Solar Sail Propulsion

Technology Readiness Level Database

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The NASA In-Space Propulsion Technology (ISPT) Projects Office has been sponsoring 2 solar sail system design and development hardware demonstration activities over the past 20 months. Able Engineering Company (AEC) of Goleta, CA is leading one team and L'Garde, Inc. of Tustin, CA is leading the other team. Component, subsystem and system fabrication and testing has been completed successfully. The goal of these activities is to advance the technology readiness level (TRL) of solar sail propulsion from 3 towards 6 by 2006. These activities will culminate in the deployment and testing of 20-meter solar sail system ground demonstration hardware in the 30 meter diameter thermal-vacuum chamber at NASA Glenn Plum Brook in 2005. This paper will describe the features of a computer database system that documents the results of the solar sail development activities to-date. Illustrations of the hardware components and systems, test results, analytical models, relevant space environment definition and current TRL assessment, as stored and manipulated within the database are presented. This database could serve as a central repository for all data related to the advancement of solar sail technology sponsored by the ISPT, providing an up-to-date assessment of the TRL of this technology. Current plans are to eventually make the database available to the Solar Sail community through the Space Transportation Information Network (STIN).

I. Introduction

For many years NASA has used the Technology Readiness Level (TRL) as a method of judging the maturity of a particular technology. 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 (Levels 1-2) technology conceptualization and analytical demonstration, (Levels 3-4) laboratory technology demonstration, component and analytical model validation, and (Level 5-6) component, subsystem and system demonstrations in a relevant environment.

As the TRL of Solar Sail technology has progressed, a tremendous amount of test results, computational models and analysis results have been generated. The Solar Sail Propulsion TRL Assessment Database facilitates the organization, storage and access to this vast amount of data. Correlation of the data with the TRL milestones allows the current level of the technology to be evaluated.

The following sections provide a description of the structure of the database files and configurations of the main and supporting spreadsheets. Features of the program are also described including lists of the technology tasks (tests, demonstrations and inspections) performed on the solar sail hardware. Representative image handling capabilities of the program are demonstrated. Data handling and manipulation features are described, including examples of test results reports and model descriptive data. The solar sail relevant environment definition section of the database is described. Finally, the TRL definition and assessment sections are presented, along with future additions to the database.

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II. Database structure

The solar sails TRL database is structured into 3 folders (References, Pictures and Test Data) as illustrated in Figure 1.

The database utilizes Microsoft Office applications (Excel, Power Point Word, and Access) and Adobe Acrobat Reader. The main application is launched from the Solar Sail Environment Test Checklist spreadsheet file. This file is contained in the Solar Sail Technology Development folder. The "References" folder contains copies of all of the presentations and report files generated during the solar sail technology development program. The "Pictures" folder contains copies of the photographs and video files generated to date. The "Models" folder contains information on the computational models being developed in support of solar sail technology development.

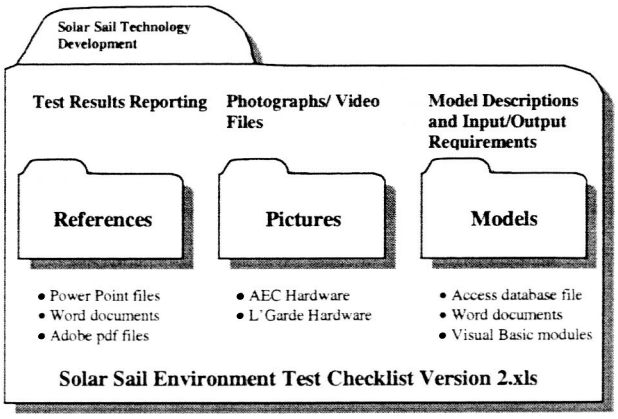


Figure 1. Database File Structure

Utilizing the hyperlink, automation functions and Visual Basic for Application (VBA) features of Microsoft Office to integrate applications, the numerous Power Point, Word, Excel, and Adobe Acrobat files are accessible from within a single file, facilitating review of the vast amount of data generated during the on-going technology development. This integration of data will permit a rapid assessment of the TRL of solar sail propulsion.

A. Main Workbook Configuration

The primary platform for viewing and manipulating the database information is the Solar Sail Environment Test Checklist spreadsheet file. This workbook consists of 7 worksheets that correspond with the 3 major near-term products identified in the Solar Sail Technology Assessment Group Roadmap[1]. The roadmap is illustrated in the appendix. The "Solar Sail Testing", "L'Garde Hardware Descriptions" and "AEC Hardware Descriptions" worksheets contain information that is a near term product of "Scalable ground test demonstration system" identified on the roadmap. The "Computational Models" and "Model Descriptions" worksheets contain data resulting from the "High fidelity model of test system that demonstrates scalability" roadmap product. The "Relevant Environment" and "References" folders contain information that is a product of the "Set of quantitative laboratory characterization tests".

The "Solar Sail Testing" and "Relevant Environment" worksheets are described in more detail in the following sections. The "L'Garde Hardware Descriptions" and "AEC Hardware Descriptions" worksheets contain photographs of hardware components and systems, as well as computer generated images of systems under development. The "Computational Models" and "Model Descriptions" worksheets contain graphical images of models being developed for solar sails, as well as model descriptive data. The "References" worksheet contains a database table listing of all of the reference files stored in the "References" folder, shown in Figure 1.

The Solar Sail Testing worksheet is illustrated in Figure 2. As highlighted in this figure, technology development tasks are listed in the leftmost column of this worksheet. This list incorporates all of the inspections, demonstrations and tests performed by AEC and L'Garde.

