

ABSTRACT

The Transient Pressure Test Article (TPTA) test program is being conducted at a new test facility located in the East Test Area at the National Aeronautics and Space Administration's (NASA's) Marshall Space Flight Center (MSFC) in Huntsville, Alabama. This facility, along with the special test equipment (STE) required for facility support, was constructed specifically to test and verify the sealing capability of the Redesigned Solid Rocket Motor (RSRM) field, igniter, and nozzle joints. The test article consists of full scale RSRM hardware loaded with inert propellant and assembled in a short stack configuration. The TPTA is pressurized by igniting a propellant cartridge capable of inducing a pressure rise rate which simulates the ignition transient that occurs during launch. Dynamic loads are applied during the pressure cycle to simulate external tank attach (ETA) strut loads present on the ETA ring. Sealing ability of the redesigned joints is evaluated under joint movement conditions produced by these combined loads since joint sealing ability depends on seal resilience velocity being greater than gap opening velocity. Also, maximum flight dynamic loads are applied to the test article which is either pressurized to 600 psia using gaseous nitrogen ( $\text{GN}_2$ ) or applied to the test article as the pressure decays inside the test article on the down cycle after the ignition transient cycle. This paper will present the uniqueness of this new test facility with respect to its capabilities. In addition, the paper will also touch on both the topic of test effectiveness versus space vehicle flight performance and new aerospace test techniques, as well as presenting a comparison between the old SRM design and the RSRM.

Introduction

As a result of the Space Shuttle Challenger accident in late January of 1986, changes were required in the Space Shuttle Transportation System to enable the resumption of safe space flight. One of the main components requiring extensive redesign by NASA was the Solid Rocket Motor (SRM) joint sealing system. The Challenger accident resulted from the escape of hot gases and flames from the SRM which ignited the external fuel tank of the Shuttle. The SRM is developed and manufactured by Morton Thiokol Incorporated (MTI) located in Utah.

Testing of the redesigned joints is essential to verify the performance of the SRM under conditions that simulate a portion of the flight environment. A major test program was initiated to prove the overall integrity of the RSRM which includes full scale hardware test programs such as the Joint Evaluation Simulator (JES) tests, Nozzle Joint Evaluation Simulator (NJES) tests, Referee tests, full duration horizontal firing motor tests, Assembly Test Article (ATA) tests, Structural Test Article (STA-3) tests, and the Transient Pressure Test Article (TPTA) tests. Several subscale test programs, such as the 70-lb motor tests and O-ring fixture testing, were also initiated to obtain data utilizing both a quicker and a lower cost test process. This paper will address the TPTA test

program, but some of the test programs mentioned above will be discussed briefly, as required, when used in a comparison with TPTA.

Joint Redesign Task

Following the Challenger accident, the redesign effort on the SRM joints became extensive. An SRM Redesign Team, identified as RA01, was formed consisting of NASA MSFC personnel from several disciplines involved in the SRM project to obtain the needed expertise. This MSFC team worked closely with MTI to develop concepts of improving joint sealing performance of the SRM. After consideration of many concepts, the final design was baselined. This design implements a capture feature hook which produces an interference fit to stiffen the joint and also incorporates a third O-ring to enhance joint sealing ability. A comparison between the old design and the redesigned joint is presented in Figure 1. The redesign of the nozzle-to-case joint incorporates the addition of a third O-ring known as the wiper O-ring, the addition of radial bolts, and aft dome structural modifications to strengthen the joint. Figure 2 shows a comparison between the redesign and the previous design.

The insulation configuration was also changed to prevent hot gases from reaching the field joints. The new design in the field joints is known as the J-seal as shown in Figure 1. Pressurization of the J-seal closes the bondline between the insulation of two segments during motor operation. The insulation design in the nozzle-to-case joint has elongated vent slots which allow air trapped during the mating of the joint to escape without creating blow holes. The insulation in the joint provides an interference fit for a tighter bondline.

MSFC worked closely with USBI on several components of the Solid Rocket Booster (SRB). The two of main concern to the TPTA test program are the external tank attach (ETA) ring and the aft skirt. The ETA ring has been changed from a 270-deg design to a 360-deg design. This full circle design eliminates the ovality of the motor case in the vicinity of the ETA ring which was caused by the 270-deg design and also provides additional strength in this area. The new ring has been fully instrumented to obtain data during the strut loading applications of TPTA. The aft skirt has also been modified to provide additional strength. Limited data on an unmodified aft skirt was obtained during TPTA testing; however, most aft skirt evaluation was accomplished in other testing. The STA-3 test program, also conducted at MSFC, tested this redesigned aft skirt and the 360-deg ETA ring to 140-percent design loads to obtain data to verify the redesign.

