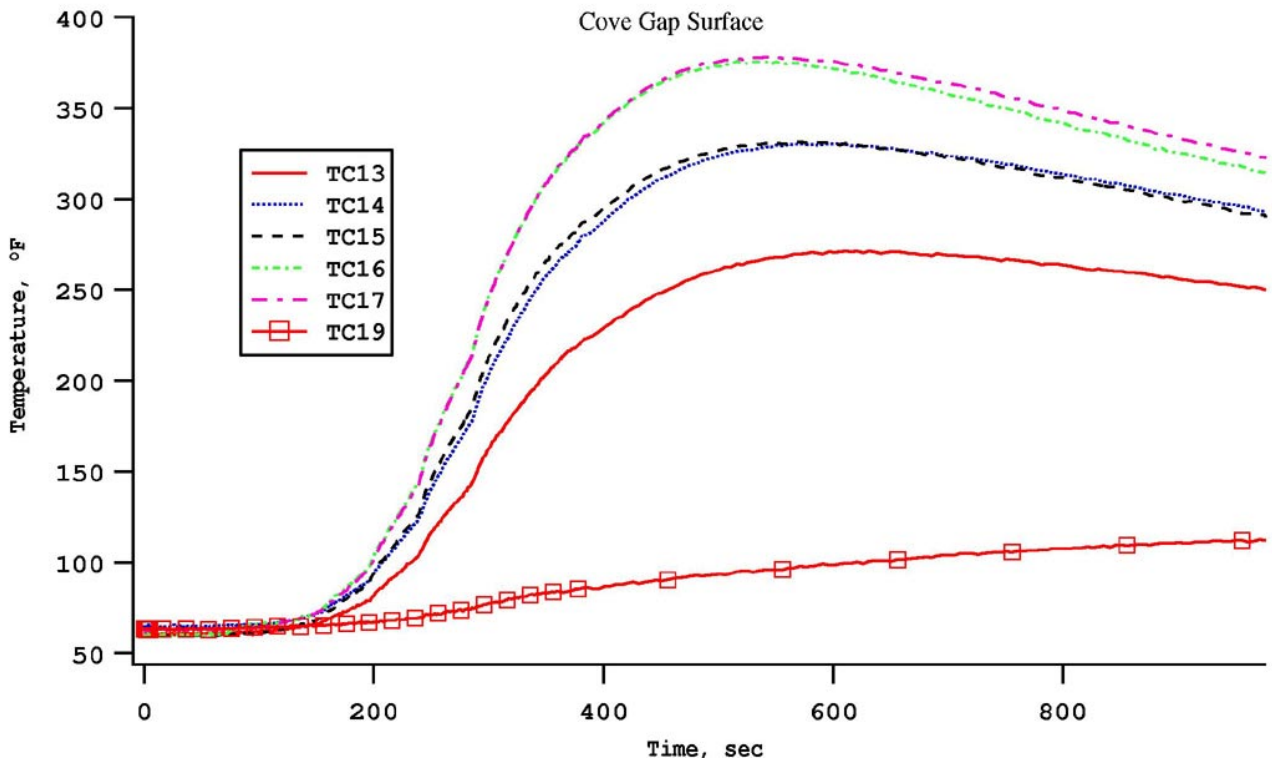
**Table 9.—Temperatures from Optical Pyrometers and from Thermocouples on Upper Surfaces of the TUF/RCG Coated AETB Tiles**

Run No.	M190R2 Pyrometer	M90R2 Pyrometer	TC1	TC2	TC3	TC4	TC5	TC6
001	1650	2000	2000	2000	1990	2010	2030	2050
004	1870	2080	2090	2100	2080	2090	2120	2110
005	1980	2200	2190	2240	2220	2220	2260	2240
006	1990	2220	2220	2260	2230	2240	2290	2210
007	2000	2180	2200	2230	2210	2210	2250	380 <sup>a</sup>
008	2000	2190	2190	2240	2210	2220	2270	2230
009	2030	2220	2200	2250	2240	2250	2290	2250
010	2000	2150	2150	2190	2160	2170	2220	2200
011	2020	2160	2170	2200	2180	2190	2240	2220
012	2170	2210	2130	2220	2210	2210	2250	2200

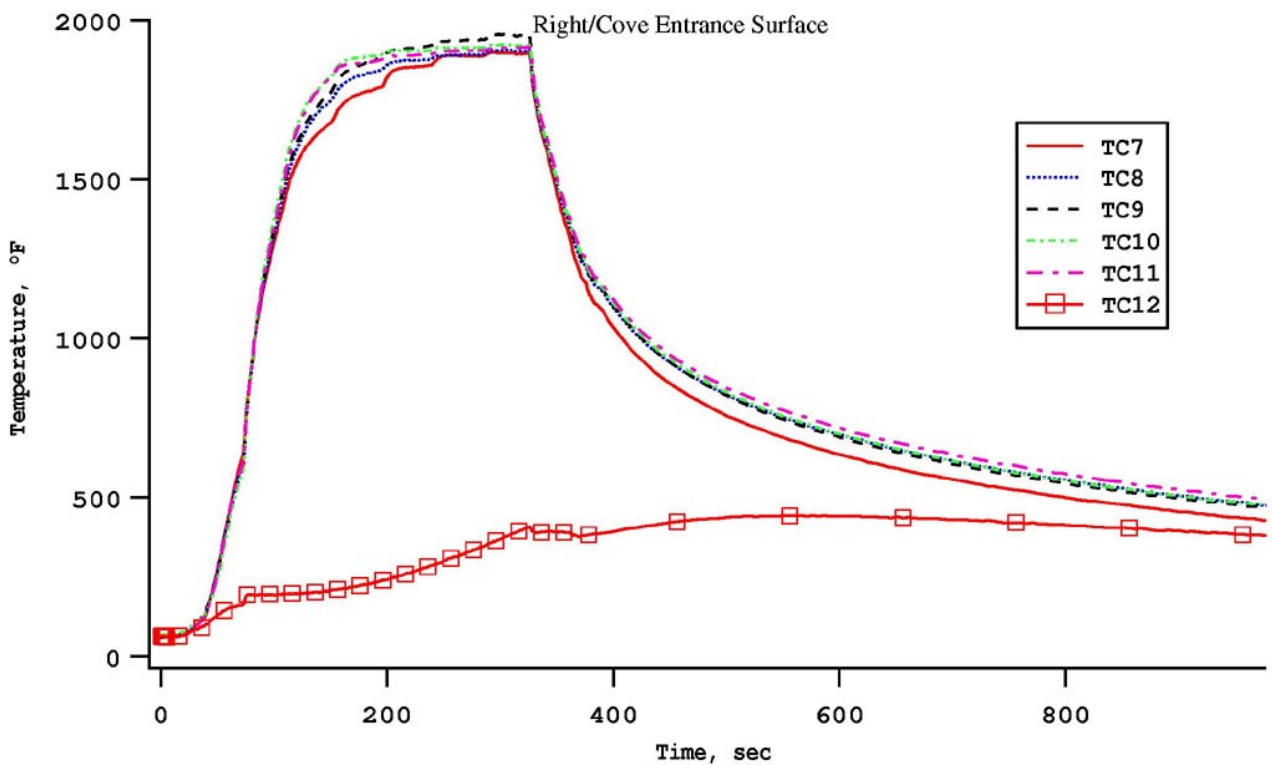
<sup>a</sup> Thermocouple was damaged prior to the run

## 6.5 Data Plots

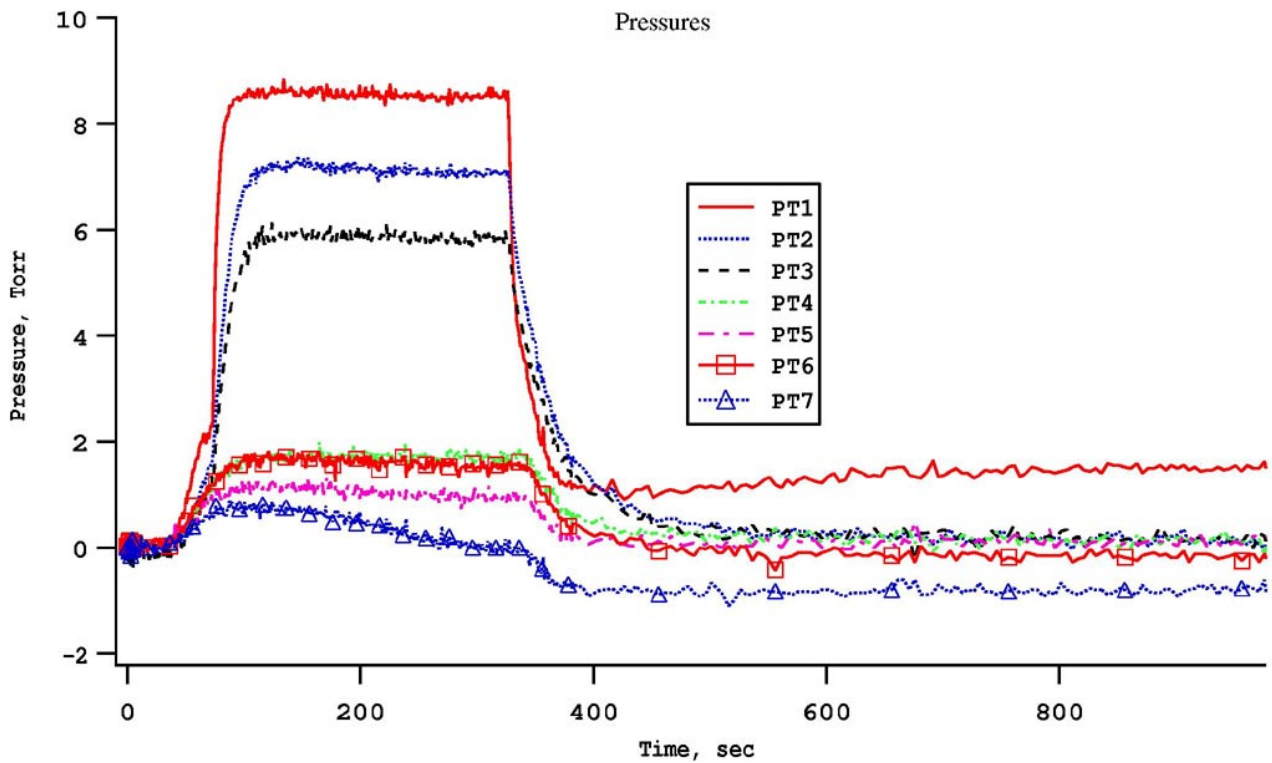
Typical plots of the measured data from thermocouples and pressure transducers are shown in Figures 26 through 37. Temperature data and pressure data are provided for arc-jet runs 7, 9, 11, and 12. Plots for all of the arc-jet runs, including arc-jet parameters, are in Appendix B.



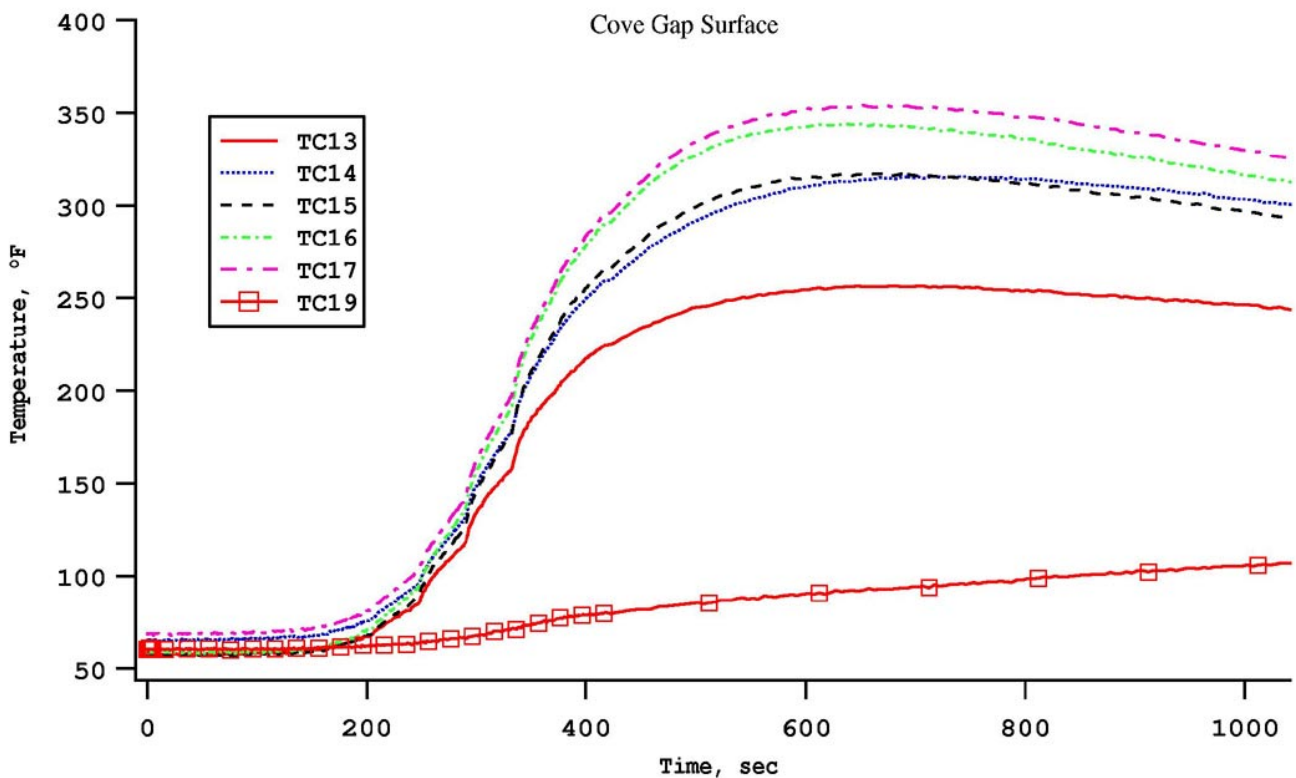
**Figure 26.—Temperature Plot from Run 98-07(Below the Seal).**



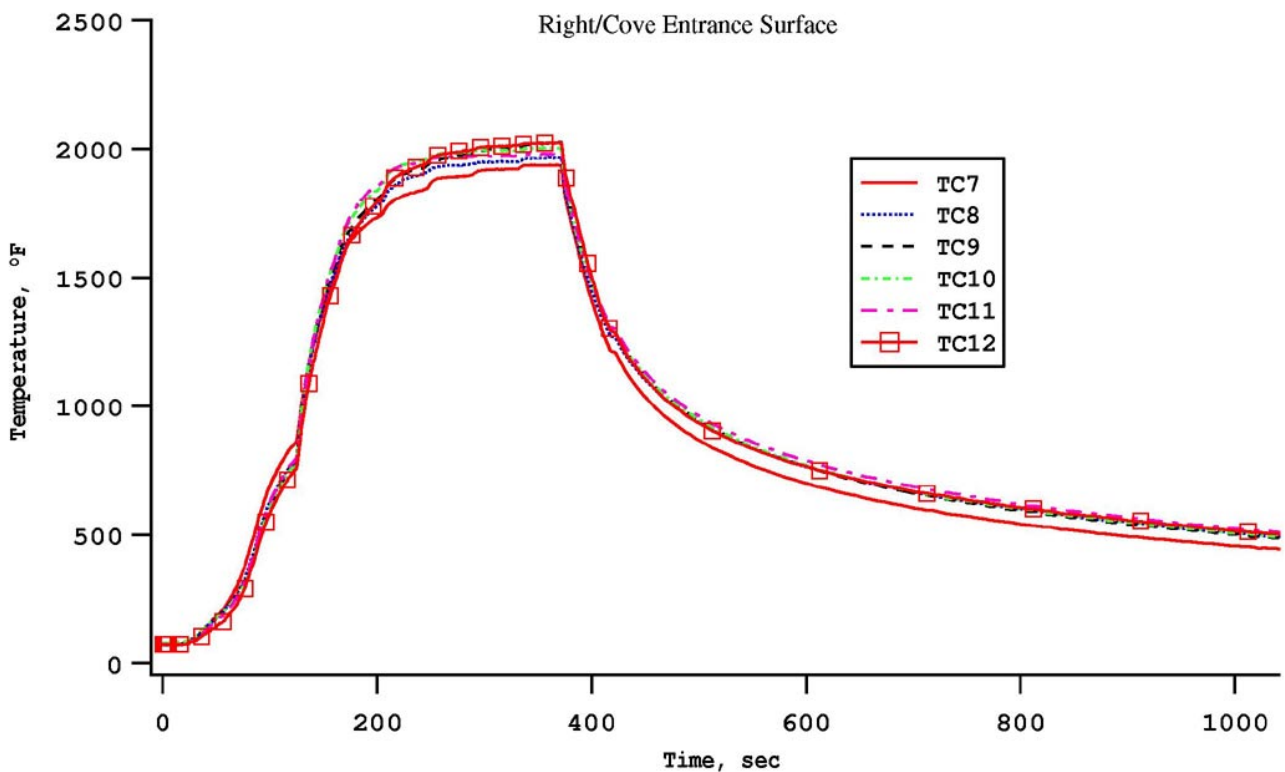
**Figure 27.—Temperature Plot from Run 98-07(Above the Seal).**



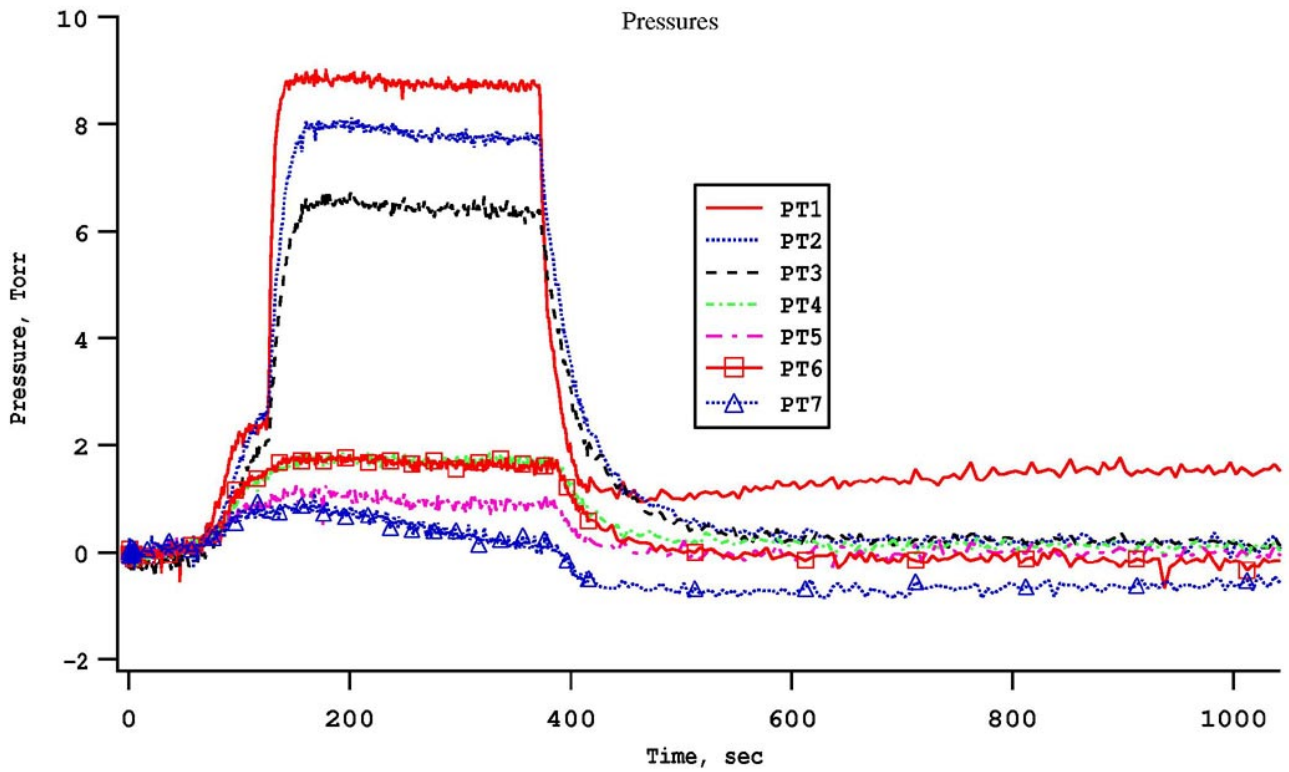
**Figure 28.—Pressure Plot from Run 98-07.**



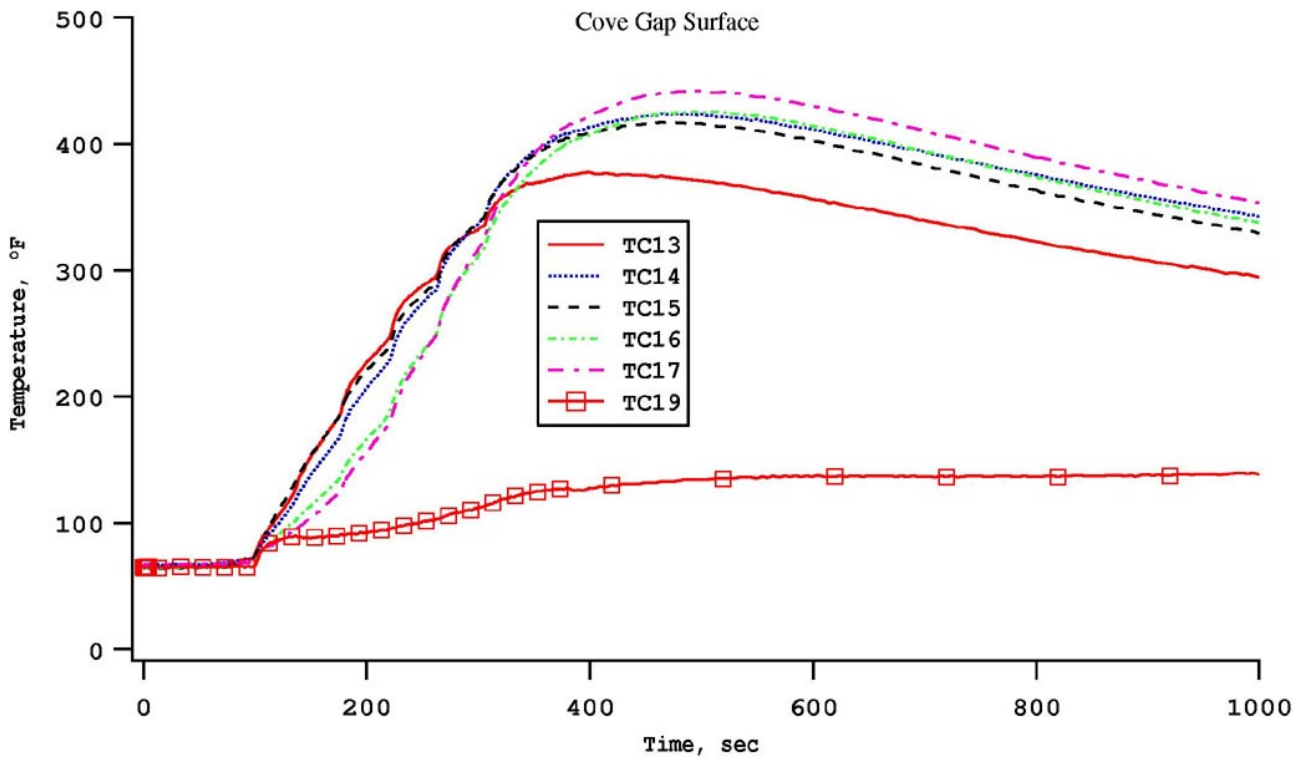
**Figure 29.—Temperature Plot from Run 98-09 (Below the Seal).**



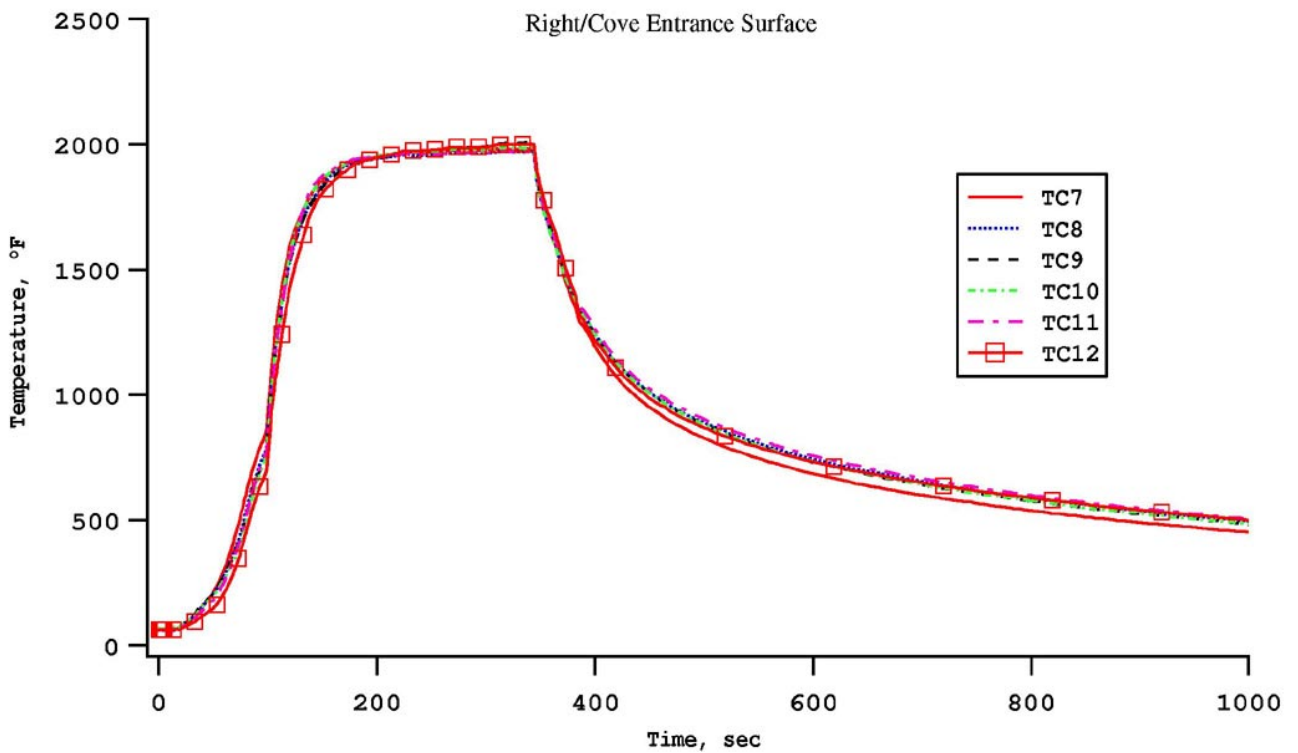
**Figure 30.—Temperature Plot from Run 98-09 (Above the Seal).**



