

# Gas Strut Separation Alternative for Ares I

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## Abstract

This paper presents a design alternative and the rationale for a stage separation system based on Metering Adiabatic Gas Struts (MAG Struts) for the Ares 1 launch vehicle. The MAG Strut separation system was proposed as an alternative to the current Ares 1 separation system, which relies on small solid rocket motors to provide the main separation force. This paper will describe technical issues that were addressed during the trade study and present a conceptual design of the strut system that best resolved the issues. Needed development testing and programmatic considerations will be addressed as part of the paper.

## Introduction

Gas struts show promise as an efficient way to provide the separation force for launch vehicle staging. Strut systems are currently in use on a number of vehicles, but so far all have been unmanned. Several factors make the MAG Strut system unique. The struts are entirely self-contained. They are themselves pressure vessels, which are pre-charged with gas prior to launch. They require no additional actuation, but simply act as springs when the physical connection between stages is severed. Due to the mass properties of the separating stages, this system provides excellent nozzle clearance during fly-out in off-nominal conditions. Consequently, safety and mission success objectives are enhanced. Since the struts are light weight relative to other separation systems capable of applying the same force, the separation timing can be adjusted to separate earlier during the ascent trajectory, increasing payload lift capability. The proposed struts apply the separation force smoothly during release in order to minimize disturbance of the Upper Stage propellant and reduce the buckling loads applied to the upper stage aft skirt. The trade study also predicts significantly lower life-cycle-cost. Since the MAG Strut system is not in flight operation on any launch vehicle, development testing and system-qualification introduce some risk into the Ares program, which is a barrier to adopting the system.

## Background

The Ares I launch vehicle will lift the Orion crew vehicle to low-earth orbit for manned missions to the International Space Station and to the moon. Ares I consists of two stages. The first stage is a modified Space Shuttle Solid Rocket Booster (SRB) with 5 solid motor segments instead of the 4 segments currently used for shuttle. The Ares I upper stage is a LOx / LH2 stage powered by a J-2X engine. The stages are connected by a cylindrical interstage and a conical frustum. The J-2X engine is housed in the compartment formed by the interstage and frustum.

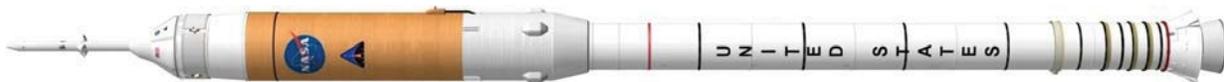


Figure 1 - Ares I

In the current flight trajectory baseline, the first stage ascent phase ends when the first stage reaches 178 kN of residual thrust. Eight Booster Deceleration Motors (BDMs) fire to push the first stage aft. Eight Ullage Settling Motors (USMs) thrust forward to maintain positive acceleration on the upper stage. Once

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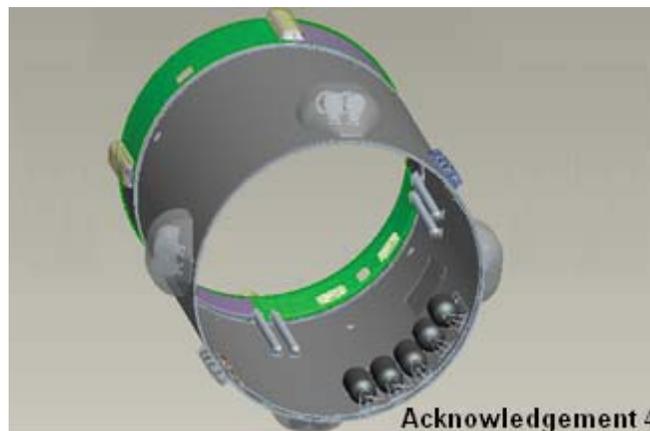
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the USMs and BDMs are ignited, a pyrotechnic joint at the forward end of the interstage initiates and the vehicle begins to separate. Figure 1 shows the Ares I configuration with the BDMs mounted on the interstage. In the most recent configuration, they are relocated to the aft skirt of the first stage. The J-2X nozzle exit plane is 7.1 meters aft of the separation plane. With the current arrangement separation system, it takes approximately 1.7 seconds for the nozzle to pass the forward end of the interstage.

### Nozzle Clearance During Fly-Out Considerations

Many factors affect the amount of radial clearance between the engine nozzle and the interstage wall during the fly-out. The most significant factor contributing to clearance issues for BDM separation is asymmetric plume impingement force on the first stage that can occur if one motor fails to fire. Secondly, since the first stage has 178 kN of residual thrust at the time of separation, significant pitching and yawing loads may be imposed on the stack before separation and on the first stage after separation due to thrust vector pointing uncertainties. With one BDM out, a worst-on-worst analysis of the separation shows contact between the interstage and the engine nozzle during fly-out. Monte Carlo analysis of this scenario shows that nozzle clearance can only be demonstrated to a 2.5-sigma level.

The proposed MAG Strut system uses eight gas-charged struts mounted inside the interstage to force the two stages apart. The struts essentially act as alignment guides during separation. Figure 2 shows the relative position of the struts on the interstage to the USMs and the BDMs they will replace.



**Figure 2 - Interstage showing BDMs and Struts**

Although the struts extend above the separation plane, they provide superior clearance, even with one strut out. The primary reason for this superior performance is that the mass-moment-of-inertia of the Ares I upper stage/crew vehicle is approximately  $\frac{1}{2}$  that of the mass-moment-of-inertia of the expended first stage, while the distance from the upper stage/crew vehicle center-of-gravity to the J2 nozzle exit plane is approximately  $\frac{1}{2}$  the distance of the center-of-gravity of the first stage to the separation plane. Figure 3 shows the relative positions of the centers-of-gravity of the separated stages to the nozzle exit plane and first stage separation plane. With a strut system, any disturbance force, regardless of its origin, is compensated for by the struts, forcing the separated stages to rotate in the opposite directions. The rate-of-rotation,  $W$ , induced on the two bodies is always close to 2/1 with the upper stage/crew vehicle rotating at twice the rate of that of the first stage. The rate of rotation of each body is small with the gas strut system. Distance  $D3$  is considerably larger than distance  $D4$  so some of the disturbance force coming from the first stage results in translating the upper stage in the same direction the interstage is moving. This translation effect, though beneficial, is not as significant as the rotational compensation.

