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Enhanced Large Solid Rocket Motor Understanding Through Performance Margin Testing — RSRM Five-Segment Engineering Test Motor (ETM-3)

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ENHANCED LARGE SOLID ROCKET MOTOR UNDERSTANDING THROUGH PERFORMANCE MARGIN TESTING — RSRM FIVE-SEGMENT ENGINEERING TEST MOTOR (ETM-3)

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ABSTRACT

The Five-Segment Engineering Test Motor (ETM-3) is an extended length reusable solid rocket motor (RSRM) intended to increase motor performance and internal environments above the current four-segment RSRM flight motor. The principal purpose of ETM-3 is to provide a test article for RSRM component margin testing. As the RSRM and Space Shuttle in general continue to age, replacing obsolete materials becomes an ever-increasing issue. Having a five-segment motor that provides environments in excess of normal operation allows a mechanism to subject replacement materials to a more severe environment than experienced in flight. Additionally, ETM-3 offers a second design data point from which to develop and/or validate analytical models that currently have some level of empiricism associated with them. These enhanced models have the potential to further the understanding of RSRM motor performance and solid rocket motor (SRM) propulsion in general. Furthermore, these data could be leveraged to support a five-segment booster (FSB) development program should the Space Shuttle program choose to pursue this option for abort mode enhancements during the ascent phase. A tertiary goal of ETM-3 is to challenge both the ATK Thiokol Propulsion and NASA MSFC technical personnel through the design and analysis of a large solid rocket motor without the benefit of a well-established performance database such as the RSRM. The end result of this undertaking will be a more competent and experienced workforce for both organizations. Of particular interest are the motor design characteristics and the systems engineering approach used to conduct a complex yet successful large motor static test. These aspects of ETM-3 and more will be summarized.

INTRODUCTION

During the last 2½ years (2001 through 2003), NASA MSFC and ATK Thiokol have jointly designed, verified, and produced a five-segment Engineering Test Motor (ETM-3). The focus of this endeavor has been on providing the opportunity for learning and improvement. Challenging a new generation of people (i.e., SRM technical personnel) is an investment for the Space Shuttle program in not only maintaining and enhancing current capabilities, but also providing possibilities for future upgrade enhancements.

The current Space Shuttle RSRM is a post *Challenger* (late 1980's) derivative of the original SRM designed back in the 1970s. The design and analysis engineers of today were not involved in the original design activities; therefore, the opportunity to build upon the successful trial and error works of their predecessors is of primary importance towards enhancing a new generation's understanding for the new century. Today's engineers have used the ETM-3 activities to accomplish that goal and set the stage for testing the largest SRM to date. The ETM-3 static test article configuration (Table 1) will increase motor performance and internal environments above the current four segment motor and thus provide a mechanism for margin testing of RSRM components.

Techniques have been improved for exercising and upgrading RSRM and ETM-3 analytical models and design methods. Technical skill enhancement has been accomplished in the following areas: propellant formulation, ignition transient modeling, erosive burning, computational fluid dynamics (CFD), fluid structural interaction (FSI), loads allocations, structures, thermal, material recession, instrumentation, and the T-97 test stand facilities. Testing of the RSRM design well outside its intended performance environment will demon-

* Authors are RSRM chief systems engineer, ballistics/grain design supervisor, and ETM-3 project engineer; respectively.

strate its robustness and shed light on component response to reduced margin conditions. Pre- and post-test data from these areas can be used to enhance and validate models and analysis techniques with a second large SRM data point. The data can also be used to support a FSB development program should the Space Shuttle program choose to pursue this option for ascent abort mode enhancements.[1, 2, 3, 4, 5]

Table 1. ETM-3 Component Overview

Component	ETM-3 Design: Same as RSRM	ETM-3 Design: Modified	ETM-3 Design: New
Case	X		
Nozzle		X (Open Throat, EAEC)	
Igniter	X		
Aft Skirt	X		
Field Joints	X		
Factory Joints	X		
Nozzle to Case Joint	X		
Main Grain Propellant		X (Reduce Burn Rate)	
Grain Design		X (Chamfers)	
Insulation		X (Thickness Increases)	
Liner	X		

PROGRAM REQUIREMENTS

The RSRM top level margin test program requirements applicable to ETM-3 consist of the following:

1) Do not destroy the motor or the test stand
2) Maintain reusability of the metal hardware
3) Obtain margin test data
4) Enhance analytical modeling capability

The ETM-3 static test article is a unique end-item configuration that will not be flown. It is being used as a mechanism to overtest RSRM component hardware and materials and to provide insight into a larger SRM with a greater length/diameter (L/D) ratio, higher internal Mach number, and a larger internal static pressure drop down the bore (Table 2 and Figure 1).

Table 2. ETM-3 vs. RSRM Key Parameters

Key Comparison Parameters	RSRM 1-D	ETM-3 1-D
Reference Burn Rate (ips)	0.368	Reduced
Nozzle Throat Diameter	53.858 in.	Increased
L/D Ratio	23.08	28.42
Maximum Operating Pressure (psia)	906.8	918.9
Static Pressure Drop (psia)	110	135.2
Max Mach No.	0.39	0.44
Maximum Vacuum Thrust (Mlbf)	3.145	3.65
Specific Impulse	268.4	267.5
Web Time (sec)	111.1	114.8
Action Time (sec)	123.5	127.8
Web Time Avg Pressure (psia)	665	733.2
Web Time Avg Mass Flow Rate (lbm/sec)	9,746	11,652