**Figure 31.—Pressure Plot from Run 98-09.**

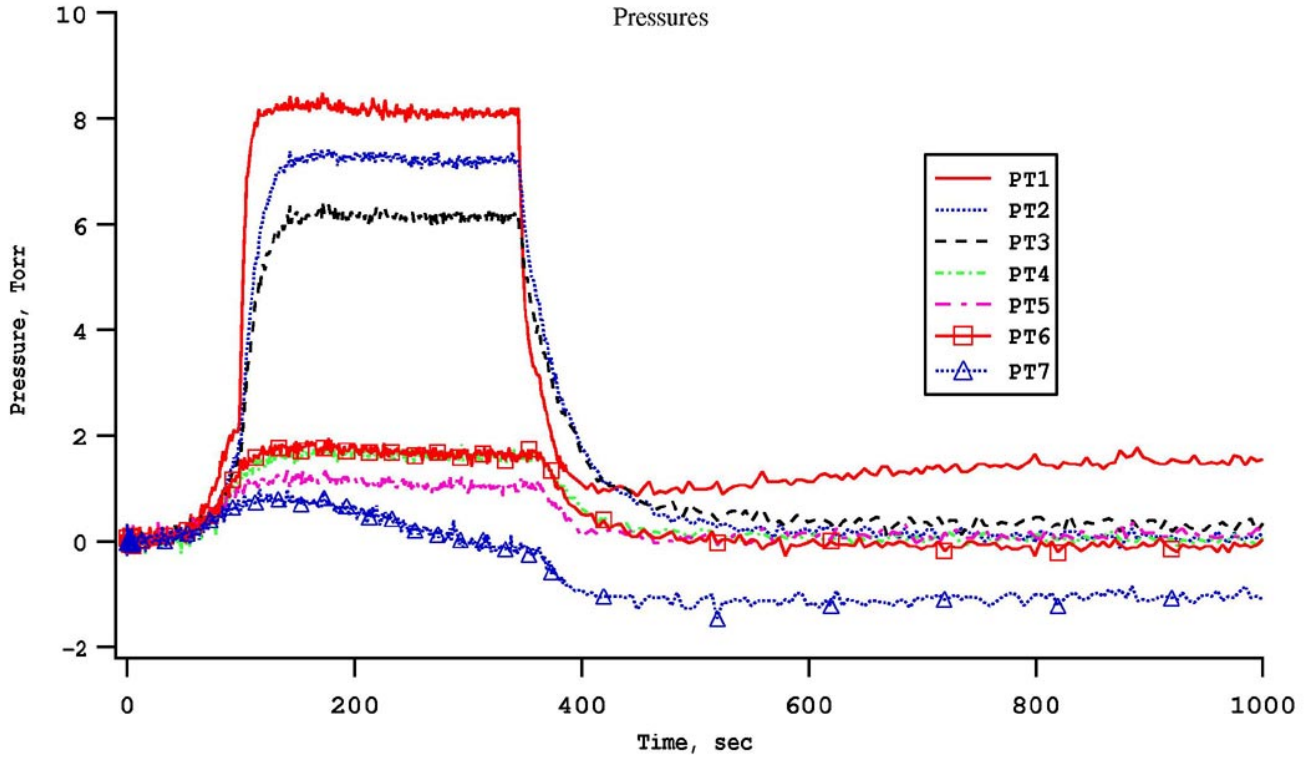


**Figure 32.—Temperature Plot from Run 98-11 (Below the Seal).**

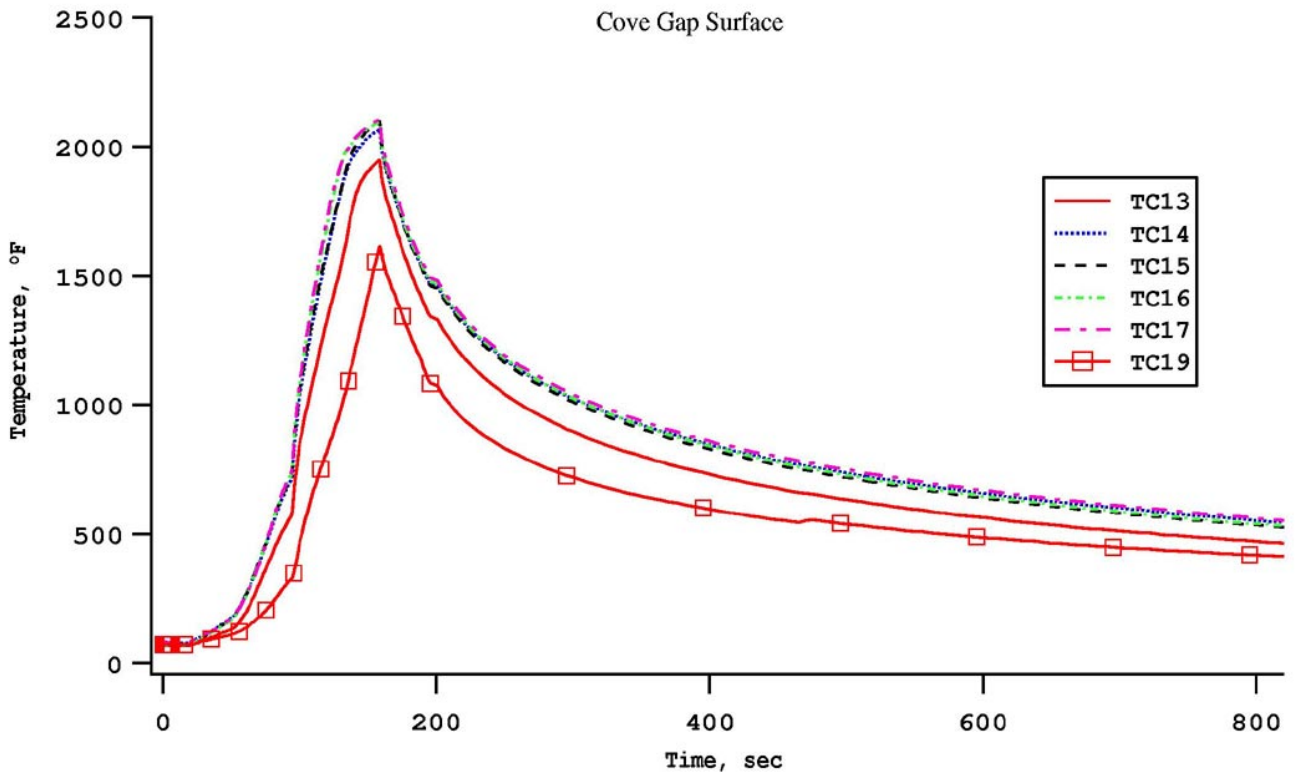


**Figure 33.—Temperature Plot from Run 98-11 (Above the Seal).**

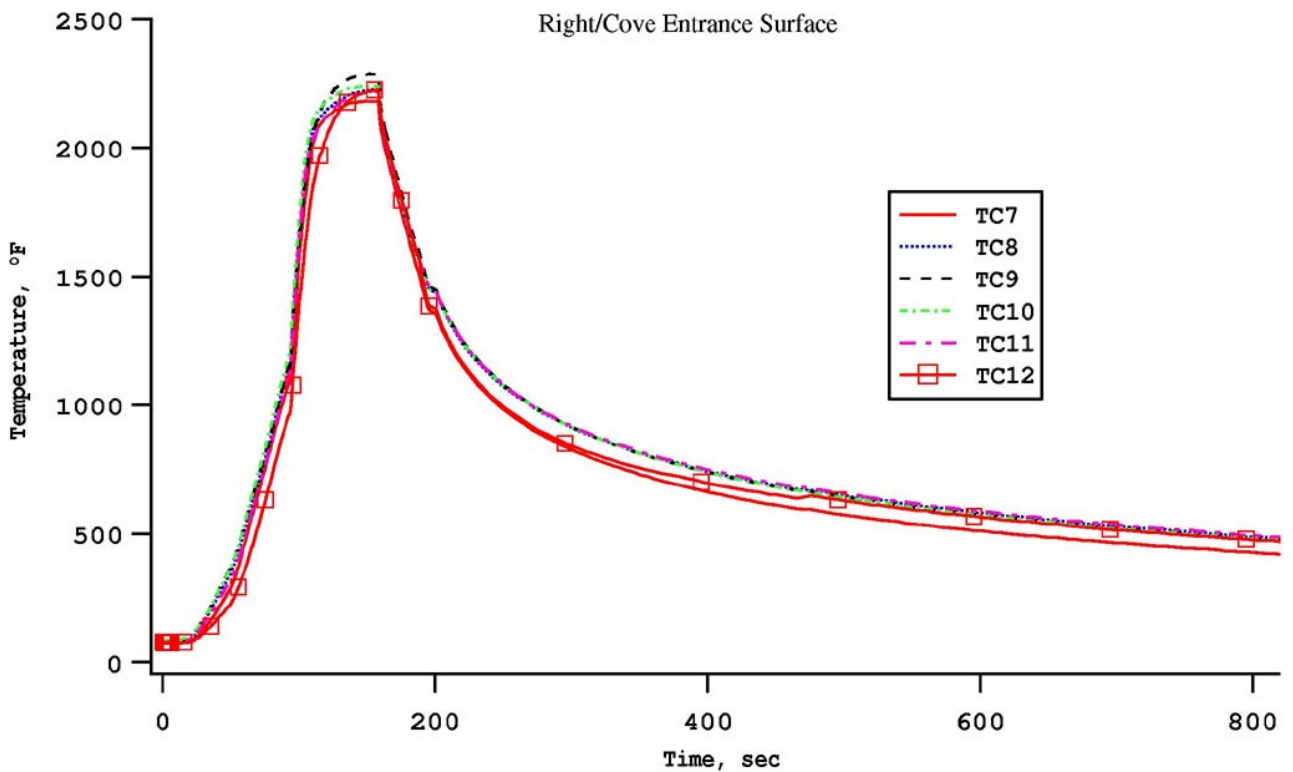




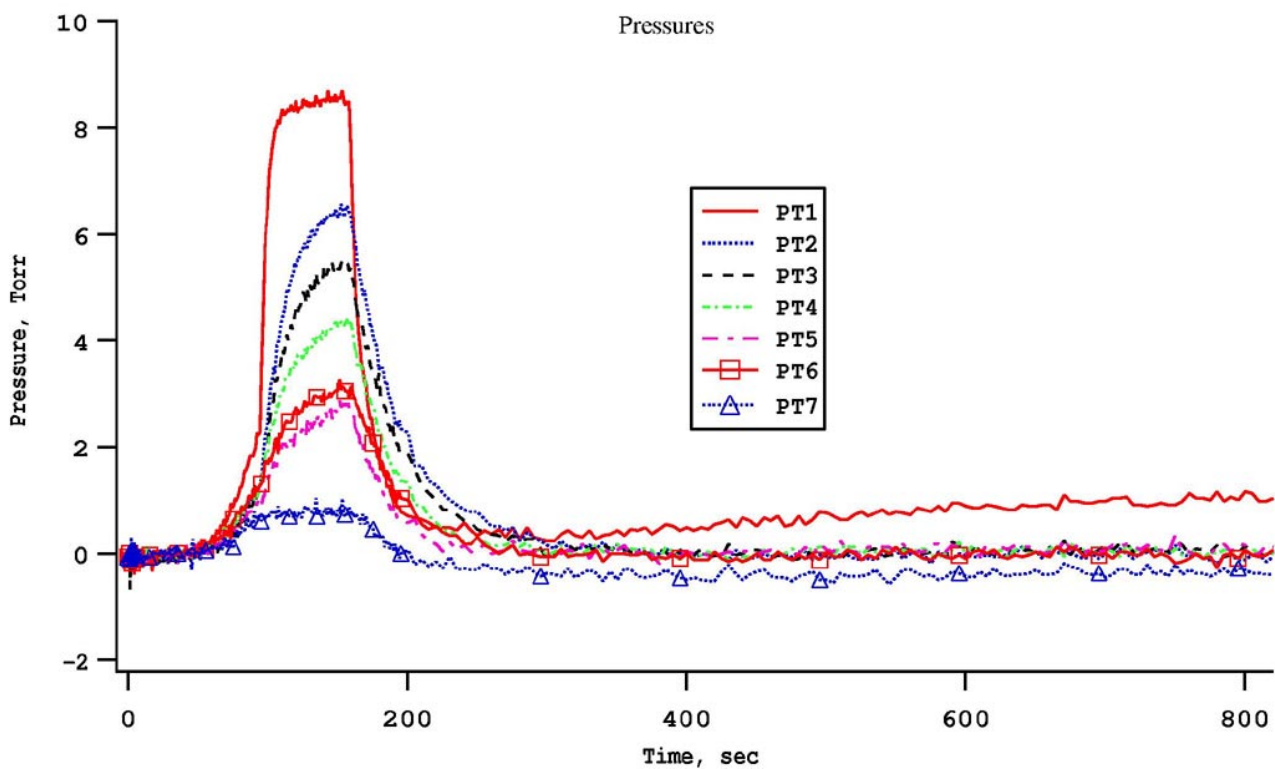
**Figure 34.—Pressure Plot from Run 98-11.**



**Figure 35.—Temperature Plot from Run 98-12 (Below the Seal).**



**Figure 36.—Temperature Plot from Run 98-12 (Above the Seal).**



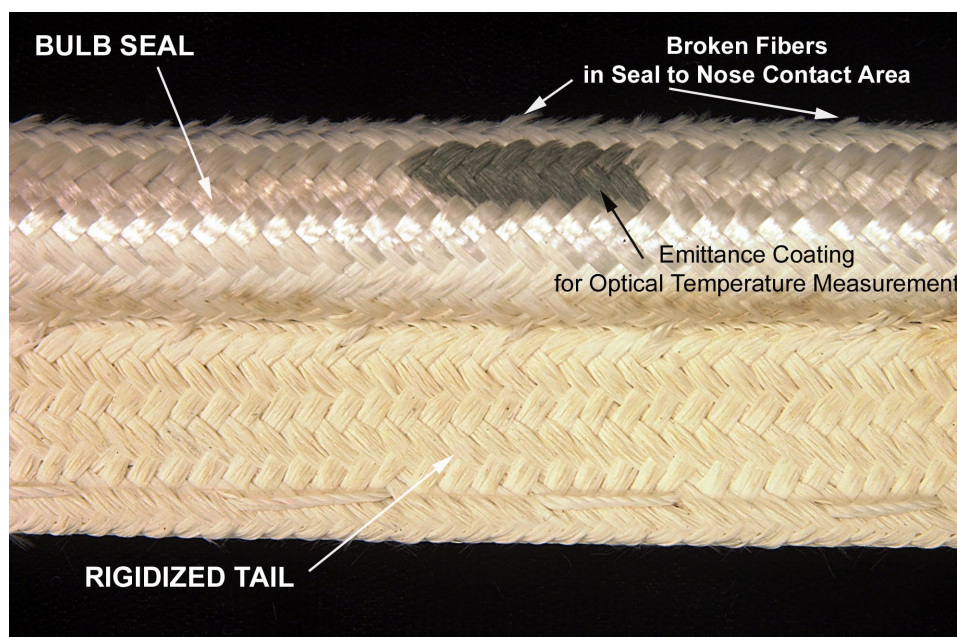
**Figure 37.—Pressure Plot from Run 98-12.**

## 6.6 Visual Examination of Seals After Arc-Jet Exposure

Post-test examination of the test seals revealed some minor discoloration in the seal and the attachment “tail” areas and some damage of Nextel filaments in the bulb-to-nose contact area. The worst damage was in test seal #1, shown in figure 38. The seals with Nextel 440 outer layers seemed to have the least amount of damage. This was especially true for the concentric-braided test seals #5 and #6 and test seals #7 and #8 that were used for the larger gap testing runs. However, the minor differences between test seals #3 through #8 would be difficult to quantify.

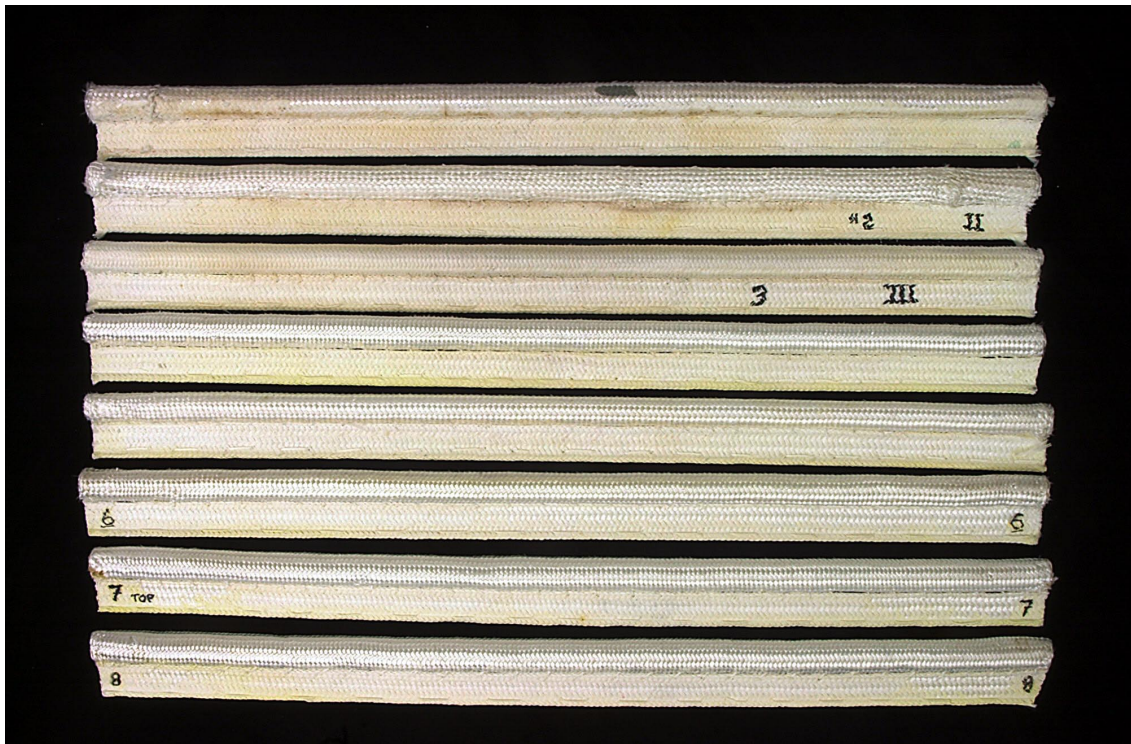
The above paragraph is true with only one exception – a portion of test seal #3 had a negligible amount of wear. This section was the 1/3 of the length that had some of the rigidizer solution that had wicked onto the outer surface of the seal. This ceramic matrix appeared to dramatically reduce the seal “wear.” This is in keeping with experience on coated ceramic fabrics in general. By preventing the movement of filaments within fiber bundles damage in sliding contact or in acoustic environments can be greatly reduced.

Figures 39 and 40 are photographs of the two sides of the test seals after arc-jet exposure in the movable elevon fixture.

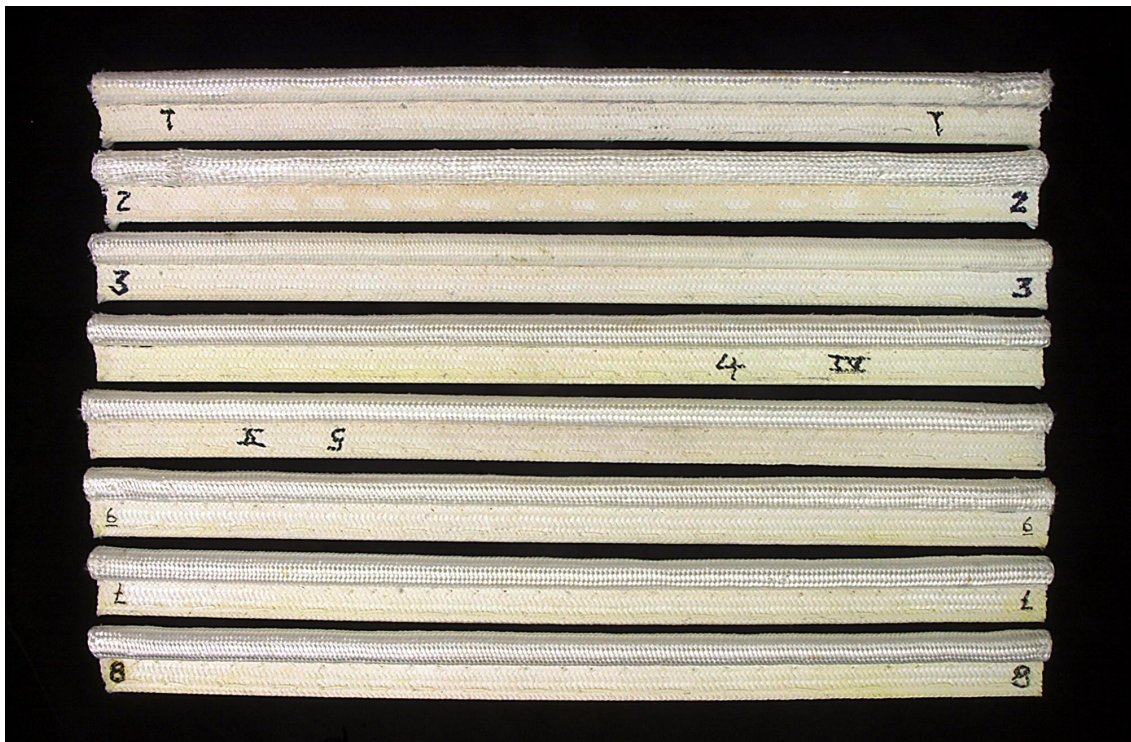


**Figure 38.—Post Test Seal #1 Showing Damaged Fibers in Contact Area.**





**Figure 39.—Backside view of Test Seals—Post-Test.**



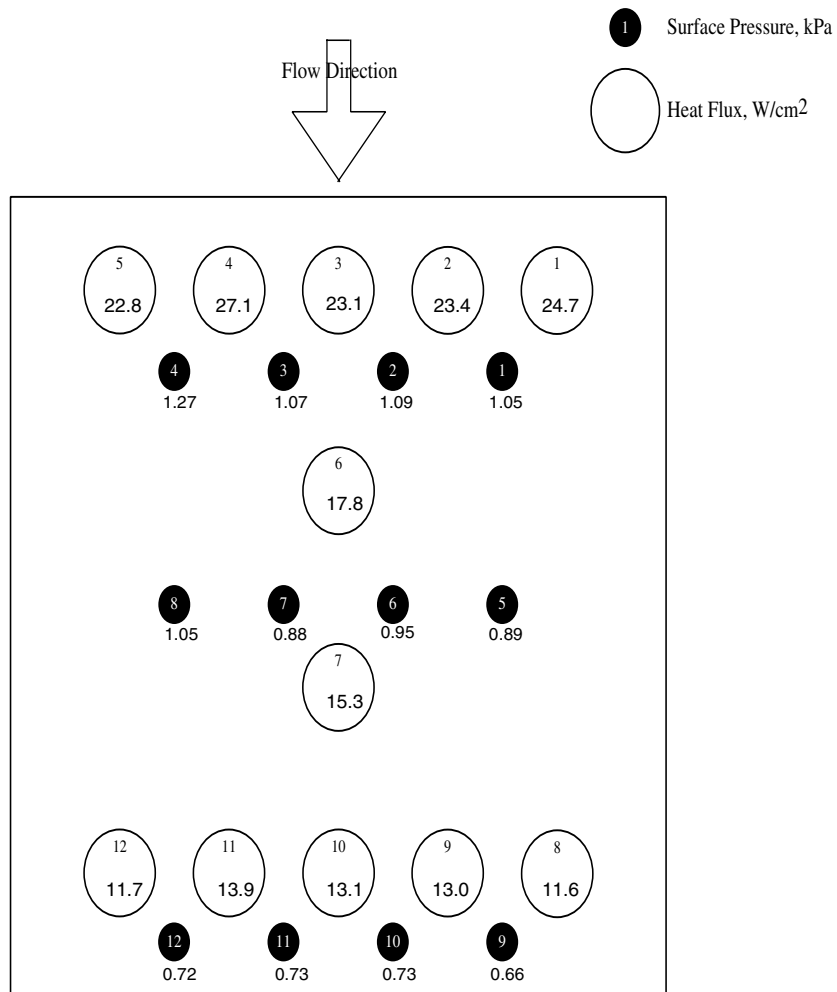
**Figure 40.—Front Side View of Test Seals—Post-Test.**

## **7 RESULTS OF POST-TEST FACILITY CALIBRATION TESTS**

Calibration of the heating and flow environment was performed following the initial test series with the seal test fixture. The calibration runs were conducted at the conditions listed in Table 4 with the ARC PTF calibration plate. Figure 41 shows the measurement locations for surface pressure and heat flux on the calibration test fixture. The calibration plate was run to simulate the elevon angles. Heat flux measurements were taken using new calorimeters.

Figures 42 and 43 show the averaged data (averaged over roughly 30 seconds) from one run. During this one run, the test conditions were set and the table angle was varied, holding each angle for 30 seconds. Nine (9) degrees was the maximum table angle possible for the calibration plate.

# Pressure and Calorimeter Data - PTF



Average CL Heat Flux 16.55

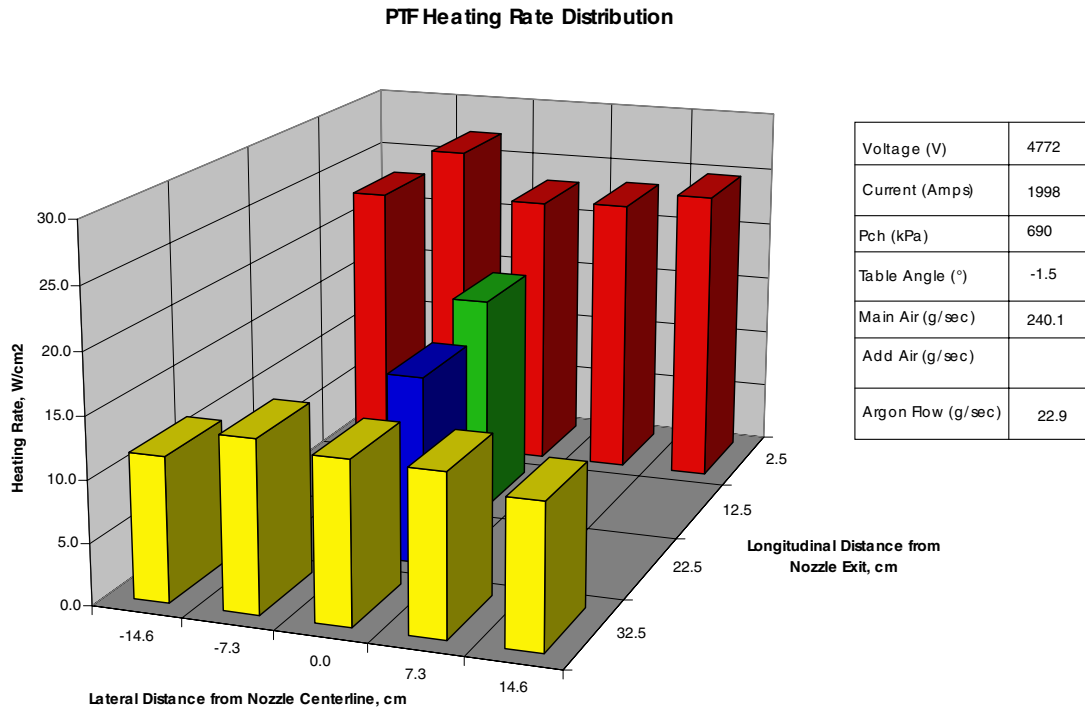
Average CL Surface 0.92

## Test Conditions

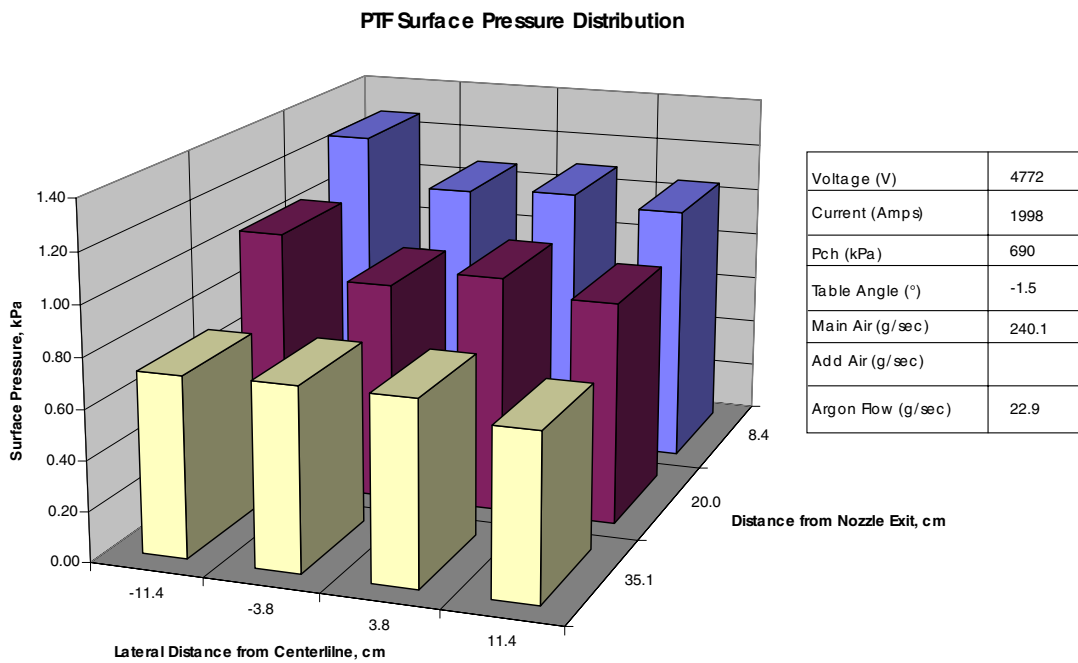
Test number	CAL	Voltage (Volts)	4772	Main air (g/sec)	240.1
Run number	4	Current (amps)	1998		
Date	7/27/200	Pressure (kPa)	690	Argon (g/sec)	22.9
		Table Angle (i)	-1.5	Enthalpy (MJ/kg)	19.1

Note: These data represent mean values of the tabular data

**Figure 41.—Post-Test Calibration Test Fixture Showing Measurement Locations.**



**Figure 42.—Post-Test Calibration of PTF Heating Rate Distribution.**



**Figure 43.—Post-Test Calibration of PTF Surface Pressure Distribution.**



## **8 LESSONS LEARNED**

Some of the indirect lessons learned during the course of this project have been mentioned elsewhere in the report and in appendix A. This section is intended to be a more a more complete listing of what we considered to be valuable “lessons learned.”

