A Review of ETM-03 (A Five Segment Shuttle RSRM Configuration) Ballistic Performance

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Marshall Space Flight Center and ATK Thiokol Propulsion worked together on the engineering design of a five-segment Engineering Test Motor (ETM-03), the world's largest segmented solid rocket motor. The data from ETM-03's static test have helped to provide a better understanding of the Reusable Solid Rocket Motor's (RSRM's) margins and the techniques and models used to simulate solid rocket motor performance. The enhanced performance of ETM-03 was achieved primarily by the addition of a RSRM center segment. Added motor performance was also achieved with a nozzle throat diameter increase and the incorporation of an Extended Aft Exit Cone (EAEC). Performance parameters such as web time, action time, head-end pressure, web time average pressure, maximum thrust, mass flow rate, centerline Mach number, pressure and thrust integrals were all increased over RSRM. In some cases, the performance increases were substantial. Overall, the measured data were exceptionally close to the pretest predictions.

Nomenclature

C* = Characteristic Exhaust Velocity
CFD = Computational Fluid Dynamics
CP = Center Perforated
EAEC = Extended Aft Exit Cone
ETM = Engineering Test Motor
FSI = Fluid Structural Interaction
FSM = Flight Support Motor
HTPB = Hydroxyl Terminated Polybutadiene
η_r = Pressure Recovery Factor
I_{sp} = Specific Impulse
NBR = Nitrile Butadiene Rubber
PBAN = Polybutadiene Acrylonitrile
PMBT = Propellant Mean Bulk Temperature
RSRM = Reusable Solid Rocket Motor
SBRE = Surface Burn Rate Error
SPP = Solid Propellant Program (Software and Engineering Associates, Inc.)
SPRITE = Solid Propellant Ignition Transient Evaluation

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I. Introduction

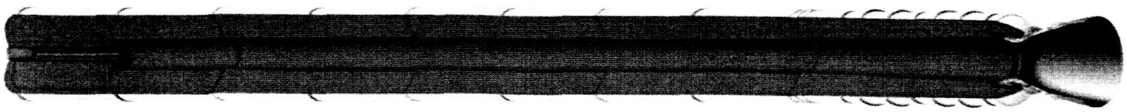

Figure 1: ETM-03 Design Configuration

THE five-segment Engineering Test Motor (ETM-03) is the world's largest segmented solid rocket motor. It was designed to subject the Space Shuttle program's Reusable Solid Rocket Motor (RSRM) components to harsher conditions that would test their margins of performance. Adding an additional center segment, enlarging the nozzle throat diameter, and using the Extended Aft Exit Cone (EAEC), as seen in Fig. 1, achieved this enhanced performance for ETM-03. ETM-03 also tested the ability to extrapolate assumptions used in modeling the RSRM to a larger motor. This paper contains an overview of the modeling assumptions made and explains how assumptions from the RSRM were extrapolated or altered to account for the added center segment. Topics include erosive burning, burn rate, and ballistic performance. The paper also contains a comparison of predicted and measured performance.

Ballistic modeling of ETM-03 was completed using standard RSRM models that had been modified to include the design changes. As much as possible, modeling coefficients, and empirical values were held constant for the ETM-03 design. Some of these values had to be changed for known differences or extrapolated beyond RSRM experience. This paper will investigate the validity of this approach by comparing predicted and delivered performance.

The design resulted in increased pressure, thrust, mass flow, and internal gas velocities for the entire time of motor operation. Early on in the program, it became evident that the harsher environment could cause additional concerns beyond those of the standard RSRM, particularly with the possibility of the increased gas velocities in the bore. The predicted increase in velocities posed the potential for erosive burning and increased propellant deformation. Extensive analyses were performed, and small design changes were made to safeguard the integrity of the motor. This paper will briefly cover the work completed to address these concerns and show how the test results demonstrate successful mitigation of that risk.

Overall, the final delivered performance of ETM-03 was very close to the prefire predictions. Figure 2 shows the ballistic prediction and reconstructed performance at standard conditions with a common Propellant Mean Bulk Temperature (PMBT) and burn rate of 60°F and 0.343 in/s respectively. The test and resulting data are providing much insight into the methods used to predict motor performance, as well as ways to improve the accuracy of future predictions.

