EELV SECONDARY PAYLOAD ADAPTER (ESPA) STATIC QUALIFICATION TESTS

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ABSTRACT

The United States Air Force Research Lab is currently examining options to launch small satellites (<200 kg e.g., 440 lb) more economically and efficiently. This class of satellite is quickly becoming a government and industry mainstay due to their ability to inexpensively demonstrate new technology, test prototype operational hardware, as well as perform space experimentation. Most of existing launch options include foreign sources, such as the Ariane launch vehicle, that are not available to Department of Defense (DoD) launches. Through the efforts of team members from the Air Force Research Lab/Space Vehicles Directorate (AFRL/VS), DoD Space Test Program (STP), TRW, and CSA Engineering, a secondary payload adapter has been developed to allow small satellites to be launched with the primary payload. This is to be accomplished by using an adapter on the upcoming Evolved Expendable Launch Vehicles (EELV), DoD medium lift vehicles; more specifically, the Boeing Co. Delta IV and the Lockheed Martin Atlas V launch vehicles. This adapter, known as the EELV Secondary Payload Adapter (ESPA) will take advantage of the primary payload's unused volume and mass margins.

As with any aerospace structure, the ESPA was subjected to a rigorous test program as a means of qualifying the structure for flight. For this program, the structure was tested in a static load environment determined to adequately represent the dynamic launch environment. Details of the static qualification tests, including test hardware and software, and test philosophy will be presented in this paper as a four part series. The first of the four, this installment will serve as the introduction and detail the process of determining qualification loads.

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INTRODUCTION

The design philosophy behind the ESPA from its inception was to be as transparent as possible to the primary payload. The goal of adding six secondary payloads with minimal impact on the primary payload had numerous aspects, including electrical, thermal, and integration issues that are not detailed in the present paper [1]. Several trade studies were performed in an effort to determine the optimum ESPA configuration including material, mass, strength, and stiffness studies that ultimately led to the final ESPA configuration, as shown in Figure 1.

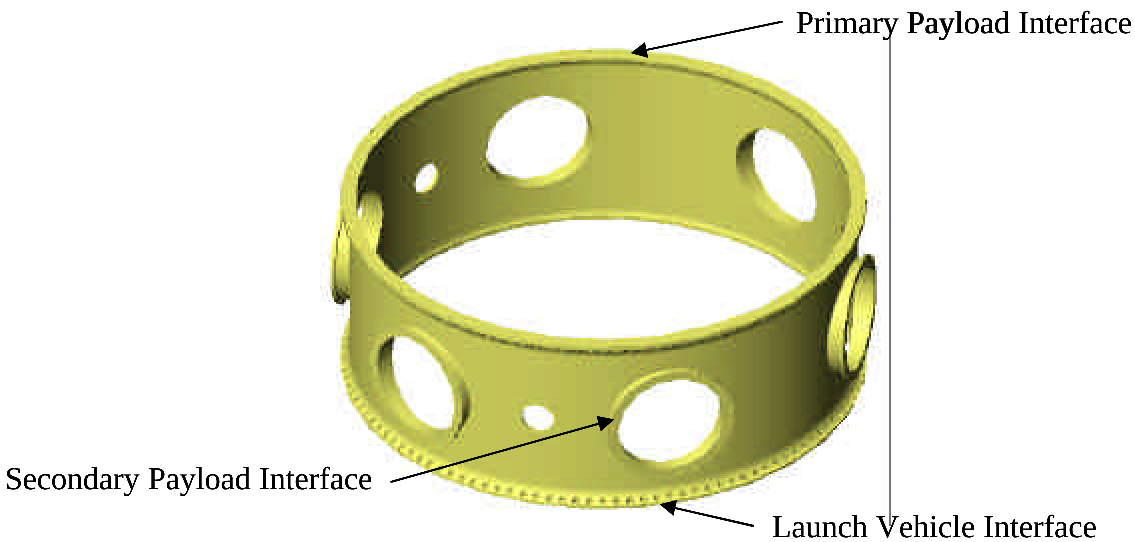


Figure 1. The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA).

During launch, the ESPA is physically located between the primary payload and the launch vehicle, as shown in Figure 2. Because of this location, the most significant design challenge for the ESPA was to minimize the influence it has on the primary payload stack. Based on this design goal, several additional constraints were identified. First, the ESPA must simulate the existing primary payload flight interface of the Atlas V and Delta IV launch vehicles. Essentially, this constraint made the ESPA a stiffness-critical design in that it must maintain the stiffness seen by the primary payload without the ESPA structure. Other design considerations for the ESPA include having the capability for secondary and primary payload shock mitigation and whole spacecraft vibration isolation systems, minimizing the secondary payload dynamic influence on the primary payload, and having no effect on the vehicle guidance and control. All of these considerations will help to nullify any adverse affects the ESPA and the secondary payloads may have on the primary payload.

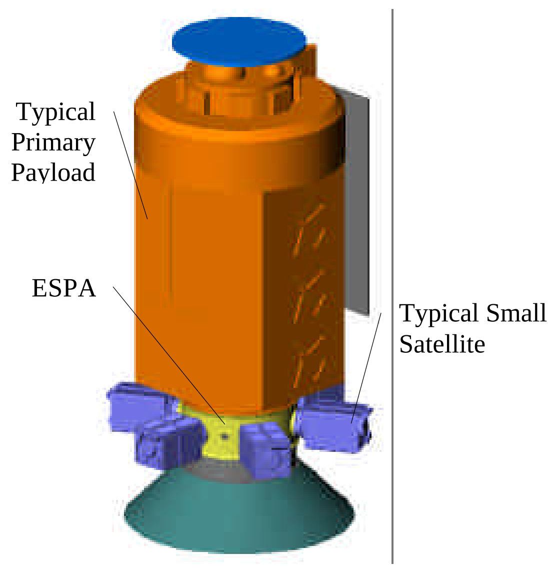


Figure 2. Example of an EELV Payload with a Fully Populated ESPA.

