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SECTION IV (Cont'd)
WORKSHOP PANEL REPORT

3. MATERIALS AND STRUCTURES

Theodore T. Saito, Lawrence Livermore National Laboratory, Chair

Sharon L. Langenbeck, Jet Propulsion Laboratory, California. Institute of Technology, Co-Chair

Materials and Structures Panel Participants

Ghanim Al-Jamily	Barr Associates
Joe Arnold	United Technologies Optical Systems
Troy Barbee	Lawrence Livermore National Laboratory
Dan Coulter	Jet Propulsion Laboratory, California Institute of Technology
Ben Dolgin	Jet Propulsion Laboratory, California Institute of Technology
Buck Fichter	NASA Langley Research Center
Patricia George	Aerojet Corporation
Paul Gorenstein	Harvard Smithsonian Center For Astrophysics
Steve Jacobs	University of Arizona
Mike Krim	Hughes Danbury Optical Systems
Angus Macleod	University of Arizona
Ramsey Melugin	NASA Ames Research Center
Don Rapp	Jet Propulsion Laboratory, California Institute of Technology
Nasrat Raouf	Jet Propulsion Laboratory, California Institute of Technology
Melville Ulmer	Northwestern University, Dept. of Physics and Astronomy

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INTRODUCTION

Materials and structures technology covers a wide range of technical areas. Some of the most pertinent issues for the Astrotech 21 missions include dimensionally stable structural materials, advanced composites, dielectric coatings, optical metallic coatings for low scattered light applications, low scattered light surfaces, deployable and inflatable structures (including optical), support structures in 0-g and 1-g environments, cryogenic optics, optical blacks, contamination hardened surfaces, radiation hardened glasses and crystals, mono-metallic telescopes and instruments, and materials characterization. Some specific examples include low coefficients of thermal expansion (CTE) structures (0.01 ppm/K), lightweight thermally stable mirror materials, thermally stable optical assemblies, high reliability/accuracy (1 μm) deployable structures, and characterization of nanometer level behavior of materials/structures for interferometry concepts. Large filled-aperture concepts will require materials with CTEs of 10^{-9} at 80 K, anti-contamination coatings, deployable and erectable structures, composite materials with CTEs < 0.01 ppm/K and thermal hysteresis, 0.001 ppm/K. Gravitational detection systems such as LAGOS will require rigid/deployable structures, dimensionally stable components, lightweight materials with low conductivity, and high stability optics.

The Materials and Structures panel addressed these issues and the relevance of the Astrotech 21 mission requirements by dividing materials and structures technology into five categories. Table 23 summarizes these categories, the necessary development, and applicable mission/program development phasing. For each of these areas, technology assessments were made and development plans were defined.

The performance of materials and structures is an integral part of the success of spacecraft and instruments in meeting their mission goals. Performance demands can range from lightweight, stable, environmentally resistant materials to unique structural designs maximizing dynamic response, stability, or minimizing weight. Advancements are continually being needed in materials and structures to meet current and future mission requirements such as increased payload, improved optical properties, improved thermal control, cryogenic temperature operation, longer lifetime, and increased reliability.

There are some recent examples of the benefits of advanced materials and structural concepts. One such example is the Hubble Space Telescope (Figure 25), which used graphite/epoxy to achieve a more stable and lightweight truss structure than would have been achieved with conventional metallic materials. With graphite/epoxy composites, the structural design can be tailored to maximize the structural performance by taking advantage of the materials' unique properties.

Materials and structures will continue to play a major role in advanced optical systems such as telescopes, interferometers, and imaging spectrometers. These systems will require ultra-lightweight materials that must often operate at cryogenic temperatures. These materials must maintain their dimensional stability to high precision, despite being exposed to a space environment characterized by low temperatures, thermal gradients, vacuum, radiation, and atomic oxygen exposure (in Earth orbit).

Advanced composite materials for structural components and reflector substrates can greatly reduce the amount of thermal expansion and structural weight. Advances are being made in designing and processing graphite/epoxy composites for low cost, lightweight reflector panels (Figure 26) for large astronomical facilities such as LDR, as well as for a variety of optical benches and other elements of advanced optical systems. However, there remain many challenges in developing these materials to the point where they are ready for space applications. New materials could also revamp the approach to the structural design of composite parts.

Advanced coatings are essential to optimized systems performance are and minimized environmental effects. Coatings contribute in many ways including environmental and impact protection as well as radiation handling capabilities for optical performance. Understanding the operational environment for the Astrotech 21 missions is important in order to provide the best protective systems for each instrument.