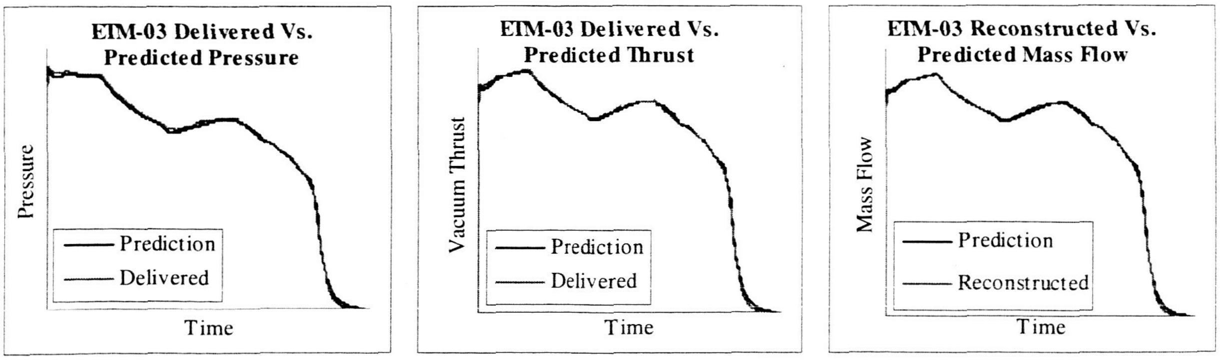

Figure 2: ETM-03 Delivered Pressure, Thrust, and Mass Flow At Standard Conditions Compared to Prefire Prediction

II. ETM-03 Design

ETM-03 had several key design features that deviated from the standard RSRM. These changes include chamfers on the leading edge of the aft and center segments, altered inhibitor heights on the center segments, a larger nozzle throat diameter, and an EAEC. A more detailed overview of the design process is presented in an earlier paper by Huppi, Tobias, and Seiler[1].

A. Propellant Grain Modifications

The ETM-03 propellant grain design consists of a forward segment with an eleven point star that transitions into a tapered center perforated (CP) configuration; three center segments with a double tapered CP configuration and leading edge propellant chamfers; and an aft segment with a triple taper CP configuration, leading edge propellant chamfer, and a cutout for the partially submerged nozzle. The added center segment served to increase average mass flow, thrust, and pressure throughout motor operation. This increase is the primary contributor for the substantially harsher environment that pushes the boundary of many of the RSRM's components beyond their design levels.

The propellant chamfers mentioned above were necessary to avoid a potential phenomenon known as "bore choking"—a flow driven effect that segmented solid rocket motors are susceptible to. The phenomenon is caused when pressure gradients across the propellant surface, particularly near steps and leading edges, causes the propellant surface to deflect inward, further restricting the gas flow in the bore. The problem can have a cascading effect. 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-03 design aggravates these conditions. Consequently, the forward facing propellant corners were 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 was performed for the ETM-03 grain design using an iterative fluid-structural interaction analysis to ensure minimal deformation. Figure 3 and Fig. 4 show the leading chamfers and propellant grain regression for the center and aft segments respectively.

The nitrile butadiene rubber (NBR) inhibitor height for each center segment was modified to accommodate the propellant chamfer. These inhibitors were made to be the same height as the aft segment NBR inhibitor. The aft segment inhibitor was short enough to handle the increased propellant radius and the mold tooling was easily adaptable for use with the center segment casting operation. Since trace shape tailoring was unimportant for ETM-03, this was deemed the most straightforward, economical design solution.