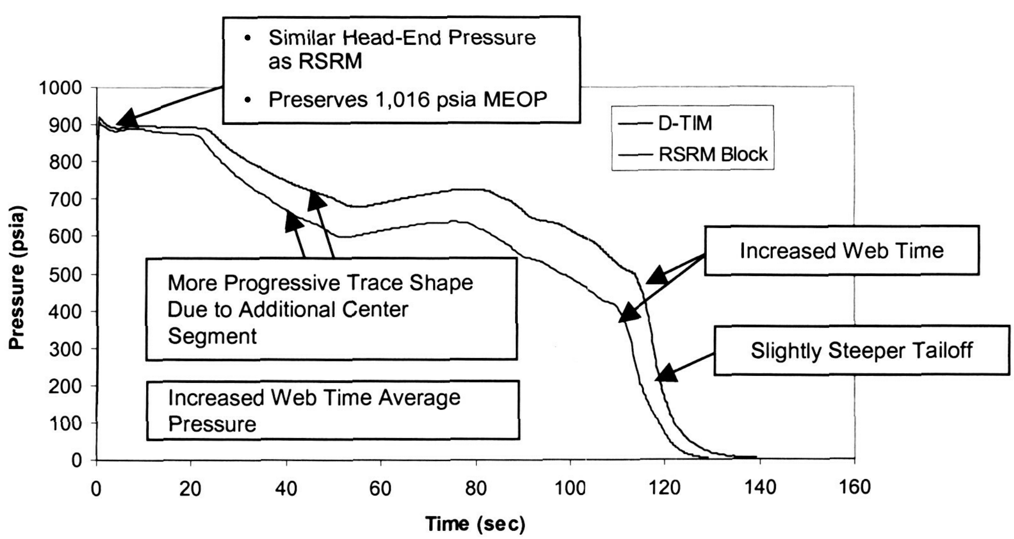

Figure 1. ETM-3 Design TIM (D-TIM) Predicted Performance: Comparison to RSRM Block Model

The ETM-3 project has been structured to mitigate the overall concern of a potential negative impact to the RSRM flight motors. Design verification is based on pre-test activities that support test readiness (subscale testing and analysis) and not on post-test performance. The joint MSFC and ATK Thiokol team has orchestrated critical reviews that have scrutinized the design verification process. The process has consisted of taking exceptions to the current RSRM requirements, allocating unique loads, and performing necessary design activities (subscale testing and analysis) that provided component verification compliance. This was all done to manage the inherent risks and enhance the positives that ETM-3 has to offer.

SYSTEMS ENGINEERING APPROACH

In order to orchestrate a successful design verification phase, early upfront planning was a key activity that could not be overlooked. An ATK Thiokol-dedicated planning team was established consisting of a program manager, a project engineer, and a systems engineer with like counterparts at NASA-MSFC. Major events associated products were scheduled into the 2½ year window per an ETM-3 Milestone Logic Flow (Figure 2). Project planning dictated that evolution of verification phase products would be tracked primarily in the following areas: Requirements, Verification Plan, Configuration, Safety and Mission Assurance (S&MA), and the T-97 test stand.

Once the point design was established, changes to the current RSRM static test requirements via a Contract End Item (CEI) addendum became necessary in order to accommodate the unique changes of ETM-3 (Figure 3). Lead component design engineers were designated to assist in developing a preliminary requirements assessment matrix and component verification logic flows. These logic flows were later integrated at the motor level to produce an ETM-3 Project Road Map (PRM) that was color-coded by component (Figure 4). A high-fidelity schedule definition (utilizing each PRM block) was also created for tracking and status purposes. Weekly systems integration telecons with MSFC and internal component team meetings were also utilized to discuss PRM progress and action item closures.

