TRL Assessment of Solar Sail Technology Development Following the 20-Meter System Ground Demonstrator Hardware Testing

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Abstract

The NASA In-Space Propulsion Technology (ISPT) Projects Office sponsored two separate, independent solar sail system design and development demonstration activities during 2002-2005. ATK Space Systems of Goleta, CA was the prime contractor for one development team and L'Garde, Inc. of Tustin, CA was the prime contractor for the other development team. The goal of these activities was to advance the technology readiness level (TRL) of solar sail propulsion from 3 towards 6 by the year 2006. Component and subsystem fabrication and testing were completed successfully, including the ground deployment of 10-meter and 20-meter demonstration hardware systems under vacuum conditions. The deployment and structural testing of the 20-meter solar sail systems was conducted in the 30 meter diameter Space Power Facility thermal-vacuum chamber at NASA Glenn Plum Brook in April though August, 2005. This paper will present the results of the TRL assessment following the solar sail technology development activities associated with the design, development, analysis and testing of the 20-meter system ground demonstrators.

1.0 Introduction

NASA's ISPT goal is the advancement of key transportation technologies that will enable or enhance future robotic science and deep space exploration missions. Through a Research Opportunities in Space Science (ROSS) NASA Research Announcements (NRA) announcement in 2002 contracts for solar sail technology development were awarded to a team headed by L'Garde Inc., and another team lead by ATK Space Systems. The contracts were awarded to independently design, develop and test system ground demonstrator hardware. 10-meter quadrants/systems were fabricated and tested in 2004. Higher fidelity 20-meter systems were produced and tested in 2005 during the third phase of the contract. The L'Garde team included Ball Aerospace (system integration and ACS design/test), JPL (systems analysis), and LaRC (modeling, structural testing). The ATK team included SRS Technologies (now ManTech, Inc. - sail provider), LaRC (modeling, structural testing), Arizona State University and Princeton Satellite Systems (attitude control system modeling, design) and MSFC for materials testing.

NASA uses the Technology Readiness Level (TRL)[1] as one method of judging the maturity of a particular technology and its readiness for infusion into a space application. Higher TRLs are representative of increases in the technology maturity, ranging from initial concept development to flight quality hardware development. TRLs are generally categorized into technology conceptualization and analytical demonstration (Levels 1-2), laboratory technology demonstration, component and analytical model validation (Levels 3-4), and component, subsystem and system demonstrations in a relevant environment (Level 5-6). An initial TRL assessment[2] was conducted in 2004 to provide a measure of the state of solar sail technology following the 10-meter system tests. This paper will update the TRL assessment to include the 20-meter systems.

The L'Garde design[3] utilized their patented inflation deployed, sub-Tg rigidized boom with a Kevlar line sun-side truss stiffener system. The sails were constructed from 2 micron aluminum coated Mylar with an integral ripstop feature. The sails transferred loads to the beams through a novel "stripped net" architecture that resulted in a lightweight beam design and low tensile stresses in the sail membrane. The L'Garde design has articulated tip vanes for attitude control. Rotation of the tip vane offsets the location of the center of radiation pressure from the center of mass and induces torques to provide roll, pitch and yaw control. Figure 1 is a photograph of the L'Garde 10 meter system after a successful ambient

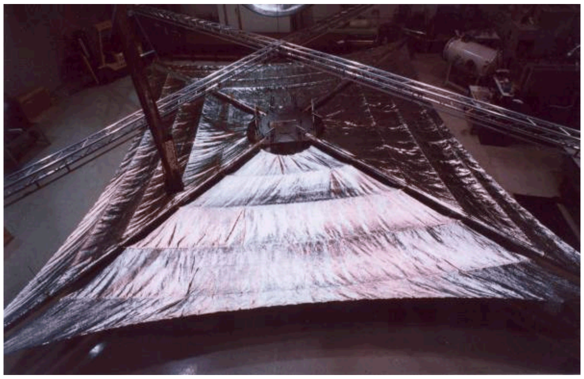


Figure 1. L'Garde 10M System

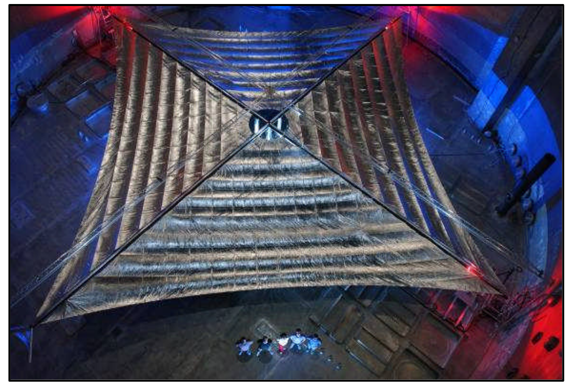


Figure 2. L'Garde 20M System

deployment. Figure 2 is the L'Garde 20 meter system at the Plum Brook 100 ft diameter vacuum chamber. The tip vane is visible in the lower left corner of the photograph.

The ATK team design[4] utilized their "CoilABLE" mast technology, with its high packing factor and high strength to weight ratio for their primary structural mast elements. The ATK 10-meter quadrant in the LaRC vacuum chamber in shown in Figure 3, and the 20-meter system in the Plum Brook vacuum chamber is shown in Figure 4. The sails were fabricated by SRS Technologies from 2.5 micron aluminum coated CP1, with a 3-point (mast tips and central structural) attachment configuration. The sails were tensioned to provide a nearly flat sail topography. Attitude control is provided by two translating ballast masses internal to the mast and mast tip rotating spreader bars. The ballast masses can translate the entire length of the masts to offset the system center of mass from the center of pressure and provide pitch and yaw attitude control. The mast tip spreader bars can be rotated to provide a "pinwheel" effect roll control for the sail. Micro-pulsed plasma thrusters were also specified in the ATK design for secondary/ backup attitude control.

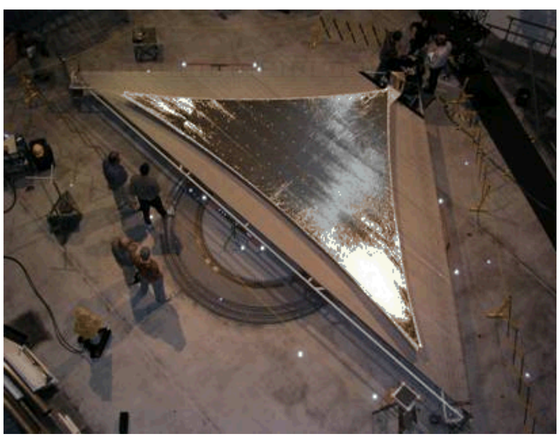


Figure 3. ATK 10M System

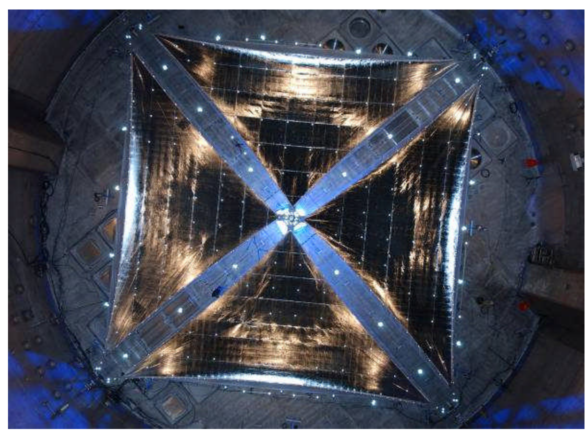


Figure 4. ATK 20M System

2.0 20-meter System Design Modifications

In addition to the increase in size from 10 meters to 20 meters, numerous design refinements and improvements were applied by both sail development teams during Phase 3. Components of the L'Garde inflatable booms were improved, including the selection of an alternate material for the boom tip mandrel that improved deployment reliability and addressed leak issues (see Figure 5). Analysis, design and fabrication of an articulated tip vane were included in the L'Garde 20-meter system and are detailed in Figure 6. Line management techniques for the Kevlar truss structure were advanced, including improvements to the truss system spreader bar web configuration, resulting in a more uniform beam deployment sequence. Boom insulation changes were also made after the 10 meter testing

