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Finite Element Simulation of Solid Rocket Booster Separation Motors During Motor Firing

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One of the toughest challenges facing Solid Rocket Booster (SRB) engineers is to ensure that any design changes made to the Shuttle-Derived Booster Separation Motors (BSM) for future space exploration vehicles is able to withstand the increasingly hostile motor firing environment without cracking its critical component – the graphite throat. This paper presents a critical analysis methodology and techniques for assessing effects of BSM design changes with great accuracy and precision. For current Space Shuttle operation, the motor firing occurs at SRB separation – approximately 125 seconds after Shuttle launch at an altitude of about 28 miles. The motor operation event lasts about two seconds, however, the surface temperature of the graphite throat increases approximately 3400°F in less than one second with a corresponding increase in surface pressure of approximately 2200 pounds per square inch (psi) in less than one-tenth of a second. To capture this process fully and accurately, a two-phase sequentially coupled thermal-mechanical finite element approach was developed. This method allows the time- and location-dependent pressure fields to interact with the spatial-temporal thermal fields throughout the operation. The material properties of graphite throat are orthotropic and temperature-dependent. The analysis involves preload and multiple body contacts.

Nomenclature

BDM = Booster Deceleration Motor
BSM = Booster Separation Motor
BTM = Booster Tumble Motors
CFD = Computational Fluid Dynamics
CLV = Crew Launch Vehicle
deg, ° = Degree
F = Temperature, Fahrenheit
FEM = Finite Element Model
FOS = Factors Of Safety
F_{tu} = Ultimate Tensile Strength
HLV = Heavy Lift Vehicle
MEOP = Maximum Expected Operating Pressure
MS = Margin of Safety
NT = Nodal Temperature
NASA = National Aeronautics and Space Administration
psi = pounds per square inch
RTV = Room Temperature Vulcanizing
s = Stress
SFT = Stress Free Temperature
SRB = Solid Rocket Booster
SRM = Solid Rocket Motor
ult = Ultimate
UT = Total Displacement

I. Introduction

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THE Booster Separation Motors (BSMs) have been essential components and have repeatedly demonstrated successful operations for the Space Shuttle. The purpose of the BSMs is to push the Solid Rocket Boosters (SRBs) away from the External Tank and the Orbiter after the Solid Rocket Motors have completed the boost phase (Figure 1). Since the BSM technology is reliable and performance is consistent, they are proposed for use with future space exploration vehicles of the Constellation Program – the Crew Launch Vehicle and the Heavy Lift Vehicle (Figure 2). The new vehicle design will use similar motors oriented in various directions to provide either a separation (BSMs), a rotation (Booster Tumble Motors or BTMs), or a deceleration (Booster Deceleration Motors or BDMs) assist necessary for stage separation events to occur at approximately Mach 6 (Figure 3). One of the toughest challenges facing Solid Rocket Booster engineers is to ensure that any design changes made to the Shuttle-Derived BSM is able to withstand the potentially increasing hostile motor firing environment of the future vehicles without cracking its critical components – including the graphite throat[1] – affecting performance and generating debris. For current Space Shuttle operation, the 16 BSM firings occur at SRB separation – about 125 seconds after Shuttle launch at an altitude of about 28 miles and at a comparatively low Mach 4 (Figure 1). The propellant primary burn lasts for less than one second but the motors continue to tail-off for about another second. During this period, the BSM components experience a sharp thermal-mechanical load cycle. The surface temperature of the graphite throat increases approximately 3400°F in less than one second with a corresponding increase in surface pressure of approximately 2200 pounds per square inch (psi) in less than one-tenth of a second after ignition.