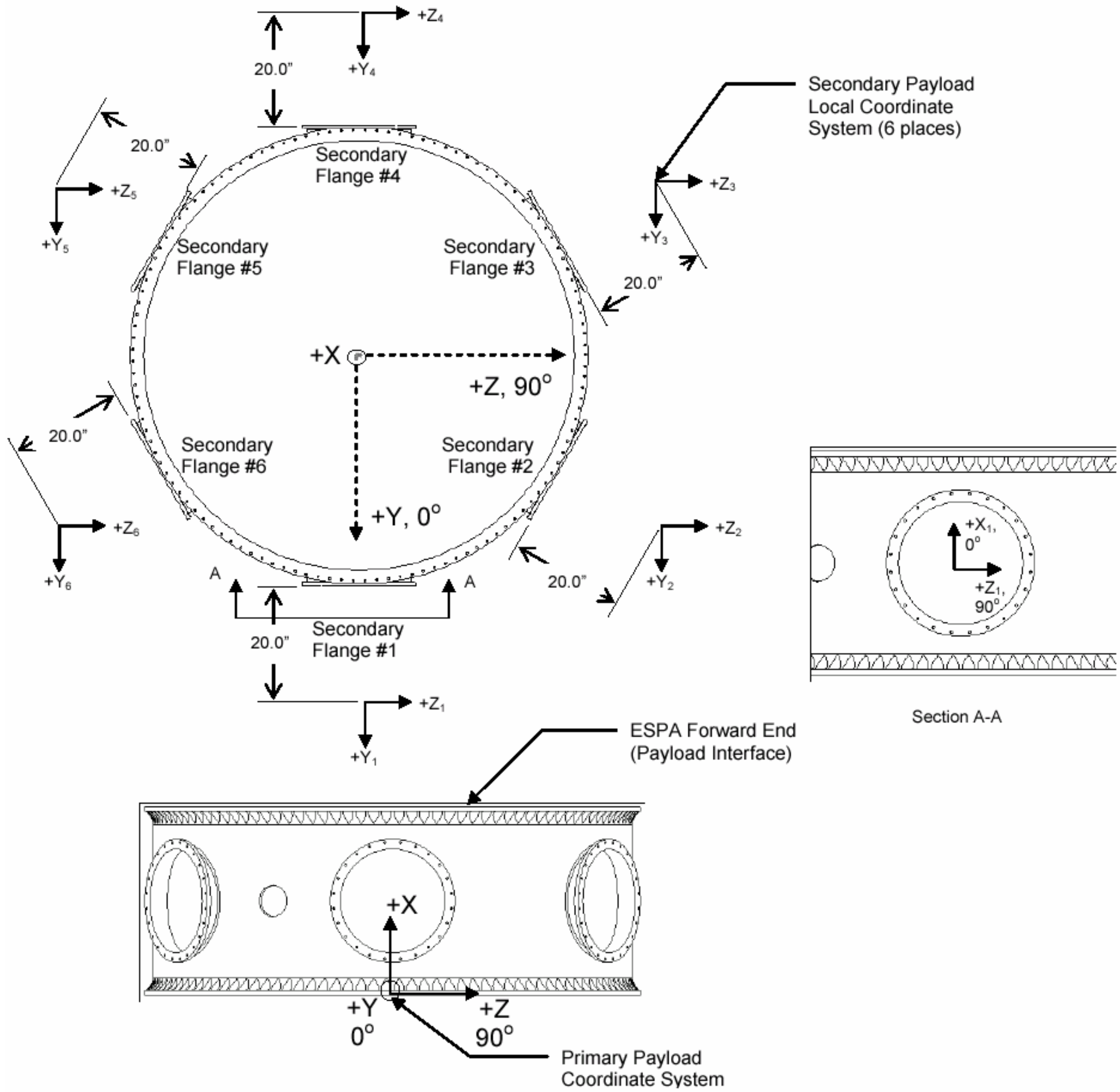
After optimizing the design of the ESPA to most efficiently use the available mass and volume of EELV launches, the final ESPA design is capable of supporting one 6,800 kg (15,000 lb) primary payload while accommodating up to six 181 kg (400 lb) secondary payloads. Each of the secondary payloads is required to fit into a volume of 61.0x61.0x96.5 cm (24x24x38 in) that is ultimately defined by the envelope of the launch vehicle fairing, the payload attach fitting, and the primary payload. The ESPA was machined from a single aluminum forging having final temper of 7050-T7451. The main cylindrical section of the ESPA is 60.96 cm (24.00 in) tall with a 151.56 cm (59.68 in) inside diameter and a 12.70 mm (0.50 in) wall thickness. Both the top and bottom flanges of the ESPA match the standard EELV primary payload hole pattern comprised of 121 through holes on a 1.58m (62.01 in) bolt circle [2]. Each of the six secondary payload flanges is equally spaced around the ESPA cylinder with 24 through holes on a 38.1 cm (15.00 in) bolt circle.

PRE-QUALIFICATION TEST DESIGN AND ANALYSIS

Prior to performing the qualification tests of the final ESPA configuration, considerable effort was expended into the identification of appropriate instrumentation, qualification loads, and the design of the reaction structure. While many decisions regarding these issues were based on results generated from the numerous structural analyses of the ESPA structure during design, the performance of the ESPA during the qualification tests ultimately determines whether it is suitable for flight. As a result, extreme measures were taken to ensure that the test design, and subsequent experimental data generated during the qualification tests accurately represented the design flight load and performance of the ESPA.

