INFLATABLE SPACE STRUCTURES TECHNOLOGY DEVELOPMENT FOR LARGE RADAR ANTENNAS

R.E. Freeland
Jet Propulsion Laboratory
California Institute of Technology

Richard G. Helms
Jet Propulsion Laboratory
California Institute of Technology

M. M. Mikulas
University of Colorado

Wayne Stuckey
The Aerospace Corporation

Gary Steckel
The Aerospace Corporation

Judith Watson
NASA Langley Research Center

Paul Willis
Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

There has been recent interest in inflatable space-structures technology for possible applications on U.S. Department of Defense (DOD) missions because of the technology's potential for high mechanical-packaging efficiency, variable stowed geometry, and deployment reliability. In recent years, the DOD-sponsored Large Radar Antenna Program (LRA) applied this new technology to a baseline concept: an inflatable/rigidizable (RI) perimeter-truss structure supporting a mesh/net parabolic-reflector antenna. The program addressed (a) truss concept development, (b) rigidizable materials concepts assessment, (c) mesh/net concept selection and integration, and (d) developed potential mechanical-system performance estimates. Critical and enabling technologies were validated, especially orbital radiation durable rigidized materials, and high modulus, inflatable-deployable truss numbers.

These results in conjunction with the U.S. Defense Advanced Research Projects Agency (DARPA) sponsored mechanical-packaging structures studies were the impetus for the initiation of the DARPA/SPO Innovative Space-based Antenna Technology (ISAT) Program. The sponsor's baseline concept consisted of an inflatable-deployable truss structure for support of a large number of rigid, active radar panels. The program was intended to determine the risk associated with the application of these new structures and radar technologies. The approach used to define the technology maturity level of critical, structural elements was to: (a) develop truss concept configuration, (b) advance inflatable-rigidizable materials technologies, and (c) estimate potential performance. The results of the structures portion of the program indicated there was high risk without the appropriate technology flight experiments, but only moderate risk if the appropriate on-orbit demonstrations were performed.

Part 1: Large Radar Antenna Technology Program

I. Introduction

The results of the NASA-sponsored Inflatable Antenna Experiment (IAE)[1,2,3,4,5] illuminated high potential mechanical performance in specific areas of serious interest to the DOD. Specifically, in technology for mechanical-packaging efficiency, variable stowed geometry, deployment reliability, and low-cost hardware for very large reflector-antenna systems. In order for the DOD to establish the potential package volume savings of these technologies for a specific class of reflector-antenna systems, a technology-assessment study was initiated. This study addressed the generation of estimates of potential mechanical performance for a reference reflector-antenna functional configuration definition. After considering a number of structural configurations, the sponsor picked a specific hybrid-configuration design to develop. This new design was based on combining an inflatably deployed, orbitally rigidized perimeter support truss with a metallic mesh reflector that was contoured by a flexible net structure (see Figure 1).

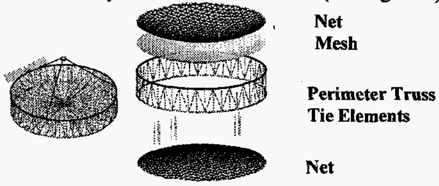

Fig. 1. LRA Baseline configuration

Such a flexible system, prior to rigidization, had great potential for packaging a very large antenna structure into a reasonably sized launch vehicle with all the associated cost savings.

II. Large Radar Antenna Program

The Large Radar Antenna Program (LRA) was initiated to: (a) identify the critical, enabling technologies, (b) evaluate competing technology options, (c) select the most promising technologies for experimental characterization to the extent possible, (d) advance critical, enabling technology maturities to enable meaningful evaluations, and (e) generate estimates of potential mechanical performance, based on the program's technology database. The specific technical tasks emerging from program objectives include (a) functional mechanical performance requirements, (b) an antenna mechanical system configuration, (c) concepts for on-orbit rigidization of the flexible materials, and (d) the development and application of analytical models to predict very large radar antenna on-orbit mechanical performance.

III. Program Approach

The LRA program was unique in that it was the first application of a totally new and low maturity technology to a *very* large, high precision space structure during a climate of low U.S. national technology resources. Available resources and expertise had to be identified and integrated with an approach that recognized the program's cost and schedule constraints. The resulting team consisted of the appropriate participants from JPL, The Aerospace Corp, Langley Research Center, University of Colorado Center for Space Construction, and L'Garde, Inc. This team collectively addressed the program objectives and implemented the technical tasks. The program flow diagram, Figure 2, delineates functional and institutional interactions.

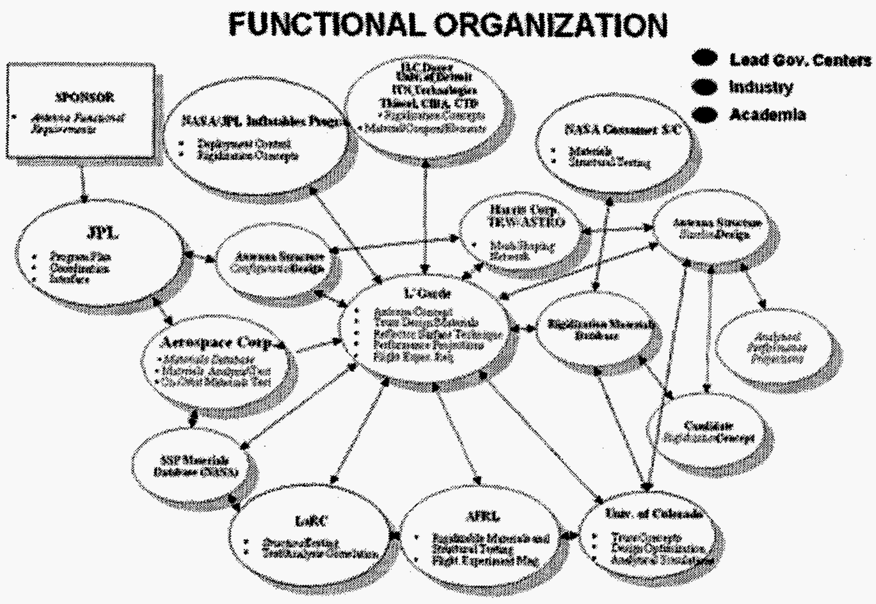

Fig. 2. Large Radar Antenna program flow diagram

IV. Program Implementation

Program implementation depended on the specific technical task(s) the LRA team members managed. Additionally, the program benefited from the consultation from several highly specialized experts with general support from others. The integral of the outputs from the tasks and other related activities resulted in a successful assessment of the key and enabling technologies.