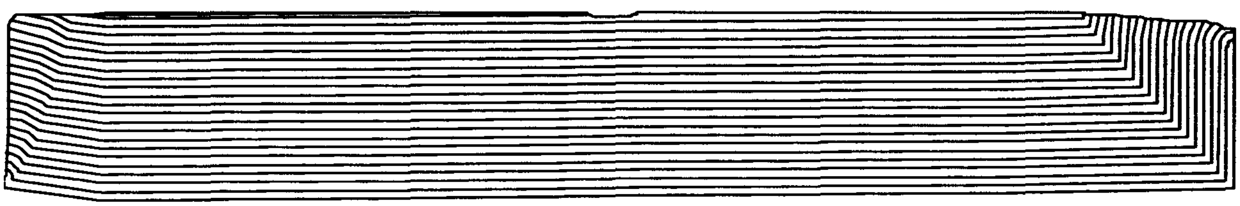

Figure 3: ETM-03 As-Built Center Segment Grain Regression

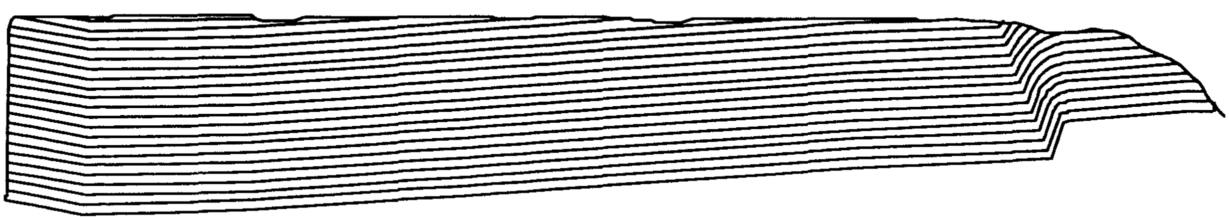

Figure 4: ETM-03 As-Cast Aft Segment Grain Regression

B. Insulation Thickness

The ETM-03 insulation profile deviated from that of RSRM for the center and aft segments. The propellant chamfers and shortened NBR inhibitors on the center segments resulted in significantly increased exposure times for the forward most area of the three center segments. This forced an increase in the insulation thickness in order to protect the case hardware. Exposure time is the amount of time between when the insulation is no longer covered by propellant and the end of motor operation. Exposure times are used to predict how much of the insulation will be consumed due to high heat or eroded away by gas flow across the insulation surface. Longer exposure times are a result of two different changes: an increase in total motor operation time (also known as action time) and the shortened inhibitors. The longer action time is due to a slower propellant burn rate, which was necessary to control the maximum internal pressure in the head-end of the motor.

ETM-03's forward segment profile remained the same as RSRM's. No changes in the forward segment insulation were required because the RSRM forward segment design already withstands large exposure times with a high factor of safety.

C. Nozzle Throat Diameter

ETM-03 also had a larger nozzle throat diameter than RSRM. The increased diameter served to keep the maximum head-end pressure relatively close to RSRM's (average pressure was significantly higher), to increase the maximum thrust level, and to increase the velocity of the gasses inside the bore of the motor. The increase in velocity increased the severity of the internal motor environment beyond the effects of the increased length and mass flow. The harsher environment was designed to study the effects of higher velocities in large motors and the propensity for erosive burning. This also caused much of the concern with propellant deformation that led to the leading edge chamfers in the aft and center segments.

D. Extended Aft Exit Cone

Incorporation of an EAEC achieved added motor performance. Flight Support Motor Five (FSM-05) last tested the EAEC as an RSRM enhancement. Although qualified, the EAEC never became part of the flight baseline configuration. The EAEC increases the exit area of the nozzle; thereby increasing total thrust. The FSM-05 test did not measure actual thrust, so no data had previously existed to confirm the expected change in specific impulse (I_{sp}). ETM-03 has shown that the I_{sp} increase Solid Performance Program (SPP) predicted was very close to the actual measured performance increase.

III. ETM-03 Prediction

The ETM-03 ballistic prediction was completed using ATK Thiokol's internal ballistics prediction code for segmented solid rocket motors. This is the same program used for predicting and reconstructing RSRM flight and static test motors. This is a 1-D ballistics code that uses ideal rocket equations identical to those found in most textbooks on rocket motor performance. Other efforts that contributed to the ETM-03 prediction include the characterization of a modified propellant formulation and a study of erosive burning in large motors. The erosive burning study lead to the development of a new erosive burning model, which was applied to the ETM-03 prediction. Figure 5 shows the ETM-03 prediction compared to the nominal RSRM performance.

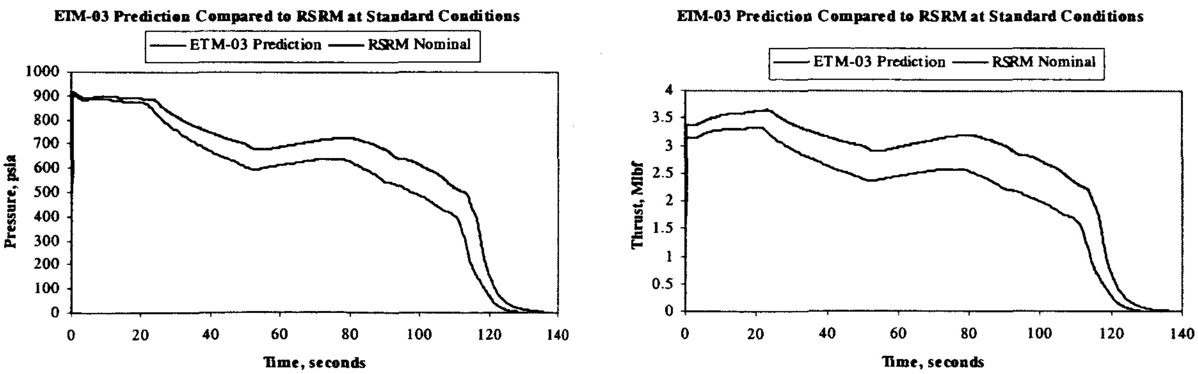

Figure 5: ETM-03 Prediction Compared to RSRM Nominal Performance at Standard Conditions

A. Geometry Input

The inputs for the ballistics prediction include several surface area tables to model areas of the motor that the basic geometry driver does not handle, including forward segment fin to bore interface and slots between the segments. The center segments were modified to have a chamfered leading edge (see discussion on propellant deformation) and altered inhibitor heights. Because of the historical pedigree of the RSRM model, small grain changes have historically been modeled as deltas applied to these tables. For ETM-03, separate predictions were made using this approach, as well as putting in all new geometric data based on the as built geometry. The resulting traces did have some subtle differences, but when compared to the measured results, they both had places where one was better than the other. In general, the model built using deltas applied to the surface area tables captured the transient areas of the performance slightly better. This is actually expected because of how the predicted surface burn rate error (SBRE) is calculated from real data using the historical model. However, the historical model is much more difficult to recreate due to the nature of it's evolution. The new model would be easier for future engineers to recreate and could be quickly grounded based on multiple test firings.