### **8.1 Test Fixture Design**

#### **8.1.1 Design Considerations and Model Check Out**

The most important aspect of the design process was to build a full-scale model of the fixture in order to check out the fit and function within the arc-jet facility and consultation with the test facility staff.

We solicited comments from numerous NASA personnel (both test facility and CFD analysts). These comments and the issues identified during the model check out in the PTF were incorporated into the final design.

This was the first time that a test fixture with movable components had been attempted in the PTF arc-jet facility and we wanted to make sure that all available resources were focused on the design. Arc-jet facility staff mentioned that many past test fixture problems would have been prevented had engineers consulted with them or built and test fit a model in the facility.

#### **8.1.2 Side Seals**

Rigidized blankets were used for the side seals of the fixture against which the ends of the nose tile and the cove tile were sealed – to prevent arc-jet flow under the test surface. This concept worked well.

#### **8.1.3 Tile Coating Roughness**

The RCG coating over the TUF1 treatment of the AETB insulation tiles was much rougher than anticipated. Significant areas were quite rough – varied considerably over the entire surface – and required hand sanding to achieve a sufficiently smooth surface to prevent dramatic wear on the contact area of the seal. Hand sanding worked well, but parameters were not quantified.

## **8.2 Seal Construction—Rework to Lengthen Seal After Design Change**

A very late design change resulted in the necessity to add another 1.25 inches in length to the supplier fabricated bulb seals (without the “tail”). The process for this and the splicing development is discussed fully in section 4.3. After the problems that were noted for seal #1 we developed a method to close the ends of the seals so that there was minimal change in the resiliency and diameter of the bulb in the closure region. We also used a variant of this method for splicing the additional 1.5-inch length onto the original seal ends. The basic concept consisted of folding back the first braid layer into the core of the bulb and inserting a core plug into both ends to be spliced. The slice was then sewn with Nextel 440 sewing yarn. Subsequent to the fabrication and testing of these seals we learned that using a Nextel 610 sewing yarn newly developed by 3M Company could dramatically relieve the many problems that we had sewing with Nextel 440 sewing yarn.

## **8.3 Seal Groove Rework**

The ends of the first seal were larger than the planned 0.625-inch bulb diameter and also stiffer than the rest of the bulb. These conditions created excessive pressure against the nose tiles and prevented proper installation. The rework selected was to relieve the seal groove in the end area by removing sufficient AETB material so that the seal contact surface at the ends was in the same plane as the rest of the seal bulb. The rework was easy and worked well during run #1.

The end closures were redesigned for seal #2 and the remaining baseline and the modified-baseline seals. This resulted in a larger than required seal groove at the ends because of the rework for seal #1. The solution that worked well was to use Saffil as a packing material under the seal bulb in the groove to adjust for a proper fit.

## **8.4 Flexible Shaft to Actuate Crank Mechanism for Control Surface Angle Change**

A flexible shaft from the outside of the test chamber to the actuation crank mechanism was an inexpensive solution that ultimately worked well. However, there were a number of lessons learned that enabled proper function.

The most important lesson to be learned was a general one about flexible shafts. They are usually only for torque in one direction. What was required for this application was a “bi-directional” flexible shaft – and one that is heavy duty. There is still some amount of hysteresis in changing direction; but of a degree that can easily overcome by ensuring that calibration and normal operation is in one direction only – to retain calibration. The hysteresis is a function of the degree of force that is required to move the control surface and the friction between the seal and the nose tiles, and between the tiles and the sides. Each run was calibrated (to translate outside shaft movement into degrees of control surface elevation) because the frictional effects were not sufficiently predictable. If the

fixture were to be used again we would install a more heavy-duty flexible shaft that would decrease the amount of hysteresis.

## **8.5 Change in Gap Size with Control Surface Angle**

The gap between the cove and the nose tiles was supposed to be constant with movement of the control surface. However, the gap closed slightly as the control surface angle was increased. This was due a varying radius of the nose tile surface relative to the pivot point of the control surface. The discrepancy was the sum of tolerances from the manufacture of the support structure, assembly of the metallic fixture, and installation of the coated insulation tiles. The test fixture should be reworked before further use

We were fortunate that the gap closed slightly as the control surface angle increased. The pressure increases as the control angle goes up, resulting in higher temperatures and overall a more demanding environment for the seal area. More compression of the seal ensures fewer areas of misfit gaps and lower probability of leakage.

## **8.6 Test Facility Limitations**

Run time was a significant limitation for a project that was attempting changes in the test article geometry during the run. But this was a limitation determined by the capability of the facility and the conditions that were required for this project.

The limits for differential pressure across the seal were limited by facility capability at our required operating conditions. The result was that the highest differential pressure that we achieved was 6.08 Torr.

The upper angle for the table (upon which the test fixture was mounted) was 6 degrees. It was a result of temperatures generated on the test article and the heating on the ceiling of the facility (from hot gas of the deflected arc-jet flow) at higher angles of the control surface. The high limit angle of the test fixture's control surface was 10 degrees relative to its base. This resulted in the upper limit of the angle of the control surface to the arc-jet flow of 16 degrees – *sum of the table angle of 6 degrees and control surface angle of 10 degrees*.

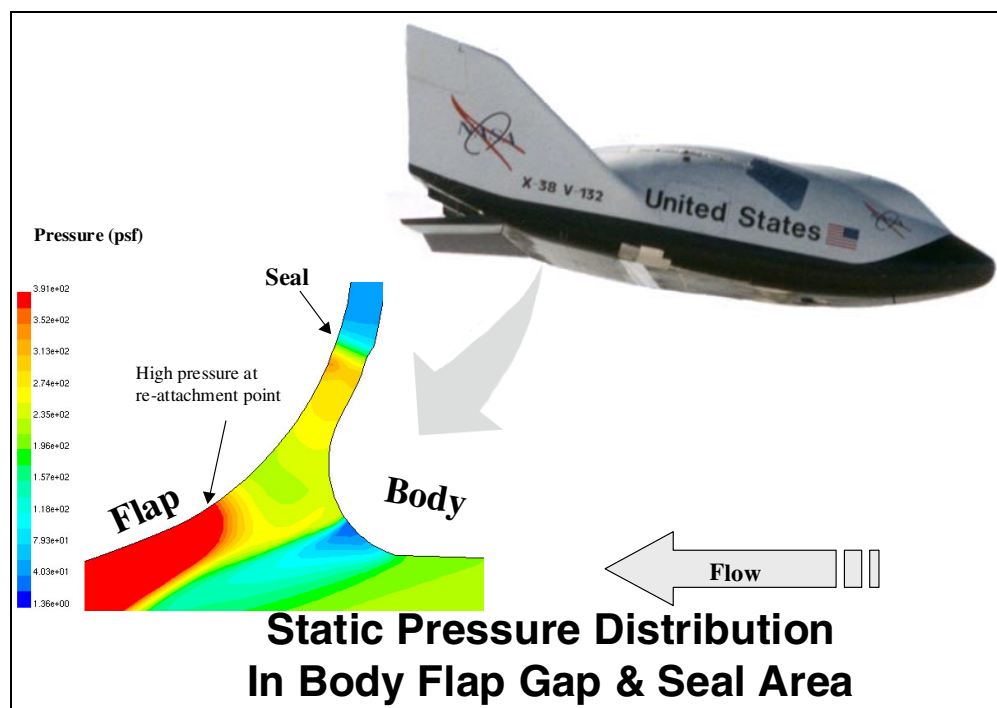
## 9 SUMMARY OF CFD AND THERMAL ANALYSES

### 9.1 Aerothermal Analysis

#### Introduction:

An aerothermal analysis was performed using an X-38 environment and a 2-D body-to-flap control surface seal arrangement that was based on one of the X-38 candidate designs. This vehicle and its parameters were selected because they were representative of the types of designs for the new generation, smaller vehicles. The analysis included computed fluid dynamics (CFD) analysis using FLUENT software for 2-D analysis of gas temperatures, pressures, and flow vectors.

Figure 44 is a representation of the X-38 vehicle showing the location of the body-to-flap region along with the static pressure contour map for a 20-degree flap angle (with an impermeable seal). This plot is used for illustration purposes because static pressure correlates better than other CFD outputs with the heat transfer and ultimately with the temperatures of the structural components.



**Figure 44.—Static Pressure Distribution in Body Flap Gap and Seal Area.**

### Aerothermal Analysis:

The analysis focused on the seal area and two seal conditions: (1) an impermeable seal, and (2) a permeable seal—permeability,  $k = 1 \times 10^{-7} \text{ ft}^2$

The seal aerothermal environment was estimated with a steady state flowfield solution. The steady state flow solution assumes constant energy flow into the cove sufficient to balance heat flux into the 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 that 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 analyses had resulted in seal temperatures on the order of 2650 °F. Figures 49 and 50 contain the data as summary and plot, respectively.

Details of the aerothermal analyses are shown graphically in Figures 45 through 51, and a brief description follows for each of the figures.

Figure 45 shows the grid used for the localized area of the 2-D representation of the flap-to-body area, including the seal.

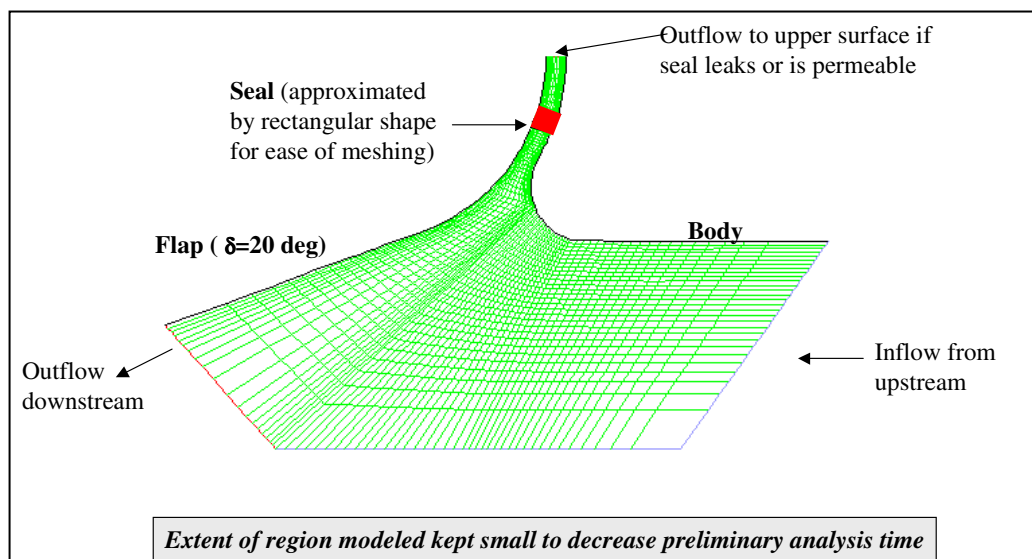
Figure 46 shows the flow pathlines for both cases of seal permeability. The extreme degree of permeability for the porous seal does not appreciably affect the flow structure.

Figure 47 of the static pressure distribution indicates that there is not a significant pressure difference at the seal area for the two seal cases.

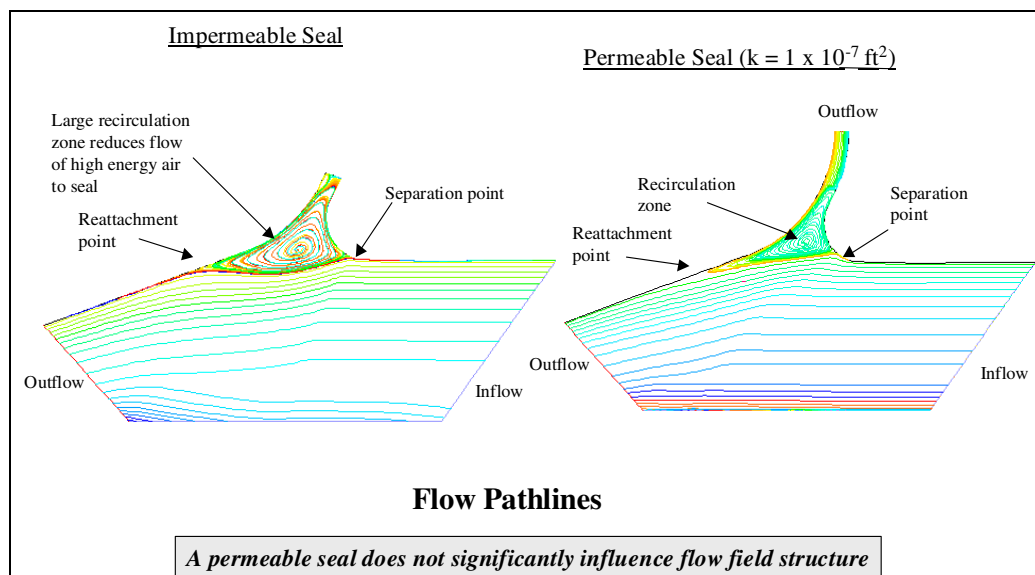
Figure 48 shows the total temperature (in degrees R) distribution in the gap and seal region. It should be noted that the total temperature is for the fluid only. The distributions indicate that hot gas will be forced further into the gap; and some amount of hot gas will flow through the permeable seal.

Estimates for the heat transfer from the hot gas environment were made based on radiation equilibrium at the surface (an idealized surface assuming emissivity = 0.8; no flow through surfaces; no conduction into structure). Results for these calculations are presented in Figure 49 in degrees F and indicate that the seal temperatures are higher, as expected, for the permeable seal. The permeable seal temperatures are approximately 2300 °F – for this idealized and worst case condition. In a 2-D transient structural thermal analysis the temperatures are expected to be slightly lower due

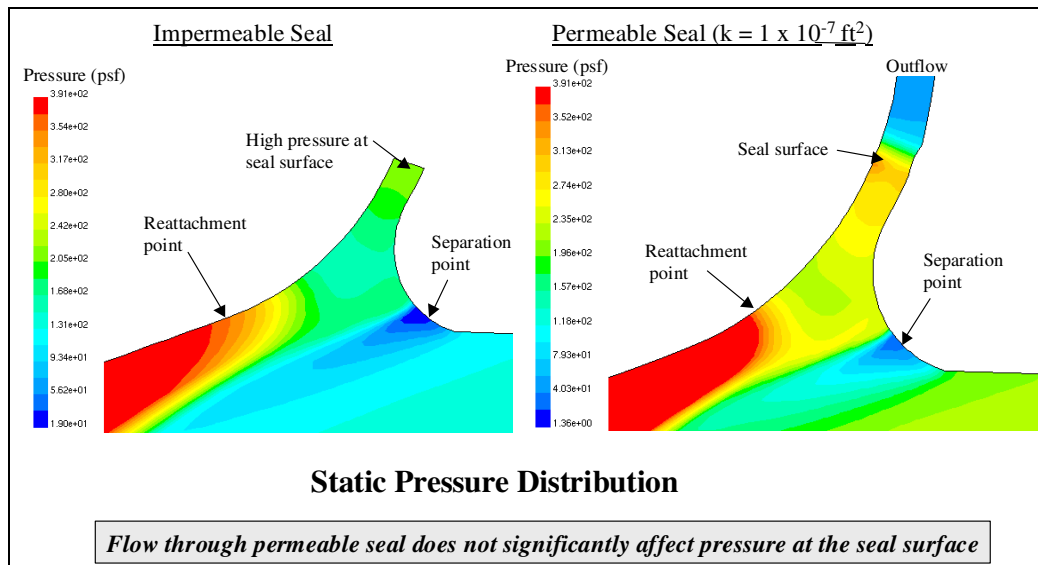
to conduction of heat into the structure of the body and the flap. The temperatures provided by the radiation equilibrium temperatures at the surface are a maximum.



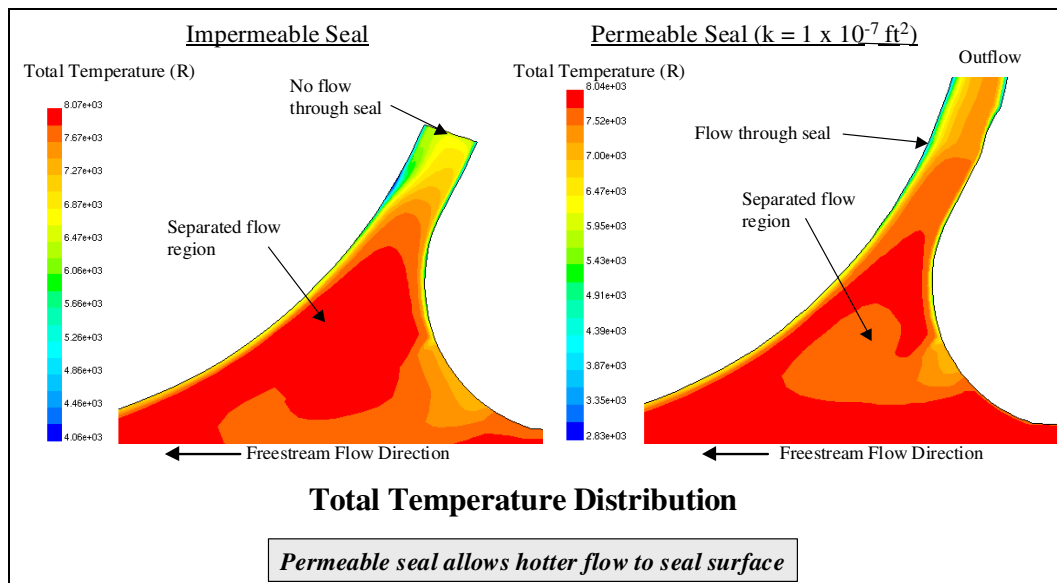
**Figure 45.—Computational Grid.**



**Figure 46.—Flow Pathlines.**



**Figure 47.—Static Pressure Distribution.**



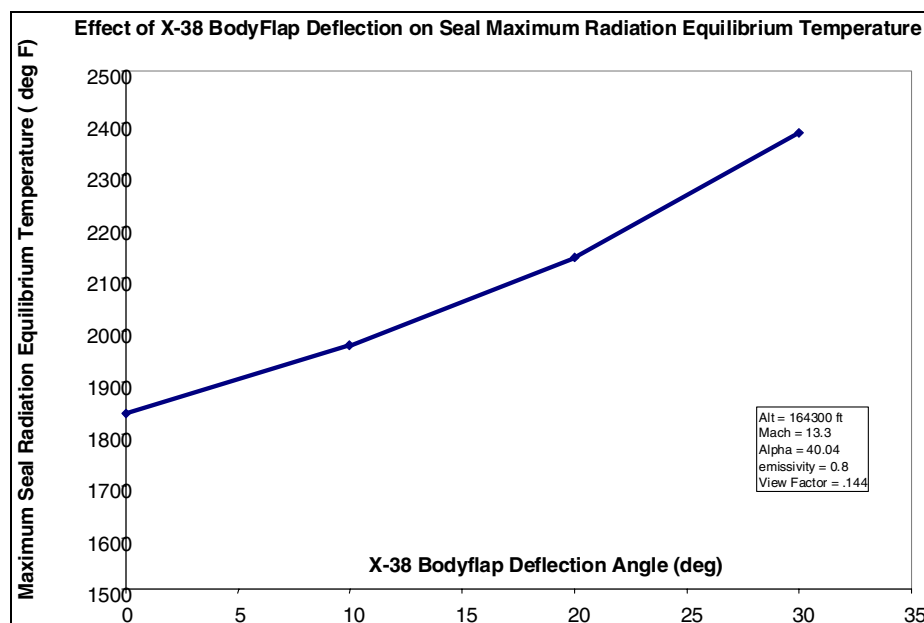
**Figure 48.—Total Gas Temperature Distribution.**



Seal Surface Condition (20° flap $\delta$ )	Impermeable	Permeable <small>Permeable Seal (<math>k = 1 \times 10^{-7} \text{ ft}^2</math>)</small>
Radiation Equilibrium Heat Flux (Btu/sq ft-hr)	7000 to 9000	15000 to 30000
	<i>Seal permeability significantly increases seal heating.</i>	
Radiation Equilibrium Temperatures (°F)	2000 to 2200	2300
	<i>High seal permeability significantly increases seal temperatures</i> <i>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.</i>	

**Figure 49.—Predicted Seal Temperatures.**

The previous five figures were based on a flap deflection angle of 20°. The maximum radiation equilibrium temperatures from CFD analyses of other flap deflection angles for the impermeable seal were also determined and are plotted as Figure 50. The conclusions of the preliminary aerothermal analysis are listed in Figure 51.



**Figure 50.—Flap Deflection vs. Seal Maximum Radiation Equilibrium Temperature.**

- Preliminary CFD analysis indicates that handbook cavity correlations slightly under-predict the aerothermal environment for deflected flaps.
- High seal permeability results in slightly increased aero-heating to the seal. Actual ceramic fiber seals are expected to be considerably less permeable than our initial analysis resulting in lower seal temperatures.
- Maximum seal surface temperatures are expected to be in the neighborhood of 2300 °F for a 20-degree flap deflection for an impermeable seal and higher for the high permeability seal.
- Seal temperatures increase as body flap deflection angle increases.

***Figure 51.—Conclusions. Aerothermal Analysis.***

## **9.2 Relating X-38 Flight Condition Analysis to Arc-Jet Conditions**

Three approaches were considered to relate analysis of the arc-jet conditions to those of flight. They are discussed below and summarized in Figures 52, 53, and 54.

For all the methods, since there was no data at actual flight conditions, it was assumed that (1) the important parameters in the flow were modeled and (2) that if the method matched data at the test conditions it would also be valid at flight conditions. For the three methods that were considered those assumptions were more or less true.

### Method 1, FLUENT:

Since **FLUENT** has no real gas model, flows with total temperatures greater than 3000 °R would not be modeled correctly. That included both the arc-jet and flight environments. This violated assumption (1) above. However, this method was able to analyze complex flow fields relatively quickly and could give good indications of the trends due to seal porosity and other parameters.

#### Method 2, Correlations of Arc-Jet Data:

**Correlations of the arc-jet data** would inherently include the real gas effects in the arc-jet. So this should be an improvement over the FLUENT predictions. However, it still assumed that the real gas and chemistry effects in the arc-jet could be extrapolated to flight. This violated assumption (2) to some degree.

#### Method 3, Ames Model:

It is planned that NASA ARC will use the arc-jet data from this program and correlate it with a CFD analysis of the arc-jet environment; and then correlate this with the analysis of flight environment.

**The Ames CFD** work will use a sophisticated model of the air chemistry that is based on substantial 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. One can probably claim a high amount of confidence in flight predictions made with this method.

Collaboration with NASA Ames Research Center's RFE Branch has resulted in suggested aerothermal analysis tasks of benefit to the Advanced High Temperature Seals program. The objective is to use the most sophisticated analysis 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 have been 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 arc jet conditions

## 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

**Figure 52.—Thermal Analysis Considerations for “Approximate Methods.”**

## THERMAL ANALYSIS -- Higher Order Method

### Non-Equilibrium Air 3D CFD Analysis

(NASA ARC Reacting Flow Environments Branch)

#### Arcjet Conditions

1. Conduct 3D non-equilibrium 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

**Figure 53.—Thermal Analysis Considerations for “Higher Order Method.”**

## **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.

***Figure 54.—Summary of Thermal Analysis Methods.***

## **10 RECOMMENDATIONS FOR FUTURE WORK**

Correlate the CFD model to arc-jet facility results and then correlate to re-entry conditions.

Investigate techniques and designs to minimize fiber damage on rubbing surfaces. The results in this study demonstrated that infiltration of fabrics with a compatible ceramic matrix significantly reduces fiber damage from rubbing against a TUF/RCG coating on AETB tiles – this should be explored more thoroughly. Another aspect that needs development is the use of fabrics on the exterior of seals that have a preponderance of exposed surface yarns that are parallel to the direction of sliding.





## **Appendix A**

### **A-1. Chuck Newquist's Notes from Arc-Jet Tests**

#### **Arc-Jet Run #1 of Ames test Series #98 (Run 98-01)**

##### **Test 98-01**

Seal Test #1 – Nextel 312, 9PCF Saffil

Dated 21Dec00

Replaced Dremel flex shafts w/ Sears Flexible Drill Shafts. Chuck screws onto flex shaft so had to put set screws into threaded section to keep from unscrewing.

Raising elevon – 2 turns/degree of lift, rotating shaft in counterclockwise direction.

Side seals on each side elevon – ½” blankets – caused enough drag on elevon to make raising and lowering a bit difficult. Enough to cause Dremel flex shaft to break and Sears Flex shafts to come unscrewed.

Seal ends were stiffer than center section and would not compress enough to fit, so we cut away relief grooves in entrance and cove tiles at those locations. Seal then fit well, but still required some manual “stuffing” to get the bulb section compressed into the gap.

Elevon was cycled 15 to 20 times prior to the test, resulting in a white “mist” of Nextel filaments on the nose tile. The Silfrax leading edge blocks had a chip repair about 4” upstream of the PT#1. Dark flow stains on the tile just to the left of PT#1 indicated a flow disturbance which could affect PT#1 pressures. All pressures were constant during the run except PT#1, which rose from 6 to 7 torr. The chip repair lifted ~1/8” during the run and may be related to the PT#1 pressure change.

The elevon was raised in 1° increments during the run. After arc-on, the table was raised from -2° to +4° degrees. 7 degrees was chosen because the resistance to motion appeared to increase above this angle. The second run was going to be at 5° and 10° with a new seal.

Surface temp was at 2000 °F as measured by optical pyrometers and type R thermocouple. Temps were much lower in the gap. No thermal indication of flow past the seal. Delta P across the seal was about 6 torr.

Run duration was about 6 minutes.

Some slight brown staining and fiber wear was noted on seal – along the contact line with the nose tiles – after removal from the test fixture.

Installing the second seal took about 30 minutes. It was slightly shorter than the first seal which had an interference fit with the side blankets. Needed to stuff fiber batting into

~1/16<sup>th</sup> inch gap at each end of the second seal, as well as in relief grooves in tile from the 1<sup>st</sup> seal.

Leading edge Silfrax block cracked during re-installation, probably due to tighter fit. Possibly seal tail was longer than for seal #1, causing cove entrance tile to shift toward the nozzle. Will need new leading edge Silfrax block with more free-play and preferably without seam on centerline – due to PT#1 just downstream of the joint.

On disassembly, #1 seal was difficult to remove. Elevon had to be lowered to “free” the seal. It may have been “pinched” in the gap by the elevon as it went from 0 to 7 degrees.

Test fixture design worked well. No unexpected flow or heating, except at tile steps and repairs. Side blankets worked well. Flow did not recirculate around back of elevon. Shock detachment was about 15 degrees around arc from TC#4 location and aimed up away from elevon nose.

=====

### **Test 98-04 dated 27 Feb 01**

Control Surface Seals – Arc-Jet test #4 with Seal #2

(Run #2 was a checkout run.)

(Run #3 – stopped before table-up – table inclinometer was not working).

Seal – Made by Hi-Temp, Inc.

Nextel 312 Covering, 2 layers

Inconel tube spring

Saffil batting at 6 lbs/ft<sup>3</sup>

### **Run conditions in PTF**

Arc-Jet gas 8% argon, 92% air

Table angle -2 degrees startup. 4 degrees — run

0 0 to 30 secs

2 0:30 to 1:00

4 1:00 to 1:30

6 1:30 to 2:00

8 2:00 to 2:30

10 2:30 to 3:00

Max Surface Temp = 2060 °F

Optical Pyrometers

■ Next to PT-1 (upper surface, centerline, 6.5 degrees from nozzle)

■ On control surface nose – about 1” from seal in 0 degree position

Other instruments monitored in real time:

TC 4, 10, 16, 20, 23

Pressure: PT-1

## TEST 98-05

### Arc-Jet Test #5 Dated 27 Feb 01

Table angle: -2 deg on startup; 6 deg Run  
Control surface angle: 0 to 10 deg in 30 second increments

PT-1 – 8.6 torr      TC-4 – 2200 °F

---

## TEST 98-06

Arc-Jet Test # 6,    Seal #3  
Dated 28 Feb 01

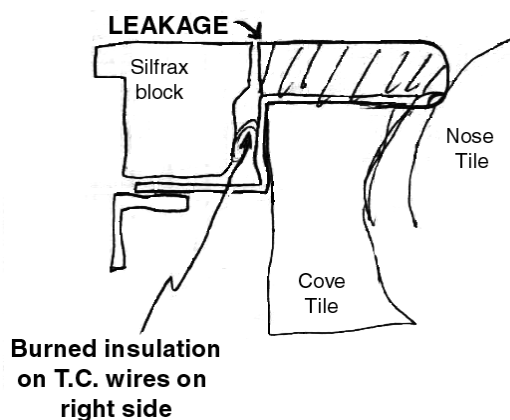
Table angle	PT-1 pressure tap	T-4 thermocouple
-2 deg start-up	---	---
8 deg	12.24	2350 °F
6 deg	9.9 to 12.0	2225 °F

Started table in -2 deg position.