V. Functional Requirements

The LRA functional requirements were derived from a class of mission concepts. As a consequence, requirements varied depending on the specific performance parameter. It should be noted that such parametric variations tended to converge in proportion to the *increase* in concept feasibility, and the program's degrees of freedom. Mechanical functional requirement estimates are found in Figure 3.

Large Radar Antenna Requirements	
Aperture Diameter	Same as AIAT baseline
Range of Orbits	Medium to High
F/D (range)	0.5 to 1 (Baseline F/D = .5)
Highest Operation RF Frequency	F = same as AIAT
RF Feed Configuration/Options	TBD
Antenna Surface Precision	ε = 2.00 mm rms (1.00 mm goal)
Operational Lifetime	Five year requirement, ten year goal
Materials Outgassing Req. (min. Levels)	<1% TML, 0.1% CVCM>
Maximum Slewing Rates/Range	Angular acceleration about three axis of: TBD < α < TBD
Deployed Max. Acceleration	±0.005 g
Deployed Stiffness Characteristics	TBD
Contamination	TBD
ESD/Constraints	Each Cond. layer of MLI is grounded
Settling time	TBD
Launch Vehicle Options	TBD
Launch Vehicle Shroud Options	TBD

Fig 3. Large Radar Antenna program flow diagram

VI. LRA Mechanical-System Configuration Development

The mechanical system configuration definition was based on a number of requirements and considerations that included the (a) sponsor selected hybrid structural system concept, (b) LRA RF geometric design, (c) LRA system mechanical performance requirements, (d) selection and integration of a concept for the mesh/net reflector structure, (e) anticipated truss tube orbitally rigidized materials stiffness, and (f) loading imposed on the perimeter truss resulting from the tension field in the mesh net structure. The starting point was the LRA baseline reflector antenna configuration patterned after the previously developed and successfully flown Astro Aerospace Corp. *Astro-mesh Reflector*.

The LRA baseline truss concept was developed by L'Garde, Inc., which had recently innovated, designed, manufactured, and flown the IAE. The University of Colorado *Center for Space Construction* assisted L'Garde with *critical* performance analysis. The candidate perimeter inflatable deployable truss configurations were developed and characterized by a new and automated design/analysis code.

More to the point, the LRA baseline antenna design needed an optimized perimeter truss design mass and stowed package. Various truss types were compared including the (a) standard, (b) two-story, (c) prestressed, (d) offset, (e) Warren, and (f) diamond truss (with diameter variations between the top and bottom "longeron ring"). See Figure 4.

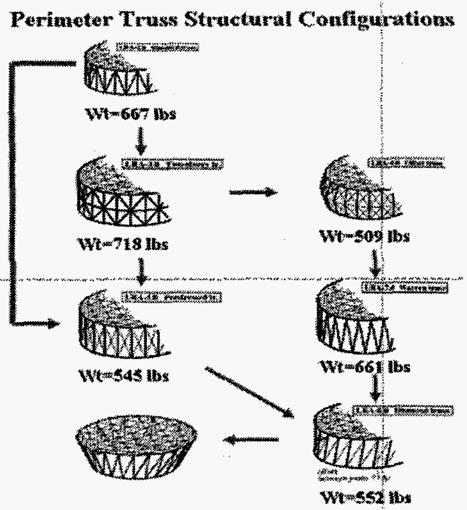

Fig. 4. Large Radar Antenna Truss Structure Concepts

The Astro-Mesh's utilization of two "back-to-back" mesh/net structures inter-connected with multiple ties was the starting point for the LRA baseline. The primary structures difference between the LRA baseline and the Astro-Mesh antenna was that the latter used an all-mechanical perimeter support truss.

As to other modifications that made the LRA a hybrid, consider the Tension Drum innovation, developed by the University of Colorado, with support from L'Garde, Inc, Figure 5. The tension drum acted as a transition structure that interfaced the inflatable truss with the mesh/net reflector structure. Its purpose was to support the reflector surface with a stable, high precision "inner" perimeter tension strap truss while "isolating" the mesh from manufactured/deployed/thermal irregularities in the outer RI truss. This technique transferred the requirement for high precision from the RI truss to this secondary "tension" structure.

This mechanical system configuration study resulted in a number of candidates which resulted in a downselect to the *tension drum* in combination with the *standard* truss configuration.

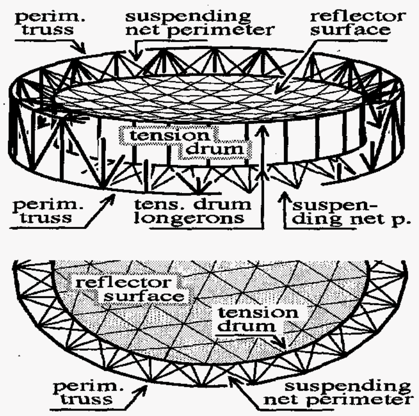

Fig 5. Open ring and tension-drum concepts

VII. Rigidizable Materials Concepts Evaluation

This task addressed the technology maturity level and *applicability* of specific concepts for the orbital rigidization of flexible materials to the LRA structural system. This was accomplished through (a) identification of existing concepts, (b) evaluation of existing data base, (c) selection of potential concepts, (d) experimental characterization of promising concepts and (d) technology advancement of high potential concepts to enable meaningful assessment.

The materials Rigidization task began with the deterimination of criteria for the evaluation of truss tube rigidization concepts, Figure 6. These criteria were developed by the "Team" and applied to a technology database that was compiled from various programs between 1987 and 1999. The results of this process identified three basic classes of concepts as the most promising to warrant their continued investigation. These *composite materials* concepts included (a) UV rigidizable, (b) Sub-Tg rigidizable/thermoplastics and elastomeric, and (c) thermoset rigidizable. The aforementioned technology database as it applied to each of these concepts was then used as the starting point to project more realistic estimates of potential performance (see summary Figure 7).

The technology advancements were based on (a) experimental characterization, (b) tailored laminate designs, (c) specialized fabrication techniques and (d) functional and mechanical performance tests (see Figure 8 as an example). This test matrix, used for each concept, identified all the tests, hardware, responsible organizations, and schedule.