Test Objectives

The main objective of the TPTA test program is to provide data to verify the sealing capability of the RSRM field joints, the nozzle-to-case joint, and the igniter joint. Test data is also obtained for the new 360-deg ETA ring and limited data on the unmodified aft skirt as stated previously. Instrumented studs secure the test article to the four flight

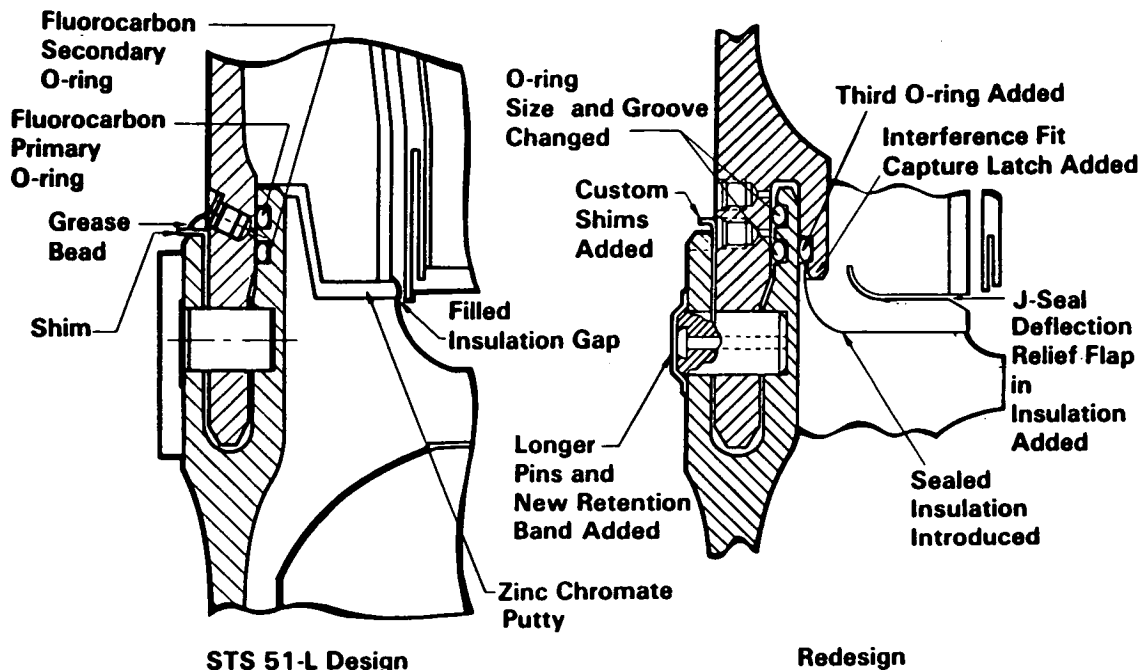


Figure 1. SRM Field Joint Comparison

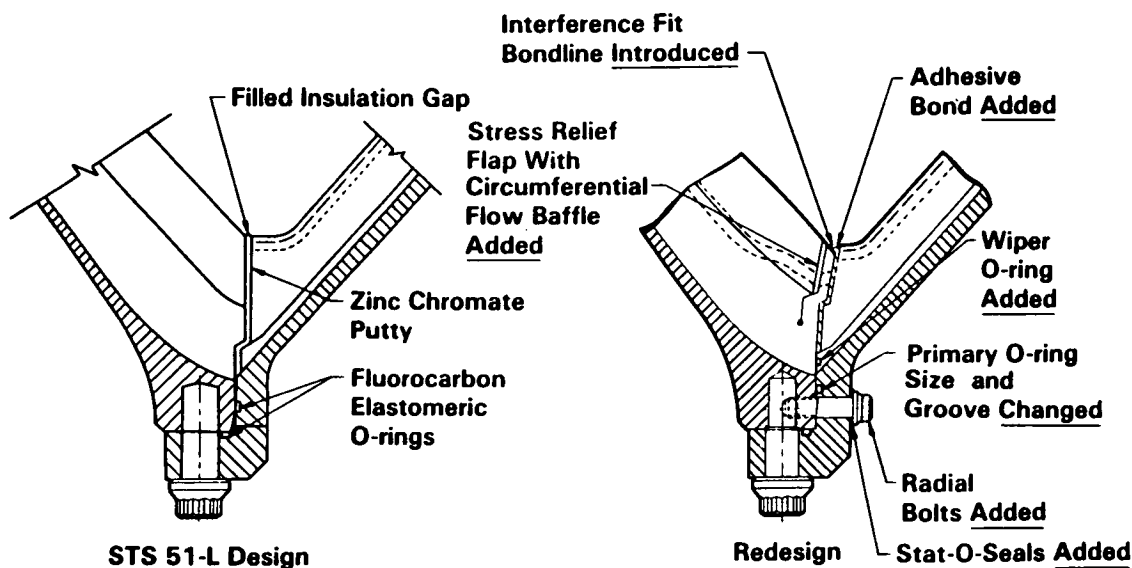


Figure 2. SRM Nozzle-to-Case Joint Comparison

holddown posts and acquire strain data which adds to the overall data base. The TPTA test program also allows for the demonstration of the assembly/disassembly and reusability of the redesigned joints along with demonstrating the adequacy of assembly/disassembly tooling, procedures, and inspections. Training of personnel for the stacking of flight hardware is also accomplished during this test program. The test program is a joint effort between MTI, USBI, Wyle Laboratories and MSFC, along with various subcontractors required for specific tasks. MSFC has primary responsibility for test implementation.

#### Test Article Configuration

The TPTA consists of full-scale RSRM hardware assembled in a short-stack configuration as shown in Figure 3. The hardware is comprised of two baseline capture feature cylinder segments, forward and aft domes, ETA stiffener segment, nozzle fixed housing, and a modified flight igniter. Inert propellant is used in lieu of live propellant and is protected from burning with insulation. The aft skirt, the 360-deg ETA ring, and the holddown studs are also a part of the test configuration. Four flight holddown posts support the test article during testing.

