IUS/SRM-2 NOZZLE THERMAL ASSESSMENT

Dr. Kenneth E. McCoy and J.L. Vaniman
NASA/MSFC
Huntsville, Alabama

ABSTRACT

During the space shuttle mission (STS-6) on April 5, 1983, the inertial upper stage/tracking data relay satellite-A (IUS/TDRS-A) payload experienced a loss of control at ≈ 85 seconds into the planned 105 second burn of the second stage (SRM-2). The anomaly was reviewed by several ~~review~~ teams, indicating the most probable ~~cause~~ being failure of the thermal protection system (TPS) causing overheating of the *Techroll Seal (TRS) resulting in loss of the silicon fluid bearing surface required for nozzle vectoring. Detailed TPS failure scenarios were investigated that would allow hot combustion gases to overheat the titanium TRS housing. Based upon these investigations and supporting thermal analyses, two areas were found in the nozzle TPS design where this could occur (see figure 1): (1) The nose cap carbon phenolic to silica phenolic bond surface where temperatures were predicted to exceed the bonding material limit; and (2) the grafoil seal/exit cone joint area where leakage of the grafoil seal would allow hot combustion gases diffused from the integral throat entrance (ITE) 3-D carbon-carbon material to impinge onto the titanium housing. This paper ~~will~~ deals principally with the second area and go into the details of the investigation and describe the design enhancements which were added to the existing IUS motor.

FAILURE EFFECTS ANALYSIS

GAS FLOW ESTIMATE

Inspection of the detailed nozzle design, figure 1, shows 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 2. 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 inches with an effective area of 10.6 square inches, see figure 3. By neglecting the dynamic term, the gas diffusion equation can be integrated to give

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

where:
- R = gas constant
- T = gas temperature
- L = path length
- μ = viscosity
- ρ = density
- P = pressure
- u = velocity
- β_o = Darcy coefficient (2.6×10^{-9} cm^2)

*Techroll Seal (TRS) is a registered trademark of Chemical Systems Division (CSD).

Using 94% of the chamber pressure as the driving force for hot gas diffusion, the maximum flow curve of Fig. 4 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 flow impingement on the TRS housing, a thin plate calorimeter experiment was set up in the Test Laboratory at MSFC.

The thin plate calorimeter, a 0.030 inch, 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, see Figs. 5 and 6. 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 I. The thermocouples were placed on the thin plate as shown in Fig. 7.

A heat transfer coefficient was calculated for each thermocouple location from the recorded time and temperature data. Figure 8 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 Fig. 9. Note the peak values at a slot width of approx. 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 MSFC's UNIVAC 1100/82 computer. The model consists of nine "wedges" with conduction between the "wedges" (see Fig. 10). The width of the "wedges" could be varied to obtain the desired angular coverage. Each "wedge" is broken down, see Fig. 11, 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, 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 baseline (BL-1) firing, 7.5° wedges were used. Table II 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 Fig. 4. With these input data, the model gave the correlations shown in Figs. 12, 13, and 14 at the 0.3 inch, 0.8 inch, and 1.5 inch 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 inch depth and much too high at the 1.0 inch and 1.5 inch depths in the TRS housing. The heating rates were then adjusted until an agreeable correlation was obtained. As indicated in Figs. 15, 16, and 17, the heat flux was removed completely from the shear lip and only 12% 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 overwarp, 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 (see Fig. 18): (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 Fig. 19. 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. Figure 20 shows the maximum and minimum predicted Techroll Seal temperature along with the allowable TRS temperature.

The allowable TRS temperature predicted is based on experimental pressure vs. burst temperature data, obtained during component tests using the predicted pressure vs. 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 we have:

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.

REFERENCES

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

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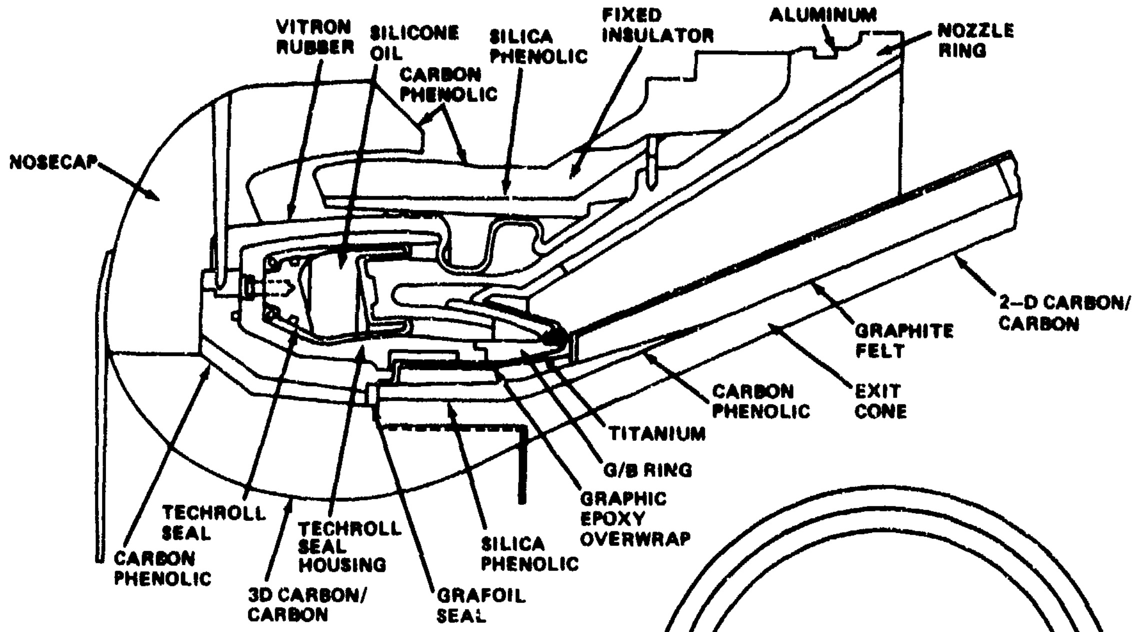