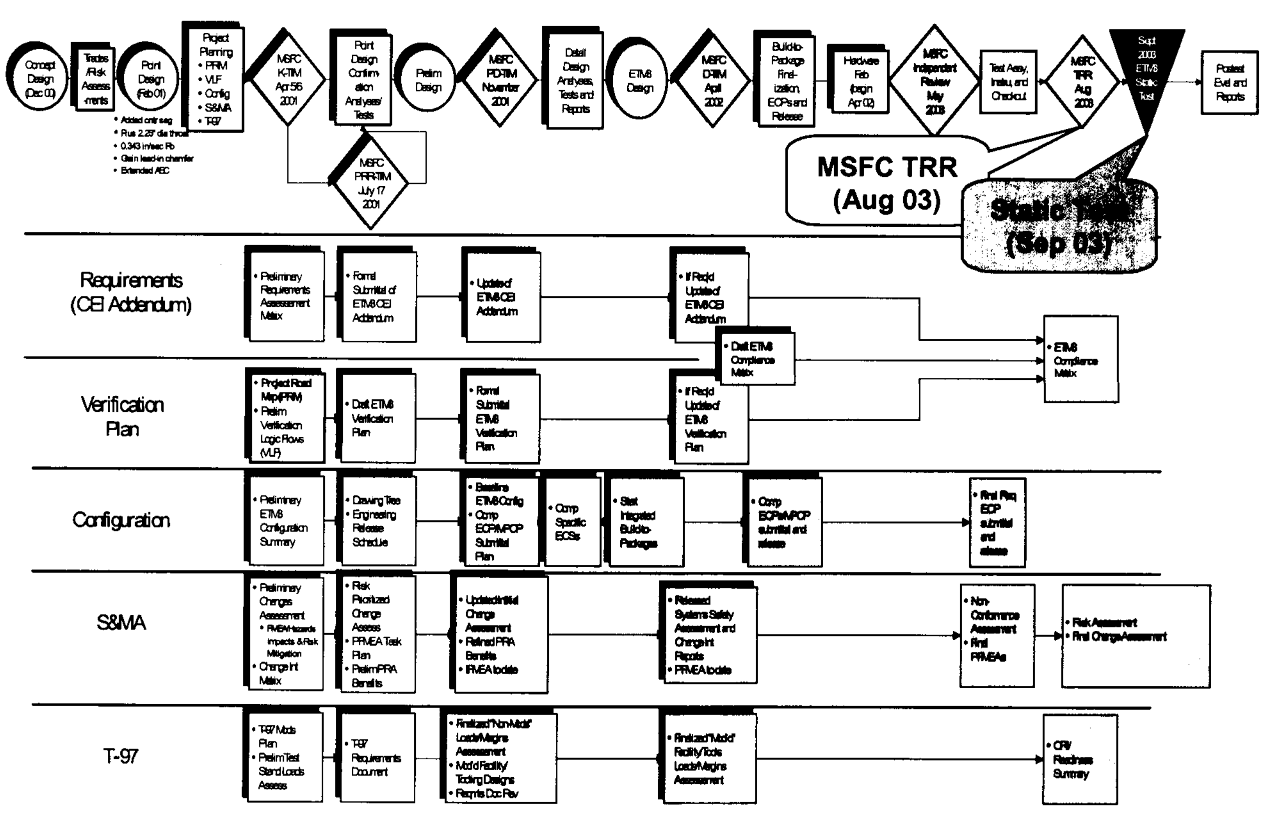

Figure 2. ETM-3 Milestone Logic Flow

(MSFC RSRM Project and Independent Reviews) and

A Verification Plan was formalized which documented the proposed testing and analysis activities that were linked to the PRM. ETM-3 unique changes and RSRM demonstration changes received a change interaction assessment in both the engineering and system safety communities. Also, S&MA risk assessment studies and Integrated Failure Modes & Effects Analyses (IFEMA) were performed. Final Engineering Change Packages (ECP) containing all verification documents were approved by MSFC. In order to accommodate the extended length ETM-3, T-97 test stand tooling and facility modifications were necessary (Figure 5).

