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Breadboard Development of the Advanced Inflatable Airlock System for EVA

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ABSTRACT

The Advanced Inflatable Airlock (AIA) System is currently being developed for the Space Launch Initiative (SLI). The objective of the AIA System is to greatly reduce the cost associated with performing extravehicular activity (EVA) from manned launch vehicles by reducing launch weight and volume from previous hard airlock systems such as the Space Shuttle and Space Station airlocks. The AIA System builds upon previous technology from the TransHab inflatable structures project, from Space Shuttle and Space Station Airlock systems, and from terrestrial flexible structures projects. The AIA system design is required to be versatile and capable of modification to fit any platform or vehicle needing EVA capability. During the basic phase of the program the AIA conceptual design and key features were developed to help meet the SLI program goals of reduced cost and program risk. Option 1 focused on development of key design features and testing of breadboard units to demonstrate effectiveness of the design solutions. This paper discusses the progress made during option 1 of the AIA program.

BACKGROUND

The basic phase of the program focused on requirements definition, material selection and conceptual design definition (See Reference). Key requirements were identified to set the boundary conditions for the materials research and final selection. Requirements focused on pressure containment, minimizing leakage, allowing multiple folding cycles, ability to withstand the environments of low earth orbit (LEO), and provide micrometeoroid and orbital debris (MMOD) protection. Figure 1 shows the Mock-up/test article fabricated for the basic phase.

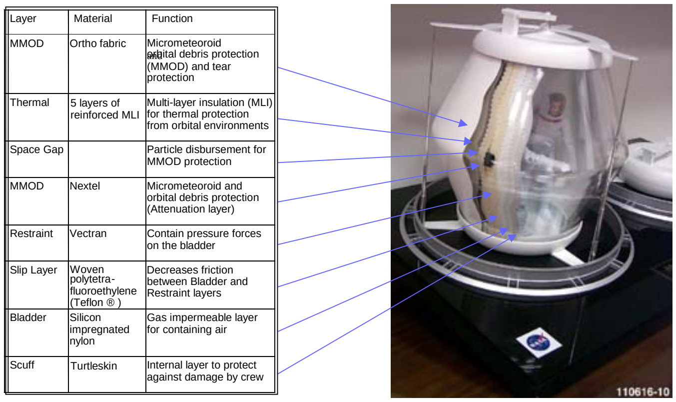
The materials selected for the AIA fabric layers were based on requirements to be flexible, to stow in a minimum volume, possess high strength to handle the operating pressures, withstand the extreme on-orbit environment, provide micrometeoroid/orbital debris (MMOD) protection for the crew and equipment, plus withstand many deploy and retract cycles without degradation of the material properties. The approach to support these requirements was to use multiple layers. Each layer provides specific capability to the fabric system. The layers, materials and function are shown in Figure 2.

Deployed **Stowed**

Figure 1. Basic Phase Test Article

Option 1 focused on development of key design features for demonstrating the structural stability of fabric materials. Testing of materials and breadboard units was performed in the first quarter of 2003 to demonstrate effectiveness of the design solutions. Figure 3 shows the general arrangement of the pressure integrity test article fabricated for option 1. The key objective of the pressure integrity test is to prove the restraint layer and restraint-to-rim design meets the minimum factor of safety of four.

To minimize cost of the pressure integrity test article, only elements key to maintaining pressure integrity were included.



Layer	Material	Function
MMOD	Ortho fabric	Micrometeoroid and orbital debris protection (MMOD) and tear protection
Thermal	5 layers of reinforced MLI	Multi-layer insulation (MLI) for thermal protection from orbital environments
Space Gap		Particle disbursement for MMOD protection
MMOD	Nextel	Micrometeoroid and orbital debris protection (Attenuation layer)
Restraint	Vectran	Contain pressure forces on the bladder
Slip Layer	Woven polytetra-fluoroethylene (Teflon ®)	Decreases friction between Bladder and Restraint layers
Bladder	Silicon impregnated nylon	Gas impermeable layer for containing air
Scuff	Turtleskin	Internal layer to protect against damage by crew

