Three-Dimensional Thermal Analysis for the Inertial Upper Stage SRM-1 Techroll Housing

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Abstract

An efficient technique for three-dimensional thermal modeling that involves automated preprocessing, analysis, and postprocessing is used to predict the thermal penetration in the inertial upper stage (IUS) SRM-1 Techroll housing (TRH) subject to the worst-case combustion diffusion gas heating. The technique is based on a finite-element method and computer-aided-design geometry modeling. The thermal analysis utilizes the test data obtained for (1) thermal contact resistance between the titanium housing and the titanium gib ring and (2) heating rate distribution on the exposed surfaces of the shear lip and the gib ring. The computed results show that, under normal nozzle assembly and worst-case conditions, a combustion gas leak should not pose a threat to the SRM-1 Techroll seal (TRS) thermal integrity throughout the duration of motor firing.

Contents

The IUS is used to put large payloads into geosynchronous orbit. It consists of two solid-rocket motor stages (SRM-1 and SRM-2) and an equipment support section containing the avionics necessary for guidance and control. During the second IUS flight on April 4, 1983, the fully loaded second-stage rocket motor (SRM-2) experienced a thrust vector control anomaly at approximately 84 s into the burn. The nominal total burning time for the SRM-2 is 105 s. After extensive investigation, in-flight loss of thrust vectoring capability for the IUS SRM-2 has been attributed to bursting of the pressurized TRS on which the nozzle rides. An overview of the IUS motor assembly, flight data, anomaly investigation, design enhancements and modifications, and motor test program has been presented.[1] A localized combustion gas leak through the nozzle thermal protection system has been identified as the most likely cause of excessive heating to the SRM-2 TRH and, subsequently, of the thrust vector control anomaly during the April 1983 flight. Design enhancements and modifications of the TRH thermal protection system, therefore, have been incorporated into the SRM-2[1] to cope with the worst-case heating condition for future IUS flights. A critical question remains to be answered before any future IUS flights take place: "Without any design modification, can the TRH design and thermal protection system for the SRM-1 withstand a severe heating from a combustion diffusion gas leak?" To answer this question, an efficient technique involving the use of PATRAN software[2] for arbitrary three-dimensional geometry modeling and the finite-element thermal analyzer in NASTRAN[3] for general three-dimensional thermal analysis, discussed in Ref. 4, is applied to the SRM-1 TRH thermal environment assessment. The analysis for a worst-case scenario is briefly discussed here. More detailed information is presented in Ref. 5.

The IUS SRM-1 nozzle assembly is schematically illustrated in Fig. 1. It is important to notice that the TRS is located 0.62 in. forward of the shear lip in a nongimbaled nozzle position in the SRM-1, whereas in the SRM-2 the TRS rides on the titanium housing directly above the shear lip. Therefore, under the same heating condition imposed on the exposed surfaces of the shear-lip and gib ring, the TRS in the SRM-1 is less susceptible to a destructive thermal overload than the TRS in the SRM-2 without design enhancements. The complete three-dimensional finite-element geometry model (2262 nodes, 1596 elements) generated from the method discussed in Ref. 4 is illustrated in Fig. 2.

For the worst-case scenario, the TRH is subject to a direct impingement heating of combustion diffusion gas emanating from a slot of length L and width W, as shown schematically in Fig. 2. The TRH is considered to be insulated on all surfaces except the areas exposed to slot gas jet heating. A plane of symmetry is taken to pass through the midlength of the slot. The nodal points of the computational mesh have been

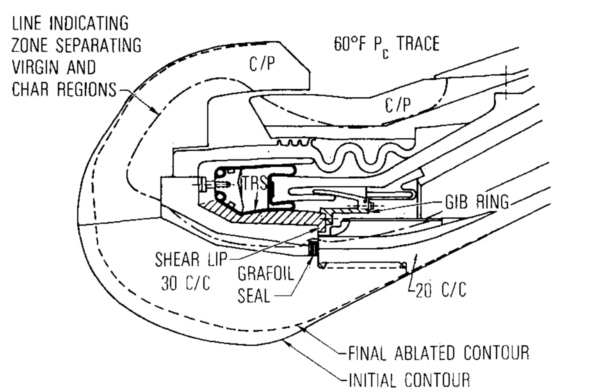

Fig. 1 IUS SRM-1 nozzle assembly schematic.

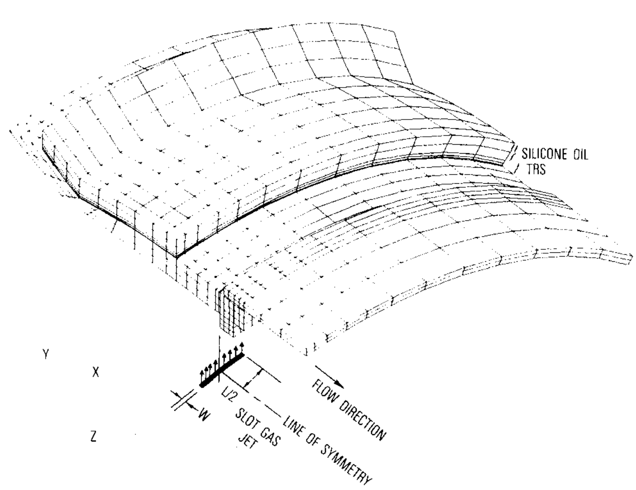

Fig. 2 Three-dimensional SRM-1 TRH finite-element thermal model (back-side surface view).

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clustered near this plane of symmetry to catch any steep temperature gradients in this region. The circumferential region included in the three-dimensional model shown in Fig. 2 is 45 deg. Considering flow symmetry, this effectively represents a 90-deg region of interest.

