

ARES I STAGE SEPARATION SYSTEM DESIGN CERTIFICATION TESTING

Stephen L. Mayers, Bernard B. Beard, and R. Kenneth Smith
ARES Corporation
Jacobs ESTS Group
Huntsville, AL

Alan Patterson
NASA Marshall Space Flight Center
Huntsville, AL

ABSTRACT

NASA is committed to the development of a new crew launch vehicle, the Ares I, that can support human missions to low Earth orbit (LEO) and the moon with unprecedented safety and reliability. NASA's Constellation program comprises the Ares I and Ares V launch vehicles, the Orion crew vehicle, and the Altair lunar lander. Based on historical precedent, stage separation is one of the most significant technical and systems engineering challenges that must be addressed in order to achieve this commitment. This paper surveys historical separation system tests that have been completed in order to ensure staging of other launch vehicles. Key separation system design trades evaluated for Ares I include single vs. dual separation plane options, retro-rockets vs. pneumatic gas actuators, small solid motor quantity/placement/timing, and continuous vs. clamshell interstage configuration options. Both subscale and full-scale tests are required to address the prediction of complex dynamic loading scenarios present during staging events. Test objectives such as separation system functionality, and pyroshock and debris field measurements for the full-scale tests are described. Discussion about the test article, support infrastructure and instrumentation are provided.

INTRODUCTION

The design, development, and testing of separation systems (also known as severance systems) represents one of the more difficult systems engineering challenges for launch vehicle development. Failure to properly understand and control the diverse array of dynamic loading influences during separation can lead to recontact, propellant slosh induced ullage collapse, or loss of vehicle control. Pyroshock vibrations and aerothermal environments induced by small solid motors and other pyrotechnics can damage avionics or lead to upper stage engine (USE) overpressure or overtemperature. Numerous design solutions to these problems must be evaluated from a total system and life cycle perspective, as severance system design decisions significantly impact not only safety and reliability but also overall vehicle performance and cost.

Figure 1 summarizes the record of several launch vehicle programs in overcoming the risks specific to staging.¹ All of these vehicles and others not shown such as Space X have suffered mission failures due to separation system problems at some point in their history. Of all launch vehicle failures in the U.S. between 1983 and 1998, 5 out of 22 failures are attributable to separation systems. The Ariane launch vehicle has the lowest staging-related failure rate of all those shown in Figure 1. Ariane uses an explosive cord severance device, retro-rockets on the lower stage and acceleration rockets on upper stage.

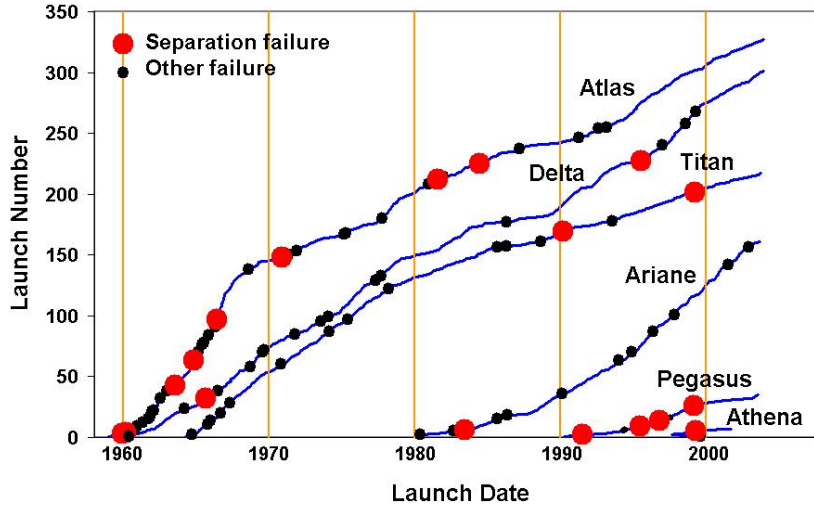


Figure 1. Historical Launch Vehicle Stage Separation System Failures¹

Figure 2 highlights one of the more common causes of separation system failures: staging-induced pyroshock loads.² These loads are created by the detonation of explosives used to sever the interstage holding/attachment mechanisms. Depending on the design of the severance system, these pyroshock loads can generate induced forces from accelerations ranging from several hundred to several thousand g's, over a frequency spectrum of 100 to 10,000 kHz. Devices mounted near the separation joint such as ceramics, circuit boards, valves, and relay switches are particularly vulnerable to failure by fatigue in these environments. Although these loads attenuate as they travel through structural members and across interfaces, the rate of attenuation is difficult to predict accurately. In instances where pyroshock load predictions have been underestimated, mission failure can be the end effect. Historically, system level testing has been used as corrective action for at least 34 launch vehicle failures – occurring in the 1960s and 1970s – attributable to pyroshock environments.



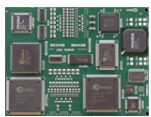
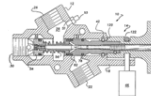
Failure Categories	Number of Failures Confirmed or Suspected (1960's to 1970's)	Estimated Peak g's (100 - 10K Hz)	Space Systems Involved	Number of Programs Affected	Root Cause / Corrective Action
 Relays & Switches	4 Total (All Leading to Loss of Mission)	600 to 4,000 g's	Launch Vehicles	4	1) system level testing to define environments 2) shock isolate components 3) redesign/requalify vulnerable components 4) relocate components to lower shock regions
 Fracture of Brittle Materials	30 Total (17 - Loss of Mission; 14 - Loss of Performance)	≥ 3,000 g's	Launch Vehicles	6	1) system level testing to define environments 2) redesign ordinance to reduce shock 3) shock isolate components 4) redesign/requalify vulnerable components 5) improve acceptance testing, including shock
 Short Circuits	29 Total (24 Loss of Mission; 4 Loss of Performance; 1 Unknown)	200 to >3,000 g's	Launch Vehicles	8	1) Institute Particle Impact Noise Detection Tests 2) Passivate Internal Piece Part Conducting Surfaces 3) Institute Shock & Vibe Component Screening Tests
 Deformation of Delicate Structures (Valve Cap)	1 Total	Unknown	Soyuz II Space Capsule	1	Cabin Pressure Release Valve Tripped Open Due to Shock from Explosive Bolts (Valve Cap Safety Device Loosened)

Figure 2. Pyroshock Induced Launch Vehicle Failures and Anomalies.²

ARES I SEPARATION SYSTEM RISK ASSESSMENT AND TRADE STUDY

The Ares I stage separation system presents unique dimensional challenges that influence the probability of the interstage contact with the USE nozzle extension after separation. As illustrated by Figure 3, the axial distance to clear the USE nozzle is requires a precision maneuver, whereas the comparable S-IVB clearances with the USE are much more tolerant to error.

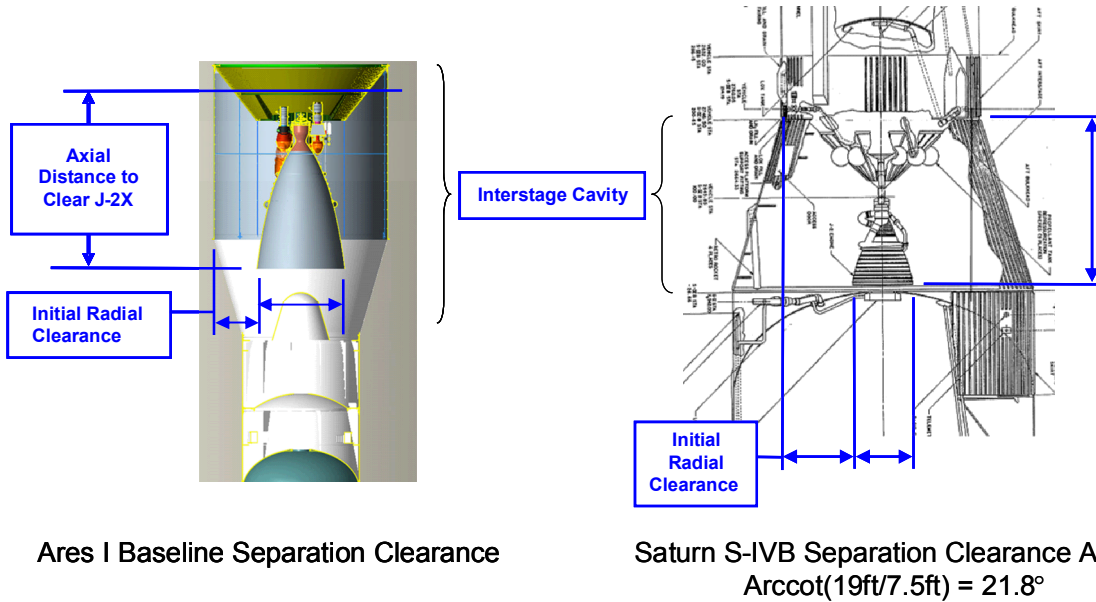
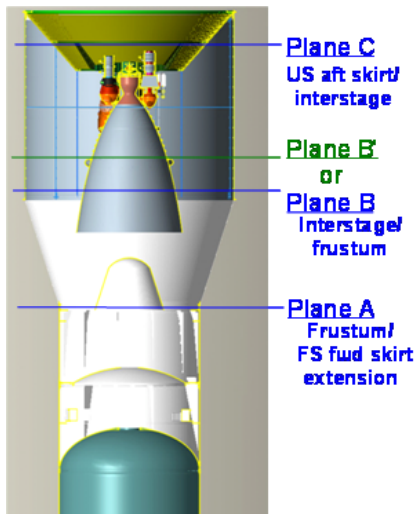


Figure 3. Ares I Staging Event Clearances in Contrast with Saturn S-IVB.