Figure 2. AIA Material Lay-up

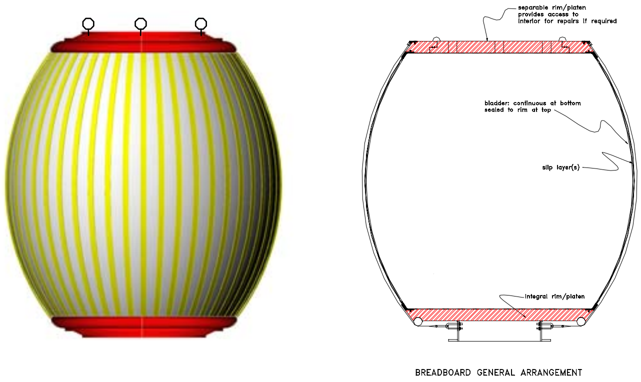


Figure 3. AIA Breadboard Sketches

The ultimate goal of the Advanced Inflatable Airlock (AIA) program is to develop a full-scale prototype AIA system that will demonstrate the materials, structures, inflation and deflation, and life cycle characteristics at a technology readiness level (TRL) of 6.

OPTION 1 PROGRAM OVERVIEW

During option 1, a full-scale breadboard unit of the advanced inflatable airlock was developed and tested with the following tasks accomplished:

Development of restraint layer braid and bladder fabrics

Development of restraint layer to platen interface

Development of the pressurization and depressurization system for airlock and various subsystems

Development of the deployment, retraction and latching subsystems

Materials testing of the restraint and bladder fabrics

Thermal modeling and analysis of the AIA

Testing of the breadboard in a 1-g relevant environment

The general layout of the design consists of two platens (lower and upper) with the restraint and bladder layers attached to the platens (the bladder is only attached to the upper platen). The function of the bladder layer is to provide containment of the air while the restraint layer/belt system provides the load bearing capability during pressurization.

The breadboard test article consists of a braided restraint layer, a rim to attach the restraint to the end caps, and low-fidelity bladder. The general design is based on optimizing the braid for stability and ease of manufacture. The braid angle is large and is determined by the requirement for a tight, high coverage braid rather than structural equilibrium. This results in an imbalance of hoop and longitudinal stress. To overcome this imbalance, a set of belts is added to carry the longitudinal stress, while the braid carries the hoop stress. The belts are terminated on the rim with commercial rigging screws and shackles. This is reliable and allows for adjustment during assembly. The restraint is attached to the rigging rings using polyurethane adhesive to hold the restraint in position when the unit is unpressurized. The upper platen has a hatch with an O-ring interface between the hatch and platen. The platen design was not optimized for weight, but for ease of manufacturing.

BRAID CANDIDATE SELECTION

Six braiding schemes were considered for the AIA option 1 breadboard. A set of criteria was established for downselecting. The criteria take into account the results of coverage trials performed by A&P technologies. The geometry of the coverage trial was developed by FTL. The results of the trails demonstrated the need to select a design that could be manufactured by an existing braiding process.

The six braiding schemes evaluated during option 1 were:

Single layer: axials and wide-angle braids

Multiple layers: axial and wide-angle braids

Multiple layers: isotensoid

Single layer: isotensoid

Single layer: isotensoid with 90-deg threads

Double layer: inner isotensoid, outer wide-angle braid axial

Due to schedule and budgetary constraints, an interim design was adapted. The wide-angle braid with belts was chosen and is based on optimizing the braid for stability and ease of manufacture. The design is not an optimal flight article design, but rather a proof that a fabric airlock can be designed that will meet the performance requirements.

For an eventual flight article, it would be more reliable and more efficient, if the technology could be extended to allow the fiber orientations of both these layers to be incorporated into one single layer, as a single layer isotensoid with braids only.

RESTRAINT LAYER ANALYSIS

Finite modeling of the restraint layer and the axial belts was performed to determine the predicted hoop stress on the braided layer and the axial stresses on the belts. The equilibrium shape of this design, and its associated stress, were previously calculated by direct solutions methods. The study verified this solution and confirmed that the stresses were within the limits of the vectran restraint layer.

BRAID COATING AND ADHESION

To maintain braid stability throughout the breadboard testing phase, it was determined that two different coatings would be required: one joining the braid to the rim, and one for the free braid area between the rims. Clemson and FTL initiated research and trial experimentation to identify the most suitable coating material and technology. Elementary tests were performed to assess the strength and suitability of the coatings. These tests showed ample capacity in excess of the design requirements.