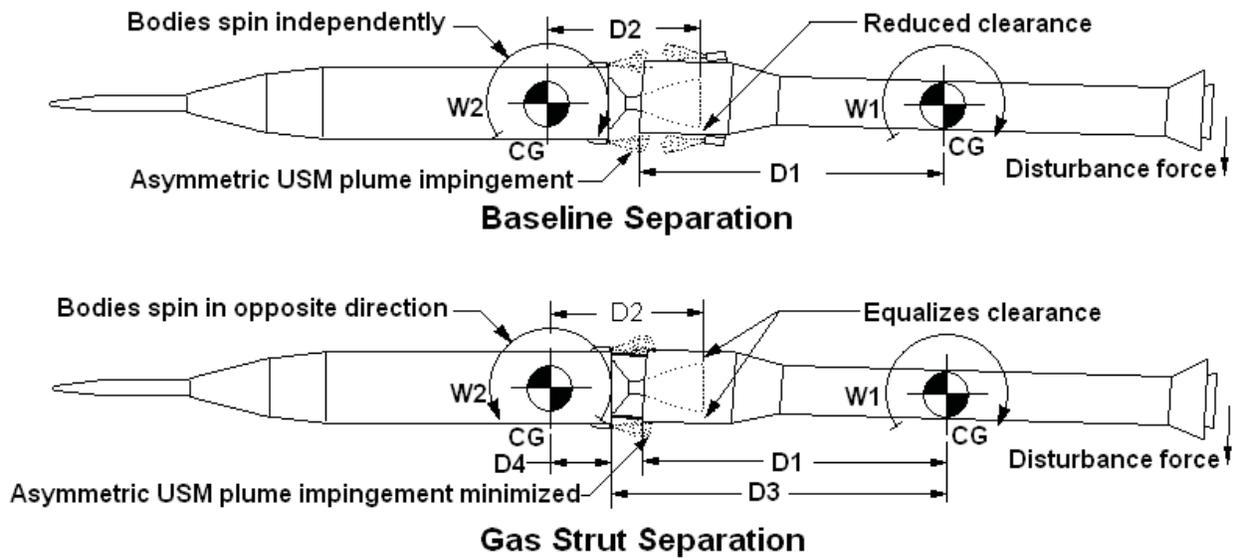


Figure 3 - Comparison of Gas Strut Separation and BDM Separation

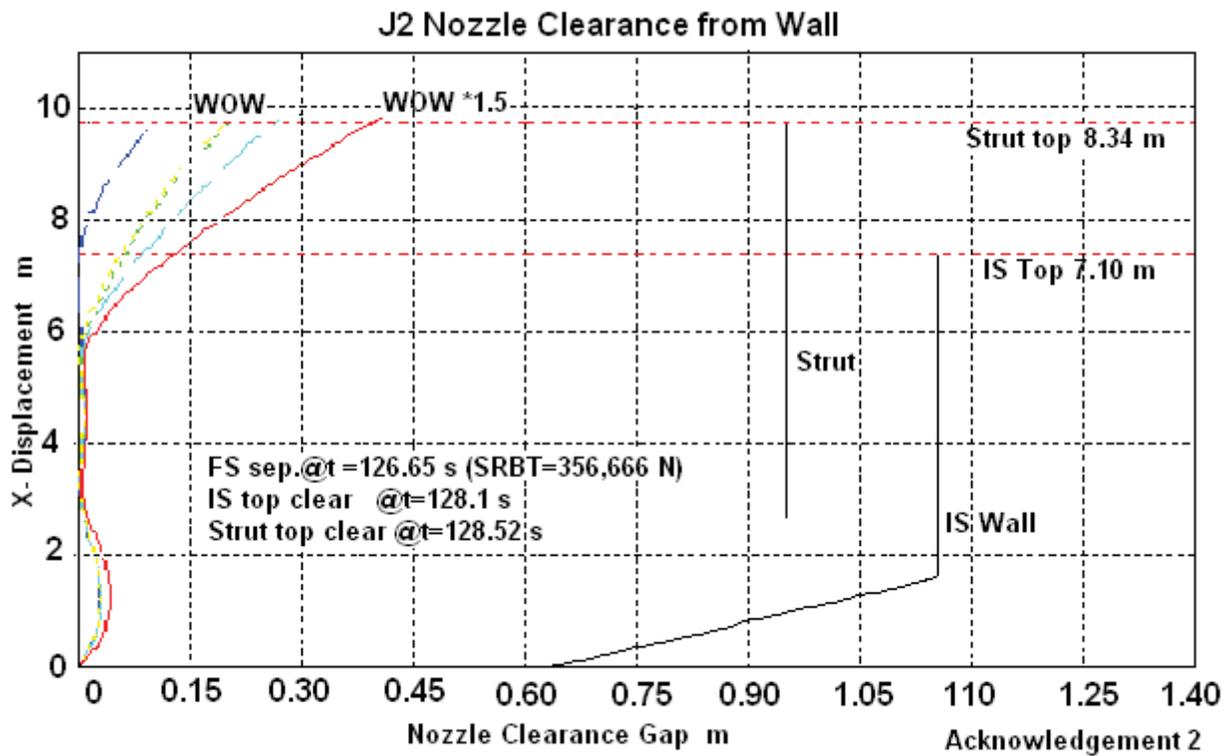


Figure 4 - Ares I Separation Clearance using Gas Strut System

Figure 4 shows the preliminary clearance results for the Ares I upper stage engine nozzle with one strut out. The WOW\*1.5 curve represents a worst-on-worst assessment of the radial clearance with a margin of 50% added to account for unknowns in the analysis. Even in this conservative case, the nozzle clears the extended end of the strut by 45.7 cm. The dash lines represent WOW case clearances for different failed struts with different disturbance scenarios. Two seals must fail on the same strut to result in a 100%

pressure loss. Based on the analytical results, one strut failure cannot result in the loss of an Ares I mission due to nozzle contact. Consequently, the MAG Strut system is inherently two-fault tolerant.

### Plume Heating on Upper Stage

At the Ares I System Definition Review, the vehicle was configured with BDMs mounted near the aft end of the interstage in four pods containing two motors each. The USMs were mounted on the upper stage aft skirt, also in four pods of two at the same angular positions around the cylinder. One problem with this configuration is the interaction of the USM and BDM plumes. Even though the nozzle exit planes were separated by over 4.5 meters axially, extreme heating was predicted in the upper stage engine compartment during separation because the BDM plumes deflect the USM plumes into the interior of the interstage. Also, debris generated by the separation pyrotechnics will likely be propelled into the engine compartment by the interacting plumes. The use of gas struts eliminates these debris and heating concerns. Relocating the BDMs to the first stage aft skirt would resolve this issue.

### Payload-to-Orbit Benefits

Gas strut separation produces a significant increase in payload-to-orbit capability. This gain is a result of reduced aerodynamic drag, momentum transfer between the stages, and ascent trajectory optimization.

The interstage-mounted BDM pods are the largest protrusions from the nominal outer moldline (OML) of the vehicle. As such they account for a total of a 110 to 120 kilogram payload penalty due to aerodynamic drag. The proximity of the BDMs to transition from the conical to cylindrical is a major factor in the high drag. Locating the struts inside the interstage eliminates all aerodynamic drag effects.

For the baseline trajectory, the amount of residual first stage thrust at separation is limited by the capability of the BDMs. For an 8 BDM configuration with one motor out, separation must wait until first stage thrust drops to 178 kN. Because the struts have a better weight to performance ratio than BDMs, the trajectory can be optimized to improve performance. Figure 5 indicates the amount of payload that can be gained relative to the baseline flight profile. The steeper section of the curve indicates a significant payload improvement, but the strut system mass (including additional upper stage structural mass) begins to offset the benefit as residual thrust increases. Separation at 356 kN of residual first stage thrust is thought to be optimum for Ares I. This results in approximately 90-kg additional payload due to improved trajectory performance.