Raised table to 8 deg to get pressure and temp readings – PT-1 was 12.24 torr and T-4 was 2350 °F. After about 10 seconds at 8 deg, lowered table to 6 deg and continued with testing at elevon positions of 0, 2, 4, 6, 8, and 10 deg.

Some TC wires in the upstream cavity were overheated, with insulation missing from TC 6 and 12 (?). Both of these TC's had erratic data.

Cause was leakage between upstream tile and Silfrax block. Several areas of Saffil gap filler were missing, with evidence of heating below the Silfrax.



Connection between elevon and drive shaft is loosening. Appears to be free-play at set-screw locking elevon to the shaft. Will repair after run #7 by raising elevon to vertical and drilling through bottom side tile into collar and shaft and inserting screw or pin.

---

### **Test 98-07**

Dated 1 March 01

Arc-Jet Test #7, Seal #4

Table angle during start-up: -2 degrees

Raise to 6 deg for run duration.

Elevon positions at 0, 2, 4, 6, 8, 10 deg relative to test fixture , 30 seconds at each elevon position.

T-4: 2186

PT-1: 8.6

—Normal Test – No problems.

---

### **Test 98-08**

Dated 12 March 01

Arc-Jet test #8, Seal #5

Same conditions as the previous test.

Seal Construction: (fab by JV 28 Feb 01)

1        2 layers of ¼ inch dia sleeving – Nextel 440

2        4 layers of 1/ inch dia sleeving -- Nextel 440

OD is ~ 0.54 inch

Table angle at start-up: -2 deg

Raise table to 6 deg for duration of the run.

Control surface positions: 0, 2, 4, 6, 8, 10, 30 seconds at each

TC-4    ~2230 °F

TC-10   1985 °F

TC-23   1125 °F

TC-16   280 °F at end of run

**Normal Test ---nothing unexpected**

## **Arc-Jet Run # 98-09**

Seal # 6

Dated 12 March 01

Same conditions as all previous tests in this series

Seal Construction—Concentric Nextel 440 braid, fabricated 9 March 01 by JV at Boeing

1/8 inch dia braid – 0 layers

1/4 inch dia braid – 2 layers

1/2 inch dia braid – 3 layers

Outside diameter ~ 0.57 inch

TC-4            1800 °F at –2 deg table angle  
                  2300 °F at 6 deg table angle

PT-1            8.8 Torr at 6 deg table angle

TC-23 temperatures:

<b>Table Angle</b>	<b>Temperature at TC-23 (deg F)</b>
0	
2	
4	1390
6	1215
8	1050
10	934

TC-16 reached 250 °F at end of the run.

---

## **Arc-Jet Run # 98-10**

Seal #7

Dated 14 March 01

6 lbs/ft<sup>3</sup> Saffil batting inside Inconel spring tube

Nextel 312 sleeve over spring

Nextel 440 sleeve on outside

Adjusted gap distance to 0.375 inch just below seal position – it was 0.25 for all previous runs.

Contact of seal to control surface had ~ 0.0 to 0.013 inch gap.

Seal was not compressed in this installation. Used a folded paper shim to measure gap between seal and control surface. Seal diameter is slightly non-uniform—leading to contact in some areas and gaps in others—at 0 deg. Seal was in contact with control surface at 10 deg angle.

Will watch lower gap TC's carefully — #16 and #20 and upper gap TC #10

Run #9 temps for comparison with run #10 Temps:

TC	Temps for Run #9 (deg F)	Temps for Run #10 (deg F)
4	2250	2200
10	2000	2000
16	275	420
20	145	145
23	1400 to 800	1600 to 900

PT-1 7.6 Torr

Below-the-seal cove temperature at TC-16 was about 140 °F hotter than previous run with a compressed seal.

Seal compression had been about 1/8<sup>th</sup> inch on the diameter previously.

=====

### **Arc-Jet Run # 98-11** **Seal #8**

**Dated 15March 01**

6 lbs/ft<sup>3</sup> Saffil batting inside Inconel spring tube  
Nextel 312 sleeve over spring  
Nextel 440 sleeve on outside

Adjusted gap to give ~ 0.020 space between seal and nose to control surface.  
Gap closes tight when elevon is at 10 degrees.

#### **Temperature at the Time of Run Indicated**

TC #	Run #9 @400 seconds	Run #10 @ 400 seconds	Run #11 @400 seconds
4	2250	2200	2200
10	2000	2000	1985
16	275	420	373
20	145	145	130
23	1400 to 800	1600 to 900	1500 to 1000
PT-1	8.5 Torr	8 Torr	~8 Torr

No evidence of additional flow through gap from 0.020 space between seal and elevon nose.

The 0.020 inch space between seal and elevon nose closed to zero at about 5 deg elevon position. At 10 deg there was slight compression of the seal.

---

## **Arc-Jet Run # 98-12**

### **No Seal in the gap**

**Dated 15March 01**

No seal, elevon cove gap set at 0.25 inches just above seal cavity.

#### **Temperature at the Time of Run Indicated**

<b>TC #</b>	<b>Run #11 @ 400 seconds</b>	<b>Temperature Limit</b>	<b>Run #12 @ ~45 seconds</b>
4	2250	2200	2200
10	2000	2000	2200
16	275	420	2050
20	145	145	200
23	1500 at 0 degrees 1000 at 10 degrees	2600	-----

Table at 6 degrees, elevon at 0 degrees (30 seconds) and 2 deg (15 seconds)

Cove gap measurement above seal after run was 0.2875 at 0 degrees. Before run it was 0.25.

<b>Elevon Angle</b>	<b>Gap (inches)</b>
0	0.2875
2	0.2870
4	0.2805
6	0.277
8	0.2695
10	0.2595

Gap was reduced by 0.028 inch at 10 deg – compared to 0 deg.

Run was stopped at ~ 45 seconds when TC-16 exceeded 2000 °F and ice was seen forming in bottom of vacuum chamber. The ice was from a water leak in the cooling water manifold to the model. It was not a problem.

## **A-2. AMES Notes on Runs — from their APPENDIX**

A total of ten model runs were conducted in support of this test program. Items of note are summarized in this appendix.

### **Run 001**

12/21/2000

MODEL: SINGLE BULB NEXTEL 312/SAFFIL

The objective of this run was to evaluate the performance of the seals and to determine the maximum elevon deflection angle that can be run in the facility.

The elevon angle was calibrated prior to the run to correspond to 2 turns-of-the-crank per degree of elevon angle. This calibration was used throughout the run; however, at the end of the run, it appeared that the calibration changed once the test article was immersed in the test environment. The final elevon position was moved before its reading could be verified; thus the elevon test angles are unknown for this run. The desired test angles were from 0 to 7° (relative to the table angle), in 1° increments.

The model was in the stream for 5 minutes. The M190R2 pyrometer did not read during the run because the target was below the M190R2's threshold value.

### **Run 002**

2/22/2001

MODEL: SEAL #2

The objective of this run was to evaluate the operation of the steam vacuum system (SVS). The SVS had been down for a several-week maintenance period. It was desired to evaluate its operation prior to committing to resuming the test series.

Everything worked as it should. The test model was not raised into the stream for this run; it remained inclined at -2.5° to the flow. Total run time was 2:58.

### **Run 003**

2/27/2001

MODEL: SEAL #2

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

During the run, the M90R2 readings were compared with those of the 760 IR camera: The readings from the IR camera were higher than those of the M90R2. This run was aborted due to a malfunction in the table's angle indicator.



#### **Run 004**

2/27/2001

MODEL: SEAL #2

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

TC18 readings look suspect. It is likely that the source of the problem is inside the model: The accessible connections were checked and nothing anomalous was found. TC18 will be removed from the data report for this and all subsequent runs.

The External Optics Transmission on the 760 IR camera was changed from 0.58μm to 0.80μm for this run in order to better match the readings from the M90R2. This change worked out well, as the readings now differ by 10 to 20 deg. F.

#### **Run 005**

2/27/2001

MODEL: SEAL #2

The objective of this run was to evaluate the seal performance at higher  $\Delta p$ 's, relative to Run 004: The table angle for this run was increased to 6°.

Post-test photos were not taken for this run.

#### **Run 006**

2/28/2001

MODEL: SEAL #3

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

After the nominal test sequence was completed, the table angle was increased to 8° to evaluate facility operation at this angle. Because of this increased table angle, there was flow-through at the junction of the leading edge tile and the cove tiles, resulting in damage to the insulation of the thermocouple wires that reside in that gap. The readings of TC6 and TC12 were obviously affected by this damage.

Spot comparison of optical instruments:

M90R2 = 2240 °F; 760 IR camera = 2201 °F.

### **Run 007**

3/1/2001

MODEL: SEAL #4

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

Note that no repairs to thermocouples were performed prior to this run, so the damage that occurred during Run 006 is still present for this run. These were repaired after this run. Prior to this run, it was noticed that the calibration of the actuating crank versus elevon angle had changed (recalibration was performed prior to the run); extensive work was required to correct this, as it appeared that the attachments to the shaft was deteriorating. This problem was also repaired after the run.

### **Run 008**

3/12/2001

MODEL: SEAL #5

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

Spot comparison of optical instruments:

4° elevon angle:

M90R2 = 2190 °F; 760 IR camera = 2176 °F

6° elevon angle:

M90R2 = 2201 °F; 760 IR camera = 2186 °F

8° elevon angle:

M90R2 = 2227 °F; 760 IR camera = 2221 °F

Nothing of note to report.

## **Run 009**

3/12/2001

MODEL: SEAL #6

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

Spot comparison of optical instruments:

6° elevon angle:

M90R2 = 2258 °F; 760 IR camera = 2253 °F

8° elevon angle:

M90R2 = 2234 °F; 760 IR camera = 2225 °F

10° elevon angle:

M90R2 = 2268 °F; 760 IR camera = 2266 °F

Nothing of note to report.

## **Run 010**

3/14/2001

MODEL: SEAL #7

The objective of this run was to evaluate the seal performance at elevon angles, relative to the table, of 0° to 10°, at 2° increments.

This seal resulted in gaps due to non-uniformities in the seal's diameter. The gap varied from 0 to 0.013 in.

0° elevon angle:

M90R2 = 2133 °F; 760 IR camera = 2091 °F

2° elevon angle:

M90R2 = 2150 °F; 760 IR camera = 2140 °F

4° elevon angle:

M90R2 = 2162 °F; 760 IR camera = 2140 °F

6° elevon angle:

M90R2 = 2170 °F; 760 IR camera = 2154 °F

8° elevon angle:

M90R2 = 2178 °F; 760 IR camera = 2154 °F

10° elevon angle:

M90R2 = 2179 °F; 760 IR camera = 2161 °F

## **Run 011**

3/15/2001

MODEL: SEAL #8

The objective of this run was to evaluate the seal performance at elevation angles, relative to the table, of 0° to 10°, at 2° increments.

The gap at the seal interface at elevation angle of 0° is 0.020 in.

The seal gap varies as the angle is increased.

Spot comparison of optical instruments:

0° elevation angle:

M90R2 = 2204 °F; 760 IR camera = 2007 °F

2° elevation angle:

M90R2 = 2182 °F; 760 IR camera = 2069 °F

4° elevation angle:

M90R2 = 2180 °F; 760 IR camera = 2062 °F

6° elevation angle:

M90R2 = 2187 °F; 760 IR camera = 2132 °F

8° elevation angle:

M90R2 = 2195 °F; 760 IR camera = 2142 °F

10° elevation angle:

M90R2 = 2198 °F; 760 IR camera = 2149 °F

## **Run 012**

3/15/2001

MODEL: NO SEAL

The objective of this run was to evaluate the effects of having no seal. The temperatures inside the model increased rapidly, resulting in a shutdown sequence beginning 17 seconds after a 2° angle setting had been achieved on the elevation.

Spot comparison of optical instruments:

0° elevation angle:

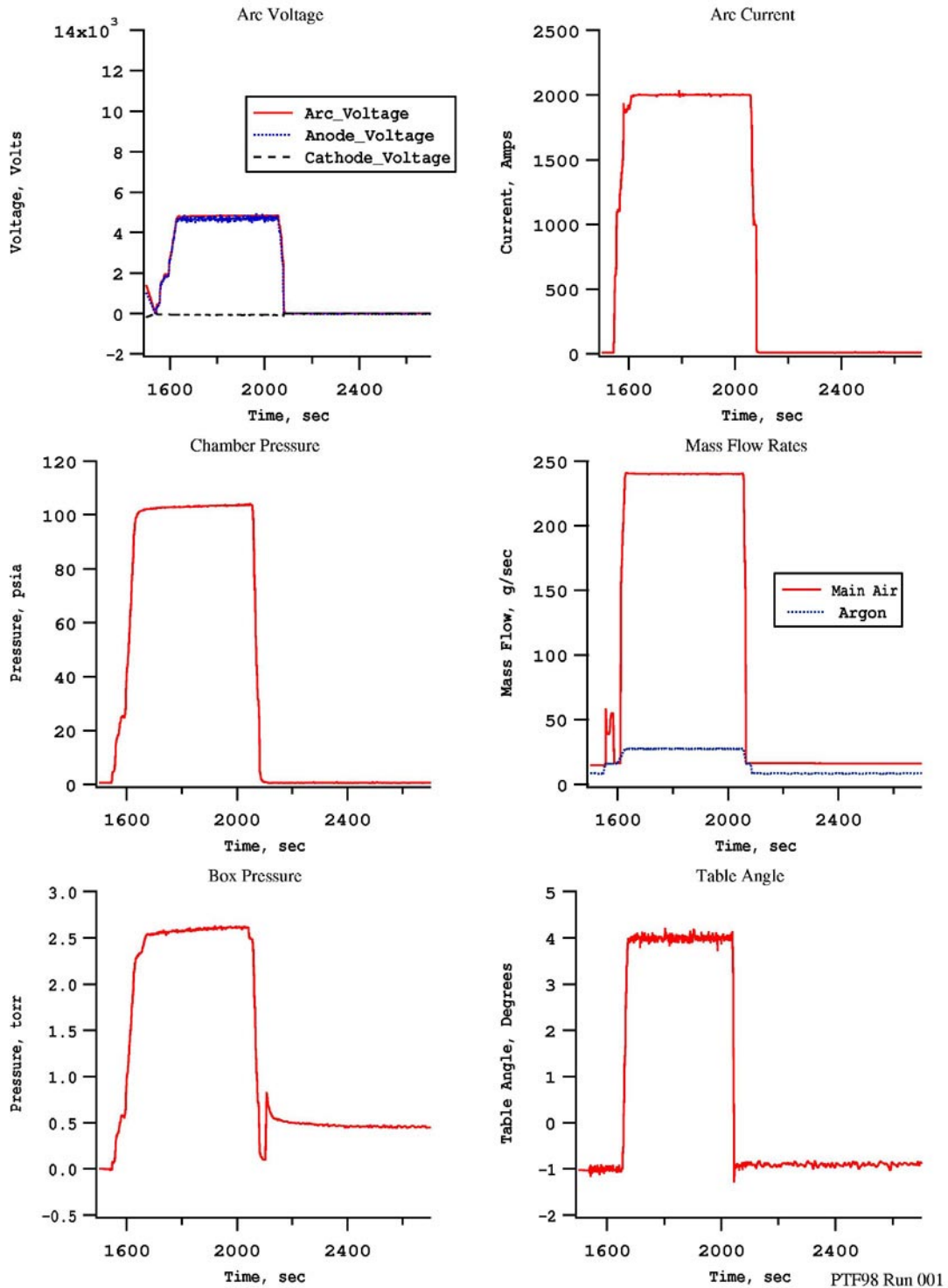
M90R2 = 2218 °F; 760 IR camera = 2196 °F

2° elevation angle:

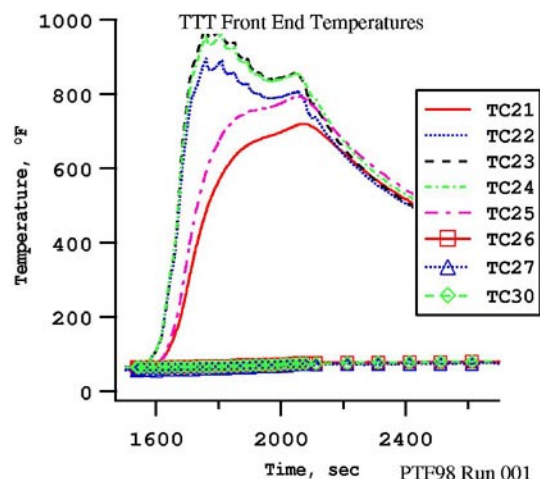
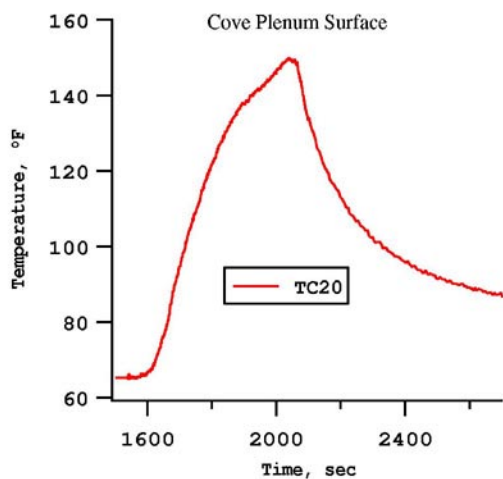
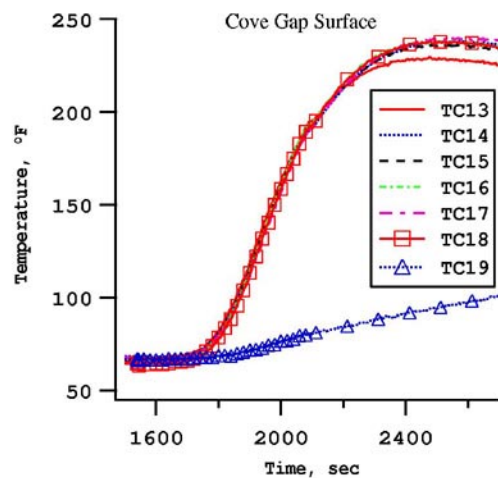
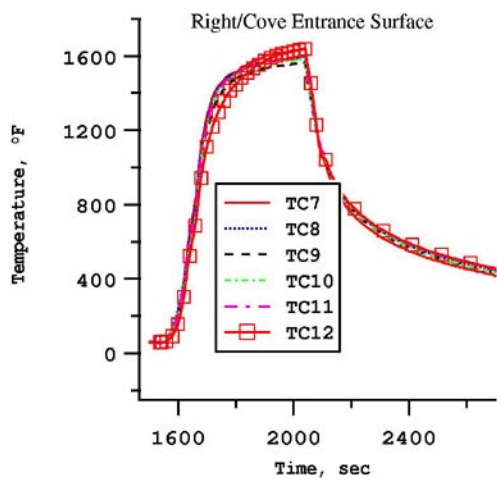
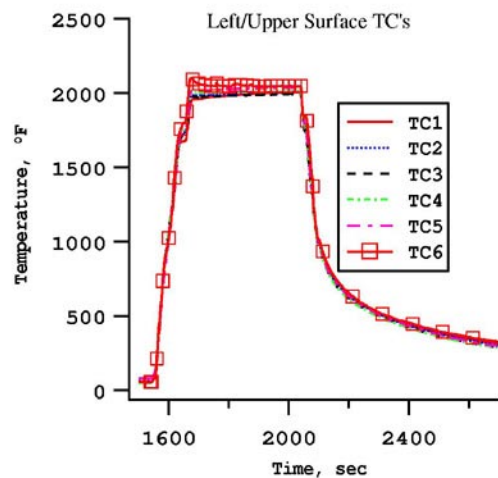
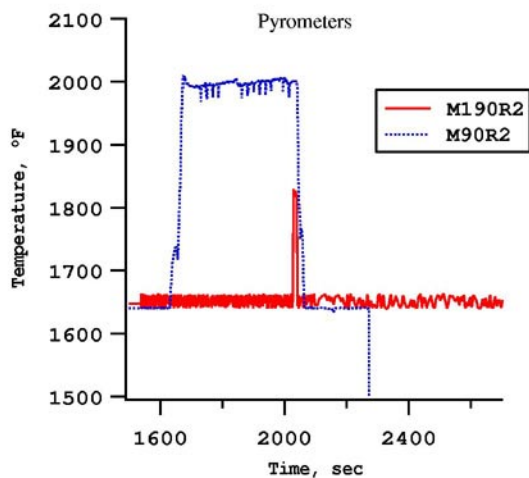
M90R2 = 2210 °F; 760 IR camera = 2217 °F

## Appendix B

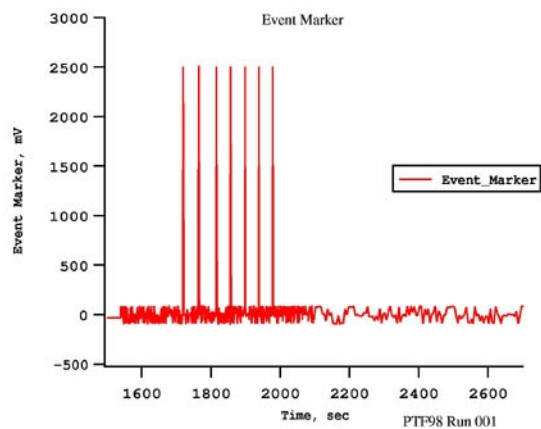
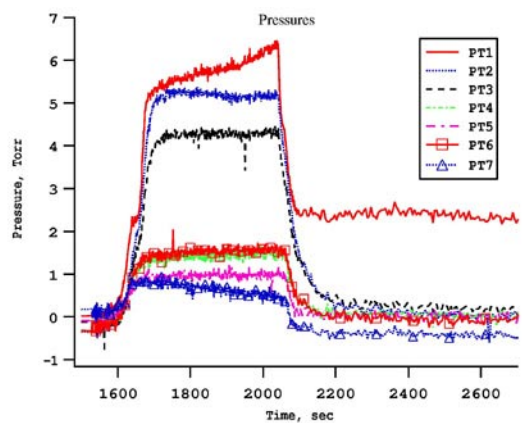
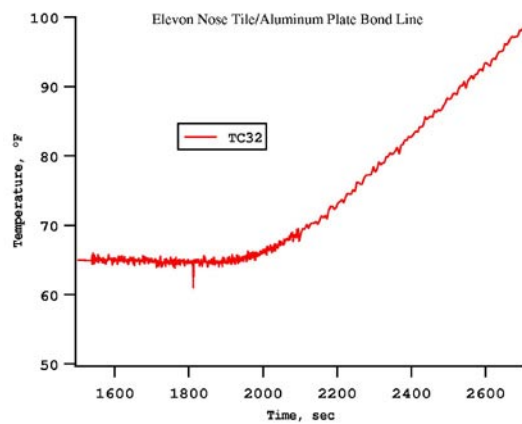
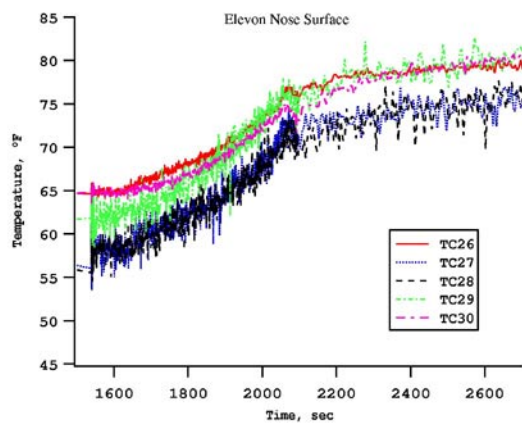
### Arc-Jet Test Data Plots



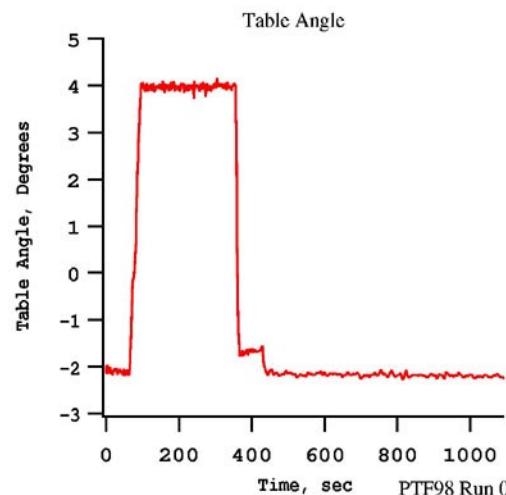
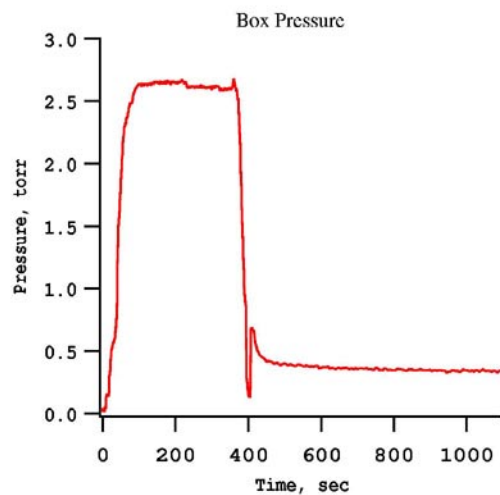
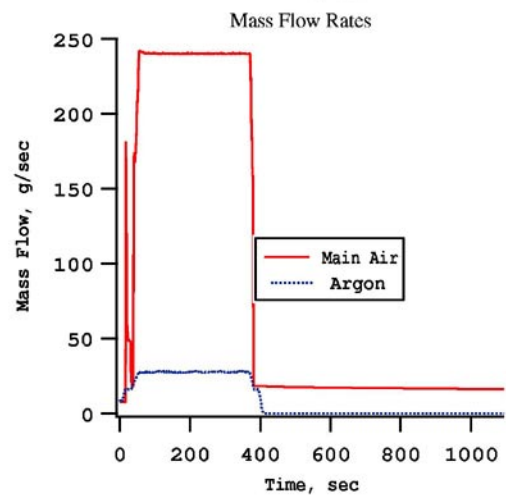
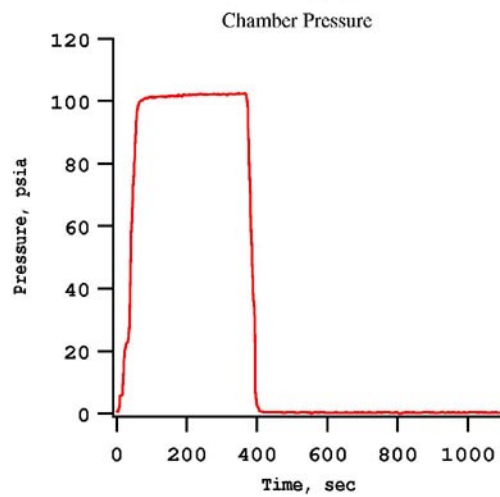
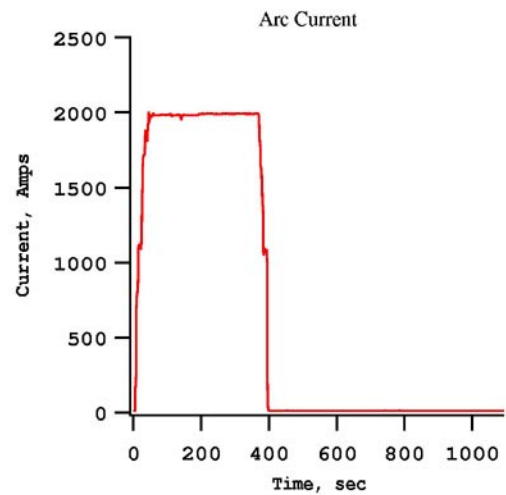
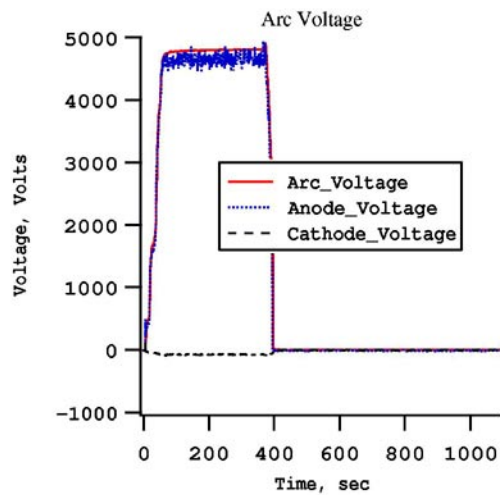
Run 98-01 — page 0