Given the unusually tight clearances for Ares I and severity of consequences for contact with the USE nozzle, NASA initiated a formal trade study to evaluate design options for the stage separation system. After developing extensive option trees for single and dual plane staging concepts, five general approaches were selected for further study. These options are summarized in Figure 4.



Single-plane options

- Option 1: Plane C, with Booster Deceleration Motors (BDMs) moved to aft skirt
- Option 2: Plane C, with gas struts in lieu of BDMs

Dual-plane options

- Option 3: Plane A, then C. Actuators push I/S before USE start
- Option 4: Plane B or B', then C. Drop Interstage (I/S) through USE plume
- Option 5: Plane B or B', then clamshell opens at plane C

Figure 4. Ares I Separation System Design Configuration Options

In fall 2007, options were down-selected to dual-plane option 3 and the single plane option 1. Conceptual design activity supported evaluation of these options against eight Figures of Merit (FOMs): 1) flight safety, 2) ground safety, 3) design robustness and “margin-to-musts”, 4) payload to orbit, 5)

induced environments, 6) non-recurring DDT&E costs, 7) recurring costs, and 8) risks and opportunities. The single-plane option evaluated higher in five out of the eight FOMs 1,2,4,5, and 6, and the dual-plane option evaluated higher in only one FOM 3, design robustness and “margin-to-musts”. The two options tied in two FOMs 7 and 8. The overall score favored option 1 and this configuration became the baseline staging system.

In addition to selection of the single-plane BDM retro-rocket option 1, the trade study identified the need to mature plans for design qualification and certification, including required testing to characterize inputs, anchor models, and mitigate risks. Risks inherent in the Ares I First Stage / Upper Stage separation event include:

- Pryoshock-induced vibration environments may damage vulnerable components in the vicinity of the separation system joint with a consequential failure of the mission
- Linear Shaped Charge (LSC) generated debris may damage sensitive components with consequential failure of the mission
- Off-nominal performance by multiple elements i.e. the first stage SRB, or subsystems such as the separation subsystem may lead to contact between the interstage and the J-2X nozzle with consequential failure of the mission.

HISTORICAL PRECEDENTS FOR FULL-SCALE SEPARATION SYSTEM TESTS

Separation tests have been performed on all launch vehicle development programs. Historical launch vehicle development programs surveyed for separation testing lessons learned and best practices include the Atlas-Centaur, Saturn S-IVB, Delta IV, and X-43A. These tests are primarily concerned with assessing the ability of the separation system to reliably sever the structural connection between stages without generating loads, vibrations, thermal environments, or highly energetic debris that inhibit the functionality of other launcher subsystems. This section of the paper provides a summary of prior launch vehicle development program separation tests.

Atlas-Centaur

In the mid 1960s, the Atlas-Centaur program invested substantially in stage separation ground testing.³ Atlas was unique among all the historical programs reviewed, in that an entire full-scale booster stage (including solid-fueled retro-rockets) was tested in a vacuum chamber, simulating the 100,000 ft. separation altitude. Eighteen total full-scale functional severance tests were conducted. Five of these full-scale tests involved retro-rockets firing. High-speed motion-picture cameras were used to measure relative axial movements, and flight-type rate gyros were used to measure angular relative movements.

The test program uncovered a number of problems before they could pose a risk during flight. Hardware reliability issues with the retro-rocket igniters were revealed. The tests identified a 20% reduction in retro-rocket impulse compared to predictions based on component testing. This loss was attributed to skin friction associated with the interaction of the retro-rocket plume and the vehicle sidewall. Concerns about “ice bonding” between stages – due to the presence of cryogenics close to the separation plane – were demonstrated to be irrelevant. And most significantly, analysts responsible for predicting the probability of recontact after separation were able to anchor their vehicle dynamic behavior models. These anchored models were able to prove that the separation system could tolerate a retro-rocket out scenario and still maintain adequate clearance between the interstage and the Centaur upper stage engine. A plot of interstage position vs. axial distance during separation obtained from these tests is provided in Figure 5.

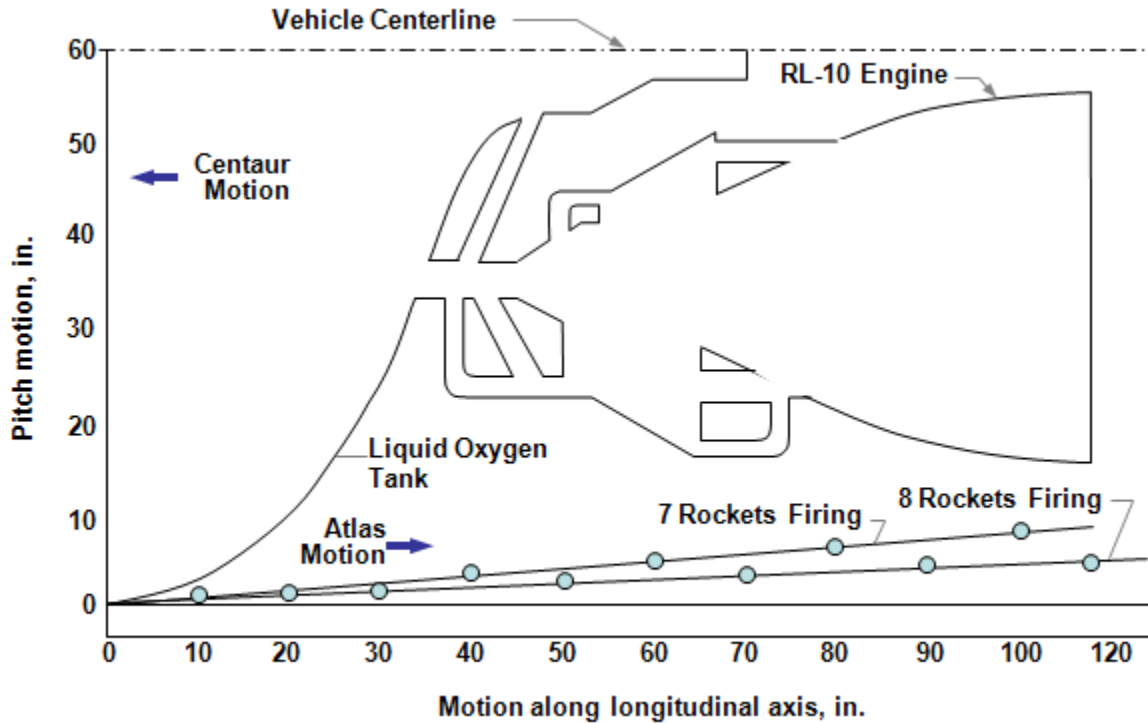


Figure 5. Measured Clearance between the Upper Stage Engine Nozzles and Booster Interstage Adaptor Rim as a Function of Axial Distance during Atlas-Centaur Separation Testing.³

Saturn S-IVB

The Saturn V's third stage (S-IVB) uses a single plane separation system.⁴ Also, both Ares and Saturn separation systems rely on an explosive circumferential charge to sever the stages, as well as retro-rocket and ullage settling motors. S-IVB separation is initiated when stage thrust decays to a value equal to or less than 10% of rated thrust. A short coast mode is used to allow separation of the spent stage, and to effect ullage settling of the successive stage prior to engine ignition. Stage separation ground tests were used during development of the S-IVB separation system, primarily to collect pyroshock attenuation measurements. Multiple free-fall separation tests were conducted with a full-scale diameter and ~6' long interstage. The interstage was caught by an arresting net so it could be reused in subsequent tests. The Saturn V stage separation subsystems are depicted in Figure 6.