During the course of this study, the computed TRS temperature was found to be strongly dependent on the contact resistance between the titanium housing and the titanium gib ring. Consequently, an experiment was conducted to evaluate the surface thermal contact resistance. Two titanium pieces were fastened together by the screws torqued to 2 ft-lbf, which is the same torque applied to the IUS motor Techroll joint. The end surface of one titanium piece was heated by a propane torch flame, whereas all the other surfaces were insulated. The thermal contact resistance was then evaluated by matching the results of a simple one-dimensional calculation (in the immediate neighborhood of the contact surface) with the thermocouple data. The computed temperatures are very close to those measured from the experiment, when a thermal contact resistance of 1000 in.^{2}-s-°F/Btu is introduced at the contact surface. This contact resistance is applied to the three-dimensional thermal model.

Realistic values of the heat-transfer coefficient (htc) and its distribution on the exposed surface downstream of the shear lip for the SRM-1 TRH were obtained from a calorimeter test. The results of the calorimeter test show that the peak heating rate on the gib ring is 21% of that on the shear lip. The test also shows that the peak heating rate on the shear lip is 49% of that derived theoretically. The time-varying heat-transfer coefficient history on the shear lip for a 2 × 0.0045-in. (length × width) slot has a maximum value of 6 × 10^{-4} Btu/in.^{2}-s-°F at 80 s after ignition. The diffusion gas temperature, which is essentially the temperature at the interface of the Grafoil seal and the three-directional carbon/carbon integral throat entrance (ITE), is obtained from a nozzle in-depth thermal analysis. Since the NASTRAN thermal analyzer used for the present three-dimensional analysis cannot handle a time-varying heating boundary condition, the heat-transfer coefficient history is modeled in a stepwise fashion. Within each time step, the heat-transfer coefficient is constant. Along the circumferential direction in the three-dimensional model, the heating rates on the exposed shear-lip and gib-ring surfaces are assumed to have the same distribution as those on the symmetry plane up to the circumferential edge of the slot. Beyond the edge of the slot, the heating rate falls off rapidly, much as in the case discussed in Ref. 5. Moreover, different slot sizes have been investigated. The 2×0.0045-in. slot was found to provide the worst heating condition as far as the TRS temperature is concerned and is considered in this study.

The computed three-dimensional temperature contour is given in Fig. 3. The three-dimensional temperature contour clearly demonstrates that under the intensive localized heating a small portion of titanium housing and gib ring can get very hot and become "soft" near the end of burn when, fortunately, the chamber pressure load on the nozzle assembly is small. The margin of safety of the Kevlar layers is illustrated in Fig. 4. On the hot side of the hot Kevlar layer, the maximum temperature reaches 705°F; on the cold side of the cold layer, the maximum temperature is 510°F at the end of burn for a combustion diffusion gas leak starting 47 s after ignition. The computed TRS temperature is within the average maximum allowable temperature defined for SRM-1 TRS,[6] with the minimum thermal margin of safety occurring at approximately 140 s into the burn.

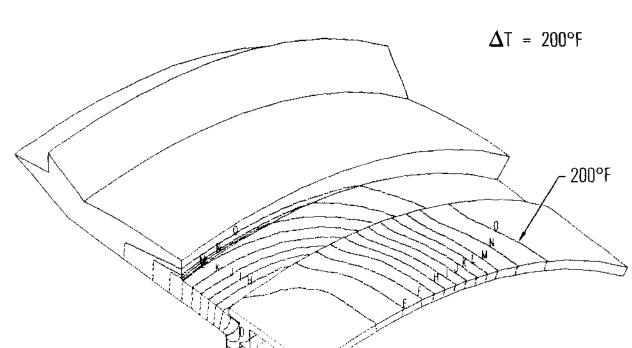

Fig. 3 Three-dimensional temperature contour for the SRM-1 TRH worst-case heating (back-side surface view).

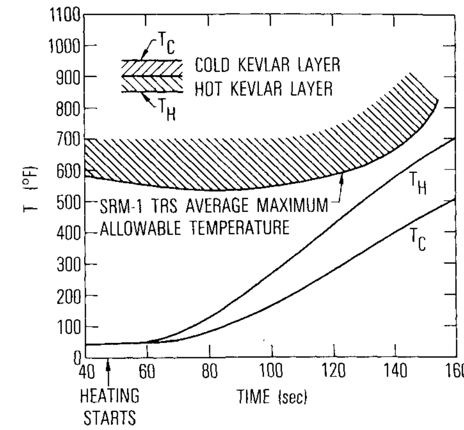

Fig. 4 Comparison of computed Kevlar layer temperatures from three-dimensional analysis with TRS average maximum allowable temperature.

It is important to notice that the results discussed above are based on the situation for a normal nozzle assembly, namely, without a gap forward of the shear lip. If a direct jet impingement heating on the surface forward of the shear lip occurs in a misaligned nozzle assembly, the thermal margin of safety for the TRS, shown in Fig. 4, is greatly reduced.

The results of the analysis indicate that the TRS in SRM-1 is capable of withstanding the worst-case heating, discussed above, without the need for expensive design modifications such as those implemented in SRM-2. Previous studies[4] have shown that despite the limitation of constant specific heat for materials involved in NASTRAN thermal anlaysis modeling, the results obtained from this methodology agree well with the measured data; the maximum difference is less than 10%. Since the completion of this paper, improvement of the three-dimensional finite-element thermal modeling to include variable specific heat and time-varying heating boundary conditions has also been pursued with the use of the finite-element analysis program ABAQUS, which is a useful tool for a highly nonlinear conductive heat-transfer analysis.[7]

Acknowledgment

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