Coordinate Axis Definition

The first requirement for the successful completion of the ESPA qualification tests was the determination, and subsequent adherence to, of a coordinate system for both the primary and secondary axes (payloads) of the ESPA. For clarity, the coordinate systems used throughout the design, analysis, and testing of ESPA are presented here as Figure 3 without further justification. These coordinate systems will be used throughout the remainder of the present paper.



***All secondary payload coordinate systems are used for test operations only. They <u>are not consistent</u> with the standard coordinate system located in the ESPA Secondary Payload Planner's Guide.**

Figure 3. Qualification Test Coordinate Systems [3].

Load Factor Determination

The first requirement for performing the qualification tests, or even to design the ESPA structure shown in Figure 1, was an accurate determination of the applicable flight loads. The very objective of the ESPA accommodating secondary payloads made this step both critical and difficult. While the ESPA has gone through extensive static and dynamic structural analyses based upon worst-case flight load conditions, little information was available to analyze the impact of the secondary payloads. These design loads simulate both the steady state and the dynamic forces on the primary and secondary payload centers of mass during a typical launch. Table 1 presents the predicted g-loads, or load factors, for both the primary and secondary payloads [4,5]. Three combinations of axial and lateral loads were found to represent these load profiles. Because the ESPA structure is not axially symmetric about the launch vehicle thrust vector, the direction of the lateral load creates unique load profiles on the structure. These load profiles were fully encompassed by applying the combination of axial and lateral loads in two configurations for the six load cases detailed in Table 1. The first configuration consisted of the axial loads being applied simultaneously with the lateral loads in the +Y direction. The second configuration had the same axial loads and the lateral loads applied in the +Z direction.

Table 1. ESPA Load Factors.

	Primary Load Factor, g's			Secondary Load Factor, g's		
Load Case	**Axial**	**Lateral +Y**	**Lateral +Z**	**Axial**	**Lateral +Y**	**Lateral +Z**
1A	-3.5	2.5	0	-10	10	0
1B	-3.5	0	2.5	-10	0	10
2A	-6.5	1.5	0	-10	10	0
2B	-6.5	0	1.5	-10	0	10
3A	0.2	2	0	10	10	0
3B	0.2	0	2	10	0	10

Load factors applied at payload CGs

As shown in Table 1, the secondary payload load factors are much higher than those seen by the primary payload. The undetermined launch environment that a secondary structure will see drives this apparent imbalance. During a typical launch, smaller appendages, or secondary structures, on a payload tend to be subjected to much higher load factors. Because of this behavior, the load factors of 10 g's in two directions were predicted as a conservative estimate for the ESPA secondary payloads.

Qualification Test Forces and Moments

The load factors presented in Table 1 represent a normalized load imposed on the primary and secondary payloads by the EELV during flight. Additional calculations are required to determine the required forces and moments applied to ESPA during the qualification tests that represent the flight loads. The primary loads derived from the load factors in Table 1 were calculated from a combination of a 6,800 kg (15,000 lb) payload, with center of gravity 304.8 cm (120 in) from the aft, or bottom end of ESPA, and the mass of a flight ESPA (estimated at 160 kg, e.g., 350 lb) with a center of gravity 30.5 cm (12 in) from the aft end of ESPA. Loads for secondary payloads were calculated based on 181 kg (400 lb) secondary payloads, with each load applied at the individual center of gravity of 50.8 cm (20 in) from the secondary interface flange. Per industry standard, qualification loads and moments that were calculated and multiplied by a flight qualification load factor of 1.25 [6] are shown in Table 2. The forces and moments presented in Table 2 were then used to determine the appropriate capacity of fasteners, hydraulic actuators, and load cells needed to perform the qualification tests.

Table 2. ESPA Qualification Loads.

	Loads at Primary Coordinate System					Loads at Secondary Coord. Sys.		
Load Case	Axial (X) kN (kips)	Lateral (Y) kN (kips)	Lateral (Z) kN (kips)	Moment (Y) kN m (kips in)	Moment (Z) kN m (kips in)	Axial (X) kN (kips)	Lateral (Y) kN (kips)	Lateral (Z) kN (kips)
1A	-298.7 (-67.2)	213.4 (48.0)	-	-	637 (5638)	-22.2 (-5.0)	22.2 (5.0)	-
1B	-298.7 (-67.2)	-	213.4 (48.0)	-637 (-5638)	-	-22.2 (-5.0)	-	22.2 (5.0)
2A	-554.8 (-124.7)	128.0 (28.8)	-	-	382 (3383)	-22.2 (-5.0)	22.2 (5.0)	-
2B	-554.8 (-124.7)	-	128.0 (28.8)	-382 (-3383)	-	-22.2 (-5.0)	-	22.2 (5.0)
3A	17.1 (3.8)	170.7 (38.4)	-	-	510 (4511)	22.2 (5.0)	22.2 (5.0)	-
3B	17.1 (3.8)	-	170.7 (38.4)	-510 (-4511)	-	22.2 (5.0)	-	22.2 (5.0)

Instrumentation Selection and Placement

Finite element analysis (FEA) was used extensively in the design phase to determine stresses and deflections in the ESPA. While one of the principal objectives of the ESPA qualification tests was to validate these models, these preliminary analyses are required to determine the best location of the instrumentation for the qualification tests. In addition, these FEA values will be used as target or prediction values during qualification test operations. Actual measured strain and deflection data will then be folded back into the original FEA models as a final model correlation step. Figure 4 presents a representative FEA stress contours calculated from one of the loading conditions derived from the predicted load factors of Table 1. The highly stressed areas were consistently found in the regions closest to the secondary interface flanges. This remained true for all load conditions, and is primarily due to the large load factors applied to each secondary payload. Further support for this argument was found when considering the factors of safety generated using the maximum von Mises stress for each of the applied loading conditions. It was apparent from the analysis that the highest stresses do not change when the loading conditions change drastically, as the yield and ultimate factors of safety for ESPA with these worst-case loads were found to be very near 2.0 and 2.3, respectively, for all load cases. For the margin calculations, the compressive yield and ultimate strengths of the 7050 aluminum were taken to be 414 and 483 GPa (60 and 70 ksi), respectively.