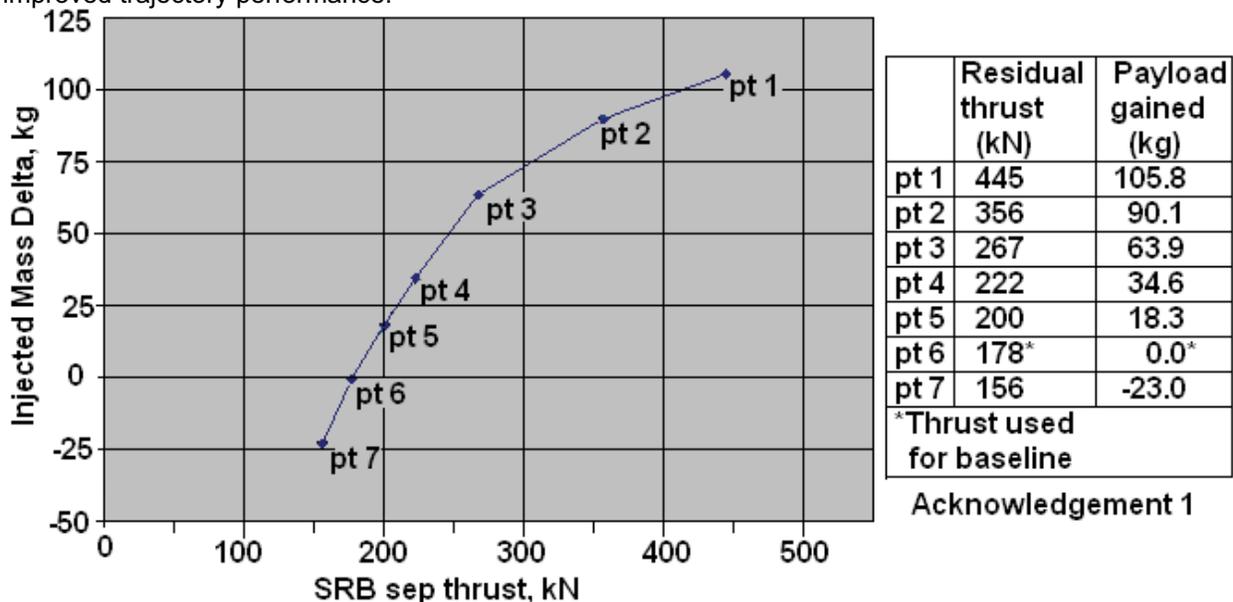
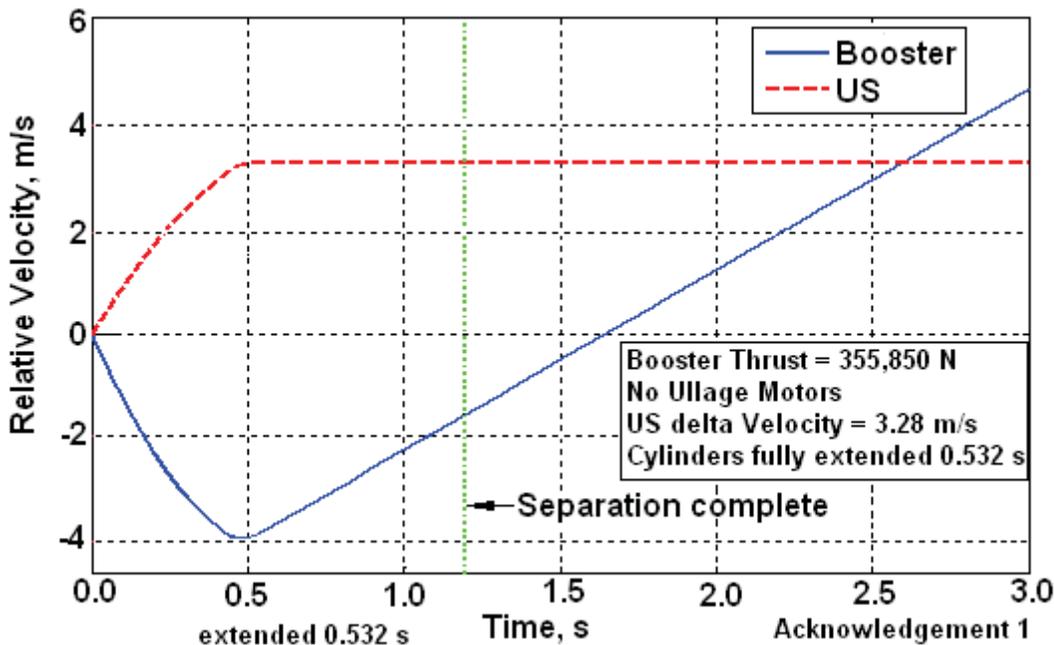


Figure 5 - Payload Delta from Baseline vs. Separation Thrust

During separation with gas struts, the first stage thrust continues to act on the upper stage until the end of the stroke. Initial calculations show that this momentum transfer adds payload performance at a rate of 8.93 kilograms for every meter per second of  $\Delta V$ . Preliminary strut designs result in an increase in upper stage  $\Delta V$  of 3 to 3.7 meters per second. This amounts to 27 to 33 kilograms of additional payload. Figure 6 shows the relative velocity gained by the upper stage for a separation with 356 kN of residual thrust.



**Figure 6 - Momentum Transfer Effects for a Separation at 356-kN SRB Thrust**

The mass of the struts and upper stage fittings for a 356 kN thrust separation are about half that of a BDM system that separates at 178 kN of residual thrust; however, because more of the mass remains with the upper stage, no additional payload advantage from the change in system mass is realized.

**Table 1 - Approximate Payload Benefit**

Reduced Drag	110 kg
Earlier Separation	90 kg
Momentum Transfer	27 kg
Mass Delta Benefit	0 kg
<b>Total Payload Benefit</b>	<b>227 kg</b>

### Cost Considerations

The projected unit cost for each BDM is approximately \$200,000. There are many reasons for this high cost. One of the most risky processes of solid rocket motor manufacturing is the casting and curing of the solid rocket propellant. The process is very hazardous and requires extensive risk mitigation to prevent inadvertent propellant ignition. The risk mitigation techniques are well known, and accidents are now rare, but the process is expensive. Additionally, post-casting inspection sometimes reveals defects in the cast propellant. If a defect is found, most often the motor is discarded.

Per unit cost for gas struts should be significantly less than BDMs, since there is no hazardous material to procure and handle. Also each flight unit can be acceptance tested, so manufacturing will not require the strict process control necessary for solid motors. If a defect is discovered during the acceptance testing,

in most cases the strut could be saved by simply reworking or replacing the defective parts. In addition, since the struts are inert until they are pressurized, ground handling hazards are eliminated, making handling a low-cost operation.

Parametric cost modeling bases the estimated cost on weight and similarities to selected components for which cost are available. Since the struts are half the weight of BDMs, they would be half the cost assuming equal complexity. This is the only level of cost analysis that is possible given the maturity of the MAG Strut design. Actual per-unit cost would need to be reevaluated after developed units have been fabricated and the design finalized.