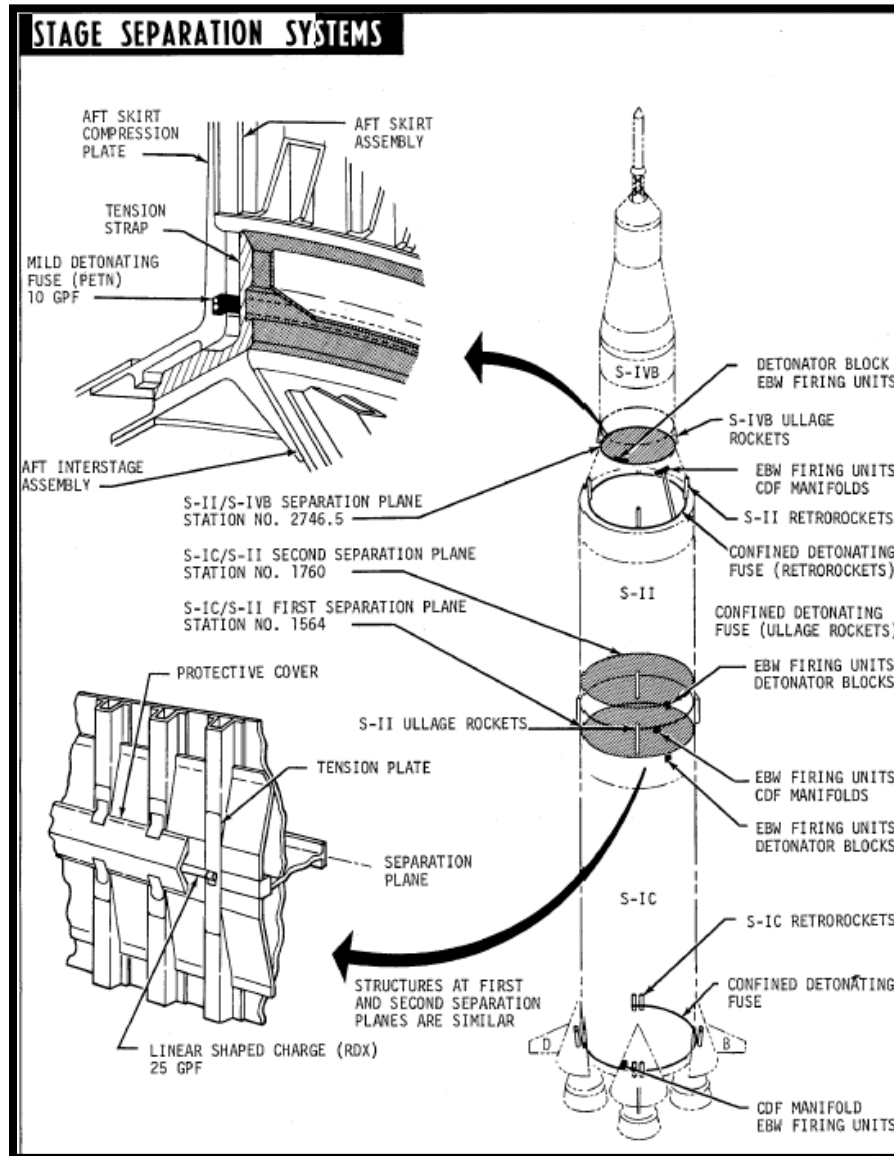


Figure 6. Saturn V Stage Separation Systems.⁴

Delta IV

Details of the Delta IV separation system test activities and results, provided in a 2005 AIAA paper, were reviewed for relevant technical insights.⁵ Separation testing was conducted on full-scale diameter test articles in a vertical orientation. The test article and separation joint involved in this test are depicted in Figure 7. A simple counter balance system with dead weights, pulleys, and cables was used to simulate the load environments present at the separation joint during flight. Two of these full-scale tests were conducted. The counterbalance system experienced a structural failure during the first test, which was successfully repaired for an effective second test. Pyroshock measurements were recorded at multiple locations, and pneumatic actuation system pressures were measured as a function of axial separation distance. The Delta IV test program is considered a success, as all flights to date have occurred with separation systems working nominally without incident. Boeing attributed several factors to this success record, including the adoption of flight proven severance system technologies and integrated "test-as-you-fly" testing approaches. Specific severance technologies developed by Boeing include a

proprietary frangible joint design, ordinance for disconnection of electrical wiring between stages, initiators set off ordinance, and pneumatic actuation systems to force the stages apart.

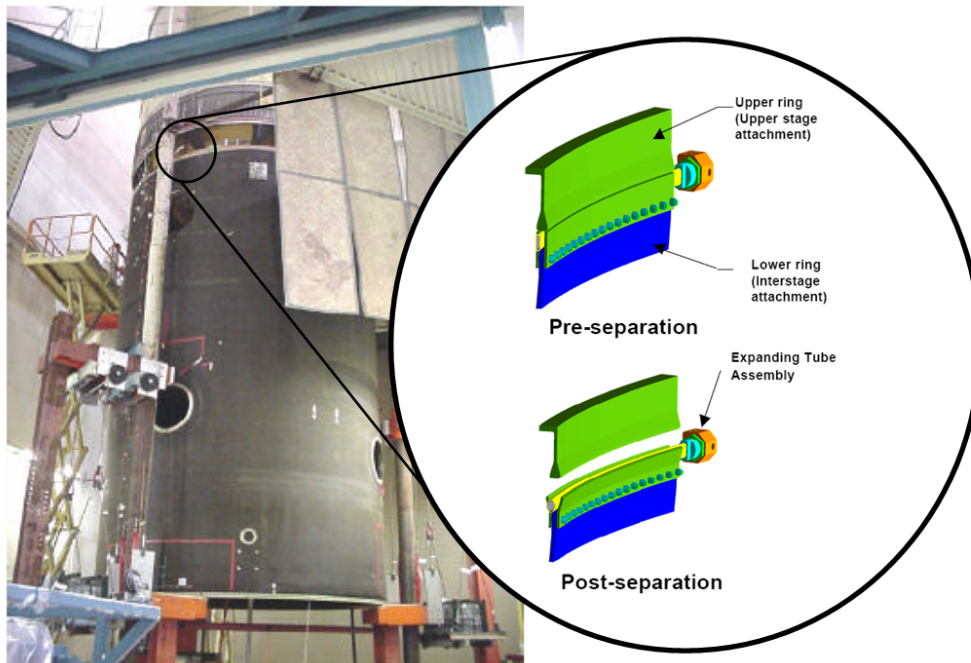


Figure 7. Full-Scale Separation Ground Test Set-up for Delta IV 1st & 2nd Stage.⁵

X-43A

The X-43A was a NASA-funded, unmanned, experimental hypersonic aircraft.⁶ The X-43A's scramjet propulsion system was designed to work in a hypersonic flight regime at altitudes greater than 100,000 feet, therefore to obtain required altitude it was boosted into its flight envelope by a Pegasus launch vehicle. Full-scale stage separation ground tests – depicted in Figure 8 – were conducted to mitigate risks specific to the Pegasus-to-X-43A separation event. These tests involved all of the key components in the separation subsystem, including explosive bolts, ejection system (pistons), and instrumentation. The tests helped to determine explosive bolt firing time latency, verify piston performance under both no-load and side-load conditions, and quantify pyroshock loads and attenuation.

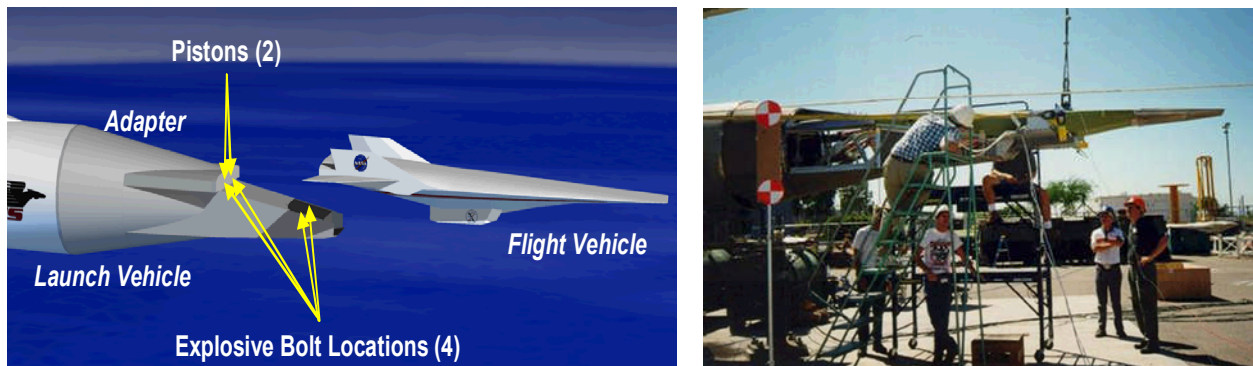


Figure 8. X-43A Separation Joint Configuration (left) and Full-Scale Ground Tests (right)⁶

ARES I SEPARATION SYSTEM TEST CONSIDERATIONS

Based on our review of historical launch vehicle development programs and the unusually high risk associated with the Ares I stage separation design, a robust full-scale stage separation test series is required. The primary test objectives are: demonstration of a clean and complete cut of the severance system without reweld of the joint, measurement of pyroshock source and transmissivity on the upper stage aft skirt and interstage and measurement of the debris fields. Secondary objectives include: measurement of lateral, radial and axial movement of the separation ring, measurement of tip-off forces, and measurement of pressure and temperature inside the aft skirt and interstage.

Ares I stage separation test objectives will be met by both sub-scale and full-scale tests, as illustrated in Figure 9. Note: Sub-scale tests are typically performed on simple flat panels instrumented with accelerometers. Numerous sub-scale tests are performed to anchor the analytical code (Hydrocode) to improve the accuracy of pyroshock and debris field environment predictions. Limitations of the sub-scale tests include inability to predict how pyroshock will attenuate through complex structures such as the Y-joint. Nevertheless these numerous sub-scale tests are complementary with the much more expensive full-scale tests and serve to qualify the LSC joint design.