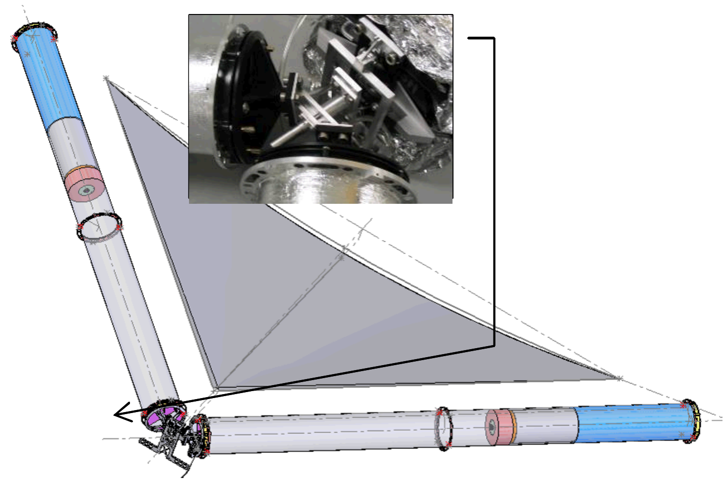
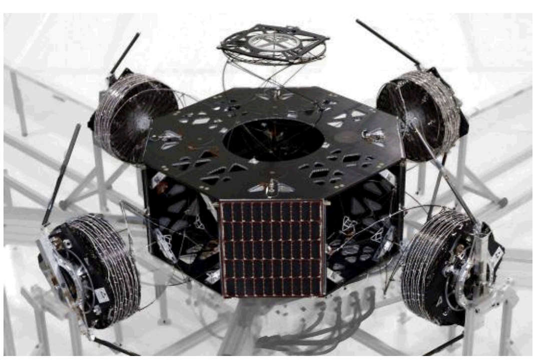


Figure 5. Boom Tip Mandrel Improvement **Figure 6. Tip Vane and Tip Vane Mechanism**

ATK also implemented design improvements based on "lessons learned" from their 10 meter quadrant system design and testing in 2004 (Figures 7 and 8). Significant changes were required to implement their attitude control system. A higher fidelity central structure was designed and fabricated to contain the mast deployment mechanisms and ballast mass drive systems. A spreader bar rotation drive mechanism was added to the ends of each mast, including a negator spring system to insure constant tension in the sails during all operational modes. The sail membrane design was refined to increase the total area of the sail, as well as improve the sail corner to halyard connection. Sail rip-stop features were added to the final sail quadrant fabricated for the 20 meter testing. Sail folding and rolling techniques were refined and the techniques for proper deployment sequencing of the sail were improved to provide for a smoother sail deployment and reduce the risk of rips and tears during deployment. Minor structural refinements were made to the mast corner fittings to increase the reliability of the batten-to-corner group structural attachment.

3.0 20 Meter System Testing

Both teams began by designing, fabricating and testing components and subsystems in preparation for full 20-meter system integration and testing. Detailed computational models were created by both teams in order to develop predictions of how each system would perform during performance testing. Detailed test plans and test procedures as well as success and pass/fail criteria were prepared and approved by the ISPT office prior to the start of testing.



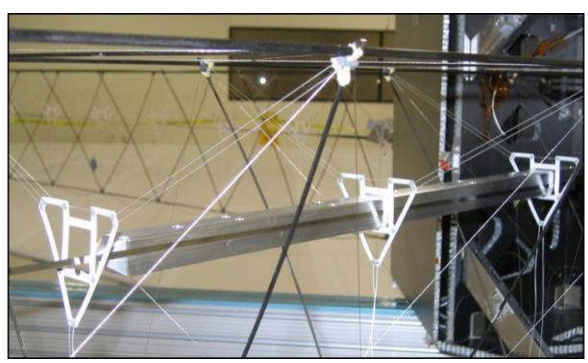


Figure 7. Central Structure and Attitude Control System Design Changes

Figure 8. 20-Meter Sail Design Improvements (Ripstop and Sail Corner modifications)

Functional tests were performed to demonstration form, fit and function. Ambient deployments were performed prior to the high vacuum testing at the GRC Plum Brook Space Power Facility. Since these sails represent the largest ground systems that will be deployed and tested in the world's largest vacuum chamber, a significant effort was made to collect static and dynamic data on the sails and booms with approximately 400 Gb of data collected, primarily raw photogrammetry data. After the high vacuum deployment tests were completed, sensors, instrumentation and actuators were installed on the test articles to support structural static and dynamic testing. Photogrammetry techniques were utilized to make global and local shape measurements of the sail membranes and beams. A laser vibrometer instrument was also used to gather the dynamic characteristics of the structures at both ambient pressure and vacuum. Both ATK and L'Garde were able to achieve good correlation between their computational model predictions and the actual hardware performance. In addition to functional and structural testing, other analyses and tests were performed during Phase 3, including space environment testing of both the CP1 and Mylar sail membrane materials. Detailed studies were also conducted to analyze the spacecraft charging characteristics of both designs. Technical descriptions of work being performed by AEC[5,6,7] and L'Garde[8,9,10] on the 20-meter GSD can be found in the respective team's papers.

4.0 TRL Assessment

A technical assessment was made of both the L'Garde and ATK 20-meter GSD sail systems. The assessment addressed TRLs 3-6 by the process shown in Figure 9. The subsystem components of each SGD were assessed from levels 3-5 and the systems assessment for each GSD was performed at TRL 6. These assessments were first performed separately by each member of the assessment team. Final scores were agreed upon following detailed discussions and achievement of a consensus within the TRL assessment team. The subsystem and component breakdown for the ATK and L'Garde SGD designs are listed in Table 1. The NMP TRL exit criteria[11] were applied at each TRL level and an evaluation was performed to determine the completion percentage for a particular TRL level for the listed component, subsystem or system. The maturity of the analytical models and analytical model performance predictions were also judged at the component, subsystem and system levels. As an example, a score of 75 indicates that a particular element is assessed to be 75% complete for that particular TRL. The assessment of overall relevant environment test compliance is an average of the assessments for on-orbit, launch and ground environments.

5.0 Conclusion

The TRL assessment conducted after the 10-meter and 20-meter system testing clearly documented that both contractors had demonstrated full attainment of the TRL 3 and 4 requirements. Table 2 below provides a comparison of how well each team demonstrated TRL 5 and 6 after the completion of the 10-meter system testing and the 20-meter system testing. Both teams clearly advanced the state of the art of solar sail technology. Shortfalls and gaps identified as a result of the TRL assessment will be the basis for future ISPT solar sail analysis. These gaps include the following: 1) more detailed deployment dynamics modeling, 2) additional environmental testing of sail and boom materials, 3) manufacturing and assembly process issue resolutions, 4) design and manufacturing scalability issues, 5) additional charging and plasma interaction analysis and testing, and 6) design and demonstration of an attitude control system, including algorithm/ software development.

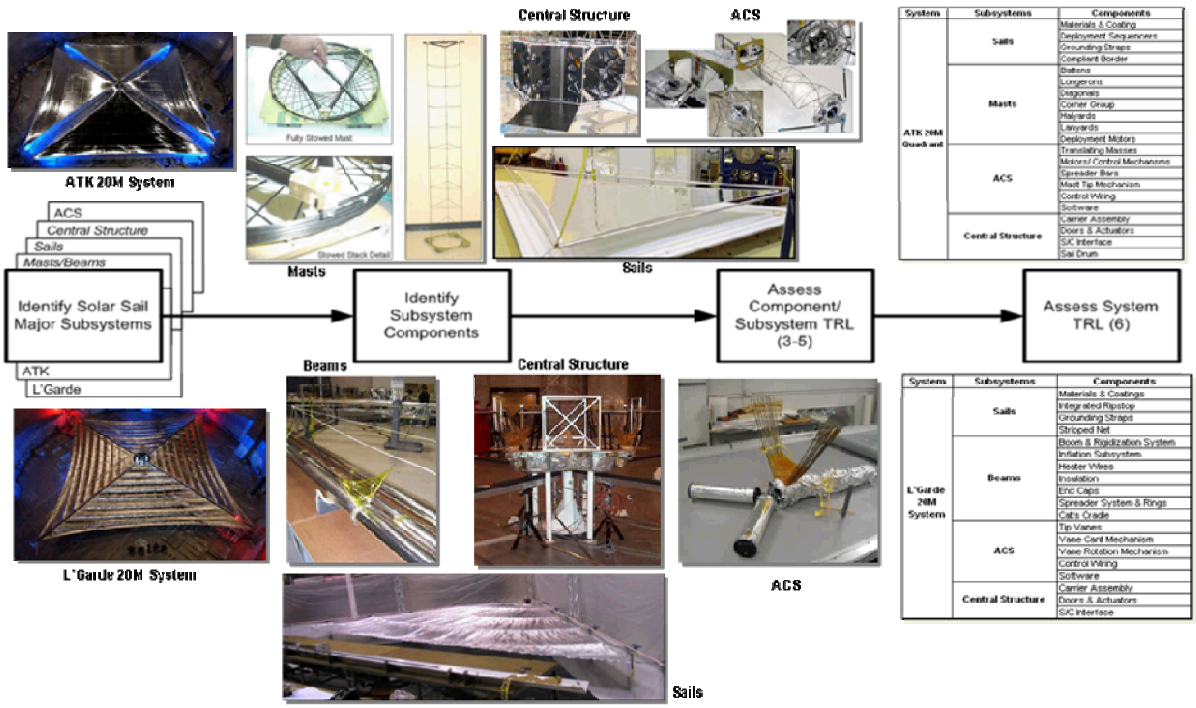


Figure 9: TRL Assessment Process

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8. D. Lichodziejewski et al., “Vacuum Deployment and Testing Of a 20 meter Solar Sail System”, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, May 2006, AIAA 2006-1705