Table 23. Required Materials and Structures Technologies for Astrophysics Missions : 1992-2010

TECHNOLOGY AREA	OBJECTIVES	REQUIRED DEVELOPMENT	MISSIONS IMPACTED	TECH. FREEZE DATE
Vacuum Coatings	Develop the Techniques for Reliable (Survivable, Durable, Stable) Coatings for Mirrors, Filters, and Thermal Control	New High Performance Materials Microstructure Engineering Large Area Processes Advanced Deposition Technologies Improved Characterization Technologies	NGST LAGOS MOI SIRTF LDR AXAF	'02 '08 '97 '92-'94 '01 '90
Materials Science and Engineering	To Develop, Characterize, and Demonstrate Materials, Test Methods and Predictive Models for Astrophysics Missions	Dimensional Stability Measurements Dimensionally Stable Materials Cryogenic Materials Coatings Interfaces, Joints, Contact Surfaces Novel Materials	All	'95, '98, '00 '95, '98, '06 '99, '01, '98, '02 '98, '00 '98, '00 '98, '06
Environmental Protection	Test Materials and Structures In a Simulated Space Environment Develop Specifications for Flight Qualified Hardware Monitor and Maintain Optical Performance In Space	Contamination Control of Materials and Processes Cryogenic Testing Metrology Ground-Based Simulations Early Warning Contamination/Degradation Monitoring	All	'00, '05 '00, '05 '00, '05 '05, '10 '00, '05
Reflector Substrates	Develop Reflectors With Low Areal Density, High Surface Accuracy, Smoothness, Size, Shape, and Optical Stability at Desired Wavelengths and Operating Temperatures	Materials/Processes For Precision Mirror Replication Optically Stable Materials and Designs Large Area Segments and Monolithic Mirrors Active/Adaptive Optics Materials and Techniques for Efficient High Precision Figuring and Polishing Lightweight Materials for Large Mirrors	XST VHTF LTT MOI FFT NGST SIRTF SMIM LDR OVLBI Interferometers	'95 '03 '95 '97 '04 '02 '94 '96 '01 '00 '05
Structures	Develop/Verify Structures and Mechanisms for Precision Erection, Alignment, and Control Large Scale Micro-Dynamics Structures Breadboard and 6 to 8 m 50 kg/m^2 Mirror Structural Model	Advanced Dynamics Modeling Noise Transmission and Dynamic Response Prediction Capability Dimensional Repeatability Prediction and Tests Highly Stable Structures Design and Verification Substrate Automatic Deployment and Alignment	NGST LTT LDR SMIM AIM	'02 '95 '01 "96 '97