FIG. 1. IUS SRM–2 NOZZLE

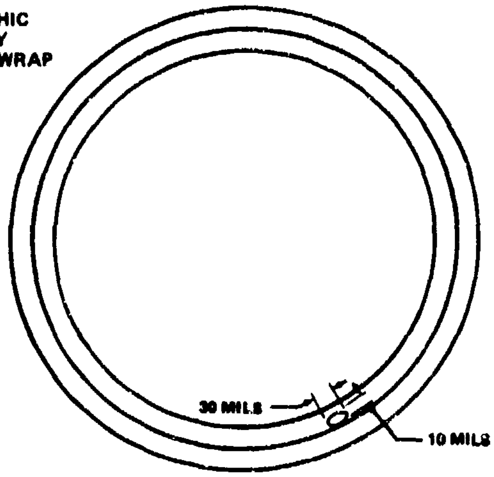

FIG. 2. BASELINE TEST GRAFOIL SEAL CRACK

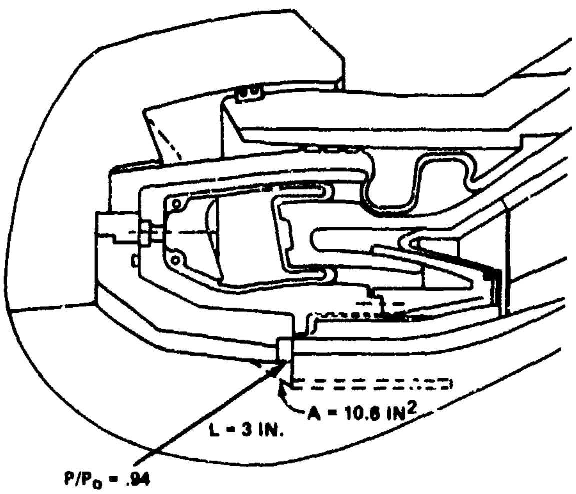

FIG. 3. ITE ONE–DIMENSIONAL APPROXIMATION

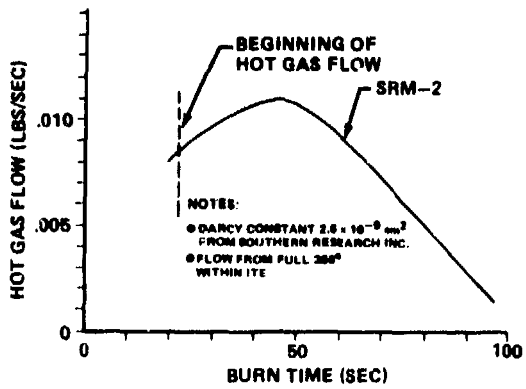