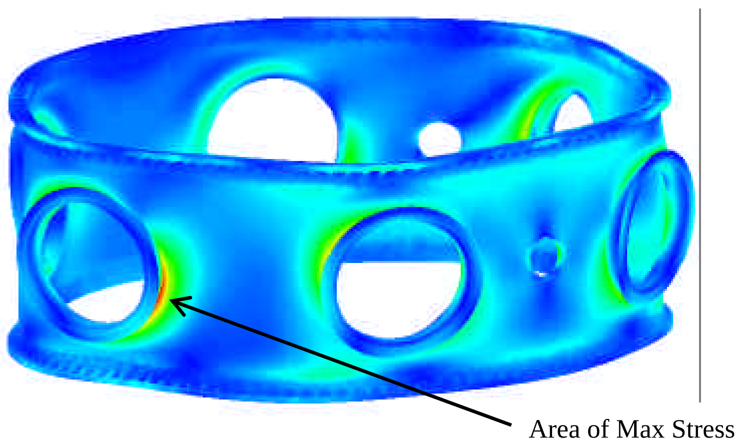


Figure 4. Typical FEA Results of the ESPA Structure Subjected to Appropriate Load Factors (units in psi).

As previously mentioned, one of the principal objectives of the ESPA qualification tests was the validation of the numerous FEA models used to design the structure. Critical to this validation were the data generated from strain gages. These data provided perhaps the most comprehensive verification of the performance of the ESPA structure and FEA models. Specific strain gage locations were determined by analyzing FEA stress contours from each of the six qualification models. As illustrated in Figure 4, high stress regions were found at 45^o angles to the mid-plane of ESPA around each secondary flange. Due to symmetry of the structure and loading, five of the six secondary flanges were instrumented with 4 Measurements Group [7] Model CEA-13-250UR-350 3-gage rosettes in these regions. Additional strain gages were located on the structure to measure the overall strain field in ESPA. These included 28 Measurements Group Model CEA-13-250UW-350 uniaxial gages back-to-back near the top and bottom flanges, and 18 back-to-back Model CEA-13-250UR-350 3-gage rosettes at the equator of ESPA between the secondary flanges.

FEA also gave some insight into the way the qualification loads were transferred into ESPA and the way these loads were distributed into the structure bolted to the launch vehicle interface when configured in the test as shown in Figure 5. As a result, 24 Model CEA-13-250UW-350 strain gages were applied to the smooth wall test cylinders that were bolted to the top and bottom flanges of ESPA. These gages were equally spaced every 30^o around each cylinder at their equators. Data collected from these strain gages were used to analyze how the loads were applied to and transmitted by ESPA, thereby determining the effects of any unforeseen test-specific loading conditions. Additionally, 22 Model CEA-06-250UT-350 biaxial (0° and 90°) strain gages were placed at 3^o intervals from 0^o-30^o and 60^o-90^o near the interface of the lower adapter to monitor load peaking induced by the geometry of ESPA. Because the ESPA structure contains 6 secondary payload adapter locations (portholes), the axial stiffness of ESPA is not constant around the perimeter of the structure, which introduces nonuniform load transfer (load peaking) through ESPA. There was a strong desire by the aerospace community to quantify the amount of load peaking introduced by ESPA. A row of Measurements Group Model CEA-06-125UT-350 strain gages used to approximate the load peaking on the lower test adapter is shown in Figure 6.

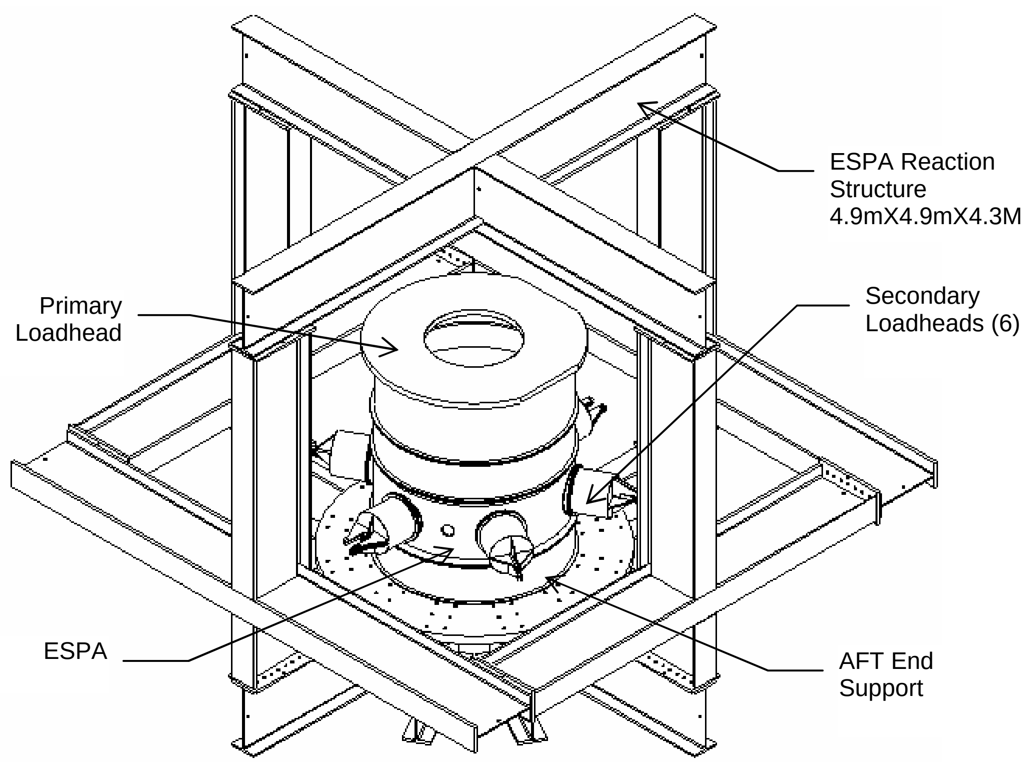


Figure 5. Solid Model of Qualification Test Configuration for ESPA.