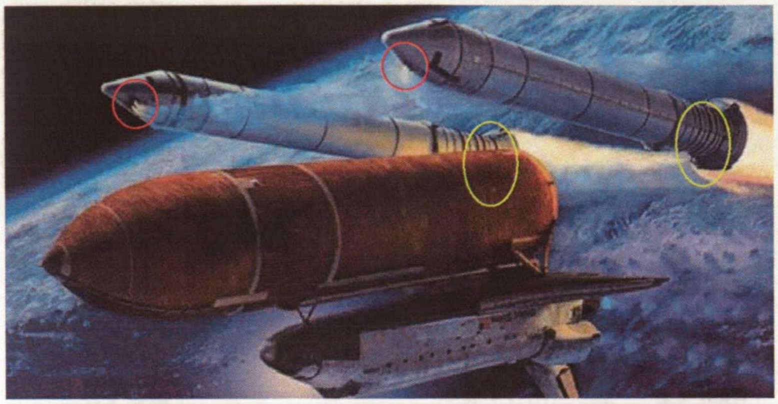
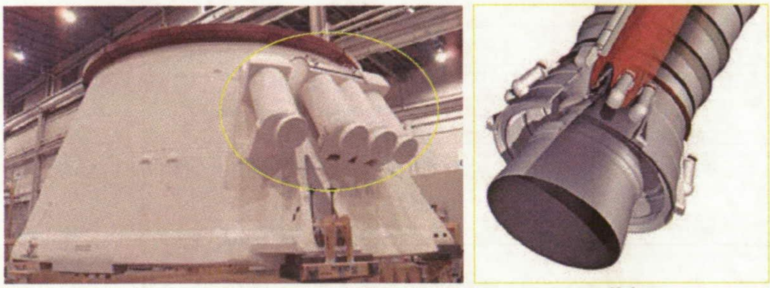


Figure 1. Eight BSMs attached to each Solid Rocket Booster (SRB), four on Frustum (red circles) and four on Aft Skirt (yellow circles)

Figure 2. Crew Launch Vehicle (right) and Heavy Lift Vehicle



(a) **(b)**

Figure 3. Existing Aft BSM configuration (a) and future BTM or BDM configuration (b)

Previously, finite element models developed to evaluate the response of the graphite throat lacked sufficient details to thoroughly capture component response. Adhesive bondlines, assembly threads and Motorcase attachment details had historically not been included. The resulting thermal and mechanical induced stresses were relatively high and barely met the Factors-of-Safety (FOS) requirement under the current condition. With the increasing loading environment expected, the Shuttle-Derived BSM (BTM or BDM) analysis will require a more detailed and accurate modeling methodology in order to meet the strict FOS requirement specified for manned spaceflight vehicles. To achieve this, a two-step sequentially coupled thermal-mechanical finite element approach was developed. First, a heat transfer analysis was conducted with SINDA/G on the 3-D, 180 degree symmetric structural model's element mesh to obtain a sequence of spatial-temporal thermal fields. Second, a sequentially coupled analysis – intertwining the thermal fields with the pressure fields obtained from CFD analysis – was performed to achieve the combined time-dependent thermal-structural effect. The model also contains the overclosure due to assembly torque and contact interactions between the threads of different parts, adhesive bondlines, and RTV/sealant.

II. BSM Configuration and Issues

As shown in Figure 4, the BSM assembly consists of a lined aluminum motor case that houses the solid rocket propellant, an igniter assembly that initiates the motor firing, and an aluminum closure assembly. Shown in Figure 5 is a cross-section view of the closure subassembly. It includes a graphite throat insert, an aluminum aft closure, and a steel exit cone. The graphite throat is bonded with the aluminum closure using an adhesive. The exit cone is threaded into the aluminum closure all the way until touching the other end of the closure. The assembling process results in an overclosure between the exit cone and closure, creating a preload at the interface. Separating the exit cone from the graphite throat is a small gap, or aft gap. The aft gap is filled with a sealant to prevent local overheating.

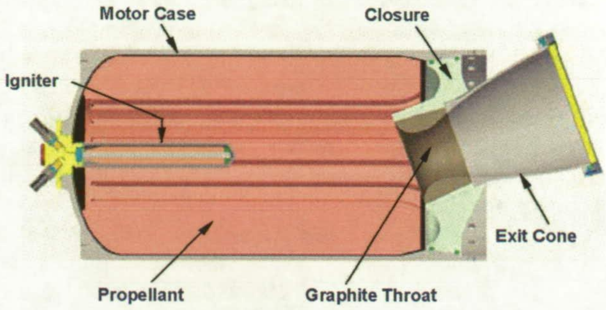


Figure 4. BSM Motor Assembly

One of the most critical issues of BSMs is about the potential for cracking of the graphite throat (Figure 6). Historically, there have been two (2) known cases of graphite throat cracking. One was observed in post-flight inspection and one occurred during a Lot Acceptance Test in 2001. Prior analyses conducted, without the advantage of recently added finite element model enhancements, concluded that the entire graphite throat was under compression and, therefore due to the high compressive capability of graphite, the throat should not crack. In addition, the graphite throat has not been considered to be a load-bearing structural component; therefore, a program mandated strength requirement had not been imposed.