FIG. 4. ITE TO GRAFOIL SEAL MAXIMUM DIFFUSION FLOW

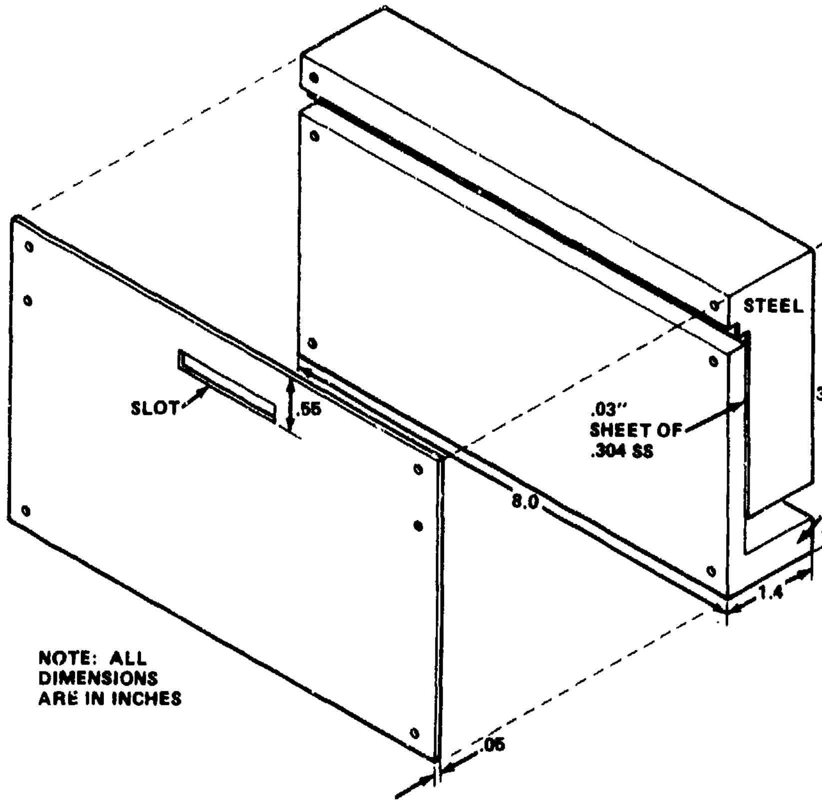

FIG. 5. TEST MODEL FOR EVALUATING HOT GAS EXPANSION ON TITANIUM HOUSING

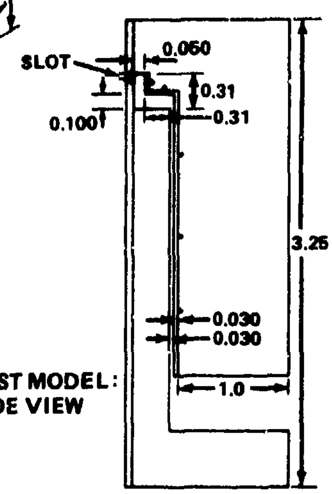