PRESSURIZATION SYSTEMS

The preliminary design for the prototype breadboard pressurization system consists of five subassemblies (Figure 4):

Internal volume pressurization valve assembly to control inflation of airlock to a maximum pressure of 15.2 psia at a flow rate of 0.15 lb/sec.

Internal volume depressurization valve assembly to control deflation of airlock at a maximum flow rate of 0.12 lb/sec. The system is designed to use a modulating depressurization valve, and a butterfly or similar type valve.

High pressure (HP) air beam valve assembly to provide pressure for controlling internal volume of airlock and to depressurize HP air beams. The maximum pressure is designed to be 104.7 psia at a maximum flow rate of 0.16 lb/sec. A pressure source of 200 to 1500 psia is assumed.

A low-pressure (LP) air beam valve assembly to provide pressure for controlling external volume of airlock and to depressurize LP air beams. The maximum pressure is designed to be 19.7 psia at a flow rate of 0.03 lb/sec.

Pneumatic muscle valve assembly to control folding of fabrics during retraction and stowage of airlock. The maximum design pressure of the pneumatic muscles is designed to be 87 psia at a flow rate of 0.01lb/sec.

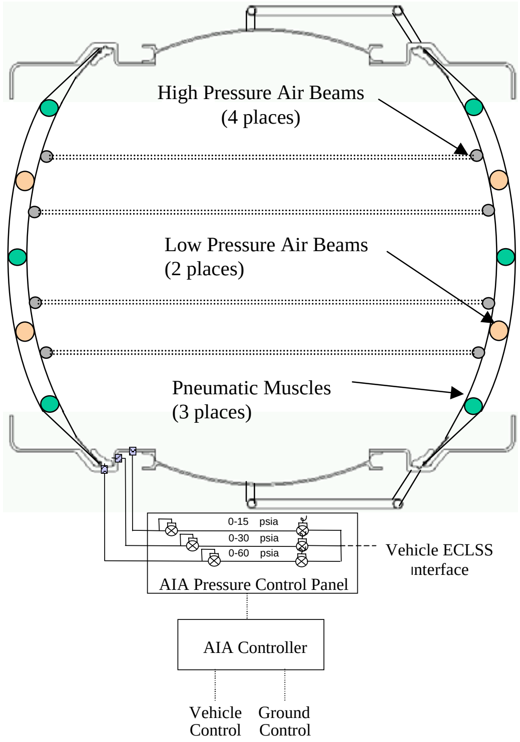


Figure 4. Preliminary Prototype Pressurization Schematic

The pressurization system for the two-cycle demonstration unit uses off the shelf hardware and consists of the:

Blower for inflation of airlock to 14.8 psia

Manual butterfly valve for controlled deflation of airlock

Low-pressure air beam valve system built with off-the-shelf solenoid shutoff valves, relief valve, and pressure regulator. The design pressure of the air beams is 15.2 to 15.7 psia.

Pneumatic muscle valve system build with off-the-shelf solenoid shutoff valves, relief valve, and pressure regulator. The pneumatic muscles are designed to operate at 45 psia, max.

DEPLOYMENT/RETRACTION AND LATCHING SYSTEMS

The telescoping design was based on using four telescoping arm assemblies to deploy and retract the airlock during pre-EVA and post-EVA (Figures 5 and 6). The two extending segment telescoping assemblies consist of four ball screw assemblies driven by individual linear actuators. Each telescoping assembly has a 0.2-in. lead and 237 rpm, provided 8-foot extension in 2.5 min. The four actuators provide two triangular sets to maximize lateral stability during retraction. The lower mount surface provides 3 degrees of freedom (X, Y, and rotation about the Z axis). The upper mount surface provides 2 degrees of freedom (X & Y motion only, rotation). Due to funding restraints in option 1, the telescoping assembly size and weight could not be optimized. The latching system used in the mockup demonstrated electromechanical actuation. The two latching designs used for the mockup accommodate a wooden support structure. The latching design provides 1 in. of vertical travel and 187 degrees of rotation within 1 to 2 seconds (Figure 7).