Four MSFC Project Reviews

- **Kick-off**
- **Project Requirements**
- **Preliminary Design**
- **Design**

One MSFC Independent Review

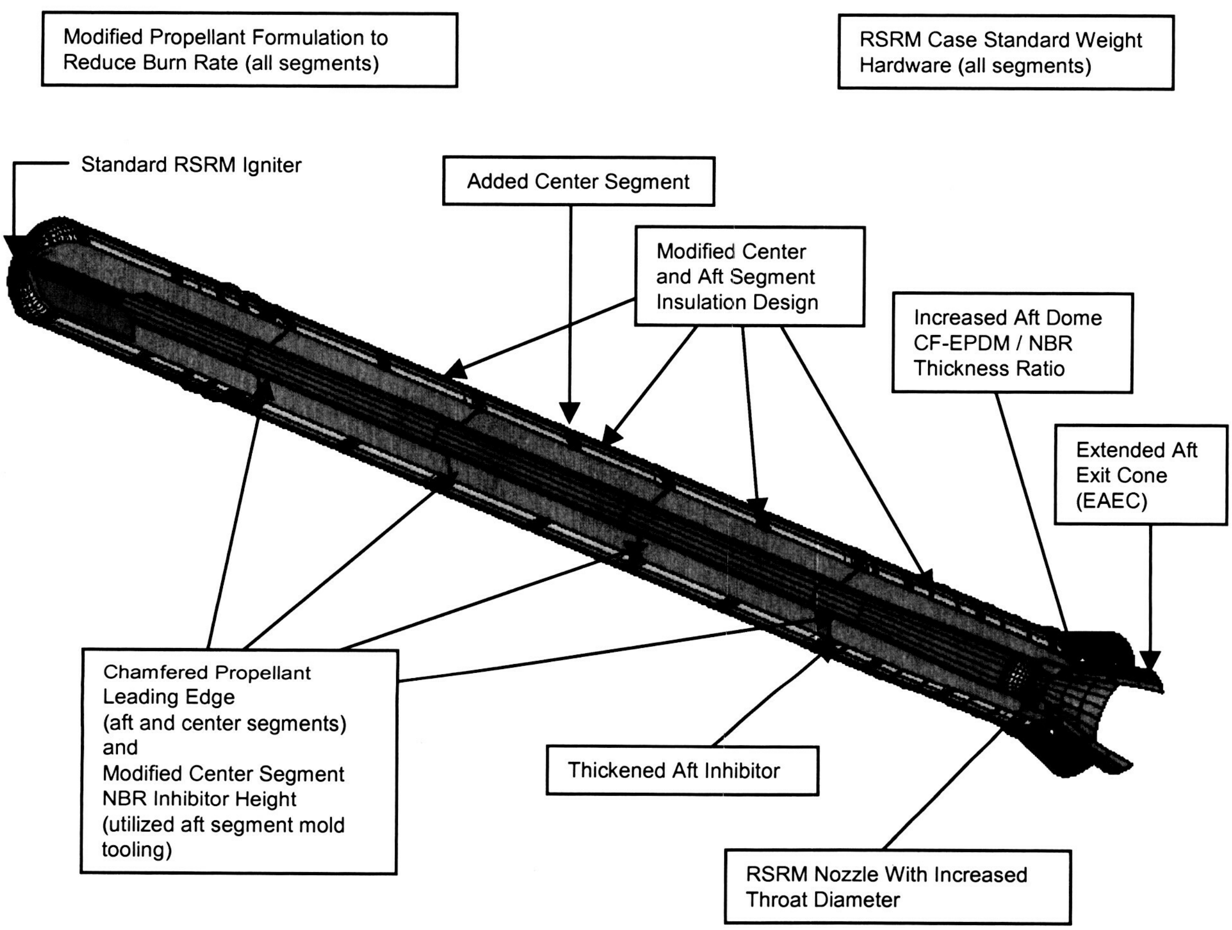

Figure 3. ETM-3 Unique Changes

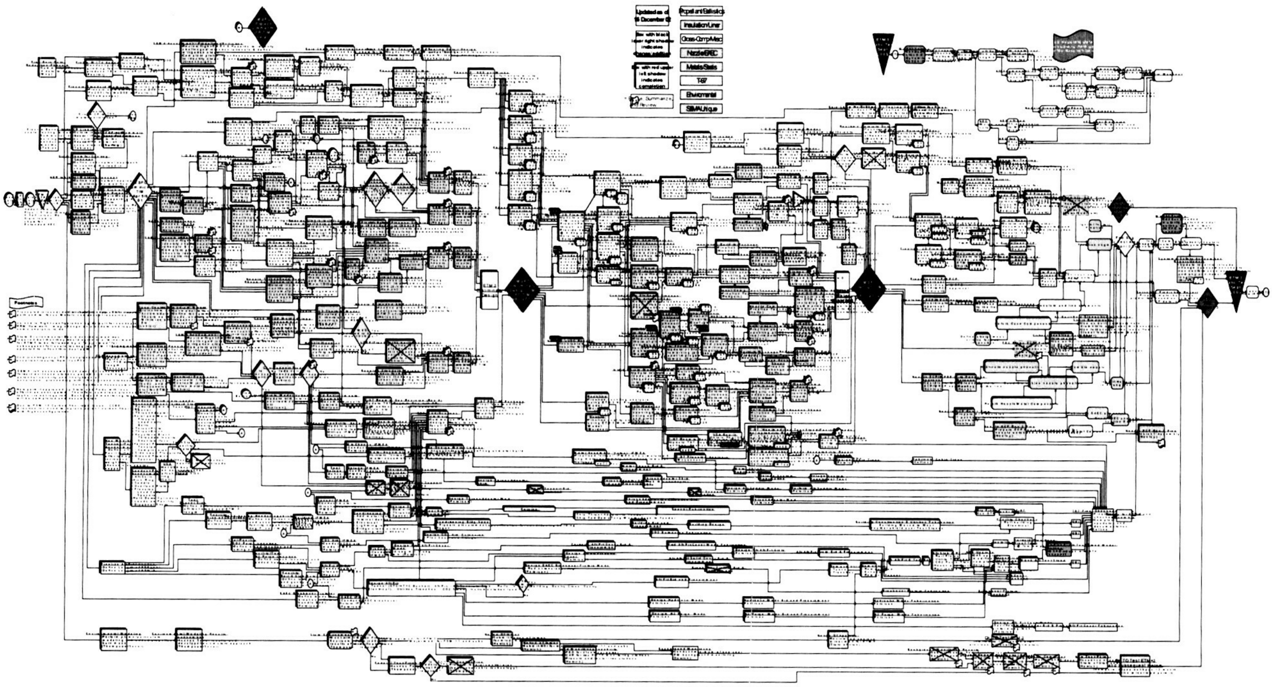

Figure 4. ETM-3 Project Road Map (PRM)

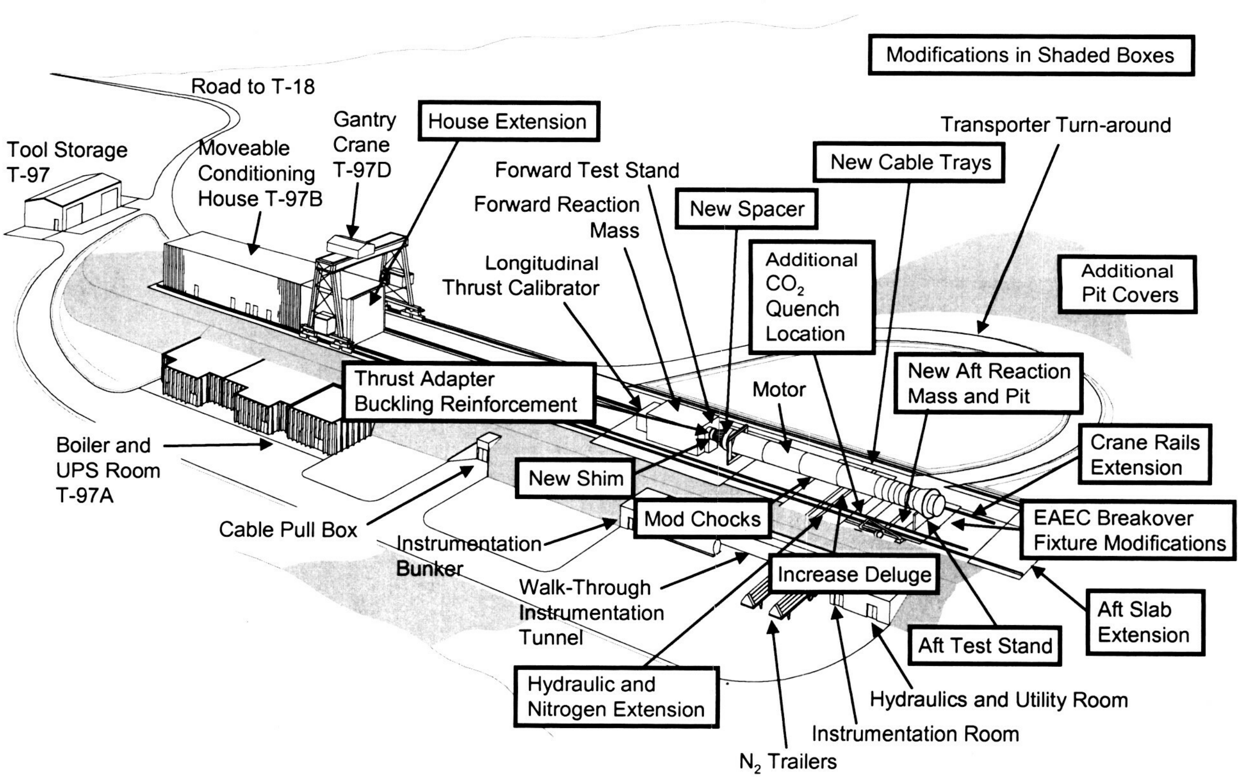

Figure 5. T-97 Tooling and Facility Modifications

MOTOR / COMPONENT DESIGN CHARACTERISTICS

The enhanced performance of ETM-3 is achieved primarily by the addition of a RSRM center segment. However, added motor performance has been achieved with a throat diameter increase and the incorporation of an extended aft exit cone (EAEC) (Figure 6). The EAEC was previously tested on Flight Support Motor No. 5 (FSM-5) as an RSRM enhancement, although it was never implemented as part of the flight baseline configuration. Parameters such as average pressure, maximum thrust, mass flow rate, centerline Mach number, pressure and thrust integrals have all increased over RSRM (Table 2 and Figure 1). In some cases these increases are substantial. These increased environments have been characterized and assessed by the various component disciplines.