PTF98 Run 001

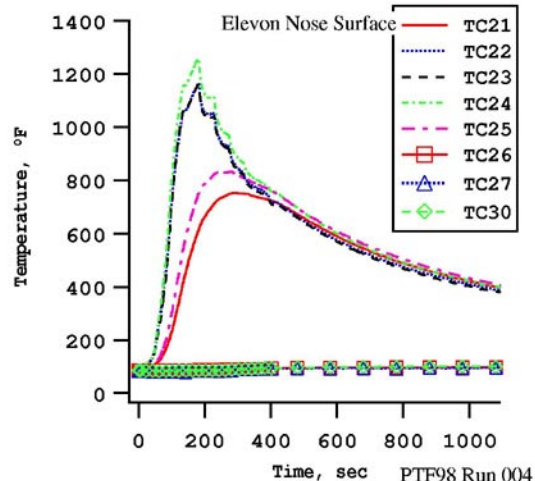
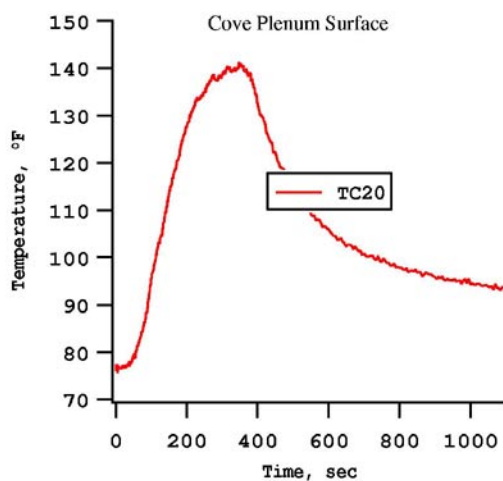
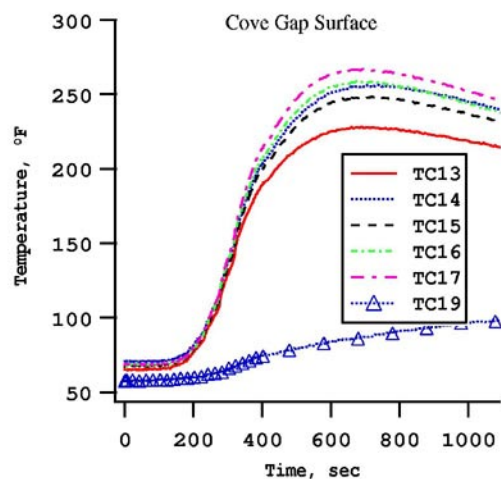
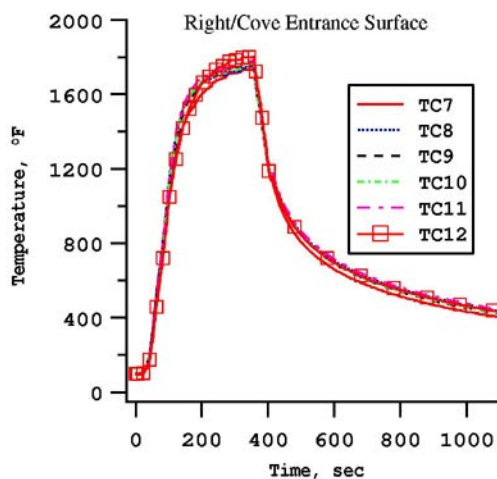
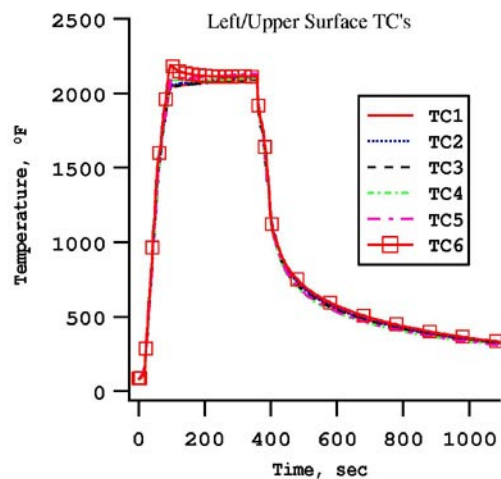
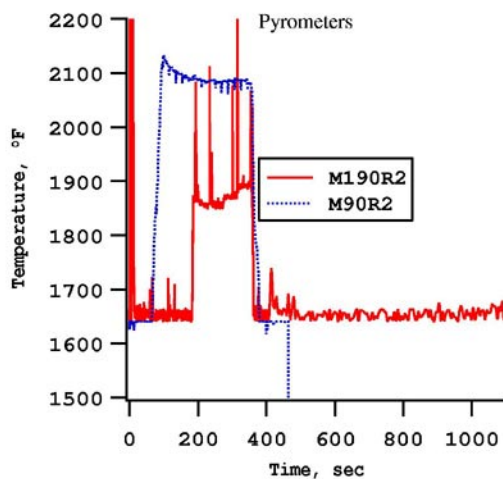


Run 98-01 — Page 2

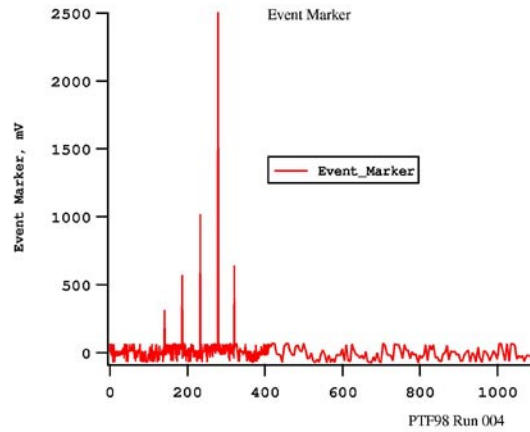
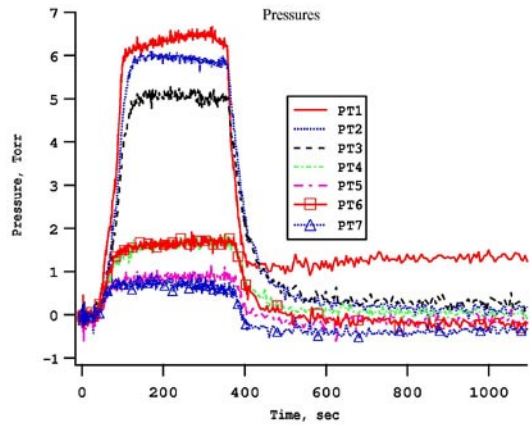
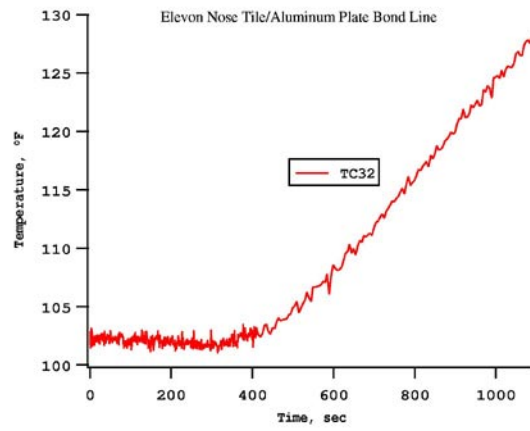
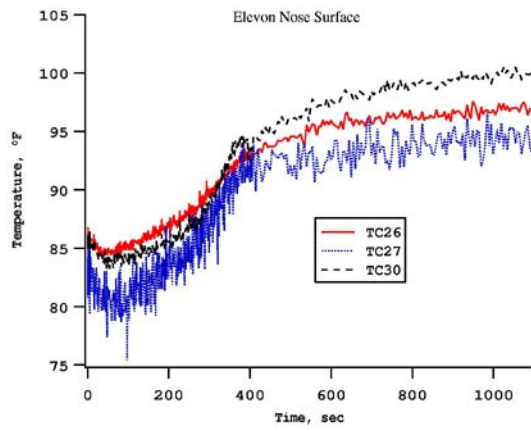


PTF98 Run 004

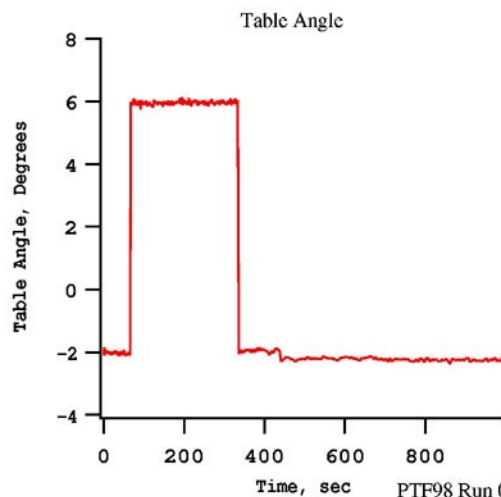
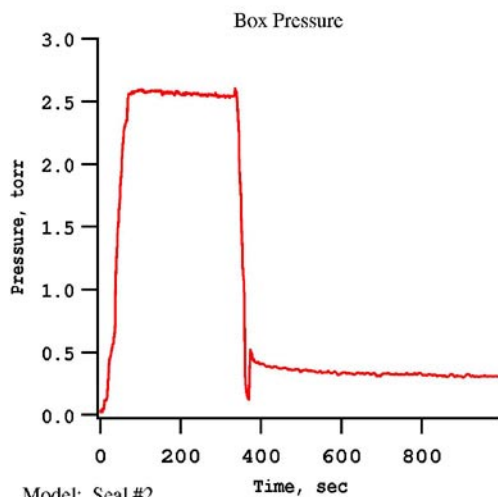
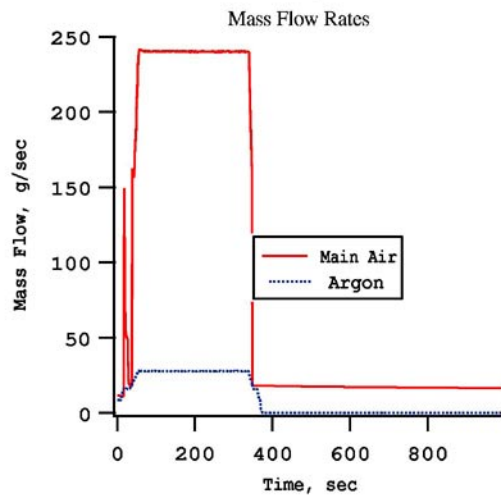
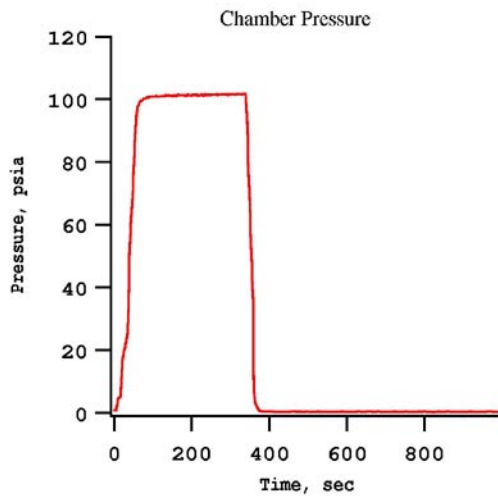
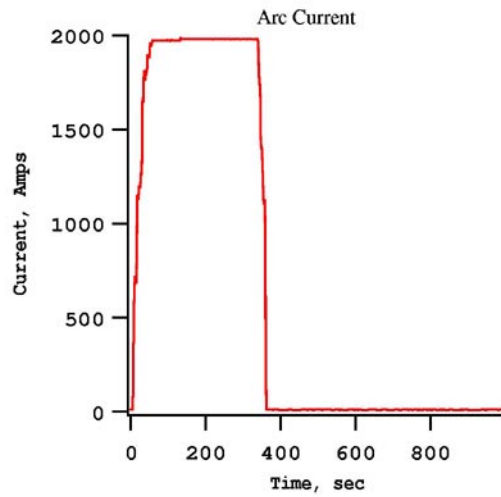
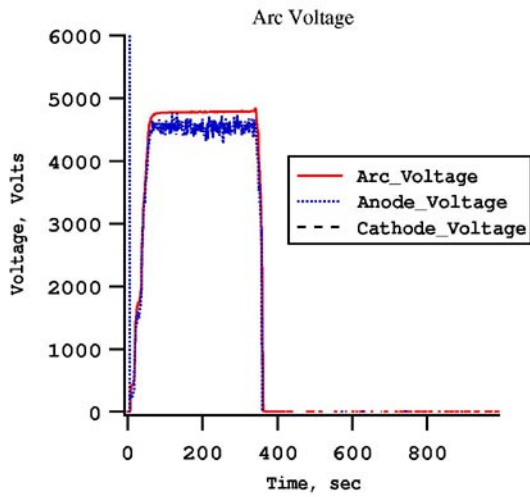




Run 98-04 — Page 1

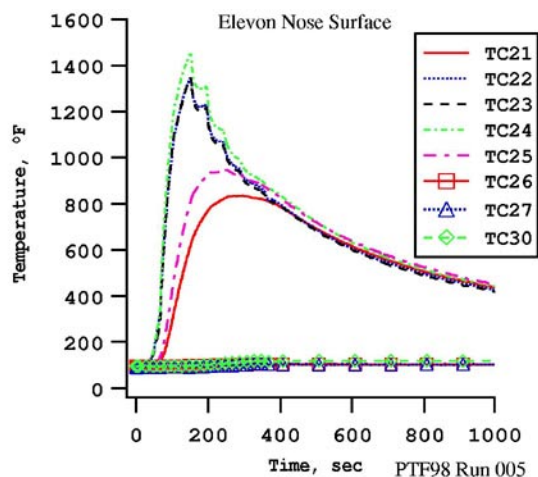
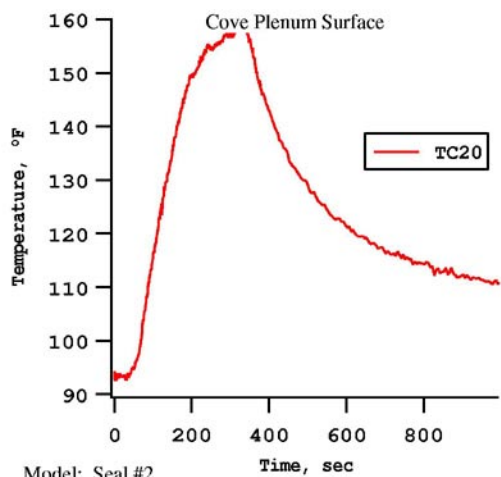
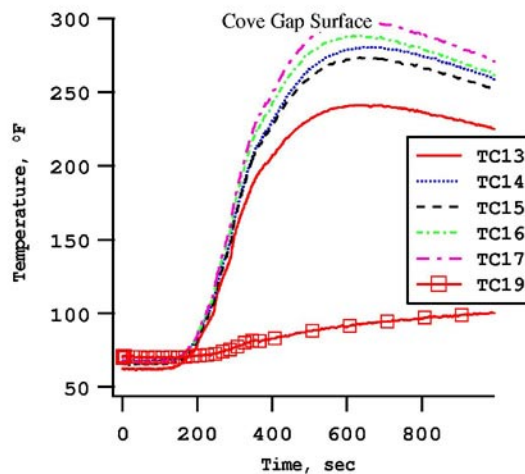
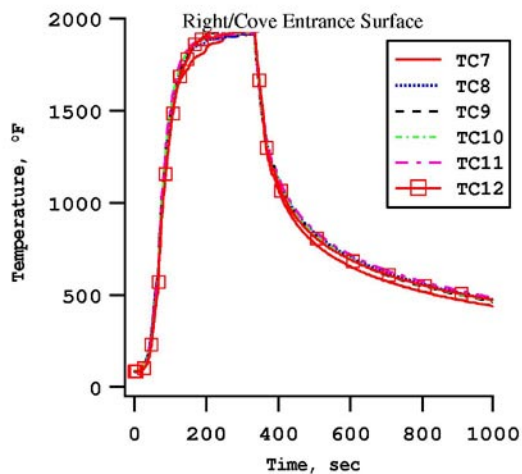
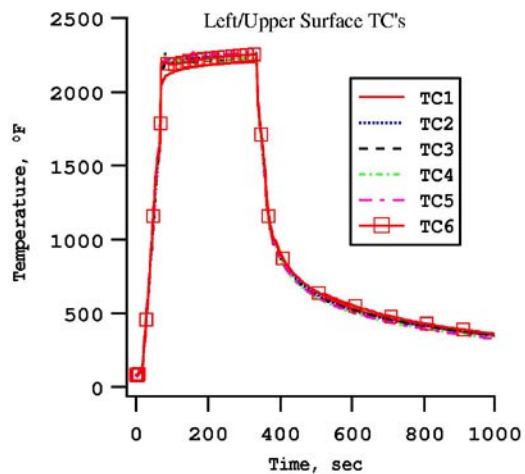
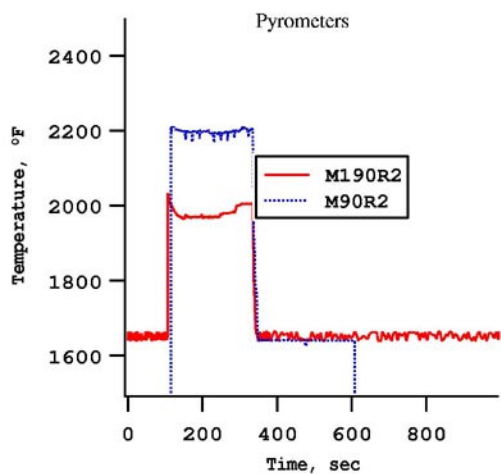


**Run 98-04 — Page 2**



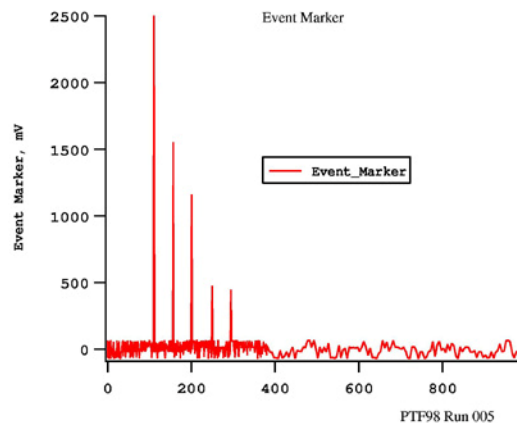
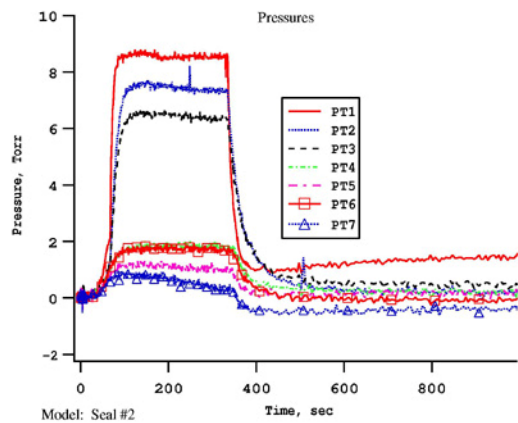
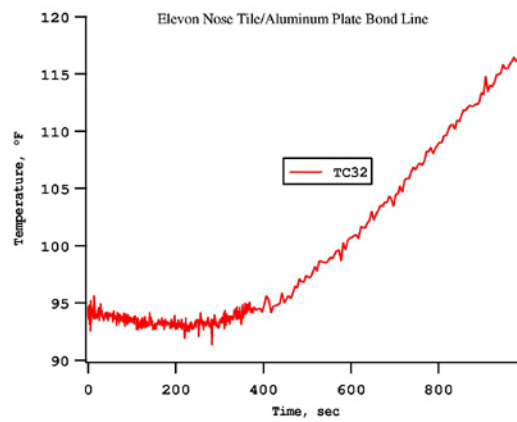
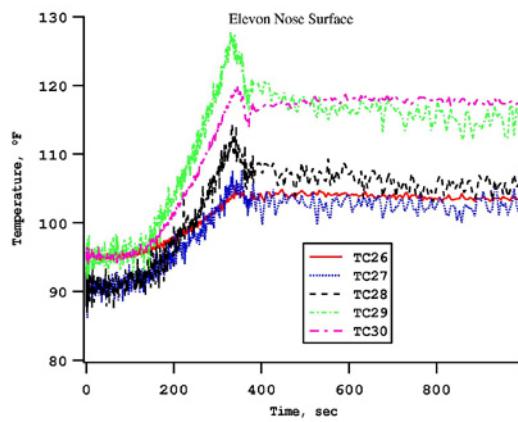
Model: Seal #2

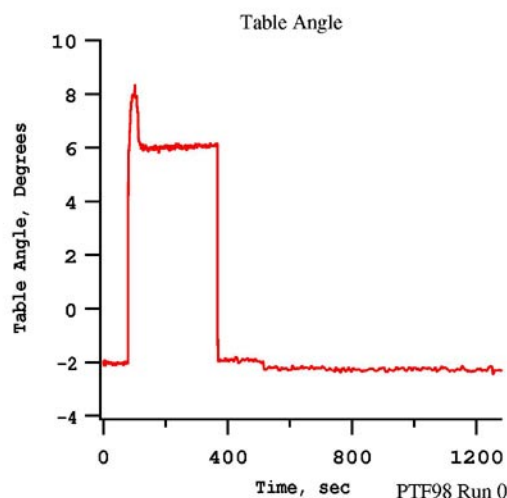
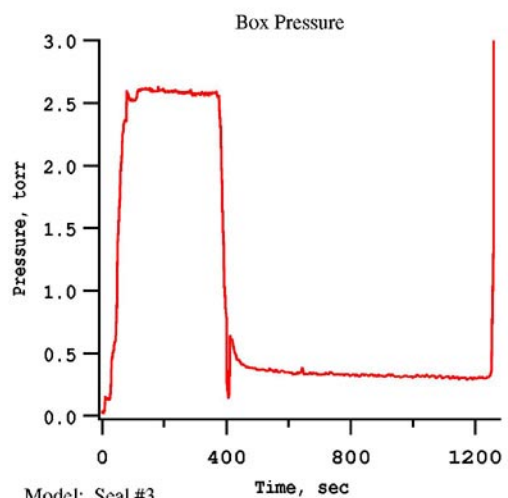
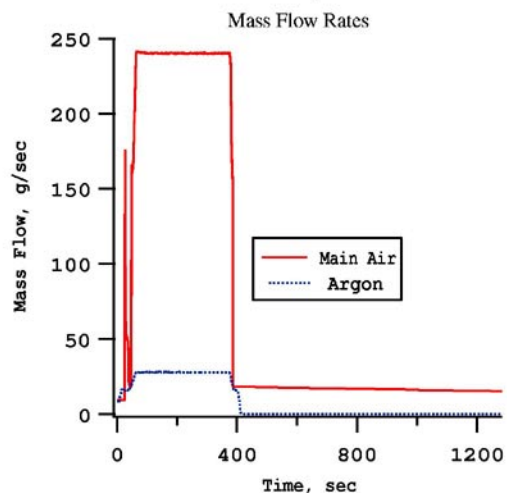
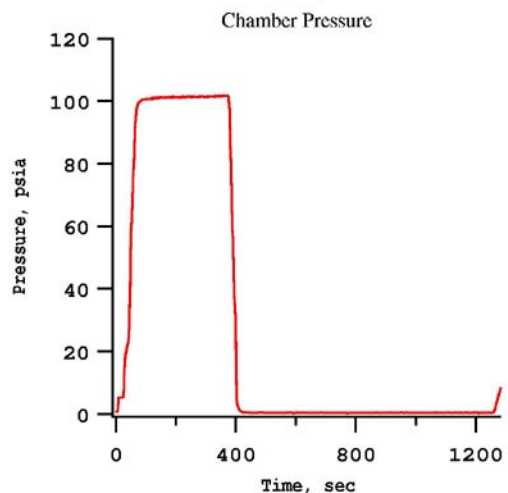
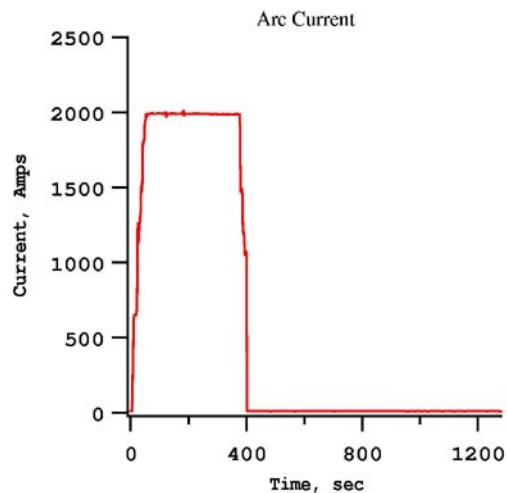
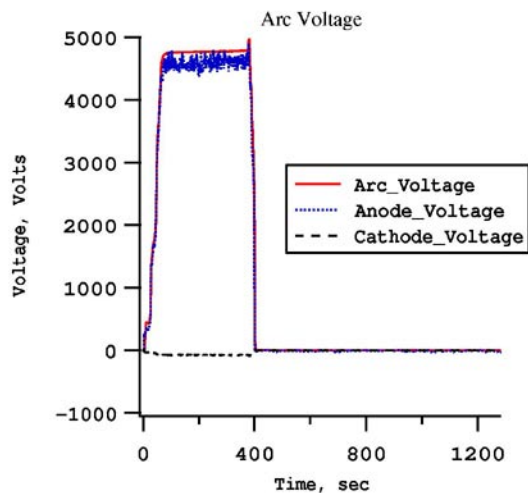
PTF98 Run 005



Model: Seal #2

PTF98 Run 005



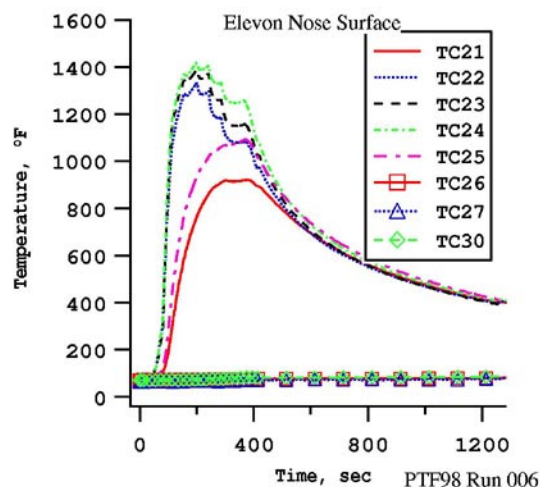
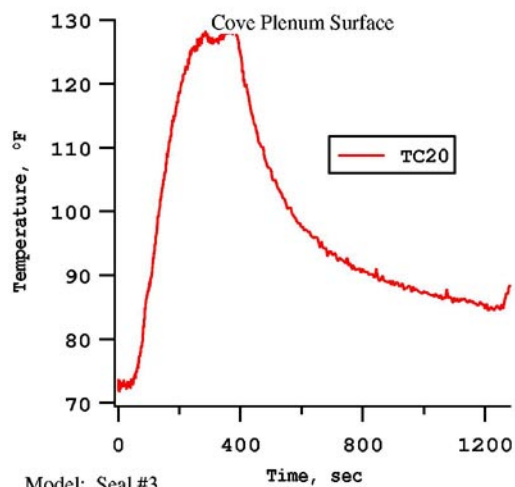
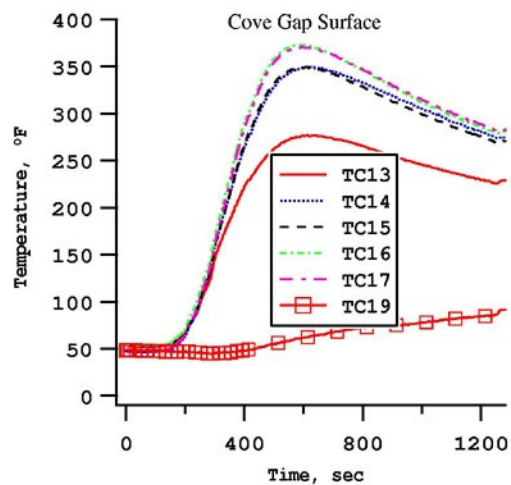
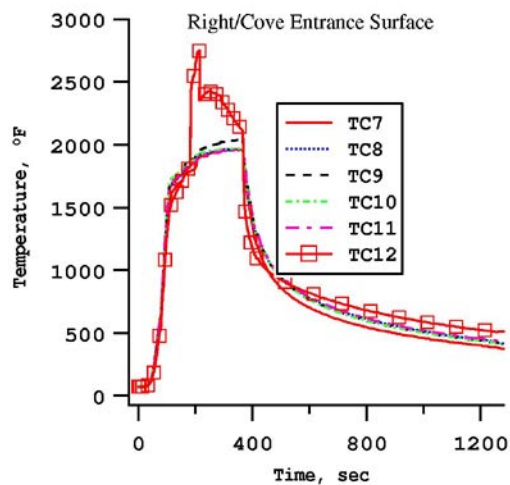
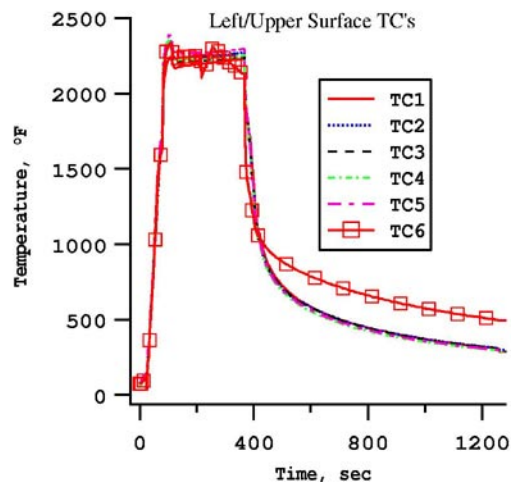
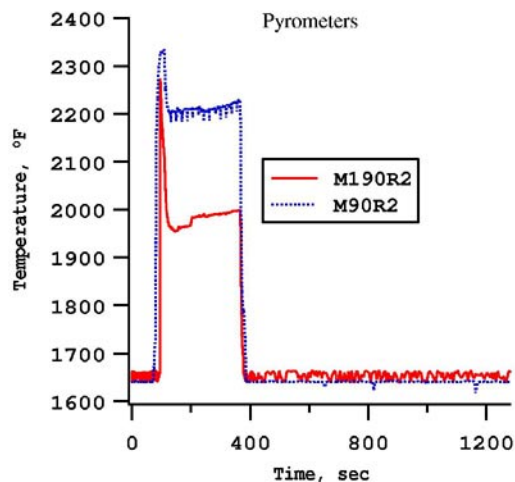