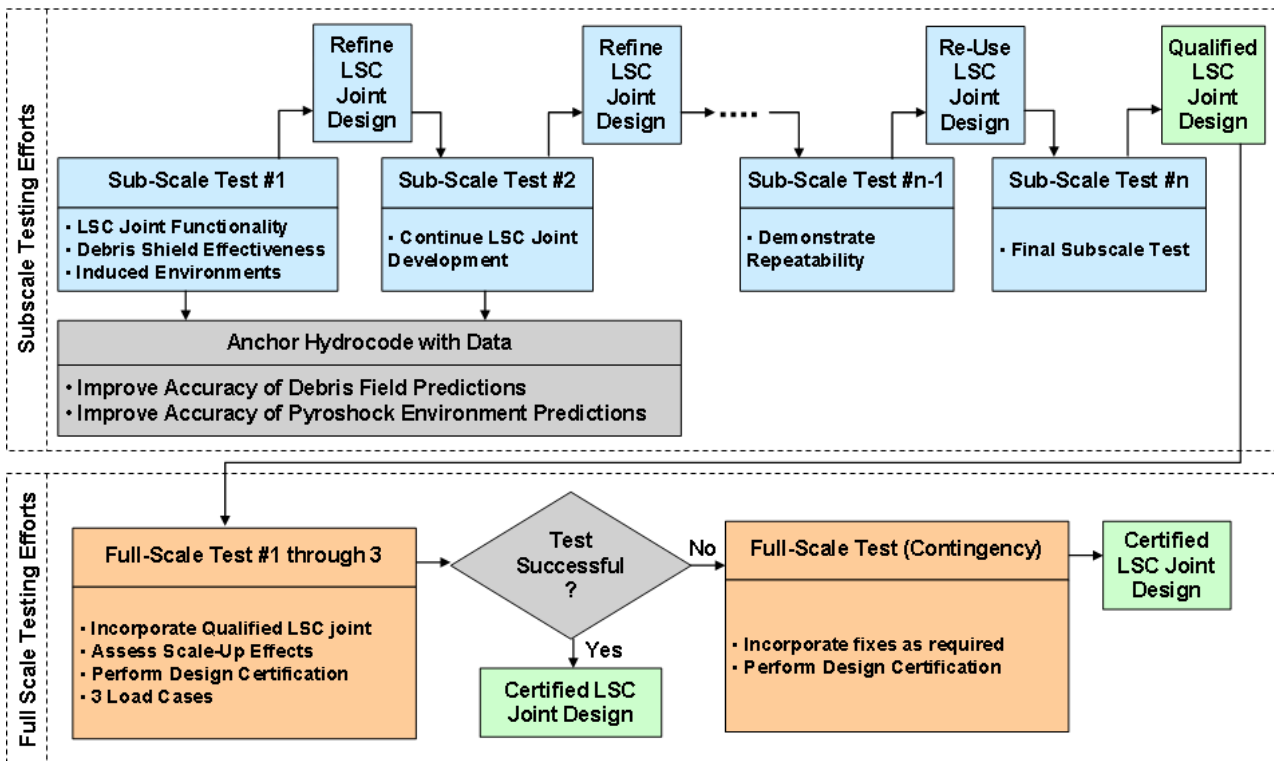


Figure 9. Subscale Development and Full Scale Separation Systems Certification Tests.

Full-Scale Test Article

Preparation for an effective full-scale separation testing program centers on choosing an appropriate level of fidelity for the test article and the simulated flight environments. Figure 10 depicts a candidate Ares I separation test configuration. Test article scale is driven primarily by pyroshock attenuation measurement needs. These measurements will be used to establish acceptance test requirements for avionics and other components on the launcher that are vulnerable to pyroshock damage. No single factor influences the cost of the test program more than test article scale and fidelity.

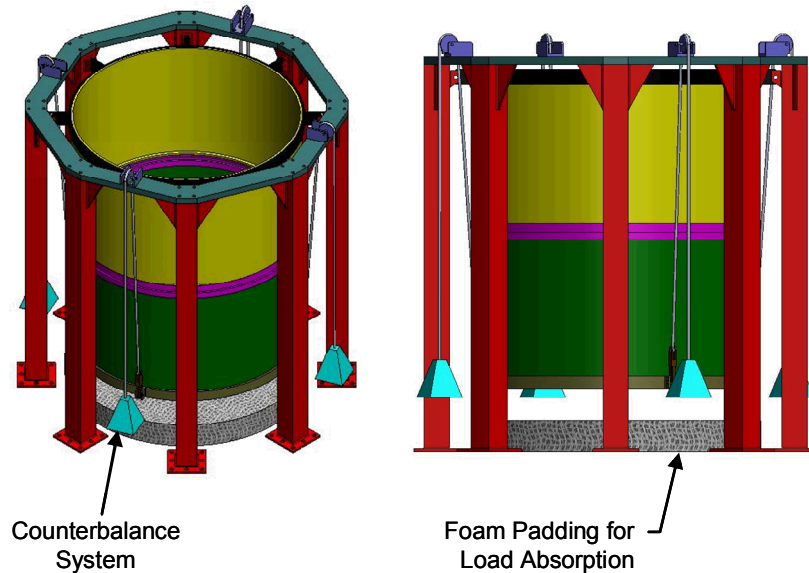


Figure 10. Ares I Stage Separation Test Conceptual Design.

The proposed test article consists of an Ares I separation joint and portions of the upper stage aft skirt and interstage. The full-scale article will be manufactured to match Ares I and will be constructed from the same materials which are to be used on Ares I. Witness panels will be installed on the interior of the test article to measure the debris field and aid assessment of the debris shields. A total of six tests are under consideration to evaluate different load cases as outlined below:

- 2 each no load case: This will test the basic functionality of the configuration.
- 2 each nominal load case: Test article will be stressed to simulate in flight compression loading. Nominal LSC timing.
- 2 each worst case scenario: Nominal load case with worst case off-nominal LSC initiator timing

Instrumentation and Data Acquisition

The data system for the Ares I stage separation test will require high speed sampling rate on the order of 100,000 samples per second per channel or more. The high cost of these tests precludes repeating a test if data is lost. For this reason, reliability of the data system, the instrumentation and the wiring is important. A comprehensive pre-test checkout procedure must be developed that will ensure that all channels are operational. Redundant measurements will reduce the risk of lost data. Roughly 120 channels will be required.

Full-Scale Separation Test Instrumentation			
Instrument	Purpose	No of Insts	No of Chans
3-axis extensometers	Measure trajectory after separation	4	12
Linear position transducers	Backup trajectory measurement	6	6
Make wires	Measure ordinance timing	18	18
3-axis accelerometers	Measure near field shock	12	36
Thermocouples	Temperature within IS and AS	2	2
Pressure transducers	Interior and exterior shock pressure	12	12
Voltage sensors	Record LSC initiation	14	14
Redundant and miscellaneous		20	20

In addition, seven high-speed cameras (5,000 and 10,000 frames per second) will be required, plus two NTSC video cameras for area surveillance.

The limited vertical extent of the test article will make interpretation of near field shock measurements difficult. After one millisecond or so, reflections from the upper and lower edges of the test article will interfere with the primary shock measurements. The limited extent also precludes making shock measurements at the locations of avionics components. The shock environment at these locations will have to be estimated from rather uncertain calculations, with no data to anchor the calculations.

Shock reflections from hard surfaces in the vicinity of the test article could interfere with acceleration measurements after five or ten milliseconds. These surfaces should be covered with sound-absorbing material.

Support Infrastructure

Test article fixture concepts must take into account the broadest spectrum of considerations, including how loads will be applied to simulate flight, access for installation and inspection, special precautions to allow reuse of the test article and test fixture, placement of debris witness panels, drop height, instrumentation cable routing, and cost of design, fabrication, and assembly. The test articles will be suspended approximately 2 to 6 feet above the ground. A scaffolding structure will be constructed to support the test articles. The upper stage section will be bolted and secured to the top of the scaffolding. Witness plates will be implemented in order to record the debris pattern.

A simple counter balance system with dead weights, pulleys, and cables will be used to simulate the load environments present at the separation joint during flight. The counterbalance system will be attached to the test article using electrically actuated hooks which will be set to release approximately 10 to 20 milliseconds after the firing of the LSC.

Rolls of fiberglass insulation will be placed under the test stand in order to reduce acoustic noise reflections, which may interfere with the instrumentation and compromise data. A removable tent will be constructed around the test article in order to protect the test article from the weather and from any debris, which may cause damage. This tent is temporary and will be removed prior to testing.

Test Site Location

Separation test planning must also take into account the selection of a test site. Severance tests involve explosive devices, therefore one of the primary facility selection criteria is the remoteness of the location. Some locations such as the flame buckets of test stands offer some protection. An ideal facility candidate for severance testing would be one with existing infrastructure in place for a control and data acquisition. Multiple locations at Marshall Space Flight Center are being considered.

SUMMARY AND CONCLUSIONS

Stage separation, a crucial phase of launch vehicle operation, is implicated in a plurality of launch vehicle failures. Risk assessment, trade studies, historical surveys, and recommended integrated system testing for stage separation were discussed in detail for the Ares I launch vehicle. Historical programs providing precedents for stage separation tests include the Atlas-Centaur, Saturn S-IVB, Delta IV, and X-43A. Based on these precedents, and on specific attributes of the Ares I, ground tests of a full-scale separation system with adequate test article scale and fidelity are recommended. As an example, the upper stage aft skirt Y-joint and substantial portions of the interstage should be included to assure valid measurements of pyroshock attenuation.