Computational models created as part of the technology development are also listed in the leftmost column. These models are categorized as structural, materials, environment, and guidance, navigation and control (GN&C). A hyperlink is provided to access more detailed model descriptive information.

The Technology Readiness Level definitions are listed in the rows below the computational models section of the worksheet.

AEC and L'Garde hardware components, subsystems and systems names have been entered into the columns across the top of the main worksheet. Command buttons in each of these areas provide access to photographs and video files of hardware items.

Results of the technology tasks performed on each component, subsystem and system are entered in the appropriate intersection of worksheet rows and columns. Comments are entered into each cell to identify the reference document from which the results were obtained.

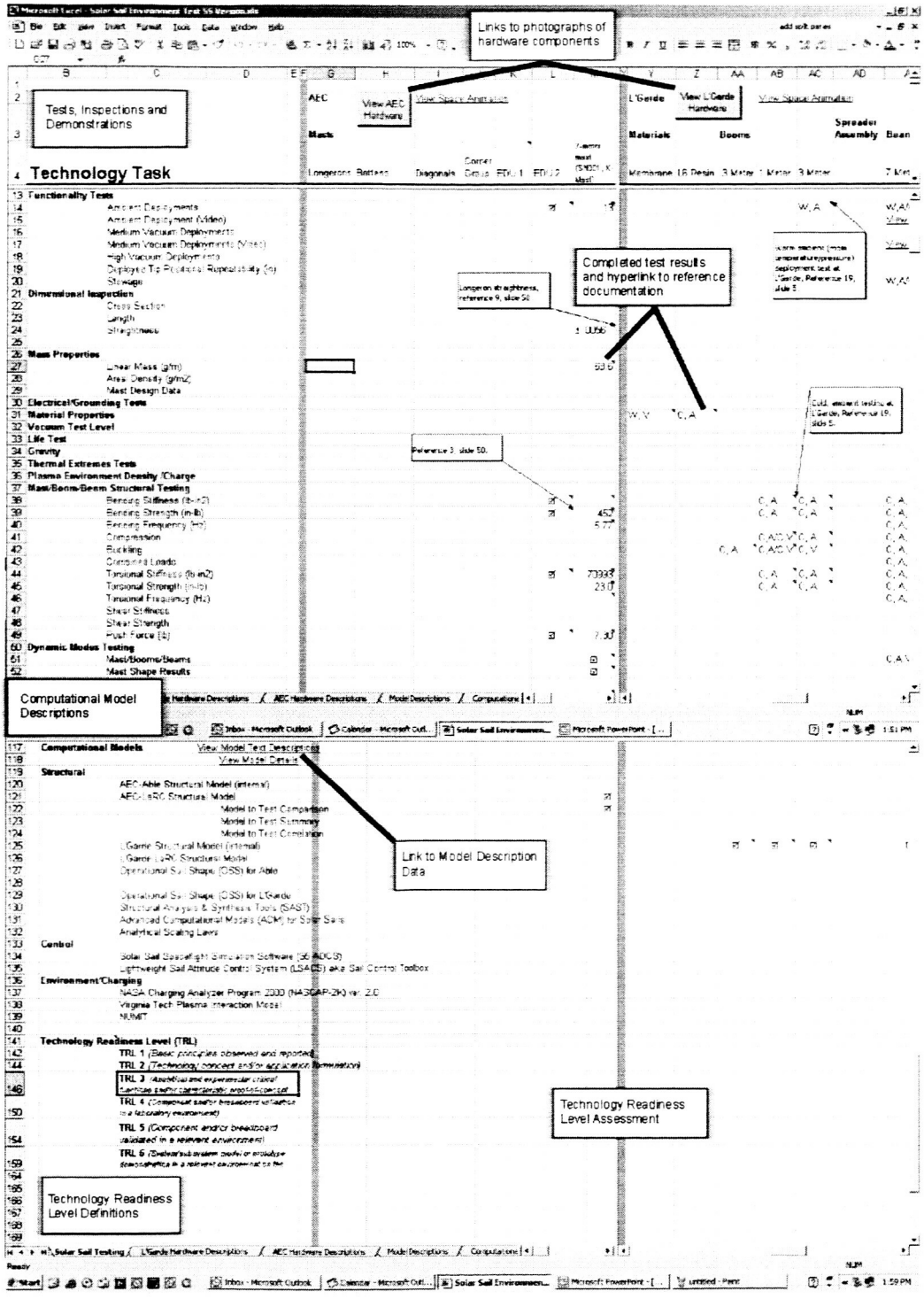


Figure 2. Main Worksheet Configuration

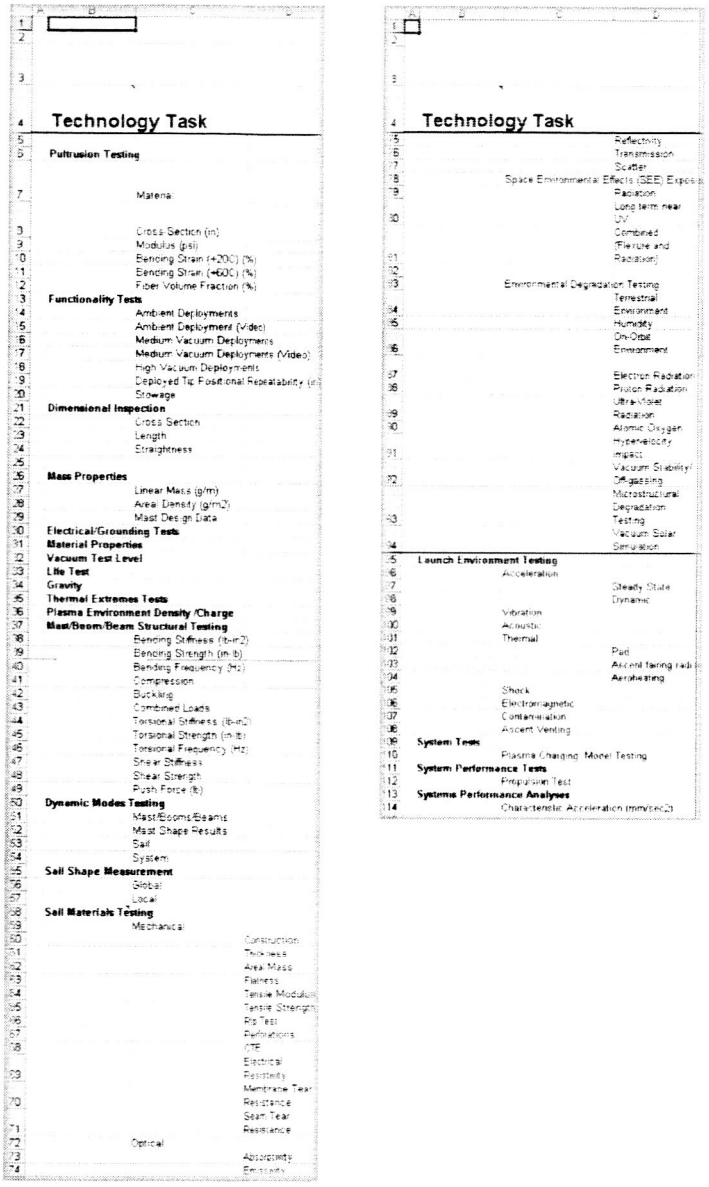
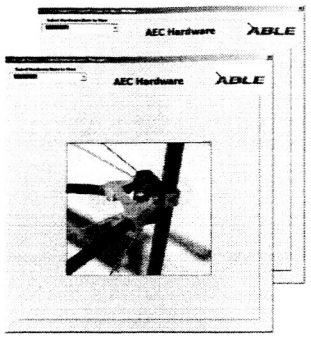


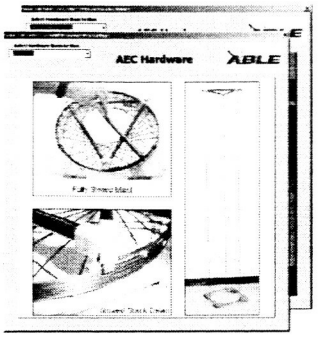
Figure 3. Technology Tasks List