In order to handle the increase in head-end pressure that the additional center segment provides, the RSRM reference burn rate has been reduced. This has been accomplished with minor alterations to the TP-H1148 Type IV propellant formulation. Iron oxide type, ammonium perchlorate (AP) unground-to-ground ratio, and ground AP particle size have been optimized to provide the lower burn rate. The changes have resulted in a TP-H1148 Type VII classification.

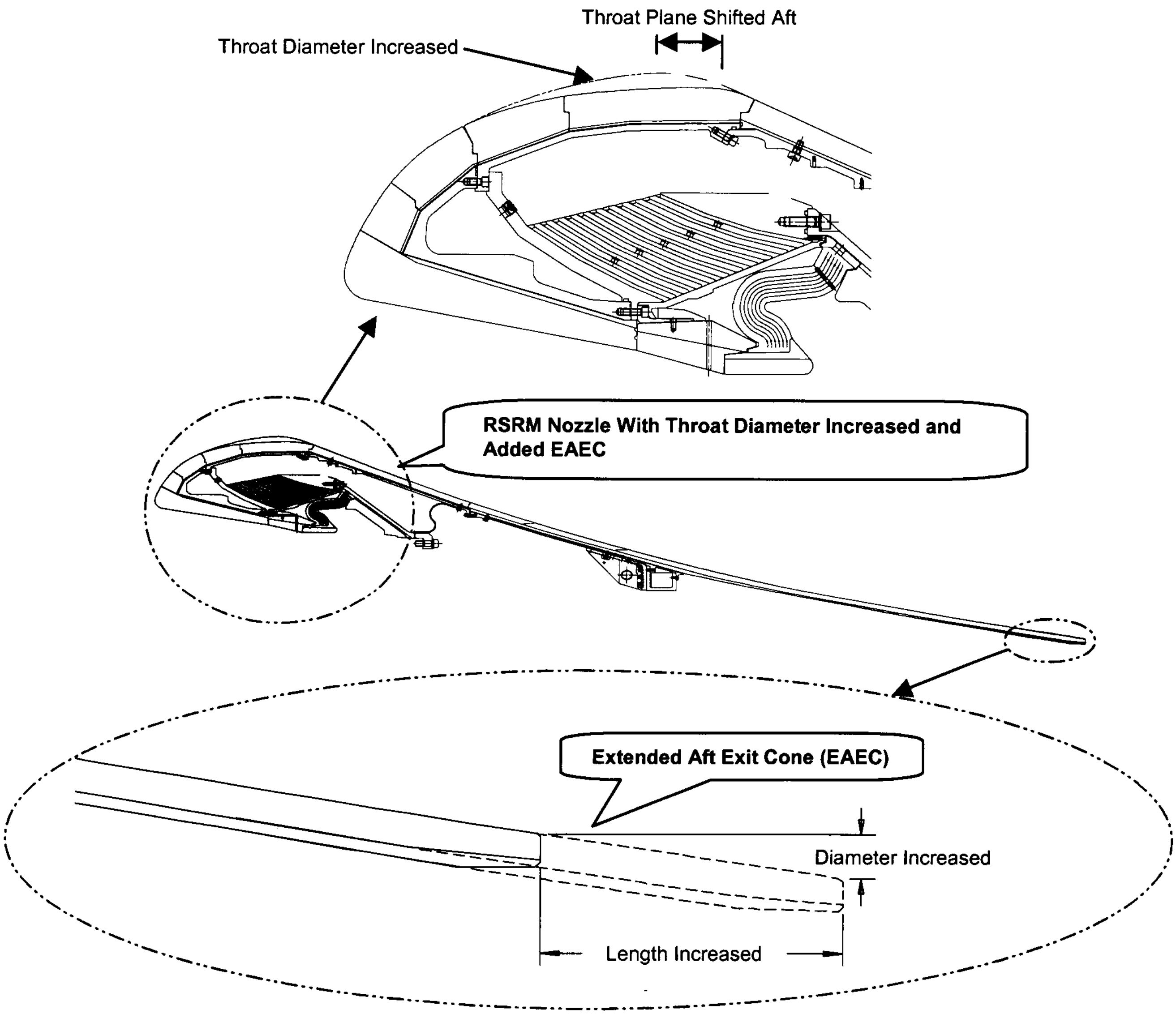

Figure 6. ETM-3 Nozzle and EAEC

The ETM-3 grain configuration is similar to previously fired RSRMs with the primary exception of leading edge propellant grain chamfers on the center and aft segments (Figure 7). These chamfers are nominally sized in the radial and axial directions. Previous design iterations considered a smaller sized chamfer. Detailed FSI analyses indicated additional margin against unrestrained propellant deflections could be gained with a larger chamfer. Hence, the larger sized chamfer was adopted as the baseline grain geometry. The chamfers were cast in place via new tooling rings that bolt to the existing center and aft casting pit mold plates and interface with the current casting cores (Figure 8).