B. Surface Burn Rate Error

To account for non-ideal behavior, several empirical parameters are typically input to the one-dimensional models. For the most part, these were assumed to be the same as that of the RSRM, for which there is a wealth of historical information. One of these inputs is the SBRE. The SBRE, seen in Fig. 6, is an empirical multiplier used to account for non-ideal propellant burn rate behavior. In other programs, this is frequently referred to as the "hump factor" or "burning anomalous rate factor" (BARF). For predictions, this value is input for each of the solid rocket motor segments. For this model, it was assumed that the center-center segment SBRE would be the average of the RSRM block model forward-center and aft-center segments. The RSRM block model was generated using a population of RSRM data representative of today's materials and processing. This is commonly referred to as the "WECCO" block model.

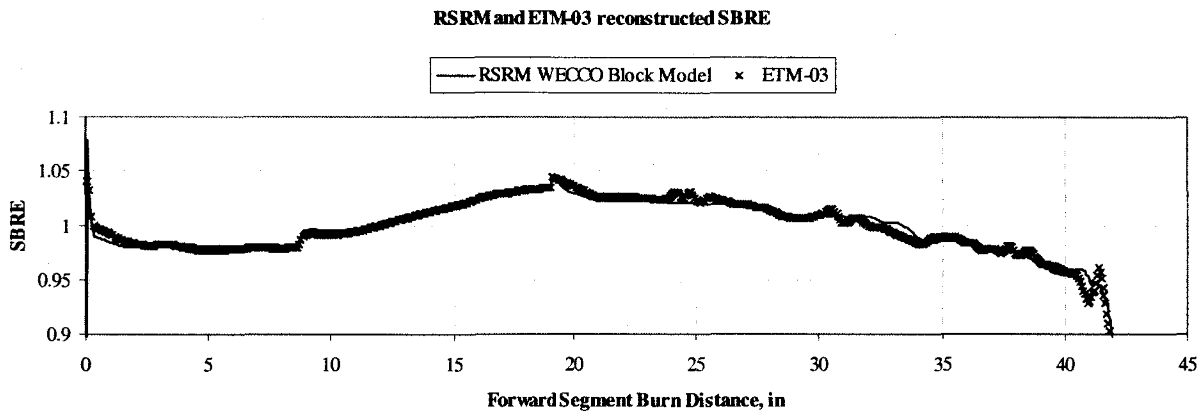

Figure 6: Reconstructed SBRE from the RSRM WECCO Block Model and ETM-03

C. Erosive Burning Assessment

One of the significant technical questions regarding ETM-03 was whether or not the phenomenon known as "erosive burning" would manifest itself in a substantive magnitude.

Erosive burning is a solid propellant combustion phenomenon in which the local burn rate is enhanced above the base burn rate in the presence of high cross-flow velocities at the burning propellant surface. This burn rate enhancement is typically present only in the very early portion of motor operation and rapidly dissipates as the grain regresses and bore cross-flow velocities decrease. Solid rocket motors that have high length-to-port diameter ratios and low port-to-nozzle throat diameter ratios can have the potential for erosive burning since their flow velocities tend to be higher than other motor designs. It is generally accepted that macroscopic erosive burning is not present in the current RSRM; however, there is some evidence to suggest local areas of erosive burning may exist. Certainly, the RSRM does not exhibit any characteristics of large scale, classical erosive burning, thus it can be considered negligible.