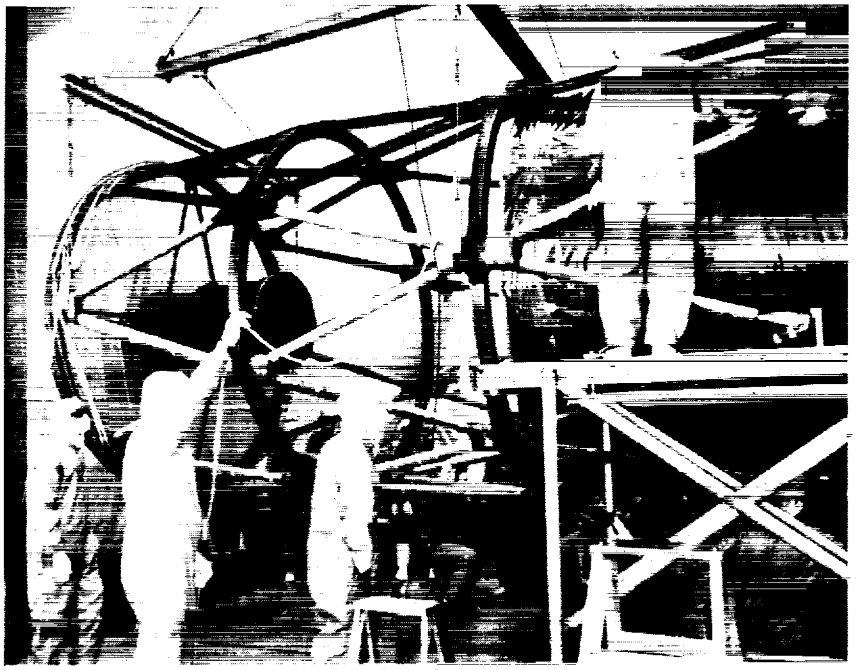

Figure 25. Hubble Metering and Focal Plane Truss Structures

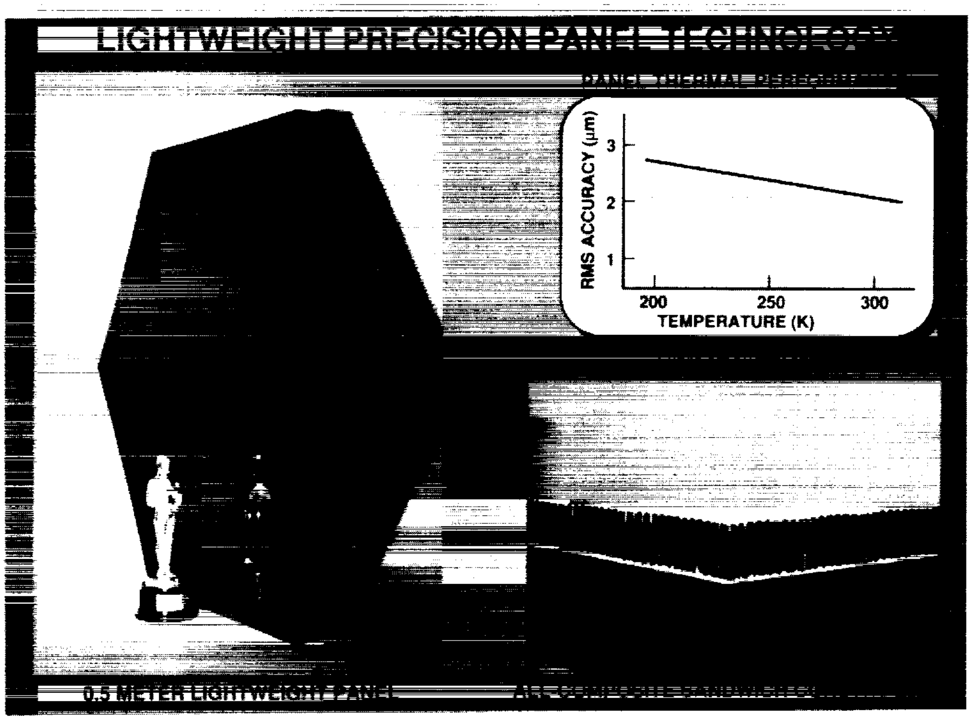

Figure 26. Composite Reflector Panels – Composite panels developed in NASA's Precision Segmented Reflector (PSR) Program. (Courtesy of Rick Helms.)

VACUUM COATINGS

A. Technology Assessment

Vacuum Coating is the preparation and placement of materials in thin layers. The optical and x-ray coatings necessary for the Astrotech 21 missions are characterized by performance exceeding the state of the art. Existing technology is rudimentary, application and material specific, based upon traditional techniques, and at scales less than required. Ongoing development efforts require a focused investment program along with support for new, promising techniques. Technology developments are required for fabrication of reliable coatings of all kinds (survivable, durable, stable in all relevant ways, especially with respect to temperature and chemicals) at the scale required for future missions.

B. Development Plan

The areas of technology development recommended are summarized in Table 24. The required developments for this item include new high performance materials, microstructure engineering, advanced deposition technologies, and improved characterization techniques. (Note that "Improved Characterization Techniques" has been deleted from the recommended program due to funding limitations identified after the workshop.)

New high performance materials include very thick multi-layer coatings that are built up from many thin coatings. Samples as thick as 0.25 mm in 100 mm square formats have been demonstrated in the laboratory. This program would concentrate on the development of analytic tools necessary to evaluate materials and process efficiency.

Coatings of different materials (stainless steel/zirconium in altering layers) can provide unusual properties. Fracture strengths of 700 ksi with very fine microstructure and moderate-to-low ductility can be made in the earlier deposition stages. Layers with moderate strength and moderate ductility can be deposited in later stages so that the final material is a tough "composite." (Figure 27) Super smooth substrates allow very thin, very smooth, shells for x-ray telescopes to be built. A second application is shields for micro-meteoroid impact protection. These are revolutionary concepts for very light materials with excellent and tailored properties.

Advanced deposition techniques include the improvement of methods such as ion beam, ion assisted, and ion cluster deposition. Part of the improvement will be to scale to large areas, and achieve uniformity and adhesion. The benefit of improved surface roughness from ion cluster deposition will be reflected in reduced cost (especially for pre-cleaning and pre-treatment).