Evaluation Criteria & their Importance Rating for Selecting Rigidization Technique in Space

Criteria	*Importance Rating* (0 to 1.0)
• MECHANICAL PROPERTIES	1.0
• STRUT ACCURACY & PRECISION (REPEATABILITY)	1.0
• PACKAGING EFFICIENCY	1.0
• RESISTANCE TO SPACE ENVIRONMENT	1.0
• TRUSS WEIGHT	0.9
• IMPLEMENTATION COMPLEXITY	0.9
• GROUND TESTABILITY	0.9
• RELIABILITY & SIMPLICITY	0.9
• THERMAL STABILITY (CTE, SHRINKAGE)	0.9
• OUTGASSING BEFORE, DURING & AFTER RIGIDIZATION	0.8
• REPEATABILITY & PRECISION OF DEPLOYMENT	0.8
• STOWAGE & SHELF LIFE LIMITATION	0.7
• POSITIVE RIGIDIZATION CONTROL	0.7
• *OTHERS..*	

Fig. 6 Evaluating Rigidizing Techniques

	Advantages	Disadvantages
Aluminum Laminate Thin shelled aluminum structure, high pressure removes packaging wrinkles & work-hardens aluminum leaving very stable structure	• High modulus • Mature concept,space environment qualified • No power requirements • Ground testable before flight • No shelf life limitation • No auxilliary equipment & hardware • Positive rigidization control • Unlimited pre-deployment life time • Stable material	• Thickness limited, limited scalability • 120 lb max compression • Requires higher pressures for rigidization • High CTE • Difficult to implement for complex structures
Sub Tg/Thermoplastic Composite matrix becomes rigid below a tailorable temperature	•Simple passive rigidization •Reversible and ground testable •Long shelf -life •No maximum thickness limitations •Tailorable Tg (glass transition temperature) •No auxiliary equipment and hardware • Composite manufactured on ground •Unlimited pre-deployment life time •Stable matrix •No need to control pre deployment environment • Low CTE	•Thermal environment requirements •May require low power heaters for deployment • Less mature

Fig. 7. LRA Rigidization Materials Tradeoffs

TEST	Sub-Tg[6] (Urethane-based)	Sub-Tg[7] (Epoxy-based)	Thermoset[6,8,9,10] (0 Candidates)
Modulus of Tubes			
Test Method	Vibration*	Vibration*	Vibration*
Sample Required	Tube	Tube	Tube
Sample Size	36" (L) x 4"(D) x 0.012"(T)	36" (L) x 4"(D) x 0.012"(T)	36" (L) x 4"(D) x 0.012"(T)
Sample Condition[1]	D,E	D,F	B,D
N of Samples	3	3	3
Facility	NASA Langley	NASA Langley	NASA Langley
Contact Person	Judith Watson	Judith Watson	Judith Watson
Phone Number	(757)864-3116	(757)864-3116	(757)864-3116
Start Date[12]	TBD	TBD	Oct. 15, 1999
End Date	TBD	TBD	TBD
Temperature Range	TBD	TBD	TBD
Modulus & Poisson's Ratio of flat coupons, E1 ,E2, Nu			
Test Method	DMA	DMA	DMA
Sample Required	Flat coupon	Flat coupon	Flat coupon
Sample Size	6" x 6"	6" x 6"	6" x 6"
Sample Condition[1]	E[15]	F[15]	A,B[15]
N of Samples	1	1	1
Facility	Aerospace	Aerospace	Aerospace
Contact Person	Wayne Stuckey	Wayne Stuckey	Wayne Stuckey
Phone Number	(310) 336-7389	(310) 336-7389	(310) 336-7389
Start Date[12]	TBD	TBD	Sept. 30, 1999
End Date	TBD	TBD	TBD
Temperature Range	TBD	TBD	TBD

* Non-Destructive

Fig. 8. Test Matrix (Example) for the Large Radar Antenn

The test matrix illuminates the large number of necessary characterizations. However, in terms of the risk of using this new technology, there were two key and critical issues that had essentially no meaningful database at the initiation of the program. These issues were the (a) orbital radiation durability of rigidized flexible materials and (b) feasibility of achieving high modulus rigidized truss tubes on-orbit. They represented major challenges to the LRA Program.

The characterization and validation of space radiation durability of rigidized flexible materials were accomplished through accelerated radiation testing. Sample coupons of all the materials under evaluation were exposed to medium to high doses of simulated orbital radiation equivalent to 10 years. The coupons were periodically removed and tested for modulus, CTE, outgassing, and surface degradation in intervals equivalent to 2 to 3 years of on-orbit exposure. The testing was done at the Aerospace Corporation arranged in sample/chamber configurations as illustrated by Figure 9.

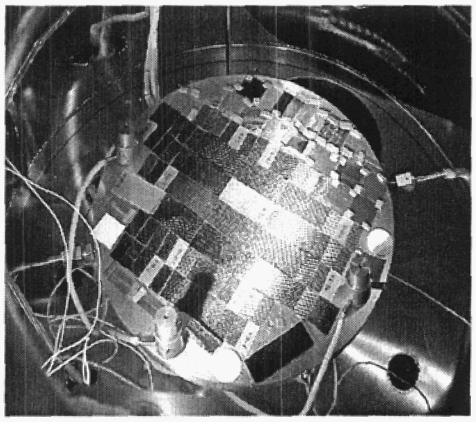

Fig. 9. LRA Samples in Test Chamber

The test results indicated that a number of exposed materials showed surprising durability in their modulus and CTE. Figure 10 is a generic plot of sub Tg resins that were being developed at L'Garde, Inc. for the LRA Program. The experimental results clearly indicated the high potential of this class of materials for space applications.

Placeholder for Fig. 10

Large Radar Antenna Requirements	
Aperture Diameter	Same as AIAT baseline
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Highest Op	
RF Feed C	
Antenna S	m goal)
Operations	n year goal
Materials (min. Levels)	
Maximum Slewing Rates/Range	Angular acceleration about three axis of: TBD < α < TBD
Deployed Max. Acceleration	±0.005 g
Deployed Stiffness Characteristics	TBD
Contamination	TBD
ESD/Constraints	Each Cond. layer of MLI is grounded
Settling time	TBD
Launch Vehicle Options	TBD
Launch Vehicle Shroud Options	TBD

Fig. 10. Materials Properties as a Function of Radiation Dosage

The potential of this new technology for achieving high modulus truss members on orbit was further addressed by the development of realistic size test hardware, and mechanical laboratory characterization. The detail designs of the truss strut elements were a function of (a) the specific rigidization concept, (b) loading and stiffness requirements, and (c) fabrication techniques capability. A minimum statistical test set of three strut samples was used. Four-inch (full-scale) diameter and 3m (scaled) length tubes, were tested as representative of full-sized truss bays. All of the strut testing was done at the NASA Langley Research Center and all the truss test hardware was developed and fabricated by L'Garde, Inc. The modulus was determined by bend testing and axial capability by tension/compression testing, Figures 11 and 12.