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10. T. Mann et al., “Ground Testing A 20-Meter Inflation Deployed Solar Sail”, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, May 2006, AIAA 2006-1707
11. “New Millennium Program (NMP) Technology Readiness Levels for the New Millennium Program - Version 1”, May 22, 2003, New Millennium Program Office.

L'Garde Subsystem Components	***TRL 5***	***TRL 6***
Boom Components		78%
Boom and Rigidization System	72%	
Inflation Subsystem	42%	
Heater Wires	100%	
Insulation	58%	
End Caps	100%	
Spreader System and Rings	75%	
Cat's Cradle	100%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Sail Components		79%
Material & Coatings	83%	
Integrated Ripstop	75%	
Grounding straps	75%	
Stripped Net	75%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
ACS Components		91%
Tip Vanes	95%	
Vane Cant Mechanism	95%	
Vane Rotation Mechanism	100%	
Control Wiring	100%	
ACS Software	67%	
Models Replicate Performance	90%	
Analytical Predictions Complete	90%	
Central Structure Components		77%
Carrier Assembly	78%	
Doors & Actuators	78%	
Spacecraft Interface	75%	
Models Replicate Performance	50%	
Analytical Predictions Complete	75%	
Model Validation		63%
Packing/Flight Design/Interface Effects Advancement		81%

ATK Subsystem Components	***TRL 5***	***TRL 6***
Mast Components		80%
Battens	62%	
Longerons	78%	
Diagonals	75%	
Corner Groups	62%	
Halyards	92%	
Lanyards	100%	
Deployment Motor/Mechanisms	92%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Sail Components		92%
Material & Coatings	100%	
Tear Resistant Design	67%	
Deployments Sequencers	95%	
Grounding straps	100%	
Compliant Border	100%	
Models Replicate Performance	91%	
Analytical Predictions Complete	100%	
ACS Components		92%
Translating Masses	100%	
Translating Mass Motors/	100%	
Tip Spreader Bars	100%	
Mast Tip Mechanism	100%	
Control Wiring	100%	
ACS Software	50%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Central Structure Components		82%
Carrier Assembly	88%	
Doors & Actuators	88%	
Spacecraft Interface	75%	
Drum	75%	
Models Replicate Performance	88%	
Analytical Predictions Complete	88%	
Model Validation		88%
Packing/Flight Design/Interface Effects Advancement		84%

Table 1. 20M System TRL 5 and TRL 6 Assessment Results

Vendor	Post 10-meter TRL 5 Completion Average	Post 20-meter TRL 5 Completion Average	Post 10-meter TRL 6 Completion Average	Post 20-meter TRL 6 Completion Average
ATK	76%	89%	60%	86%
L’Garde	75%	84%	68%	78%

Table 2. TRL 5 and TRL 6 Comparison

TRL Assessment of Solar Sail Technology Development Following the 20-Meter System Ground Demonstrator Hardware Testing

IN-SPACE PROPULSION

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Acknowledgement

This work was funded in whole or in part by the In-Space Propulsion Technology Program, which is managed by NASA's Science Mission Directorate in Washington, D.C.

The program objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing cost, mass, or travel times.

Objective

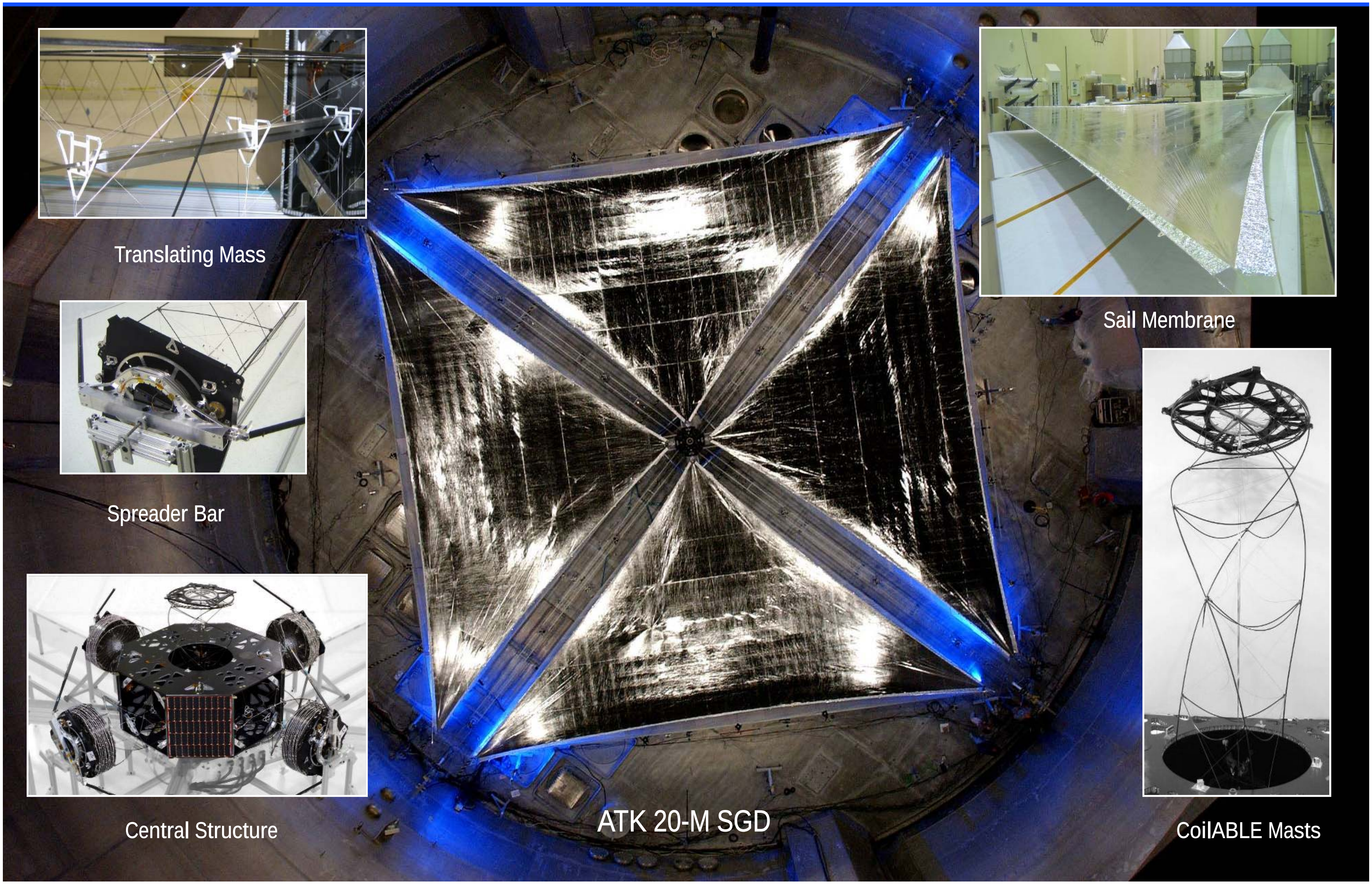
Provide an updated assessment of technology readiness of the Solar Sail Technology Area after completion of the 20-meter System Ground Demonstrators for the In-Space Propulsion Technology (ISPT) Project.

Solar Sail Project Goal: Increase the Technology Readiness Level (TRL) of Solar Sails to TRL 6, if possible on the ground.