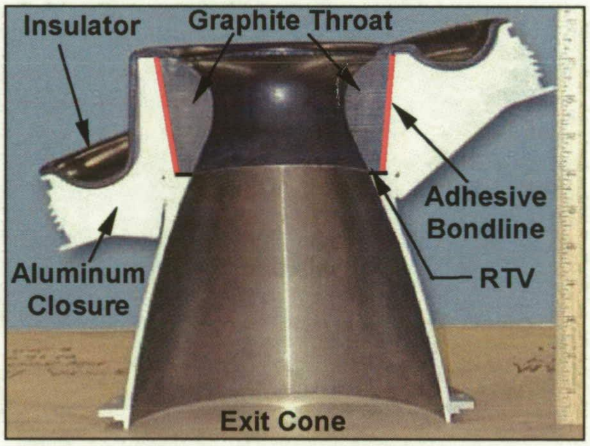


Figure 5. BSM Closure Subassembly

Only since 2004, after the Columbia accident, has a graphite throat of a BSM been classified as a critical structural component, thus requiring adequate safety factors for manned spaceflight supported by analysis and model validation from testing[2]. Since then, the finite element model has been refined, supported by unique validation tests. As a result, advanced finite element analysis methodologies and techniques have been developed and verified.

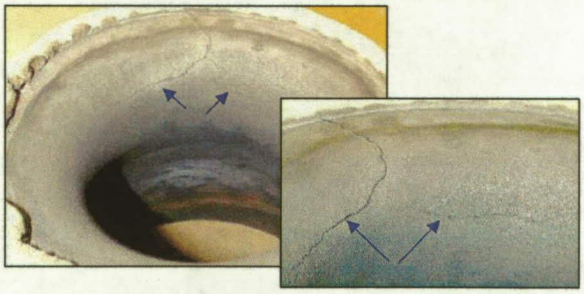


Figure 6. Cracked Graphite Throat from Tests

III. Modeling Approach

After careful study of all the past analyses and the test results, the following four areas have been determined to be essential to the modeling of a BSM:

1) The number of elements through the thickness of the adhesive bondline.
2) The temperature-dependent behavior of the adhesive bondlines, aluminum closure, and steel exit cone, as well as the orthotropic and temperature-dependent properties of the graphite throat.

3) In a high internal pressure environment, the structural interaction between motor case and closure assembly are important.

4) The time- and spatial-dependent thermal fields.

A. Model Geometry

The overall view of the BSM Finite Element Model (FEM) is shown in Figure 7. For clarity, the connection details between the major components as well as the adhesive bondline and aft gap sealant are given in Figure 8.

Enhancements made to the FEM included a greatly increased mesh density of the graphite throat, especially at the inner diameter. This increased mesh density was required to accommodate the steep thermal gradient experienced by the graphite throat during motor burn. In addition, the mesh of the adhesive bondline was increased to include multiple elements through the thickness rather than the traditional single element representation. Again there is a steep thermal gradient across the adhesive that varies along the axial length of the throat to closure bond. This has been demonstrated to play an important role in the stresses that develop in the throat. It is believed that the refined mesh density in the adhesive bondline is able to better represent the degradation of the adhesive stiffness with temperature over the time of BSM motor operation. Additional geometric details have been added to the FEM, including RTV elements in the aft gap, motorcase with the buttress threads for closure to case connection and a better representation of the attach constraints.