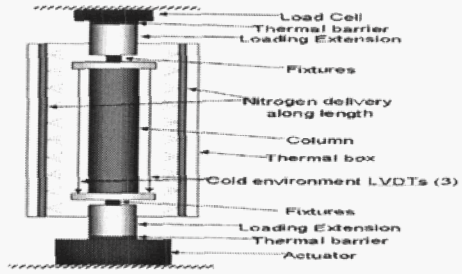

Fig. 11 Cold Axial Test Setup

Modulus test results (see Figure 12) exceed the minimum required capability of 3 MSI.

Column	Axial Tension	Axial Compression	Bending 0deg/90deg
CTS-TPC-LGD-15-TUB-01,	4.8762e+06	4.90003E+06	4.22470E+06/ 4.26970E+06
CTS-TPC-LGD-15-TUB-02,	4.81109E+06	4.76166E+06	4.16650E+06/4.02211E+06
CTS-TPC-LGD-15-TUB-03,	4.83630E+06	4.78181E+06	4.28260E+06/4.26270E+06
CTS-TPC-LGD-13-TUB-01,	5.32580E+06	5.23370E+06	4.87806E+06/4.86115E+06
CTS-TPC-LGD-14-TUB-01,	5.60750E+06	5.56410E+06	4.96300E+06/5.05670E+06
CTS-TPC-LGD-14-TUB-02,	5.54920E+06	5.42763E+06	4.86340E+06/ 4.75850E+06
CTS-TPC-ILC-16-TUB-01,	5.86500E+06	5.81203E+06	5.26060E+06/ 5.35110E+06
CTS-TPC-ILC-16-TUB-02,	5.92970E+06	5.91650E+06	5.30390E+06/ 5.41146E+06
CTP-STG-LGD-xx-TUB-01,	13.5467E+06	12.8217E+06	10.7422E+06/ 10.2476E+06
CTP-STG-LGD-xx-TUB-02,	13.8227E+06	13.4377E+06	9.54650E+06/ 9.15487E+06
CTP-STG-LGD-xx-TUB-03,	12.9372E+06	13.1823E+06	9.23210E+06/ 10.3775E+06

Fig. 12. Typical Strut Mechanical Results (psi)

VIII. Summary

The two-year LRA Program resulted in a number of meaningful developments including (a) experimental characterization of promising concepts for the RI flexible materials, (b) development of an optimal-perimeter truss concept that emerged from eight candidates, (c) estimates of potential mechanical performance for a very large hybrid antenna structure, and (d) definition of an effective interface between an inflatable truss and a flexible mesh-net reflector system.

But, the most significant developments – major inflatable structures technology advancements – were validating rigidized materials space-radiation durability, *and* the high modulus of rigidized, inflatable truss-structure elements.

Part 2: Innovative Spacebased Radar Antenna Technology Program

I. Introduction

DARPA's interest and pursuit of structures technologies for enabling a new class of very large sized, active planar radar antennas had illuminated the need for deployable structures with very high mechanical-packaging efficiency and variable stowed geometry. Its recognition of the potential of rigidizable/inflatable space structures, along with the LRA Program results, helped prompt the creation of the Innovative Spacebased Radar Antenna Technology Program (ISAT).

The structures portion of the ISAT program was established to determine the risk associated with applying this new, low-maturity technology to DARPA's baseline radar-antenna concept, Figure 1. The large dimensions of the RF planar array antenna -- hundreds of meters long and a few meters wide -- suggested a truss-type backup structure. With many repeating bays, it lent itself well to RI structures technologies where only a single-launch vehicle might be required.

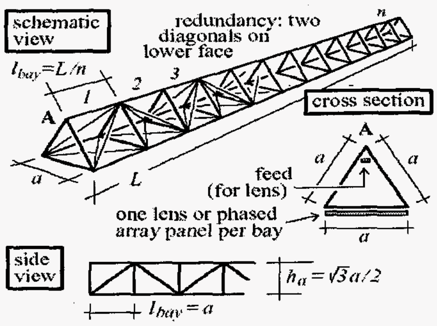

Fig. 1 ISAT Baseline Configuration Design

The ISAT program addressed the generation of system mechanical requirements, development of generic inflatable deployable truss configuration designs, advancement of the technology database for concepts for the rigidization of flexible materials, and projections of on-orbit mechanical performance.

II. The ISAT Program

The ISAT Program was a "risk" assessment activity designed and structured to establish the viability of Rigidizable Inflatable (RI) Technologies for application to a structure supporting a large number of rigid, active radar panels. The program was intended to advance previously selected RI technologies to enable such an assessment. Specific truss concepts were developed and analytically evaluated using generated statistical mechanical test data from full-scale RI structural elements. The constitutive mechanical behavior was characterized empirically and phenomenologically. This intrinsic mechanical behavior was then incorporated into high-fidelity structural models to simulate the radar-antenna performance. The overall program assessment was based on technology potential regarding system requirements, and current maturity level.

The program focused on specific technical task results that addressed the objectives. Tasks were grouped into categories that addressed (a) truss-structure concept definitions, (b) rigidizable-materials concepts, and (c) structural performance simulation.

III. Program Approach

The risk-assessment approach was so synergistic to the LRA application feasibility study, that the same LRA technical team, with a few additions, was used for ISAT (see LRA Figure 2). This team was responsible for all aspects of the implementation of the structures program.

- **Free-free frequency (f = 0.05 Hz, T = 20 secs)**
  ***Assumption*: All mass distributed along beam**
- **Strut buckling due to boost load (g = 0.001)**
- **Strut slenderness ratio (L/d < = 100)**
- **Stowage volume**
- **Controlled deployment**
- **Predictable behavior?**
- **Dimensional stability?**

Fig 2. ISAT Primary Truss Antenna Structural Guidelines

The most significant change was the addition of ILC Dover for the introduction of additional concept(s) for the orbital rigidization of flexible materials, and innovative planar truss strut structural configurations.

There were a number of obvious but different approaches for determining the risk associated with applying a relatively new technology to a specific and challenging class of antenna structures. The implementation of this assessment required the selection of an approach/technique that could be implemented with the LRA/ISAT inflatable structures technology database and, at the same time, was familiar and acceptable to the program sponsor. A well known and frequently used codification that addressed technology maturity definitions was the NASA Technology Readiness Level (TRL) System, which was based on fairly simplified narrative descriptions of each technology level. Potential ISAT risk was driven by (a) the inflatable-rigidizable materials concepts maturity, (2) truss-structural system definition maturity, (3) risk associated with advancing enabling/supporting technologies to the point of flight, and (4) how well projected performance met mechanical/structural system requirements. Accordingly, applying the NASA TRL System to ISAT seemed appropriate and straightforward.