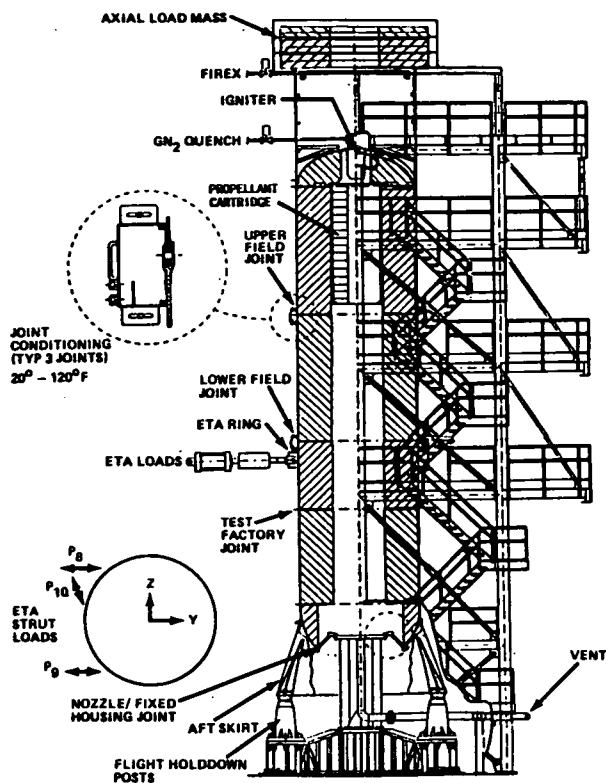


Figure 3. TPTA Configuration

The TPTA test provides for a short duration, hot-fire test with dynamic loads application during an ignition transient condition and a maximum flight dynamic load condition. Figure 4 shows a comparison between a complete SRM and the short stack test article used in this test program. In order to simulate the weight associated with the other shuttle components and provide appropriate dynamic boundary conditions, a one million pound dead weight is attached on top of the test article using a simulated forward skirt. The test joints associated with the test article include two field joints, the nozzle-to-case joint, and the igniter joint. The factory joints and non-test joints are also monitored during testing and their performance is evaluated following testing. All joints can be thermally conditioned prior to initiation of the test.

A field joint enables the mating of two casting segments with the assembly being accomplished in the field. A factory joint provides the mated connection of two segments to form a casting segment which is assembled at the factory prior to propellant casting. Potential leak paths are more likely to occur in field joints since the insulation and propellant in two segments mated in the field are not continuous across the joint bond as is the case with the factory joint. Therefore, gap movements in the RSRM have a worse effect on field joints than factory joints due to the potential of the joint bond opening during motor operation and allowing hot gas to reach the joint.