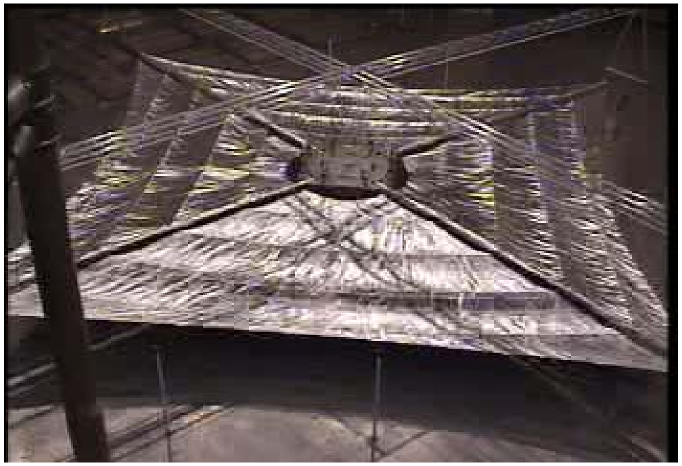
L’Garde System Ground Demonstrator (SGD)


20 Meter ISPSS
Vacuum Deploy
LGarde

ATK System Ground Demonstrator

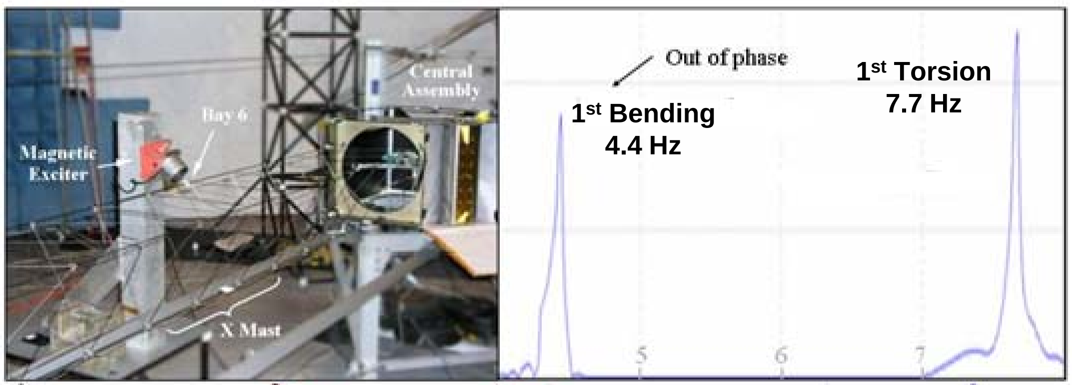


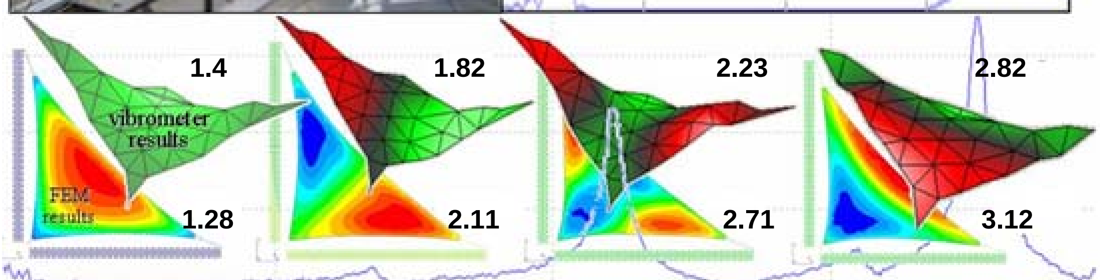
FEM Analysis



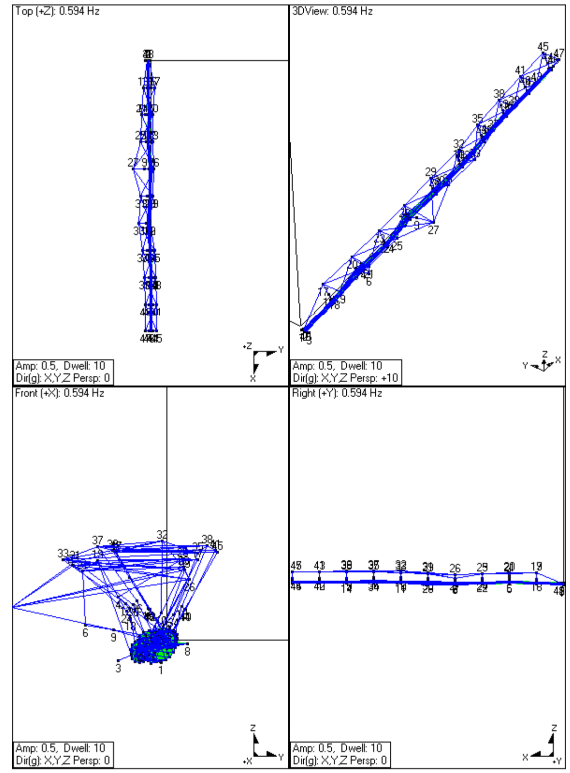
L'Garde 10m re-pressurization dynamics

ATK Results

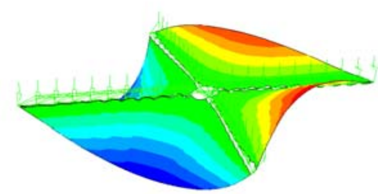




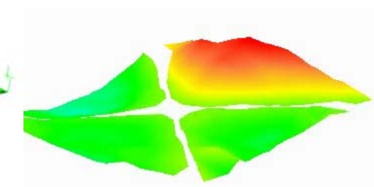
L'Garde Results



Predicted FEA Mode: 0.83 Hz



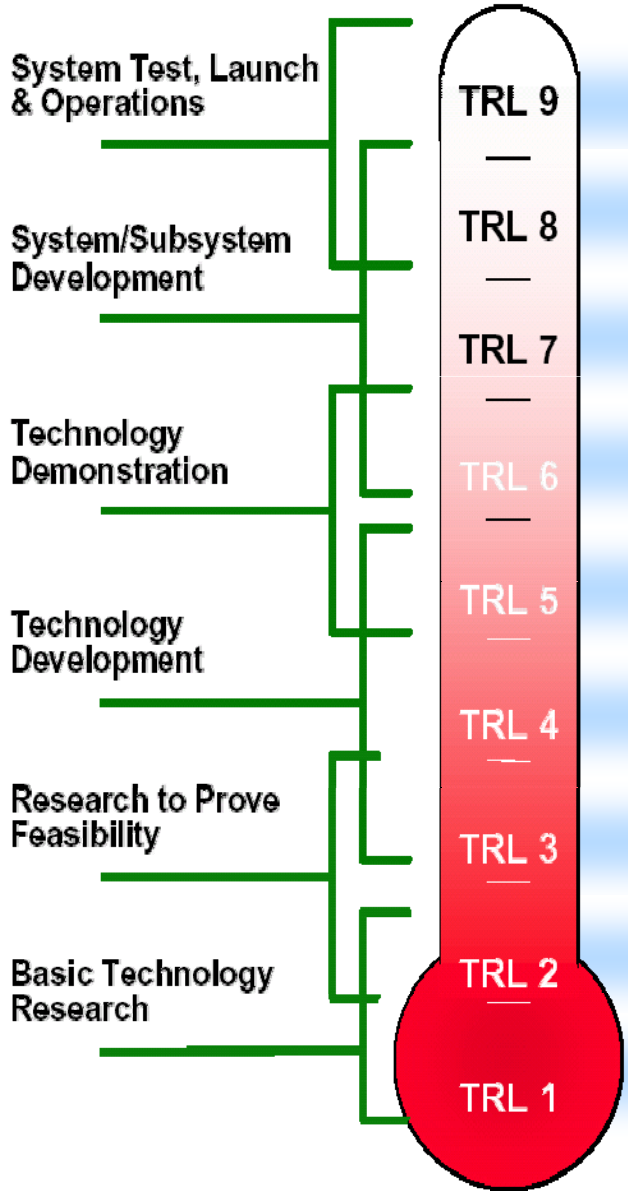
Measured Mode: 0.829/0.841 Hz



Solar Sails Notables

- Designed, built, delivered, and safely tested in a ground environment two 20m solar sail systems
- Subjected materials to high doses of radiation verifying on-orbit life time characteristics
- Developed repair techniques for membranes and booms.
- Discovered significant robustness against spacecraft charging
- Conducted static and dynamic response tests and conducted multiple deployments of two 400 square meter sail from a one meter^3 carrier at the highest vacuum ever achieved in the largest horizontal space test chamber in the world (Plum Brook).
- Subjected stowed systems to launch loads and ascent vent pressure drop
- Developed and used in test the largest high resolution photogrammetric shape measurement system in the world.
- Successfully applied conventional finite element modeling techniques to large area gossamer space structures. Modal Test Frequencies matched predicted values to within ten percent.
- Determined the extent to which gossamer structures can be verified by test on the ground.
- Discovered a significant robustness against the effect any number of wrinkles and other small defects have on propulsion performance.
- Developed a flight mechanics simulation capable of modeling solar sail non-Keplerian orbits
- Developed a mission concept to extend warning times to Earth for damaging solar events from 30 minutes to 90 minutes.