Since the database in each technology area addressed by the ISAT program, came directly from the specific program technical tasks and their interactive results, a modular format was selected for the task definitions and result summaries. The individual, technical tasks managed by the technology experts directly correlated with the TRL system rationale. Primarily, task results, along with technology databases from related DOD, NASA, and other relevant programs, determined ISAT structural technology element maturities. Technologies were separated into three areas: (a) critical and enabling, (b) secondary, supporting, and (c) ground-based, supporting.

IV. Program Technical Tasks

The technical tasks were formulated and organized such that their integral results satisfied the overall program objectives. Each technical task was managed by a recognized authority in their respective technology areas. Extensive interaction between the tasks was necessary for the effective dissemination and utilization of task results. The task descriptions and their activities are briefly summarized below. There were three generic technology areas consisting of several sub-elements.

A. Truss Structure Concept Definition

This task addressed the development and evaluation of candidate support truss concept definitions for the purpose of structural optimization.

1. ISAT Truss Design Considerations

The design guidelines (Figure 2) and/or considerations were the basis for developing an optimized ISAT antenna truss structure design (Figure 3).

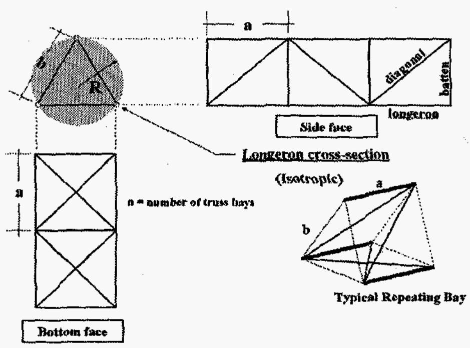

Fig. 3. ISAT Thrust Definitions

Basic design considerations included (a) structural stiffness for robust control, (b) antenna and truss tube length-over-diameter ratios to optimize antenna stiffness, (c) structural mass, (d) mechanical packaging, (e) truss-tube mechanical design properties, (f) truss loading, and (g) orbitally induced deformations. TRL estimates were made for this specific truss-design procedure. Parametric trades included (a) longeron diameter as a function of bay size, (b) truss weight as a function of bay size, (c) antenna modal frequency variation due to mass and its distribution, and (d) effect of truss design on antenna-thermal distortion. Figure 4 is an example of such results.

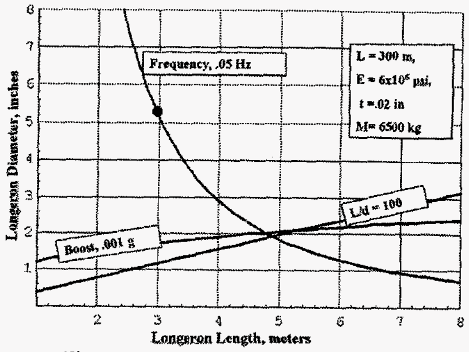

Fig. 4. Longeron Diameter vs. Bay Size

2. Structural Analysis and Design

Structural system analysis and design for the ISAT optimized truss structure addressed very large truss structural behavior, structural design of truss tubes, and buckling issues for orthotropic composite truss members. Such analysis was fundamental to the detailed design of a large truss using inflatable/rigidizable structural elements. Two basic structural element concepts were evaluated in the program: the Isogrid woven tube from ILC Dover, and the more conventional, solid monocoque thin-walled cylinder by L'Garde, Inc. The Isogrid construction is shown here as an example of the design and analysis approach used, Figure 5.

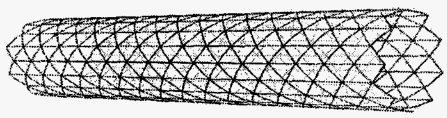

Fig. 5. ISAT Isogrid Truss Tube Configuration

The analytical-simulation tools combined and compared both standard finite-element analysis and new analysis techniques. Specific issues addressed included Isogrid truss tube grid spacing (Figure 6), local composite tube wall buckling where mass was minimized as a function of loading, and the structural and thermal behavior of very large truss structures. This included the effects of structural-element manufacturing imperfections. The design optimizations made at L'Garde, Inc. for its monocoque tube concepts were also thoroughly investigated with similar trades.

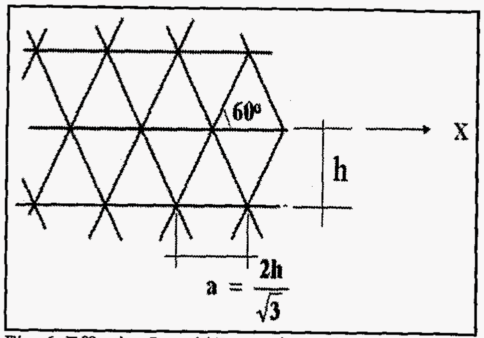

Fig. 6. Effective Isogrid Properties: Micro-mechanical Approximations

B. Rigidizable Materials Concepts Evaluation

This task addressed the determination and experimental verification of the technology maturity levels of specific concepts for the orbital rigidization of flexible materials.

1. Micro-Mechanical Analysis

Micromechanics analysis and measured mechanical properties correlation with the analytical predictions were base-lined to develop the ISAT truss RI structural composite members, Figure 7. This was to ensure the predictability and repeatability of the primary mechanical properties including all moduli and coefficient of thermal expansions, which control the truss-structure dimensional accuracy. The objective here was to establish that the fiber-dominated rigidizable composite properties correlated well with the micromechanics theory predictions. (Another sentence needed on what's involved) + Figure 7)

Table E-1. - KEVLAR 49 fiber properties.
(From Dupont Data Manual for KEVLAR 49, May 1986)
Room temperature static data for KEVLAR 49 (FIBERS)

Property	U.S. Customary
Axial modulus	$18x10^6$ psi
Transverse modulus	$1x10^6$ psi
Shear modulus	$0.4x10^6$ psi
Poisson's ratio	.36
Strain to break	.029
Tensile strength	525,000 psi
α_1, Thermal coefficient of expansion	$-2.9x10^{-6}$ in/in/°F
α_2, Transverse coefficient	$23x10^{-6}$ in/in/°F
Density	0.052 lb/in^3

Fig. 7. Micromechanical Materials Properties

2. Column Design, Manufacturing and Database

This task addressed integrating the truss longeron detailed mechanical design data with the associated manufacturing process to develop the technology databases. A particularly important portion of this database contained statistical experimental mechanical characterizations of realistically sized structural elements.