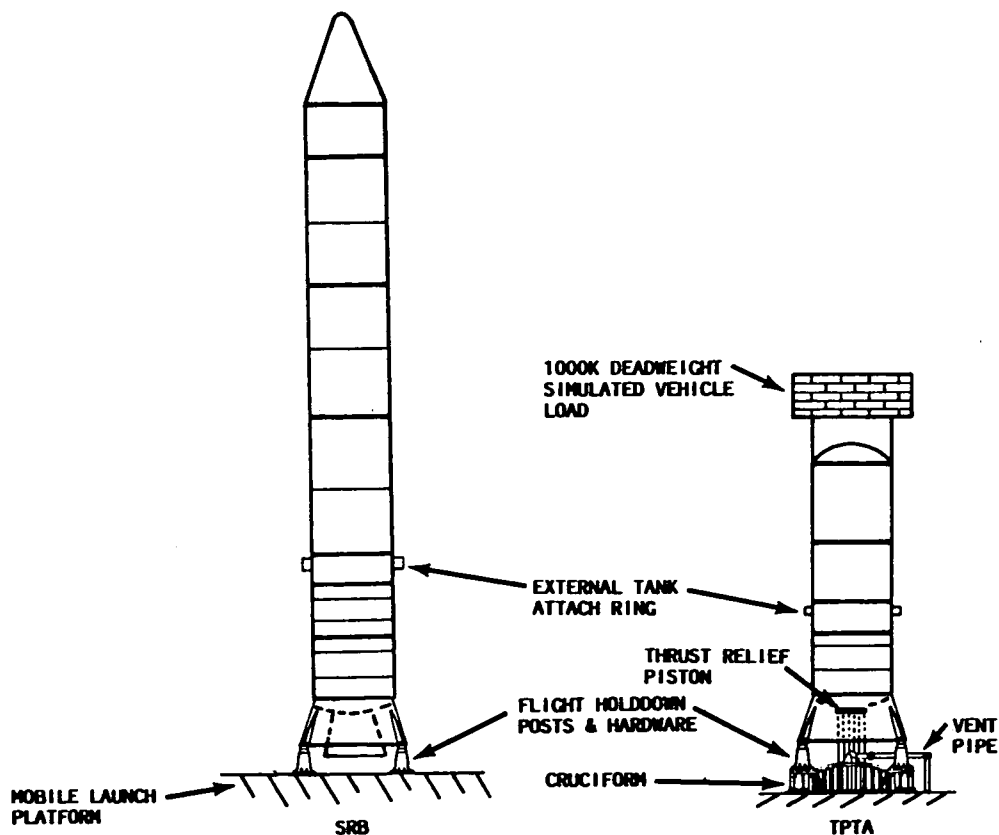


Figure 4. "Full Up" SRB and TPTA Comparison

A propellant cartridge, consisting of a multiple fin design, as shown in Figure 5, is used to induce the pressure rise rate and magnitude inside the test article which closely simulates the ignition transient that occurs during launch. Propellant strips are bonded around the two field joints which assures hot gas flow to these joints. The pressure rise rate is a function of the surface area of the exposed propellant on the cartridge. The design incorporates 45 fins with propellant bonded to each side of the fins to obtain the required surface area needed to produce the ignition transient rise rate. The total propellant weight inside the test article determines the maximum expected operating pressure (MEOP). The propellant strips bonded at the field joints are designed in conjunction with the propellant cartridge to provide the desired MEOP for each test.

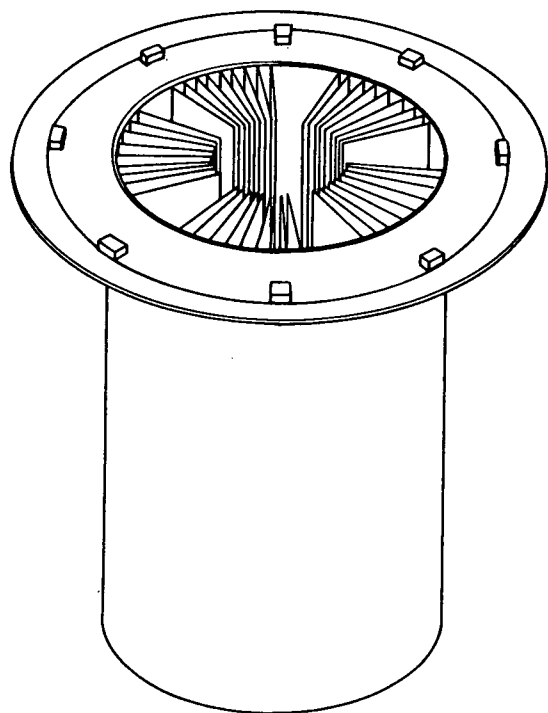


Figure 5. Finned Propellant Cartridge

#### Test Facility

The TPTA facility was constructed with the capability of inducing prelaunch, ignition, and flight type dynamic, structural, and limited thermal environments on the test article to evaluate the redesigned joint performance. The TPTA facility, depicted in Figure 6, is located at NASA MSFC in Huntsville, Alabama, and consists of the foundation, access and load towers, support structures, facility crane, support buildings, test stand utilities, a refurbishment facility, and individual systems needed for specific test functions. Four flight holddown posts, which secure the test article using instrumented studs, are attached to a cruciform support structure. The cruciform is a reaction structure comprised of welded steel plate which transfers the loads from the TPTA into the concrete foundation. An access tower, which has no structural connection with the test article or the load tower, surrounds the TPTA

and provides movable platforms to access specific levels associated with the joints on the SRM. The load tower, located next to the access tower, reacts the dynamic loading induced on the test article through the three hydraulically operated load lines which are shown in Figure 7. The hydraulic system is mounted on the top of the load tower. Existing buildings are used for test facility support such as instrumentation and test control.

A refurbishment facility, located adjacent to the test stand, provides capability for test article preparation and insulation repair during recycle between tests. The test article is disassembled and carefully inspected prior to and after the segments are moved to the refurbishment facility. Segments are loaded into the facility, which has removable roof panels, using the special facility crane which is capable of destacking the test article. The test article is cleaned of material such as charred insulation and is then repaired for the next test. Instrumentation and propellant layup are other functions performed in this facility. The facility is environmentally controlled for application of adhesives and other materials.

The TPTA test facility contains several systems which perform various functions in support of testing. These systems, which are referred to as STE, include the  $\text{GN}_2$  quench/purge system, the missile grade air system, the hydraulic system, the joint conditioning system, the sequencer system, the ignition system, the camera system, the instrumentation/data acquisition system, the firex system, and other small systems.

The  $\text{GN}_2$  quench/purge system provides a means of quenching the TPTA and purging the hot gases from inside the test article immediately following the hot-fire test. This reduces the amount of work needed to refurbish the test article and thus enhances the test turnaround time.

The missile grade air system is used to pressurize the SRM for leak check operations when intentional flaws do not allow performance of the standard flight motor leak check. This system is also used to purge the test article of any inert gases prior to testing.

The hydraulic system provides power for dynamic loading of the test article through three load lines. A programmable Cyber controller is used for the application of selected static and dynamic loading profiles.

The facility provides the capability for conditioning the joints to various temperatures. This system is comprised of heating and cooling devices with programmable controllers to maintain the joint temperatures within specified tolerances. Temporary shrouds enclose the two field joints and are removable prior to testing for camera viewing. A shroud also encloses the igniter joint which uses expanded missile grade air to cool the joint or heated missile grade air to heat the joint. The nozzle-to-case joint incorporates a heating, ventilation, and air conditioning (HVAC) system to condition the joint to the desired temperature. Strip heaters are used to maintain the minimum required temperature, usually 60 degrees, for all nontest joints.