A stage separation test series for Ares I will need to demonstrate reliable severance of the structural connection between stages without generating loads, vibrations, thermal environments, or highly energetic debris that inhibit the functionality of other launcher subsystems. Multiple load cases including off-nominal conditions are recommended.

These recommendations are based on the best available lessons learned from the numerous launch vehicle failures attributable to stage separation problems. NASA is currently weighing options for stage separation testing and will be making decisions in the coming months on the best tradeoffs of cost, schedule, and risk mitigation for the Ares I program stage separation system.

REFERENCES

1. Isakowitz, S. J., Hopkins, J.B., Hopkins, Jr., J.P., ***International Reference Guide to Space Launch Systems, Fourth Edition***, American Institute of Aeronautics and Astronautics, Inc., (2004).
2. Moaning, C.J., "Pyrotechnic Shock Flight Failures", Institute of Environmental Sciences Proceedings
3. W. Heath, H. Synor, R. F. Schmiedlin, and J. H. Povolny, "Study Of Separation Dynamics And Systems Related To Staging Of Atlas-Centaur", NASA TM-X-52292, July 1967
4. ***Saturn V Flight Manual (SA-503)***, NASA, (1968)
5. Stockinger, J., Shen, F., Bowers, G., Pan, M., and Whalley, I., "Delta IV Evolved Expendable Launch Vehicle Ordnance Overview", 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2005-3655
6. Wayne B.D., Reubush, D.E., "X-43A Stage Separation System – A Flight Data Evaluation", AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies, AIAA 2005-3335



ARES I STAGE SEPARATION SYSTEM DESIGN CERTIFICATION TESTING

**Stephen L. Mayers, Bernard B. Beard, and R. Kenneth Smith
ARES Corporation
Jacobs ESTS Group
Huntsville, AL**

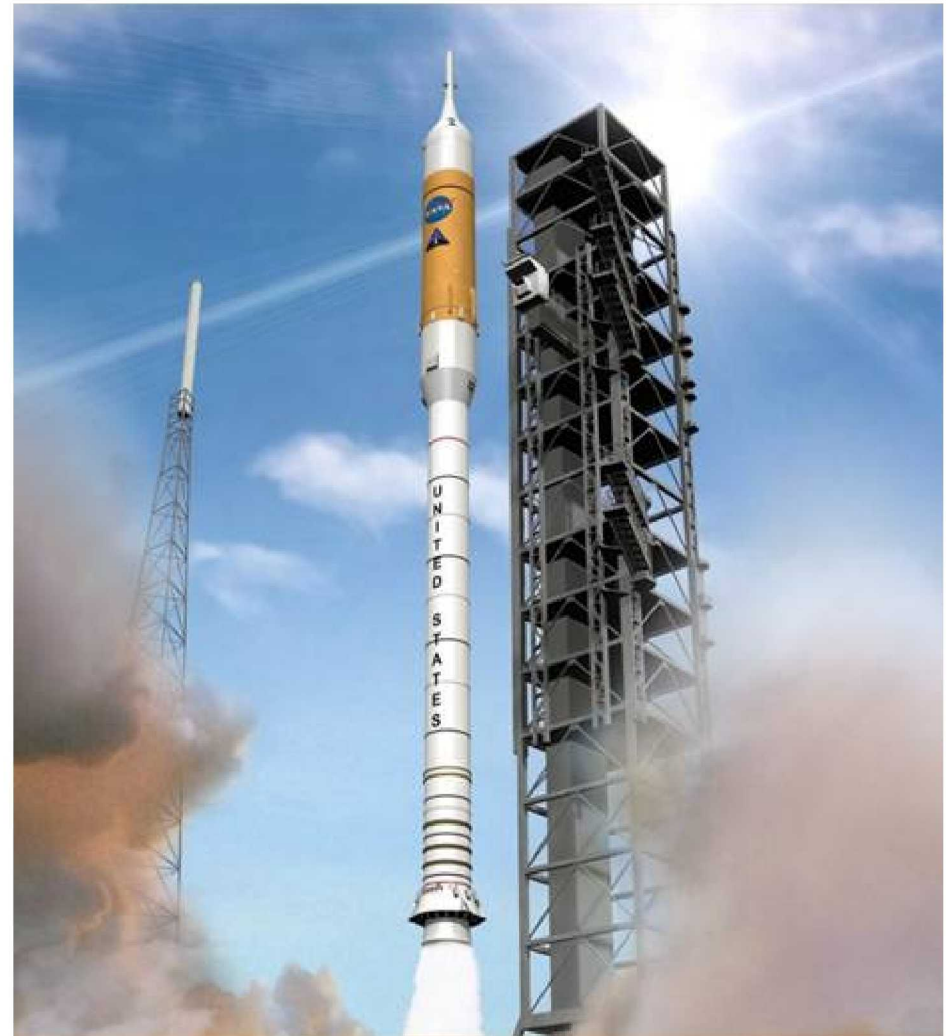
**Alan Patterson
NASA Marshall Space Flight Center
Huntsville, AL**



Outline

2

- ◆ **Introduction**
- ◆ **Ares I Separation System Risk Assessment and Trade Study**
- ◆ **Historical Data**
- ◆ **Ares I Separation System Test Considerations**
- ◆ **Summary and Conclusion**





Introduction

- ◆ **Ares I (NASA's newest crew launch vehicle) is designed to support human missions to low Earth orbit (LEO) and the moon with unprecedented reliability and safety.**
- ◆ **Based on historical precedence, stage separation is one of the most significant technical and systems engineering challenges in this endeavor. The challenges associated with stage separation must be overcome to achieve a level of reliability and safety.**
- ◆ **Historical launch vehicle development program data regarding separation system testing is useful in determining lessons learned and best practices.**



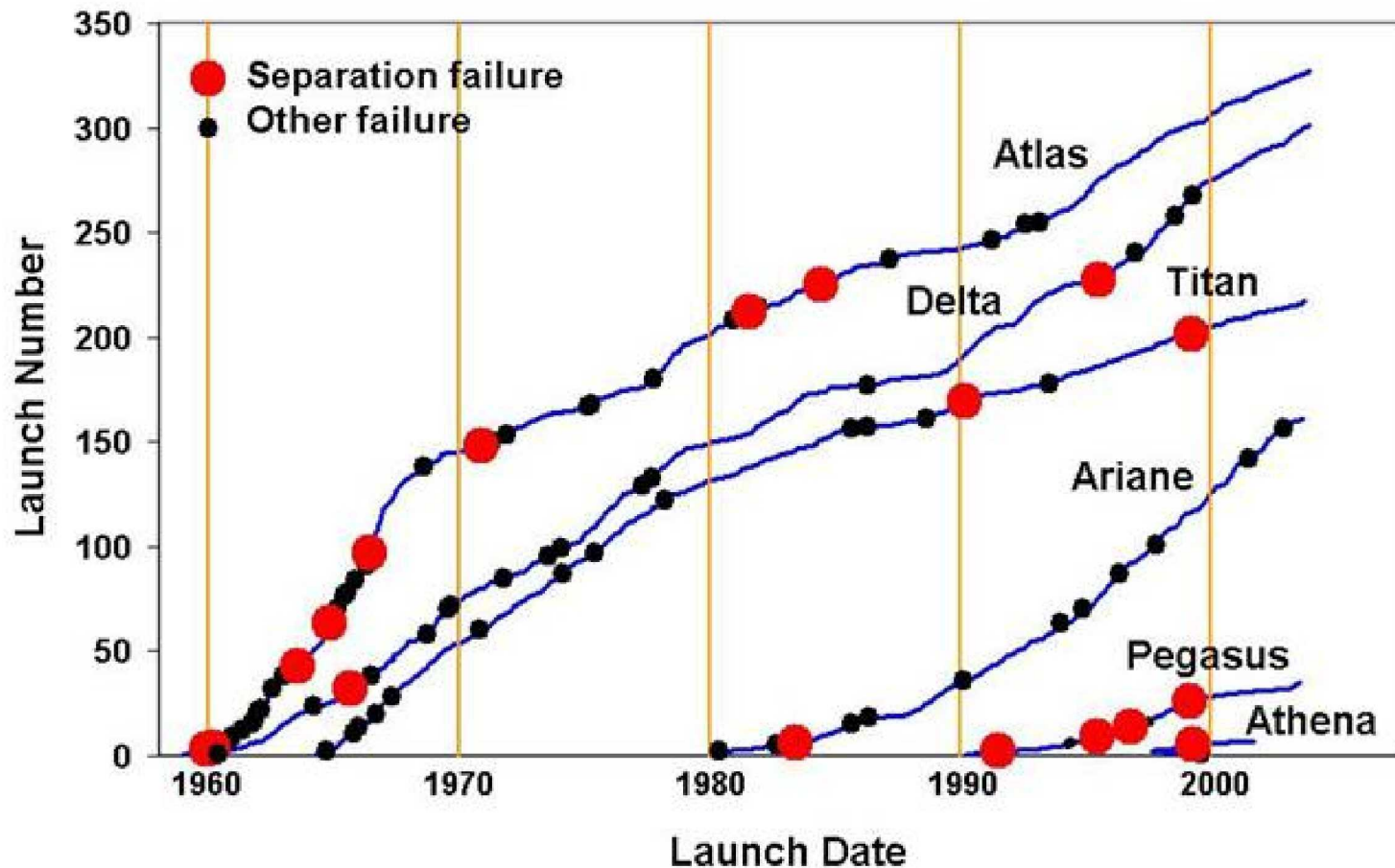
Introduction - Cont'd

4

- ◆ **Key separation system design trades evaluated for Ares I include single vs. dual separation plane options, retro-rockets vs. pneumatic gas actuators, small solid motor quantity/placement/timing, and continuous vs. clamshell interstage configuration options.**
- ◆ **Both sub-scale and full-scale tests are required to address the prediction of complex dynamic loading scenarios present during staging events. Test objectives as well as the test article, support infrastructure and instrumentation are provided.**