Figure 3 provides a more complete list of technology tasks tracked on the "Solar Sail Testing" worksheet. The general categories of technology development tasks include structural, materials, space environmental effects and launch environment. These general categories are further subdivided into dimensional inspections and functionality tests, static and dynamic structural testing, and materials properties measurements (optical, mechanical, thermal). As additional testing requirements are identified, this section of the main worksheet will be expanded to track these test results.

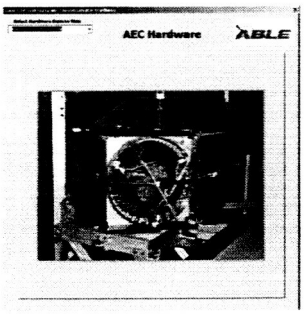
Command buttons provided in the hardware components section of the main worksheet provide the capability to view photographs of the solar sail hardware, as illustrated in Figure 4. AEC solar sail mast components include



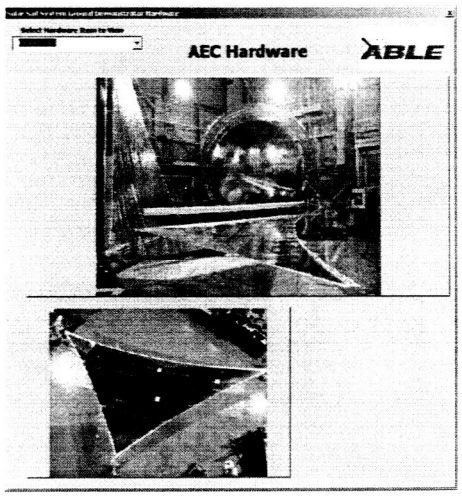
Mast Components



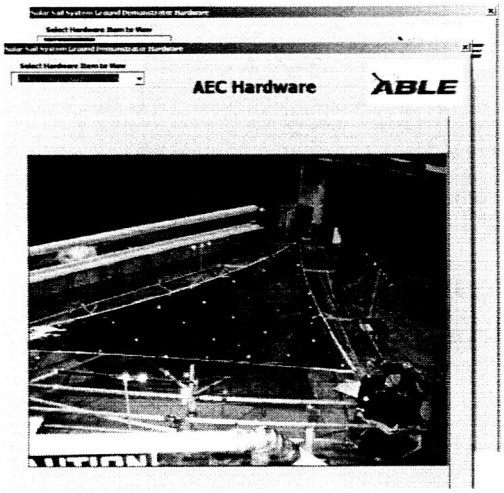
Masts



Central Structure



Sails



Systems

Figure 4. AEC Hardware

longerons, battens, diagonals and corner groups. These components are assembled into mast subsystems. AEC has fabricated several masts to support their technology development activities. Sails developed by the AEC team include the workhorse, RS5, RS3 and the performance sail. The AEC ground support central structure is also shown in this figure. These subsystems are assembled to create the 10 Meter Quadrant and 20 Meter 4 Quadrant Systems.