### MAG Strut Design

The MAG Strut struts are designed to take advantage of the increase in payload to orbit by separating at 356-kN residual first stage thrust. To achieve this, a significant force is required. Consequently, the struts can place a substantial bending moment into the edge of the aft skirt, increasing the potential for buckling during ascent. Also, sudden release of the energy stored in the struts could result in a significant jerk to the upper stage, which could affect propellant quality and tank pressure. The MAG Strut design is proposed in order to counter these effects. During ascent, only a low pressure acts against the upper stage aft skirt. At separation, the force applied increases gradually, which minimizes potential for skirt buckling and mitigates concerns about sloshing induced in the propellant tanks.

The MAG Struts are designed with two chambers as shown in Figure 7. The low-pressure chamber is meant to provide the initial force requirement for separation. The initial force calculation for each strut would be as follows:

$$\left\{ \left[ \frac{(7.62 \text{ cm}^2)}{4} \right] * \pi \right\} * 10,342 \text{ kPa} + \left\{ \left[ \frac{(17.78 \text{ cm}^2 - 7.62 \text{ cm}^2)}{4} \right] * \pi \right\} * 1,034 \text{ kPa} = 68,124 \text{ N}$$

With 8 struts, the force of 545 kN is more than sufficient to overcome a SRM residual thrust of 356 kN and the transient oscillatory force from the SRM, and therefore preventing re-contact of the two stages during separation. (See Figure 8 for a plot of the transient oscillatory thrust of the Ares 1 first stage.) The high-pressure chamber is intended to store the gas needed for the main part of the strut stroke. After 40 cm of stroke, this force reaches 1,495 kN. This force is capable of driving the first stage and upper stage apart with sufficient velocity margin to achieve separation with a residual first stage thrust of 356 kN.

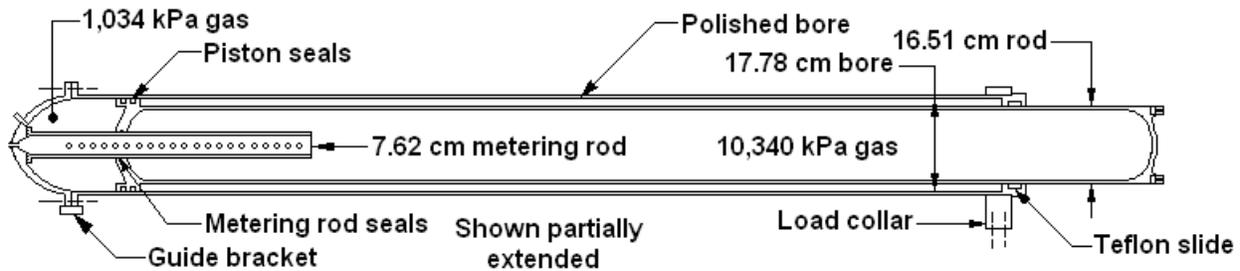


Figure 7 – Schematic of the Proposed MAG Strut Design

The metering rod has a pattern of holes that are exposed as the strut strokes, providing a gradual force buildup that will minimize impulse on the upper stage. Figure 9 shows a computer-aided design (CAD) rendering of the strut in the collapsed position. Figure 10 shows a CAD rendering of the strut in the extended position. Initially no holes are exposed. Once the strut has stroked 2.54 cm, 6 holes are exposed. Figure 11 shows the cumulative area for the exposed holes as a function of stroke. Every 2.5 cm of additional stroke exposes more holes to achieve the gradual force build-up. (The summation of

the total exposed hole-area for two different hole-sizes is shown at the bottom of the chart.) A large range of force profiles is possible with different hole-patterns. Holes larger than the “O” ring seal diameter would likely catch the seal, causing damage during stroking. A hole diameter of 3.96 mm would be the largest recommended hole size for a seal with a 4.83-mm diameter cross-section.

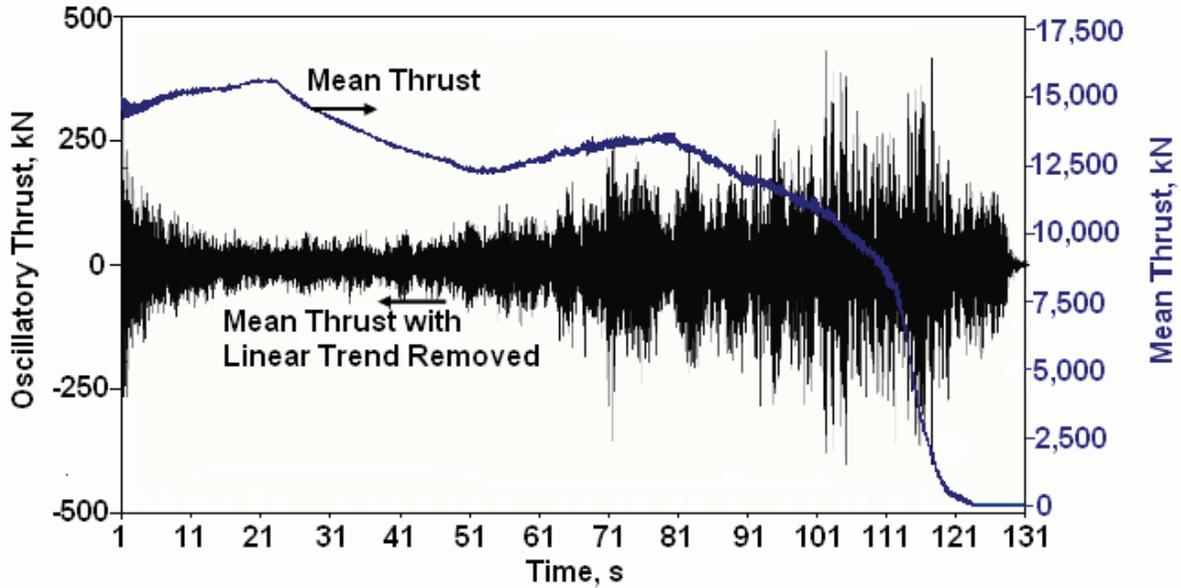


Figure 8 – Average Thrust and Oscillatory Thrust Test Data for 5 Segment SRM

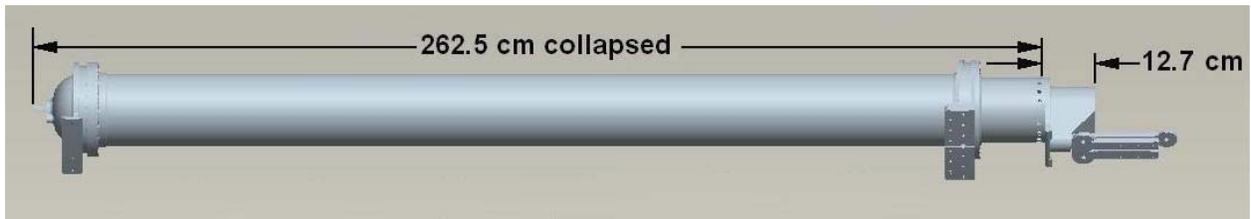
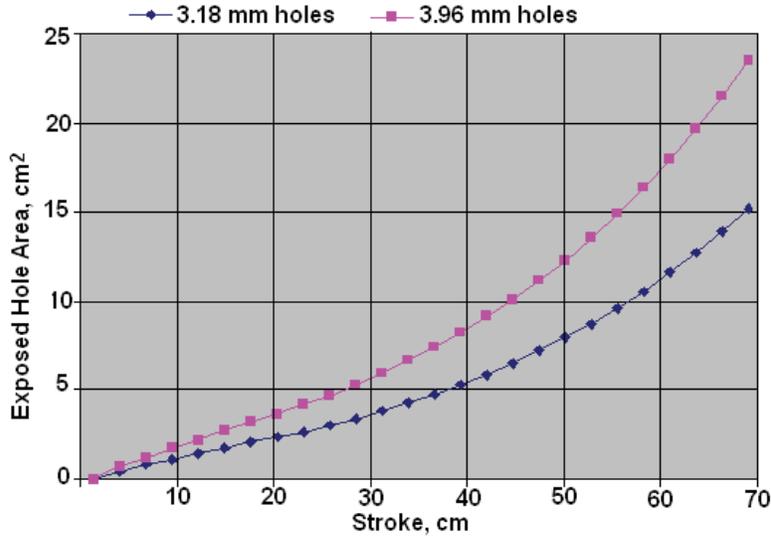