Improved characterization will include using techniques such as Raman and x-ray spectroscopy for in situ diagnostics. The benefits of these improved diagnostics will include real time process diagnosis and control, and a better understanding of deposition processes.

MATERIALS SCIENCE AND ENGINEERING

A. Technology Assessment

The objective of the Materials Science and Engineering thrust is to develop, characterize and demonstrate materials, test methods, and predictive models. The five required technologies encompassed are: (1) dimensionally stable materials; (2) cryogenic materials; (3) thermal protection systems; (4) interfaces, joints, and contact surfaces; and (5) novel materials.

The dimensionally stable materials area includes the development of test methods, fundamental understanding of dimensional stability, and development of materials. In order to enhance a material's stability, accurate and meaningful three dimensional Coefficient of Thermal Expansion (CTE) measurements must be made over the applicable range of temperatures.

Table 24. Required Vacuum Coatings Technology for 1992-2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
High Performance Materials	Traditional, Simple Compounds and Metals	Develop Analytic Tools Over Material Ranges of Interest	'95, '00, '05, '10	'93 - '10
Microstructure Engineering	Rudimentary	Consistent, Tailored Thin-film Microstructures High Ductility Fracture Strength : > 700 ksi	'05, '10	'93 - '10
Local Area Processes	≈ 1 m	Coat 10 m Reflective Primary Mirror	'99, '05	'93 - '00
Advanced Deposition Techniques	Application Specific	Measurement of Thin-Film Properties at All Temperatures (including cryogenics)	'98, '00, '05	'93 - '10
Improved Characterization Technologies	Material Specific	High Optical Performance, Low Scatter, Durable Coatings Over Wide Spectral Range Resistance to Atomic Oxygen In Situ Diagnostics	'00, '10 '96	Deleted Due to Funding Profile Cap

Figure 27. Hubble Primary Mirror – After being installed in a uniquely designed 14-ft diameter vacuum chamber, the primary mirror underwent a coating deposition process that took less than 1 minute. The mirror is coated with a reflective layer of pure aluminum 2.5 millionths of an inch thick. (Photo courtesy of Hughes Danbury Optical Systems.)

The more inherently stable we can develop materials, the less we need active controls on structures to meet mission goals. Stability includes both temporal and thermal. Today, we have the capability to measure CTE at the 0.01 ppm level in one direction. The best materials have a dimensional stability of 1 ppm.

Questions still exist as to materials performance at cryogenic temperatures. There is limited data at 2 to 4 K on materials and what data exists are for conventional metallic materials. The new advanced metals and composites are just now being fully evaluated at room and low (80–120 K) temperature much less at 2 to 4 K. Systems requiring operation at 2 to 4 K need both optical and structural materials to meet mission goals. Not only is a materials database needed for the design, but also such factors as insulation materials and joints are essential to the system performance.

Many of the missions require some form of thermal insulation or barrier. Improvements in these would enhance performance. Thermal blankets are typically used for insulation. Multilayer insulation films may replace some of the blanket usages today. In addition, instruments may require protection from orbital debris and micrometeorites. Protective systems such as blankets and films need further development.

The technical area of interfaces, joints, and contact surfaces encompasses many aspects of the system design and performance. Degradation of seals and elastomers is a significant issue. Compatibility of joints, coatings, thin films, reinforcements and matrix materials must be assessed for each operating environment.

The final technical area, called novel materials, provides for innovative, new developments to be included as potential materials for Astrotech 21 missions. These materials may be considered more high risk but because of their improvement potential they need to be supported. Smart materials are considered here; although they are early in their development stage they offer large payoffs in their ability to actively control structures and optical systems. Development of new materials for improvements in low density, high specific stiffness, high specific strength, and low temperature performance needs to be an ongoing effort to assure materials will meet the needs of the astrophysics future missions.

B. Development Plan

The measurement of material stability to one part per billion simultaneously in three dimensions is required, and is an enabling technology. The measurement equipment needs to evaluate materials in vacuum and cryogenic environments as well as standard room environments. Long term stability of the instrument must be guaranteed to allow slow changes in material properties to be measured. This equipment will be used to measure thermal stability, material hysteresis and thermal cycling, as well as true isotropy and homogeneity.

The dimensional stability of materials needs modeling and quantification of the physical and chemical mechanisms, particularly of composite materials and novel materials. Predictive models that accurately describe the changes of materials in a space environment over time are needed.