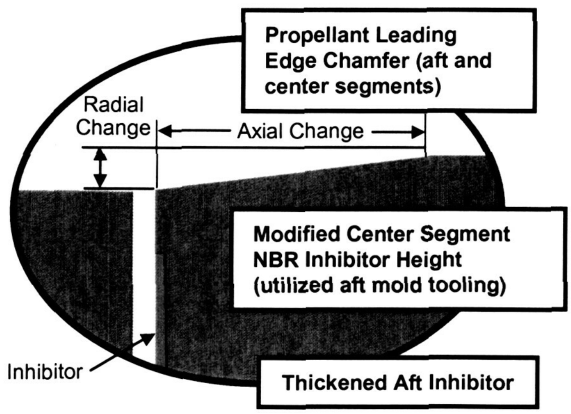

Figure 7. ETM-3 Grain Chamfers and Inhibitors

The propellant chamfers are necessary to mitigate the potential for a phenomenon known as "bore choking." Segmented SRMs with forward facing grain steps are susceptible to this flow-driven event. These forward facing steps protrude into the free stream flow acting as flow restrictors. Local pressure gradients develop across the forward facing propellant corner, which promotes grain deformation toward the centerline of the motor. If port velocities are high enough and the propellant modulus low enough, unrestrained deformations can develop leading to motor failure from over pressurization. The increased mass flow rate and port velocity of the ETM-3 design aggravates these conditions. Consequently, the forward facing propellant corners have been chamfered as mentioned above. These chamfers significantly reduce local pressure gradients and minimize the inward deflections of the propellant grain. A detailed assessment of this phenomenon has been performed for the ETM-3 grain design.[6]

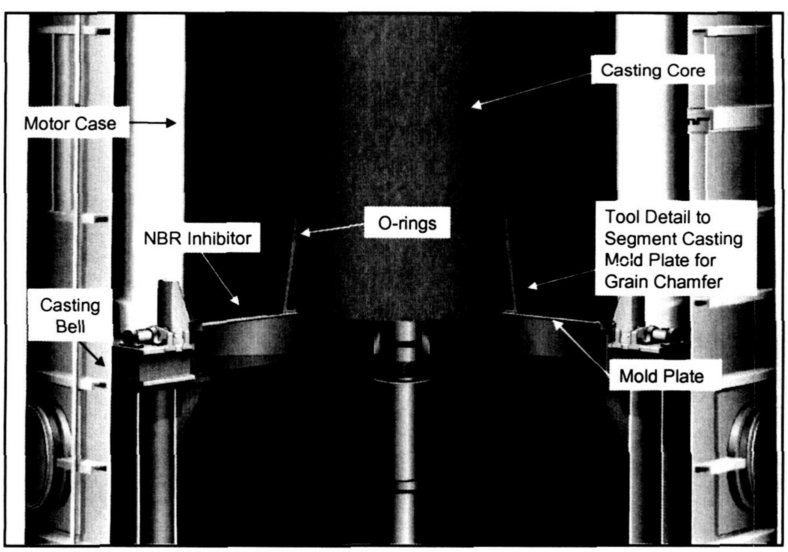

Figure 8. ETM-3 Propellant Grain Chamfer Cast Tooling

The nitrile butadiene rubber (NBR) inhibitor height for each center segment has been modified to accommodate the propellant chamfer. These inhibitors are now the same height as the aft segment NBR inhibitor. The aft segment inhibitor is short enough to handle the increased propellant radius and the mold tooling is easily adaptable for use with the center segment casting operation. Since trace shape tailoring is unimportant for ETM-3, this was deemed the most straightforward, economical design solution.

The ETM-3 case insulation profile has been changed from RSRM for the center and aft segments. The forward segment profile remains the same as RSRM. Insulation thicknesses for the aft and center segments have been increased to account for longer exposure times and increased mass flow rates. The aft dome carbon fiber (CF)-EPDM / NBR insulation thickness ratio was also increased. This was accomplished by reducing the NBR thickness and replacing it with staged CF / EPDM to maintain the design profile (Figure 9).

MOTOR / COMPONENT VERIFICATION SUMMARY

All ETM-3 predicted margins (including those less than RSRM) have been justified through performance and environments requirements definition, com-ponent verification tests and analyses, and both ATK Thiokol and MSFC review processes. Depicted in Figure 10 is an example of the magnitude of documentation that was submitted to MSFC during the design re-

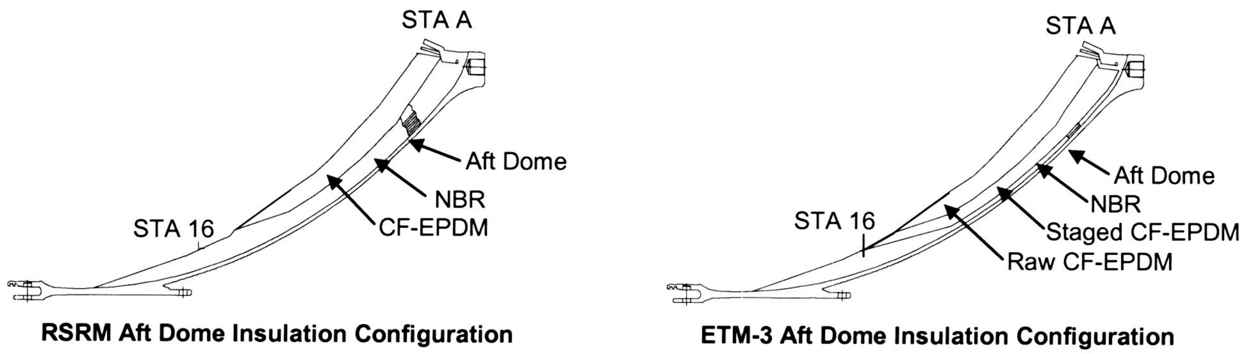

Figure 9. RSRM vs. ETM-3 Aft Dome CF-EPDM / NBR Thickness Ratio Increased

view period. In some areas updates to the documents were prepared to support delta design activities and final component change submittals. Tied to the RSRM challenged and/or modified requirements per the CEI ETM-3 addendum and verification plan, a summary of compliance rationale is contained in each applicable document and compiled in a motor level CEI verification compliance matrix.