Figure 9 - Strut Rendering (Collapsed)



Figure 10 - Strut Rendering (Extended)



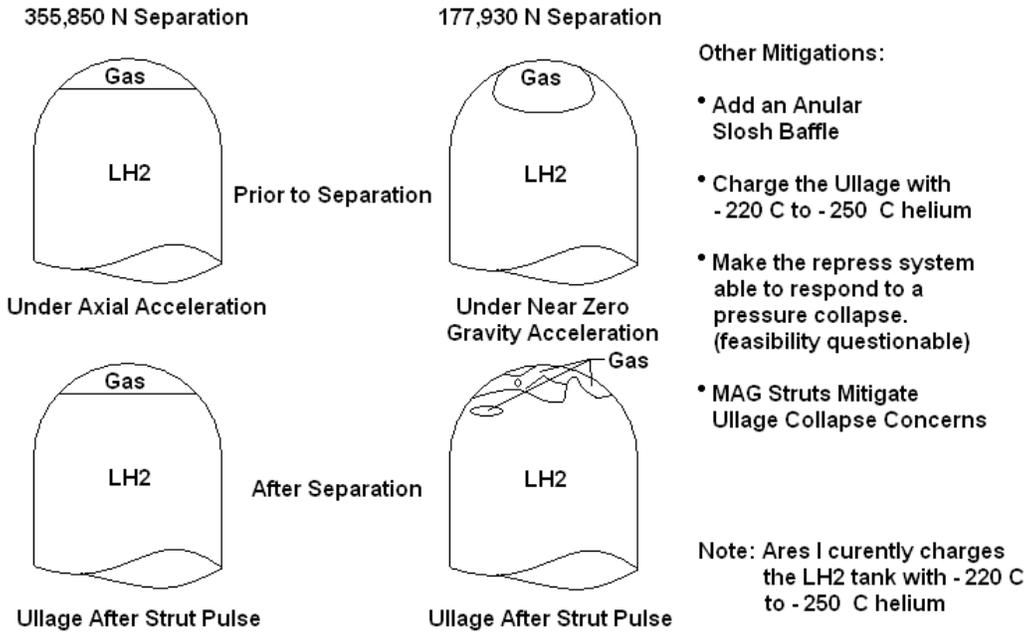
**Figure 11 – Exposed Hole Area for Two Candidate Hole-Patterns**

If the low pressure chamber is allowed to be at ambient pressure by providing a very small hole to the exterior of the strut, the strut can operate with only one pre-pressurized volume. This variation would make it possible to charge only one chamber prior to launch, eliminating some potential failure modes. A strut with a 9.208-cm diameter metering rod and with no pressure in the small chamber would provide slightly more initial separation force than the strut shown in Figure 7. This strut variant opens up the possibility of designing a hermetically sealed strut or other point design.

Since the desired thrust profile for the struts is based on requirements derived from a fluids analysis of the hydrogen tank pressure, having a strut capable of accommodating a range of force profiles is preferable. For a -147 degree C initial ullage gas charge temperature, an acceleration rate of change of 2.5g per second is acceptable. A higher axial rate of change may be acceptable with the currently proposed -220 to -250 degree C pre-charge gas. Table 2 shows the predicted effect of lowering pre-charge gas temperature on the make-up gas required to recover from an ullage collapse. A change out of metering rods could adapt a set of struts to revised ullage requirements. Sloshing risk increases as the axial acceleration of the rocket diminishes. Surface tension and vibration force the fluid in the tank up the tank walls as shown in Figure 12. Stage separation with 356 kN of residual thrust assures that the average axial acceleration never drops below .12g. This is enough acceleration to force the ullage gas to remain in a hemispherical shape bubble. The MAG Strut system further mitigates the risk of ullage collapse by limiting the axial acceleration rate of change.

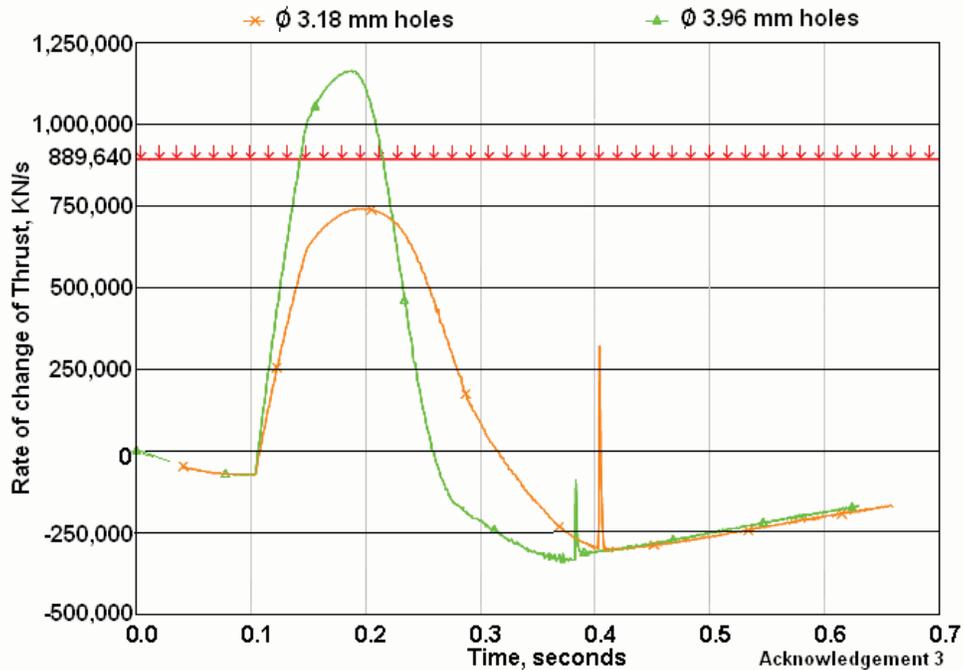
**Table 2 – Hydrogen Tank Recovery Gas Requirements**