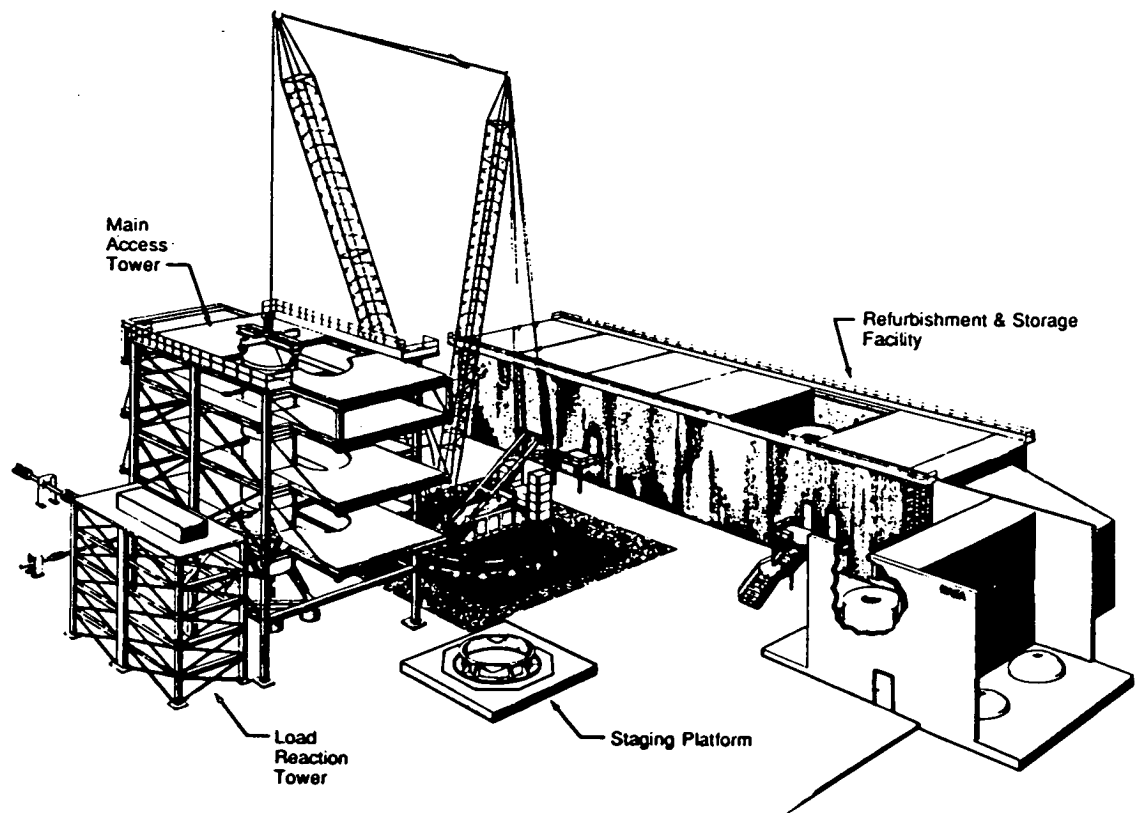


Figure 6. TPTA Test Facility

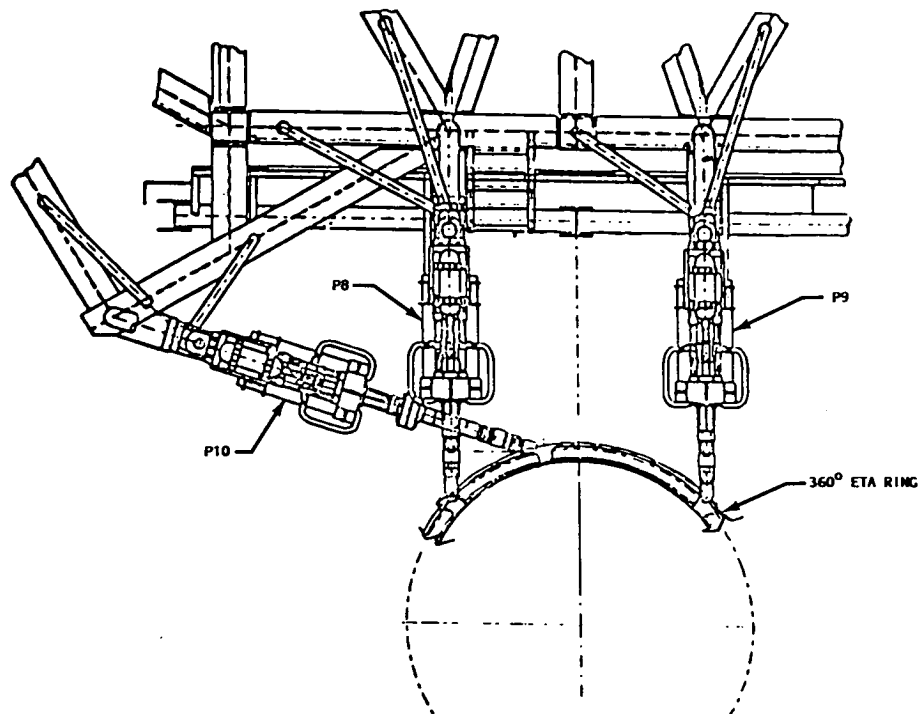


Figure 7. Hydraulic Load Lines

The facility is also equipped with a programmable controller used to assure that critical pretest conditions are present and to provide sequencing and logic for orderly control of the test. This controller is known as the sequencer and serves as the brain for the tests.

