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Propellant Stress Relief Groove for the Titan IV Solid Rocket Motor Upgrade

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A method has been developed to design a propellant stress relief groove (SRG) for solid rocket motors. The method considers a time-dependent pressure distribution in both burn-back and burn-forward analyses and allows a desired bondline stress condition to be incorporated into the SRG design. Application of the method to obtain an improved propellant SRG for the Titan IV solid rocket motor upgrade (SRMU) is illustrated in this paper. The improved propellant SRG obtained from this method for the Titan IV SRMU provides significant enhancement in the propellant structural margin of safety throughout motor firing.

Nomenclature

a = constant for propellant burn-rate equation
H = detachment height of the propellant stress relief groove in Fig. 8, in.
L = depth of the propellant stress relief groove in Fig. 8, in.
n = pressure exponent for propellant burn-rate equation
P = pressure, psia
R = radial coordinate from motor centerline, in.
r = propellant burn rate, in./s
X = axial coordinate for the SRG analysis, in.
x = axial coordinate for the pressure distribution, in.
β = intersection angle between propellant and bondline, deg

Introduction

THE U.S. Air Force Titan IV solid rocket motor upgrade (SRMU),[1] shown in Fig. 1, is being developed to launch large payloads. This is a 126-in.-diam, 112.4-ft-long, three-segment motor with a graphite/epoxy composite case. The motor is loaded with 688,850 lb of hydroxyl-terminated polybutadiene (HTPB) propellant and weighs about 772,750 lb. The nozzle throat is made of graphite/phenolic. The forward and aft exit cone insulators are made of tape-wrapped carbon/phenolic. The nozzle is supported by a flexseal assembly with a maximum 6-deg gimbal capability. The maximum mass flow rate is 5700 lb/s, which produces approximately 1.6 million lbf thrust for each SRMU during liftoff. The Titan IV with two SRMUs is designed to provide a 25% increase in payload delivery capability from the current Titan IV with the steel-case motors. The Titan IV SRMU will be the most powerful solid rocket motor in the U.S. Air Force space launch vehicle program.

To avoid an excessive stress concentration at the bondline between the propellant and the motor case insulation during motor processing, storage and firing, a propellant stress relief groove (SRG) is molded into the forward and aft faces of the propellant grain in the center segment and into the forward face of the propellant grain in the aft segment of the SRMU shown in Fig. 1. For a giant motor like the SRMU, incorporation of a robust SRG in the grain during the motor qualification stage is of paramount importance. This paper discusses a novel analysis method that will generate an improved SRG design for the SRMU. The method considers an unconventional "burn forward" in time from a desired burn-back configuration that will aid in determining the initial SRG shape for the required burn-back configurations. The method is equally applicable to other motors with a stress relief groove molded in the grain of a different configuration from that of the SRMU. Furthermore, the method can be extended to the entire grain design to achieve a predefined, unique ballistic feature for a solid rocket motor.

Method of Analysis

The basic reason for using the stress relief groove in the solid propellant is to alleviate the stress concentration at the bondline between the propellant and the motor case insulation. Making a stress relief groove in the grain, however, will directly affect the propellant stress distribution. From the viewpoint of a grain structural analysis, an optimized SRG design requires that the strength degradation in the grain and the stress concentration at the bondline be minimized throughout motor firing. Depending on the grain and the insulation configuration, each solid rocket motor has its own specific characteristics and, hence, a unique stress relief groove configuration.