FIG. 6. TEST MODEL: SIDE VIEW

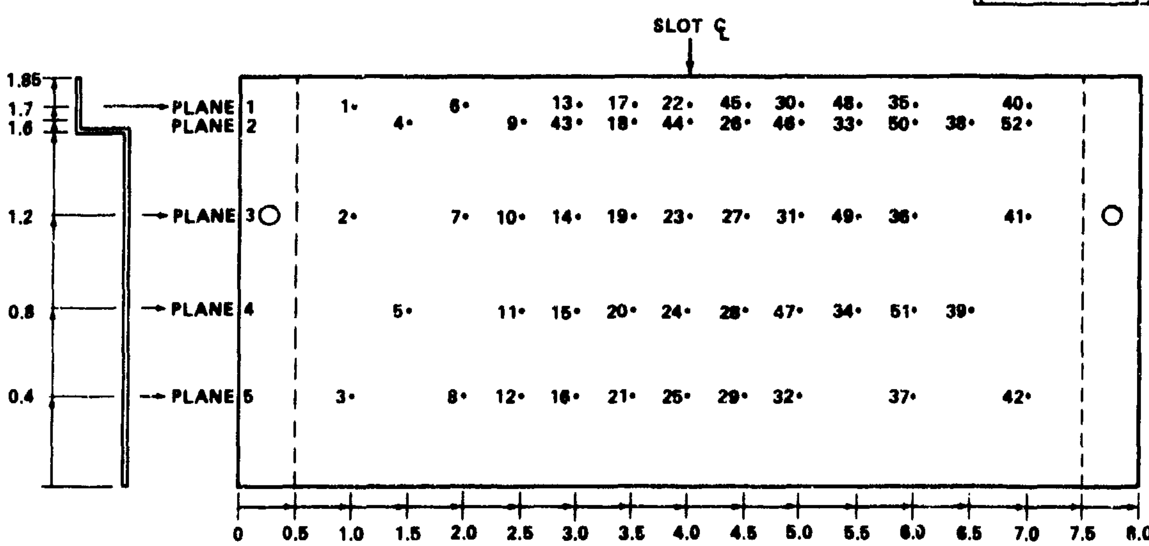

FIG. 7. THERMOCOUPLE LOCATIONS

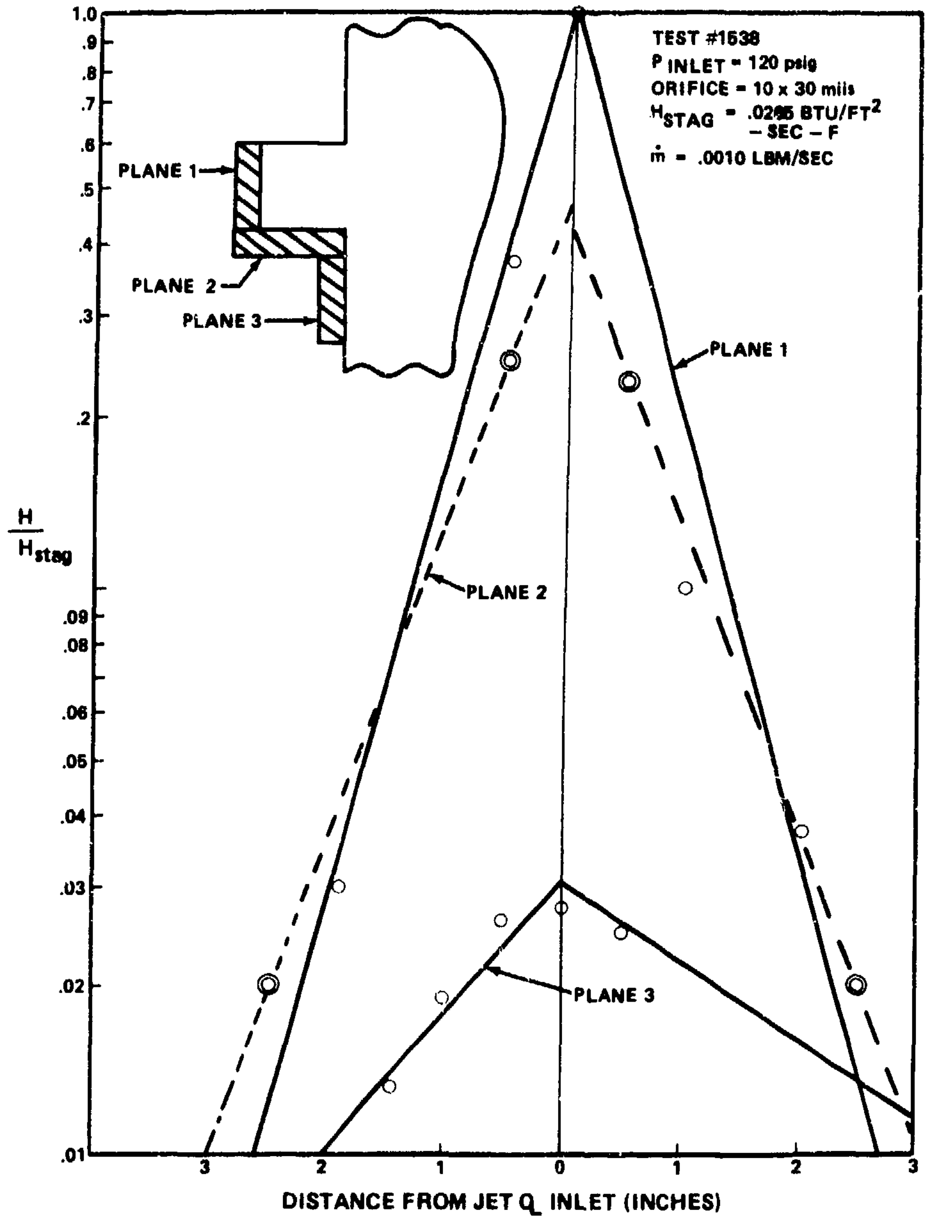

FIG. 8. TEST COEFFICIENTS

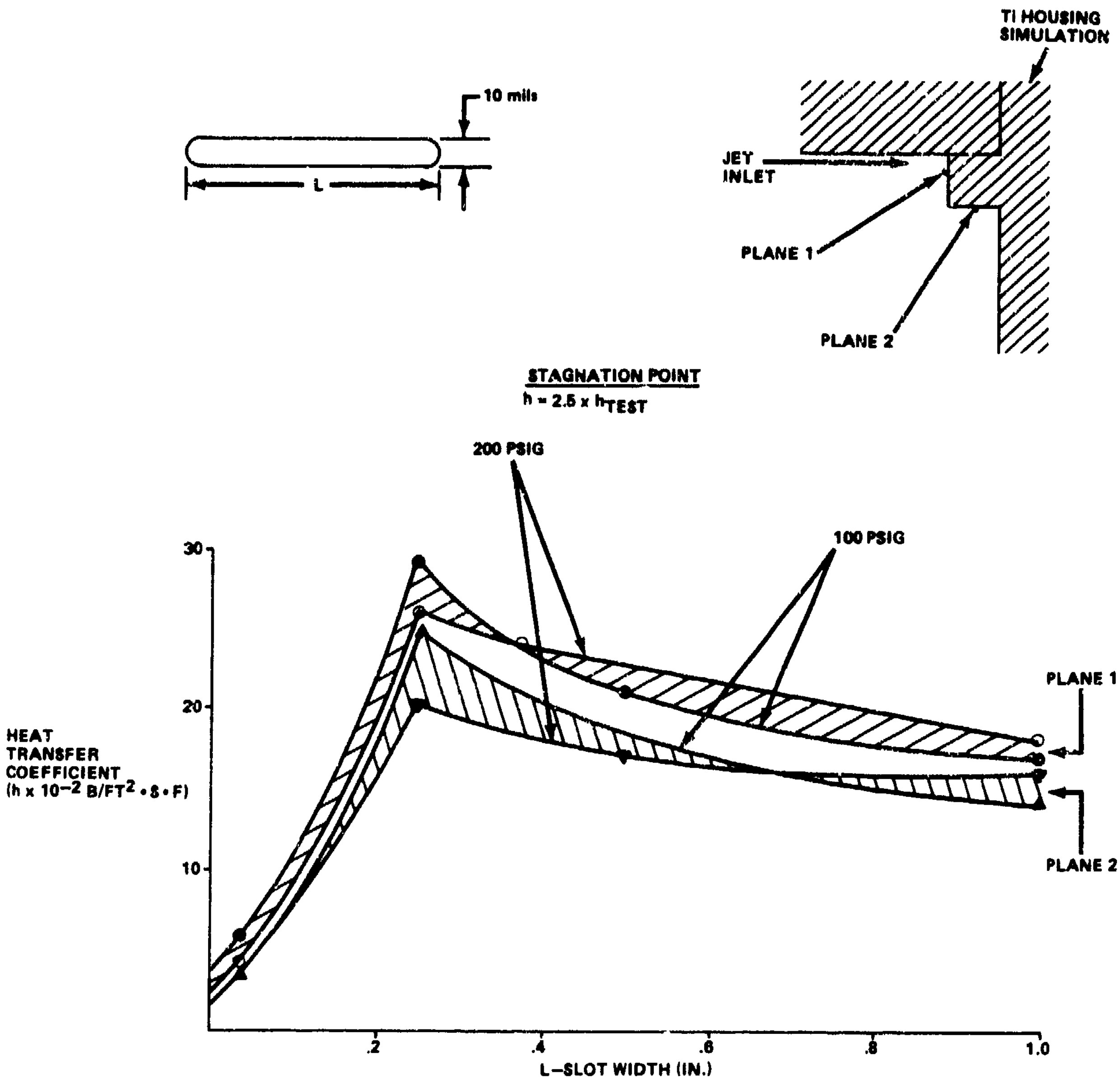