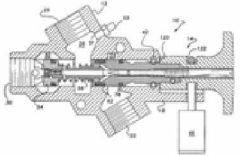


Historical Launch Vehicle Stage Separation System Failures





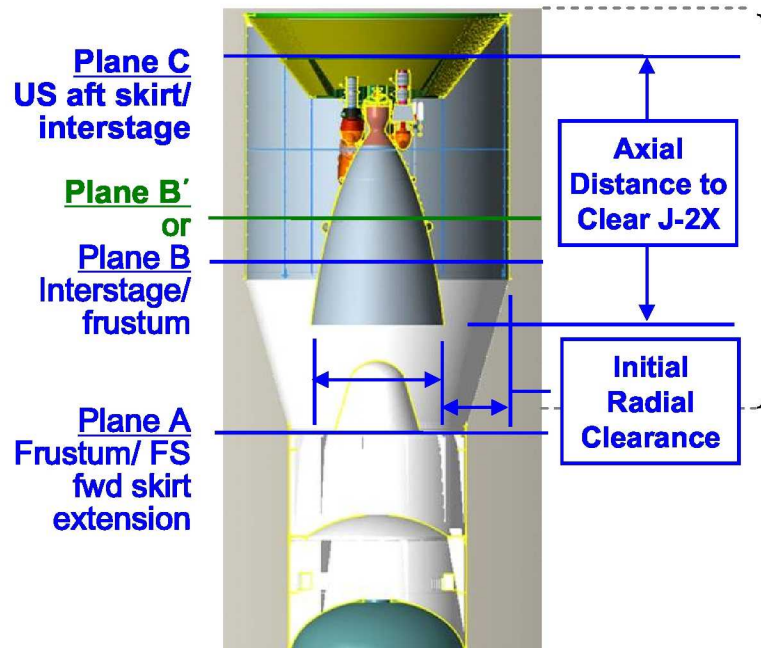
Pyroshock Induced Launch Vehicle Failures and Anomalies

Failure Categories	Number of Failures Confirmed or Suspected (1960's to 1970's)	Estimated Peak g's (100-10K Hz)	Space Systems Involved	Number of Programs Affected	Root Cause / Corrective Action
 Relays & Switches	4 Total All Resulted in Loss of Mission	600 to 4,000 g's	Launch Vehicle	4	1) System level testing to define environments 2) Shock isolate components 3) Redesign/requalify vulnerable components 4) Relocate components to lower shock regions
 Fracture of Brittle Materials	31 Total 17-Loss of Mission 14-Loss of Performance	≥ 3,000 g's	Launch Vehicles	6	1) System level testing to define environments 2) Redesign ordinance to reduce shock 3) Redesign/requalify vulnerable components 4) Improve acceptance testing, including shock
 Short Circuits	29 Total 24-Loss of Mission 4-Loss of Performance 1-Unknown	200 to > 3,000 g's	Launch Vehicles	8	1) Institute Particle Impact Noise Detection Tests 2) Passivate Internal Piece Part Conducting Surfaces 3) Institute Shock & Vibe Component Tests
 Deformation of Delicate Structures (Valve Cap)	1 Total	Unknown	Soyuz II Space Capsule	1	Cabin pressure release valve tripped open due to shock from explosive bolts (valve cap safety device loosened)

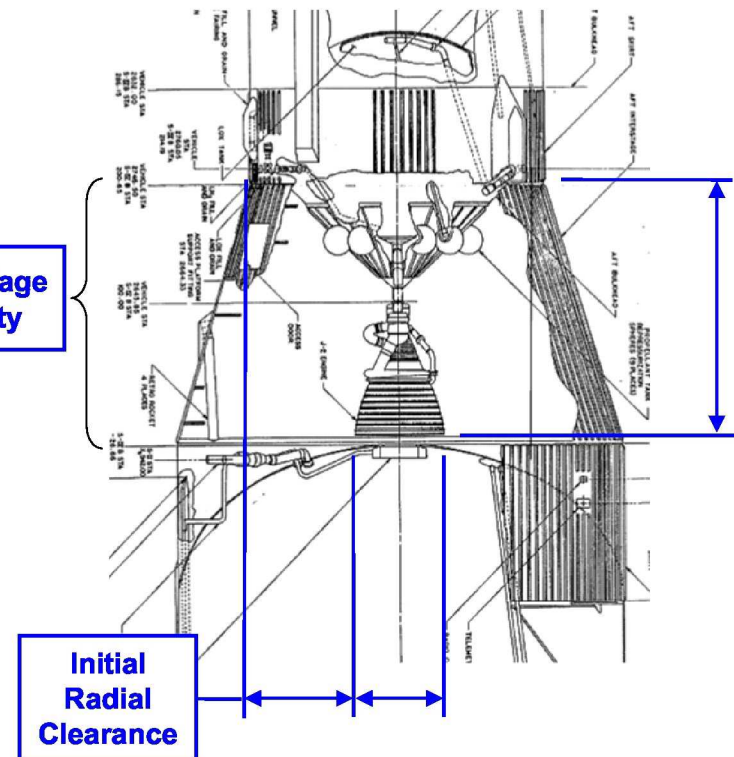


Ares I Separation System Risk Assessment and Trade Study

- ◆ Ares I dimensional challenges present unique challenges that influence the probability of interstage contact with the Upper Stage Engine nozzle extension after separation.



Ares I Baseline Separation Clearance



Saturn S-IVB Separation Clearance Angle:



Ares I Separation System Risk Assessment and Trade Study - Cont'd

8

- ◆ **In the fall of 2007, design options were down-selected to dual-plane option 3 and the single-plane option 1.**
- ◆ **Eight Figures of Merit (FOM) were used to evaluate these remaining design options: 1) flight safety, 2) ground safety, 3) design robustness and “margin-to-margin”, 4) payload to orbit, 5) induced environments, 6) non-recurring DDT&E costs, 7) recurring costs, and 8) risks and opportunities.**
- ◆ **The single-plane design option evaluated higher in five out of the eight FOMs (1, 2, 4, 5 and 6) and was selected as the baseline staging system.**
- ◆ **NASA trade studies indicated the following risks inherent in the Ares I First Stage/Upper Stage separation event:**
 - Pryoshock-induced vibration environments
 - Linear Shaped Charge (LSC) generated debris
 - Off-nominal performance by multiple elements



Historical Precedents for Full-Scale Separation System Test

9

- ◆ **Historical launch vehicle development programs surveyed for separation testing lesson/best practices include:**
 - Atlas-Centaur
 - Saturn S-IVB
 - Delta IV
 - X-43A

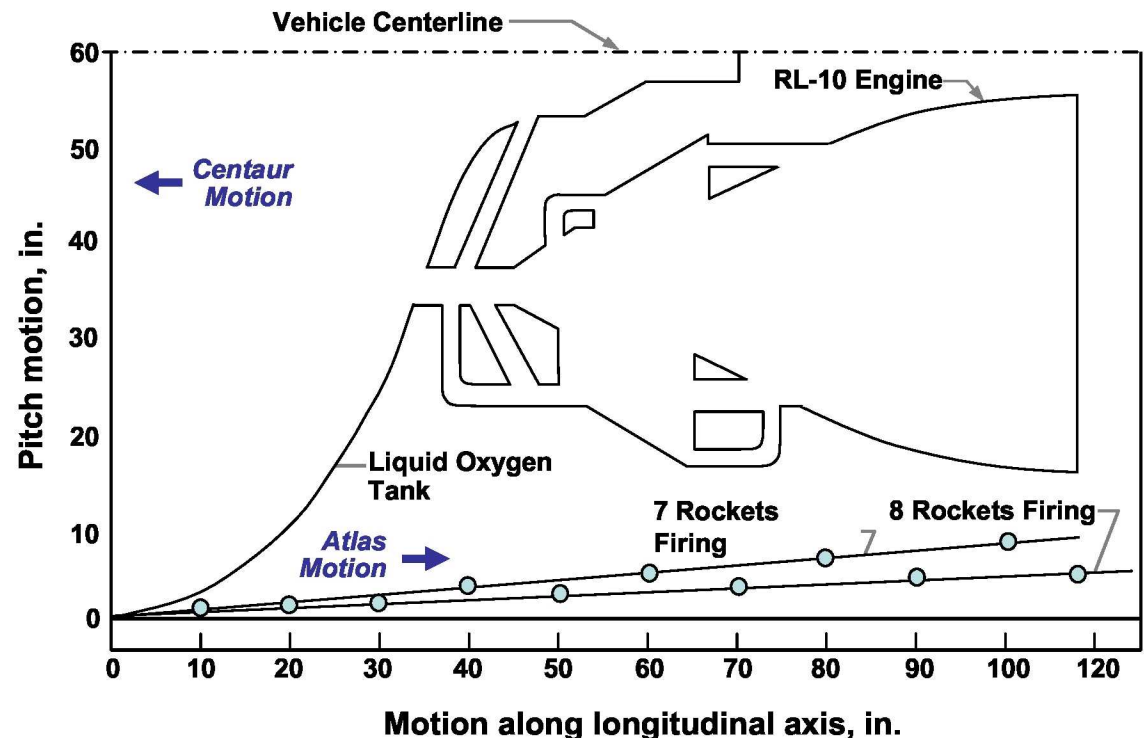
- ◆ **Primarily, these tests are concerned with determining and assessing the ability of the separation system to reliably sever the structural connection between stages without generating the following:**
 - Loads
 - Vibrations
 - Thermal environments
 - Highly energetic debris that inhibit the functionality of other launcher systems