Cryogenic materials engineering is required to determine adequate structural materials, actuator technology, insulation materials, and low expansion/high expansion compatible joint materials. Materials that will provide mechanical damping at cryogenic temperature are also required.

Specific need dates have been identified for the five technology areas in materials science and engineering (Table 25)

Table 25. Required Materials Science and Engineering Technologies

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Dimensional Stability Measurements	1-D, at 1 ppm	Temporal Stability : 1 ppb, 3-D Thermal Stability , Hysteresis on thermal cycling : 1 ppb Isotropy and Homogeneity (Non-Destructive Measurements)	'93 - '94	'92 - '10
Dimensionally Stable Materials	CTE : 1 ppm/K, Temporal Unknown	Physical and Chemical Mechanisms Predictive Models Novel Materials/Technology CTE : < 0.01 ppm/K	'95 '98 '06	'92 - '08
Cryogenic Materials	Very Limited	Structural Materials Actuators Isolation Materials Low Expansion/High Expansion Material Joints Damping Materials	'99 '01 '98 '02 '02	'94 - '08
Coatings		Thermal Control Coatings Wavelength Selective Coatings Encapsulation/Barrier Atomic Oxygen	'98 '02 '02	'94 - '10
Interfaces, Joints, Contact Surfaces	Being Assessed	Coatings/Thin Film Interfaces, Reinforcement/Matrix Interfaces, Sliding Surfaces, Zero Gap Joints	'98 - '10	'94 - '10
Novel Materials		Smart Materials, Low Density, High Specific Strength, Stiffness, etc.	'98 - '06	Deleted Due to Funding Profile Cap

ENVIRONMENTAL PROTECTION

A. Technology Assessment

The Environmental Protection objective is to monitor and maintain performance in the presence of a hostile space environment and self-contamination from the spacecraft.

The required technologies for this thrust include controlling the contamination of (and from) materials and from fabrication processes. Material properties, such as outgassing, need to be better understood and well controlled. Fabrication processes may directly contaminate materials or make materials more susceptible to becoming contaminated.

Cryogenic testing is needed to measure the effects of cryogenic cycling and cryogenic contamination. (For example, issues like "How does contamination grow?" and "How can it be removed at cryogenic temperatures?") Ground-based simulations of the space environment will provide greater insight into space contamination. Early warning of contamination coupled with degradation monitoring will be helpful in controlling contamination sources and effects in their early stages during the mission.

Technology is needed to protect exposed components from micro-meteroids, atomic oxygen, and natural space radiation. Alternative materials need to be identified. Valuable information was derived from the Long Duration Exposure Facility (LDEF). A variety of material samples placed on LDEF have been analyzed for degradation. Many of the composite samples had almost disintegrated from the atomic oxygen and radiation exposure. As new materials are developed and incorporated into instrument designs, information on materials degradation and protection must be available.

B. Development Plan

This objective has three subobjectives. First, to develop the materials to protect the hardware in a space environment. Second, to ensure that protection is adequate by testing materials and structures in a simulated space environment (Figure 28). Third, to develop protection specifications for flight qualified hardware. Metrology of contamination and environmental effects in space must also be developed.

To meet the overall objective of environmental protection, six specific tasks have been identified. The tasks and technology need dates are presented in Table 26.