A prerequisite for an accurate grain structural analysis is the knowledge of pressure distribution on the regressing surface of the grain during motor firing. This information can be obtained, for example, from Ref. 2, which provides a full Navier-Stokes solution inside motors of an arbitrary configuration. Based on a time-dependent pressure distribution, the burn-back configurations at several time slices during motor firing can be constructed from Ref. 2 as a byproduct of the flowfield solution or from a well-known standard method for the grain design given in Ref. 3. From these propellant burn-back configurations, the intersection angles

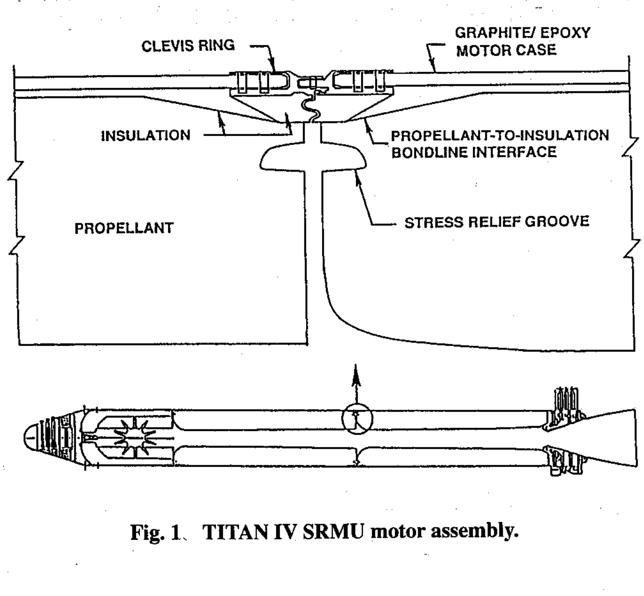

Fig. 1. TITAN IV SRMU motor assembly.

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at the bondline between the propellant and the motor case insulation can be determined. These intersection angles affect the stress condition at the bondline. A singular-point behavior may occur at large intersection angles at the bondline, which cannot be analyzed structurally and needs to be avoided. Adjusting the intersection angles has the similar effect of changing the stress condition at the bondline at any particular time during motor firing. A desired SRG design requires that the stress condition at the bondline not exceed a critical value not only during motor ignition but also throughout motor firing. This can be accomplished by insuring that the propellant burn-back configurations follow a predetermined pattern during motor firing.

A burn-forward analysis is applied here to ascertain that the sequential burn-back configurations of the grain for an improved SRG design follow a predetermined pattern and therefore provide the desired bondline stress condition throughout motor firing. Starting with any burn-back configuration, one can reconstruct the corresponding initial grain shape by applying the propellant burn rate artificially in the opposite direction from that of the normal propellant regression. This is called a burn-forward analysis in this study to differentiate it from the usual burn-back analysis in the standard grain design of Ref. 3. In the burn-forward analysis, the burn rate is also a function of pressure, but it follows a reversed relationship of the pressure variation with time. For each modified burn-back configuration with a selected intersection angle (stress condition) at the bondline, a burn-forward analysis is performed to obtain a unique, initial SRG shape. There will be an initial SRG shape corresponding to each burn-forward analysis at a particular time slice. Enveloping these initial SRG shapes will result in a portion of an SRG configuration, which will produce the desired bondline stress condition throughout motor firing. The remainder of the SRG configuration will be determined by the propellant stress consideration.

The procedures for designing an SRG can be listed as follows:

1) Perform a standard burn-back analysis based on a time-dependent pressure distribution for a grain with a candidate SRG design.

2) Modify propellant burn-back configurations to get the selected intersection angles (stress condition) at the bondline throughout motor firing.

3) Perform a burn-forward analysis with a reversed relationship of the pressure variation with time at several time slices to obtain several initial SRG shapes.

4) Envelop these initial SRG shapes to obtain a portion of an SRG configuration.

5) Adjust the depth and the detachment height of the SRG to get an adequate margin of safety at the bondline and in the SRG during motor ignition.

If necessary, the procedures just listed can be repeated to ensure that the intersection angles at the bondline do not exceed a critical value at any time during motor firing and the final SRG has the desired structural margin of safety. An example of applying this method to improve the structural margin of safety for an SRG design of the Titan IV SRMU is given in the next section.