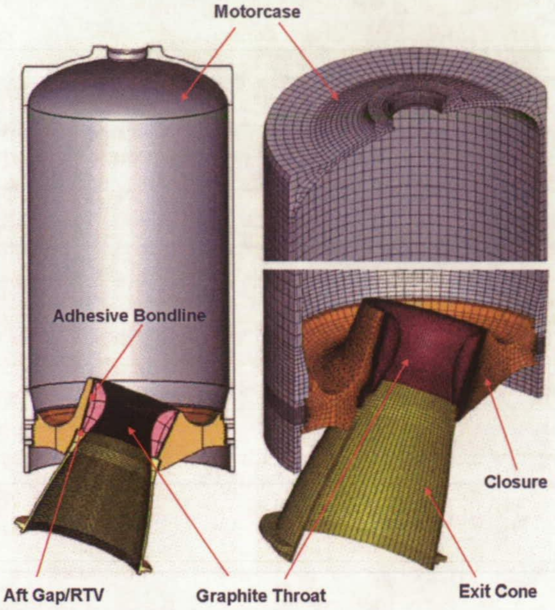


Figure 7. BSM FEM Configuration

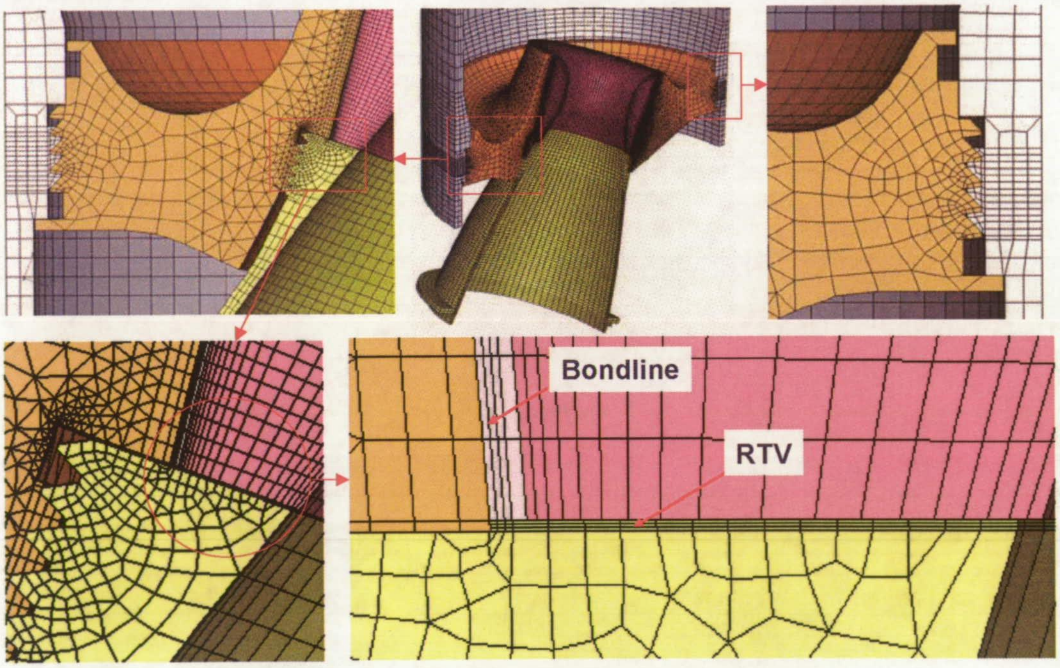


Figure 8. Close-up Views of BSM Model Configuration

B. Material Properties

As an input to the FEM, temperature dependent material properties were used for the components being modeled, namely the coefficients of thermal expansion, elastic modulus and Poisson's Ratio. The material properties required for the analysis are well established for the throat, aft closure, exit cone and throat to exit cone sealant.

The throat to closure bondline however was not completely characterized for this application. The different rates of thermal expansion for the graphite and aluminum, and the pressure from the short duration of the motor burn actually put areas of the bondline into compression. Generally, only tensile and shear material properties are available for adhesives. Thus understanding the compressive response of the adhesive bondline at various temperatures was identified as necessary for best assessing resulting stresses within the throat. Testing was conducted to obtain the compressive modulus of the adhesive and incorporated into the finite element model for results comparison[3].

Material strength plays an important role in determining whether the factor of safety is met. The allowable stress value is determined from the ultimate tensile strength of the graphite material. As a brittle material, graphite does not have a yield point, thus the ultimate strength of the material is used for factor of safety and margin of safety calculations. Strength of graphite, relative to billet location from which a throat is machined, is known to vary. Therefore, "A" basis properties have been obtained and used as the minimum allowable strength for the graphite. Graphite is an orthotropic material with varying properties designated for across-grain ("c") and with-grain ("ab") material directions[4]. The axis of the throat with respect to grain direction is typically such that the with-grain, or "ab" strength is associated with the radial/hoop orientation.

The BSM graphite throat is a unique component and the traditional method (applying a load to result in 1.4 times the stress state) for model validation as interpreted from MSFC-HDBK-505 does not apply. Increasing the thermal and pressure inputs by 40% in a BSM static firing is not a realistic option for the graphite throat. Determining and testing a condition that increases stresses within the graphite throat by a 1.4 factor would present a test configuration grossly outside the potential physical bounds of a BSM firing. Therefore, model validation testing for the BSM at the component level is the most reliable approach for assessment and validation of the modeling input.