Future additions to this portion of the database will include details of the AEC thrust vector control authority demonstration hardware and provisions for an optical diagnostics system. This section of the database will be updated to accommodate hardware component advancements as they are developed.

A command button is also provided in the L'Garde hardware section of the main worksheet. This command button provides access to photographs of L'Garde hardware items as illustrated in Figure 5. L'Garde hardware categories include materials (resin, membrane), boom components, beams, central structure, sails and systems. L'Garde has fabricated and tested .3, 1 and 3 meter long booms. The booms and spreaders are assembled together to create a beam. The L'Garde 7 Meter beam is illustrated in the figure. L'Garde has fabricated and assembled sails including the 2/3 sail, a 9 cell rip-stop sail and a 10 Meter quadrant. Photographs of the L'Garde central structure, 10 Meter 4 Quadrant and a concept for the 20 Meter ground system demonstrator are also shown in the figure.

Future additions to this portion of the database will include details of the L'Garde thrust vector control authority demonstration hardware and provisions for an optical diagnostics system. This section of the database will be updated to accommodate hardware component advancements as they are developed.

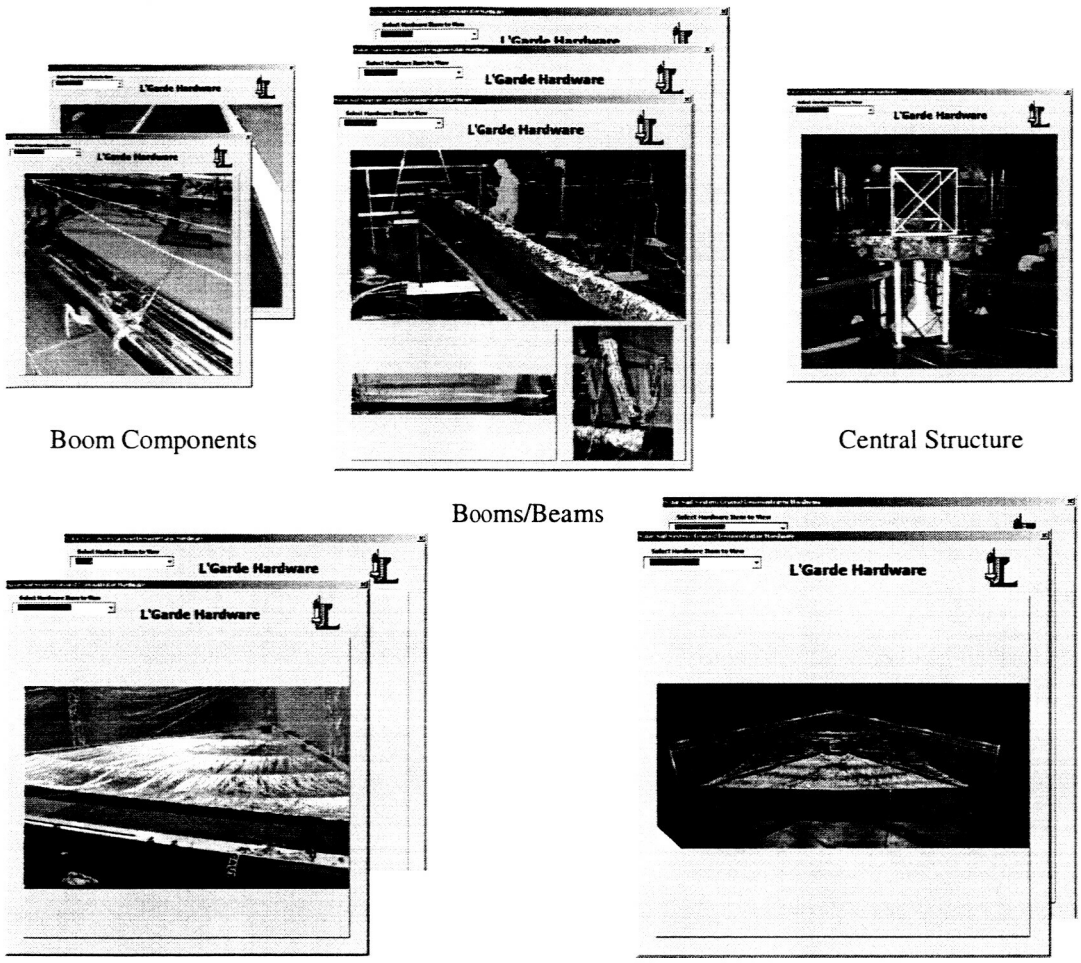


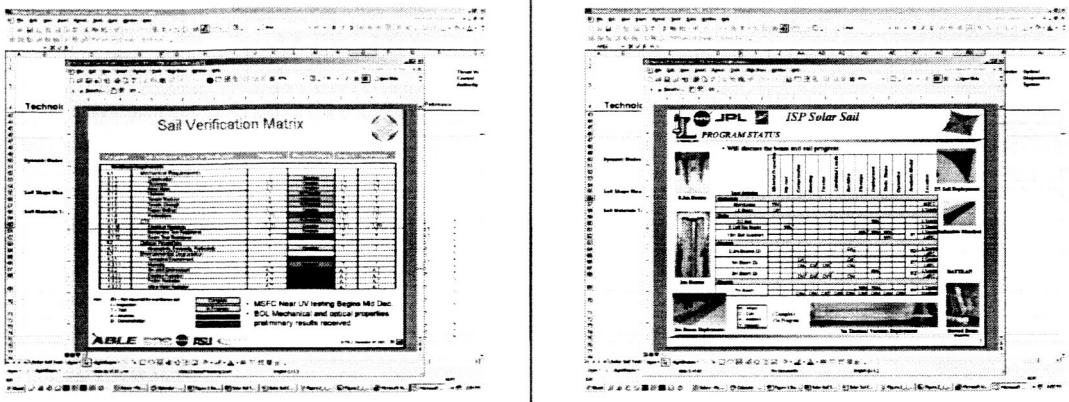
Figure 5. L'Garde Hardware

Hyperlinks are also provided in the main worksheet to view deployment video files and on-orbit deployment animations of both the L'Garde and AEC hardware.