Application to Titan IV SRMU

A robust SRG design is required for the Titan IV SRMU to ensure that the grain and the bondline have an adequate margin of safety and are insensitive to the change in physical properties affected by the environment over long-term storage and under a worst-case, high-temperature firing condition. The propellant burn rate r is a function of the motor internal pressure, and the motor internal pressure is, in turn, a function of time. For the SRMU, $r = a * P^n$, where $a = 0.0677$, $n = 0.2320$, and P is the local pressure on the grain surface.

A solid rocket motor often has a severe stress environment at the bondline between propellant and insulation during cool down and during motor storage at low temperatures. For the Titan IV SRMU with the stress relief groove in the propellant, grain structural analyses have been performed[1] for the initial grain temperature of 40, 60, and 90°F. It is found that during motor operation the minimum margin of safety occurs in the stress relief groove at 90°F initial grain temperature. At ignition the chamber pressure rise rate is higher, the propellant strain is higher, and the propellant modulus is lower at a high temperature than those at a low temperature.

For the motor head-end pressure given in Fig. 2, which was obtained from Ref. 3 under a high-temperature (90°F) firing condition, the pressure distributions on the deformed grain surface at 11 time slices up to 50 s after ignition have been calculated from the method discussed in Ref. 2. The pressure distribution at any other time slice before 50 s can be obtained from an interpolation. Figure 3 illustrates the pressure distribution vs motor length at four different time slices, namely, 1, 5, 10, and 20 s after motor ignition. The time-dependent pressure is used in the standard burn-back analysis for constructing the propellant burn-back configurations and in the burn-forward analysis for deriving the initial SRG shapes.

Figure 4 shows the burn-back configurations at several time slices for the preliminary SRG design. It is observed that after approximately 8 s into motor firing the burn-back configuration will intersect the motor case insulation at a location where a rapid change in the slope of the motor case insulation profile occurs. This change in the slope of the motor case insulation profile directly affects the intersection angle at the bondline between the propellant and the motor case insulation and has a bearing on the stress condition at the bondline. The implementation of the method discussed in the previous section amounts to modifying the intersection angle at the bondline and performing the burn-forward analysis at several time slices after 8 s into motor firing.

Figures 5–7 illustrate the results of the burn-forward analysis from 10, 16, and 20 s, respectively. The initial SRG shapes obtained from these burn-forward analyses are grouped together in

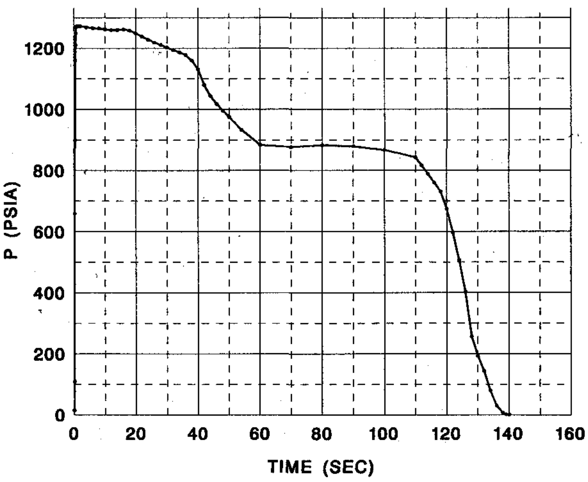

Fig. 2 SRMU head-end pressure history (90°F).