Initial tanked He assumptions: T=-250 C; P=22,00 kpa				Supply assumption: Isentropic Blowdown P=6,895 kpa				
H2 pre-press temp	Mass for ullage recovery	Initial storage density	Final storage density	Delta density	Storage volume required	Bottle mass	Total loaded He mass	Total Mass
19 C	226.9 kg	192.38 kg/m <sup>3</sup>	144.81 kg/m <sup>3</sup>	47.58 kg/m <sup>3</sup>	.486 m <sup>2</sup>	1,390.0 kg	917.2 kg	3,642.2 kg
-181 C	115.7 kg	192.38 kg/m <sup>3</sup>	144.81 kg/m <sup>3</sup>	47.58 kg/m <sup>3</sup>	.248 m <sup>2</sup>	708.6 kg	467.5 kg	1,176.5 kg
-220 C	0.0	192.38 kg/m <sup>3</sup>	144.81 kg/m <sup>3</sup>	47.58 kg/m <sup>3</sup>	0.00	0.0	0.0	0.0
-250 C	0.0	192.38 kg/m <sup>3</sup>	144.81 kg/m <sup>3</sup>	47.58 kg/m <sup>3</sup>	0.00	0.0	0.0	0.0



**Figure 12 - Ullage Gas Collapse Mitigation Proposals**

Real fluid analytical tools show that the smaller holes produce a force-profile that does not exceed 8,896.4 kN per second level as shown in Figure 13. The force-profile has some irregularities that can be eliminated through further refinement of the hole-pattern. The force spike at .4 seconds indicates that a few more holes are needed in the last 7.62 cm of stroke for the 3.18-mm diameter holes. If the first row of holes were exposed after 1.27 cm of stroke rather than 2.54 cm of stroke, more energy could be recovered from the expanding gas. If a few less holes were exposed in the middle part of the metering rod, the rate of change peak could be lowered. For Ares I, the 3.18-mm diameter holes shown in this plot meet a 2.5 g/sec jerk requirement if the decay of the thrust of the SRB is considered.



**Figure 13 – Force Rate of Change Plot**

Figure 14 and Figure 15 show the force profile analytical results for the same two hole-patterns as a function of stroke as well as a function of time respectively.