Technology Readiness Level (TRL)



Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

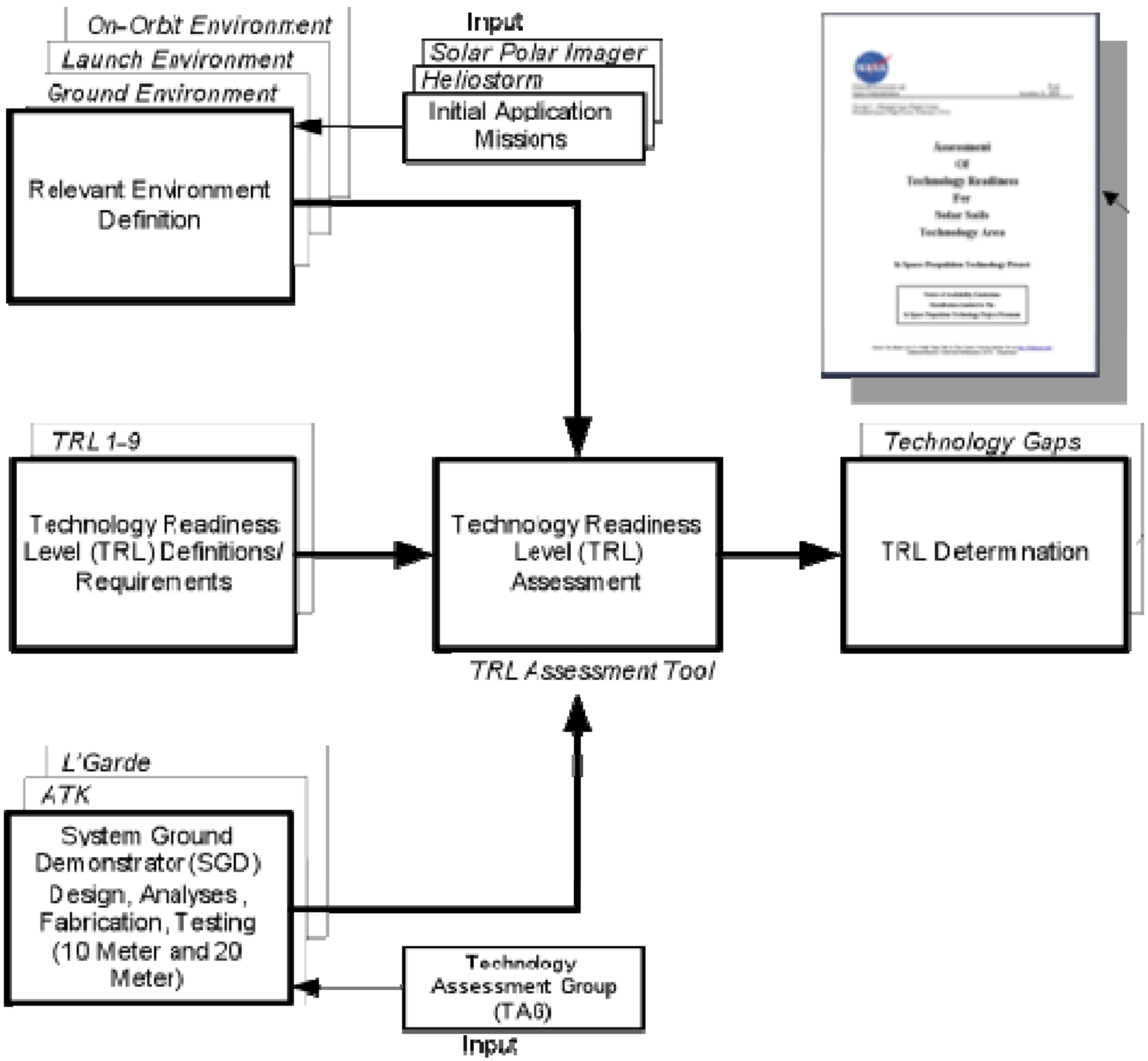
Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

Technology concept and/or application formulated

Basic principles observed and reported

Assessment Process Flowchart



Ground/Launch Environment Analysis and Testing

Ground Processing Relevant Environment Testing		
Relevant Environment	**L'Garde**	**ATK**
• Manufacturing	10M System, 20M System	10M Quadrant, 20M System
• Handling/Transportation	10M System, 20M System	10M Quadrant, 20M System
• Survivability/Life	Not tested	On-going
• Contamination	Not Applicable	Not Applicable
• Repair	Partial Demonstration	Partial Demonstration

Launch Phase Relevant Environment Testing		
Relevant Environment	**L'Garde**	**ATK**
• Fairing Internal Pressure/Vacuum (Ascent Venting)	10M System, 20M System	20M System
• Dynamics		
– Launch Vibration	10M System, 20M System	20M System

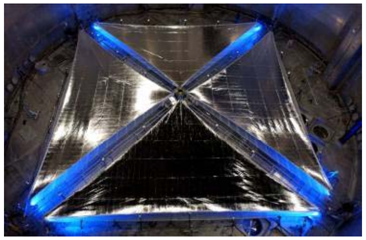
On-Orbit Environment Analysis and Testing

On-Orbit Relevant Environment Testing		
Relevant Environment	**L'Garde**	**ATK**
•Solar, Electromagnetic and Thermal		
–Direct Solar Illumination	Not tested	Sail material
–Solar Spectrum	Sail material, boom insulation	Sail material
–Energetic Solar Electromagnetic Radiation	Negligible effect	Negligible effect
–Other Natural Electromagnetic Radiation	No Issue	No Issue
–Manmade Radio Noise	No Issue	No Issue
–Earth Albedo Illumination	Not Applicable	Not Applicable
–Outgoing Long Wave Radiation	No Issue	No Issue
•Mesosphere, Neutral Thermosphere and Atmospheric Drag	No Issue	No Issue
•Plasma		
–Plasma Composition	Mission specific	Mission specific
–Plasma Charging	Sail material	Sail material testing, charge modeling
–Ionospheric Plasma	No Issue	No Issue
–Auroral Plasma	No Issue	No Issue
•Pressure and Magnetic Field		
–Pressure	10M System (Medium Vacuum), 20M System (High Vacuum)	10M Quadrant (Medium Vacuum), 20M System (High Vacuum)
–Magnetic Field	No Issue	No Issue
•Meteoroids and Orbital Debris	Not tested	Sail Materials
•Ionizing Radiation Environment and Effects		
–Galactic Cosmic Rays	Not tested	Not tested
–Trapped Proton/Electron Radiation	Not tested	Not tested
–Solar Activity Cycle	Not tested	Not tested
–Energetic Solar Particle Events	Not tested	Not tested
–Total Ionizing Dose	Not tested	Not tested
–Ionizing Radiation Single Event Effects	Not tested	Not tested
•Gravitational Field		
–Primary Gravitational Accelerations	Mission specific	Mission specific
–Gravitational Perturbations	Mission specific	Mission specific

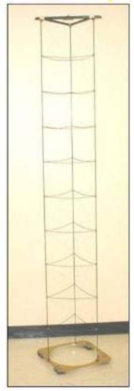
Functionality and Other Test Results

Functionality, System Characteristics and Model Validation Testing		
	L'Garde	ATK
• Deployment	7M, 14M Beams, 10M System (Ambient and Medium Vacuum), 20M System (Ambient and High Vacuum)	7M, 14M Masts, 10M Quadrant (Ambient and Medium Vacuum), 20M System (Ambient and High Vacuum)
• Sail Shape Test	10M System, 20M System	10M Quadrant (Global, Local), 20M System
• Structural Dynamics	10M (Beams, System), 20M (Beams, System)	10M Quadrant (Masts, Sail, System), 20M System (Masts, Sail System)
• Charging/Resistivity	Not tested	Measured
• On-orbit Actuator Operation	High vacuum test	High vacuum test
• Thermal	Not tested	Not tested
• Structural Model Validation	10M and 20M System (Good Correlation)	10M Quadrant and 20M System (Good Correlation)