Figure 5. Deployment/Retraction Assembly

Figure 6. Deployment/Retraction Assembly (Side View)

Figure 7. Latching System

MATERIALS AND TESTING

The fabrics used in this option were associated with only the restraint and bladder layers. The majority of the development effort focused on the restraint layer. Some effort was put forth on the bladder layer, but that effort concentrated on the bladder coating cure temperatures and the effects on the base materials. Simple slip layers were fabricated out of parachute material to provide protection of the bladder layer during assembly and test. Several tests were performed at the fabric level to verify the properties of the materials.

BLADDER LAYER – CURE TEMPERATURE

The bladder layer consists of tightly woven, high-tenacity filament nylon plain weave fabric with heavy silicon coating. The coating for the breadboard will be cured at 400°F to optimize performance versus outgassing characteristics. The construction procedure consists of CNC cutting the bladder gores to shape, sewing the gores together with a lapped seam with multiple needles, and taping the seams with a silicone sealant.

BLADDER LAYER - POROSITY TESTING

An oxygen transmission rate test was performed on a sample of the fabric to determine the porosity. The test was conducted in accordance with ASTM D 1434-V. Prior to the actual testing, the specimen was place in a desiccator over $CaCl_2$ for not less that 48 hours. The results of the test indicated an average permeance of 1.40E-12 and an average permeability of 2.72E-15.

BIAXIAL TEST OF THE RESTRAINT LAYER

Material testing of the Vectran restraint layer was performed to determine compensation or shrinkage factors to be applied to the cutting patterns to account for expected stretch due to prestressing and creep caused by service loads. The test results also provide E values, which can be used in load analyses to predict maximum fabric deflections.

The test is considered to be a large-scale biaxial test with minimum specimen size of 40 x 40 in. The sample is usually cut in cruciform shape with each leg being 14 3/4 by 45 in. long. The force is applied with 2 1/2-in. actuators with 1-in. shafts. The maximum forces applied are about 800 lb low scale and 6000 lb high scale. Most fabric compensation tests are run on the low scale. The restraint layer material was tested in the hoop and fill direction.

The results of the test indicated that the fabric specimen experienced unsettling creaks and groans at about 870 psi, thus 800 psia was used to perform all six cycles.

FREE BRAID COATING TESTS

A formulation of natural latex was sprayed onto uncoated braided vectran layers. Analysis indicated that a bond strength of 1 oz per ribbon would be sufficient to meet the needs of the design. Testing results of the bond strength at the crossings and static friction at the crossings indicated that the latex provided sufficient bond strength.

THERMAL ANALYSIS

Thermal analysis was performed on the AIA using a modeling program currently used in the Space Shuttle program, TRASYS, which was supplied by NASA. This is a transient model utilizing LEO conditions. The analysis predicted the worst case temperature extremes that the AIA materials will subjected to on-orbit.

When deployed, the inflatable airlock is exposed to the full orbital environment of LEO. This environment is a dynamic thermal environment in which the lead loads vary as functions of time, orbit, and surrounding bodies. At the present time, the orbital mission of the airlock is not specified.

The scope of this preliminary study is to determine reasonable temperature levels that can be expected for anticipated airlock operations and to highlight any thermal issues. To facilitate the analysis several assumptions were necessary. The operating envelope is similar to the environment of the existing Space Shuttle. The surface characteristics of future vehicles are similar to the Space Shuttle. Analysis was limited to the deployed condition only. Pre-launch, launch, and stored flight operation were ignored. During deployment, where the hatch is open, the airlock would be positioned between the earth and the space vehicle to protect astronauts and the airlock from meteors.

The thermal study consisted of four main tasks:

(a) Determine an environment range for orbital operations and narrow the range to the worst parameters for both hot and cold operation. The initial study would use a very simple thermal model that could be run quickly for a large number of cases.

(b) Generate a detailed thermal model for the airlock assembly, including the fabric sidewalls, hatch, internal heat loads, and any potentially critical areas of the airlock.

(c) Integrate the thermal model into the orbital environment, including a coarse model of the space vehicle. This task would include orientation of the airlock and position of the space vehicle with respect to the airlock.

(d) Analyze a range of orbital scenarios to determine critical airlock temperatures and report the findings. These analyses will extend the study begun under Task 1, but will be concentrated around the worst-case range of conditions indicated by the initial study.

Honeywell worked with HarvardThermal consulting to perform the thermal modeling necessary to conduct the analysis. HarvardThermal consulting was chosen because they used The TAS thermal analysis software and Honeywell was already familiar with the software, which offered a shorter learning curve.