The purpose of the database was to capture and archive design details, materials properties, test results, and to highlight the manufacturing processes used for the inflatable structures investigated. The subject technology databases were formatted to enable (a) easy access for archival review, (b) illumination of composite-materials properties from micromechanics analysis for correlation with constitutive behavior, (c) manufacturing approaches for subsequent development, and (d) structural test results to determine capabilities for this new class of space structures. Figure 8 summarizes the matrix of the database information.

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Fig. 8. ISAT Materials Database Summary

3. Materials Technology Risk Assessment

Materials technology risk assessment for potential space structures was approached from several perspectives. One of these approaches was Aerospace Corporation's contribution to risk assessment by making detailed coupon sample laboratory measurements for the larger ISAT structures.

This data served several purposes: (a) materials property data required for the analytical models of the space-structure mechanical performance, (b) verification of the accuracy of inputs used in the predictive models, and (c) that materials design requirements were met. The data was also used to help understand NASA Langley Research Center (LaRC) tube measurements, which should correlate with the laboratory sample measurements. Additional data not obtained in the LaRC tests could be obtained in laboratory measurements, e.g., damping and temperature-dependent properties.

For the materials being considered, understanding the property temperature dependence was critical to their successful use. Aerospace Corporation Laboratories measured a variety of temperature-dependent properties. Coupon sample measurements were a straightforward means to monitor any material-property changes that may occur during manufacturing, aging, or storage. Figure 9 represents a summary of materials test goals, and Figures 10, 11 and 12 are examples of important test results.

Test	Comments/Test Variables
Tensile Modulus	Ambient and max. & min. service temps., Assess effect of folds
Tensile Strength	Ambient temp., Assess effect of folds
Flexural Modulus	Determine temp. dependence, Relates to deployment temp., maximum service temp., & tube bending
Flexural Creep	Measure at maximum service temp.
Fiber Content	Estimate by image analysis, Determine variability between prepreg lots
Optical Microscopy	Fiber/matrix distribution, void content, folding damage, seams on tubes
Matrix Tg	Determine effects of deployment temp. exposure and outgassing. Comp[illegible] composite matrix Tg with neat resin Tg
Damping	DMA tan δ versus temp. and frequency
Outgassing	Compare to flight requirements, Effect of pre-launch bake-out
Panel CTE	Compare with tubes fabricated from same prepreg lots
Tube CTE	Laser interferometer, Effects of thermal cycling and folds

Fig. 9. Material Test Goals Summary

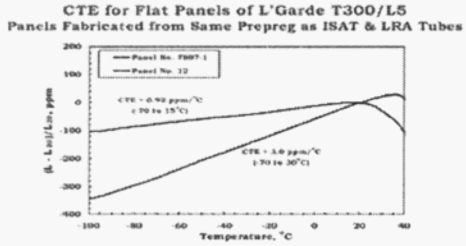


Fig. 10. Coefficient of Thermal Expansion (CTE) Coupon Tests of ISAT Truss Tubes

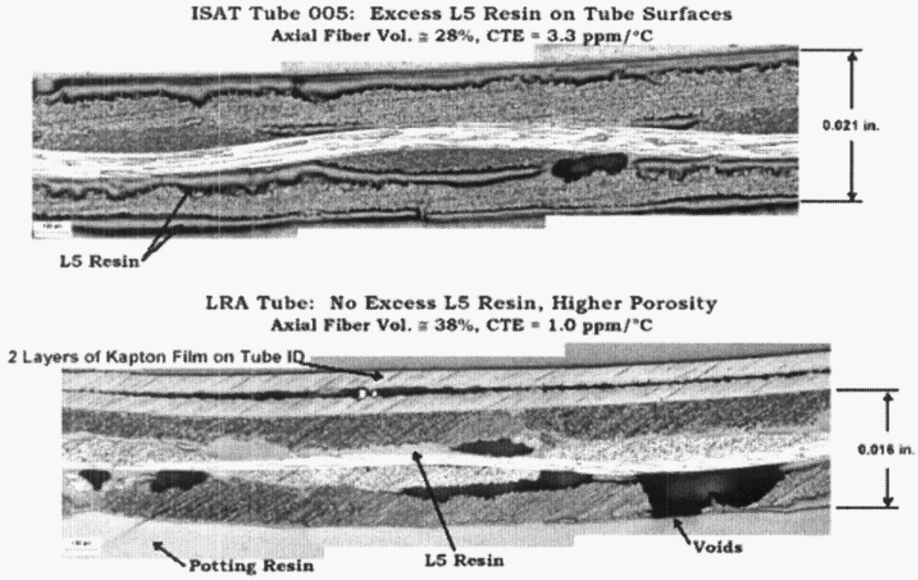


Fig. 11. Optical Micrographs of As-Manufactured Strut Tube Walls

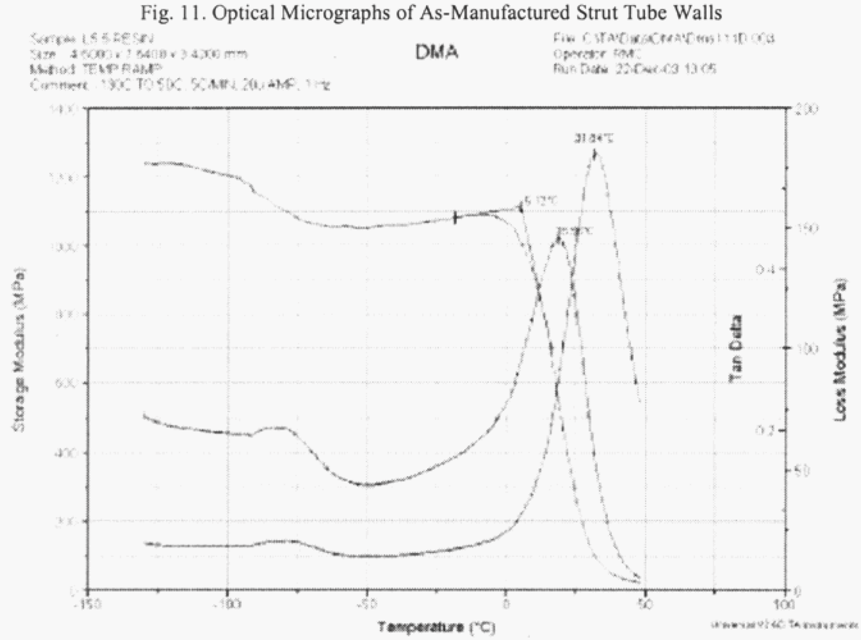


Fig. 12. Typical ISAT Thermo-Mechanical Resin Behavior

4. Truss Tube Experimental Characterization

Langley Research Center's ISAT Program objective was to experimentally evaluate the post-deployed structural properties of rigidized tubes as related to their applicability to the ISAT radar truss. Figure 13 shows a strut test-matrix summary. Specific properties evaluated were stiffness, member strength, tube length change after mechanical packaging, deployment, and rigidization.