C. Boundary Conditions

The Finite Element Model was constructed as a 180° symmetric representation. The following boundary conditions and contact surfaces were applied:

1) Symmetry plane
    a. Symmetric constraints
2) Forward face of motor case
    a. Constrained in all three directions
3) Aft face of motor case
    a. Radial constraints
4) Contact surfaces
    a. Exit cone to closure: predefined overclosure
    b. RTV to throat
    c. RTV to closure
    d. Glue contact between threads

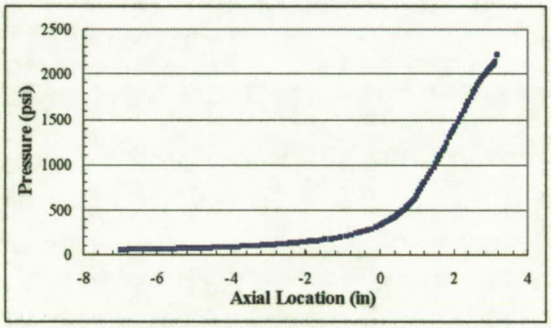


Figure 9. BSM Chamber Pressure Distribution

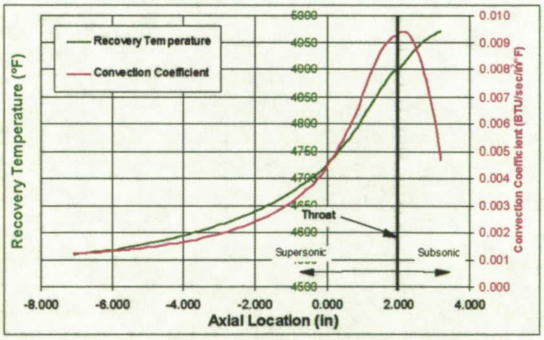


Figure 10. BSM Firing Thermal Environment

D. Loads

Of importance to the stress/strain results of a BSM finite element analysis are the loads. In this instance, the pressure and temperatures experienced during the BSM firing are the external mechanical and thermal loads, respectively, acting on the BSM assembly. The preload due to assembling overclosure is the internal load at the interface of the exit cone and closure.

Figure 9 shows a sample pressure distribution along the axial axis of the exit cone and throat on their inner diameter surfaces. Since the pressure is time-dependent, its amplitude varies with time during the course of motor firing. Figure 10 shows the sample thermal inputs to our heat transfer analysis. This temperature profile is also time-dependent and its amplitude varies with time during the motor firing.

E. Heat Transfer Analysis

The heat transfer analyses were conducted for the meshed FEM using FEMAP, which is the graphical interface for SINDA/ATM. The model is then translated into a SINDA/G input file and thermal inputs and boundary conditions are applied. Time steps for every tenth of a second generate nodal temperatures that are directly applied to the structure model. Transient temperatures are predicted from BSM ignition to 2.0 seconds to envelope the BSM function. Figure 11 is a snapshot of thermal output from SINDA/G. This approach provides a direct transfer of transient temperature conditions into the structural assessment.

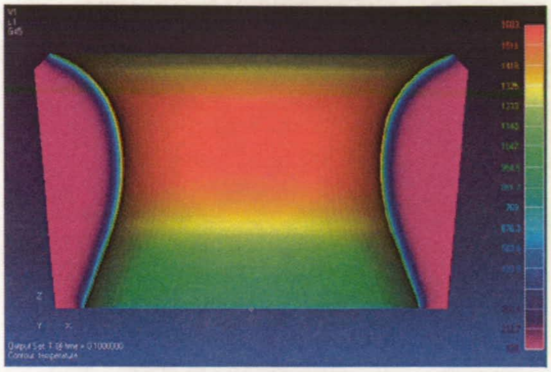


Figure 11. Snapshot of Thermal Field Output from Heat Transfer Analysis

F. Sequentially Coupled Analysis

The sequentially coupled thermal-mechanical analysis was performed using ABAQUS/Standard finite element program. The analysis process consists of following procedure.

