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ANALYTICAL INVESTIGATION OF SOLID ROCKET NOZZLE FAILURE

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Structures and Propulsion Laboratory
Science and Engineering Directorate

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16. ABSTRACT

On April 5, 1983, an Inertial Upper Stage (IUS) spacecraft experienced loss of control during the burn of the second of two solid rocket motors. The anomaly investigation showed the cause to be a malfunction of the solid rocket motor. This paper presents a description of the IUS system, a failure analysis summary, an account of the thermal testing and computer modeling done at Marshall Space Flight Center, a comparison of analysis results with thermal data obtained from motor static tests, and describes some of the design enhancements incorporated to prevent recurrence of the anomaly.

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INTRODUCTION

System Description

The Inertial Upper Stage (IUS) is a three-axis-stabilized spacecraft which can carry payloads of about 5000 lb from the low Earth orbit of the Space Transportation System (STS) to geosynchronous orbit. The IUS, shown in Figure 1, uses two solid propellant rocket motors: the SRM-1 first stage and the SRM-2 second stage. Both motors are built by United Technologies Chemical Systems Division (CSD). The SRM-1 provides the energy required to transfer to geosynchronous orbit. The SRM-2 provides the energy to circularize the orbit, resulting in geostationary capability.

The SRM-2 motor, shown in Figure 2, has an moniaxial vector requirement of 7 deg which is provided by a low-torque fluid bearing called the techroll joint (TRJ). This bearing connects the fixed and movable portions of the nozzle (Rig. 3) and allows for gimballing of the movable portion. The heart of the TRJ is a Kevlar fabric-reinforced rubber bladder, called the techroll seal (TRS).

The TRS and its titanium housing (Fig. 4) are protected from hot combustion gases by surrounding insulators. The forward face of the housing is protected by the carbon/phenolic nose cap and its silica/phenolic insulator. An overlapping of the nose cap with the fixed insulator, augmented by the Viton rubber thermal boot, provides protection to the housing outer surface while allowing gimballing motion. The 3-D carbon/carbon integral throat and entrance (ITE) is backed by carbon/phenolic and silica/phenolic insulators. The 2-D carbon/carbon exit cone threads into the ITE and has both carbon/phenolic and silica/phenolic insulators at its forward end to protect the adjacent portion of the titanium housing and the attached gib ring. A grafoil seal between the exit cone and ITE insulator is intended to prevent gas flow through that joint.

Anomaly and Failure Investigation

On April 5, 1983, during an attempt to insert the Tracking Data Relay Satellite-A (TDRS-A) into geosynchronous orbit using the IUS, a loss of control was experienced at about 85 sec into the planned 105 sec burn of the SRM-2 motor. The anomaly was studied extensively by several review teams and it was concluded that the most probable cause was failure of the nozzle Thermal Protection System (TPS), resulting in thermal rupture of the TRS. Failure scenarios that would allow the hot combustion gases to overheat the titanium TRS housing were generated and investigated. Based upon these investigations, supporting thermal analyses, and the results of heavily instrumented motor static firings, two areas were found in the nozzle TPS design where overheating could occur (Fig. 4)· (1) the nose cap carbon/phenolic-to-silica/phenolic bond surface where temperatures could exceed the bond adhesive limit, and (2) the grafoil seal/exit cone joint area where leakage of the grafoil seal would allow hot combustion gases diffused through the ITE to impinge on the titanium housing. This paper deals with the second area, describing work done at MSFC to characterize the thermal environment and reaction in the vicinity of the grafoil seal.

FAILURE EFFECTS ANALYSIS

Gas Flow Estimate

Inspection of the detailed nozzle design (Fig. 4) shows that the hot combustion gases come in direct contact only with the carbon phenolic nose cap and the carbon/carbon integral throat entrance. Although the carbon phenolic is impervious to gas flow, the ITE carbon/carbon is porous but the hot combustion gases are prevented from reaching the titanium TRS seal by the grafoil seal. However, if the grafoil seal should leak or crack, the hot combustion gases would impinge directly on the shear lip of the titanium TRS housing and vent in the area between the housing and silica/phenolic liner. After the baseline (BL-1) motor firing, inspection of the grafoil seal area revealed erosion and a hole through the seal forming a hot gas leakage path. The location and approximate dimensions of this crack are shown in Figure 5. Two questions then arise: how much gas would flow through such a crack, and how much heating would this produce on the titanium TRS housing?

To calculate the flow of gas through the ITE carbon/carbon, the complex ITE geometry was approximated by a simple one-dimensional geometry with a gas diffusion path length of 3 in. with an effective area of 10.6 in.^2 (Fig. 6). By neglecting the dynamic term, the gas diffusion equation can be integrated to give

$$\frac{P_1^2 - P_2^2}{2RTL} = \frac{\mu (\rho u)}{\beta_0}$$

where

R = gas constant

T = gas temperature

L = path length

μ = viscosity

ρ = density

P = pressure

u = velocity

β_0 = Darcy coefficient (2.6×10^{-9} cm^2) .

Using 94 percent of the chamber pressure as the driving force for hot gas diffusion, the maximum flow curve of Figure 7 was calculated. A more exact analysis [1], done later by CSD, confirmed that the mass flow curve from the above analysis was conservative.

MSFC Test Program

To determine the heating effect from hot gas impingement on the TRS housing, a thin plate calorimeter experiment was set up in the Test Laboratory at MSFC.

The thin plate calorimater, a 0.030 in., type 304SS plate, with 52 thermocouples attached to the backface was formed into a shape to simulate the path of the gas flow past the TRS housing (Figs. 8 and 9). Heated GN_2 was introduced into the plenum where the gas impinged on the thin plate calorimeter through slots of various widths and lengths, typical of the type of cracks in the grafoil seal. The various widths and lengths of cracks simulated along with their respective flow rates are shown in Table 1. The thermocouples were placed on the thin plate as shown in Figure 10.

A heat transfer coefficient was calculated for each thermocouple location from the recorded time and temperature data. Figure 11 shows the spatial variation of the heat transfer coefficients for the 10 x 30 mil slot test. The variation of stagnation heat transfer with slot width is shown in Figure 12. Note the peak values at a slot width of approximately 250 mils.

TRS HOUSING THERMAL MODEL ANALYSIS

Thermal Math Model

The thermal model of the titanium TRS housing was coded in SINDA format for solution on the MSFC UNIVAC 1100/82 computer. The model consists of nine "wedges" with conduction between the "wedges" (Fig. 13). The width of the "wedges" could be varied to obtain the desired angular coverage. Each "wedge" is broken down (Fig. 14) into 20 nodes in the titanium, four in each layer of neoprene, and four in the silicon oil. In the titanium there are three nodes radially and six longitudinally, plus two in the shear lip. Heating, from ITE gas (Fig. 15), is considered on the top and side of the shear lip as well as on the first nodes down the housing.

Baseline (BL-1) Test Data Correlation

To correlate the data from the BL-1 firing, 7.5 deg wedges were used. Table 2 gives the stagnation H values at the measured flow rates and the H ratios used in the model at each plane and angular position. To account for the differences between combustion gases and the nitrogen gas used in the coefficient tests, a factor of 2.5 was applied to the measured coefficients. The actual stagnation H used was obtained by interpolating the time dependent flow rate shown previously in Figure 7. With these input data, the model gave the correlations shown in Figures 16, 17, and 18 at the 0.3 in., and 1.5 in. depths.

Correlation of FQ-1 Test Data

The IUS motor was fired in a subsequent test, designated FQ-1, with the same TRS housing design. Initial correlations using the same heating data as the BL-1 correlations resulted in predictions much too low at the 0.3 in. depth and much too high at the 1.0 in. and 1.5 in. depths in the TRS housing. The heating rates were then adjusted until a reasonable correlation was obtained. As indicated in Figures 19, 20, and 21, the heat flux was removed completely from the shear lip and only 12 percent of stagnation heat flux was applied to the housing aft of the shear lip. Subsequent inspection of the grafoil seal-shear lip area showed no signs of any hot gas flow in this area. However, inspection did reveal numerous cracks in the silica phenolic-graphite epoxy overwrap, which indicated pyrolysis gas was impinging on the barrel of the TRS housing. These observations are confirmed by the heat flux patterns indicated by the thermal model correlations.

DESIGN ENHANCEMENTS

The most significant design changes to the TPS included (Fig. 22): (1) higher density grafoil seal, (2) extended silica phenolic to cover shear lip, and (3) silica phenolic insulator aft of shear lip. Thus, it was necessary to develop a new thermal model, the nodal layout of which is shown in Figure 23. To test the effectiveness of the design enhancements, this model was run with the "worst case" coefficients determined from the MSFC slot impingement tests. The gas temperature was defined by the ITE/grafoil interface temperature (Fig. 15). Figure 24 shows the average predicted techroll seal temperature along with the allowable TRS temperature.

The allowable TRS temperature predicted is based on experimental pressure versus burst temperature data, obtained during component tests using the predicted pressure versus time trace for the SRM-2 motor. Note that the predicted average TRS temperature is well below the allowable until just before the end of burn when it comes within 74°F of the allowable average temperature.

CONCLUSIONS

Through this program at MSFC, the following have been achieved:

1) Measured the heat transfer coefficients for hot gas flow past the TRS housing.

2) Verified the measured coefficients by correlation of the test firing data.

3) Determined the worst case coefficients for use in the design.

4) Shown the new design to have a positive margin of safety.

REFERENCE

1. "Analysis of Gas Diffusion Through the ITE." Unpublished Working Report of Chemical Systems Division, March 1984.