TRL Assessment Methodology

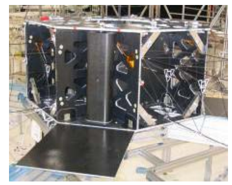


ATK 20M System

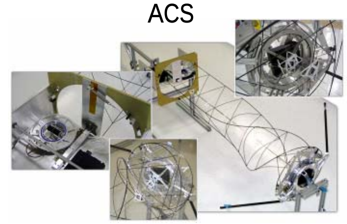


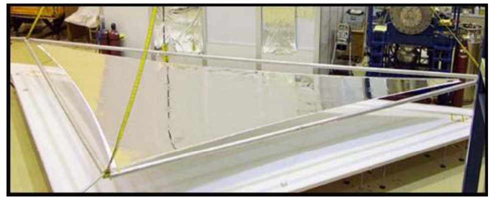
Masts

Central Structure



ACS





Sails

System	Subsystems	Components
ATK 20M Quadrant	Sails	Materials & Coating
		Deployment Sequencers
		Grounding Straps
		Compliant Border
	Masts	Battens
		Longerons
		Diagonals
		Corner Group
		Halyards
		Lanyards
		Deployment Motors
	ACS	Translating Masses
		Motors/ Control Mechansms
		Spreader Bars
		Mast Tip Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface
		Sail Drum

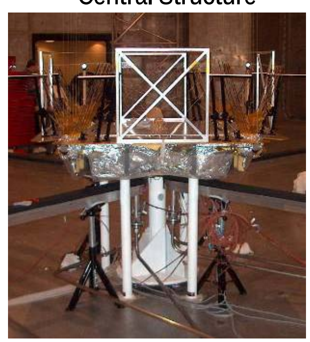
ACS
Central Structure
Sails
Masts/Beams

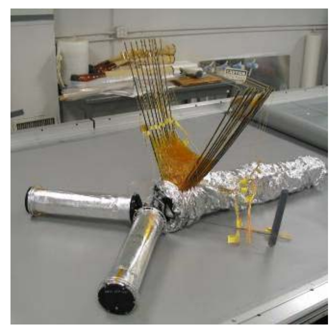
Identify Solar Sail Major Subsystems (ATK, L'Garde) → **Identify Subsystem Components** → **Assess Component/ Subsystem TRL (3-5)** → **Assess System TRL (6)**

L'Garde 20M System

Beams

Central Structure





ACS

Sails

System	Subsystems	Components
L'Garde 20M System	Sails	Materials & Coatings
		Integrated Ripstop
		Grounding Straps
		Stripped Net
	Beams	Boom & Rigidization System
		Inflation Subsystem
		Heater Wires
		Insulation
		End Caps
		Spreader System & Rings
		Cat's Cradle
	ACS	Tip Vanes
		Vane Cant Mechanism
		Vane Rotation Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface

TRL 3-5 Assessment Worksheet (Example)

L'GARDE **10m MAST** TRL ASSESSMENT

TRL LEVEL	COMMENTS	CONDITIONS	BOOM & RIGIDIZATION SYSTEM	INFLATION SUBSYSTEM	HEATER WIRES	INSULATION	END CAPS	SPREADER SYSTEM & RINGS	CATS CRADLE	TOTAL % Complete	NOTES
TRL 3: Analytical and experimental critical function and/or characteristic proof of concept achieved in a laboratory environment	At this step in the maturation process, active research and development (R&D) is initiated. This includes both analytical studies to set the technology into an appropriate context and laboratory-based studies to validate empirically that the analytical predictions are correct. These studies and experiments validate the benefits offered by the technology advancement to the applications/concepts formulated at TRL 2.	Laboratory tests have demonstrated that the technology advance as predicted by the analytical model and has the potential to evolve to a practical device.	100	100	100	100	100	100	100	100	The detailed relevant environment was not defined by the government to the contractors in the NRA, only a generic Design Reference Mission. The NASA TRL Assessment Document fully defines the relevant environment for solar sail technology at the .5 to 1 AU utilizing a Delta II launch vehicle. This definition was done at the start of Phase III of their contracts and therefore the contractors were given credit for relevant environment definition at TRL 3.
		Analytical models both replicate the current performance of the technology advance and predict its performance when operating in a breadboard environment.	100	100	100	100	100	100	100	100	
		A determination of the "relevant environment" for the technology advance has been made. (See Note)	100	100	100	100	100	100	100	100	
TRL 4: Component and/or breadboard validated in a laboratory environment	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "lowfidelity" compared to the eventual system; it could be composed of ad hoc discrete components in a laboratory.	A "component" or "breadboard" version of the technology advance will have been implemented and tested in a laboratory environment.	100	100	100	100	100	100	100	100	Models used to predict propulsion performance in a relevant environment. Propulsion qualification tests cannot be conducted on the ground for a solar sail. Analytical models not developed for other relevant natural or induced environments
		Analytical models of the technology advance fully replicate the TRL 4 test data.	100	100	100	100	100	100	100	100	
		Analytical models of the performance of the component or breadboard configuration of the technology advance predict its performance when operated in its "relevant environment" and the environments to which the technology advance would be exposed during qualification testing for an operational mission. See NOTE	100	100	100	100	100	100	100	100	
TRL 5: Component and/or breadboard validated in a relevant environment	At this TRL, the fidelity of the environment in which the component and/or breadboard has been tested has increased significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a "relevant environment".	The "relevant environment" is fully defined. See NOTE	100	100	100	100	100	100	100	100	The detailed relevant environment was not defined by the government to the contractors in the NRA, only a generic Design Reference Mission. The NASA TRL Assessment Document fully defines the relevant environment for solar sail technology at the .5 to 1 AU utilizing a Delta II launch vehicle. This definition was done at the start of Phase III of their contracts and therefore the contractors did not test components at a fully defined relevanet environment. Natural Environment - inflation system leaks - new material needed; no UV, e, p on boom material or spreader system (kapton pockets, kevlar lines), no e, p on insulation Ground environment - lines showed signs of chaffing - possible ground shipping issue. Assembly process and procedure is not repeatable and no method available to verify correct assembly. Limited test life (limited number of deployments without damage) Models - no deployment dynamics model, no charging model
		The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission. See NOTE	AVERAGE OF NATURAL, LAUNCH & GROUND ENVIRONMENTS								
			62.5	62.5	100	75	100	62.5	62.5	75	
		Component or breadboard has been tested in the relevant natural environment	50	50	100	50	100	50	50		
		Component or breadboard has been tested in the relevant launch environment	NA	NA	NA	NA	NA	NA	NA		
		Component or breadboard has been tested in the relevant ground environment	75	75	100	100	100	75	75		
		Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment"	75	75	75	75	75	75	75	75	
		Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.	100	100	100	100	100	100	100	100	

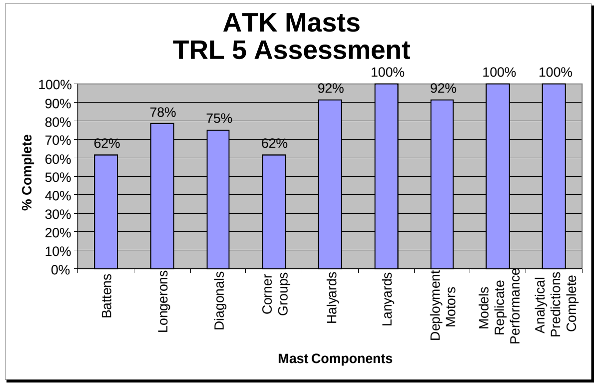
TRL 6 Assessment Worksheet (Example)