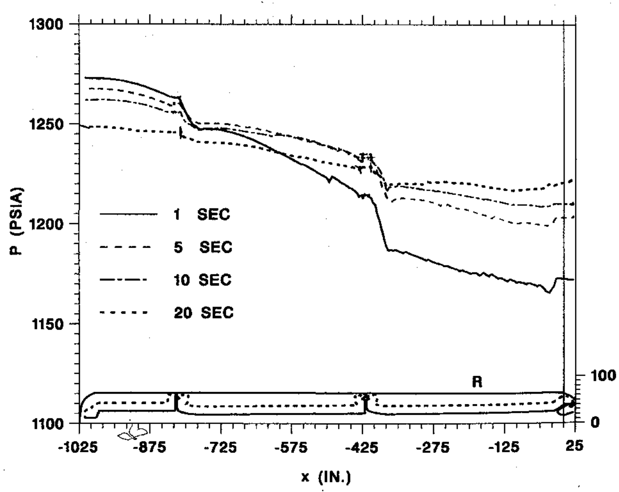

Fig. 3 SRMU pressure distribution (90°F).

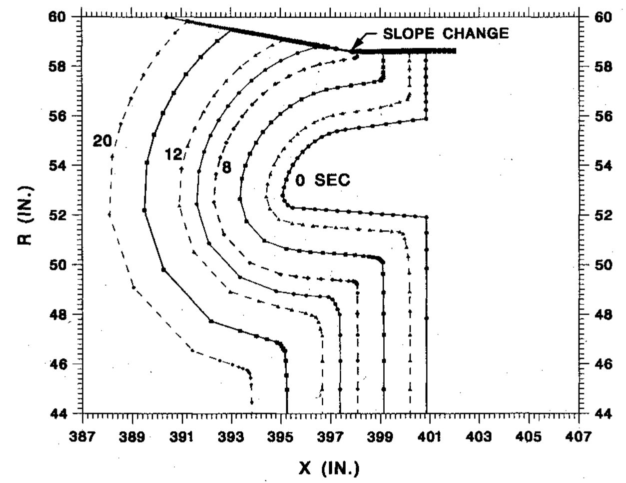

Fig. 4 SRMU preliminary propellant SRG and burn back (configurations at 0, 2, 5, 8, 10, 12, 16, and 20 s).

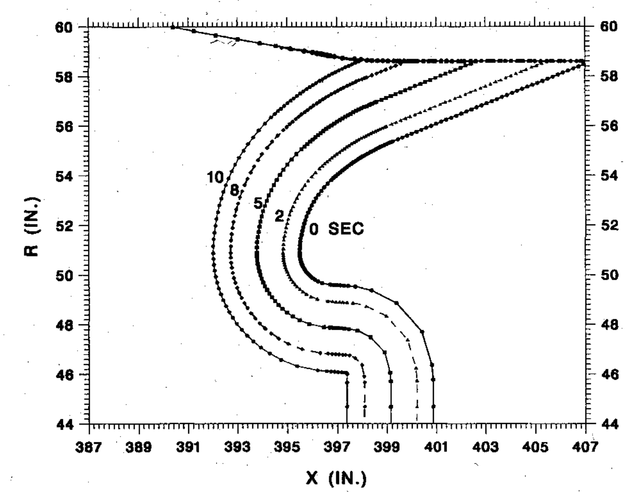

Fig. 5 Burn forward from 10 s (configurations at 0, 2, 5, 8, and 10 s).

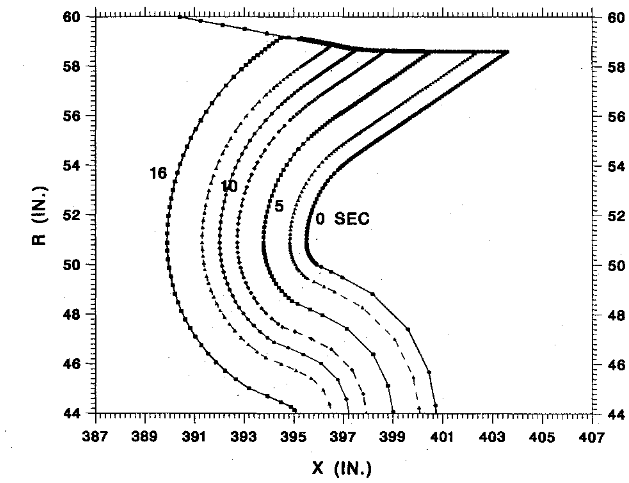

Fig. 6 Burn forward from 16 s (configurations at 0, 2, 5, 8, 10, 12, and 16 s).