- Calculate the preload due to overclosure at the initial step at an initial temperature of 70°F.
- Increase the BSM assembly model temperature from 70 to 120°F at the second load step.
- Import sequential/time-consistent temperature fields obtained from heat transfer analysis into the structural model.
- Apply time- and location-dependent pressure fields to the inner diameter surfaces of the exit cone, throat insert, closure, and motor case.
- For each selected time intervals of 0.1-second duration, perform analysis with simultaneous temperature and pressure inputs.

Combined thermal and pressure loads were evaluated for a total duration of 2.0 seconds. The extreme combined loading event that occurs for one (1) second following BSM ignition for the graphite throat is the worse case and envelopes any pre-launch or ascent loading.

IV. Analysis Results

The BSM analysis results include temperature, displacement, stress and strain from which factors of safety (FOS) and margins of safety (MS) are calculated.

A. Temperature, Displacement and Stresses

A contour plot of the closure subassembly nodal temperatures (NT) at the time of maximum surface temperature is shown in Figure 12. The displacement contour plots of the closure and graphite throat are shown in Figure 13. The top contour plot illustrates the state of the closure and throat during the initial overclosure load step, prior to pressure loading. The magnified displacements (150X) of the closure and graphite throat due to pressure loads are shown in the bottom contour plot. As seen from the plots, during motor burn, the generated pressure distorts the closure asymmetrically. The geometry of the closure provides circumferentially varying pressure surfaces for the normal pressure loads to react upon. These loads act relative to a symmetric graphite throat that is housed within. As a result, a non-uniform displacement of the closure and throat occurs, which contributes to the maximum hoop stress localized at the aft outer diameter of the graphite throat, as shown in Figure 14.

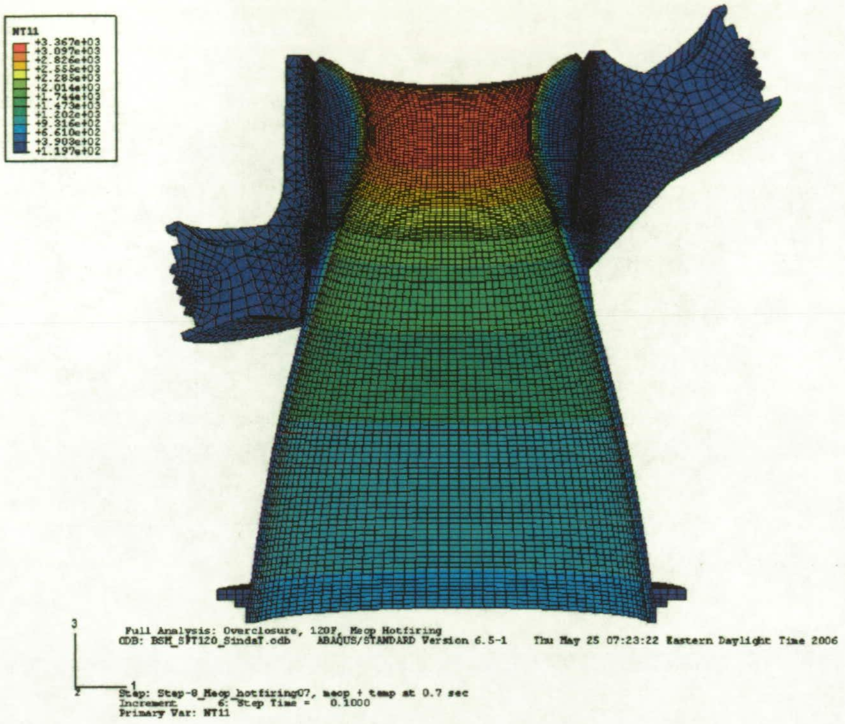


Figure 12. Thermal Plot of Closure Assembly at Time of Maximum Temperature of Approximately 3400°F