B. Worksheet Row/Column Cell Entries

Results of the tests, analyses, inspections and demonstrations performed to date on the AEC and L'Garde hardware are entered into the spreadsheet in the appropriate column and row intersection. Annotations in the cell comments are entered to link the test results to the specific reference (Power Point slide, Word document, PDF file) where the results of the specific test were documented. By "double clicking" on the specific cell of interest, a VBA

routine is activated that displays the specific reference on the screen, providing the full details of the test/demonstration/inspection/analysis. An example of this program capability is illustrated in Figure 6.



AEC Results Reporting | L'Garde Results Reporting

Figure 6. Database Hyperlink Capability

C. Solar Sail Computational Models

Model validation is a key element of TRL advancement. Detailed descriptions of the solar sail computational models can be accessed within the database by clicking on the appropriate command button. An example of the computational model descriptive data is illustrated in Figure 7. Model descriptive data displayed includes model name, purpose, owner, implementation strategy, model inputs/outputs, platform, status, pointers, status of validation and space experiment validation. Illustrations of the model graphics can also be accessed by "clicking" on hyperlinks in the "Models" section of the spreadsheet.

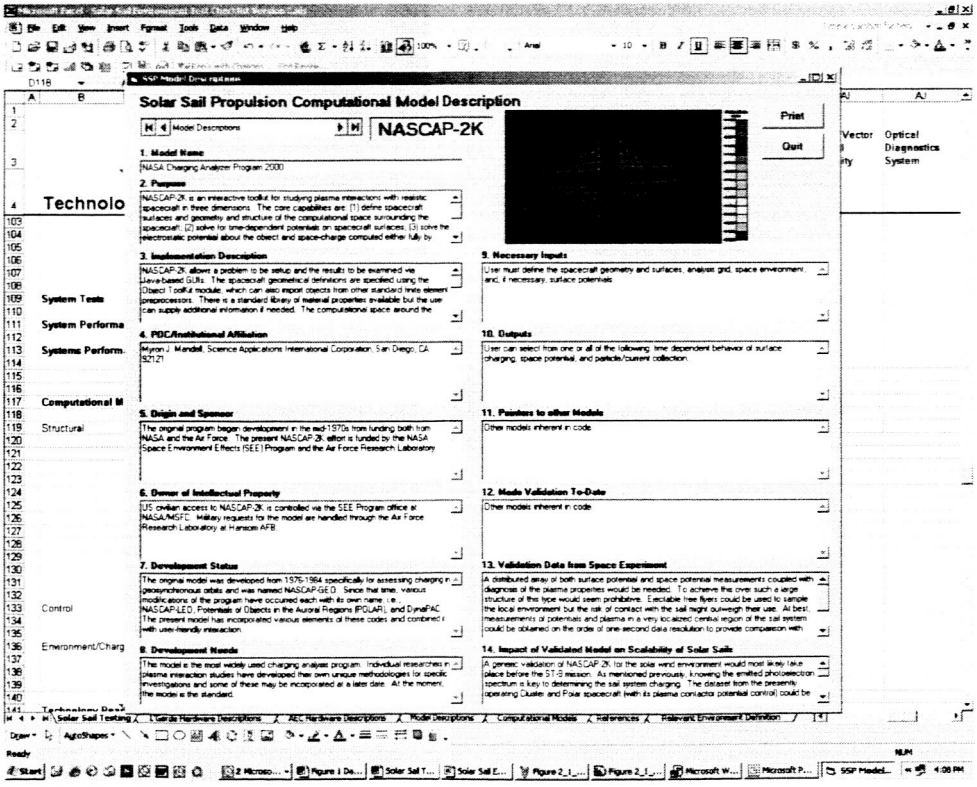
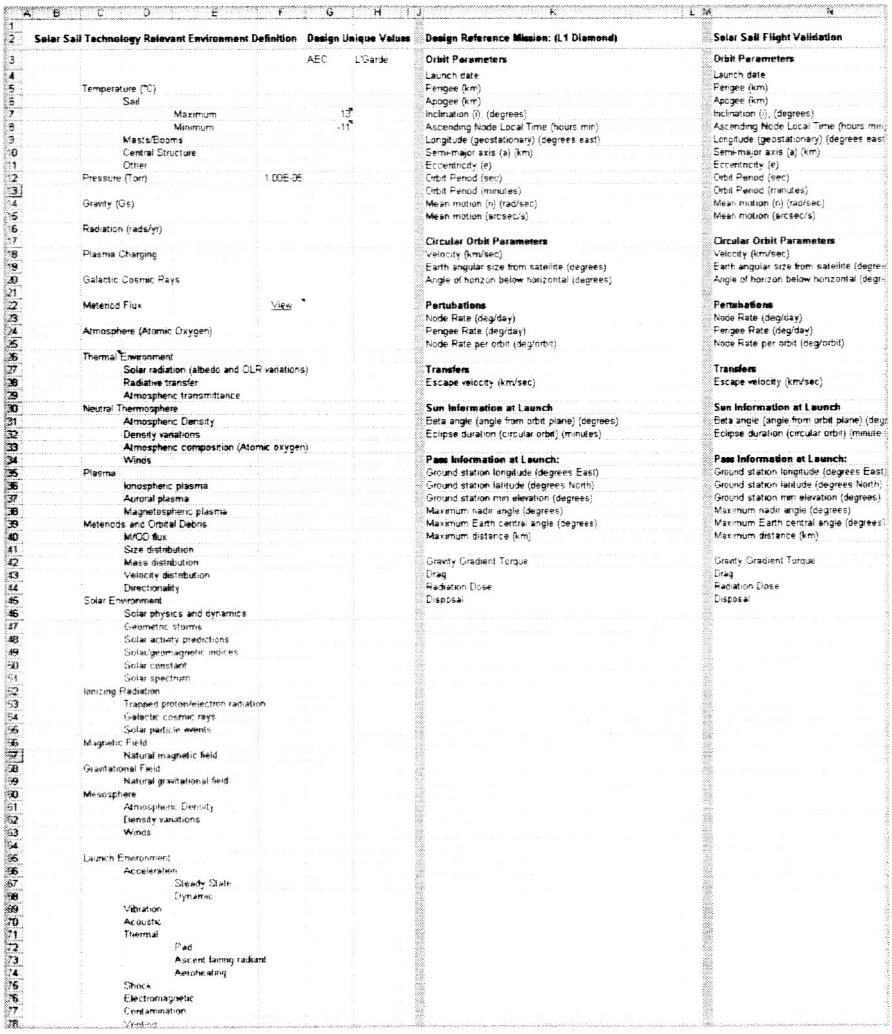