The ignition system interfaces with the sequencer and the test stand safe and arm (S&A) device to provide safe/arm and fire/abort commands to the TPTA gas generator initiator. The system uses a flight type initiator with the S&A device to initiate the firing process of the propellant cartridge.

Twelve high speed motion picture and several documentary movie cameras are positioned around the test stand and at various levels to view and document the test operation. The test article and facility is highly instrumented to obtain the necessary data for both RSRM performance and control system feedback. Instrumentation data is processed by the instrumentation/data acquisition system which consists briefly of microprocessors, static input units (SIUs), data selector units (DSUs), and multiplex cabling.

Fire protection is provided by both an on-stand firex system and a remotely-controlled monitor nozzle which enables the operator to concentrate a stream of water on selected targets.

#### Test Implementation

Testing of the TPTA consists of igniting the propellant cartridge, using a flight type igniter, which induces the simulated SRM ignition transient pressure. The required target pressure rise rate differs from test to test but 141 psi/10 ms is a typical value. This rise rate is expected to produce a MEOP of approximately 957 psia in 0.6 sec. Dynamic loads are initiated by the sequencer during this pressure cycle. Maximum flight dynamic loads (Max Q) are applied at approximately 34 sec following ignition when the pressure inside the test article drops to about 600 psi. Max Q loads are the loads present on the ETA struts at the time of maximum dynamic pressure occurring during flight. The Max Q loads can also be applied to the test article following a hot-fire test by pressurizing the TPTA to 600 psi using the facility GN<sub>2</sub> system. The hot gas and pressure are held inside the TPTA for 120 sec to allow the joints to experience the severe heating environment for an extended period of time. At the end of 120 sec, the hot gas is vented to the atmosphere through a specially designed vent pipe for this environment.

#### Test Effectiveness

Currently, four out of ten scheduled tests have been completed in the TPTA test program, each test having various requirements for dynamic loading and joint conditioning. Temporary shrouds enclose each test joint, including the igniter joint, which allow the conditioned medium to either heat or cool the joint to the required temperature environment. This capability enables the redesigned joints to be tested in a range of environments that a flight motor might experience during launch. Sealing ability of the redesigned joints is evaluated under joint movement conditions produced by these combined loads since joint sealing ability depends on seal resilience

velocity being greater than gap opening velocity. The O-ring seal resilience is greatly dependent on temperature, thus the capability to condition the joints to different temperatures is a key element of test program effectiveness. In the same context, various dynamic load profiles can be applied to the test article through the ETA ring to verify the integrity of RSRM joint sealing under different loading conditions that have been experienced during previous SRM flights.

Several tests have and will be planned in which seals and/or insulation layout in the test joints are intentionally flawed so that engineers can evaluate the reliability of the redesigned joints under different sealing conditions. In some cases the motor is flawed all the way to the secondary O-ring, thus testing the joint with no redundant seals. Grooved flaws are precisely cut through the insulation to the joint and O-rings are flawed by reduction in O-ring diameter at the flaw location. In cases where the motor has multiple flaws, the induced defects are purposely aligned to simulate a worst case situation.

The TPTA test facility is unique in its ability to simulate a realistic flight type environment on the RSRM test article. Unlike the full duration horizontal motor firings at MTI in Utah, the TPTA test facility tests the redesign in a vertical launch position. This capability, along with the capability to add weights to simulate the axial force of missing shuttle components, greatly enhance test authenticity. These two loading sources (strut and axial) are loads that have not been addressed in either the previous JES tests or in full-duration horizontal RSRM testing. The design of the facility incorporates a thrust relief piston which enables the test article to experience an upward thrust similar to that occurring at ignition on the mobile launch platform (MLP) during launch. This thrust applies realistic stresses to the motor case and SRB components, especially the aft skirt. These loads, coupled with the strut loads applied to the ETA ring, provide a very authentic test configuration.

#### Test Results

Four hot-fire tests have currently been performed at the TPTA test facility. The successful completion of these four tests were required prior to the resumption of Shuttle flights. The tests were performed utilizing two sets of RSRM hardware in order to complete these required tests in the shortest time frame possible. Tests completed thus far include TPTA Test 1.1 (first hardware set, first test), 1.2, 2.1, and 2.2. A brief summary of the test results found to date will be presented in the following paragraphs.

In late August through early October of 1987, initial tests were performed with a Pathfinder test article of non-redesign configuration. The primary objective of the Pathfinder tests was to conduct functional and procedural tests for verification of the TPTA test facility with respect to the facility/test article interfaces, dynamic strut load application and control, GN<sub>2</sub> pressurization system, joint conditioning system, data acquisition system, and other system operations. The series of testing did not include a hot-fire test, but verified the ignition circuit for TPTA Test 1.1. The Pathfinder tests

proved to be very beneficial in preparing the facility for the first test during fabrication and delivery of the first set of redesigned hardware. Several improvements were made to most systems as a result of this test which ensured that the facility was ready to accept the first RSRM test article for a hot-fire test. Transportation and handling operations were performed which resulted in refinement of handling procedures prior to TPTA Test 1.1. Data obtained during static and dynamic load tests were compared to analytical models to better understand the response of the test article in the test facility.