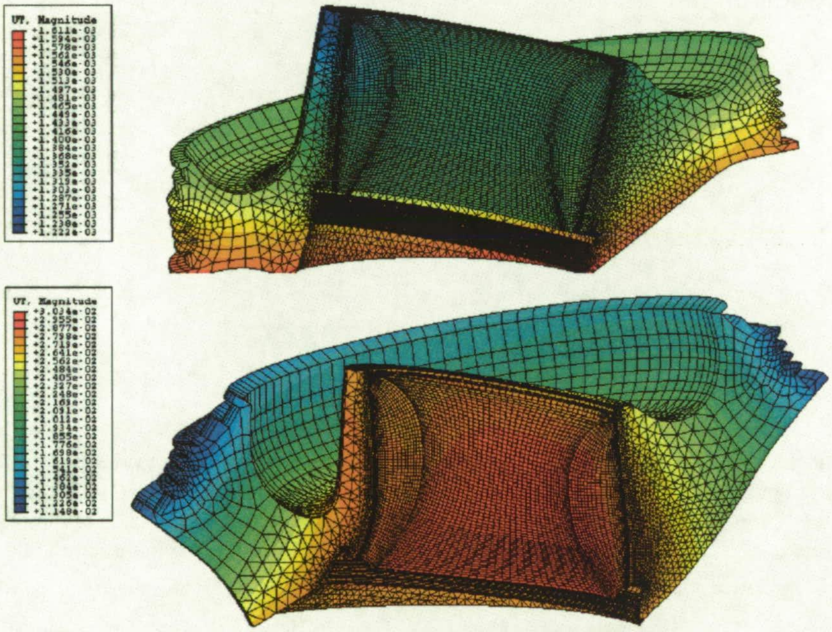


Figure 13. Displacement Contour Plots of the Closure and Graphite Throat at the Initial Load Step (Top) and at 0.3 Seconds after Motor Ignition (Bottom)

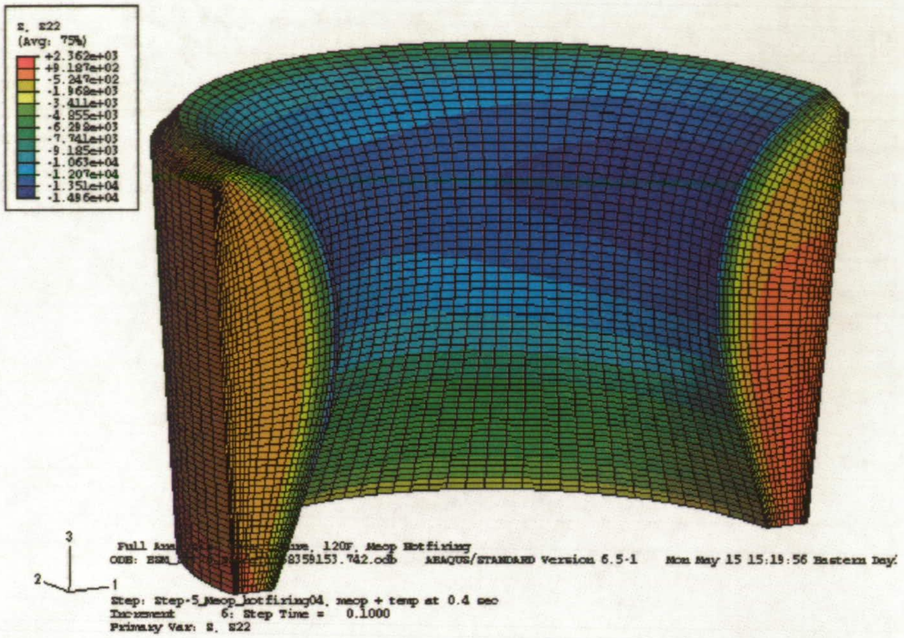


Figure 14. Stress Contour Plot of Graphite Throat at Time of Maximum Hoop Stress

B. Margin of Safety

The minimum margin of safety for the BSM graphite throat is governed by the aft hoop stress. The ultimate factor of safety is calculated as:

$$FOS_{ult} = \frac{F_{tu}("ab")}{(\sigma_{Hoop\_Max})} \tag{1}$$

Where, F_{tu}("ab") is the "A"-Basis ultimate tensile strength in the with-grain material direction; σ_{Hoop_Max} is the maximum hoop stress.

The margins of safety for all BSM components are calculated:

$$MS_{ult} = \frac{F_{tu}("ab")}{(\sigma_{Hoop\_Max})(SOF_{ult})} - 1 \tag{2}$$

V. Conclusions

The mesh refinements and new addition of pertinent geometric details made to the 3-D Finite Element Model and the sequentially coupled approach have greatly improved the stress predictions for the graphite throat as well as for the metallic components of a BSM. The lessons learned and the modeling methodology and techniques developed from this analysis shall provide improved analyses for the Booster Separation, Tumble or Deceleration Motors to support the next generation of space exploration vehicles.

Acknowledgments

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14. ABSTRACT

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