Figure 7. Computational Model Description Interface

D. Relevant Environment Definition

Another key element of advancing the TRL of a technology is defining the "relevant environment" for the technology. Data related to the relevant environment definition for solar sail technology is stored in a separate worksheet in the main workbook. This worksheet is illustrated in Figure 8. Environment conditions included in this worksheet include the launch environment (vibration, thermal, ascent venting). On-orbit environments include the vacuum level and thermal (solar direct heating, solar reflected heating and earth radiated infrared heating). On-orbit micrometeoroid/orbital debris, radiation, and atomic oxygen environments are also designated. The current design reference missions for Solar Sail Propulsion include the L1 Diamond mission and the Solar Polar Imager mission. Orbit parameters for the design reference missions are also stored in this worksheet. Another potential "relevant environment" to be considered is the ST9 Solar Sail Flight Validation (SSFV) Mission. The specific orbit parameters for this mission are still being determined. The most stringent environments for each of the missions will be considered in specifying the test conditions appropriate for relevant environment testing for TRL advancement.



Solar Sail Technology Relevant Environment Definition	Design Unique Values		Design Reference Mission: (L1 Diamond)	Solar Sail Flight Validation
	AEC	L1Garde	**Orbit Parameters**	**Orbit Parameters**
Temperature (°C)			Launch date	Launch date
Sail			Perigee (km)	Perigee (km)
Maximum		15°	Apogee (km)	Apogee (km)
Minimum		-11°	Inclination (i) (degrees)	Inclination (i) (degrees)
Masts/Booms			Ascending Node Local Time (hours min)	Ascending Node Local Time (hours min)
Central Structure			Longitude (geostationary) (degrees east)	Longitude (geostationary) (degrees east)
Other			Semi-major axis (a) (km)	Semi-major axis (a) (km)
Pressure (Torr)	1.00E-06		Eccentricity (e)	Eccentricity (e)
			Orbit Period (sec)	Orbit Period (sec)
Gravity (Gs)			Orbit Period (minutes)	Orbit Period (minutes)
			Mean motion (n) (rad/sec)	Mean motion (n) (rad/sec)
Radiation (rads/yr)			Mean motion (arcsec/s)	Mean motion (arcsec/s)
			Circular Orbit Parameters	**Circular Orbit Parameters**
Plasma Charging			Velocity (km/sec)	Velocity (km/sec)
			Earth angular size from satellite (degrees)	Earth angular size from satellite (degrees
Galactic Cosmic Rays			Angle of horizon below horizontal (degrees)	Angle of horizon below horizontal (degrees
			Perturbations	**Perturbations**
Meteroid Flux	View		Node Rate (deg/day)	Node Rate (deg/day)
			Perigee Rate (deg/day)	Perigee Rate (deg/day)
Atmosphere (Atomic Oxygen)			Node Rate per orbit (deg/orbit)	Node Rate per orbit (deg/orbit)
			Transfers	**Transfers**
Thermal Environment			Escape velocity (km/sec)	Escape velocity (km/sec)
Solar radiation (albedo and OLR variations)				
Radiative transfer			**Sun Information at Launch**	**Sun Information at Launch**
Atmospheric transmittance			Beta angle (angle from orbit plane) (degrees)	Beta angle (angle from orbit plane) (degr
Neutral Thermosphere			Eclipse duration (circular orbit) (minutes)	Eclipse duration (circular orbit) (minutes
Atmospheric Density				
Density variations			**Pass Information at Launch:**	**Pass Information at Launch:**
Atmospheric composition (Atomic oxygen)			Ground station longitude (degrees East)	Ground station longitude (degrees East)
Winds			Ground station latitude (degrees North)	Ground station latitude (degrees North)
Plasma			Ground station min elevation (degrees)	Ground station min elevation (degrees)
Ionospheric plasma			Maximum nadir angle (degrees)	Maximum nadir angle (degrees)
Auroral plasma			Maximum Earth central angle (degrees)	Maximum Earth central angle (degrees)
Magnetospheric plasma			Maximum distance (km)	Maximum distance (km)
Meteroids and Orbital Debris				
M/OD flux			Gravity Gradient Torque	Gravity Gradient Torque
Size distribution			Drag	Drag
Mass distribution			Radiation Dose	Radiation Dose
Velocity distribution			Disposal	Disposal
Directionality				
Solar Environment				
Solar physics and dynamics				
Geometric storms				
Solar activity predictions				
Solar/geomagnetic indices				
Solar constant				
Solar spectrum				
Ionizing Radiation				
Trapped proton/electron radiation				
Galactic cosmic rays				
Solar particle events				
Magnetic Field				
Natural magnetic field				
Gravitational Field				
Natural gravitational field				
Mesosphere				
Atmospheric Density				
Density variations				
Winds				
Launch Environment				
Acceleration				
Steady State				
Dynamic				
Vibration				
Acoustic				
Thermal				
Rad				
Ascent/entry radiant				
Aeroheating				
Shock				
Electromagnetic				
Contamination				
Venting				