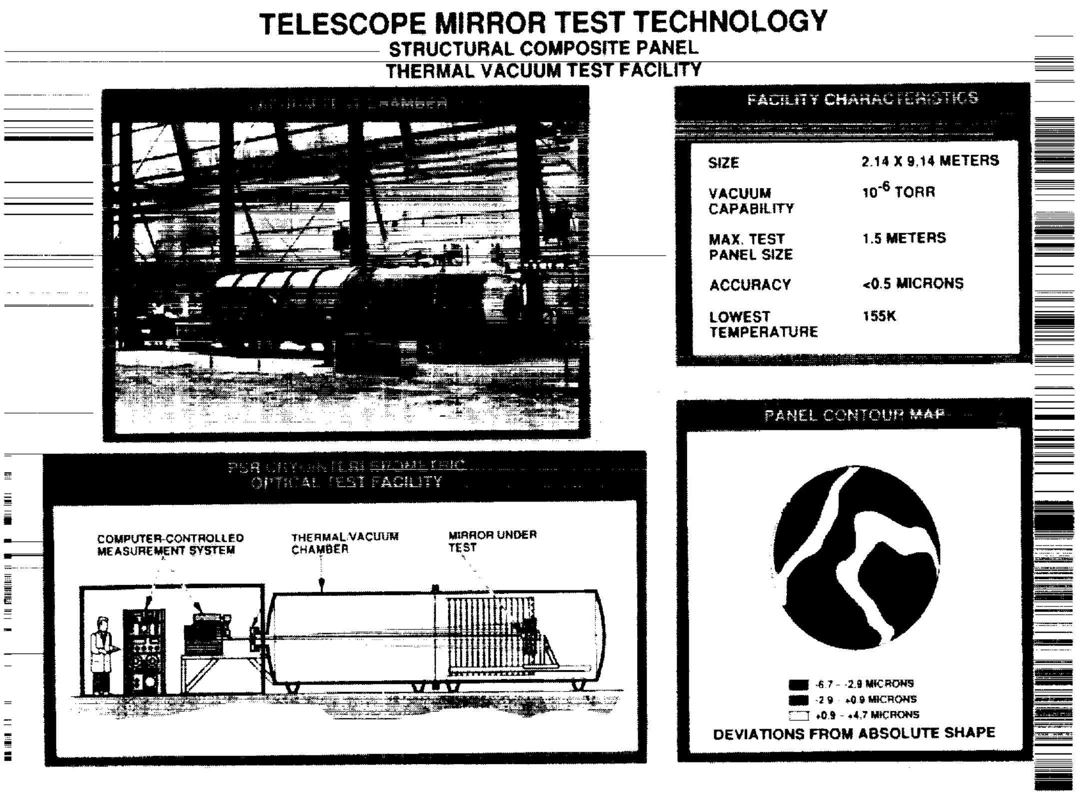

Figure 28. Thermal Vacuum Test Facility

Table 26. Environmental Protection Milestones for 1992-2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Contamination Control of Materials and Processes	Limited	Clean System Specification On-Board Contamination Removal	'97 '00	'92 - '03 '92 - '10
Cryogenic Testing	Limited	Experimental Test Facilities	'96	'92 - '99
Characterization In Space	Limited	Characterization Techniques Development	'05, '10	'92 - '10
Ground-Based Simulations of Space Environment	Limited	Design/Develop/Execute Ground-Based Experiments	'05, '10	'92 - '10
Early Warning Con-tamination/Degradation Monitoring	Very Limited	Design/Develop/Execute Space-Based Environmental Experiments	'05, '10	'92 - '10

REFLECTOR SUBSTRATES

A. Technology Assessment

Reflector substrates with required low area density, high surface accuracy and smoothness, size, shape, and optical stability at desired wavelengths and operating temperatures are needed to support astrophysics missions. Technology for reproducible, lightweight, optical quality substrates does not exist.

B. Development Plan

The required technologies for the reflector substrates can be summarized into five items. Table 27 lists those development items and their associated need dates. Several of the recommendations overlap with those of the Fabrication Panel. They are provided here as necessary developments identified by this panel from a materials and structures viewpoint.

The materials and processing for precision mirror replication will develop technology to provide substrates with < 5 Å rms microroughness with the appropriate optical figure. One particular milestone is a < 2 arcsec slope-error x-ray substrate in the year 2005. A second associated milestone is 10 Å rms figure replicate visible mirror by the year 2010.

The second development area is the materials and the designs for optically stable (both temporally and thermally) mirrors. The goal is, by the year 2004, to improve on the visible mirror performance of 70% encircled energy within 0.1 arcsec to demonstrate performance of >70% of encircled energy within 0.025 arcsec at the use temperature.

The third development area is substrates for active/adaptive optics. Current "smart" mirrors have many actuators with significant electrical power and weight requirements. The first milestone for this project will be, by the year 2008, to provide large stiff segments with one actuator per square meter. Then, by the year 2010, to demonstrate a mirror with actuators integrated into the mirror with significantly lower electrical requirements and a capability to operate at low temperatures.

The fourth area is the development of materials and techniques for reflector substrates, which are compatible with highly efficient fabrication techniques, to achieve the demanding accuracy tolerances. This will be a significant improvement on the many iterations required for the fabrication of current technology mirrors such as the Hubble Space Telescope primary mirror. (Technology development in this area was also identified by the Fabrication panel see Section IV, 2. Fabrication: Replicated Optics; Figuring Large Optics to 1 nm rms; Fabrication of a Lightweight, Cryogenic 4-m Mirror; and Innovative Techniques with Longer Range Potential.) By the year 2005, this project will demonstrate a high figure quality in the mid- and low-spatial frequencies and low microroughness on large areas with only a few iterations.