Model: Scal #3

PTF98 Run 006

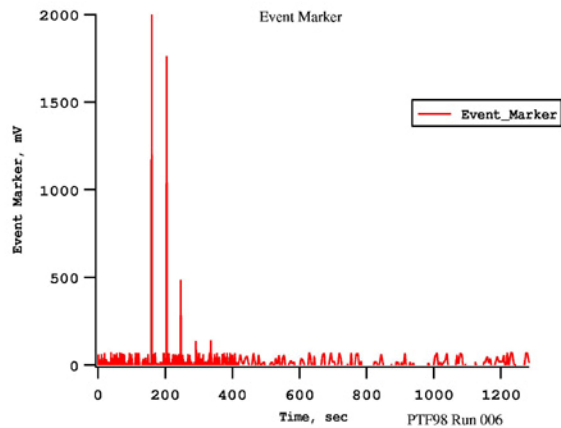
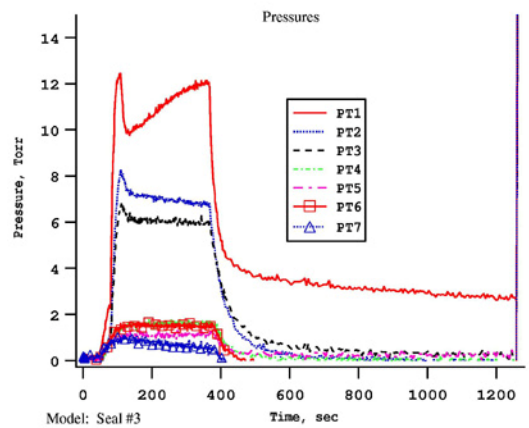
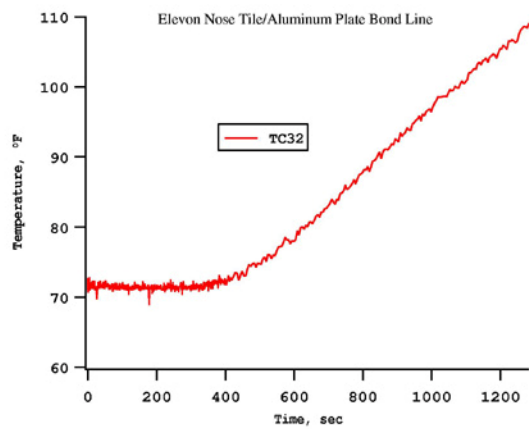
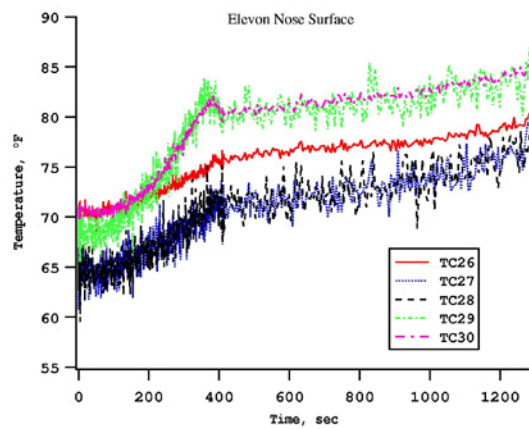
Run 98-06 — Page 0





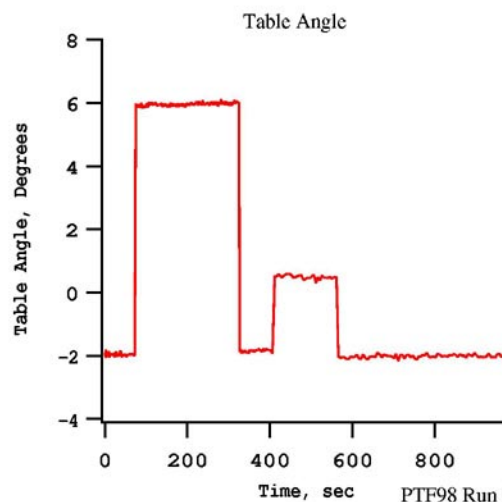
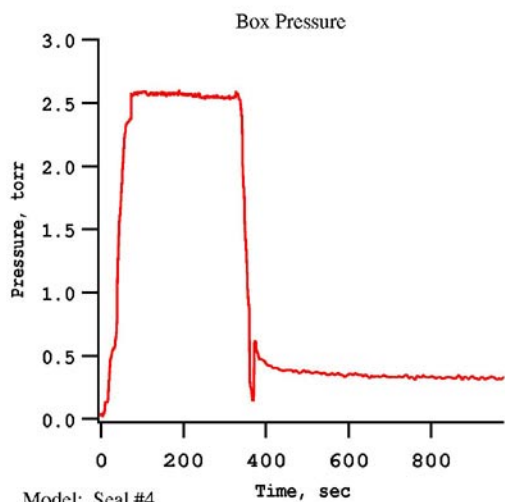
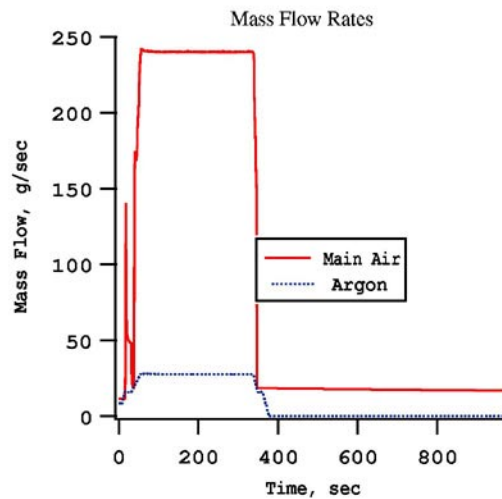
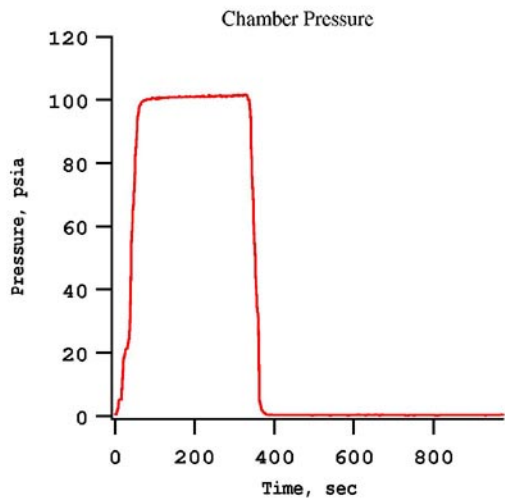
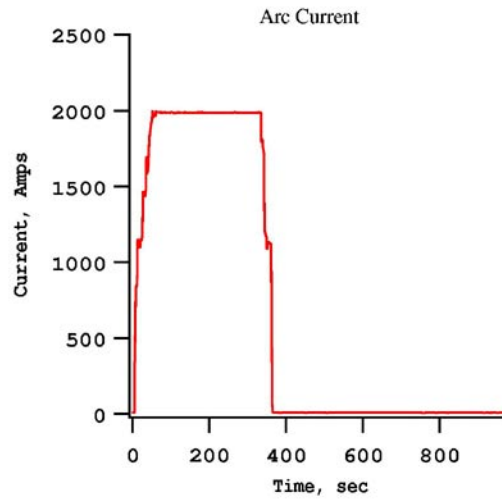
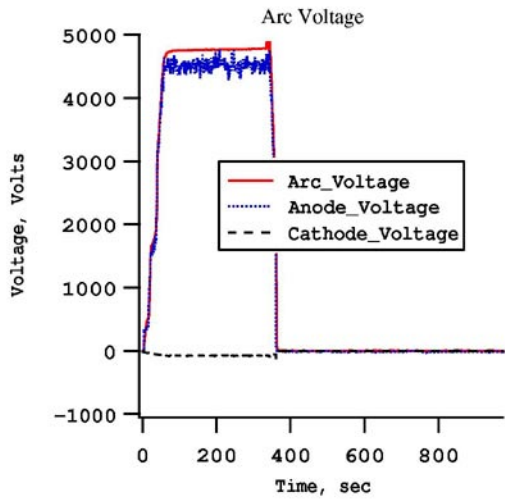
Model: Seal #3

PTF98 Run 006



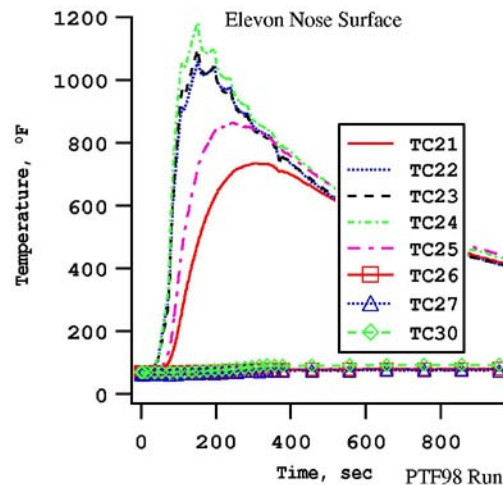
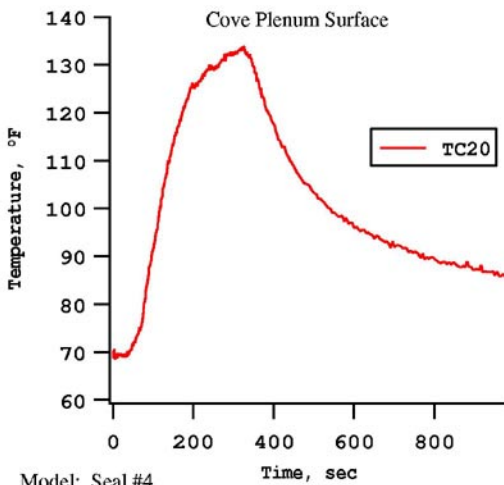
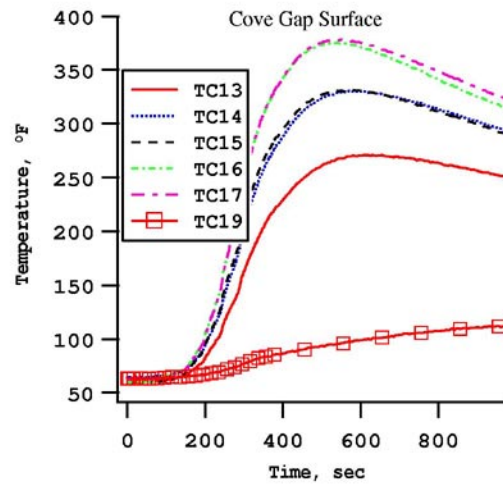
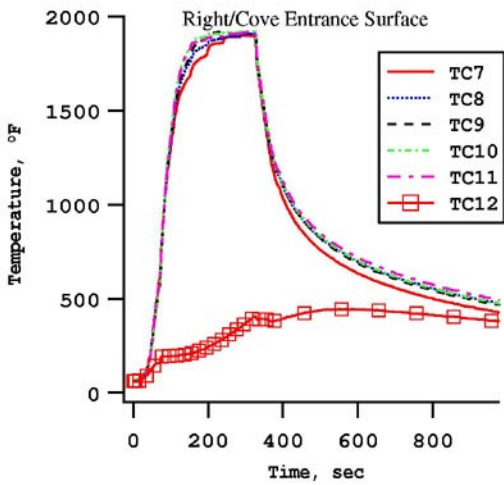
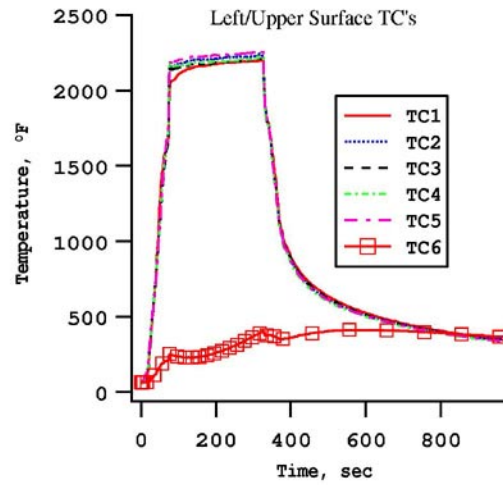
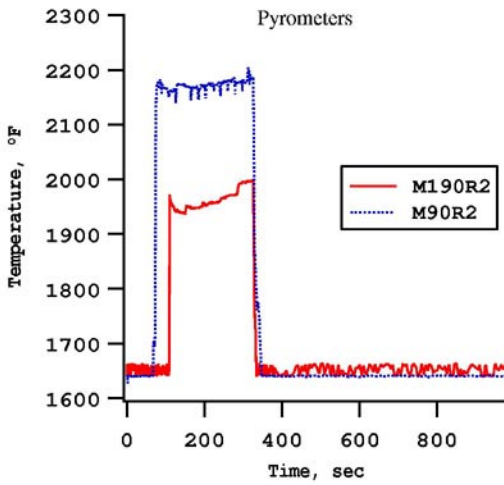
Run 98-06 — Page 2





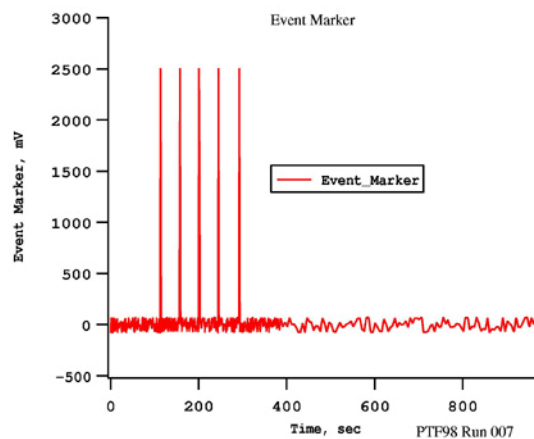
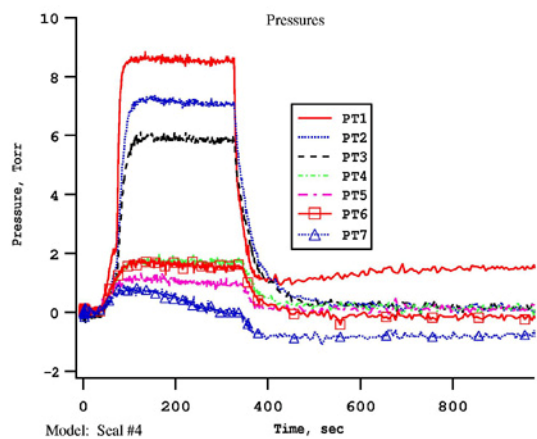
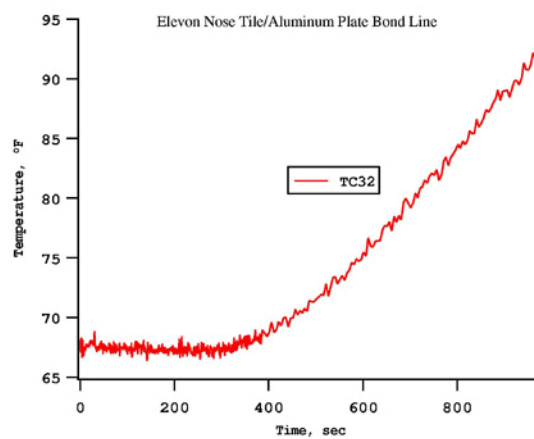
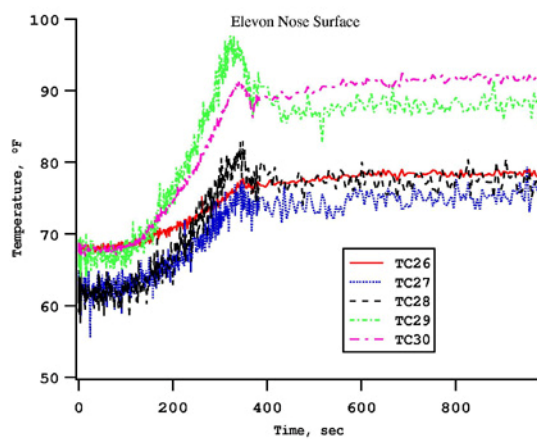
Model: Seal #4

PTF98 Run 007

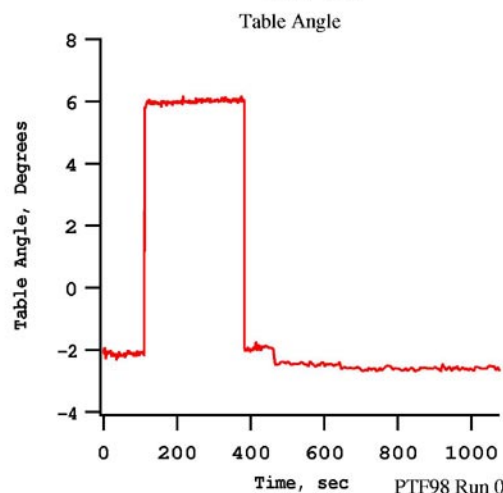
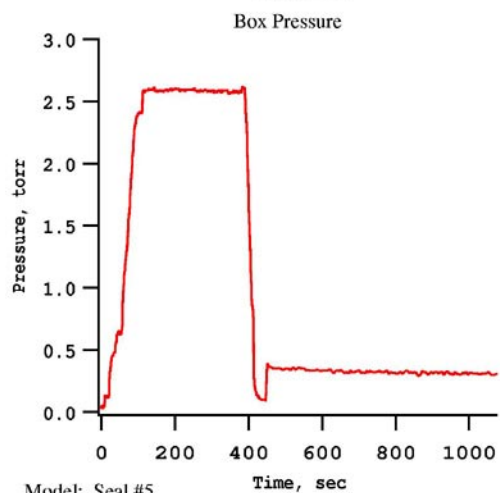
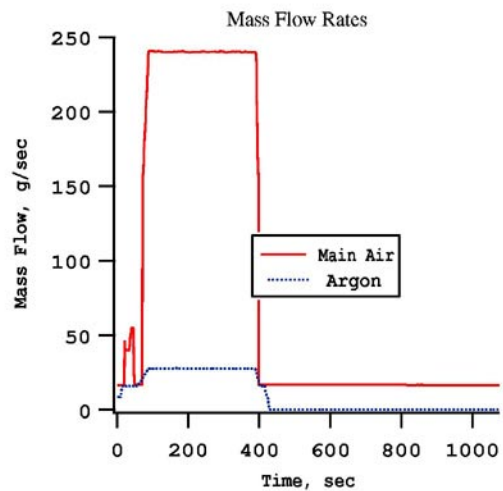
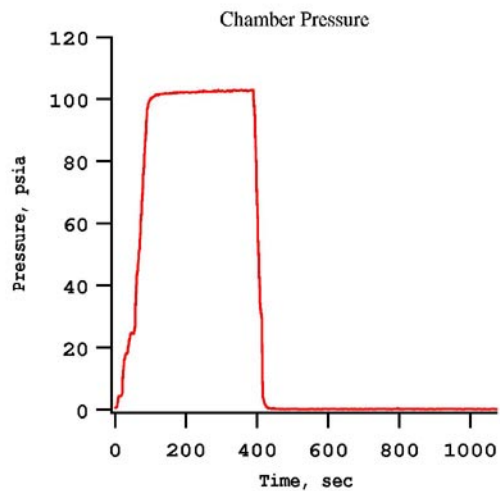
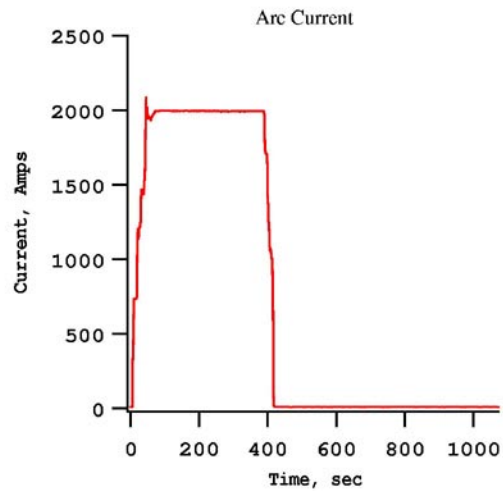
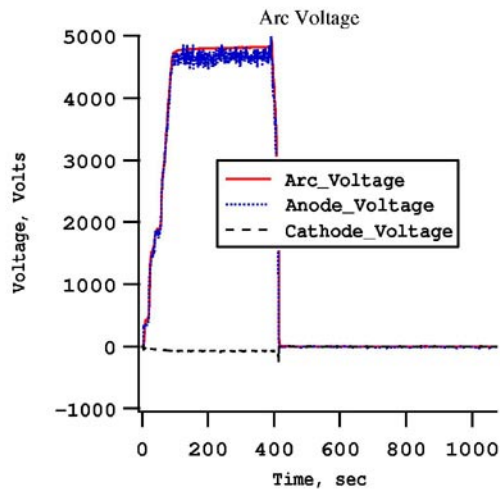


Model: Seal #4

PTF98 Run 007



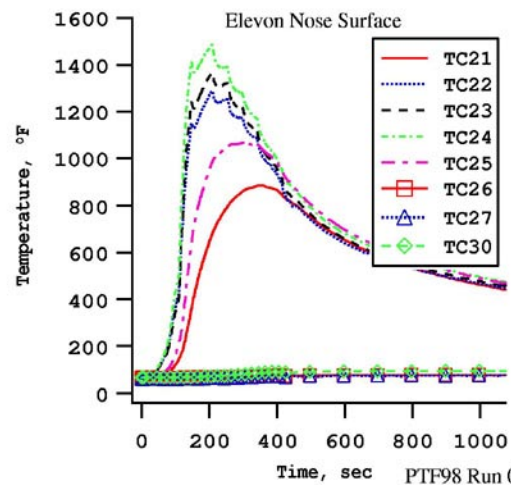
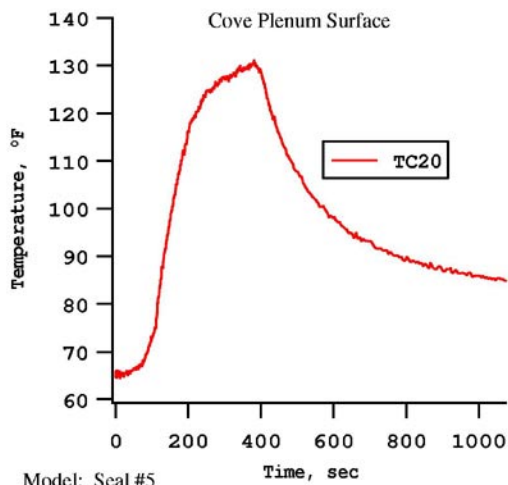
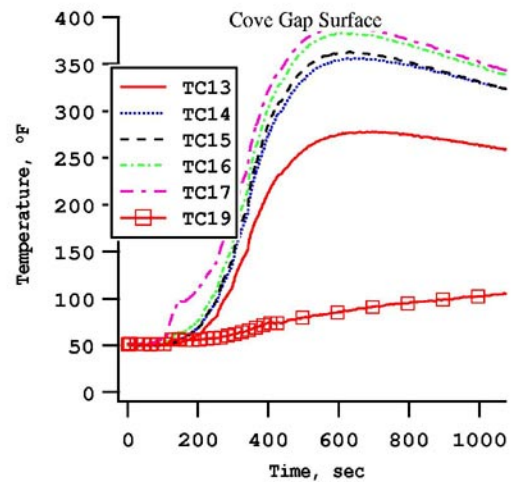
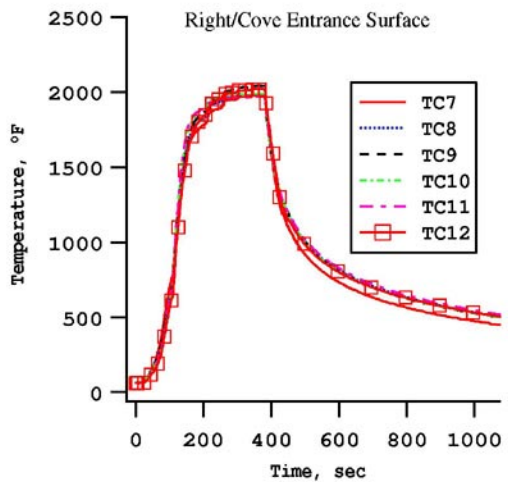
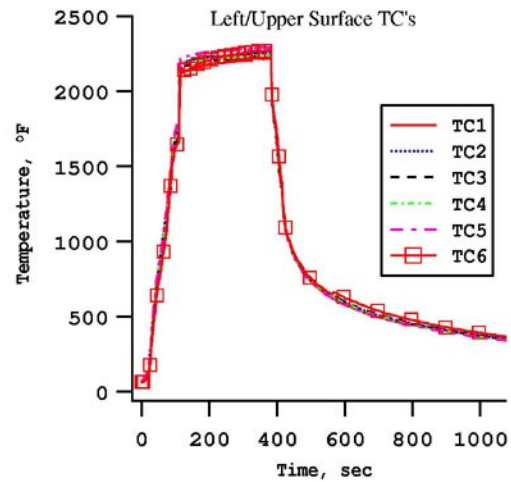
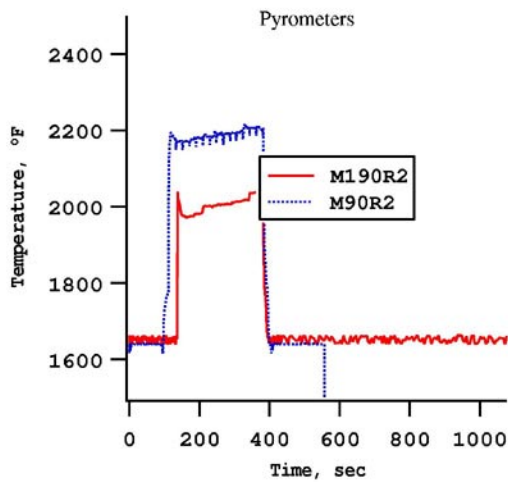
Run 98-07 — Page 2