TPTA Test 1.1 consisted of a hot-fire test and a cold-gas Max Q test. The hot-fire test was conducted on November 19, 1987, with the cold-gas Max Q test following on November 24, 1987. During the hot-fire test, strut loads were not applied to the test article due to a malfunction in the loading system. This malfunction was caused by a broken wire supplying critical information back to the sequencer which inadvertently resulted in aborted loads while ignition of the propellant cartridge was not aborted. This problem was corrected, and a more stringent checkout was initiated for systems that provide feedback for critical control of the test. Another anomaly experienced during this test was the quench injector plug blocking the vent pipe nozzle which caused the motor to experience a more severe test. The venting of the test article ceased 12 sec after ignition and remained pressurized at approximately 420 psia for roughly 11 min before an auxiliary vent valve was opened. In this static hot-firing test, all joint measurements were within the range of similar tests performed without strut loads (JES tests) and were close to the predicted values. Hot gases did not get past the J-seal insulation. This test did not have any intentional flaws in the joints. The test article performed nominally, achieving a maximum pressure of 913.3 psia at 0.609 sec.

The cold-gas Max Q test was designated as TPTA test 1.1A. This test consisted of pressurizing the test article to 612 psia using the facility GN<sub>2</sub> system and applying the Max Q strut loads to the test article. The load system performed as intended, applying the specified load profile with no anomalies. Figure 8 shows the commanded load profile for load line P-8 and the actual profile that was applied to the test article. The capture feature primary O-rings sealed and did not show any leakage during the cold-gas test. Post-test inspections revealed no joint anomalies other than a leak path through the polysulfide adhesive to the wiper O-ring in the nozzle-to-case joint.

TPTA test 1.2 was successfully tested on February 11, 1988. Two field joints and the nozzle-to-case joint had intentional flaws through the insulation to the primary O-ring. The flaws through the insulation were purposely aligned with the O-ring flaws to simulate a worst case situation. Prior to test, the test article was leak tested by pressurizing the motor to 100 psia with GN<sub>2</sub>. All the test joints were conditioned within the required temperature range of 70 to 95°F, while the nontest joints were conditioned to 60°F minimum for test. Upon ignition of the propellant cartridge, representative launch loads were applied to the RSRM during the ignition transient period as designed. During this test, hot gases were contained inside the test article for 120 sec providing extended exposure to the joints and then released through the vent pipe.

The performance of the RSRM hardware for TPTA test 1.2 was excellent and all objectives for test were met. The ballistic performance was good and fulfilled its function of creating an accurate pressure transient. Upon the successful application of dynamic loading, predictions were confirmed that the strut loads have minimal effects on joint gap deflections. This supports the findings of TPTA Test 1.1A, which show that the chamber pressure is the driver

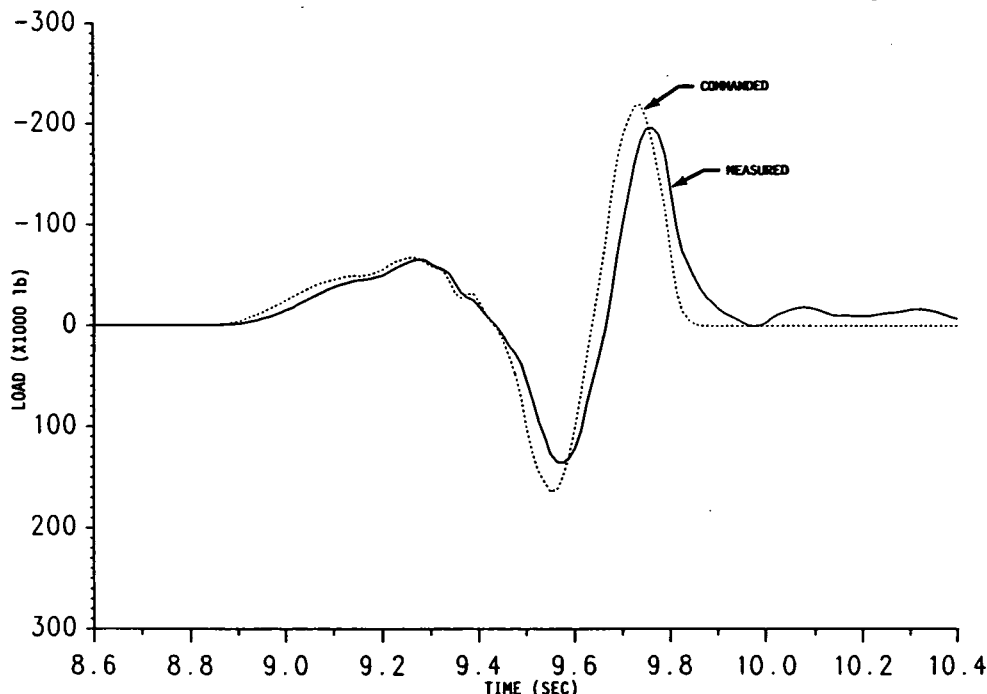


Figure 8. Loadline P-8 Load Profile

in gap movement. There was no leakage past the primary O-ring on any joint, and intentional flaws performed as expected as indicated by pressurization of the primary O-rings in all test joints.