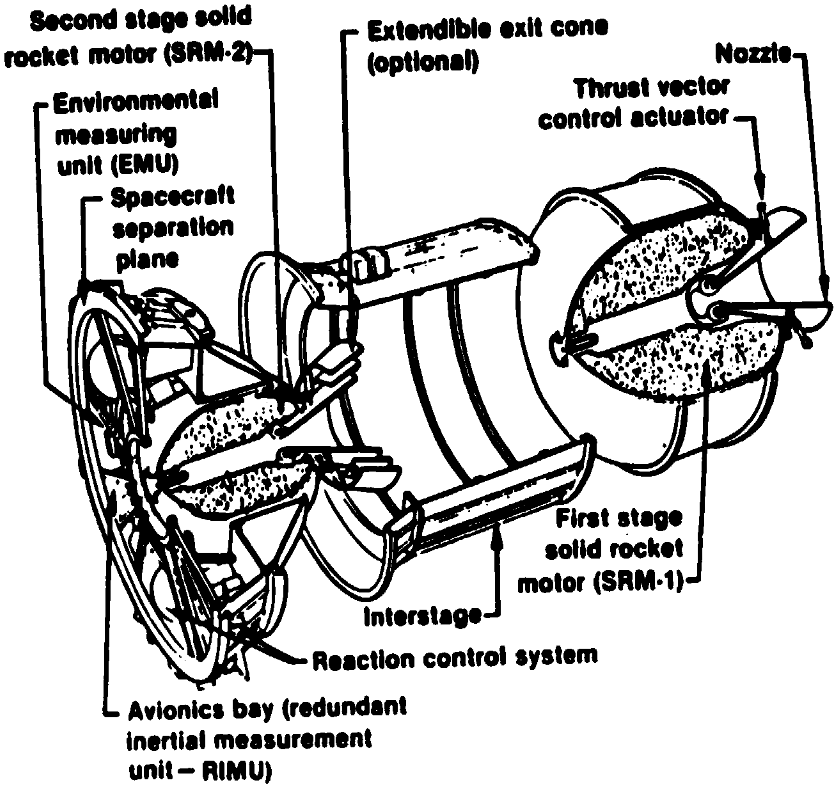

Figure 1. IUS two-stage vehicle.

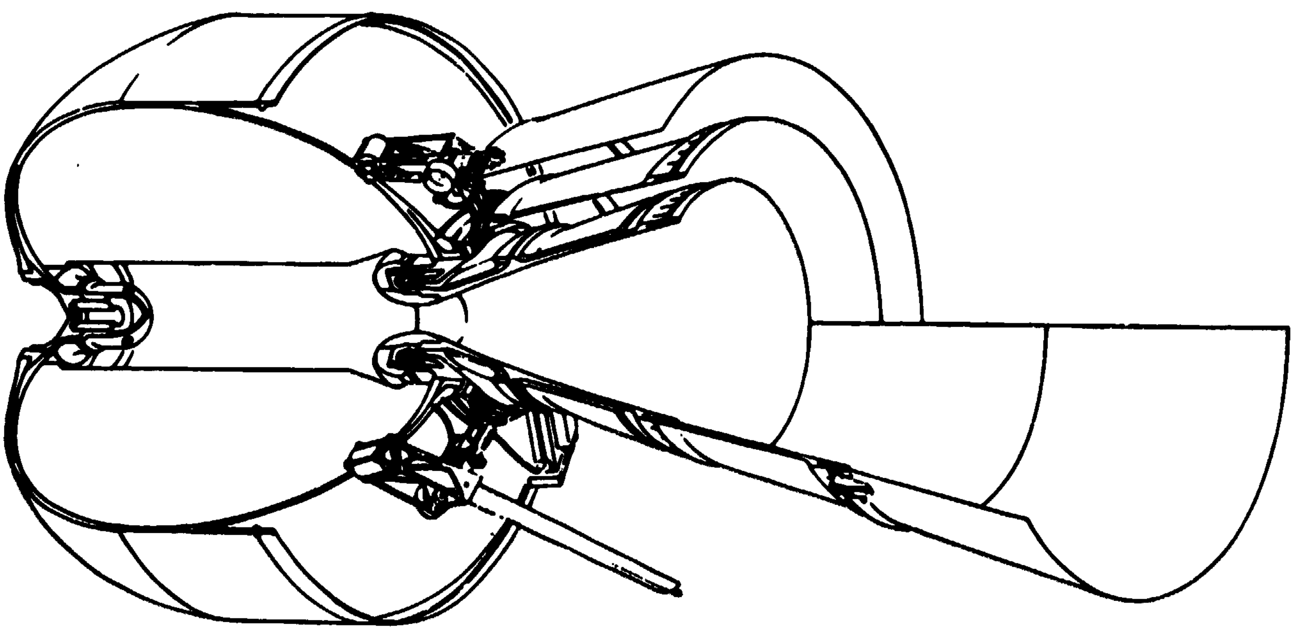

Figure 2. SRM-2 motor with ECC.

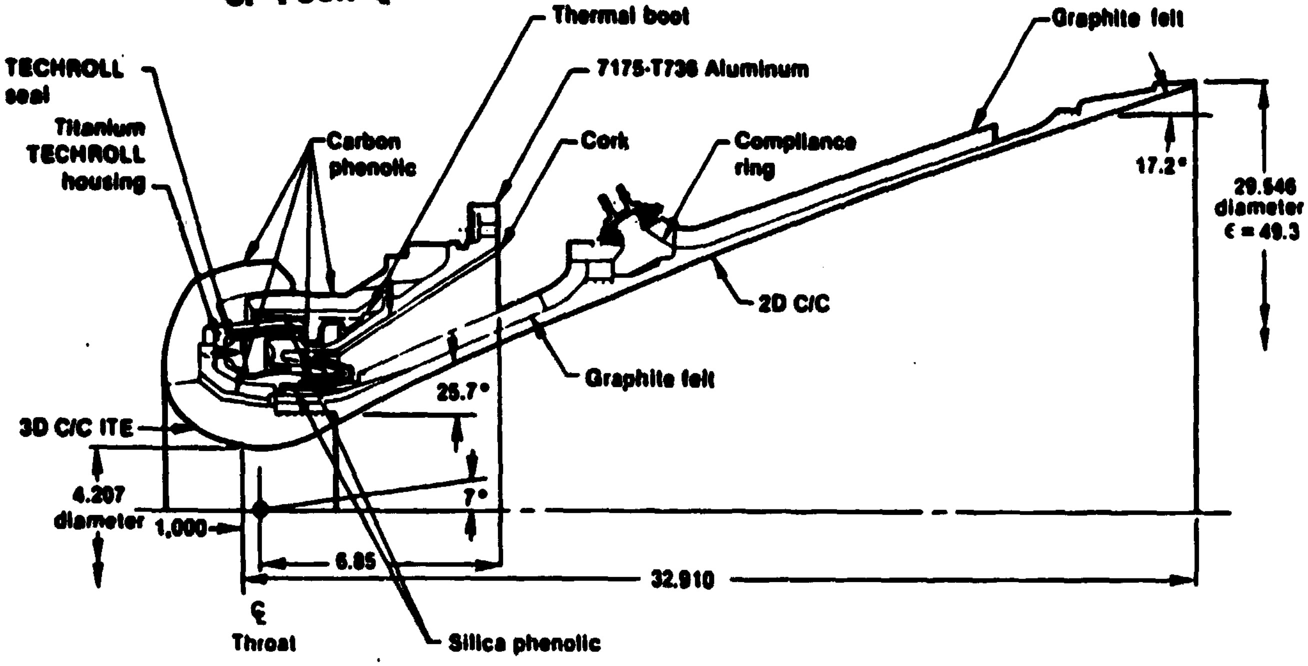

Figure 3. SRM-2 nozzle design.