Because the ESPA structure is a stiffness critical design, the deflection estimates generated by FEA have been scrutinized thoroughly. As a result, it was desired to generate experimental displacement data during the qualification tests to validate numerical models. Predicted primary and secondary payload deflections were less than 0.38 and 0.64 cm (0.150 and 0.252 in) at the payload centers of gravity. Input from various launch vehicle providers and potential primary payload organizations indicated that this level of stiffness was higher than current primary payload attachment fittings. Secondary payloads were predicted to deflect considerably more than the primary, but are still within acceptable boundaries.

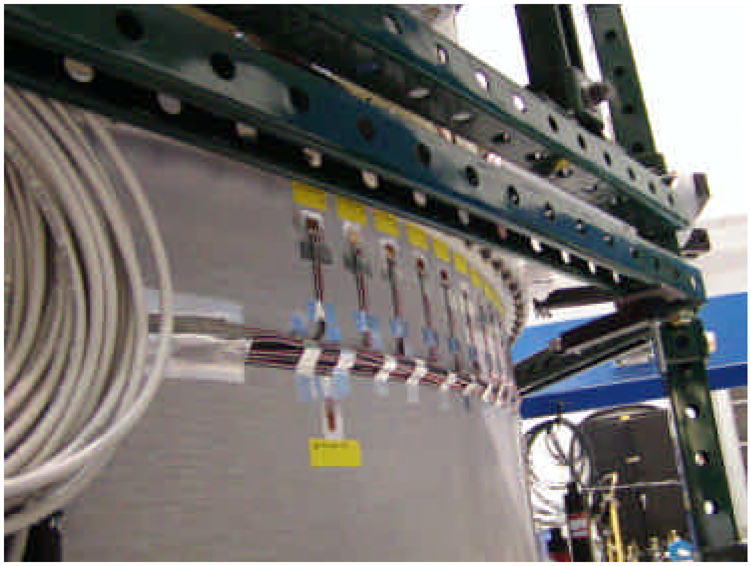


Figure 6. Photograph of Load Peaking Strain Gages on Lower Adapter.

As with the strain gages, displacement transducers were positioned on the ESPA structure based on the FEA results. Three axis translations were measured at the launch vehicle interface, the payload interface, and two representative secondary payload interfaces using either Measurements Group Model HS5 or HS10 Linear Displacement Sensors. A total of 32 displacement sensors were used for each of the qualification tests. Translations measured at the base of ESPA, or the launch vehicle interface, were used to determine displacements of the underlying test hardware. These data were then used to normalize all other measurements to determine the deflection and corresponding stiffness of ESPA. An example of displacement transducer setup is shown in Figure 7.

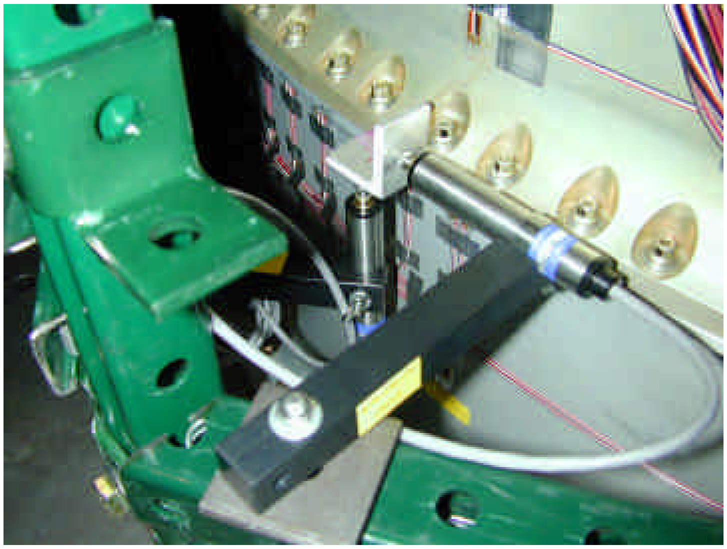


Figure 7. Photograph of a Representative Displacement Measurement Setup using Two Displacement Sensors.

ESPA TEST OBJECTIVES

As detailed throughout this paper, an iterative process between FEA models and experimental validation is required to complete not only this, but almost any other structural qualification test. It would be exceedingly difficult to design the experimental qualification tests without the results generated from the previously run FEA models, but yet, the FEA predictions are not validated until after the successful completion of the qualification tests. Because of this delicate balance between numerical and experimental methods, with ultimate validation coming only from the experimental qualification test results, numerous safeguards were employed to ensure the validity of the experimental data generated during the qualification tests. These safeguards will be described in following sections.

The specific objectives set for the qualification test of the ESPA were as follows. The structural integrity of the ESPA must not be compromised while subjected to any of the qualification loads (125% of the anticipated flight loads). Another objective of the test was to collect sufficient stiffness and strain data to correlate the finite element models to actual experimental data. These models will be used extensively for mission-specific strength, dynamic, and guidance control simulations.

While the stiffness of the ESPA could have been measured during the multi-directional loading scenarios, it is generally much easier to avoid this unnecessary complexity. For this reason, many simple unidirectional load conditions were applied to the ESPA prior to the qualification loading. Based on the acquired load and deflection data acquired during these tests, the stiffness of the ESPA was accurately determined.