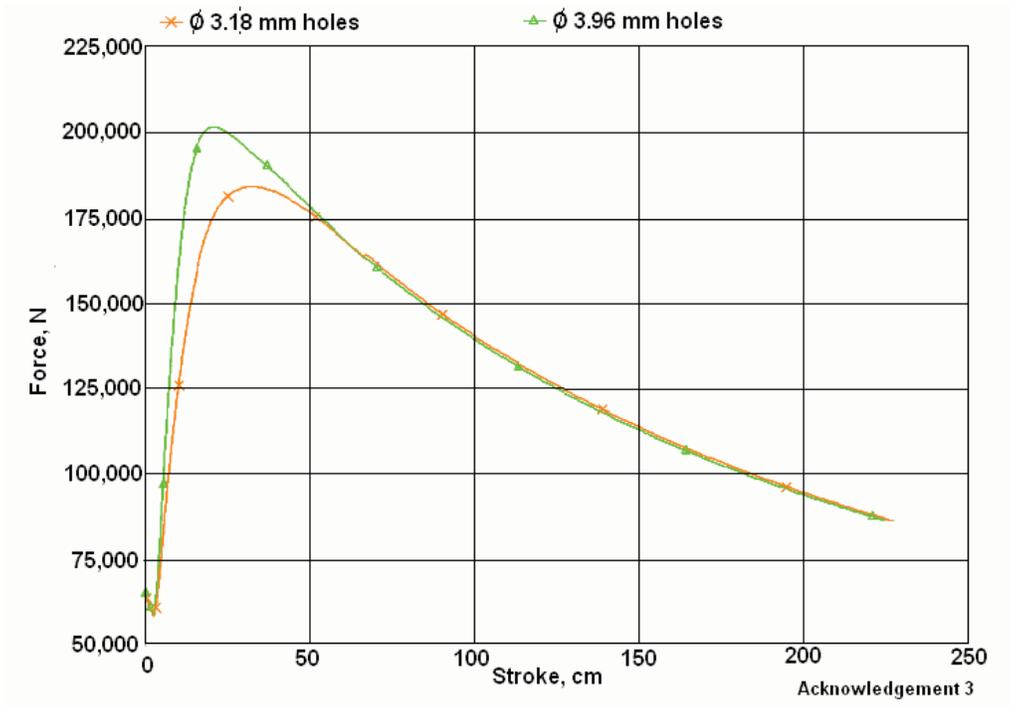


Figure 14 – Strut Force as a Function of Stroke

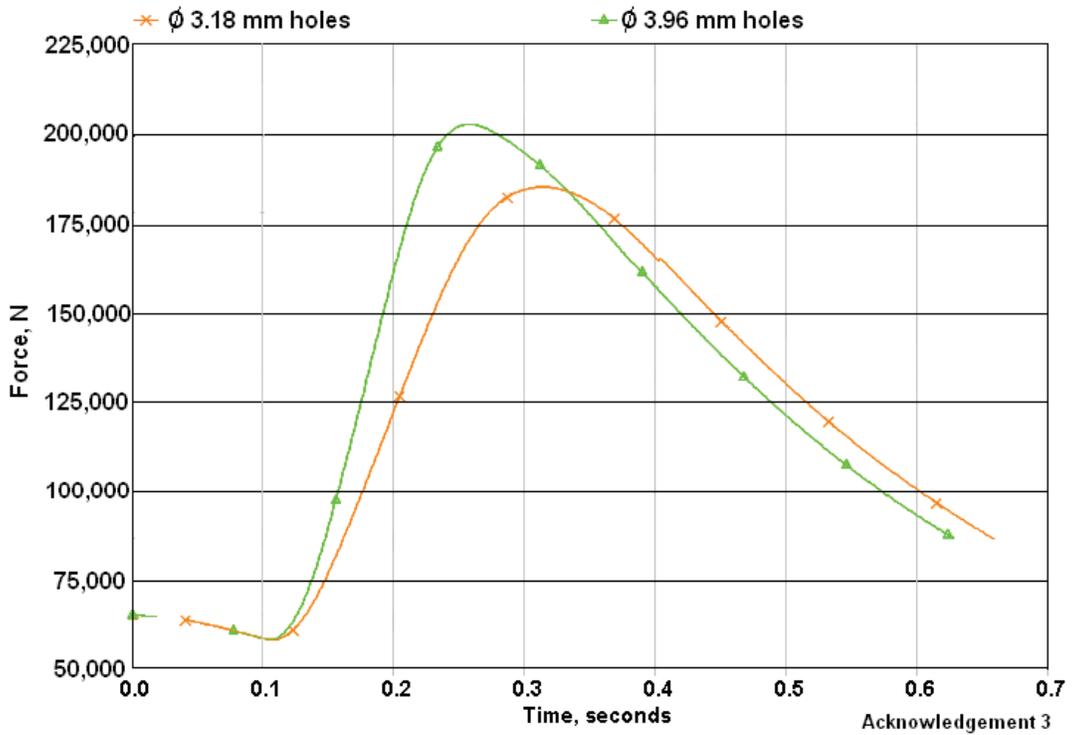


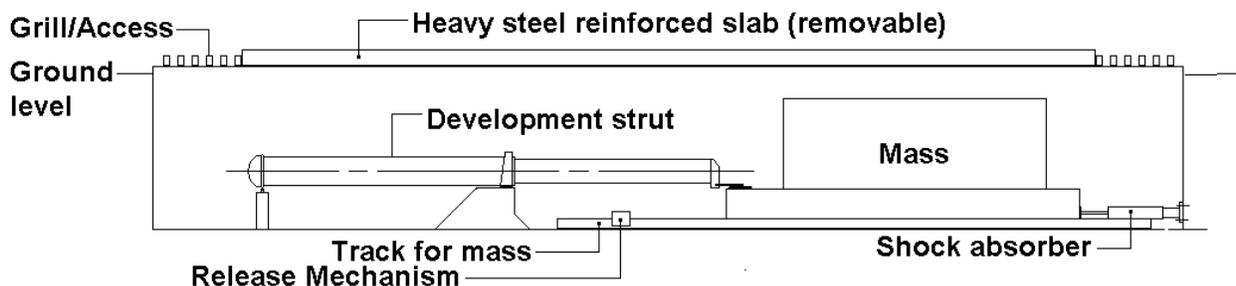
Figure 15 – Force as a Function of Time

## Development Program Goals and Objectives

Since gas struts have not been used for separation on a manned vehicle, development testing is needed to mitigate risk. The risk falls into three categories; performance related risk, reliability related risk, and programmatic risk. Programmatic risk is in some ways a sub-set of the stated technical risk because technical issues that arise in the strut development program could threaten the schedule for the launch of Ares I flight tests. This concern is one of the chief objections to this technology. A realistic approach to address this programmatic risk is to carry both BDMs and struts in the program until struts have demonstrated their capability. The struts are a bolt-on technology, using the existing hole patterns on the upper part of the Ares I interstage attach ring and a direct bolt through on the upper stage aft skirt, so they can be installed with little impact on other systems. The recurring cost of the struts will not likely increase because of the development program. Because of development testing, the qualification program cost for a strut separation system will be substantially reduced. Programmatic-risks are addressed in this paper by eliminating technical risk through a robust development test program.

### Resolving Performance Related Risk

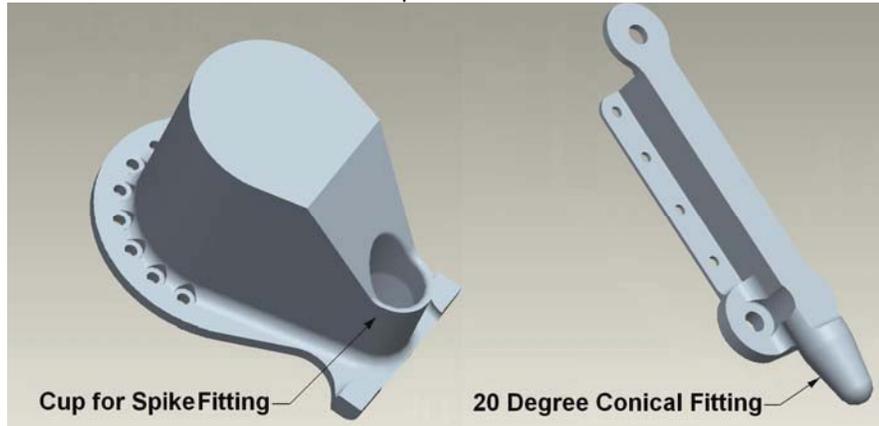
The metering function of the MAG Strut system is determined by the size and pattern of holes along the metering rod. Development testing is required to characterize the strut performance with different metering rods under different conditions that simulate nominal operations and potential failures. Mathematical models provide solid indications of the flow rates for struts with various metering rods; however, their accuracy is not good enough to use for qualification by analysis. The development testing would provide data that would validate the analytical flow models. The best way to establish the force vs. distance performance characteristics of the struts is to test them with several different metering rods moving different masses. A range of pressures could also be investigated to establish the performance characteristics of the struts under nominal and degraded performance scenarios. A relatively simple test set-up as shown in Figure 16 is required to perform the development testing. In this performance test, a mass of approximately 22,680 kg is released to be pushed by the strut. It will accelerate to approximately 6.17 meters per second and then disengage from the fitting mounted on the mass. After disengagement, the moving mass must be stopped by a snubber. Side forces acting against the fitting will be simulated by attaching a spring to the mass that applies a side force as it rolls down the track on its metal wheels. High-speed video recording will measure any twang or motion oscillations.



**Figure 16 – MAG Strut Performance Development Test Set-up**

The development program would seek to characterize the performance of the struts for several separate side force profiles that would represent a range of operational possibilities and off nominal load cases. The strut has Teflon slides on the piston and in the rod housing. If sufficient side force was present, a strut that was pressurized to less than 10% of the design pressure may bind at some point during the stroke of the strut. The mating conical interface of the rod fitting and the spike fitting on the upper stage is intended to gradually relieve side force as the struts disengage. If binding occurred on a partially charged strut, this side load relief action is intended to preclude disengagement of the strut from the fitting while pressurized. Figure 17 shows the strut rod fitting and the spike fitting that is mounted to the upper stage. Because no failure scenario has been identified that indicates that binding is a problem, development

testing will establish the amount of side loading required to cause the strut to bind such that the load relief action from the conical interfaces will not be adequate to relieve it.



**Figure 17 – Strut Fitting Aft Skirt Mounted Spike Fitting**

### **Resolving Reliability Related Concerns**

The safety of the struts must be demonstrated by test. The struts are designed to leak before burst; however, only testing can demonstrate this. If the leak before burst design is proven prior to qualification, the potential for a costly redesign and schedule slip is avoided. After completion of testing, one or more of the test struts would be subjected to extreme pressure until leakage or burst occurred. This burst test would be done with an oil or water charge to avoid the explosive hazards associated with gas.

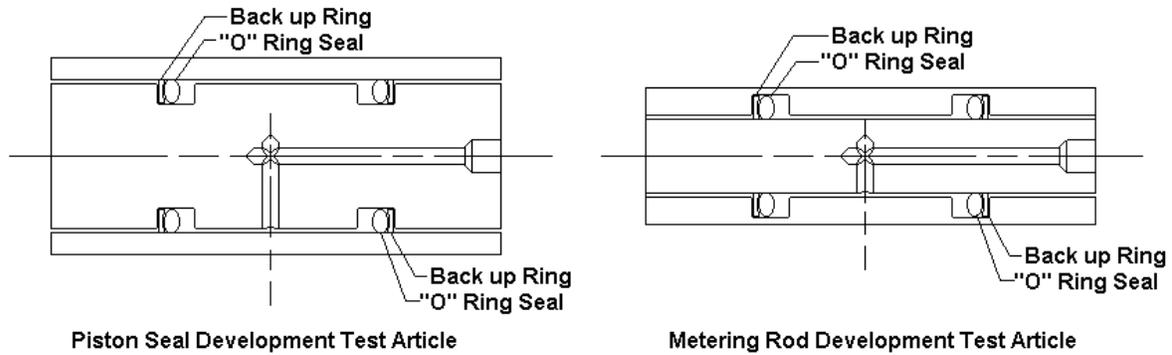
All elastomeric seals leak a minute amount of gas because of permeation of the seal material. The expected performance of each seal must be bounded in order to establish launch commit requirements and pad operations. Nominal leak rates of the seals could be established without assembly into the struts by using a test fixture as shown in Figure 18. Different elastomer compounds could be evaluated for gas permeability at the pressures used in the strut. With this data the struts could be pressurized taking into account the number of days before launch. The low pressure chamber would gain a very small amount of pressure due to seal permeation during pad operations but not enough to exceed its required operating range.