The third hot-fire test, TPTA Test 2.1, was conducted on March 21, 1988. As the test number indicates, this was the first test on the second set of RSRM hardware. The test article was intentionally flawed in one of the field joints and the nozzle-to-case joint allowing the primary O-rings to be pressurized and their sealing ability to be tested. The other field joint consisted of the baseline design with no intentional defects. A vent port plug was intentionally flawed to verify the sealing capability of the plug. Field joints were conditioned to 120 +15/-0°F and the nozzle-to-case joint was conditioned to 110 +15/-0°F. All nontest joints were conditioned to 75°F minimum at the time of the test. Ignition and pressurization performance for this test was nominal. Dynamic loads were applied to the test article during the ignition transient period, and representative Max Q dynamic loads were applied at approximately 34 sec after ignition when the pressure inside the test article decreased to about 600 psia. Hot gas and pressure were held inside the TPTA for 120 sec prior to venting.

The RSRM hardware performed flawlessly during TPTA test 2.1 and all the objectives of the test were met. The maximum chamber pressure and pressure rise rate were 8% lower than expected due to GN<sub>2</sub> present in the motor chamber prior to test. As a result of this, plans were made to purge the motor of inert gas prior to testing in future tests. The test sequence was executed as intended, producing both a simulated launch and Max Q loading condition. All the intentional flaws performed as designed, allowing the pressurization of the primary O-rings in the field joint and the nozzle-to-case joint with no leakage. The intentionally flawed vent port plug also maintained a seal during the test. Joint gap deflections were as expected and were similar to those experienced during other short-stack tests, thus establishing further confidence in the predictability and repeatability of RSRM joint hardware.

The final test completed to date was TPTA Test 2.2 which was successfully fired on May 17, 1988. This test was the worst flawed test of the RSRM performed to date in the test program. All test joints were intentionally flawed to the last seal, thus testing the RSRM with no redundant seals. These additional defects made leak checking the motor very critical. A method of leak checking the motor similar to flight motors was not readily available due to the induced flaws. The test article was pressurized to 200 psia and ultrasound equipment was used to detect any leaks. Also, the motor was pressurized to 900 psia and grease beads, placed around potential leak paths, were examined for indications of any leakage. These two tests gave engineers confidence to proceed with the test. New vent port plugs were installed on TPTA which involved using a new tool to accurately measure the plug holes for the installation of these custom vent plugs. The test joints were conditioned to 70 +15/-0°F prior to the initiation of the test. A bead of grease was applied around the potential leak paths of the test joints in order to detect any gross leaks which might occur during the test. After the initiation of the test, the dynamic launch loads were applied to the test article, and the hot gas

and pressure were contained inside the motor for 120 sec prior to venting, as in most of the other TPTA tests.

All the joints maintained a seal during this test which verified the capability of the RSRM to seal with no redundant seals. During the test the intentional flaw in the nozzle-to-case joint closed up during the hot-fire test, resulting in this joint not experiencing full motor pressure to the secondary O-ring. The ballistics and dynamic loading system performed as designed. Joint deflection data compared well to other tests as was expected.

#### TPTA Test Facility Future

A series of 10 tests were planned for the TPTA test facility to provide the data required to adequately verify the integrity of the new redesign. Four of these planned tests, which have been successfully completed, were required prior to resuming Space Shuttle flights. Areas of concern for future testing include additional flaw testing, igniter testing, margin testing, vented joint testing, verification testing, and sensitivity testing which are aimed at better understanding the performance of the RSRM. Also, different ballistic performance is planned to test the effect of various ignition burn rates. TPTA Test 1.3, which is the third test on the first set of hardware, is scheduled for early August 1988, and will include the removal of the metal interference fit on one of the field joints to determine the response of the test article with this type of defect.

In addition to other suggested areas of testing, the TPTA test facility, because of its excellent capabilities, has been selected as the facility to test and verify the Advanced Solid Rocket Motor (ASRM). The ASRM will have the capability to lift a heavier payload. The contractor selected to design and build the ASRM will be responsible for modifying the facility for ASRM testing, and also for implementing the tests.

#### Conclusion

The TPTA test program has played a vital role in verifying the sealing capability of the redesigned SRM. The test facility made it possible to test the RSRM under conditions which more realistically simulate prelaunch environments. Unlike the JES tests in Utah, the TPTA test program incorporates an aft skirt and ETA ring which enables dynamic loading to be applied to the test article to evaluate the effect of this loading, along with the axial loads, on both the RSRM and the SRB components. From this testing, it was confirmed that the strut loading has minimal effect on gap movement which is basically driven by the internal pressure of the motor. This minimal effect of strut loading on gap deflection was predicted by developing detailed models for analyzing the RSRM which are compared to the test results. Testing greatly enhances the ability to accurately build analytical models by comparing what was predicted to actual results and then refining the model to better understand the performance of the RSRM.

Measurement techniques and instrumentation have also been better understood as a result of this test program. Many lessons on instrumentation placement, limits, installation, and environments have been



learned which will not only aid in this test program but the expertise will greatly aid other test programs.

Testing to date has revealed that the RSRM joints do seal and maintain the seal during the duration of the test. Since the main objective of the test program was to obtain test data to verify the sealing capability of the RSRM field, nozzle-to-case, and igniter joints, the TPTA program is meeting the objectives. By purposely inducing defects into the motor, engineers have developed greater confidence in the sealing ability of the RSRM. The results obtained during this test program, combined with results obtained from other redesign test programs, have culminated in qualification of the RSRM sealing system and paved the way for resumption of safe Shuttle flights.