Atlas-Centaur Vacuum Chamber Full-Scale Separation Tests

10

- ◆ Significant investment in stage separation ground testing.
- ◆ Unique: entire full-scale booster stage complete with solid-fueled retro-rockets was tested, in a vacuum chamber, simulating the 100,000 ft. separation altitude.
- ◆ Eighteen total full-scale tests.
- ◆ 20% reduction in retro-rocket impulse compared to predictions.
- ◆ Analysts were able to anchor their vehicle dynamic behavior models. These models were able to prove that the separation system could tolerate a retro-rocket out scenario and still maintain adequate clearance between the interstage and the Centaur upper stage engine.

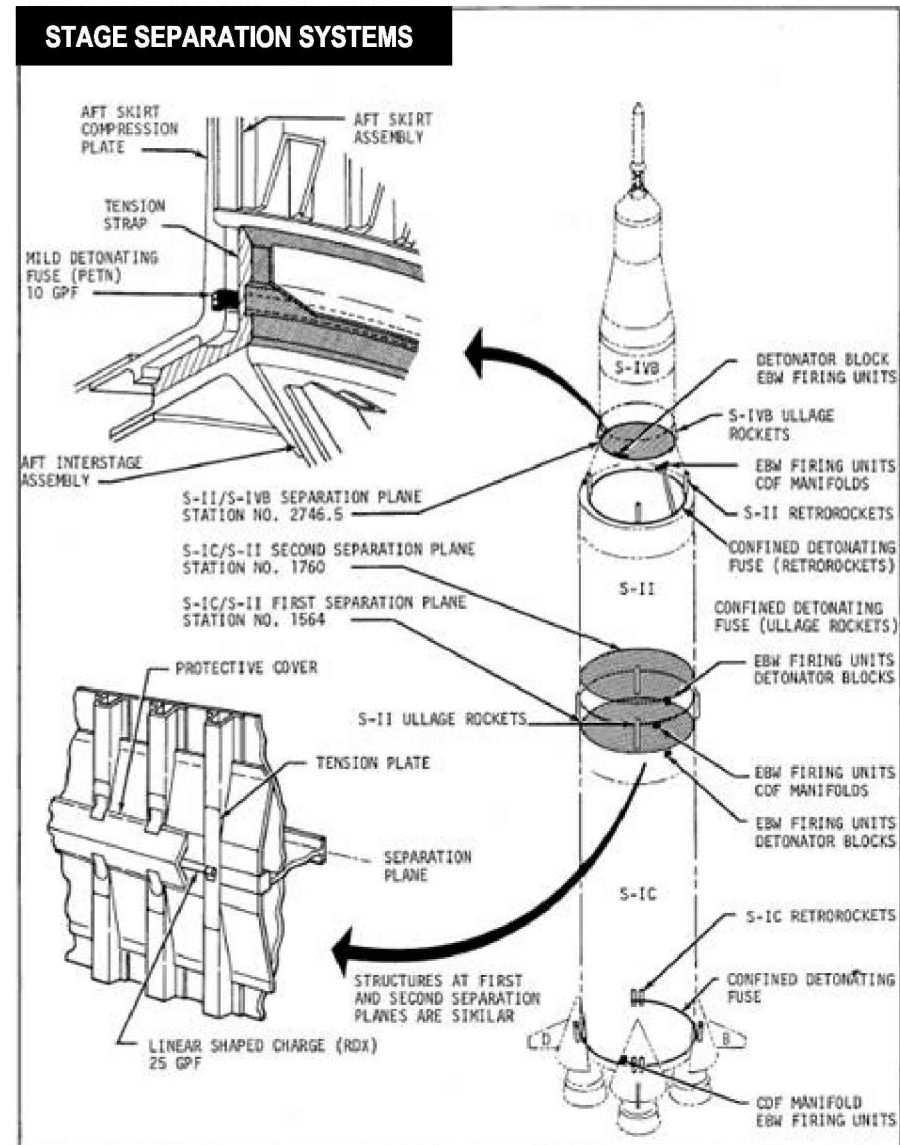


Measured Clearance between the Upper Stage Engine Nozzles and Booster Interstage Adaptor Rim as a Function of Axial Distance during Atlas-Centaur Separation Testing



Saturn V Stage Separation Systems

- ◆ The Saturn V's third stage (S-IVB) comprises a single plane separation system. Also related to Ares, the Saturn separation systems relied on an explosive circumferential charge to sever the stages, as well as retro rockets and ullage settling motors.
- ◆ Stage separation ground tests were utilized during development stages of the S-IVB separation system, primarily to gather measurements of pyroshock attenuation.
- ◆ Multiple free-fall separation tests were conducted with a full-scale diameter and a 6' long interstage.

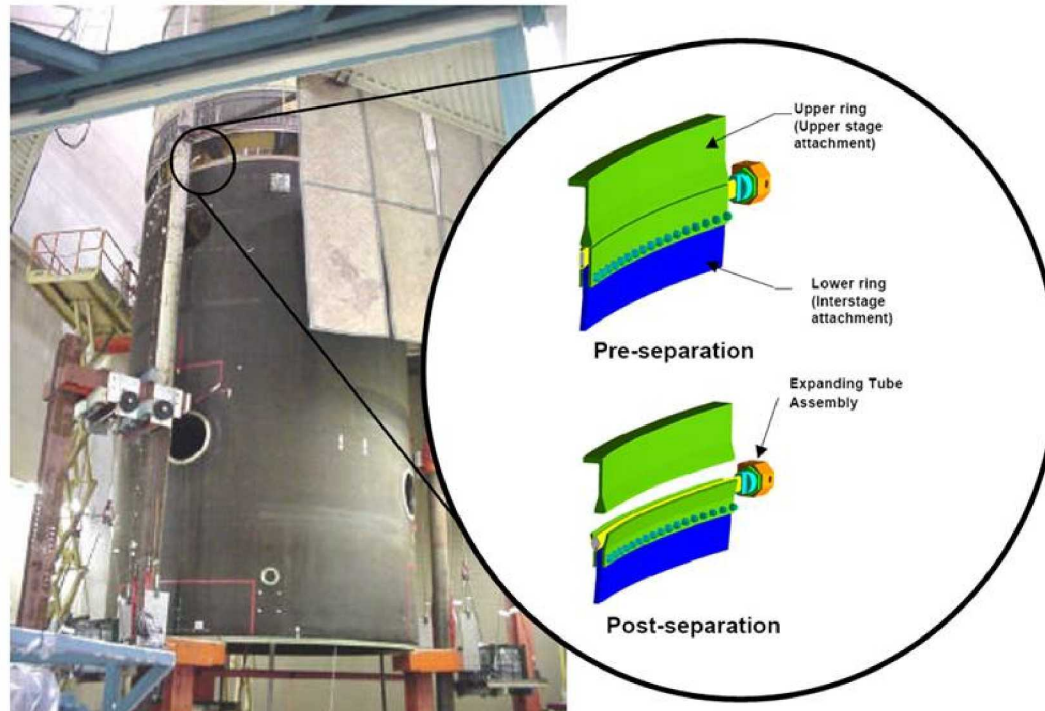




Full-Scale Separation Ground Test Set-up for Delta IV 1st & 2nd Stage

12

- ◆ Testing was conducted on full-scale diameter test articles (vertical). A counter balance system was used to simulate the load environment present at separation.
- ◆ Pyroshock and pneumatic actuation system pressures were measured as a function of axial separation distance.
- ◆ Severance technologies developed by Boeing as a result of this testing include a proprietary frangible joint design, ordinance for disconnection of electrical wiring between stages, initiators set off ordinance and pneumatic actuation systems to force separation.