Pressurizing the large volume chamber while leaving the low volume chamber at ambient pressure as discussed in the performance section of this paper would also be an option to eliminate uncertainties about rate of leakage into the low pressure chamber from the high pressure chamber. Figure 18 shows potential test configurations for two different seals. Testing 50 seals of each type would provide a large enough sample size to characterize the nature of the seals under ambient conditions. Temperature extremes could also be evaluated by placing the small seal test fixture in a thermal chamber.

### **Analysis Needed Prior to System Testing**

An analysis of the integrated system would be required to establish the overall capability of the MAG Strut system to achieve separation under all potential operational scenarios. Initial analysis shows startling results with large positive clearance margins for the nozzle during separation. Revisiting this analysis is required prior to system testing to assure that an undiscovered disturbance force acting in the system will not cause the results to degrade.

To recover the first stage, the interstage with the extended struts must be separated from the first stage. However, no analysis has been done to establish the clearance between the first stage and the interstage. The struts extend about 2.44 meters from the interstage. Consequently, their presence will make it more difficult to gain adequate clearance between the first stage and the interstage after separation of the interstage from the first stage.



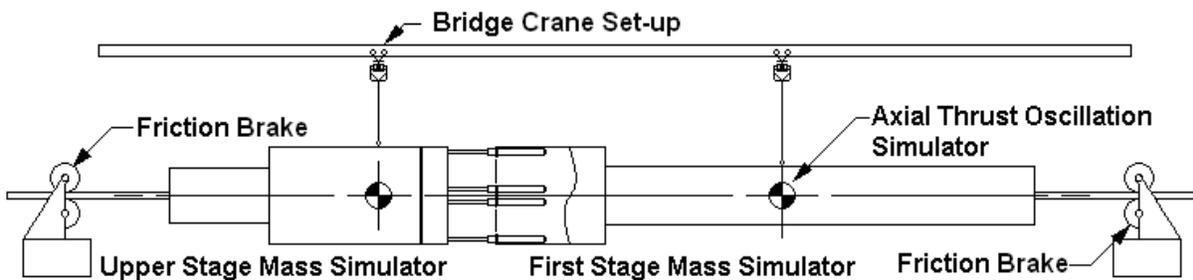
**Figure 18 - Proposed Seal Test Configurations**

Stress analysis of the second stage aft skirt interface with the spike fitting would provide a better understanding of the threat of buckling with a failed strut. If the high-pressure seal fails on a strut, the good strut will apply 68 kN of load to the structure while the failed strut will apply 236 kN of load. The safety factor is 1 for analyzing a failure case. However, the safety factor is 1.65 for buckling without a failure. Showing sufficient margin under all conditions is required prior to approving a final design configuration.

A stress analysis using finite element models of the struts themselves is required to assure adequate margin exists for all components. This analysis would allow for weight optimization of the strut prior to finalizing the design.

### Integrated System Testing

Testing the integrated system has the decisive advantage of establishing the validity of the analytical models used to evaluate separation dynamics. A close match between the development testing and the analytical models will make it possible to qualify the separation dynamics by analysis, avoiding an expensive flight test dedicated to qualifying the separation system. Actually simulating the flight conditions is not practical considering the cost and complexity of such a test set up. A test setup that is capable of simulating any flight condition in one plane could be used to demonstrate the system incrementally. Figure 19 shows a proposed test setup that would be capable of simulating all of the most relevant conditions in the horizontal plane.



**Figure 19- System demonstration test set up**

Different asymmetric strut cases could be combined with various simulated thrust conditions. The simulations could be accomplished by placing many support points at the center of gravity of each of the mass simulators. The brake rod would have a ball joint attachment at the center-of-gravity and the brake body would be free to rotate on a pivot arrangement. When the separation joint is activated, the brakes would simulate the effects of the SRB thrust and the relevant component of gravity acting on the vehicle. This set up would simulate the mass and the mass-moment-of-inertia of each of the stages. Thrust vector side loads would be simulated by springs acting between the rod coming from the brake and the end of the first stage. The brakes would also arrest the motion of the two bodies after separation was

demonstrated. The axial thrust oscillation could be simulated by 2 large asymmetric counter-rotating masses near the center of gravity of the first stage. Demonstrating the ability to prevent re-contact after initial separation is a critical part of any separation qualification program. If the thrust oscillation was to slam the two stages back together after initial separation, impact loads would be transmitted to the sensitive avionics boxes on the aft skirt. Also, the structure of the aft skirt near the contact location could fail locally and unpredictable separation dynamics would be present.

### **MAG Strut Qualification**

Qualifying the strut separation system will be a relatively quick, low cost program if a well-designed development test program is completed before hand. The separation dynamics will be qualified by analysis. The struts could be structurally qualified by analysis with the end fittings being considered qualified by test assuming that the qualification strut was pressurize with fluid that would generate sufficient force to subject the fitting to 1.4 times the limit load. Since the strut is designed with a safety factor of 2 for static pressure containments and a safety factor of 2.5 for dynamic pressure containment, the end fittings could be subjected to the limit loads without subjecting the struts to pressures that would yield the structure. The structure of the aft skirt and the interstage could be qualified by analysis. The development test would provide the data to validate the analytical models for both the struts and the structure. If some design changes were made to the flight struts that were not reflected in the development test articles, the qualification testing could be done using the same test set up used for development testing.

### **Conclusion**

The MAG Struts are the ideal separation system for Ares I. No other separation system has the capability to separate with 356 kN of residual thrust on the first stage. This capability increases the Ares I payload lift capability significantly over a BDM separation system. Secondly, the MAG Strut system is mounted internally minimizing aerodynamic drag. Finally the MAG Strut system pushes the first stage and the second stage apart increasing the momentum transfer between the stages.

The struts reduce the potential for ullage collapse in two ways. Separating with 356 kN of residual thrust mitigates the potential for ullage collapse because the liquid hydrogen does not have the tendency to climb the walls of the tank as is possible when operating at very low levels of acceleration. The MAG Strut limits the amount of acceleration the vehicle experience to less than 2.5 g per second decreasing the potential to agitate the liquid hydrogen.

The MAG Strut limits the amount of load applied to the aft skirt during ascent to 68 kN while they have the capability of stroking with a peak force 187 kN each.

The MAG Struts produce superior nozzle clearance under all conditions including one strut out cases. This means that the struts are inherently two-fault tolerant against pressure bleed down. The struts also greatly mitigate the effects of the SRB nozzle pointing accuracy and any other disturbances coming from another source because of the matching of the mass properties of the two separated stages.

Although struts have not been used on a manned vehicle, the struts can be brought up in design maturity in time to support later Ares I test launches assuming that the development test program is conducted concurrently with other Ares I development programs. Doing the development program facilitates the inclusion of the struts at a later date in the Ares program.

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