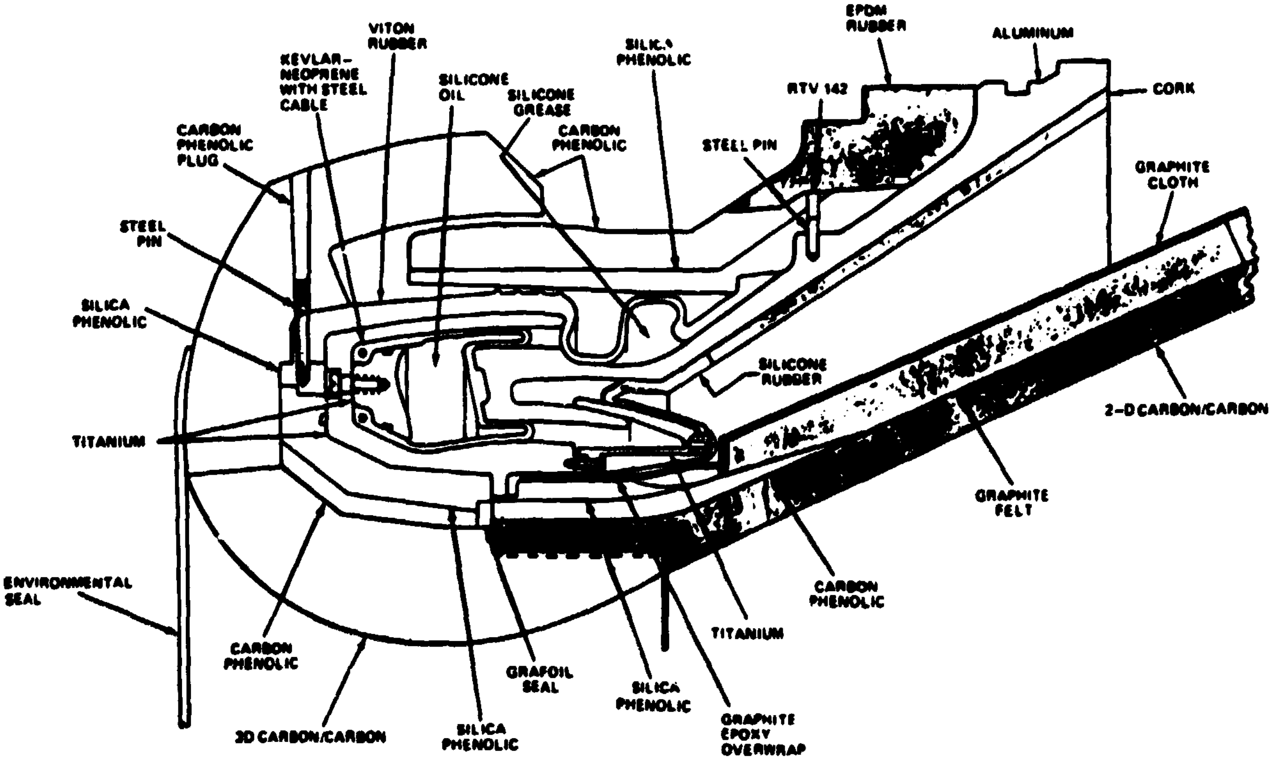

Figure 4. IUS SRM-2 nozzle.

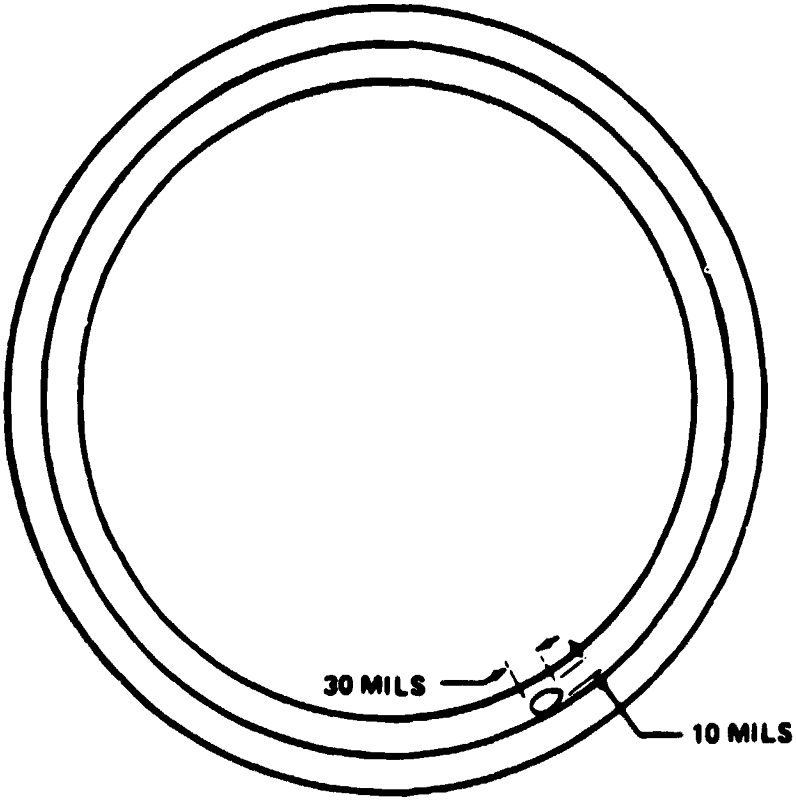

Figure 5. Baseline test grafoil seal crack.

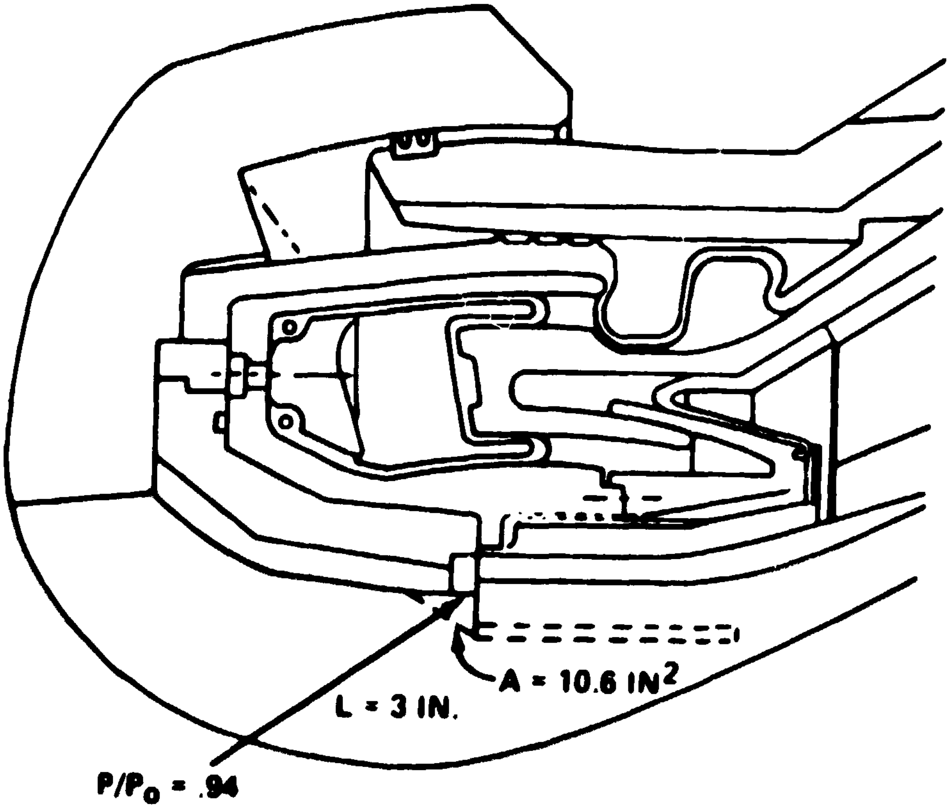

Figure 6. ITE one-dimensional approximation.

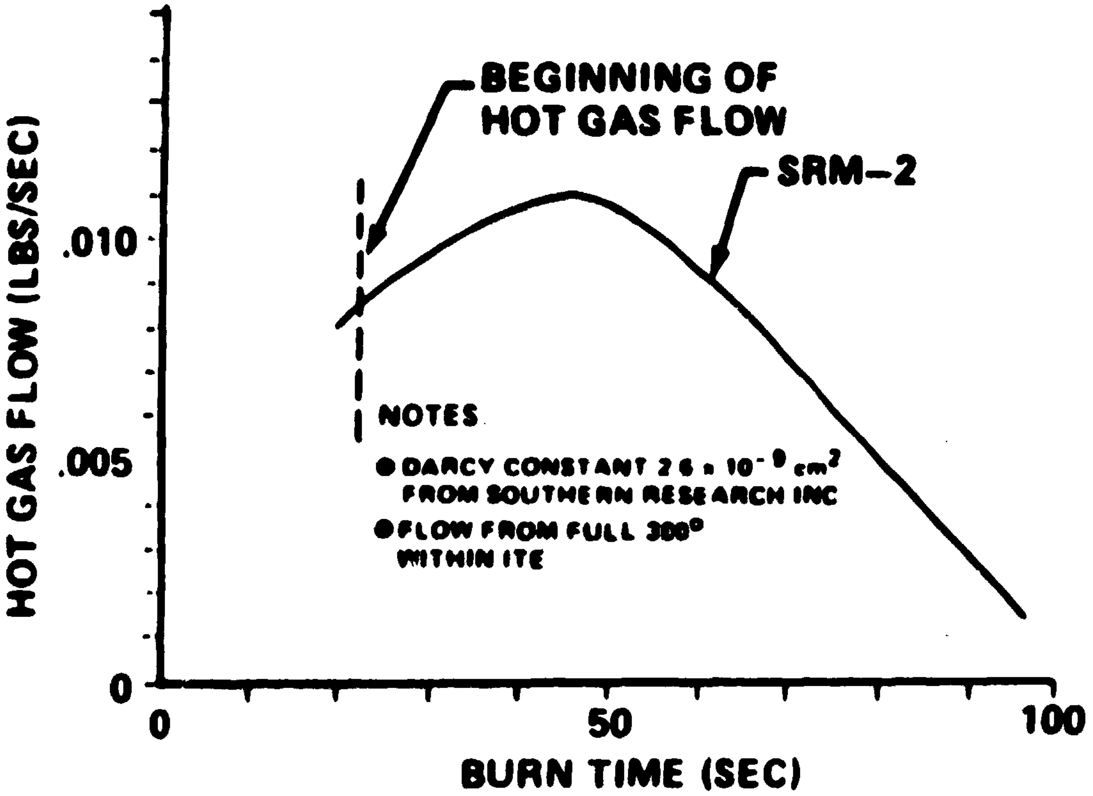

Figure 7. ITE to grafoil seal maximum diffusion flow.