The fifth area is the development of lightweight mirror substrates that meet the optical figure and scattered light requirements for UV, visible, and x-ray missions. The goal is to demonstrate a 2-m diameter substrate with a 1-5 kg/m^2 areal density for x-ray, and a larger than 2-m mirror with areal density less than 20 kg/m^2 by the year 2002.

Table 27. Required Developments In Reflector Substrates for 1992–2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Materials and Processing for Precision Mirror Replication	Epoxy, Graphite/Epoxy, Electroforming, CVD	< 5 Å rms μ-roughness X-ray: < 2 arcsec Slope Error VIS: ≤ λ/500 rms (visible)	'00, '02	'93 - '10
Materials and Designs for Optically Stable Mirrors	70% Encircled Energy In 1 arcsec (visible)	Materials/Designs Achieving: ≥ 70% Encircled Energy In 0.025 arcsec (visible)	'00	'93 - '04
Large Area Segments and Monolithic Mirrors	0.1 – 2.5 m Depending on Material	X-ray: ≥ 2 m Lightweight, Identical Segment VIS: 6 – 8 m Monolith	'99, '05	'93 - '10
Active/Adaptive Optics	Many Actuators, Added-On, High Power, High Temp., Heavy	X-ray: Large, Stiff Segments, 1 Actuator/m^2 VIS: Actuators Integrated In Mirror, Low Power and Low Temp. Ops.	'02, '04	'93 - '05
Materials and Techniques for Efficient, High Precision Figuring/Polishing	Glass, Simple Figures, Many Iterations	High Quality Figure (Mid-Low Spatial Frequencies) Low μ-roughness on Large Scales With Small Number of Iterations	'98	'93 - '03
Lightweight Materials for Large Mirrors	5 –10 kg/m^2 : Graph./Epoxy, SiC 20 –200 kg/m^2 : Glass 10 – 20 kg/m^2 : Beryllium	X-ray: ≤ 2 m Dia.,1 -5 kg/m^2 UV/VIS: > 2 m Dia, < 20 kg/m^2	'02	Deleted Due to Funding Profile Cap

STRUCTURES

A. Technology Assessment

Optical positioning structures for the next century astrophysics missions will in general be larger, lighter, and more susceptible to jitter and vibration by at least an order of magnitude beyond current systems. They will be deployable, possibly augmented by remote teleoperator intervention, and need to be able to maintain the alignment between optical elements separated by tens of meters to fractional wavelength precision. (For example, single structure interferometers will require figure initialization and maintenance to better than 12 nm [visible] over 30 m baselines.) This latter requirement will be accomplished in conjunction with alignment sensing and control subsystems, at least up to their bandwidth limits. Understanding jitter and vibration beyond the bandpass of the control systems is critical to the success of this new generation of optical systems. The development of these advanced structures and the development of techniques to characterize and verify their performance in the laboratory (Figure 29) before committing them to a mission are the principal objectives of this thrust.