The thermal analysis of the AIA was performed at the worst-case orbit for both maximum hot and minimum cold temperatures. To determine the worst-case orbit, a thermal analysis system (TAS) model of a sphere was constructed and exercised through various combinations of orbit positions. The worst case occurred with the sun declination set at -23.4, 20.0, 0.0, -20.0, and -23.4 degrees. The maximum temperature was 222°F, and the minimum temperature reached -123°F.

TWO-CYCLE DEMONSTRATION UNIT

The basic phase test article was upgraded to more closely represent the current AIA design configuration. The deployment/retraction, latching and pressurization systems, discussed previously, were incorporated in the basic phase test article. The unit was intended to demonstrate the operational sequencing and the full two cycles of operation.

The pressurization and latching systems were fully functional and integrated in the unit. However, the deployment/retraction system did not perform as expected. The problem was traced to binding of the bushings located between the actuator motors and the telescoping ball screws. The interference was binding the mechanism, which would not allow the ball screws to extend. Once isolated, the bushing, was machined smaller to increase the clearances at the interface between the actuator and the ball screws. Complete disassembly and rework of the bushings was not possible within the budget of option 1, therefore the two-cycle demonstration was halted at this point.

15% SCALE MODEL TEST

A 15 percent scale model of the airlock was fabricated, which was composed of a scaled sample of the restraint layer, a mockup of the bladder layer, and a mockup of the platens. The full-scale restraint layer is braided onto a one-piece mandrel. The purpose of the test was to study stability of the vectran restraint layer, tendency of the design to form aneurysms, study the design of the girth straps, and characterize the shape of the pressurized 15 percent model.

The test consisted of the following major sections:

Pretest (low pressure test.) the purpose of this test is to optimize the belt configuration length. The test was conducted at 15.0 psig. See Figure 8.

Belt stability test. The purpose of this test was to experiment and observe the behavior of the restraint layer, belts, and end caps under various conditions simulating displaced belts. Overall, displaced belts did not self-correct, but the displacement had no effect on restraint performance.

Figure 8. 15% Scale Model During Belt Adjustment

Fabric level stability test. The purpose of this test is to determine the requirements for size detection of braid separation or self repair of defects and to develop preflight inspection criteria for further phase development. See Figure 9.

Figure 9. 15% Scale Model During Stability Test

Ribbon stability test. The purpose of this test is to determine the self reparability of ribbons. A ribbon is separated, the test unit is pressurized, and an inspection is performed to characterize the behavior of the fabric.

Hydrostatic pressure test. The purpose of this test is to prove the rim seal design and fabric strength. The 15 percent model was tested to 120 psig, and a visual inspection of the fabric and belts was conducted after the pressure was reduced (Figure 10). No anomalies were observed after successful pressurization to 120 psig.

FULL-SCALE BREADBOARD UNIT

A high-pressure test was conducted on the full-scale breadboard to 58.8 psig to prove that the restraint design has a minimum factor of safety of four. The general design is based on optimizing the braid for stability and ease of manufacture. The braid angle is large and is determined by the requirement for a tight, high coverage braid rather than structural equilibrium. The general layout of the design consists of two platens (lower and upper) with the restraint and bladder layers attached to the platens (the bladder is only attached to the upper platen). The function of the bladder layer is to provide containment of the air while the restraint layer provides support in the hoop direction.

FULL SCALE BREADBOARD UNIT ASSEMBLY

The key design features of the pressure integrity test article:

High-fidelity rim seal design

High-fidelity braided restraint

Low-fidelity pressure containment platen

Low-fidelity bladder

The various fabric layers, platen, and straps were all shipped to Honeywell Torrance and assembled in the space laboratory in preparation for pressure testing at NTS laboratories.