Reaction Structure

Typically, a static load test consists of placing the test article into a large reaction structure capable of reacting loads applied to the test article by a series of hydraulic actuators. The reaction structure specifically fabricated for the ESPA qualification tests is shown in Figure 9. Ideally, the reaction structure would be infinitely rigid compared to the test article such that it did not deflect during the application of the qualification loads. Since this scenario is not obtainable, and quantifying the exact deformation of the reaction structure would require additional analysis and experimental instrumentation, it is critical that the test article and instrumentation be rigidly secured to the same physical location. This prevents any distortion of the reaction structure from altering the experimental data. This was achieved in the current test by bolting the ESPA test article and the instrumentation structure to the same base plate, as shown in Figure 9.

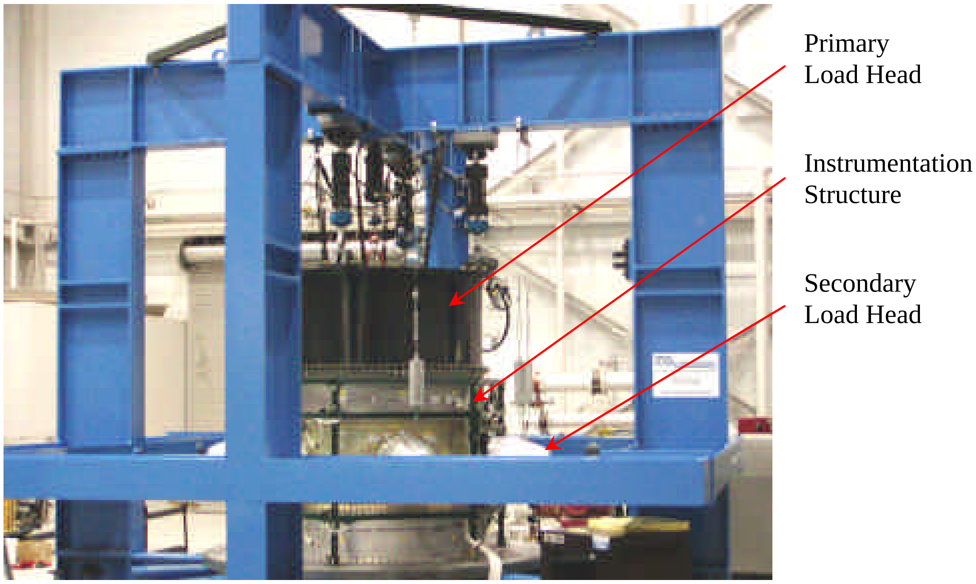


Figure 9. Photograph of the ESPA Test Article Integrated into the Reaction Structure.

Also shown in Figure 9 are six bolted aluminum adapters, or load heads, that were used to apply the correct loading into the ESPA secondary payload interfaces. All loads were applied directly to these load heads, which in turn transfer the loads into the ESPA structure. Load heads bolted to each of the six secondary interface flanges were designed to simulate actual flight conditions. To achieve the appropriate load transfer, the stiffness of each load head had to be iteratively analyzed to match the estimated flight conditions. This analysis, coupled with tight machining tolerances on the mating surfaces of the load heads ensures the ESPA will witness not only the correct loads, but also realistic load peaking. Likewise, aluminum adapters were designed to bolt to the upper and lower primary surfaces of the ESPA, as shown in Figures 5 and 9. Load applied to the primary load head was transferred into the upper aluminum adapter, which was reacted by the lower aluminum adapter. Similarly for the secondary load heads, these adapters transfer the applied qualification loads into ESPA as the predicted flight conditions.

Loading and Load Control

As previously discussed, hydraulic actuators were used to apply the qualification loads into the ESPA. For the qualification load conditions, 17 actuators were simultaneously controlled to the desired loads. Actuator capacities range from 22 to 267 kN (5 to 60 kip) based on a maximum hydraulic pressure of 20.7 MPa (3,000 psi). Pressure supplied to each actuator was regulated by an MTS Systems Corporation Model G761-3560 5-port, 3.8 Lpm (1 gpm) servovalves. As shown in Figure 10, six servovalves were mounted to each of three distribution manifolds that uniformly supplied pressure to each valve.

Figure 10. Photograph of One Hydraulic Distribution Manifold Equipped with Servovalves.

Control of the servo-hydraulic loop was performed using a 20-channel MTS Systems Corporation Aero90 LT digital control system. Control of the hydraulic equipment was accomplished through individual channel PDIF (proportional, differential, integral and feed forward) parameters that were operator-adjusted to tune the control loop and achieve optimum system performance on a channel-by-channel basis. This control loop continuously compares the load cell signal (feedback) to the desired load (command) for each actuator. The difference between the command and feedback was defined as the error. If found to be excessive, the error of each load channel was input to the PDIF parameters which resulted in an adjustment to the servovalve output current. The servovalve current controls the hydraulic flow into and out of each hydraulic actuator, which in turn, changes the applied load until the error is reduced to acceptable values.

Each load cell, manufactured by Interface Inc. [8], was calibrated by inputting the full-scale calibration value provided by the manufacturer and verified by a quality control engineer prior to performing each test. Each load cell contains a dual-bridge configuration that was utilized by the MTS control system for hardware safety. The load controller continuously conditions and samples the signals from both bridges, controlling to the A-bridge signal while monitoring the B-bridge. For the ESPA qualification tests user-defined inner and outer AB compare limits, set to 1.0 and 3.0%, respectively, in the Aero 90 control software defined the maximum allowable percent deviation between the two signals from each load cell. Exceeding the inner AB compare limit caused the load controller to place the test in a holding configuration, while exceeding the outer AB compare limit caused the test to abort by removing pressure to the hydraulic actuators. Both bridges of the load cell were conditioned with separate conditioner cards to prevent a single uniform error into both bridges, a condition that would make the comparative function ineffective.