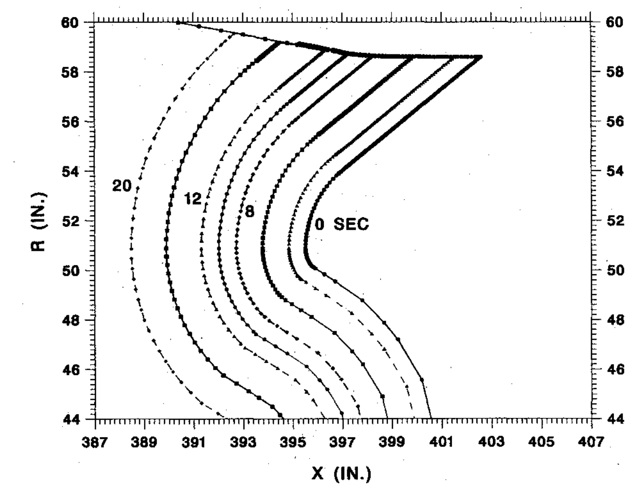

Fig. 7 Burn forward from 20 s (configurations at 0, 2, 5, 8, 10, 12, 16, and 20 s).

Fig. 8. Enveloping these initial SRG shapes will produce an upper portion (larger radial coordinate from the motor centerline) of the SRG configuration, which satisfies the requirement that the intersection angles (stress condition) at the bondline will be less than a critical value at all times during motor firing. For the SRMU this critical value is set at 45 deg for a Poisson's ratio of 0.5 and is considered by the structural analysts[4,5] to be the maximum allowable intersection angle at the bondline between 8 and 20 s after motor ignition, at which time the propellant burn-back configuration progresses beyond the location of change in the slope of the motor case insulation profile. A singular-point behavior is presumed to exist by some structural analysts, if the intersection angle is greater than this critical value after 8 s into motor firing. At 20 s into motor firing, the grain regresses far enough, and the internal pressure of the motor starts a sharp decline as shown in Fig. 2. After that time the structural margin of safety at the bondline or in the groove for the SRMU has increased.

It is necessary to ensure that modification of the propellant burn-back configuration to include the selected intersection angle (desired stress condition) at the bondline does not introduce any local stress concentration in other areas of the burn-back configuration. This means that, in addition to the 45-deg criterion at the bondline, a smooth profile for the modified propellant burn-back configuration is required.

The lower portion (smaller radial coordinate from motor centerline) of the improved SRG design is adjusted to have a shallower depth L than that of the preliminary SRG for an improved propellant strength during motor ignition. The detachment height H for the improved SRG shown in Fig. 8 is chosen such that this detachment height is reduced to zero when the propellant regression surface reaches the location where a rapid change in the slope of the motor case insulation profile occurs. This can be seen from the final burn-back configurations for the improved SRG design given in Fig. 9.

Figure 10 shows a comparison of the preliminary SRG configuration with the improved SRG configuration for the SRMU. Table 1 lists the intersection angles at the bondline after 8 s into motor firing. It shows that the improved SRG has a smaller intersection angle and less bondline stress concentration than that of the preliminary SRG. Before 8 s, both the preliminary SRG and the improved SRG have the same vertical intersection angle at the bondline. But the improved SRG, by virtue of its shallow depth and a smooth, gradual change in the slope, also provides a better structural strength during motor ignition than that of the preliminary SRG.