Figure 9. Relevant Environment Definition

E. Technology Readiness Level Definitions

The final section of the main worksheet addresses the TRL assessment of the technology. Descriptions of the requirements for each of the TRL levels are included in this section of the "Solar Sail Testing" worksheet. These definitions will be used to determine when each of the TRL milestones has been reached. Figure 10 illustrates the TRL definitions section of the "Solar Sail Testing" worksheet.

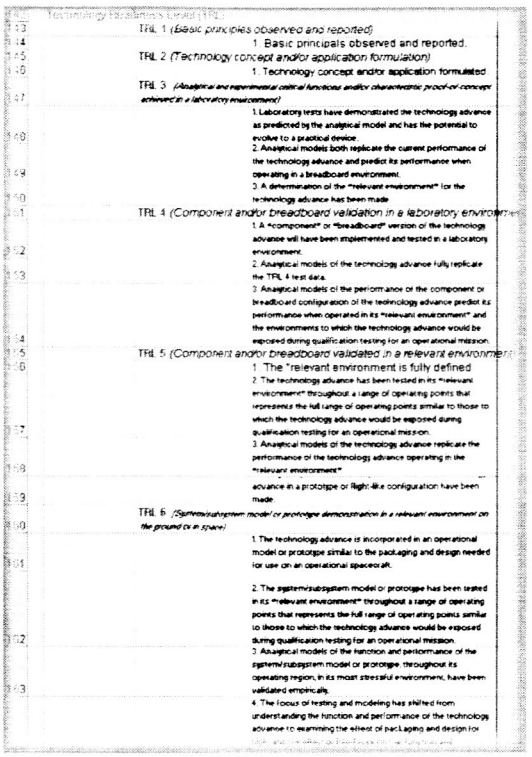
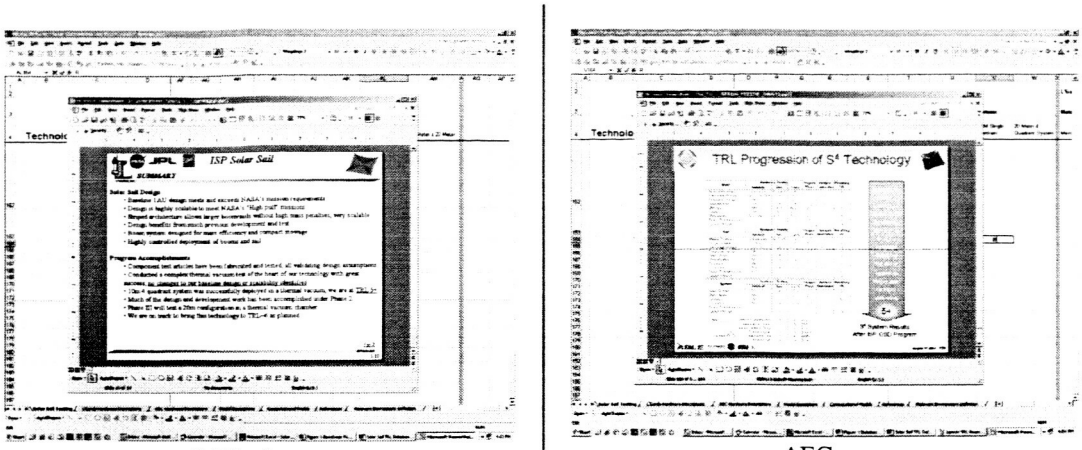


Figure 10. Technology Readiness Level (TRL) Definitions[2]

F. TRL Assessment

To assess the TRL of the technology, the definition of each TRL is compared with the results of the tests, analyses, and model validation results contained in the rows for each of the hardware items. As the requirements for TRL milestones are satisfied, the TRL for that hardware item is advanced. Individual engineering judgment does play a role in the assessment of technology maturity. However, the Solar Sail TRL Assessment Database will facilitate the comparison of TRL requirements with technology task completion. Current internal TRL assessments made by the L'Garde and AEC teams are illustrated in Figure 10. NASA is in the process of performing a separate TRL assessment of the state of solar sail technology. This assessment will be added to the database when it is completed.