FIG. 9. IUS/SRM–2 GRAFOIL SEAL HOT GAS LEAK HEATING TEST RESULTS

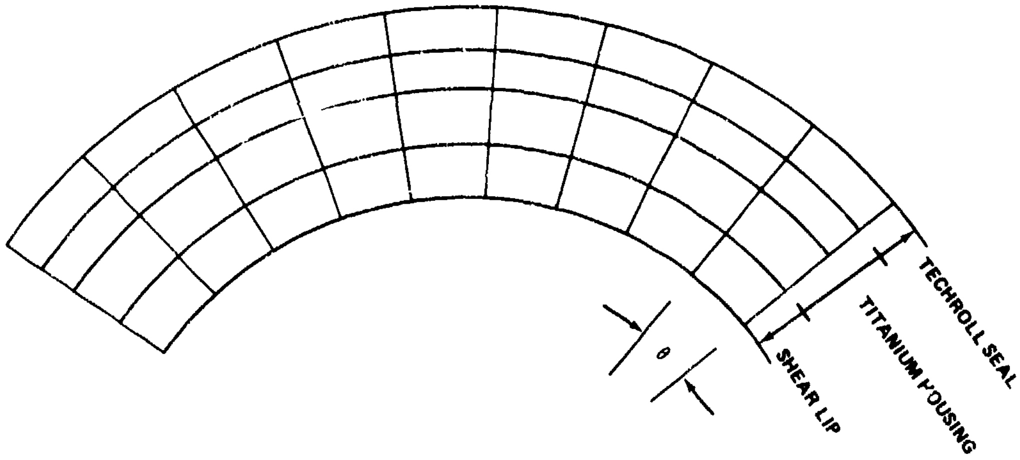

FIG. 10. ANGULAR NODE LAYOUT

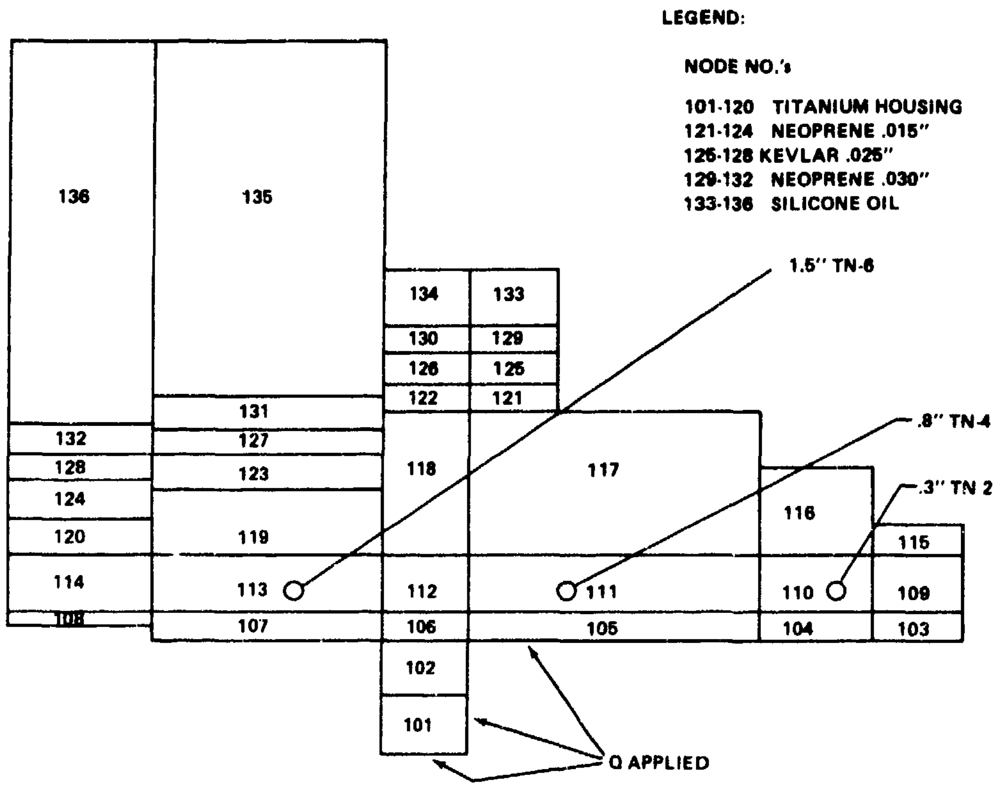

FIG. 11. TITANIUM TECHROLL SEAL HOUSING NODE LAYOUT FOR EACH "WEDGE"