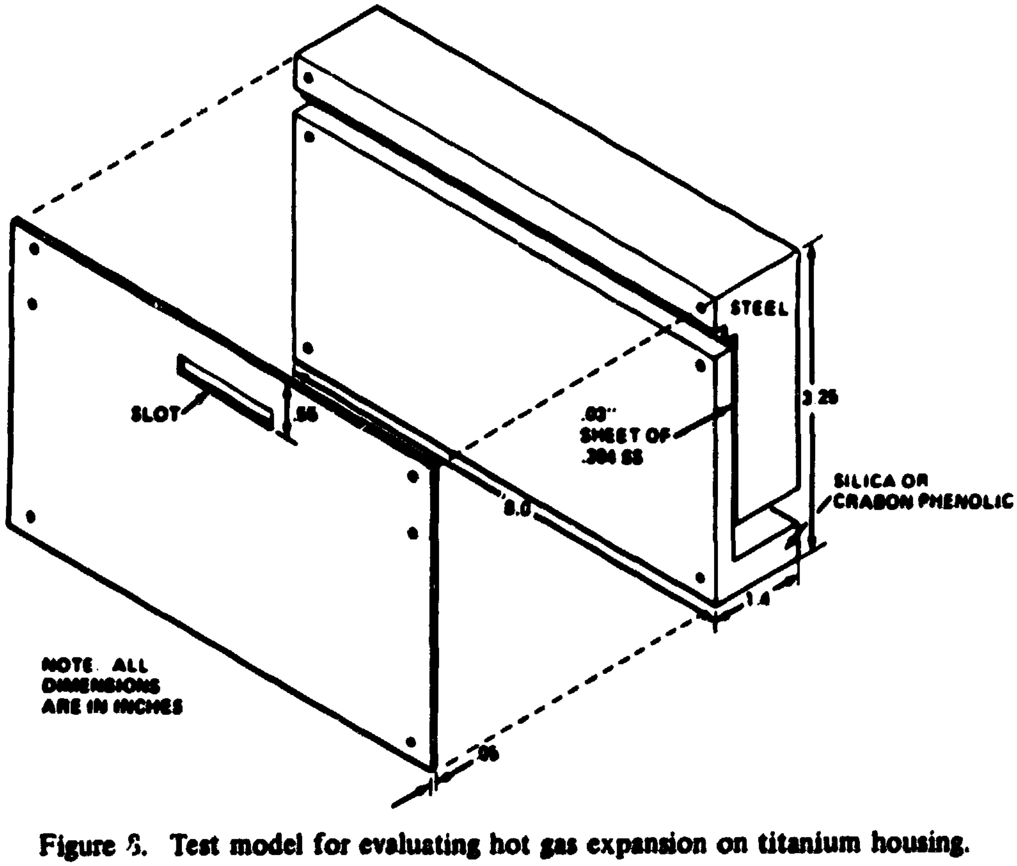

Figure 8. Test model for evaluating hot gas expansion on titanium housing.

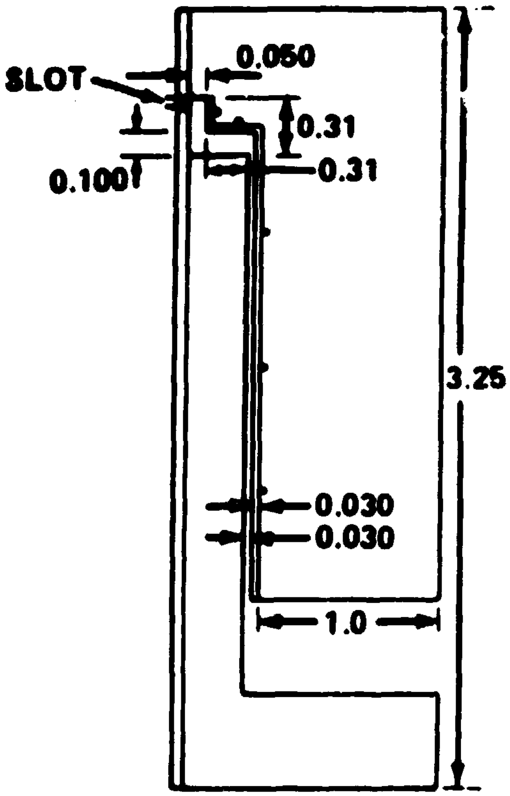

Figure 9. Test model (side view).

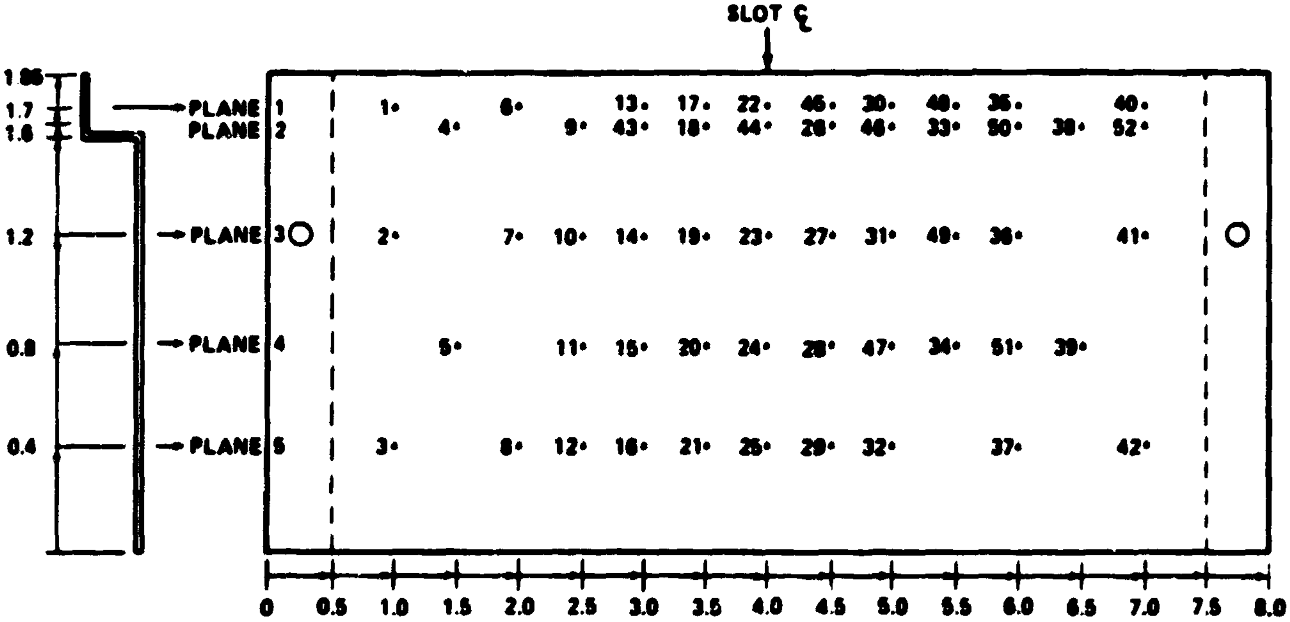

Figure 10. Thermocouple locations.

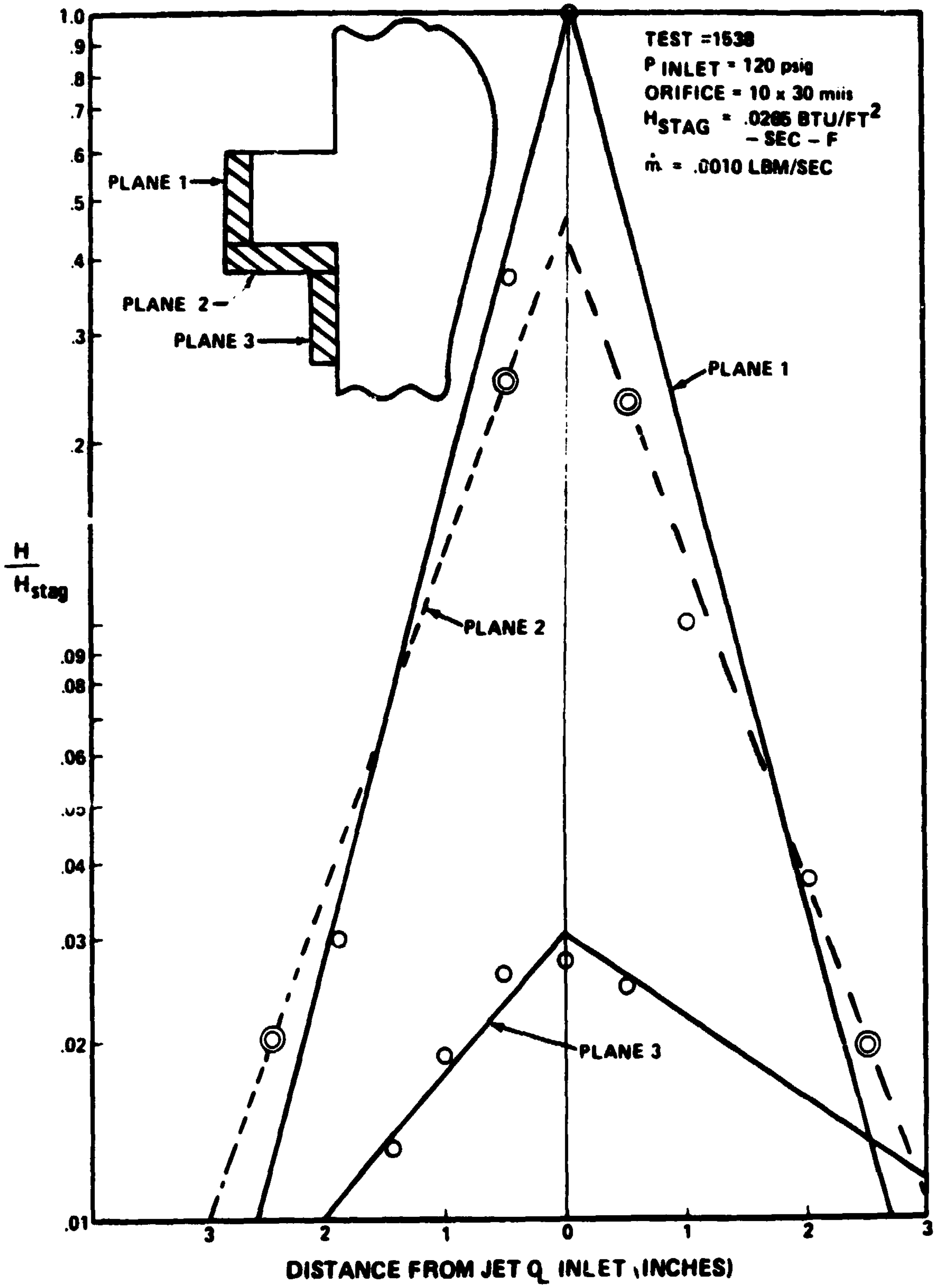

Figure 11. Test coefficients.