L'Garde AEC

Figure 10. L'Garde and AEC TRL Assessment

G. Status and Future Database Additions

Testing of 10 meter solar sail systems by both AEC (at the LaRC 16 Meter Diameter Vacuum Chamber) and L'Garde (at the GRC Plum Brook 100 Foot Diameter Vacuum Chamber) has been completed. Results of these tests are being added to the database. 20 meter system testing, including the demonstration of a thrust vector control system, will occur in the spring of 2005. These results will also be added to the TRL database.

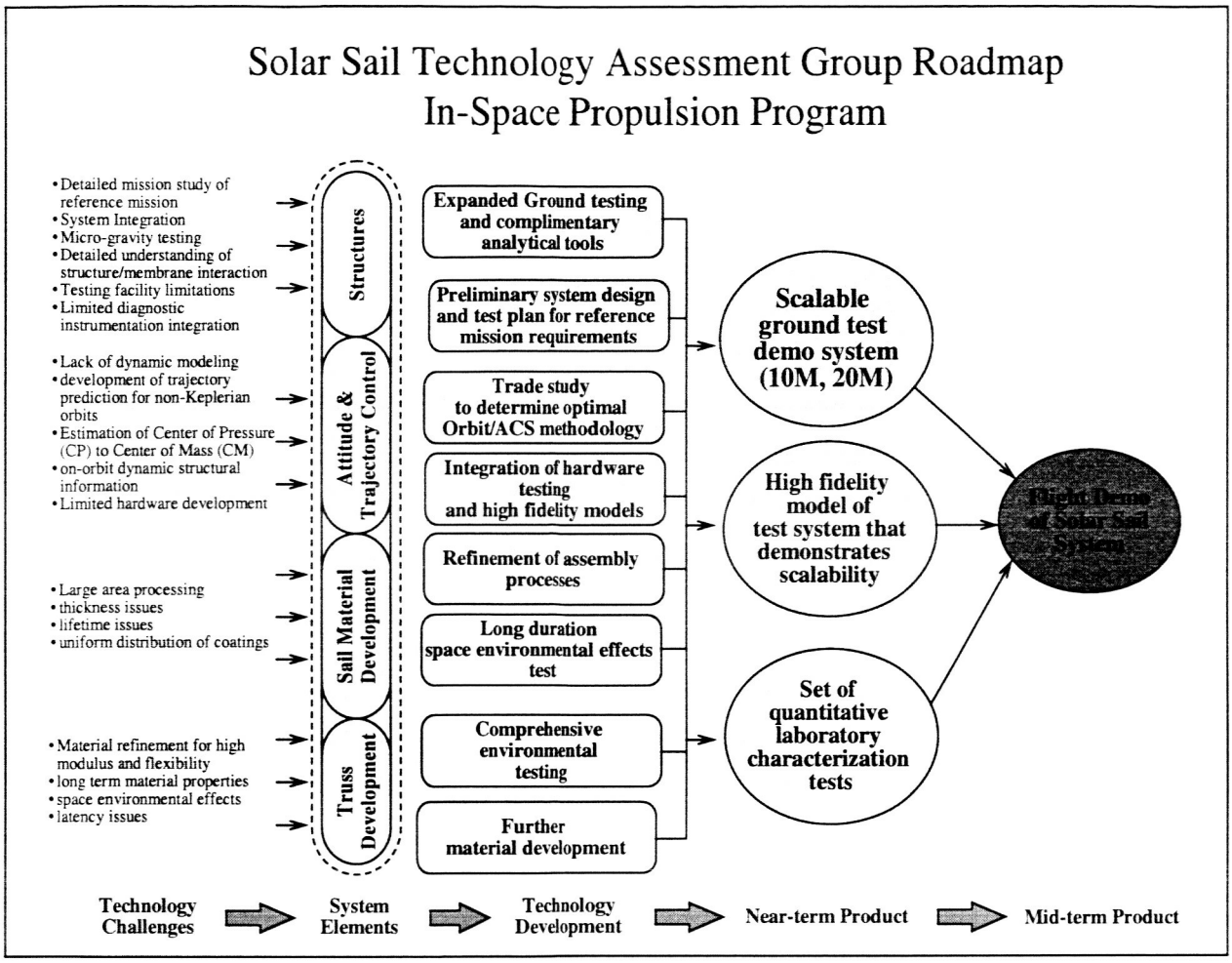
Relevant environment definitions are in progress. Following detailed definition of the proposed ST9 Solar Sail Flight Validation orbit, the launch and on-orbit environments will be defined for the mission. This will allow the complete relevant environment to be defined.

Required model input and output data requirements are being gathered for each of the models under development to support model validation. Correlation of model predictions with the test results will be entered into the computational model section of the spreadsheet as these correlation activities are completed.

H. Summary

A TRL assessment database has been developed for solar sail technology. This database provides centralized access to all of the results of hardware development testing activities, model development and correlation efforts and relevant environment definitions. The database structure can be easily reconfigured or expanded as necessary to accommodate additional data handling requirements. The database is organized to provide centralized storage and access capabilities for all of the technology development results reporting, providing an automated tool for evaluating the TRL of solar sail technology.

Appendix



Acknowledgment

The efforts reported on in this paper are sponsored under the SAIC Integrated Space Technology Assessment prime contract with the Marshall Space Flight Center In-Space Propulsion Technology Projects Office.

References

[1]"Solar Sails Technology Assessment Group Final Report", G. Garbe, NASA/MSFC, January 29, 2002.

[2] New Millennium Program (NMP), Technology Readiness Levels for the New Millennium Program, May 22, 2003, Version 1.