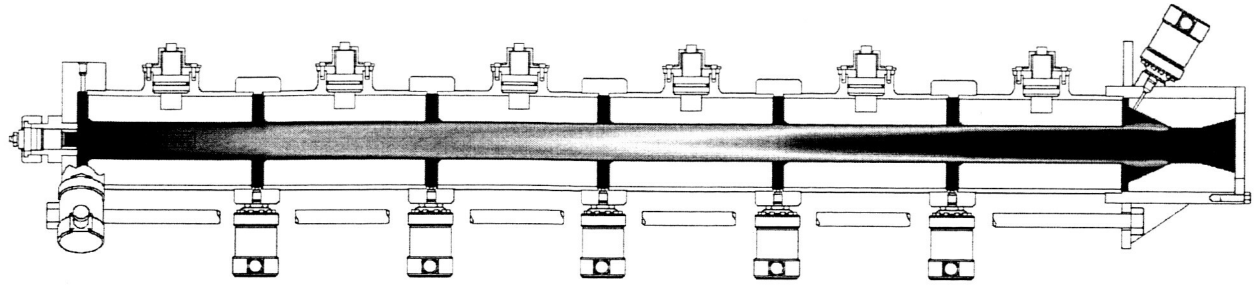

Figure 7: Erosive Burning Subscale Test Configuration

A 6-segment subscale motor, seen in Fig. 7 and Fig. 8, was developed to generate a range of internal environments from which multiple propellants could be characterized to support an erosive burning prediction for ETM-03. The motor test bed was designed to provide a high Mach number and high mass flux environment. Propellant regression rates were monitored for each segment utilizing ultrasonic measurement techniques. These data were obtained for three propellants—RSRM, ETM-03, and Castor® IVA—that span two propellant types—PBAN (polybutadiene acrylonitrile) and HTPB (hydroxyl terminated polybutadiene). The characterization of these propellants indicated a remarkably similar erosive burning response to the induced flow environment and provided enhanced burn rate data that were used to improve ATK Thiokol's in-house ballistic predictive capabilities.

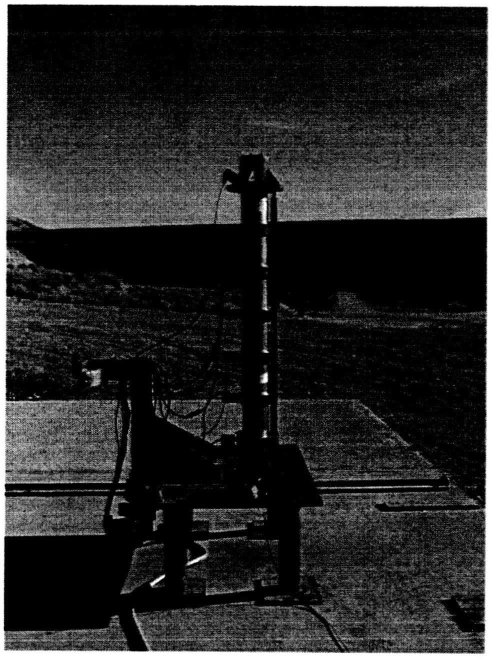

Figure 8: Erosive Burning Test Article Prior to Testing

Current in-house ballistic models are based on either an augmented heat transfer from a high cross-flow velocity at the propellant surface or alteration of the transport properties between the propellant surface and the flame zone. These models rely on a historical motor database to evaluate scaling parameters for erosive burning prediction in large motors. The subscale testing has provided additional data for the historical database of motors that exhibit erosive burning and has contributed towards ATK Thiokol's increased understanding of core fluid velocity and motor size influences on propellant erosive burning response. The expanded database has been used to improve in-house 1-D and 2-D CFD (Computational Fluid Dynamics) erosive burning modeling and predictive capabilities. A detailed account of the subscale testing is presented in AIAA 2003-4806[2] and a description of the 2D erosive burning model development is presented in AIAA 2003-4809[3].

Two different approaches were used to predict the magnitude of erosive burning in the ETM-03 test motor. The first method was to generate a ballistic prediction using the aforementioned models with the current RSRM "WECCO" block model SBRE. This approach was conservative since any amount of erosive burning present in RSRM is included in the SBRE and coupled with the theoretical erosive enhancement from the newly developed models. The second method used a refined RSRM SBRE that was generated by removing the theoretical contribution of the RSRM erosive burning rate enhancement. This was accomplished by reconstructing the RSRM block model head-end pressure trace using the burn rate enhancement contribution from the newly developed erosive burning model. Both of these analyses indicated that large scale erosive burning was not expected to be present in ETM-03. The maximum predicted head-end pressure increase was less than 10 lb_f/in^2 with a predicted duration of approximately 20 seconds that contained any pressure magnitude of significant value.

D. Ignition Prediction

Ignition events have long been the hardest event of solid rocket motor operation to model. Many programs have attempted to capture the physics of this event with only limited success. Two computer models are currently in use at ATK that are used to model the RSRM ignition event. Both of these models have been grounded to extensive data from the history of the RSRM program, but use two very different analytical approaches.