Per the verification plan, major motor or component compliance activities were performed in the following areas:

- Grain design and motor performance predictions
- Propellant formulation testing
- Ignition transient predictions
- Erosive burning test and analysis[7]
- CFD analysis[8,9]
- FSI analysis[6]

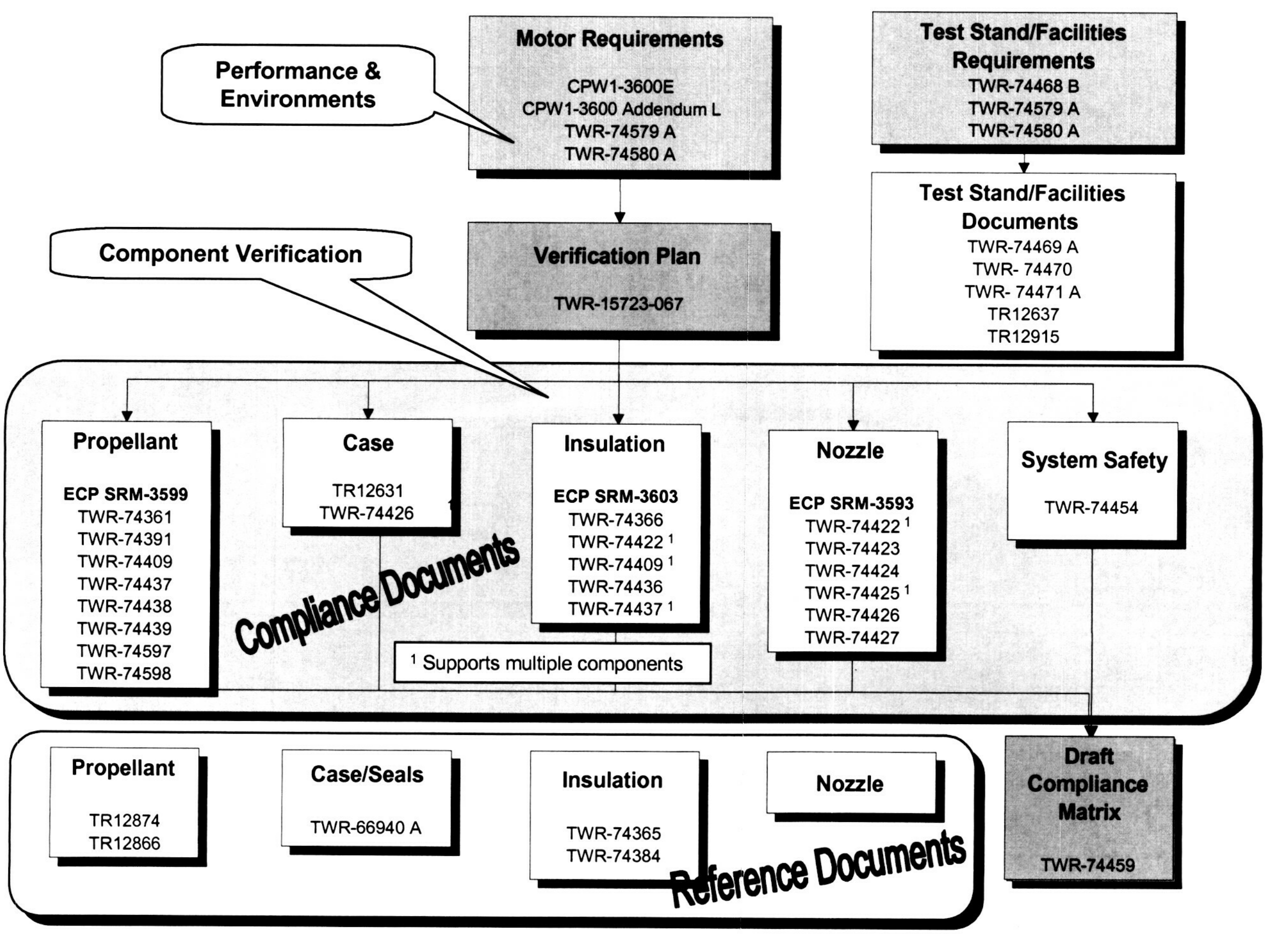

Figure 10. ETM-3 Design Review Verification Submittals

- Internal environments and mass properties
- Loads and environments
- Internal acoustics / pressure dynamics
- Case structures analysis
- Propellant, Liner, Insulation (PLI) structural analysis
- Nozzle structural analysis
- Nozzle torque / vectoring analysis
- Insulation thermal design
- Nozzle char and erosion analysis
- Nozzle joint thermal analysis
- Motor joints and seals assessment
- System Safety review

BENEFITS SUMMARY

After the ETM-3 test and the follow-on evaluations, predicted RSRM environments and margins will be better understood. Table 3 contains an overview of the ETM-3 CEI exceptions and predicted margins that permit a second motor environmental design point and over testing of RSRM hardware and materials.

ETM-3 will be fired in the T-97 static test facility. The T-97 aft test stand has been relocated to accommodate the ETM-3 increased motor length and a portion of the anticipated FSB length (Figure 5). During the test, thrust and pressure data will be recorded. Additional extensive instrumentation, both internal and external, will be used to help in understanding motor performance for axial pressure drop determination, ignition transient modeling, static test loads, case behavior subjected to gravity loading, and material recession (inhibitor, aft dome insulation, and EAEC ablatives). Internal field joint pressure gages and aft dome and EAEC recession gages are being used for the first time on a full-scale static test. ETM-3 will be the most highly instrumented full-scale static test motor in RSRM history with a total of 618 gages.