The grain structural analysis using the ABAQUS[6] finite element program for the preliminary SRG and for the improved SRG has been carried out by the structural analysts. Figure 11 shows the

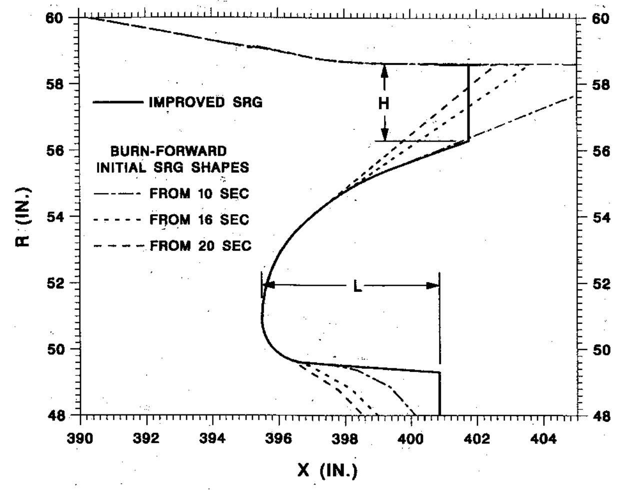

Fig. 8 Initial SRG shapes from burn-forward analysis.

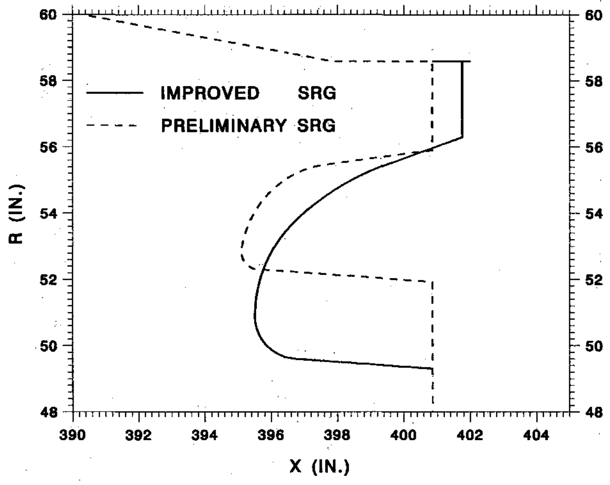

Fig. 10 Comparison of preliminary and improved SRG.

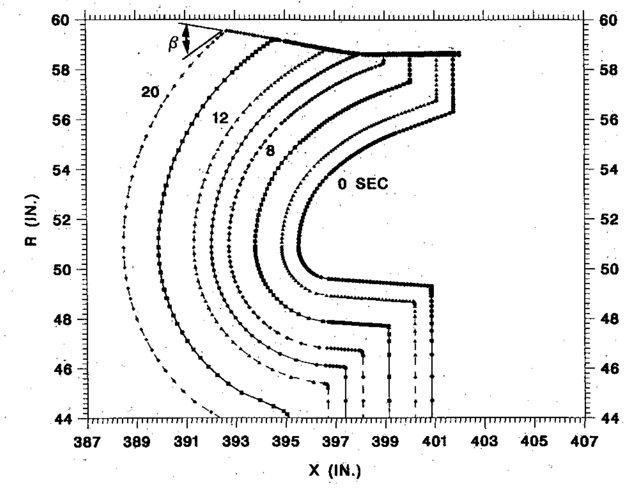

Fig. 9 SRMU improved propellant SRG and burn back (configurations at 0, 2, 5, 8, 10, 12, 16, and 20 s).