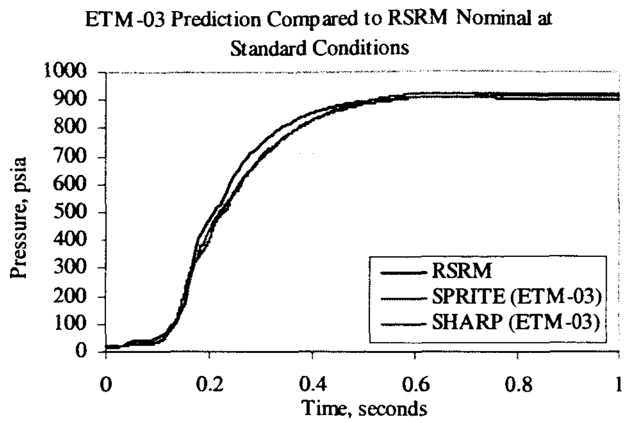

Figure 9: ETM-03 Ignition Predictions compared to the RSRM Nominal

The Solid Propellant Ignition Transient Evaluation (SPRITE) code uses a 2-D CFD-based algorithm. This code models the solid propellant heating and ignition, as well as the gas dynamics during the ignition event. The SHARP-1D2DIT model uses 1-D flow and two-dimensional heat transfer to model the ignition event. ETM-03 ignition was expected to have very similar characteristics to the RSRM ignition. The RSRM models were therefore modified to include the added center segments, leading edge chamfers on the center and aft segment, larger throat, and slightly lowered burn rate. Figure 9 show the model predictions compared to the nominal measured RSRM ignition for the SPRITE and SHARP-1D2DIT codes. The slower rise and slightly higher maximum pressure are evident in these traces. The slower rise comes mostly from the time needed to fill the larger volume with a reduced propellant burn rate and larger nozzle throat.

IV. ETM-03 Reconstruction

The post-test analysis included a full 1-D ballistic reconstruction of the motor performance and comparisons to the predicted performance. Overall, the delivered performance was very close to the predicted performance. Minor differences in performance values generally fell within the historical RSRM variation. Reconstructed values for pressure, thrust, and mass flow were compared to the predicted values. Of special interest are small differences noted in the first 10 seconds of the trace and around web time.

A. Reconstructed Performance

1. Pressure

The delivered pressure was monitored on several channels using different gauges. Pressure measurements were taken at the head-end, as well as inside the slot between each segment of the motor. Head-end pressure was slightly higher than predicted in general but stayed within ±2.2% during steady state. The post fire analysis shows that this difference is mostly due to the increased pressure loss and reduced nozzle efficiency. The reconstructed characteristic exhaust velocity (C*) value of 5098ft/sec was slightly higher than the RSRM nominal of 5080 ft/sec, but not enough to account for the majority of the pressure difference observed in the head-end of the motor.

It has long been known that CFD and 1-D ballistic models show significantly different pressure drop down the bore of long motors. Pressure gauges in each slot show good correlation between the measured pressure drop, and the 2-D CFD pressure drop predictions that were completed before the test[4]. These data confirm the 2-D CFD pressure drop results and will be used to study how the 1-D model may be modified in an attempt to better model the actual pressure drop down the length of the motor.

2. Thrust and Mass Flow

Utah site thrust was measured directly during the test, and mass flow was calculated using a 1-D ballistics code with reconstruction capabilities. Both thrust and mass flow rates were noticeably closer to the prediction than the pressure values were. The 1-D ballistics code is very good at generating the right shape of a trace. Since the total propellant weight is measured at the manufacturing time, the 1-D predictions can be forced to flow the right amount of propellant. Also, the 1-D ballistics predicted thrust output was scaled to match the I_{sp} that was calculated in the SPP nozzle analysis code. Post fire results show that the SPP nozzle analysis was very accurate and predicted the I_{sp} for ETM-03 with EAEC within the normal variation of the RSRM.

3. Burn Rate

The propellant formulation for ETM-03 was altered slightly to meet the designs' target burn rate. Much effort was put forth to properly formulate the propellant to meet the target burn rate as well as mechanical and ballistic properties. Information from the RSRM propellant standardization process was used to adjust this formulation based on lot specific properties. The resulting final propellant formulation hit the target burn rate within RSRM variation, highlighting the robustness of the RSRM standardization process.

A full-scale-to-subscale-scaling factor is used to adjust the propellant burn rate measured in sub scale tests for the full-scale prediction. For RSRM this is determined by using the average reconstructed value from the last seven flight sets. This method has been shown, statistically, to provide the most accurate prediction factor. Although it is known that RSRM static tests generally show higher full-scale burn rates than RSRM flight motors, the current RSRM prediction factor, 1.0242 at that time, was used to predict ETM-03. As expected, the final reconstructed burn rate was slightly higher than the prediction, but was well within the range of values from recent RSRM static tests. The predicted burn rate was 0.343 in/s at a propellant PMBT of 60°F and pressure of 625 lb_f/in^2; the reconstructed value was 0.3443 in/s for the same conditions. This results in a full-scale-to-subscale ratio of 1.02823

4. Erosive Burning

Direct measurement of the propellant surface regression is the only accurate method for evaluating erosive burning. Information about erosive burning in ETM-03 was limited to indirect methods. Based on available instrumentation, a pressure trace shape comparison of posttest against predicted was used to assess the erosive burning prediction accuracy. Trace shape characteristics in the first 20 seconds of motor operation agreed reasonably well with those predicted. This is an indication that the integrated burn rate enhancement of the entire surface area was predicted with reasonable accuracy. Trace shape characteristics encompassing web time roll over and tail off gave some indication that the distribution of erosive burning in the model may need to be adjusted to compensate for observed differences. At the time of writing, an effort was being made to distinguish erosive burning distribution from other performance phenomena that generates similar trace shape variances.