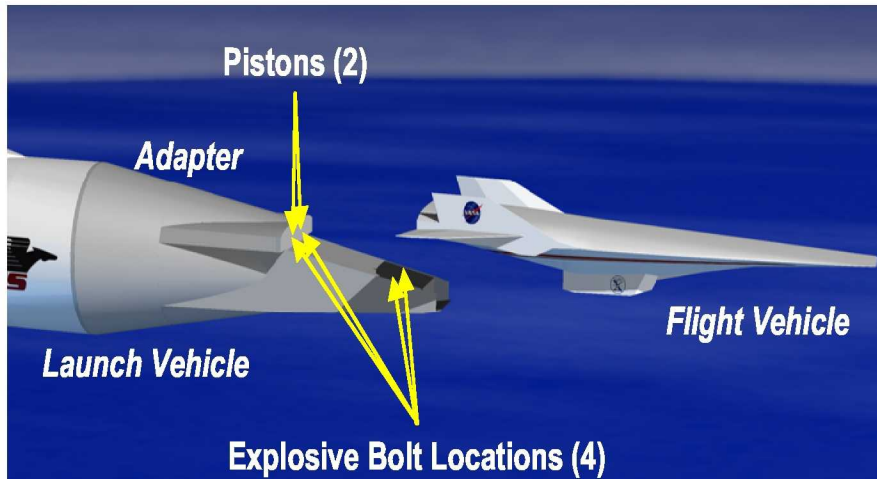




X-43A Separation Joint Configuration and Full-Scale Ground Tests

13

- ◆ Full-scale stage separation tests were conducted to simulate separation at 100,000+ ft. at hypersonic speed.
- ◆ These tests involved key separation components such as explosive bolts, ejection pistons and instrumentation.
- ◆ The tests aided in determining the explosive bolt firing time latency, the verification of piston performance (no-load/side-load conditions) and the pyroshock loads and attenuation.





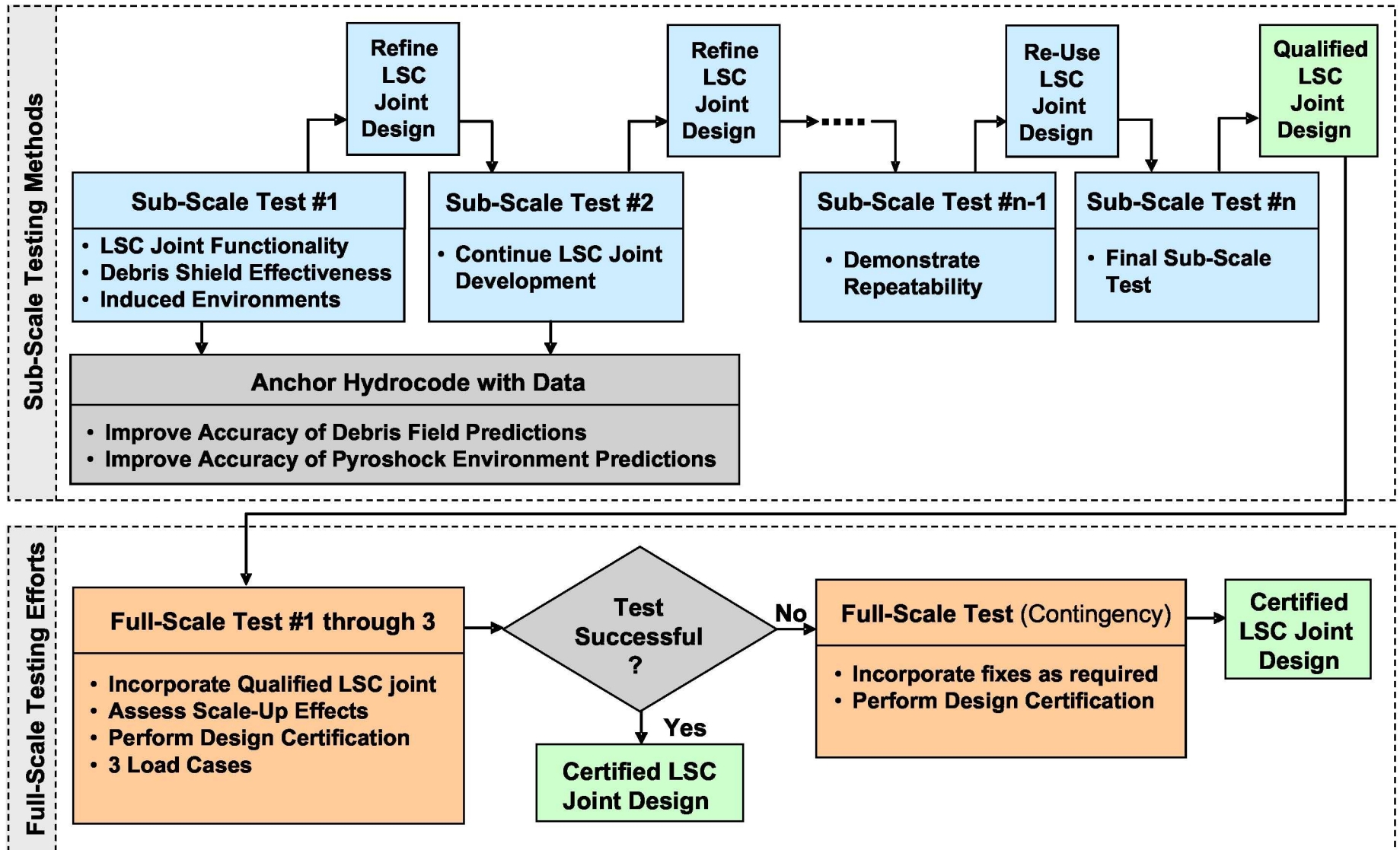
Ares I Separation System Test Considerations

14

- ◆ **Based on review of historical data, as well as, the unusually high risk associated with the Ares I stage separation design, a full-scale stage separation test series is required.**
- ◆ **Primary Test Objectives:**
 - Demonstration of a clean/complete cut of the severance system without reweld of the joint
 - Measurement of pyroshock source
 - Measurement of transmissivity on the upper stage aft skirt and interstage
 - Measurement of the debris field
- ◆ **Secondary Test Objectives:**
 - Measurement of lateral, radial and axial movement of the separation ring
 - Measurement of the tip-off forces
 - Measurement of pressure and temperature inside the aft skirt and interstage



Sub-Scale Development and Full-Scale Separation Systems Certification Tests





Separation Test Considerations

16

◆ Tests Under Consideration

- 2 each no load case
- 2 each nominal load case
- 2 each worst case scenario

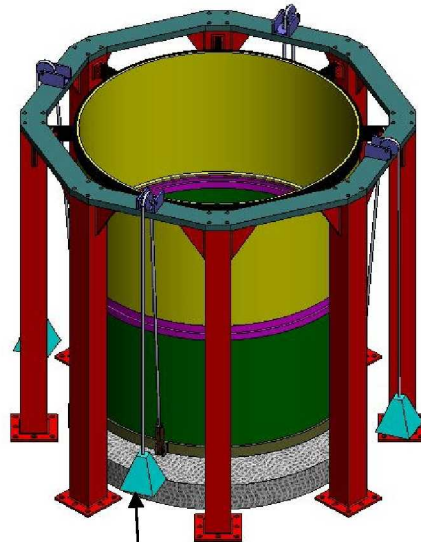
◆ Test Site Location

- The selection of a test site must be taken fully into consideration due to the involvement of explosive devices. Thus, one of the primary facility selection criteria is the remoteness of the site. Ideally the selected facility would have existing infrastructure in place for a control and data acquisition. Multiple test sites at Marshall Space Flight Center are currently under consideration.

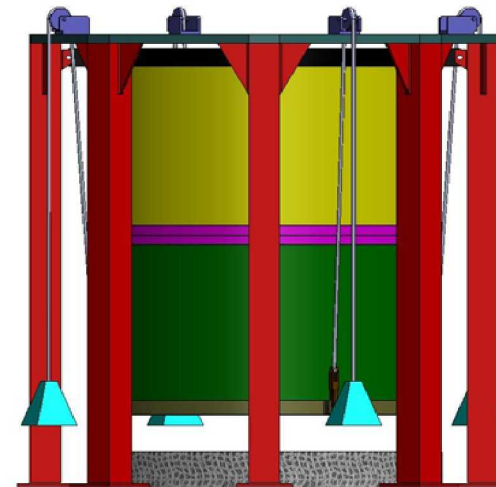


Ares I Stage Separation Test Conceptual Design

- ◆ The proposed test article consists of an Ares I separation joint and portions of the upper stage aft skirt and interstage.
- ◆ A counter balance system will be used to simulate load environments present at the time of separation.
- ◆ Foam padding for load absorption (at the base of the test stand) and witness panels to measure debris field inside the stage will be installed.



Counterbalance System



Foam Padding for Load Absorption



Summary and Conclusion

18

- ◆ **Stage separation is implicated in a multitude of launch vehicle failures. Risk assessments, trade studies, historical surveys, as well as recommended integrated system testing for stage separation were discussed in detail.**
- ◆ **Based on these precedents, as well as, the unique attributes of Ares I, ground tests of a full-scale separation system with adequate test article scale and fidelity are recommended.**
- ◆ **Stage separation test series for Ares I will need to demonstrate, on a consistent basis, reliable severance of the structural connection between stages without generating loads, vibrations, thermal environments, or highly energetic debris.**