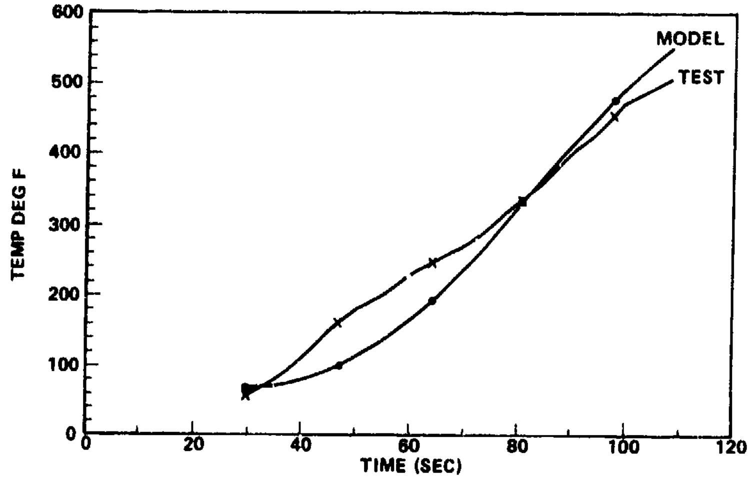

FIG. 12. BL–1 0.3 INCH CORRELATION

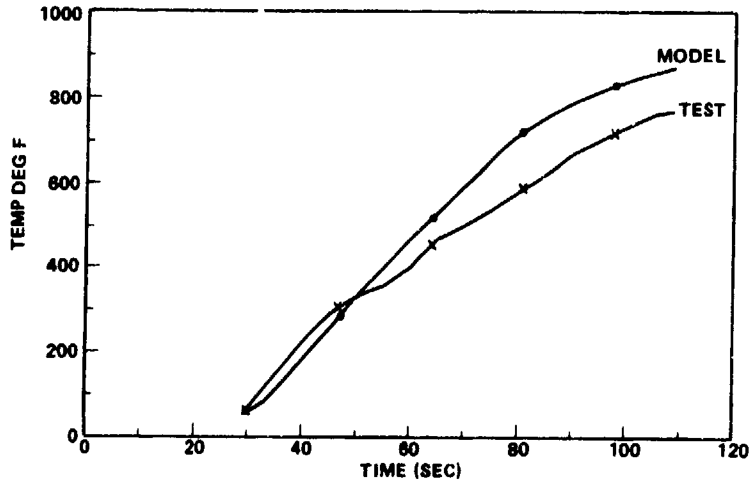

FIG. 13. BL–1 0.8 INCH CORRELATION

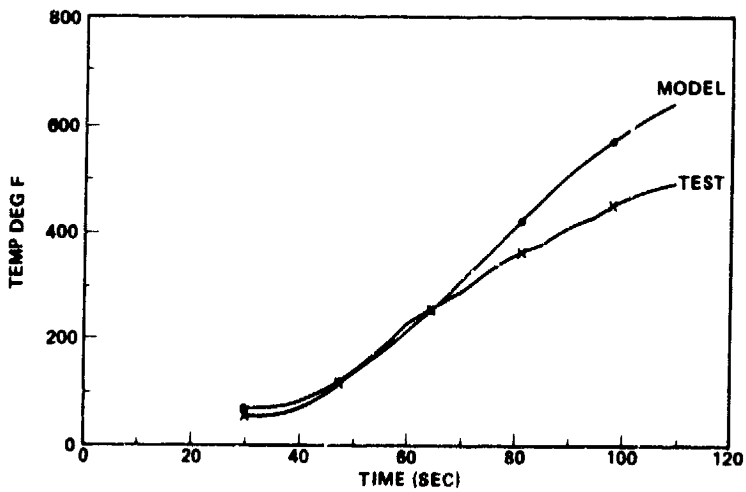

FIG. 14. BL–1 1.5 INCH CORRELATION

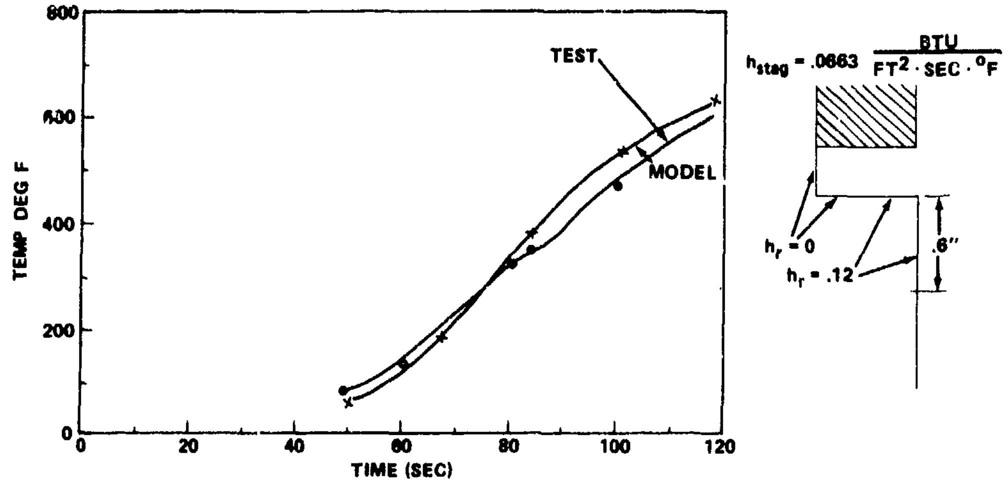

FIG. 15. FQ–1 0.3 INCH CORRELATION

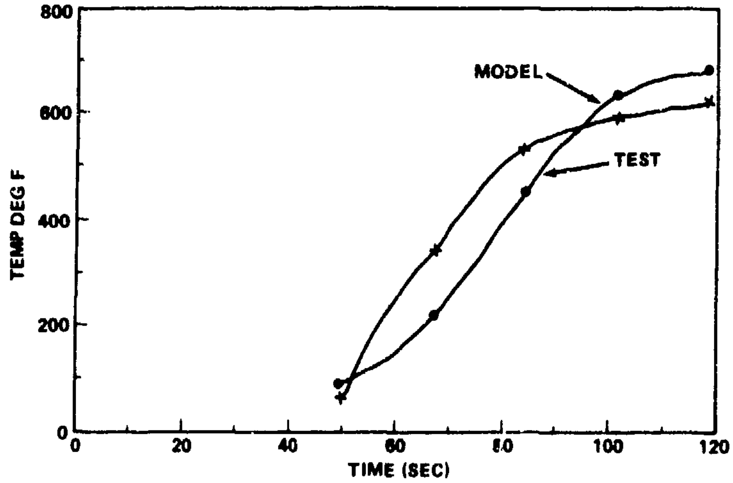