ETM-3 Instrumentation Summary by Gage Type
618 total gages
(633 total channels, 257 standard)

- 47 pressure gages (24 standard)
- 29 force (load) gages (44 channels, 30 standard)
- 167 temperature gages (89 standard)
- 45 acceleration gages (10 standard)
- 160 strain gages (56 standard)
- 11 event gages (11 standard)
- 36 displacement gages (12 standard)
- 8 voltage (command) gages (8 standard)
- 8 current gages (8 standard)
- 6 interlock gages (6 standard)
- 33 radiometer (heat flux) (3 standard)
- 60 eroding potentiometers (0 standard)
- 8 acoustic gages (0 standard)

Table 4 contains an overview of the RSRM related topics and analyses that are clearly being tested and

Table 3. ETM-3 CEI Exceptions / Predicted Margins

Requirement	RSRM	ETM-3 Exception	ETM-3 Comments or Margins
PMBT	40°-90°F	55°-82°F	Lower end for PLI SF Upper end for MEOP
Performance	Table II	Addendum L Table II	+5 sec, +65 psia avg pressure
Pressure Seals	No erosion	Erosion of nozzle joints 3 and 4 primary acceptable	Predicted <50% after Joint 4 primary groove depth reduced
Nozzle Liner Design	--	Design to minimize pocketing	High temperature carbonized material used in throat region
Environments	--	Larger mass flow and pressure drop	New loads accounted for in component analysis
Case Safety Factors (SF)	1.4	1.3 for joint pins Actual properties/dimensions for buckling and operation	0.12 margin (pins, operation) 0.16 margin (buckling) 1.4 SF 0.02 margin (operation) 1.4 SF
Insulation Decomposition SFs	2.0 factory joints 1.5 aft dome	1.5 over factory joints 1.3 in aft dome	Actual factory joint SFs >1.5 Actual aft dome SFs >1.5
Propellant SFs	--	None	PMBT exception only
Nozzle SFs	Char/erosion equation 1.5 for flex boot AEC 1.5 in.	600°F isotherm within CCP 1.3 for flex boot AEC 12 in. charred	Isotherm well within CCP 0.14 thermal margin Virgin material remaining

enhanced by ETM-3.

ETM-3 will subject some of the key motor components to a margin test environment, thus providing a mechanism to over test insulation and nozzle materials that may need to be replaced as a result of obsolescence. It will provide a second design point to better understand RSRM performance and refine analytical predictive models, thus enabling better support of RSRM flight readiness dispositions and predicting performance on future boosters. It will continue to provide technically challenging work that enhances MSFC and ATK Thiokol engineering expertise. It will continue to provide increased insight into the internal gas dynamics characteristics of the FSB, which was identified in Government-funded studies as one of the key areas of concern for FSB development. It will demonstrate that ATK Thiokol can produce two different configuration motors in the current RSRM production facilities.

ETM-3 has provided, currently is providing, and will continue to provide an endeavor focused on learning and improving. It has created opportunities that are challenging the people. It will over-test RSRM hardware and materials. It will continue to enhance the analytical techniques. These significant analytical enhancements will benefit general knowledge of large solid rocket motor propulsion such as RSRM and future projects such as FSB.

Table 4. ETM-3 Benefits

Enhancement Area	RSRM Benefits (educate people, enhance models and methods)
Steady State Ballistics	• Update models with additional design point at higher L/D
Internal Pressure Distribution	• Update CFD and FSI models with additional design point at higher L/D
Erosive Burning	• Subscale tests refine 1-D model coefficients • Develop CFD / 2-D predictive capability
Ignition Transient	• Provide second design point at higher L/D and throat diameter • Provide data concerning acoustic wave interaction with respect to rise rate • Support MSFC model updates: improve input to Level 2
Pressure Perturbation	• Potential for increased understanding concerning the effects of burn rate, Mach no., throat diameter on slag accumulation (blips)
Internal Acoustics / Pressure Dynamics	• Update model with additional design point at higher L/D • Better understanding of vortex shedding phenomenon interactions with motor internal acoustics and resulting motor loads
Motor Loads	• Update dynamics analysis model for motor in test stand • Modal survey data on T-97 will support static test simulations
Internal Thermal Environment	• Enhance CFD predictive capability with second design point • Improve understanding of aft segment internal environments
Material Overtesting	• Erosion predictions for nozzle ablatives, aft dome CF-EPDM, inhibitors
Propellant Formulation	• Use lower burn rate propellant to better understand slag accumulation • Data indicates potential to improve RSRM propellant formulation processing • Established tailorability of TP-H1148 over a wide range of burn rates • Future changes can be predicted when bounded by characterization effort
Internal Instrumentation	• J-slot pressure and aft dome recession utilizing factory joint feed through • Early development of internal bore pressure, heat flux, strain (FSM-11 target)
T-97 Test Stand (FSB capability)	• Better understanding of fwd and aft test stand components (i.e., flexures)

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Rashid Ahmad	CFD Analysis
Bob Morstadt	CFD Analysis
Andy Eaton	CFD Analysis & Internal Environments
Brian Rex / Del Hillary	FSI Analysis
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Dale Nielsen	L&E, Dynamic Interaction Study, Modal Survey
Randy Buttars	Plume Heating Environment Comparisons
Jeff Maughan	Internal Combustion Acoustics
Ken Wanlass	Internal Combustion Acoustics
Don Mason	Internal Acoustics/ Pressure Dynamics
Joe Lohrer	Case Structures Assessment
Tom Weidner	Case Buckling Analysis
Rob Wynn/Pat Downey	PLI Structural Analysis
Steve Kirkham/Jeff Astle	PLI Structural Analysis
Dan Nelson	Nozzle Design
Don Lamont	Nozzle Structural Analysis
Dave Richardson	Nozzle Structural Analysis
Craig Prokop	Nozzle Torque Analysis
Kevin Albrechtsen	Insulation Design
Mark Ewing	Insulation Thermal Analysis
Joel Maw	Nozzle Char & Erosion Analysis
Cory Smith/Joe Heman	Nozzle Joint Thermal Analysis
Karl Shupe/Gary Jepson	Seals Compliance
Brad McCann/ R.E.Lee Hamilton	System Safety Review
Gerry Collins/Phil Petersen/ Steve Hoggan	T-97 Modifications
Mick McLennan	T-97 Flexure Analysis