In addition to the inner and outer AB compare, several other limits were set by the operator within the MTS software prior to each qualification test. The first line of defense against a potential load control anomaly was the inner and outer Multiple Input/Output Processor (MIOP) limits. The MIOPs are used in the MTS control system to process, monitor, and control the performance of each load control channel. For the ESPA qualification tests, the inner MIOP limit error of 3% was set to place the system in a hold status, while the outer error limit of 4% was set to abort the test.

Independent of the MIOP error limits, error detector limits were used to set an inner and outer error band around the commanded load for each control channel. The inner error limit, set to 4% of full-scale load, was used to detect slowly developing problems common to mechanical systems. Examples of such problems are sticky actuators, sticky servovalves, hydraulic fluid leakage, or actuator linkage problems. Outer error limits, set to 5% of full-scale load, were used to detect sudden problems in the test setup. As with the other errors, the inner limit is set to hold the test, while activating the outer limit will trigger a system abort.

A generic conditioner limit was the last line of defense against overloads. Set to 7% error of the full-scale load for each channel during the present tests, these conditioner limits were programmed to trigger a system abort when reached [9]. The overarching function of each of these independent error systems was to prevent an overload of the test article, a situation that could easily ruin the test article.

Additional system features were used to protect the test article and to ensure the proper loads were applied during the qualification tests. MTS has implemented what they term dynamic and static null pacing to help assure that loads are applied with minimal error, while allowing for unavoidable nuances during a large-scale structural test. Static null pacing is used to set a maximum error band at a given command point. During ESPA testing, this maximum error was set to 0.3% of the full-scale load. In this example, the controller and data acquisition would not record a data record until all of the loads are within 0.3% of the targeted values. If the system could not achieve this balance within three seconds, a hold command was automatically triggered. Under a hold condition, all control channels were set to remain at the current command point while the operator can adjust the PDIF as necessary. The dynamic null pace feature, set to 3.0% for the present testing, was used to ensure that errors during transitions (e.g., increasing load to decreasing load) were minimized and phase or unbalanced loads did not occur [9].

Data Acquisition System And Instrumentation

Shown in Figure 11 is the 256-channel Agilent data acquisition system (DAS) used in the present study to provide instrumentation signal conditioning and data recording during the qualification tests. Additionally, MTS has developed software to integrate the data acquisition system with the load controller. In doing so, the data acquisition is synchronized with the feedback and command signals from the load controller, allowing concurrent data scans of the applied loads and instrumentation readings. The data acquisition system consists of eight model E1529A 32-channel strain-conditioning modules and one model E1422A controller. The E1529A strain-conditioning module performs signal conditioning and multiplexes the signals to a serial line for processing by the control module. Excitation for the displacement transducers was provided by the Agilent DAS power supply and read into an E1529A module configured for full-bridge strain gage-based transducers. This strain-conditioning rack utilized inexpensive and convenient RJ-45 input connectors, another advantage over conventional bridge amplifiers.

Figure 11. Photograph of the 256 Channel Agilent Data Acquisition System.

Experimental data collected during each qualification test consisted of a total of 32 displacement transducers and 210 strain gage channels. Calibration of each displacement transducer was accomplished through software driven, two-point calibration in a micrometer stand prior to performing the first qualification test. Validation of these calibration values was achieved by inserting a gage block with known thickness prior to performing each individual qualification test and verifying the software reading. Calibration of each transducer was rechecked using two-point calibration in a micrometer stand after all tests were performed to verify the transducers were performing as expected.

Based on the resistance and the gage factor of each strain gage, the MTS software also allowed for simple shunt calibration of the strain gage channels. After calibration, each channel was checked against the original shunt voltage prior to each test. An error greater than 1% generated a flag for the suspect channel, giving the operator an indication that the gage is not performing adequately.

TEST PROCEDURE

Because the ESPA is a unique and costly test article, test discipline is paramount. All operations from installation of the test article, to performing the tests, to test teardown were strictly controlled by the ESPA test procedure [10]. Based on the requirements dictated in the ESPA test plan [10], the procedure was written to guarantee all test objectives and success criteria were met. While there are no universal guidelines, and only a brief philosophy behind each step is presented, the following steps were performed by the present authors to perform each qualification test. Each step must be completed in sequential order before progressing to the following event.

1. Verify the test setup is completed per the given drawing.
2. Verity pictures have been taken of the test setup. This includes any unique instrumentation and hydraulic actuators.
3. Verify all hydraulic equipment is clear of instrumentation and instrumentation stands. Specifically, this step was used to make sure no actuators or hydraulic hoses are touching the displacement transducer support stand. Should anything come into contact with the stand, the displacement gages will be shifted, causing a retest condition.
4. Verify the loading scenario. The operator and quality control engineer must independently check all loads and hold points for each load channel. Plots of each load profile are printed and attached to the procedure.
5. Export and verify the load control setup information. Checked by both the operator and quality control engineer, the test export file details the configuration of both bridges of all load control channels. Included in the file are exact values for the limits and error detectors, as well as units, channel numbers, load cell excitation, servovalve polarity, and the load cell gain computed from the inputted load cell sensitivity. The file is printed and appended to the procedure for each load case.
6. Verify the "Event/Action" module is configured correctly. The load controller uses a series of digital inputs and outputs to specify commands (actions) when a specific condition (event) is met. Examples of event/action requirements include setting the controller to a hold command when an inner error has been reached, and commanding the system to record data when a specified load level has been reached.