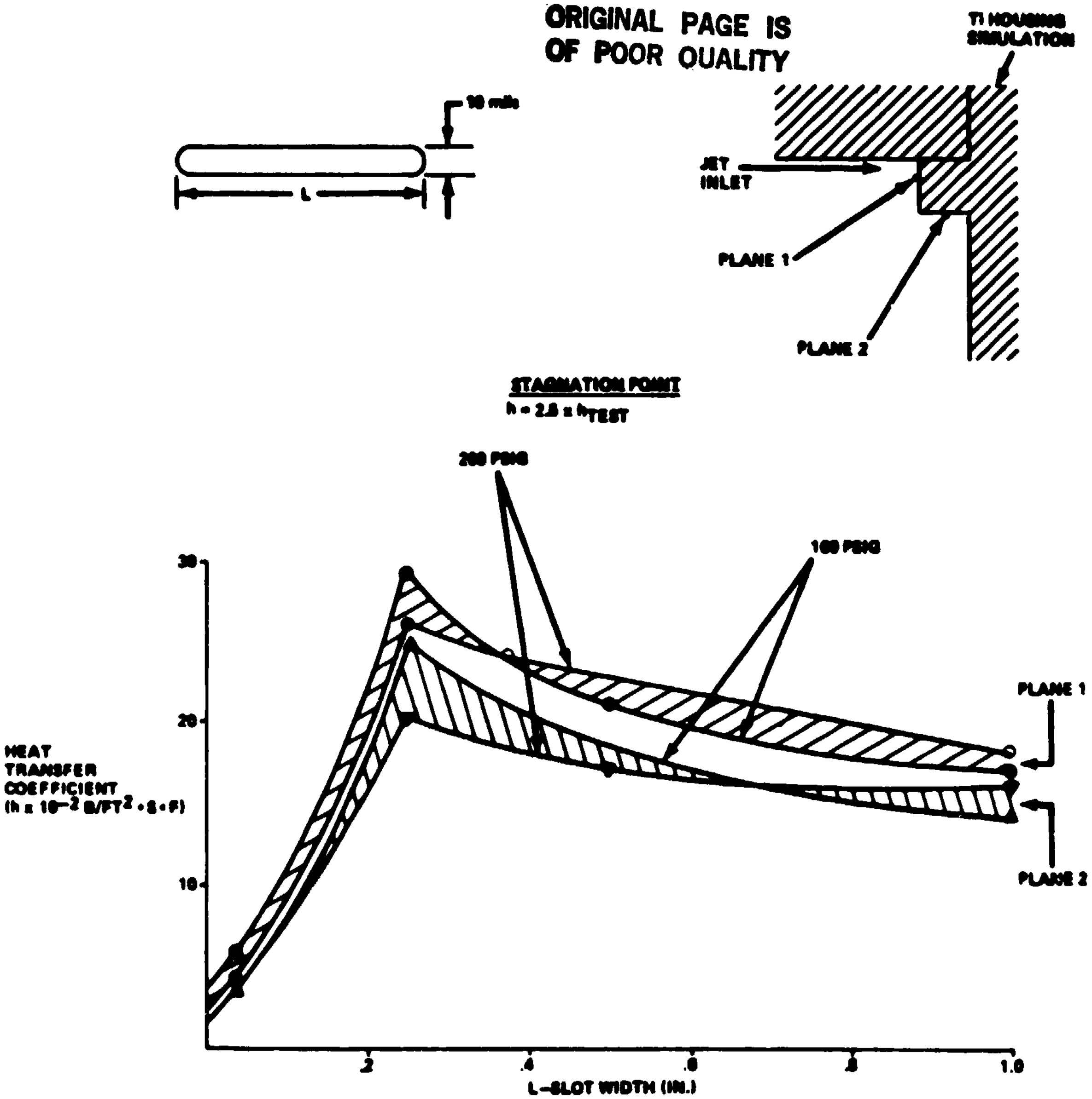

Figure 12. IUS/SRM-2 grafoil seal hot gas leak heating test results.

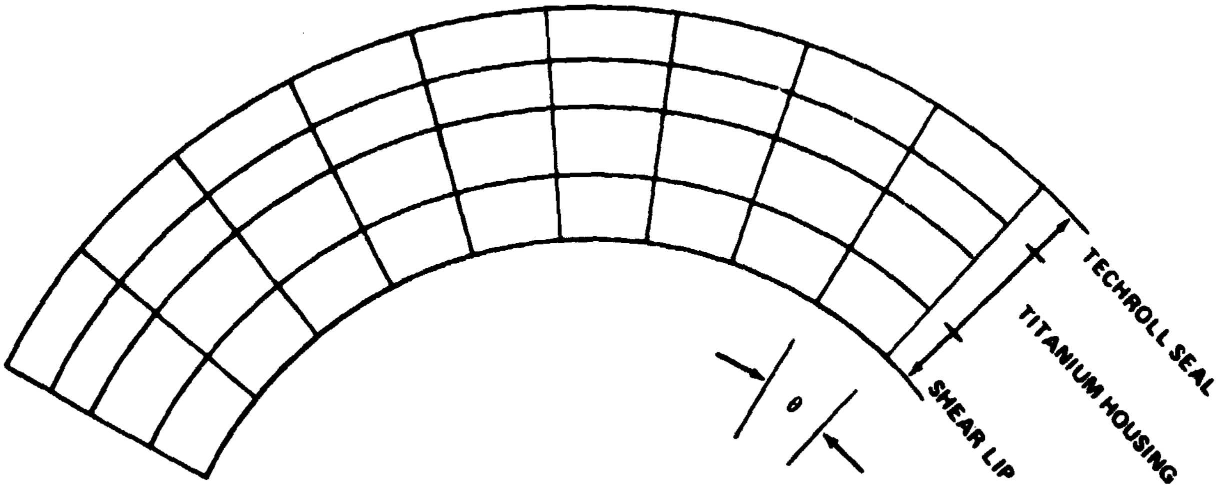

Figure 13. Angular node layout.

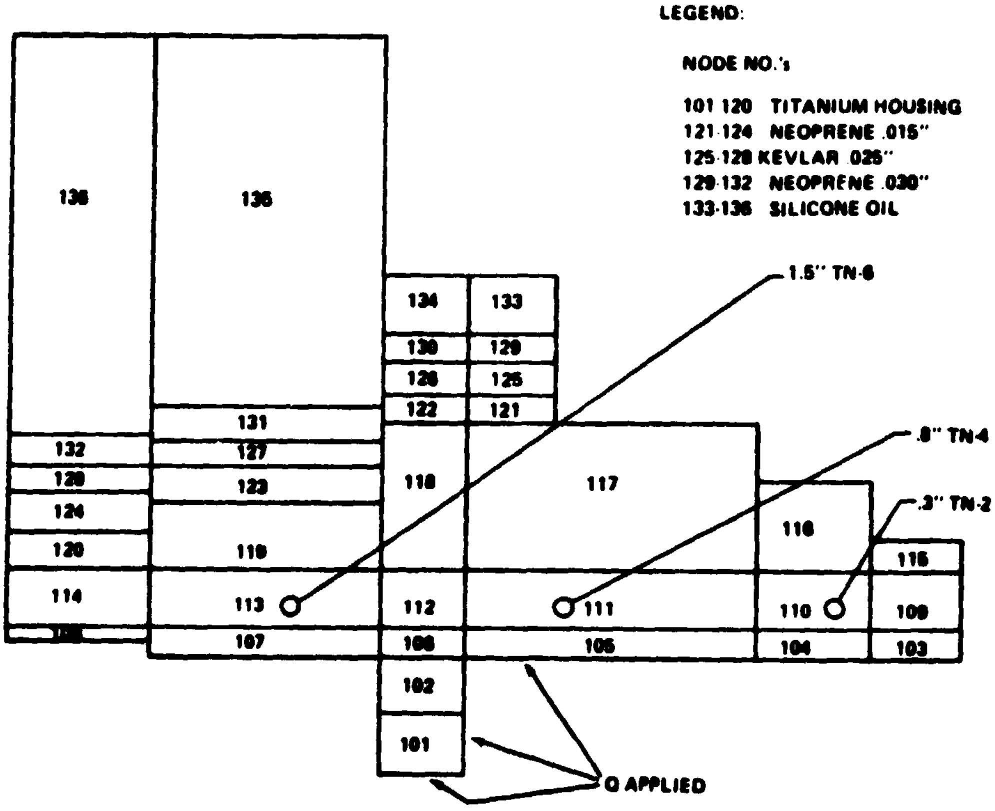

Figure 14. Titanium techroll seal housing node layout for each "wedge."