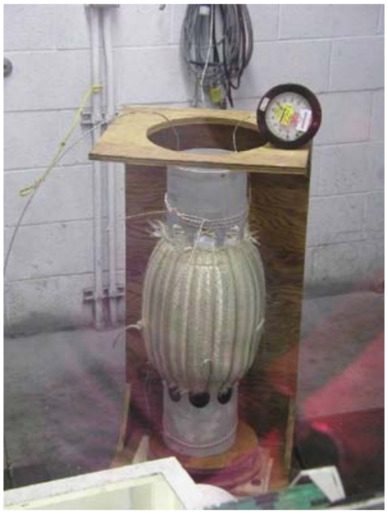


Figure 10. 15% Scale Model – 120-psig Test

The restraint layer, along with the mandrel was delivered to Torrance from A & P technologies. See Figure 9. The internal mandrel was designed to be removable, thus the first step in the assembly process was to extract the mandrel one piece at a time, see Figures 11 through 13. The next in the restraint layer preparation was the removal of the excess runout material. See Figure 14.

The next step is the assembly of the top platen to the fabric assembly. The platen is shown in Figure 14. After the top and bottom platens had been mated to the top and bottom rigging rings, the next major assembly step is the installation of the bladder layer and slip layer. The bladder layer is attached to the top platen via fasteners and silicon sealant. Figure 15 shows the orange slip layer and bladder layers. Once the bladder is installed, the next major assembly step is the installation of the 48 belts. The 48 vectran belts are mated to the top and bottom platen via shackles. See Figures 16 and 17. The last step in the assembly process is the installation of the hatch in the platen and preparation for shipment.

Figure 11. Full-Scale Restraint Layer with Mandrel

Figure 12. Restraint Layer: Mandrel with Runout Ring

Removed

Figure 13. Removal of Mandrel Components

Figure 14. Top Platen

Figure 15. Slip Layer and Bladder Layer

Figure 16. Breadboard with Vectran Belts

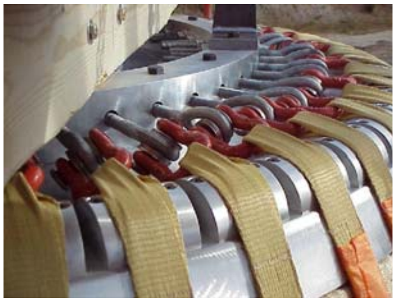


Figure 17. Vectran Belts Connection to Platen

FULL SCALE BREADBOARD UNIT TEST

The airlock test article was transported to NTS laboratories for the high-pressure test. The unit was installed onto the test site and was supported by the support frame when not inflated (Figure 18).

A high-pressure test was conducted on the full-scale breadboard to the 58.8-psig level. The test verified the design of the restraint layer, the bladder coating, and the rim-to-restraint-layer design. The major steps of the test are as follows:

The unit was initially pressurized to 10 psia, pressure was held at this pressure for 5 minutes, then pressure is relieved to 5 psia. An inspection of the belts and restraint layer was performed. Adjustment of the belts was deemed necessary to shift more of the longitudinal load to the belts.

Figure 18. Airlock Supported on A Frame

Once the adjustments were made to the belts, the unit is incrementally pressurized to 58.8 psig. When the pressure reaches 58.8 psig, the pressure is maintained for 5 minutes and then relieved back to 10 psig for a visual inspection and again relieved to 0 psig for a visual inspection. See Figures 19 and 20.

The post-test visual inspection found no major anomalies of the restraint layer, vectran belts, retaining screws and platens. Some unraveling of the stitching of the vectran belts was noted, but no failure occurred.

Figure 19. Post Test Inspection 1

Figure 20. Post Test Inspection 2

CONCLUSION

The advanced inflatable airlock concept enhances cargo and crew transfer vehicle capability for the 2nd generation RLV by minimizing weight and volume required to support EVA. The high-pressure test was successfully completed on April 2003, demonstrating a minimum factor of safety of four and the feasibility of a lightweight textile airlock technology. The technology is characterized as a multi-layer system in which the layers are free to slip over one another. The AIA remains relevant to the SLI goals for reducing cost for access to space, as well as increasing safety to crew.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIA – Advance Inflatable Airlock

EMU – Extravehicular Mobility Unit

EVA – Extravehicular Activity

LEO – Low Earth Orbit

MLI – Multi-Layer Insulation

MMOD – Micrometeoroid and Orbital Debris

NASA – National Aeronautics and Space Administration

PSIA – Pounds Per Square Inch, Absolute

RLV – Reusable Launch Vehicle

SLI – Space Launch Initiative

SSF – Space Station Freedom

TAS – Thermal Analysis System

TRASYS – Thermal Radiation System

TRL – Technology Readiness Level