7. Verify the "servo check" function was successfully completed. A feature in the load control software that allows the operator to run an exhaustive check on all channels is called the servo check. During this operation, all limits and error detectors are independently exercised and actual values are recorded in the log. Load cell calibration values are also checked across a nominal shunt resistor and compared to the theoretical voltage. Every actuator must be in a zero load state (unpinned and free from gravitational influence), as the controller also verifies the zero and voltage offset of each channel. A summary at the end of the servo check log details the number of failed operations that were performed. If a channel fails any operation, the problem must be identified and corrected prior to testing. Finally, the successfully completed servo check is printed and appended to the procedure for each load case.
8. Gage block each displacement transducer. After the displacement transducer is calibrated, zeroed, and set in the correct location, each sensor is subjected to a known offset by placing a gage block in its path. This step serves two purposes, and is performed at the beginning of each day of testing. A correct reading on the data acquisition system verifies the sensor has been calibrated properly, and the sensor has been patched to the correct location on the data acquisition system.
9. Calibrate all strain gage channels, and store/check the shunt voltage. Calibration is a simple software command that will give an indication of a bad strain channel if a calibration failure occurs. Storing the shunt voltage is also a software command that records the voltage across each shunted gage. Prior to each test, the shunt value is compared to the initial stored value. A deviation of more than 1% is flagged, and the strain channel must be repaired.
10. Short each strain gage channel. Each strain gage is shorted across the gage terminals using a simple piece of conductive wire. Shorting the gage opens the circuit, and gives a clear reading on the data acquisition system; thereby verifying the gage is patched to the correct location of the data acquisition system.
11. Verify load cell cabling. Dual bridge load cells have two individual cables that are verified prior to each test. While monitoring the load control system, each cable is individually removed from all load cells to verify the cabling has not been switched or improperly patched to the load control system.
12. Zero load cells. All load cells should be pinned to the reaction structure, but not to the test article. In this position, the load cells are not subjected to any load, and are zeroed using a software command to eliminate any unwanted offset.
13. Push/Pull each load cell. While monitoring the load controller, each load cell is manually pushed and pulled to verify they are reading compression and tension as expected. If pushing on the load cell registers a tensile load on the controller, the calibration of the channel is checked for an inadvertent negative sign.
14. Perform the servo valve steering check. At this stage, actuators are installed, but not pinned to the test article. A nominal low pressure (< 2.1 MPa e.g., 300 psi), is supplied to all actuators, and each is individually commanded to a low-level load (~4% of full-scale). Actuators should move in the direction commanded, which

in turn verifies the hydraulic plumbing is correct, the servo valve cables are correctly installed, and the servo valve polarity is not reversed. To avoid damage to the test setup, all actuators must be clear of the test article and test structure prior to this operation.

15. Bleed the air out of all hydraulic lines. While still at low pressure, all actuators are commanded to the full in and full out position three times. This operation helps to move any unwanted air pockets out of the hydraulic lines and hydraulic actuators. Care must once again be taken to avoid making contact with the test article or test structures.
16. Verify the Static Load Control Setup Sheet is completed and signed by both the operator and quality control engineer. The setup sheet serves many purposes, but is ultimately used to capture all setup information, to provide a sign-off for the above controller setup steps, and to serve as a historical record of test details and hardware used. Actuator sizes, actuator names, actuator loads, required actuator pressures, load cell sizes, load cell identification numbers, limits, error detectors, channel names, channel/cable numbers, all file names, test name, load case number, and date are among the information recorded on the setup sheet.
17. Pin actuators to the test article. While the pump remains in a low-pressure state, all actuators are manually stroked and pinned to the test article. After pinning the actuators, they are now under the control of the load controller with a command of zero.
18. Enable errors, limit detectors, null pacing, and integrators. All of these options are toggled to the on position prior to applying high pressure to the system.
19. Apply high pressure to the system. High pressure is defined as approximately 15% higher pressure than is required to achieve the desired loads.
20. Verify pump pressure. Pressure gages on each distribution manifold must be at or above the desired high-pressure setting.
21. Enable data acquisition system. A software toggle on the data acquisition system activates the system to record data as required for the test.
22. Command to 0% load. The initial step in any test is to command to 0% load so a record of all data acquisition channels can be recorded.
23. Command to 5% load and hold. All loads should increment at the predetermined pace to 5% of their full scale. While holding this load, each channel is checked for stability, and loads are verified to be as expected. At this point, some tuning of the PDIF is required to remove any error and dynamic oscillations of some control channels.
24. Proceed with performing the test. Testing can now continue to the predetermined load levels.

While the above Test Procedure represents the ideal test sequence, it is worth noting that there are far too many situations to list during the execution of a complex structural test that can cause a deviation from this ideal situation. Each condition must be individually evaluated to determine to which step should be retreated to maintain the integrity of the test. However, the value of experience when this happens should not be underestimated.

Obviously a significant amount of numerical and experimental data was generated during the current qualification tests. In fact, nearly 2 million data records were generated during the tests required to fully qualify the ESPA, and while these data are of significant value to the success of ESPA, they are omitted from this paper due to space constraints.

SUMMARY

ESPA has now been qualified for flight payloads consisting of a 6,800 kg (15000 lb) primary spacecraft and up to six 181 kg (400 lb) secondary spacecraft. Qualification loads were derived to envelope load factors published by the Boeing Co. and Lockheed Martin for EELV, making ESPA capable of withstanding any applied flight load with minimal impact on the primary payload. Based on the qualification testing and the supporting analysis, the ESPA was found to have margins of safety on yield of about 2 for all load cases.

Overall, the qualification tests were considered an overwhelming success, in large part due to the rigorous test methodology detailed in the present paper. The vast majority of the instrumentation provided clear, insightful data that can be used for analysis of future mission-specific flights. In addition, the loads applied during the test were controlled to an extremely high level of accuracy with minimal anomalies. All loads were maintained to within 1% of the flight loads during each of the recorded data points, generating significant confidence in the experimental data. Most importantly, the test procedures outlined in the present paper and meticulously adhered to for the qualification tests produced a testing environment that was safe for personnel, the test article, and hardware while generating accurate experimental data.

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