5. Ignition

The delivered ignition trace for ETM-03 was very close to the predicted traces. Figure 10 shows the delivered performance compared with the SPRITE and SHARP-1D2DIT predictions. The similarity in the traces show that the prediction codes do properly capture the physics involved with the additional segment, leading edge chamfers, reduced burn rate, and larger throat diameter.

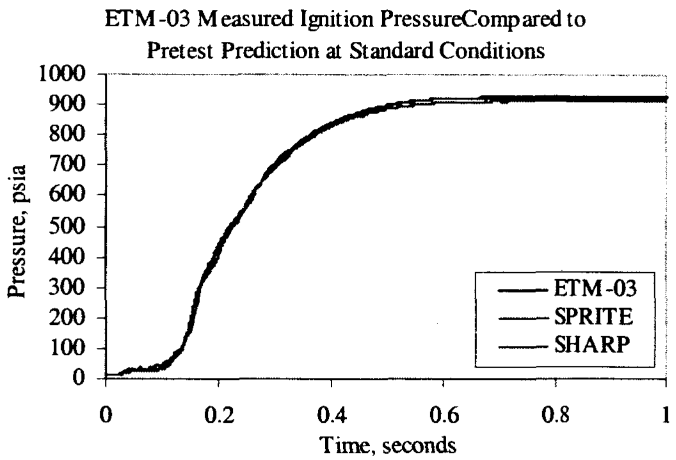

Figure 10: ETM-03 Ignition Compared to Predictions

B. Trace Shape Differences

Two distinct trace shape differences appeared in the ETM-03 measured data. These differences occur at the beginning and end of motor operation. At the time of this writing, two major hypotheses are in consideration. These could explain the observed differences as a result of erosive burning greater than what the new model would predict, or as a result of effects due to the increased pressure drop not captured by the 1-D model. Both would seem to indicate that the two differences may be consistent with each other, or at least due to the same cause. The added impulse in the early part of the trace may be a clue to the lower values seen around the timeframe of propellant web burnout.

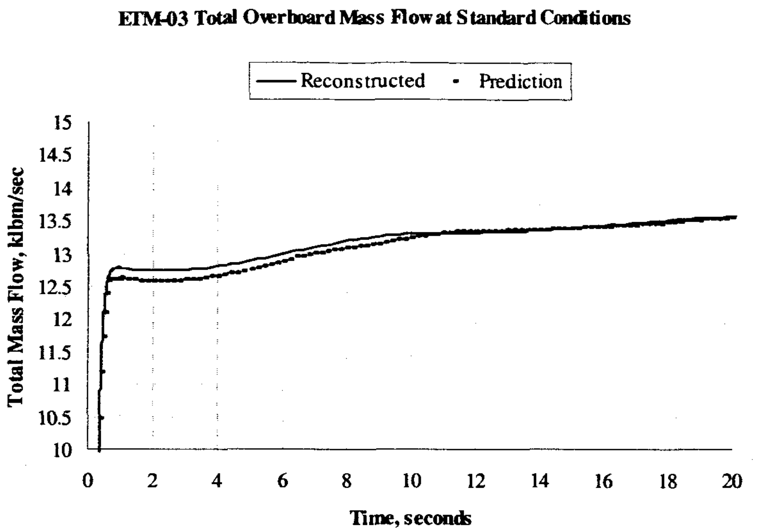

Figure 11: Early Trace Shape Difference as Seen in Total Mass Flow

The first difference displays best in the thrust and mass flow data (Fig. 11). Pressure data were further from the prediction due to a combination of several minor modeling errors that collectively impacted the predicted head-end pressure. The delivered thrust and mass flow came in higher than expected for approximately the first 10 seconds. The difference was within RSRM historical variation, so it is conceivable that this is nothing more than simple motor-to-motor variation; however, the timing, magnitude, and duration are suspiciously consistent with minor erosive burning. The data gathered in the aforementioned subscale testing do not support this hypothesis. The erosive burning needed to create this increased level of performance would be significantly greater than the testing and new model would indicate.

It is also plausible that the increased pressure drop not captured in 1-D physics could have created this difference. The reconstruction process did indicate a change in the empirical pressure recovery factor (η_r) that accounts for some of the added pressure drop. The CFD models show considerably more pressure drop than the 1-D even after the η_r is applied. It is conceivable that the added segment exaggerated this difference. CFD predictions show that the added pressure drop down the bore in the motor would result in a higher head-end pressure. This would feed back to an increase in the burn rate for the time of interest, which would then serve to increase mass flow and thrust.