Large Radar Antenna Requirements	
Aperture Diameter	Same as AIAT baseline
Range of Orbits	Medium to High
F/D (range)	0.5 to 1 (Baseline F/D = .5)
Highest Operation RF Frequency	F = same as AIAT
RF Feed C	
Antenna S	am goal)
Operation	m year goal
Materials (min. Leve	f>
Maximum Slewing Rates/Range	Angular acceleration about three axis of: TBD < α < TBD
Deployed Max. Acceleration	±0.005 g
Deployed Stiffness Characteristics	TBD
Contamination	TBD
ESD Constraints	Each Cond. layer of MLI is grounded
Settling time	TBD
Launch Vehicle Options	TBD
Launch Vehicle Shroud Options	TBD

Placeholder for Fig. 13

Fig. 13. Strut Test Matrix Summary

Tube test elements underwent axial and bending tests. For statistical relevance, seven 3-m tubes and three 5-m tubes were tested at room temperature. Additional tubes were tested at lower temperatures to simulate cold operational environment effects. Results showed that mechanically packaging and deploying the rigidizable tubes had only a minor effect on the required tube modulus, but had severe effects on the residual compressive strength. However, even with large tube compressive strength variations, the minimum demonstrated capability more than exceeded the requirements. The major technology challenge was stiffness, which also was well above requirements. Figure 14 is a test setup for the cryo-mechanical testing, and Figure 15 is an example of modulus and strength test results.

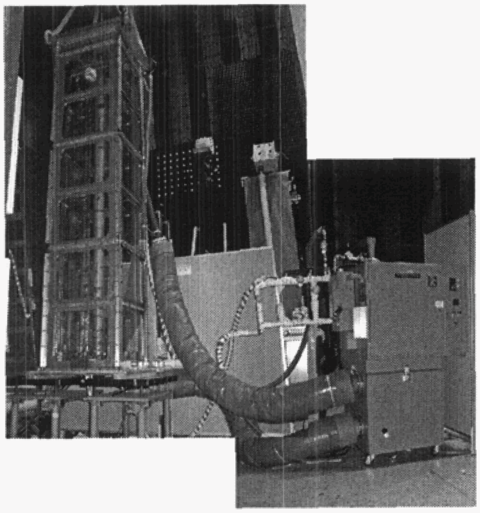


Fig. 14. ISAT Cryo-Mechanical Strut Test Facilities

C. Structural Performance Simulation

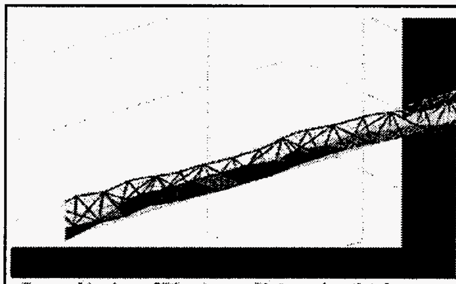
This task developed high-fidelity, specialized structural analytical simulation capabilities in order to project full-scale antenna orbital performance.

	ISAT Baseline	ILC Dover	L'Garde
Deployed Length Precision [m] [illegible]	<±3.0 <±3.0	[illegible]	[illegible]
Axial Stiffness [MN] [illegible]	>6.0/>8.0	[illegible]	[illegible]
Bending Stiffness [MN]	> 3.0	[illegible]	[illegible]
Buckling Failure Load [N]	> 35	[illegible]	[illegible]
1st Natural Frequency [Hz] [illegible]	.06	[illegible]	[illegible]
C.T.E. [ppm/C]	0.1	[illegible]	[illegible]

Fig. 15. Example of test results

1. Parametric Design Tool

To conduct a highly efficient, parametric analysis of the ISAT truss structural system, a specialized analytical tool was needed. A new, unique code, with tremendous potential, was created specifically for ISAT-type truss structures. This tool was simple to use for structures with repeated modular bays and had special "classes of super-elements" that could easily be tailored to variations in antenna structural designs. Such elements could determine RMS error surfaces driven by geometric imperfections. They could also account for the effects of tube bending and joint stiffness, and apply a wide variety of boundary conditions and constraints. Future improvements in the code will account for built-in radar panel errors in the determination of over all antenna RF signal performance. This code is currently being correlated with other more conventional codes for validation and will essentially be the primary analytical tool for the simulation of the ISAT structural/mechanical performance. The new tool's potential features are summed up in Figure 16.



Zoomed in view of 75 m truss with 1 cm length tolerances - uniform distribution (exaggerated geometrical errors)

- **Modal Analysis**
- **Forced Response**
- **Truss/Panel Tolerancing Analysis (Monte-Carlo analysis), multiple distribution capability**
- **Parametric Scriptable Code (# bays-extrusion, dimensions, properties)**
- **Validated against MSC/Nastran**
- **Control and sensor elements**

Fig. 15. ISAT Parametric Design Example (Modal Distortion)

2. Monte Carlo Shape Analysis

The objective of this effort was to develop a statistical analysis capable of guiding the specification of required manufactured error tolerances for mechanical properties and element geometries during hardware fabrication. Member component precision errors arose from a combination of fabrication imperfections, non-uniform mechanical and thermal properties, assembly and joint slop errors, and environmental effects. The analysis developed also aided in the prediction of antenna performance uncertainties pending the availability of basic component statistics.

Another objective of this work was to develop a reduced degree-of-freedom model to assess electronic and/or active mechanical antenna control needs and benefits. In particular, a method using a polynomial surface rather than a flat plane to achieve best-fit antenna shape, was devised. The specialized surface functions reduced the number of degrees-of-freedom to simplify the development of an active-control algorithm. Figure 17 is a truss schematic with associated error. Figure 18 is an example of truss deformations.