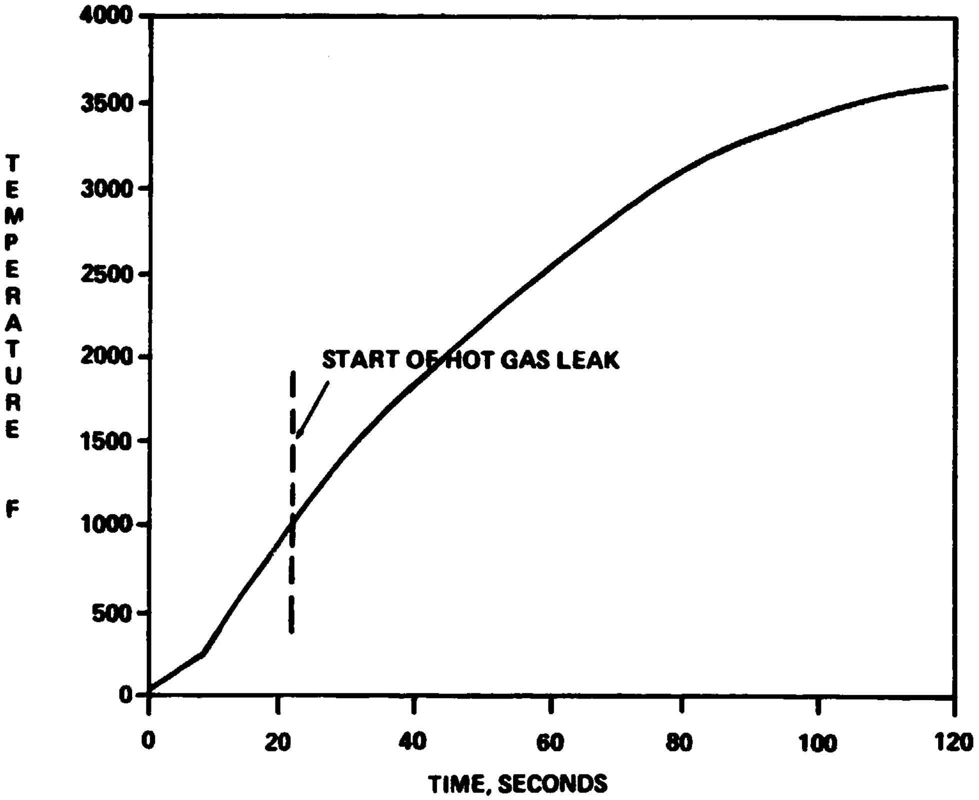

Figure 15. SRM-2 gas temperature histories.

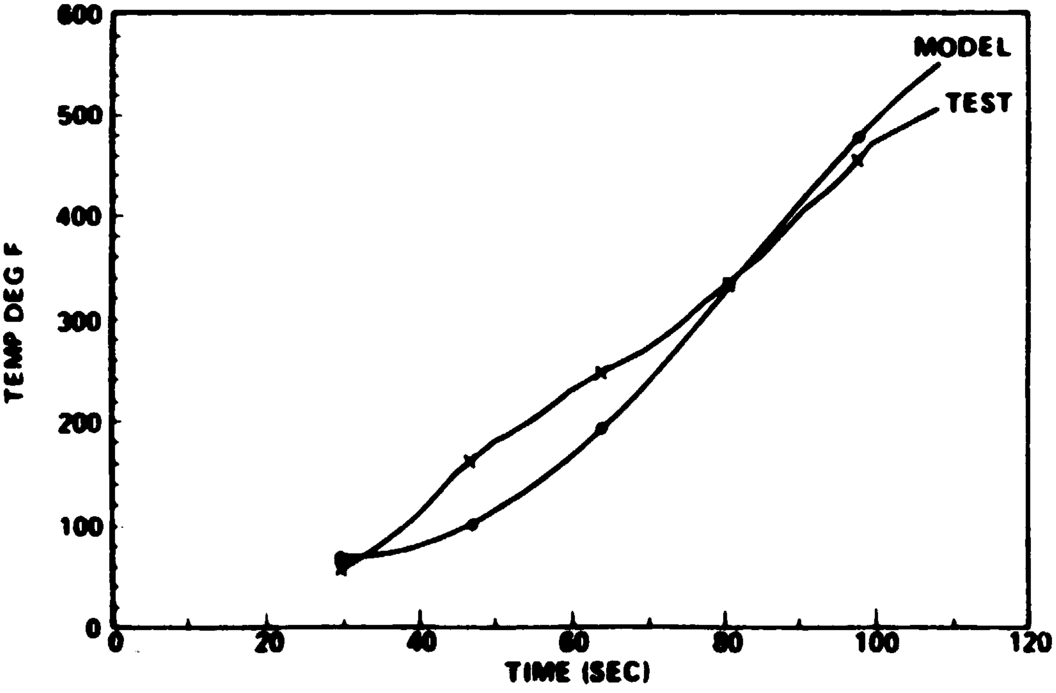

Figure 16. BL-1 0.3 in. correlation.

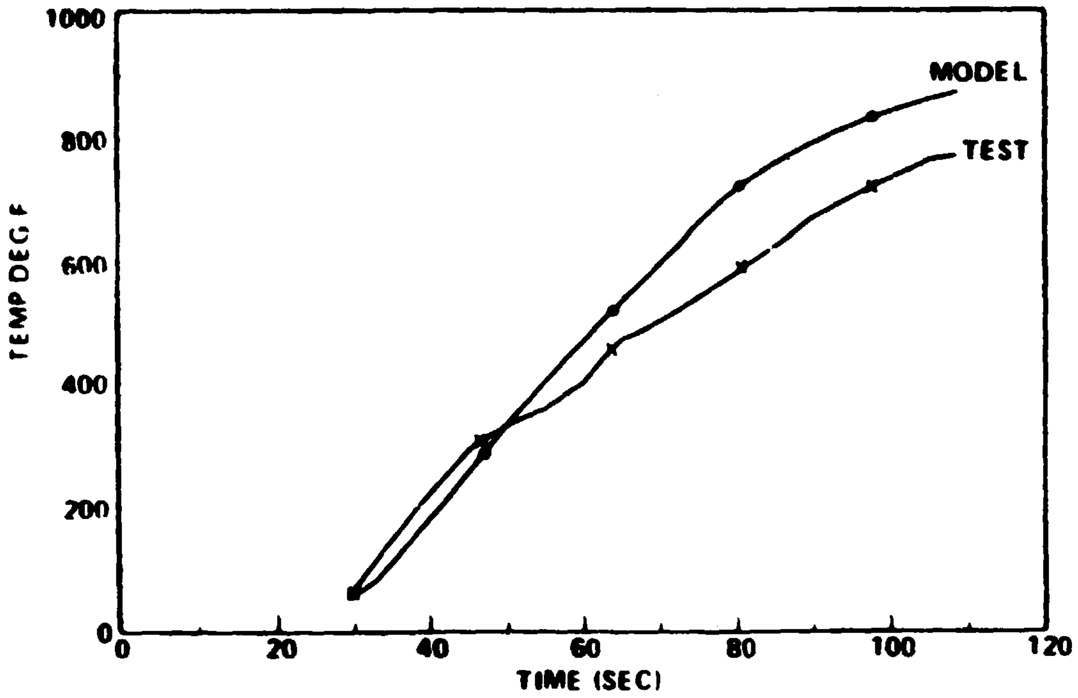

Figure 17. BL-1 0.8 in. correlation.

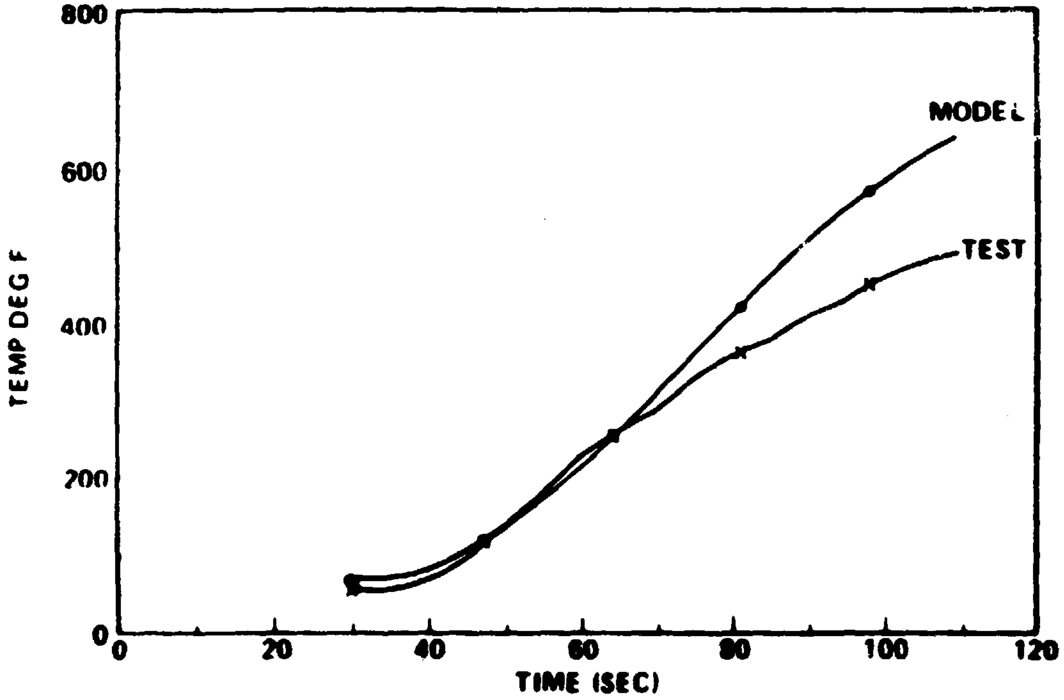

Figure 18. BL-1 1.5 in. correlation.