Model: Seal #5

PTF98 Run 008

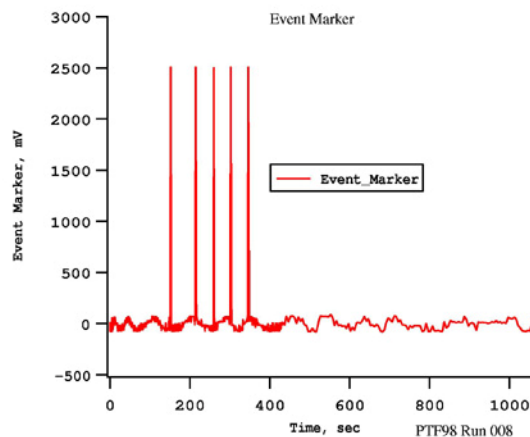
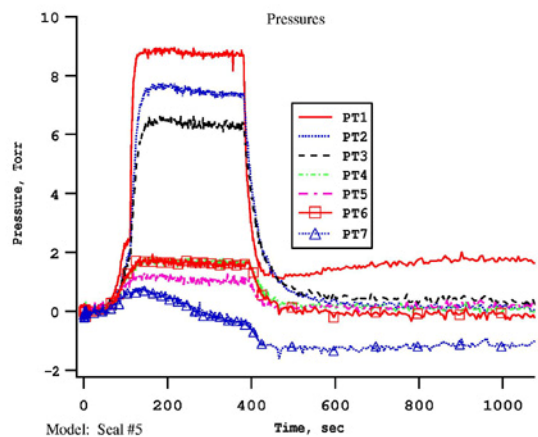
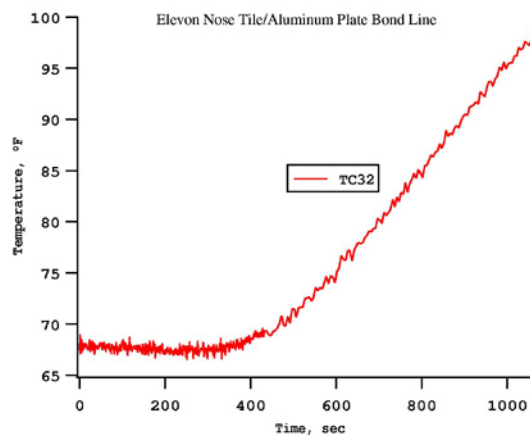
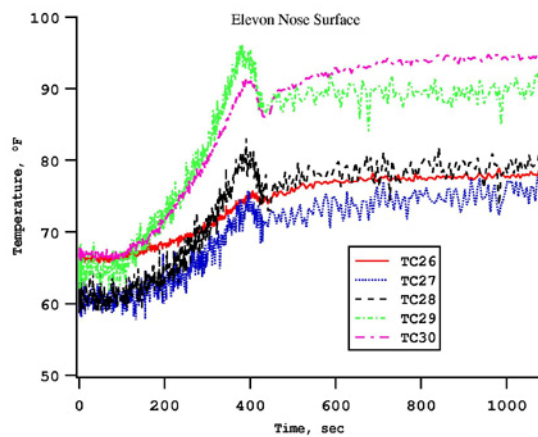
Run 98-08 — Page 0



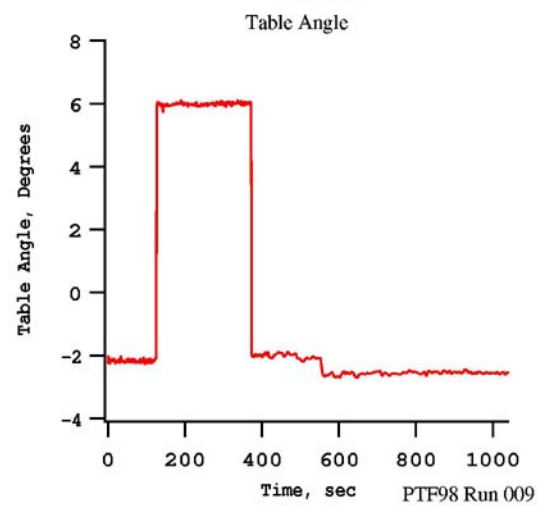
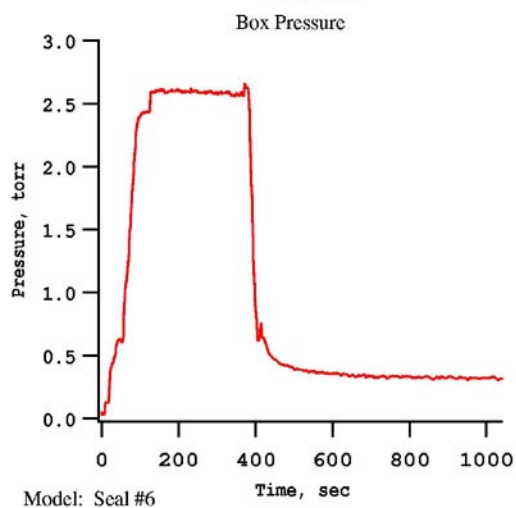
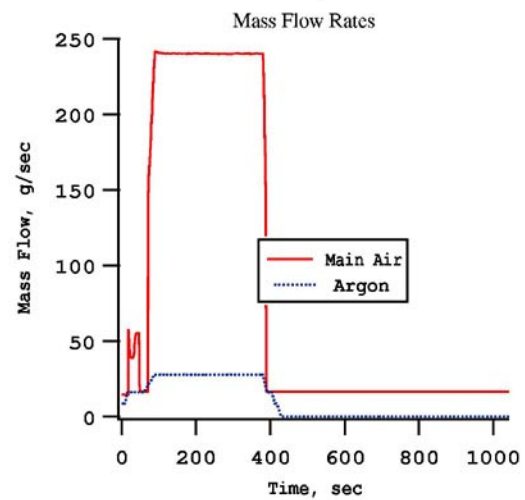
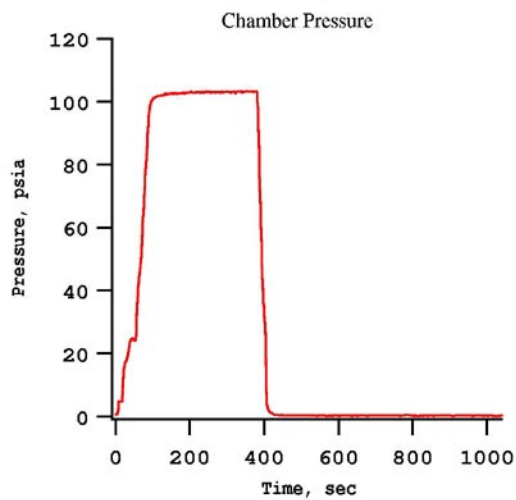
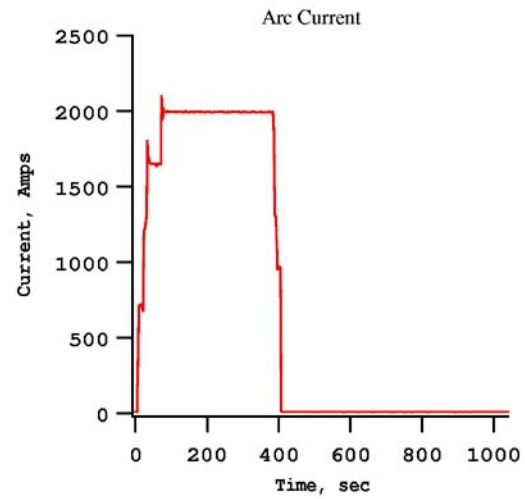
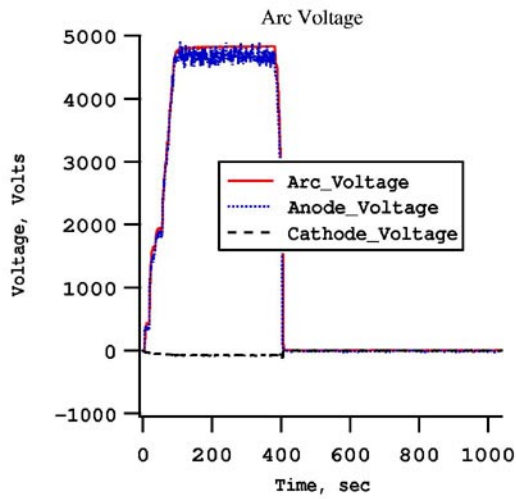
Model: Scal #5

PTF98 Run 008

Run 98-08 — Page 1



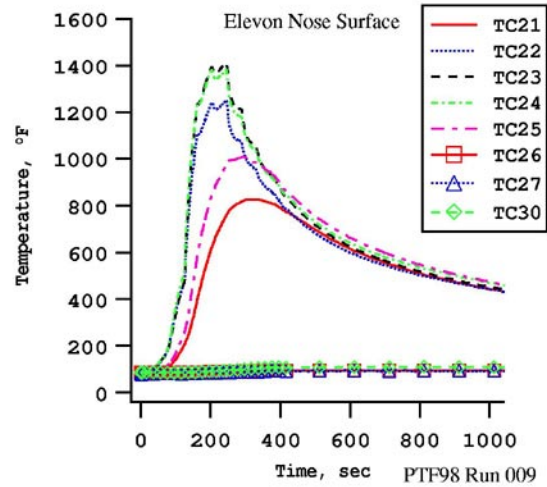
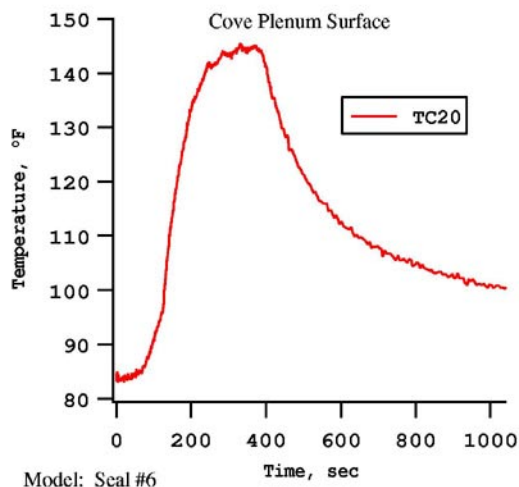
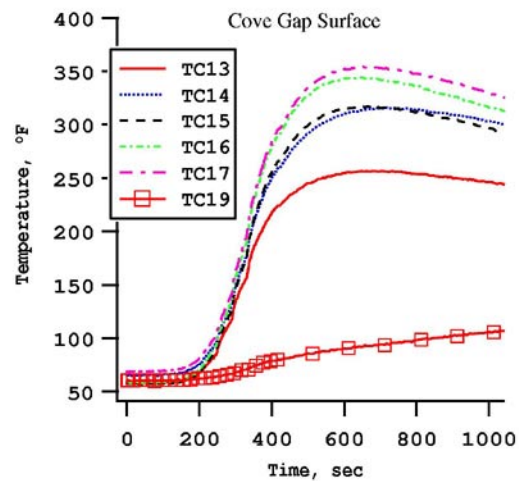
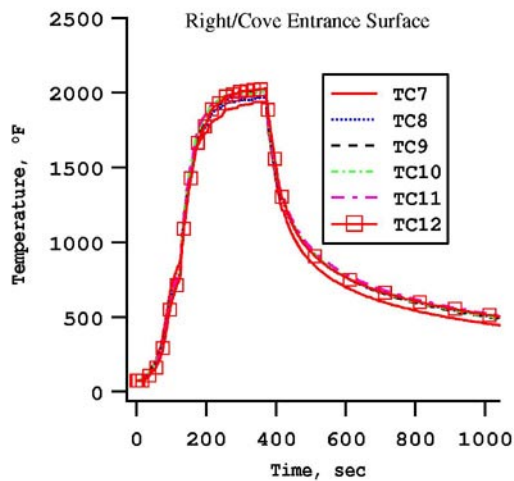
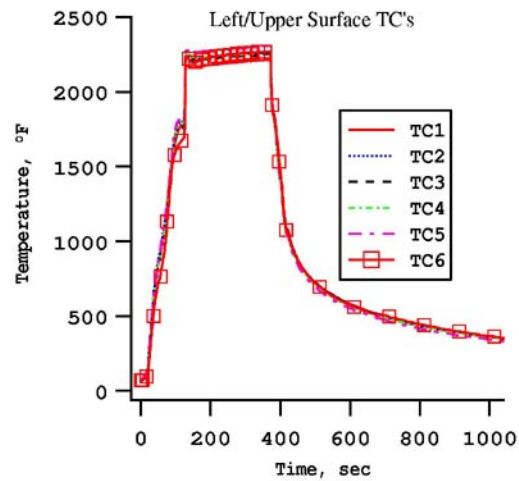
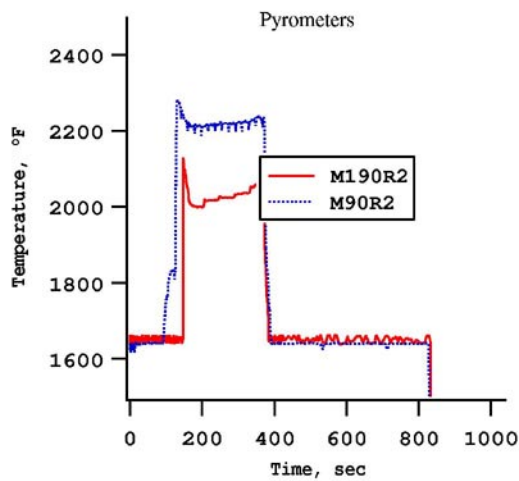




Model: Seal #6

PTF98 Run 009

Run 98-09 — Page 0

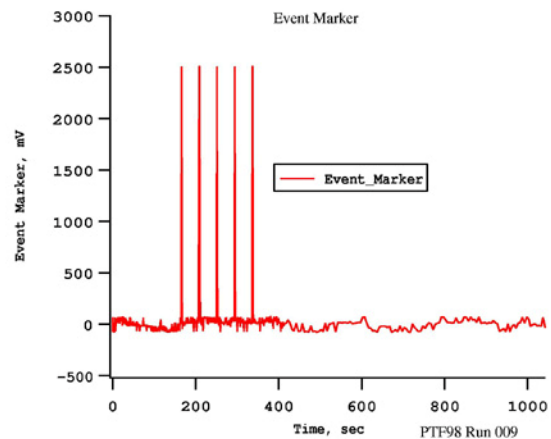
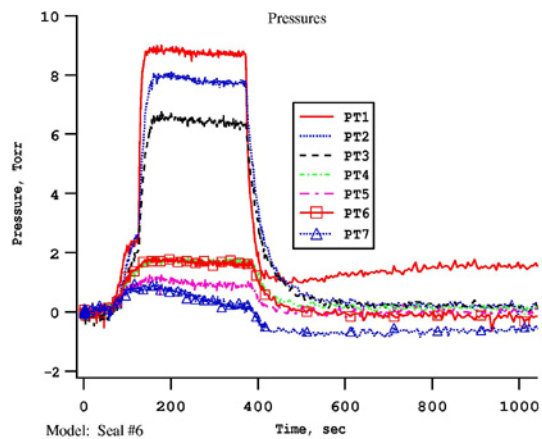
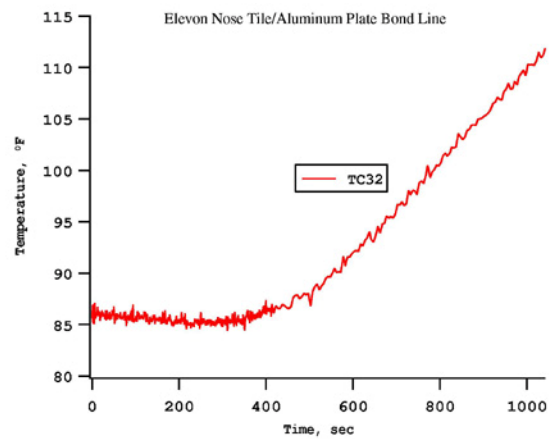
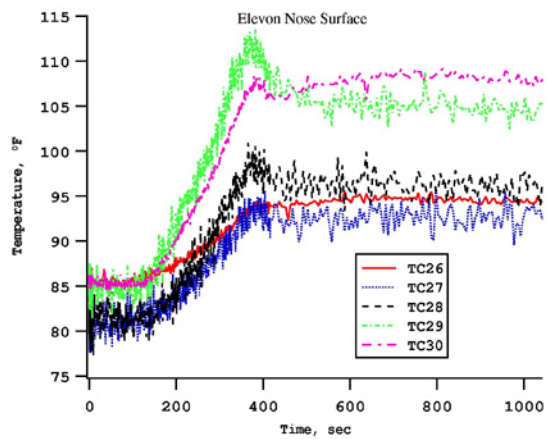


Model: Scal #6

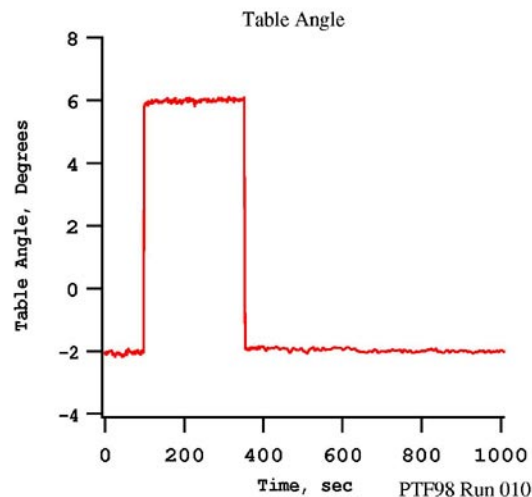
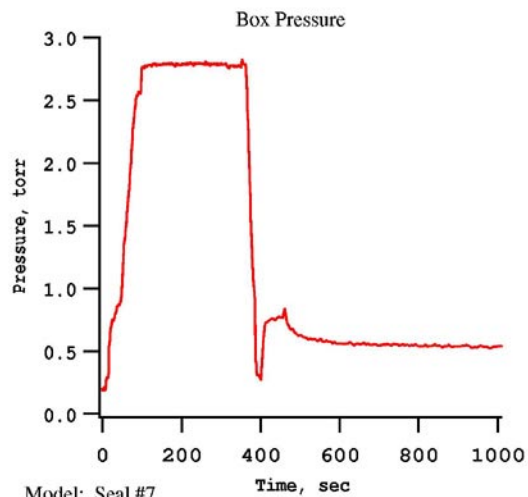
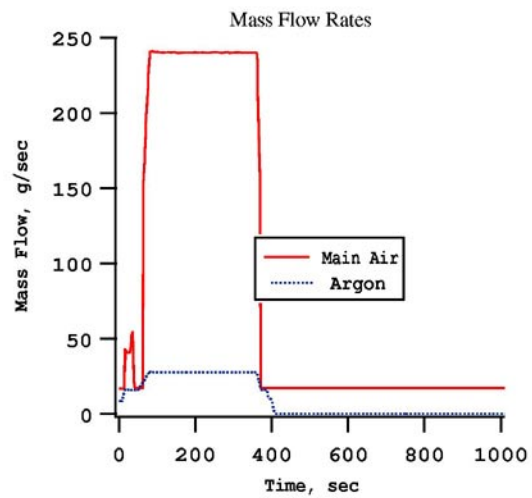
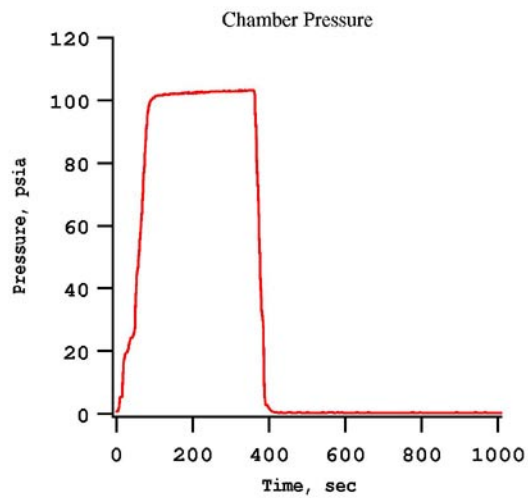
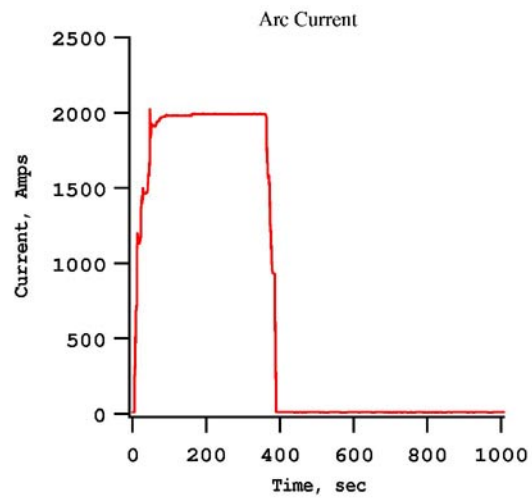
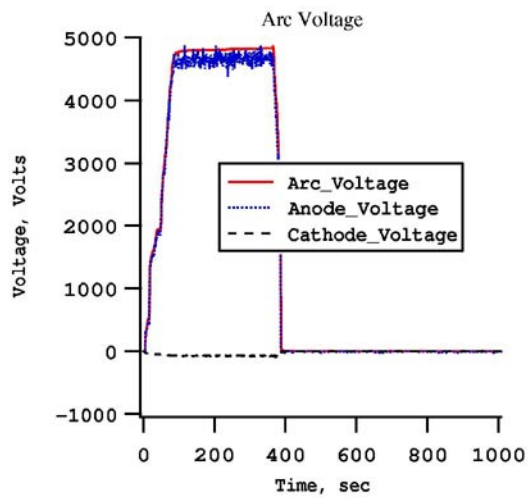
PTF98 Run 009

**Run 98-09 — page 1**





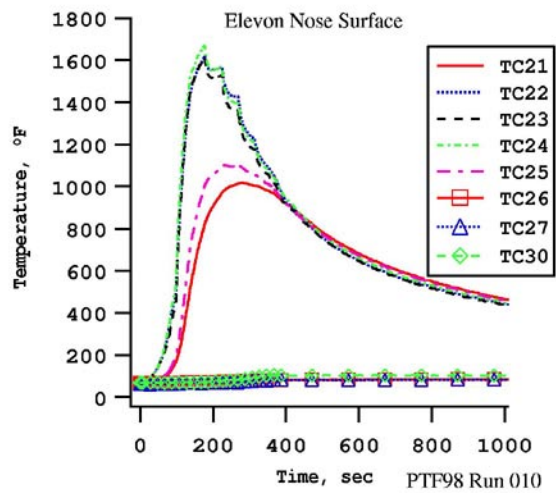
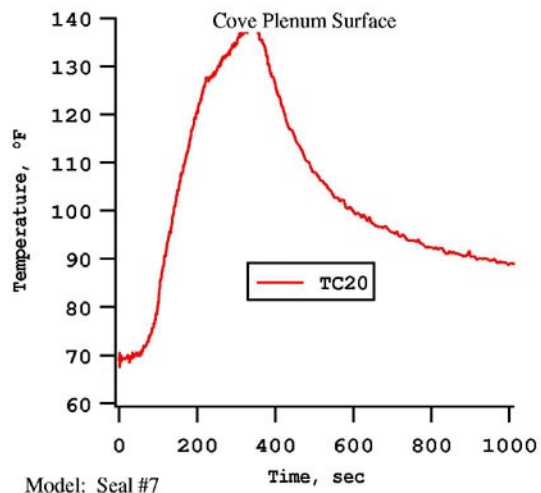
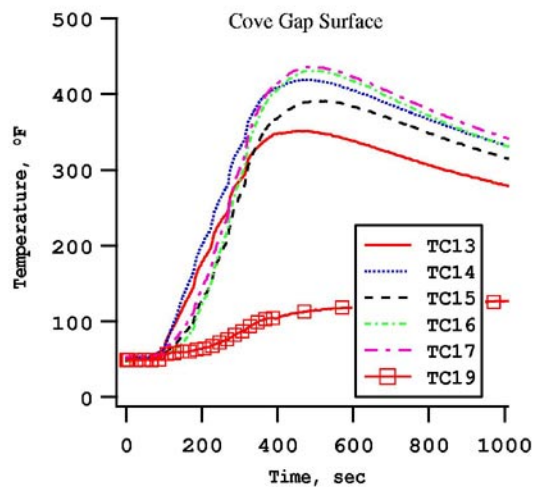
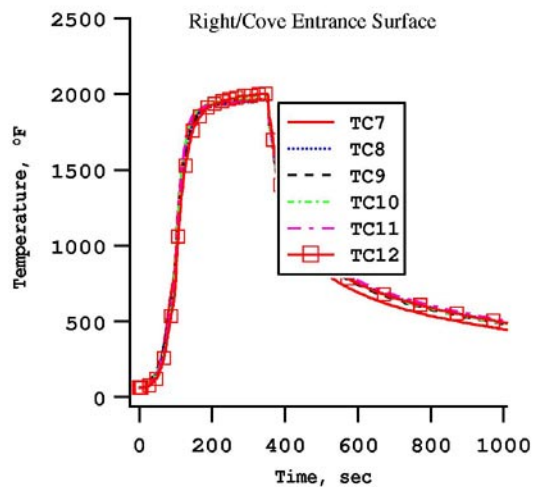
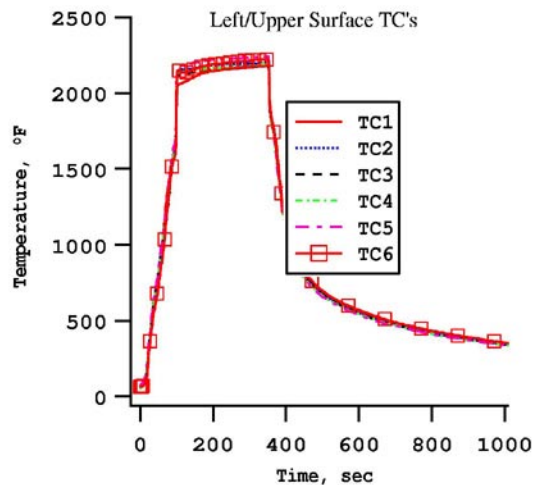
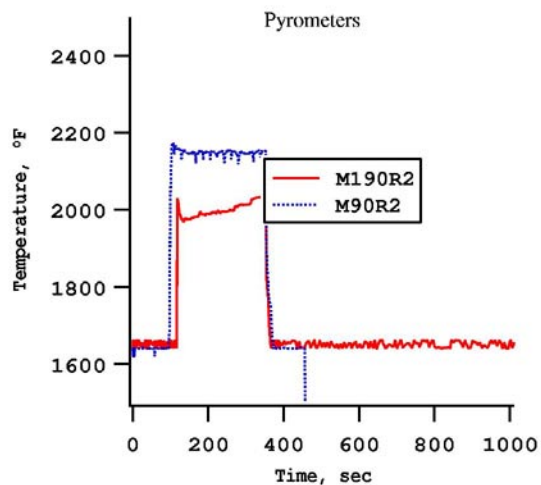
Run 98-09 — Page 2



Model: Seal #7

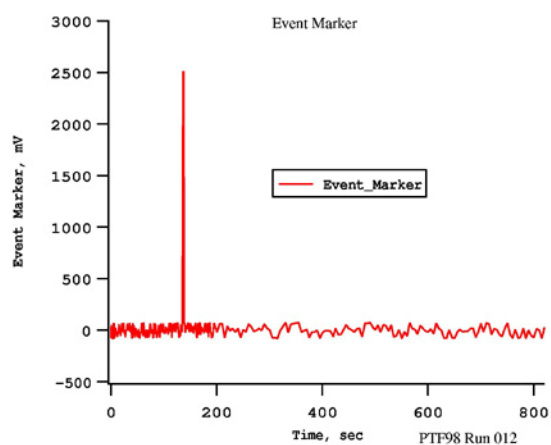
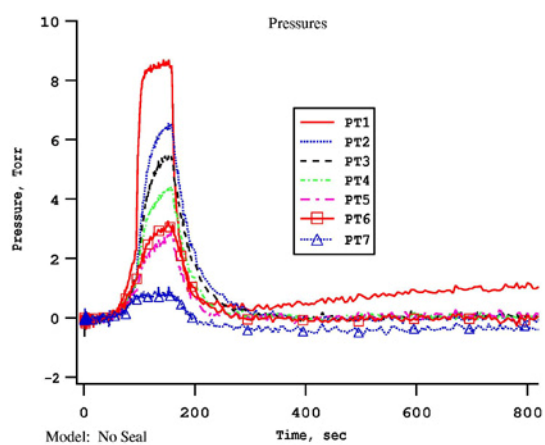
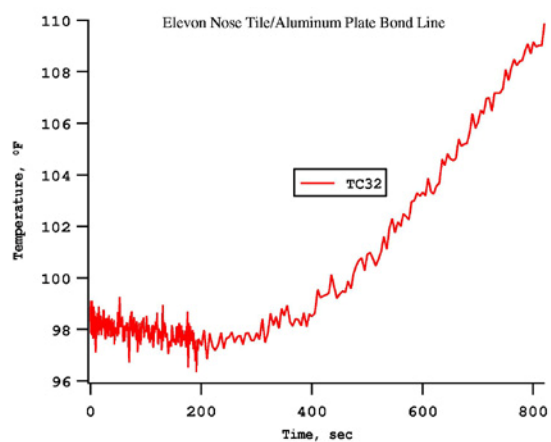
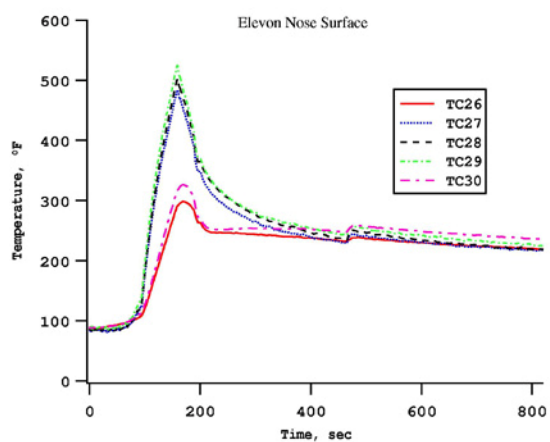
PTF98 Run 010