The other distinct trace shape difference is evident in all three traces (pressure, thrust, and mass flow). This difference is evident at the time of propellant web burn out. As the segments burn out of propellant, the time-pressure-thrust-mass flow trace declines rapidly. The point at which this happens defines the "web time" of the motor. RSRM has a noticeable step like shape right before the web time. This is because one segment burns out slightly before the other three. The step like shape is evident in the ETM-03 prediction (see Fig. 12), but ETM-03 delivered a very nicely rounded web time shape. This indicates that the segment burnouts may be more staggered than in the RSRM or that the burn out of the segments was not as sudden of an event as with the RSRM. Either the enhanced burning or the added pressure drop could have altered the segment burnout times relative to each other. The standard prediction and reconstruction assume a uniform base burn rate for each of the motor segments. At the time of this writing, analyses are looking into possible segment specific burn rates that may result in this new web-time trace shape.

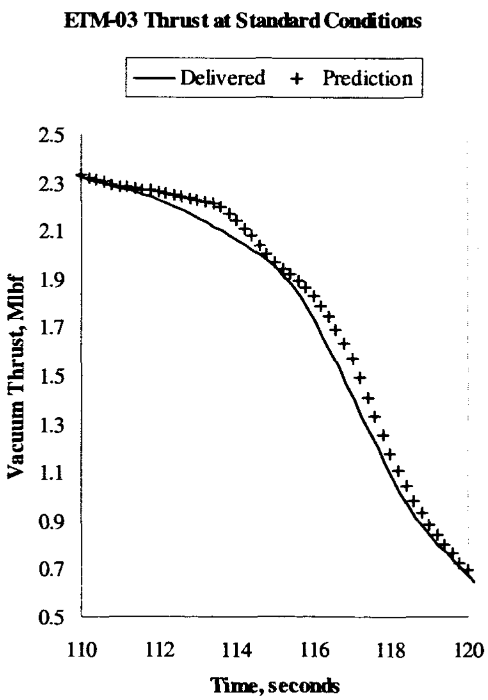

Figure 12: Web Time Trace Shape Difference as Seen in Delivered Thrust

V. Conclusion

ETM-03 successfully demonstrated that the models and assumptions used for the RSRM are acceptable to create accurate predictions of larger five-segment motors. There is still much to be learned from the ETM-03 data that could be of use not only in modeling future large motors, but also in increasing the understanding of the Space Shuttle Program's RSRM. The successful prediction and modeling of ETM-03 shows that the models are capturing the physics of solid rocket motor operation and increase confidence in the ability of those models to predict off-nominal performance for special circumstances. ETM-03 paves the way for increased confidence in today's RSRM models, developing better RSRM models for the future, and developing models to be used in future development of shuttle derived propulsion concepts, such as the Crew Exploration Vehicle or heavy lift cargo vehicles.

Acknowledgments

The authors of this paper would like to acknowledge that the success of ETM-03 was the result of several years' effort by many personnel at both ATK Thiokol and Marshall Space Flight Center. The following list is by no means an all-inclusive list of persons involved with the ETM-03 project, but is an attempt to recognize substantial contributors to the success of ETM-03.

Joint MSFC RSRM Project / ATK Thiokol Team Lead Acknowledgments

Andrew Schorr / Cary Ralston	Program
Frank Bugg / James Seiler	Project
Daryl Woods / Hal Huppi	Systems

Other ATK Thiokol Engineers Contributing to Design and Analysis Process

Mark Tobias, Joshua McMillin	Internal Ballistics / Motor Performance
Ken Sorensen, Steve Cutler	Propellant Testing
Brent Wiesenberg, Bob Lundgreen, Jonathan Janssen	Ignition Analysis
James Furfaro, Qunzhen Wang	Erosive Burning Test Analysis
Rashid Ahmad, Bob Morstadt, Andy Eaton	CFD Analysis
Brian Rex, Del Hillary	FSI Analysis
Dale Nielsen, Eric Gross	Loads & Environments
Don Mason	Internal Acoustics
Randy Buttars	Plume Heating Environments
Jeff Maughan, Ken Wanlass (Retired)	Internal Combustion Acoustics
Joe Lohrer, Tom Weidner	Case Structures Assessment
Rob Wynn, Pat Downey, Steve Kirkham, Jeff Astle	PLI Structural Analysis
Dan Nelson	Nozzle Design
Don Lamont, Dave Richardson	Nozzle Structural Analysis
Craig Prokop	Nozzle Torque Analysis
Joel Maw	Nozzle Char and Erosion Analysis
Cory Smith, Joe Heman	Nozzle Joint Thermal Analysis
Kevin Albrechtsen	Insulation Design
Mark Ewing	Insulation Thermal Analysis
Bruce McWhorter & Team	Instrumentation Development
Karl Shupe, Gary Jepson	Seals Compliance
Brad McCann, R.E. Lee Hamilton	System Safety Review
Mick McLennan	Test Stand Flexures Analysis
Gerry Collins, Phil Petersen, Steve Hoggan	Test Stand Modifications

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