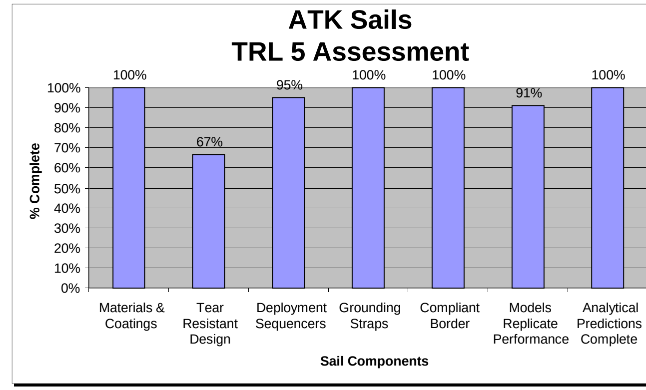
ABLE **10m SYSTEM** TRL ASSESSMENT

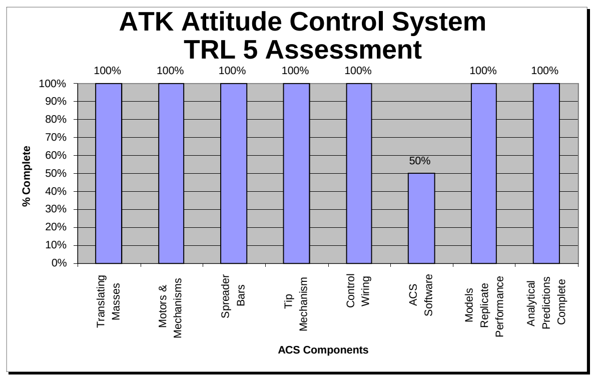
TRL LEVEL	COMMENTS	CONDITIONS	SAIL SUBSYSTEM	MAST SUBSYSTEM	CENTRAL STRUCTURE SUBSYSTEM	TOTAL	NOTES
TRL 6: System/subsystem model or prototype demonstration in a relevant environment on the ground or in space	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype of the subsystem or system, well beyond ad hoc, "patch-cord" or discrete-component-level breadboarding, would be tested in a "relevant environment". However, commercial parts are still appropriate where not contra-indicated by the environment in which they will be tested. At this level, if the only "relevant environment" is space, then to achieve TRL 6 the model/prototype must be successfully validated in space. However, in many (if not most) cases, TRL 6 can be demonstrated using tests on Earth, which tests potentially offer a broader range of operating conditions than those conducted in space.	The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft.	75	75	50	66.66666667	Sail - 10 m sail lacked ripstop; single quadrant, little testing on 3 micron sail Central Structure - no square system, not flight-like canister
		The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.	AVERAGE OF NATURAL, LAUNCH & GROUND ENVIRONMENTS				Environment - test conducted at ambient temperature, rough vacuum deployment, single quadrant only Launch - no vibration testing, single quadrant, ascent vent done with folded sail, no shock Ground - single quadrant doesn't show processing for full 4 quadrant system (GSE, handling, manufacturing), central structure not flight like
			61	61	52.66666667	58.22222222	
		System has been tested in the relevant natural environment	75	75	75		
		System has been tested in the relevant launch environment	33	33	33		
		System has been tested in the relevant ground environment	75	75	50		
		Analytical models of the function and performance of the system/subsystem model or prototype, throughout its operating region, in its most stressful environment, have been validated empirically.	75	75	50	66.66666667	No deployment simulations, central structure not flight like (was it modeled correctly), no system models produced
		The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for flight and the effect of interfaces on that function and performance in its most stressful environment.	50	75	50	58.33333333	Single quadrant - folding and sequencing design for sails still under development

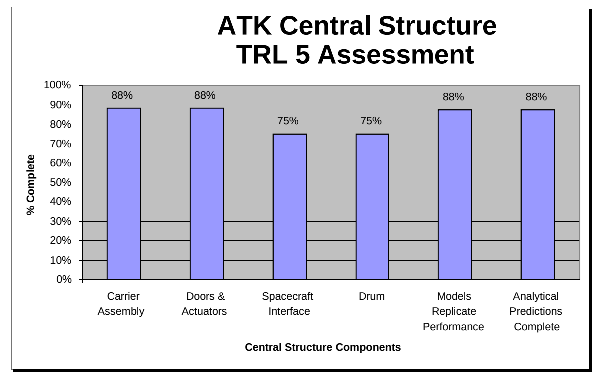
TRL 5/6 Assessment Results (ATK)

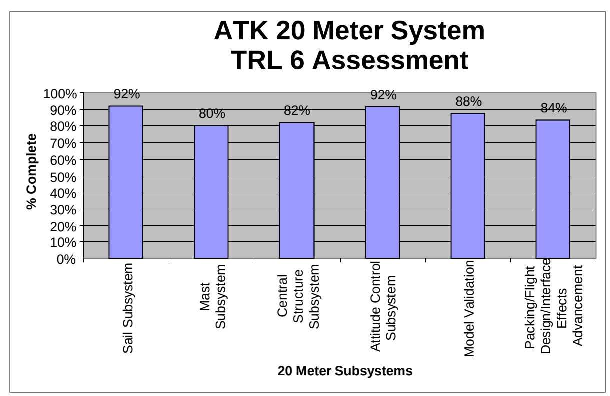
ATK Subsystem Components	*TRL 5*	*TRL 6*
Mast Components		80%
Battens	62%	
Longerons	78%	
Diagonals	75%	
Corner Groups	62%	
Halyards	92%	
Lanyards	100%	
Deployment Motor/Mechanisms	92%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Sail Components		92%
Material & Coatings	100%	
Tear Resistant Design	67%	
Deployments Sequencers	95%	
Grounding straps	100%	
Compliant Border	100%	
Models Replicate Performance	91%	
Analytical Predictions Complete	100%	
ACS Components		92%
Translating Masses	100%	
Translating Mass Motors/	100%	
Tip Spreader Bars	100%	
Mast Tip Mechanism	100%	
Control Wiring	100%	
ACS Software	50%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Central Structure Components		82%
Carrier Assembly	88%	
Doors & Actuators	88%	
Spacecraft Interface	75%	
Drum	75%	
Models Replicate Performance	88%	
Analytical Predictions Complete	88%	
Model Validation		88%
Packing/Flight Design/Interface Effects Advancement		84%





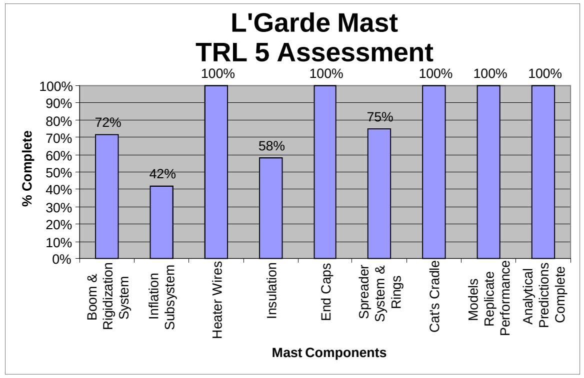


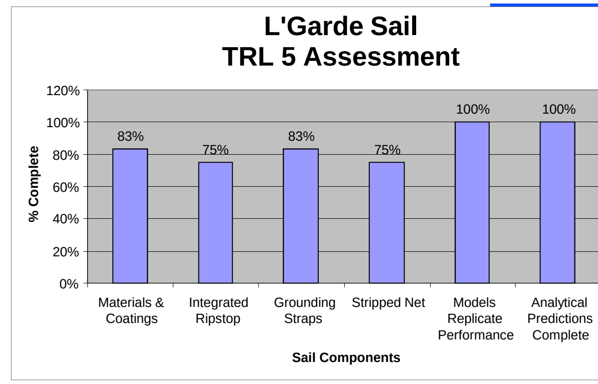


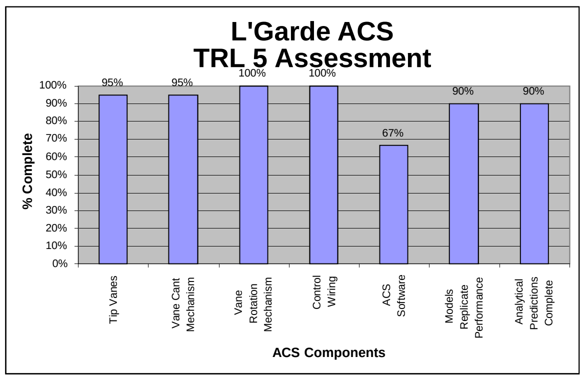


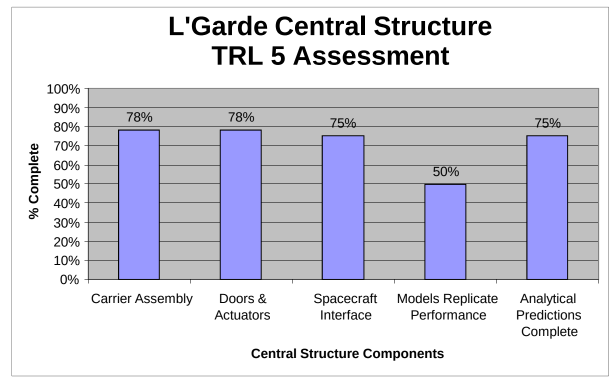
TRL 5/6 Assessment Results (L'Garde)