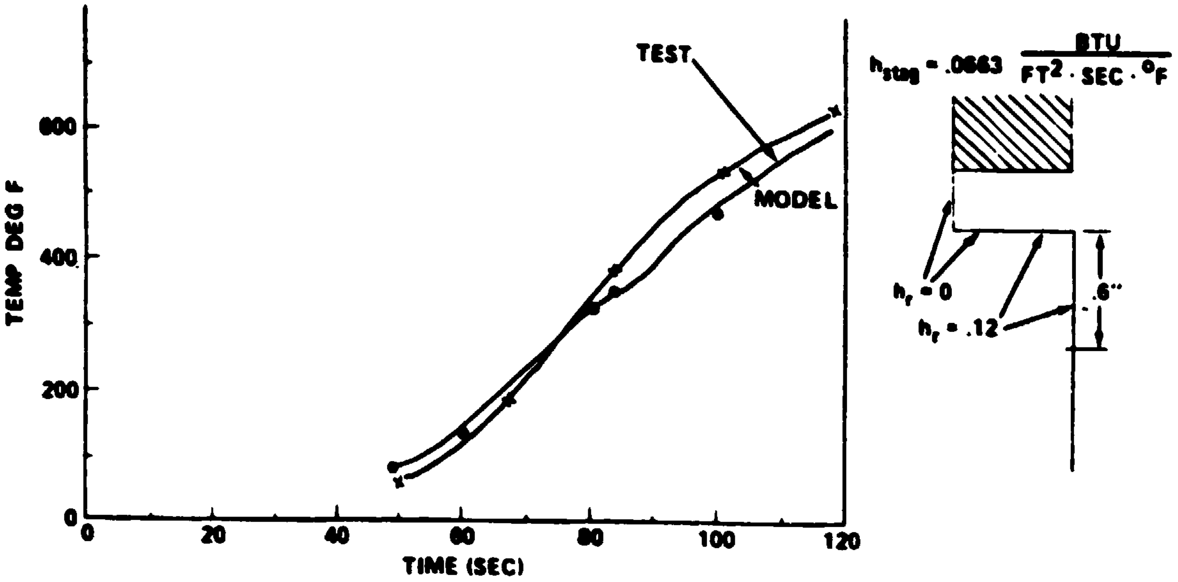

Figure 19. FQ-1 0.3 in. correlation.

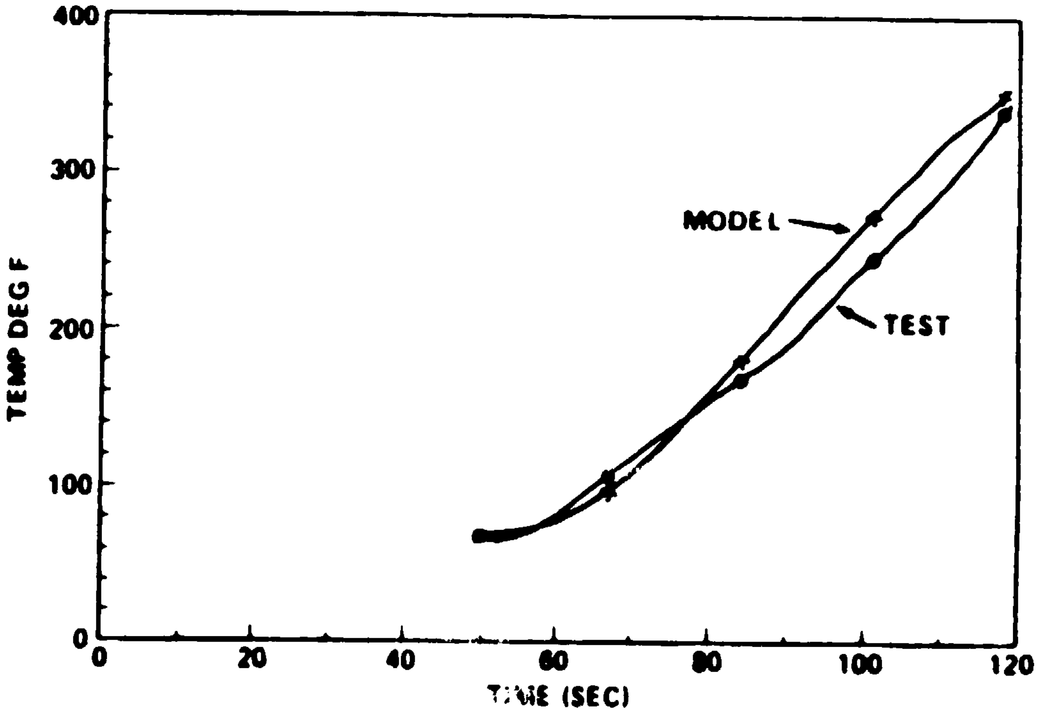

Figure 20. FQ-1 1.0 in. correlation.

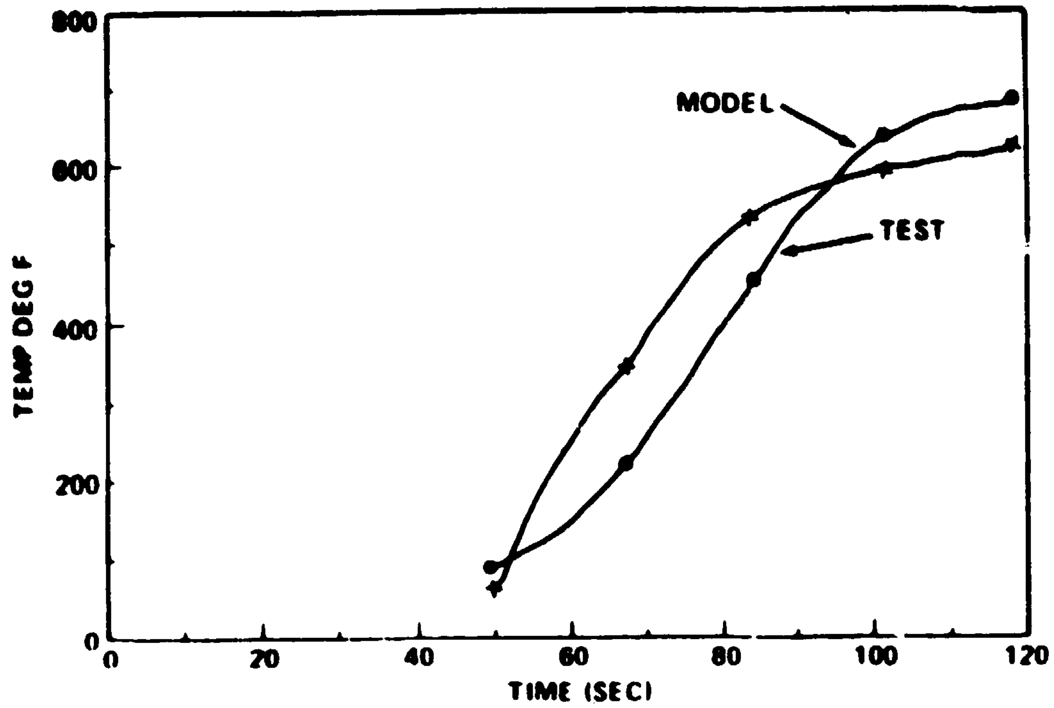

Figure 21. FQ-1 1.5 in. correlation.

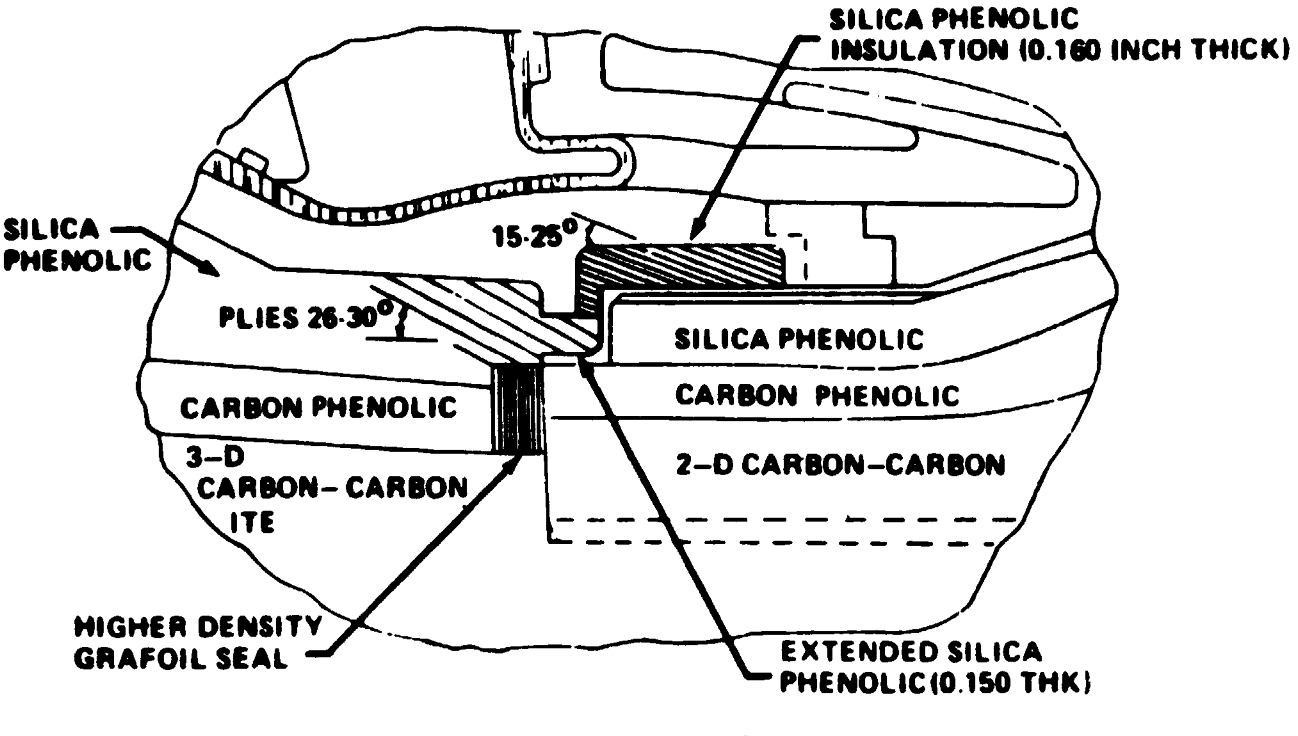

Figure 22. Enhanced TPS design.