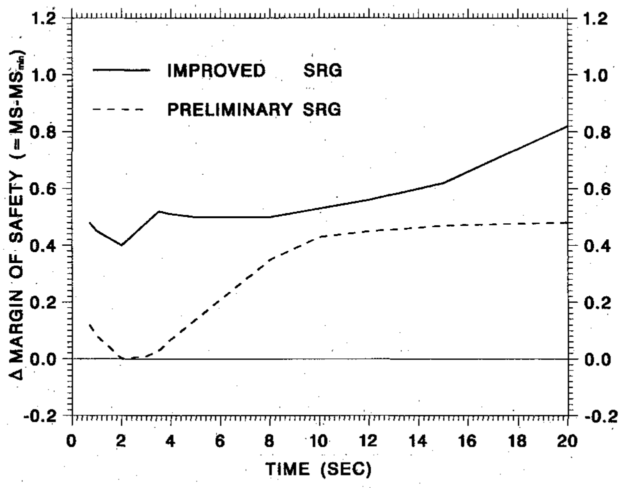

Fig. 11 Margin of safety comparison (90°F).

combined results of calculation for the minimum margin of safety in the stress relief groove and at the bondline for the preliminary and for the improved SRG under a high-temperature (90°F) firing condition. It is obvious that the improved SRG provides significant enhancement in the structural margin of safety over that of the preliminary SRG throughout motor firing. The additional margin of safety gained from the improved SRG is derived from nothing more than a simple geometrical modification in the stress relief groove design, but its effect on enhancing the integrity of the motor in the SRMU program is not trivial. The improved SRG design is more capable of accommodating variation in manufacturing processing and motor service life.

The method presented in this paper is equally applicable to other motors with a stress relief groove in the grain of a different configuration from that of the SRMU. Since every motor has its own characteristics, the stress relief groove of a particular motor, in general, will be different from that of the SRMU. The motor characteristics, such as grain design, internal pressure distribution, propellant composition, motor case insulation profile, motor case bondline capability, and nozzle geometry, influence the design of a stress relief groove. Moreover, the method is not necessarily restricted to the stress relief groove analysis. It is believed that the burn-forward analysis method and the concept presented in this study can be extended to improve the entire grain design to achieve a predefined, unique ballistic feature for a solid rocket motor.

Table 1 Intersection angle at bondline

Time, s	Preliminary SRG β, deg	Improved SRG β, deg
10	25	24
12	37	35
16	47	44
20	55	45

Conclusions

A novel method to design a propellant stress relief groove for solid rocket motors has been presented. A unique feature of the method involves the use of the burn-forward analysis, which enables the desired bondline stress condition to be incorporated in the SRG design. For the Titan IV SRMU the method presented in this study produces an improved SRG with a significantly enhanced structural margin of safety over that of the preliminary design throughout motor firing. This increases the confidence level of launching expensive payloads with the Titan IV SRMUs.

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References

[1]Anon., "Titan IV SRMU Rocket Motor Segments, Delta ICDR for the Internal Insulation, Propellant and Case Bond, and O-Rings," Hercules, Inc., SDRL SR-D04, Magna, UT, Aug. 1992.

[2]Chang, I-S., "An Efficient, Intelligent Solution for Viscous Flows Inside Solid Rocket Motors," Chemical Propulsion Information Agency, Applied Physics Lab., CPIA-PUB-560, Vol. 2, Laurel, MD, Oct. 1990, p. 47; also AIAA Paper 91-2429, June 1991, and JANNAF Paper 2D-1.

[3]Nickerson, G. R., Dunn, S. S., and Berker, D. R., "The Solid Propellant Rocket Motor Performance Computer Program (SPP) Version 7.0," Air Force Aeronautical Lab., AFAL-TR-87-078, Edwards AFB, CA, Feb. 1992.

[4]Williams, M. L., "Stress Singularities Resulting from Various Boundary Conditions in Angular Corners of Plates in Extension," *Journal of Applied Mechanics, Transactions of the ASME*, Vol. 19, No. 4, 1952, pp. 526–528.

[5]Zak, A. R., "Stresses in the Vicinity of Boundary Discontinuities in Bodies of Revolution," *Journal of Applied Mechanics, Transactions of the ASME*, Vol. 31, No. 1, 1964, pp. 150–152.

[6]Anon., *ABAQUS Theory Manual*, Hibbitt, Karlsson & Sorensen, Inc., Providence, RI, Aug. 1982.

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