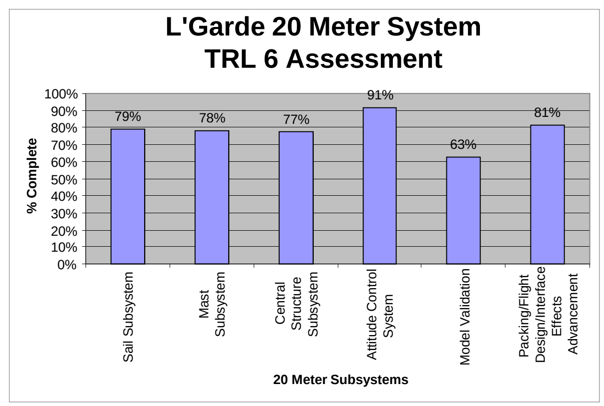
L'Garde Subsystem Components	*TRL 5*	*TRL 6*
Boom Components		78%
Boom and Rigidization System	72%	
Inflation Subsystem	42%	
Heater Wires	100%	
Insulation	58%	
End Caps	100%	
Spreader System and Rings	75%	
Cat's Cradle	100%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
Sail Components		79%
Material & Coatings	83%	
Integrated Ripstop	75%	
Grounding straps	75%	
Stripped Net	75%	
Models Replicate Performance	100%	
Analytical Predictions Complete	100%	
ACS Components		91%
Tip Vanes	95%	
Vane Cant Mechanism	95%	
Vane Rotation Mechanism	100%	
Control Wiring	100%	
ACS Software	67%	
Models Replicate Performance	90%	
Analytical Predictions Complete	90%	
Central Structure Components		77%
Carrier Assembly	78%	
Doors & Actuators	78%	
Spacecraft Interface	75%	
Models Replicate Performance	50%	
Analytical Predictions Complete	75%	
Model Validation		63%
Packing/Flight Design/Interface Effects Advancement		81%





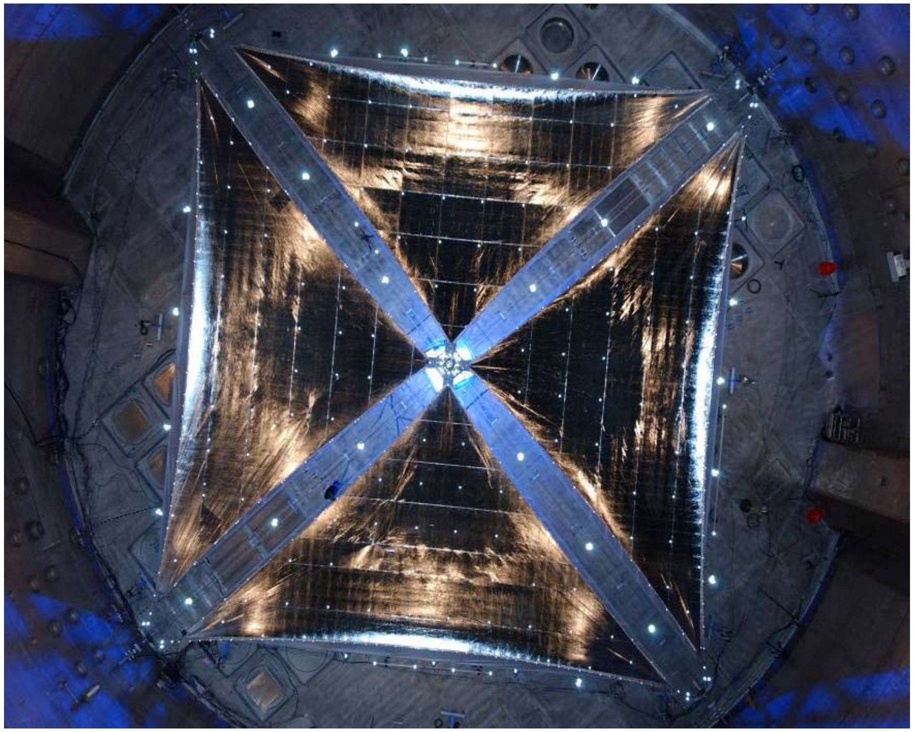




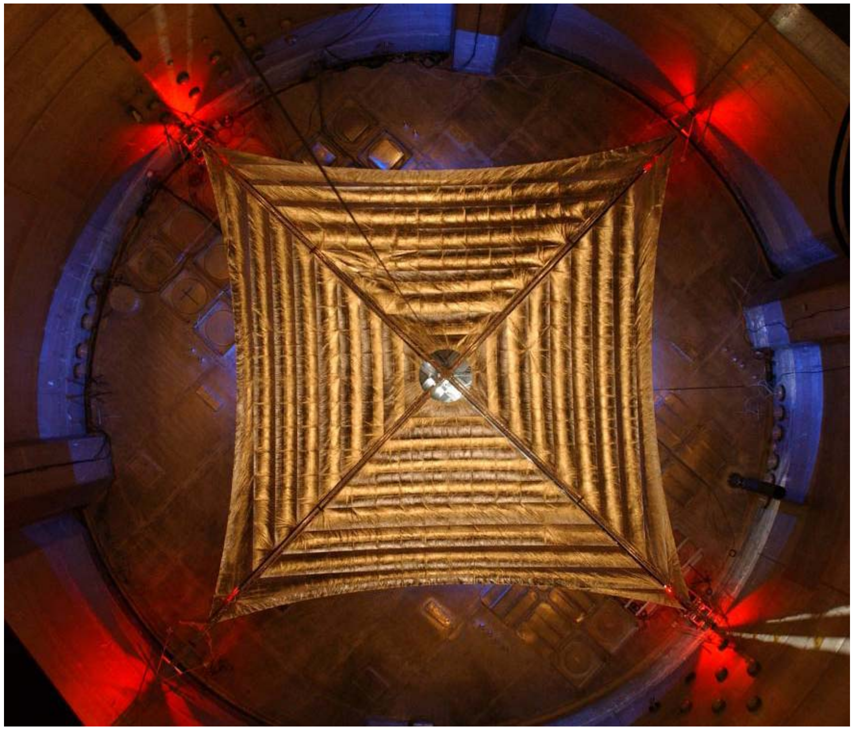


TRL Assessment
Results Comparison

Vendor	Post 10M TRL 5 Completion Average	Post 20M TRL 5 Completion Average	Post 10M TRL 6 Completion Average	Post 20M TRL 6 Completion Average
ATK	76%	89%	60%	86%
L'Garde	75%	84%	68%	78%



ATK



L'Garde

Future Planned Tasks
Top-Level Flowchart

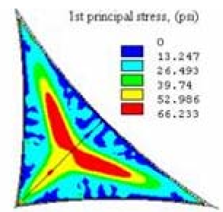
IN-SPACE PROPULSION

Heliostorm Mission Def.

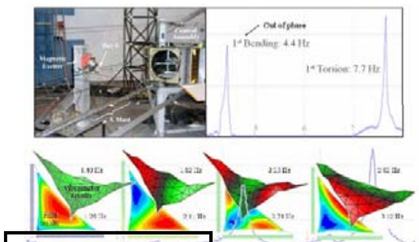
Cycle 1&2 SSP Products
- -Design
- -S5
- -Materials data
- -Charge Models
- -Test Exp.
- -Man/Fab.
- -Cost

1.1 Heliostorm Integrated Mission Studies

1.2 Mission Operations, Guidance & Navigation



1.4 Steady State Thermal Analysis

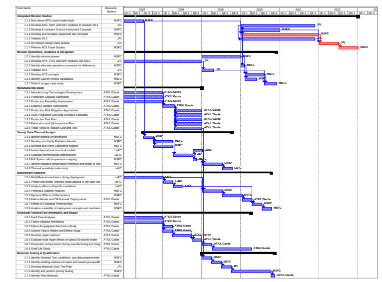


1.5 Deployment Analyses

1.6 Structural Failures/Test Anomalies, and Repair

1.3 Manufacturing Study

1.7 Materials Testing & Qualification



1.8 Hi Fidelity Ground System Demonstrator

Risk Tolerance

Flight Validation (sounding rockets, LEO, L1)

Heliostorm 2016

$30M+
ISP investment
TRL 5+

$17M+
Focused studies
TRL 5+

$12M+
Integrated System Ambient demo
TRL 5+

* Some overlap exists between these tasks and ST9 effort

QUESTIONS ??