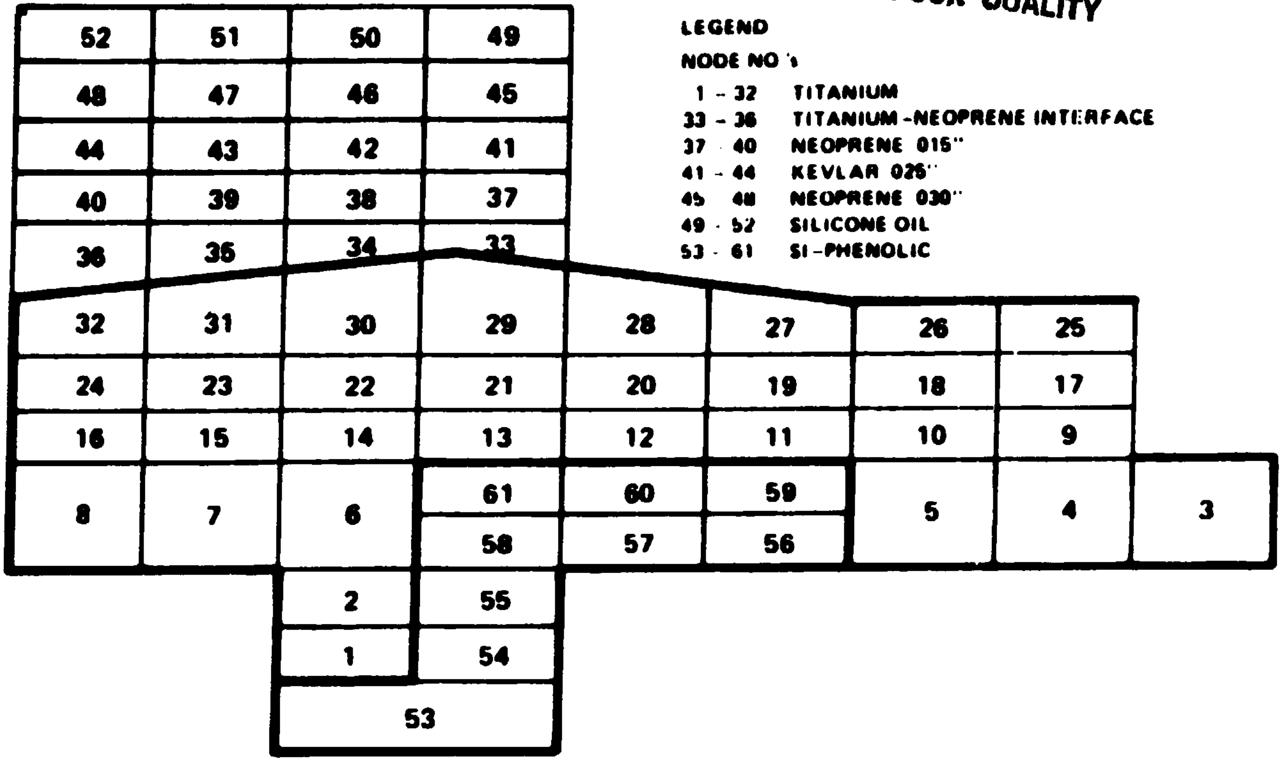

Figure 23. Enhanced design nodal layout.

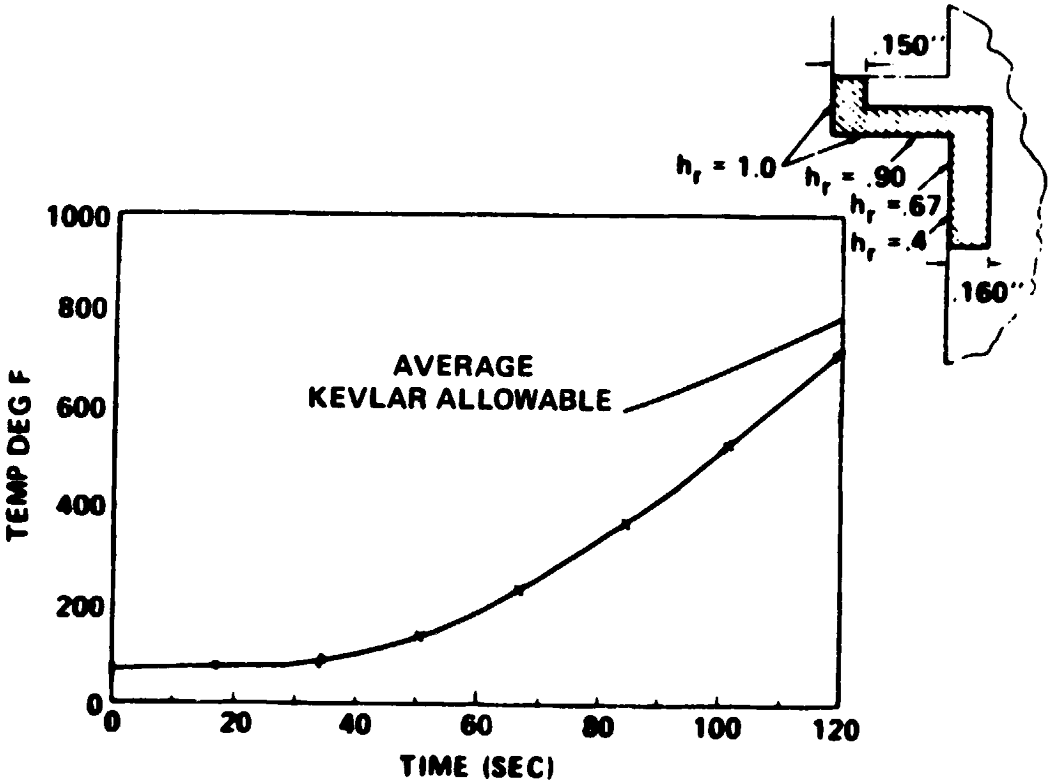

Figure 24. Average kevlar temperatures (worst case heating).

TABLE 1. HEAT TRANSFER COEFFICIENT TESTS SLOW DIMENSIONS

TEST NO.	SLOT SIZE (mils)	FLOW RATE (lbm/sec)	SLOT INLET PRESSURE (psig)	MAX. HEAT TRANSFER COEFFICIENT $H_{stag} \times 10^{-4}$ Btu/ft^2-sec
1529	10 X 250	0.0069	105	262
1530	10 X 100	0.0023	107	356
1531	10 X 100	0.0044	207	402
1536	10 X 250	0.0075	115	1129
1537	10 X 250	0.0137	218	1012
1538	10 X 30	0.0010	120	265
1539	10 X 30	0.0019	220	385
1540	10 X 500	0.0145	120	809
1541	10 X 500	0.0251	220	871
1542	10 X 1000	0.0270	120	673
1544	10 X 1000	0.0469	220	684
1545	20 X 100	0.0041	107	447
1546	20 X 100	0.0073	205	582
1547	20 X 250	0.0117	115	652
1548	20 X 250	0.0205	212	864
1549	20 X 30	0.0017	112	143
1550	20 X 30	0.0038	220	205
1552	20 X 1000	0.0462	130	966
1554	10 X 375	0.0112	120	384
1555	10 X 375	0.0107	115	2024
1556	10 X 375	0.0196	210	956
1557	15 X 590	0.0229	117	1677
1558	15 X 590	0.0417	220	1323
1559	20 X 375	0.0187	115	964
1561	20 X 375	0.0320	210	913

TABLE 2. H/H_{STAG} TABLE FOR BL-1 CORRELATION.

H_{STAG} = .0663 Btu/ft^2-sec-F @ .0010 lb/sec

H_{STAG} = .0963 Btu/ft^2-sec-F @ .0019 lb/sec

ANGULAR POSITION	PLANE 1	PLANE 2	PLANE 3
-30.0	.021	.029	.01
-22.5	.07	.07	.014
-15.0	.145	.125	.017
-7.5	.42	.24	.024
0	1.0	.45	.03
7.5	.42	.24	.024
15.0	.145	.125	.017
22.5	.07	.07	.014
30.0	.021	.029	.01

APPROVAL

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

for JPMcCarty

A. A. McCOOL
Director, Structures and Propulsion Laboratory

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