Run 98-10 —Page 0

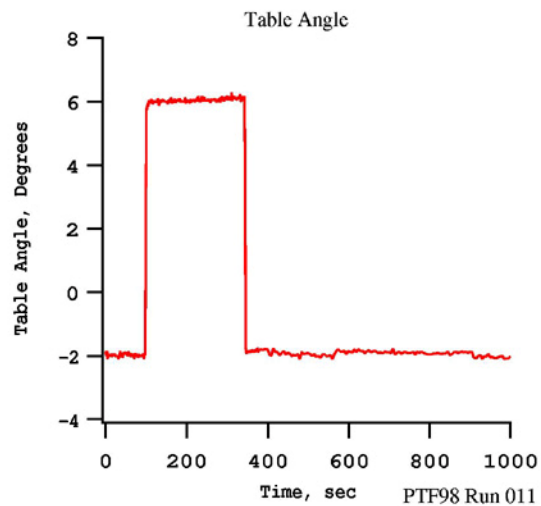
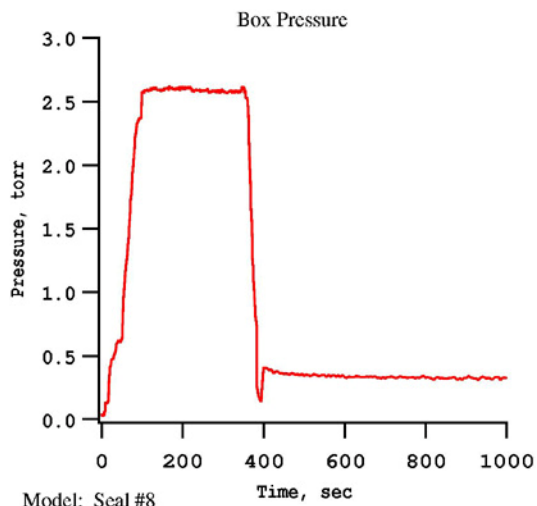
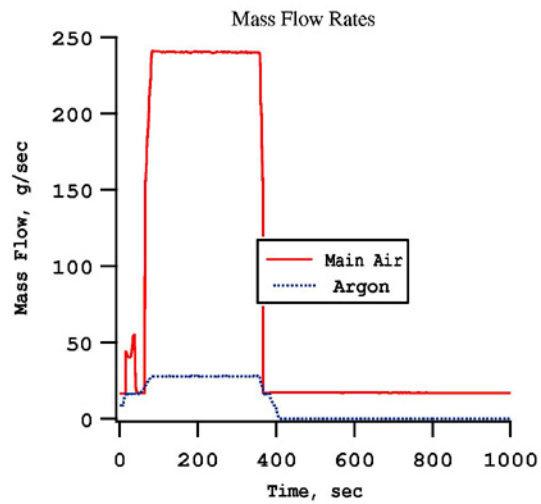
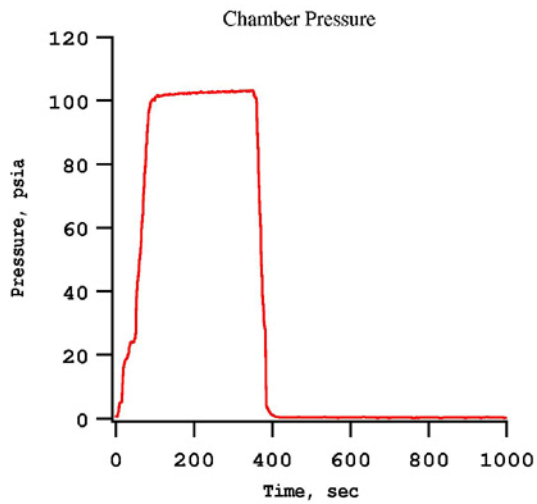
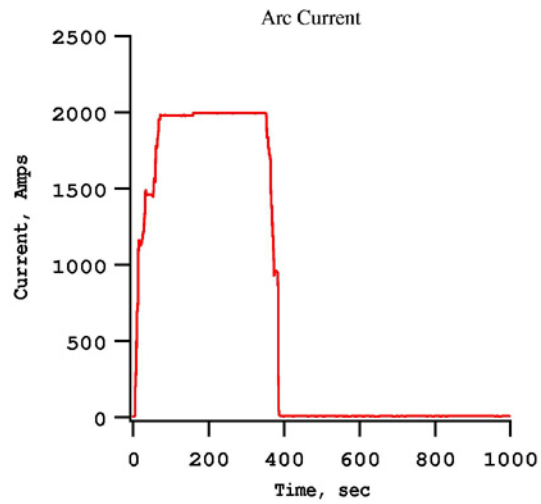
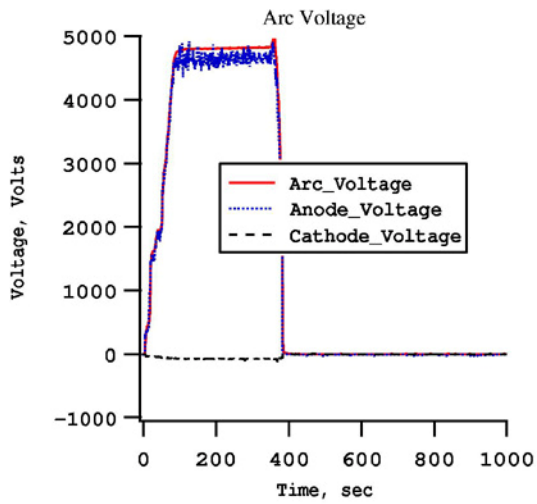


Model: Seal #7

PTF98 Run 010



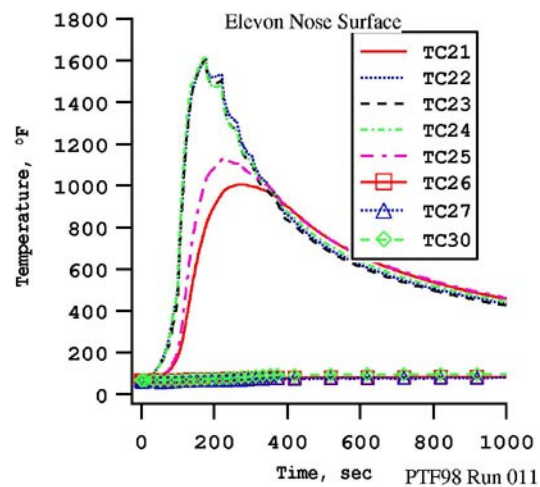
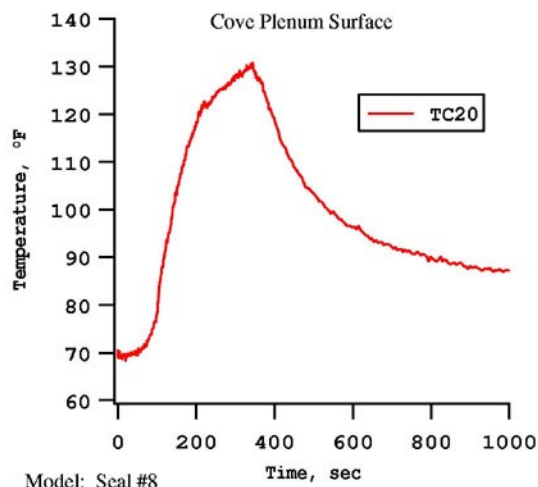
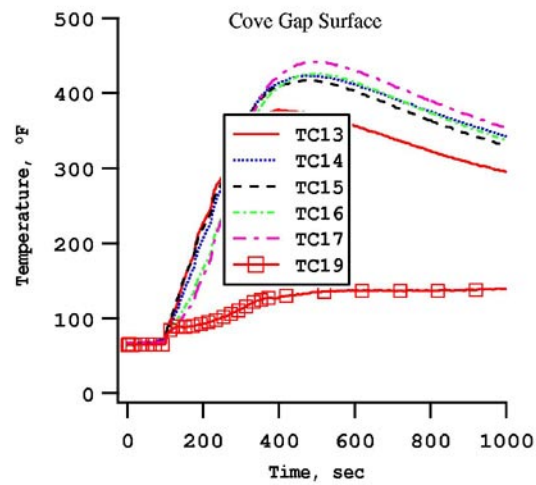
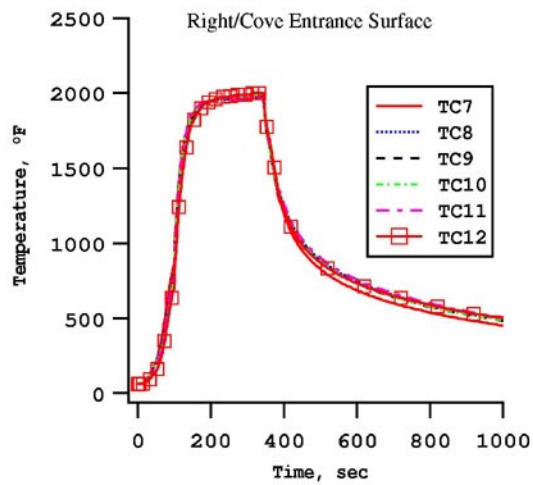
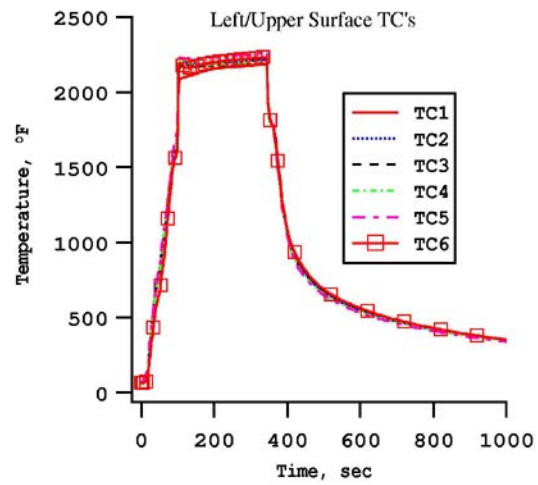
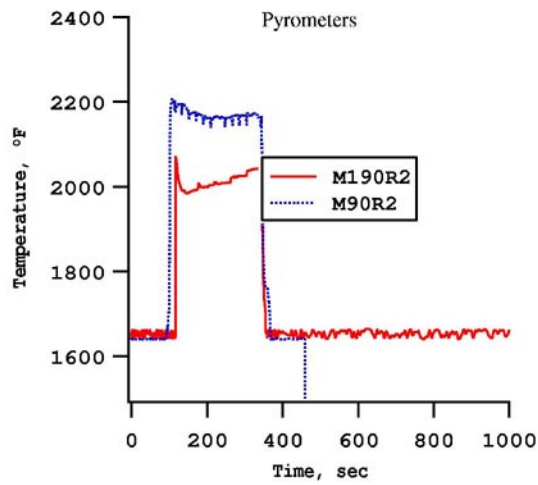
Run 98-10 — Page 2



Model: Seal #8

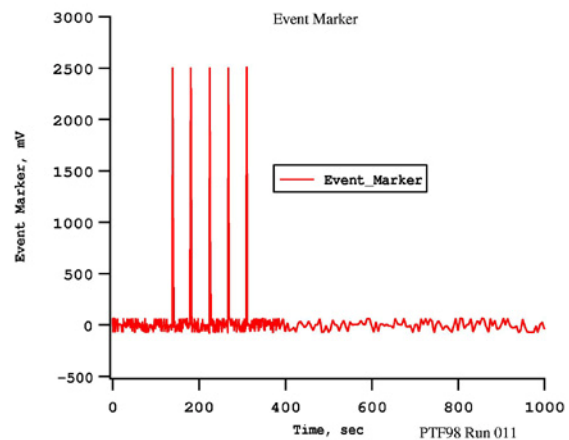
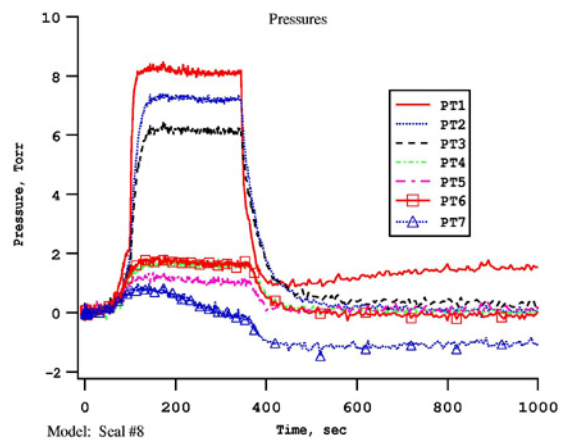
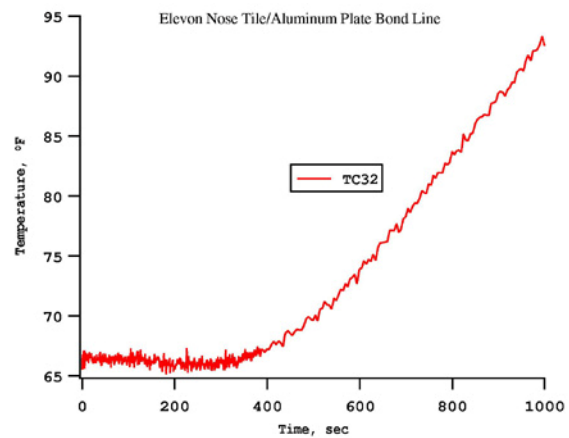
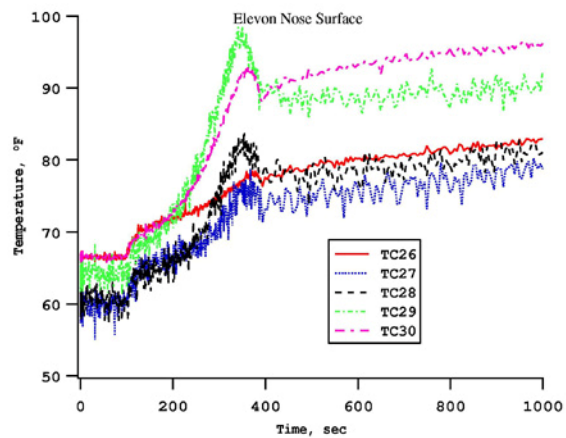
PTF98 Run 011

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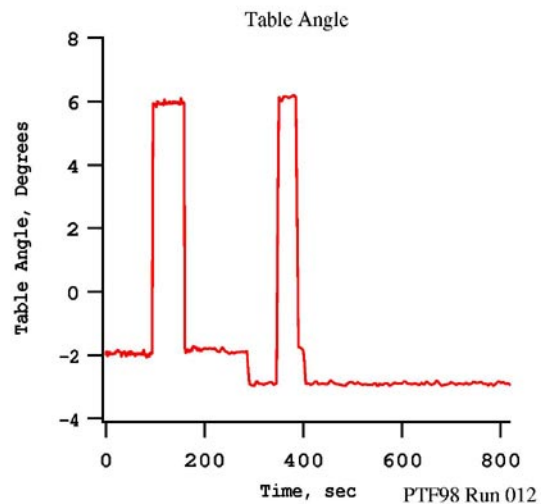
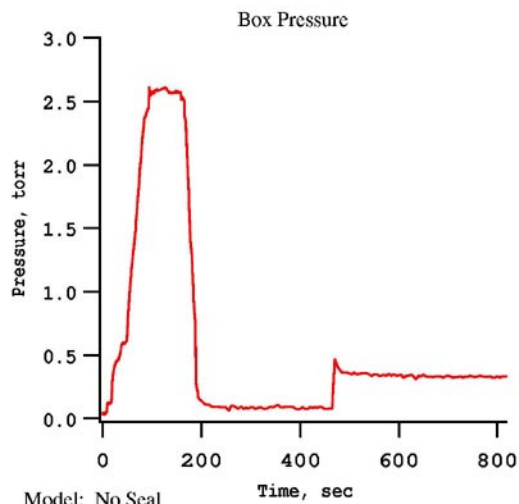
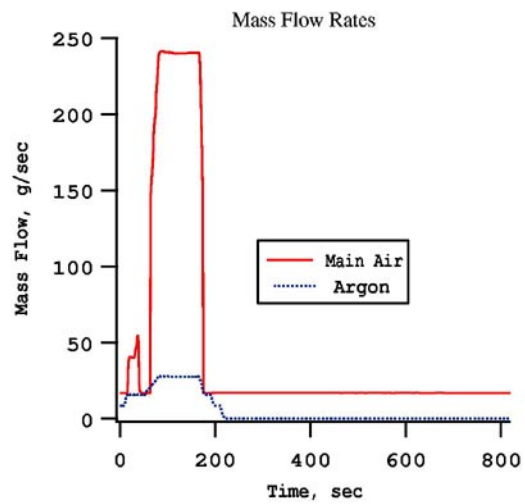
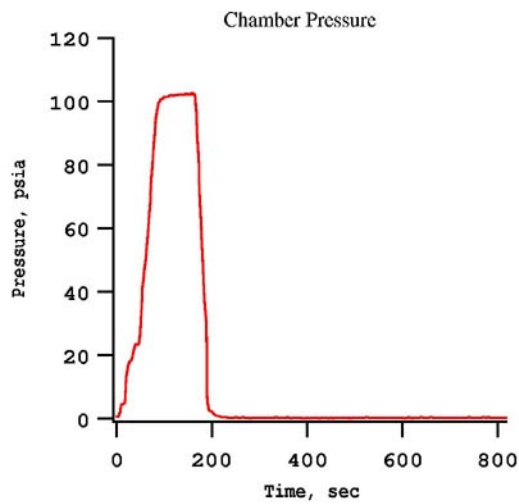
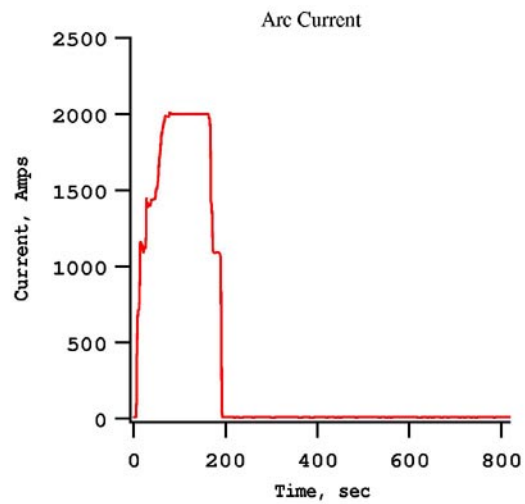
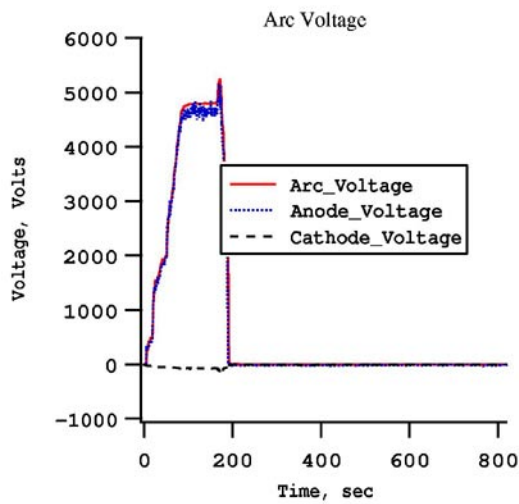
Model: Seal #8

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Run 98-11 — Page 2



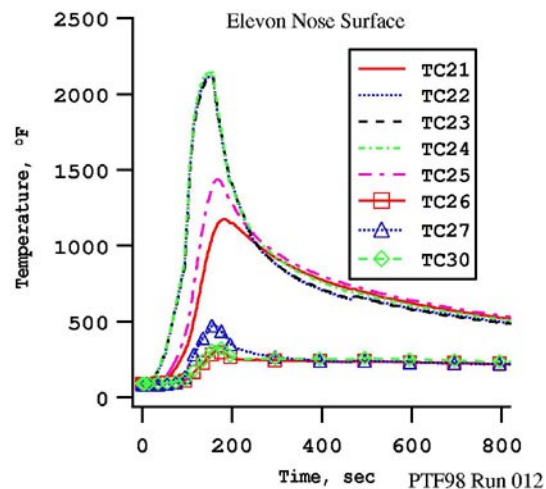
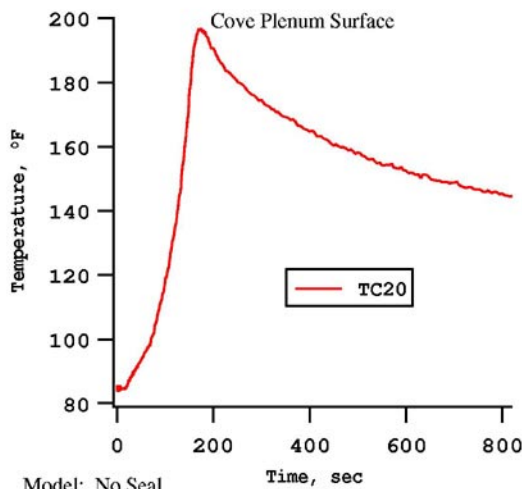
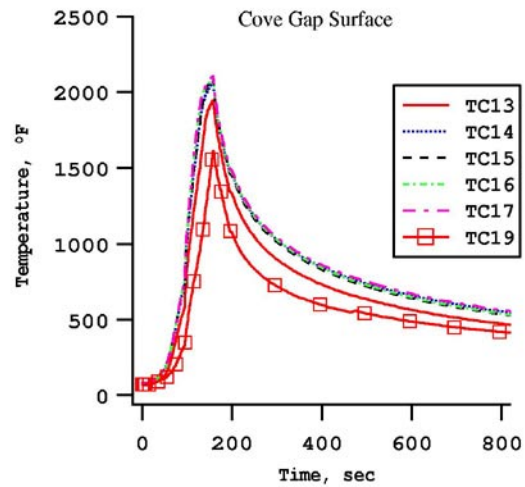
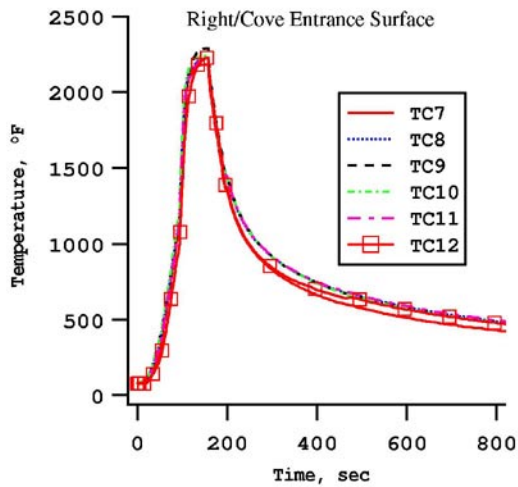
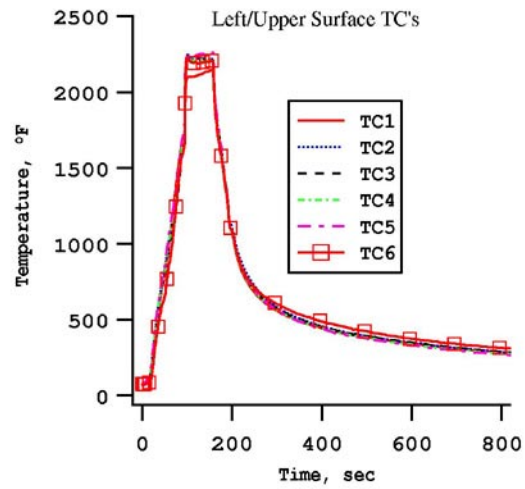
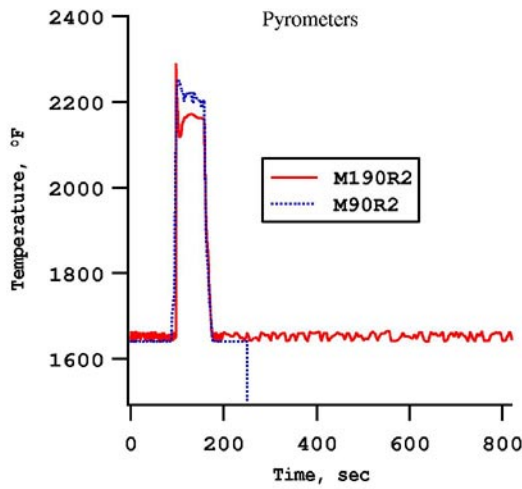


Model: No Seal

Time, sec

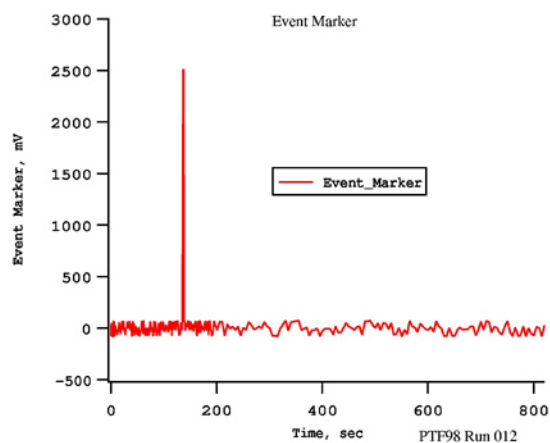
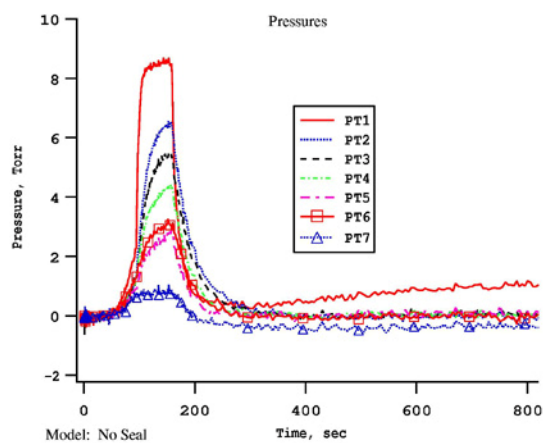
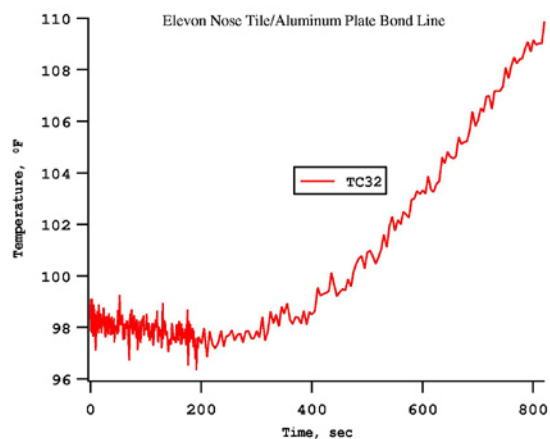
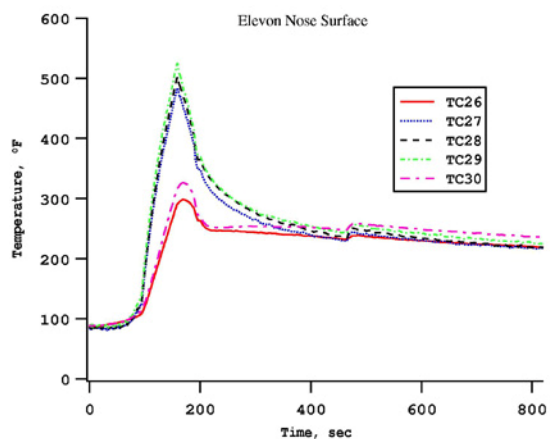
PTF98 Run 012





Model: No Seal

PTF98 Run 012



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6. AUTHOR(S) Charles W. Newquist, Juris Verzemnieks, Peter C. Keller, Michael Rorabaugh, and Mark W. Shorey				
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