FIG. 16. FQ–1 1.0 INCH CORRELATION

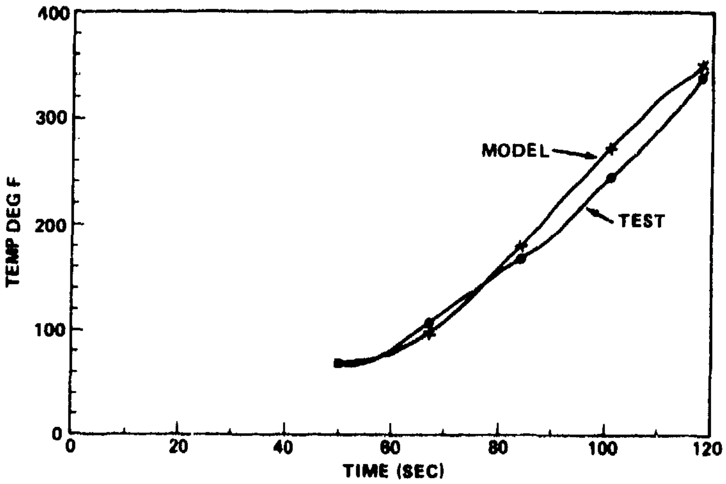

FIG. 17. FQ–1 1.5 INCH CORRELATION

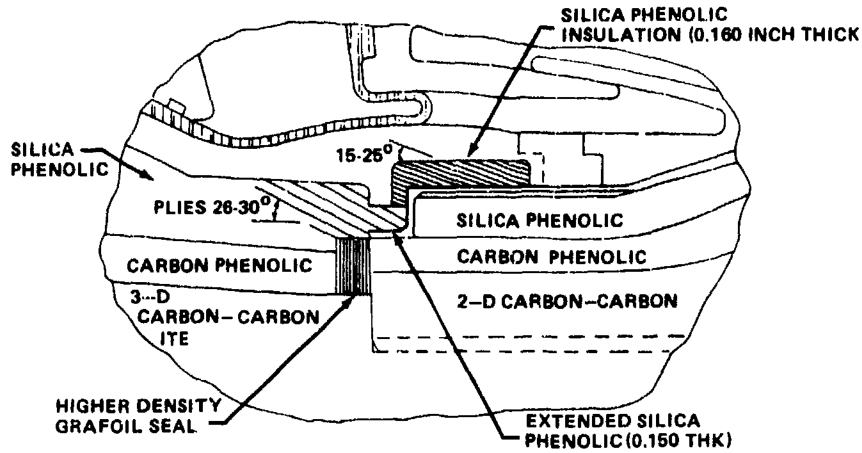

FIG. 18. ENHANCED TPS DESIGN

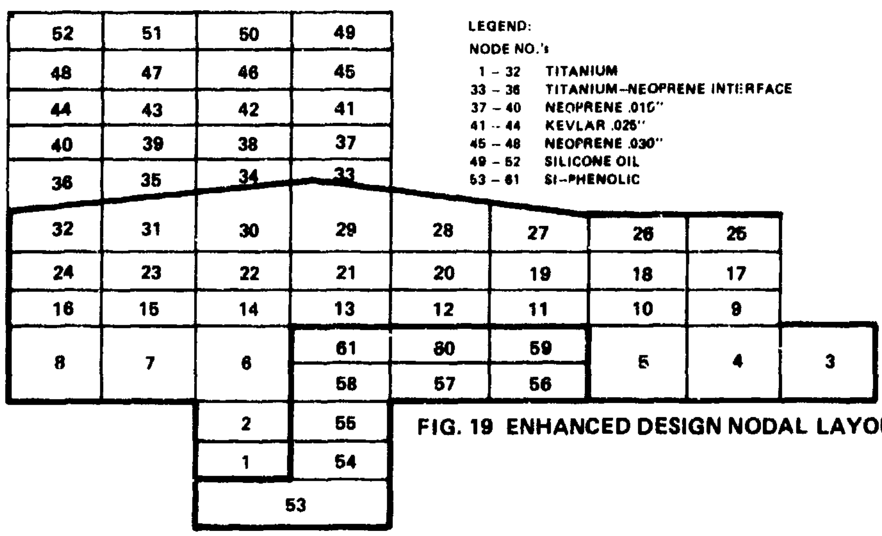

FIG. 19 ENHANCED DESIGN NODAL LAYOUT

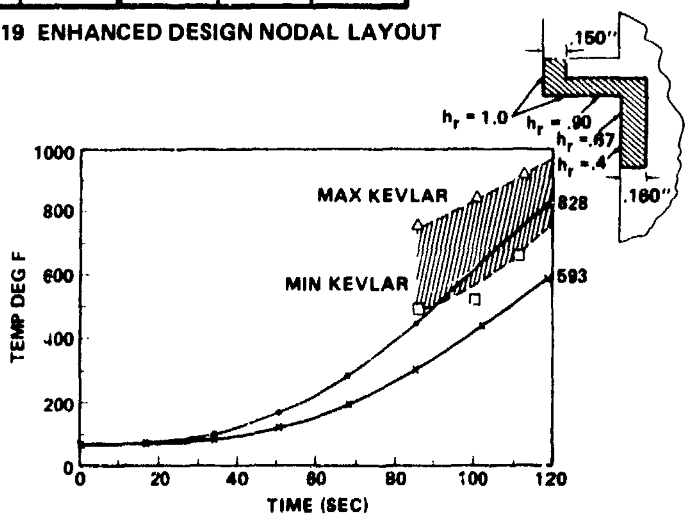

FIG. 20 (WORST CASE HEATING) MINIMUM AND MAXIMUM KEVLAR TEMPERATURES

TABLE I. HEAT TRANSFER COEFFICIENT TESTS SLOW DIMENSIONS

TEST NO.	SLOT SIZE (mils)	FLOW RATE (lbm/sec)	SLOT INLET PRESSURE (psig)	MAX. HEAT TRANSFER COEFFICIENT Hstag X 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 II. 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