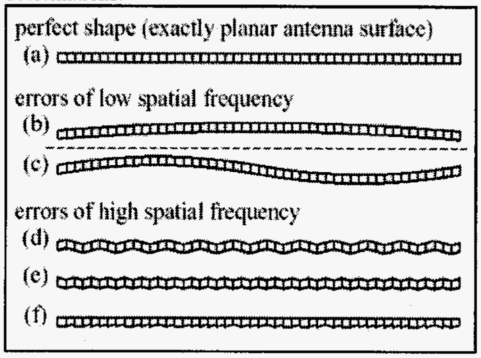


Fig. 17. ISAT Baseline Structure Manufacturing Distortion Patterns

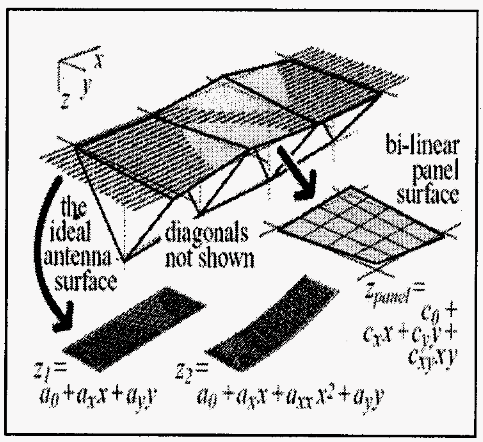


Fig. 18. ISAT Truss/Panel Deformations

V. Risk Assessment

A global risk assessment for new, immature technologies for specific applications requires identifying and defining not only critical and enabling technologies, but key supporting technologies. Consequently, a three-tier system was selected that distinguished the critical, high risk, enabling technologies from the supporting and ground-based technologies. The assessment study addressed in detail the inflatable space-structures technologies for enabling a specific class of radar antennas. Tier 1 was based on these technology assessment results. Important supporting technologies were also identified, but not evaluated in great detail since their technology advancement was considered significantly lower risk than in Tier 1. To establish the TRL metrics the JPL ISAT Design Team, with support from their consultants, made the technology maturity estimates individually and in conference.

The risk of using new, immature technologies depends on both the TRL, and risk associated with advancing the technology from the time a go decision was made, to the time it was actually used. Technology-advancement risk was a function of the (a) technical challenge associated with developing and validating technologies that were ground based, spacebased, or both, (b) total development and validation cost, and (c) total, available timeframe. Historically, sufficiently mature, reasonably funded technology advancements often have had major technical problems due to an overly-restrictive schedule.

1. Technology Maturity Matrix

TRL's were based on technical-task results: LRA Program; the ISAT Team, which draws its experience from JPL; the Aerospace Corporation; NASA LaRC; and high-technology industry – notably L'Garde, Inc. and ILC Dover.

Tier 1 (Figure 19a) critical and enabling technologies were sufficiently mature to ensure concept feasibility. Technology development was under way and functional demonstrations and validations were well defined. The risk for advancing these technologies to the point of application readiness ranges from high to moderate, depending on the specific technology element. The highest risk technology element to develop, which is considered very high, is characterizing the orbital, experimental rigidization of inflatable structural elements. Other technology elements were considered at lower development risk.

Secondary and supporting technology elements (Figure 19b), specified by Tier 2, represent wide-ranging concept-maturity levels. The challenge associated with their technology advancement, however, was generally considered significantly lower risk than for Tier 1. Since many of these technologies depended on specific application requirements, additional supporting technology elements would be identified as the system matured.

Tier 3 ground-based supporting technologies (Figure 19b) also had a wide range of technology-maturity levels. Many of them had low to very-low development risks. But some, such as techniques for ground-based functional performance demonstrations for very large inflatable structures would present a major challenge, depending on specific objectives. Generally, this class of technologies had a low to very low development risk.

SPECIFIC TECHNOLOGIES	CURRENT TRL	TECHNOLOGY ADV/RISK/COST
Material Rigidization Concepts		
• Space Radiation Durability	5	L
• Mechanical/Constitutive Properties Data Set	3	L
• Inflatable Structures Folding Capability	6	L/H*
• Rigidized Structures Element Stiffness/Strength	4/5	L
• Outgassing	4/5	L
• Long-Term Dimensional Stability	4/5	L
• Manufacturability	3	M/H
Truss Structure System Concept Definition		
• ISAT Functional Configuration	4	L
• Optimized Structural System	4/5	L
• Mechanical Packaging Techniques	2/3	M
• Deployment Control Approaches/Techniques	2/3	L/M
• Panel Alignment Precision	3	L
• Thermal/Mechanical Stability	2	L
Truss Structural System Performance Prediction		
• Structural System Stiffness	4	L
• Structural System Dynamic Characteristics	3/3	L
• Structural System Thermal Stability	3	L
• Estimates of Aperture Mounting Precision/Alignment	2	M/H*
• Structural Element Deployment Simulation	1	M/H*

Fig. 19a. Risk Assessment Technology Maturity Matrix

SPECIFIC TECHNOLOGIES	CURRENT TRL	TECHNOLOGY ADV/RISK/COST
TIER TWO –		
Secondary/Supporting Techniques	2	L/M
• Materials Orbital Rigidization Implementation Techniques	2/3	L
• Launch Restraint/Release Techniques	2/3	L
• Ascent Venting Techniques	2/3	L
• On-Orbit Inflation/Sensing/Control	2	L
• Design & Truss Cables/Battens/Diagonals Fabrication Capability	2/3	M
• Rigidizable Structures Manufacturing Capability	2/3	L
• Non-Inflatable Structures Development	2/3	L
• Thermal Control Materials		
TIER THREE –		
Ground Based/Supporting Technologies		
• Flexible Materials/Handling/Processing/Manufacturing	3/4	L
• Highly Specialized Materials/Parts/Element/Availability	3/4	L
• Manufacturing Quality Validation of Flexible Material Parts	3/4	L
• Precision Assembly of Large Flexible Structures		
• Subsystem Mechanical Performance Validation		
• Functional Subsystem/System Integration Techniques		

Fig. 19b. Risk Assessment Technology Maturity Matrix

VI. Conclusions

- Overall technology risk cannot be lower than the highest tall-pole technology risk.
- Risk associated with advancing key technologies to flight readiness depended on (a) allowable schedule, (b) magnitude of the challenge, and (c) required "validation", i.e. ground-based or on-orbit.
- LRA and ISAT Programs both made significant technology maturity advances.
- The generated structures tube test data set resulted in an excellent definition of the effects of constitutive relationships on mechanical performance.
- High-efficiency mechanical packaging of flexible members usually resulted in some damage to the matrix and/or fibers. However, when the damage was accounted for in the structural design, it was not a serious problem, but does warrant future examination.
- R/I member mechanical performance was very sensitive to the quality of fabrication.
- A number of supporting technologies were at a low TRL, but the risk of advancing them was not high.
- Ground-test limitations of the RI deployment process required orbital demonstration to establish initial space-deployed geometric precision.

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