B. Development Plan

Before initiating these technology development programs, a comprehensive systems

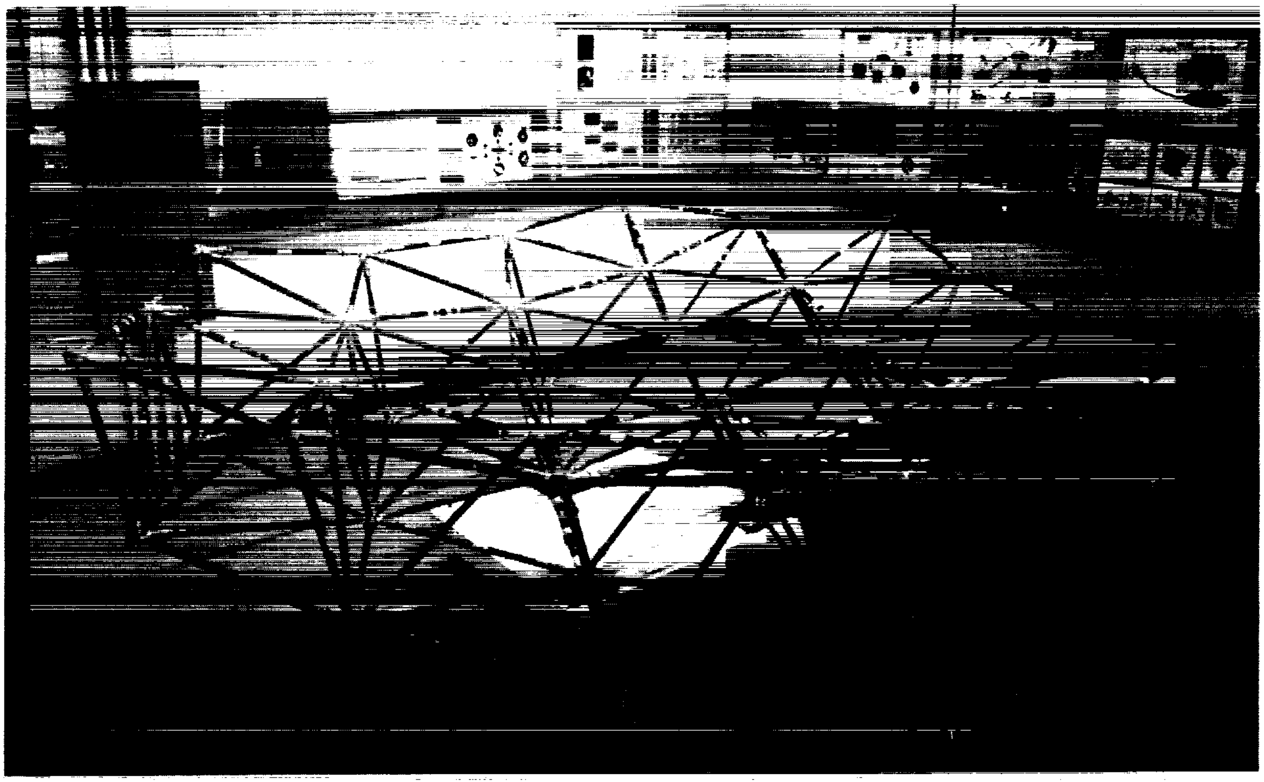

Figure 29. CSI Truss Structure

definition and requirements development activity must be undertaken to quantify what the precise goals should be. This would need to be mapped over what the next century mission requirements and science objectives are. In this activity, the synergism between structures, alignment sensing and control, performance analyses, and large scale system functional architectures would be established.

The first of the required technologies is the development of a quantitative understanding of the behavior of these systems in a (quasi) zero-g environment where self-weight preload is not available to linearize or at least monotonically bias the various hinges and pivot devices that are found in deployable systems.

A program of component level and small scale structural systems modeling and experimental work needs to be carried out in ambient conditions and in vacuum to eliminate the effects of air damping on measured material properties applicable to operation in the vacuum of space. Similarly structures could be off-loaded by floating them on a low pressure near-static air film to note any differences due to the elimination of self-weight preload. As one plateau of understanding is achieved, the size and complexity of the structures can be increased and the ability to analytically scale performance can be tested in the laboratory.

Coupled with this is research into how micro-noise dynamic disturbances are transmitted in these lightweight, pivot joint dominated structures. This is the second area where technology development is needed. The ability to model these structures and to demonstrate correlation with tests at the extremely low strain levels and concomitant low damping in the presence of cabling, thermal control blankets, and other real-world complications is essential.

The third technology development area encompasses the effect of cryogenic operating temperatures on the microdynamic and expansivity characteristics of these large structures, where response amplitudes measured in fractions of microns are important. Of particular concern are mechanical pivots where frictional changes between ambient and cryogenic operation can influence the end fixity of structural members and alter the overall dynamics and the influence of cabling and other polymers whose stiffness varies with temperature. Testing and modeling these structural systems in as large a scale as time and resources permit are recommended to gain as much real-world experience as possible and to disclose problems that might otherwise go undetected in smaller and less challenging experiments.

Lastly, and related to cryogenic operation of segmented mirror optical systems, is the need to develop and verify mirror substrates whose basic shape stability, i.e., radius of curvature over temperature is adequate to achieve ($\Delta R/R$) precisions of only several parts per million. Here trades between substrate thermomechanical stability and active shape control, as opposed to position control only, need to be explored. As cascaded control systems become more complex, the need to accurately and reliably define the 'plant' characteristics becomes increasingly important. The developments and need dates for structures are summarized in Table 28.

Table 28. Required Developments In Structures for 1992–2010

TECHNOLOGY	CURRENT TECHNOLOGY	PROGRAM GOALS	NEED DATES	TECH. DEV. TIME FRAME
Dynamics Modeling	Limited Experience Based Upon HST	Realistic/Accurate Modeling of Practical Structures Verification at m-strain Levels In a 0-g Environment	'98 Components '01 System Level	'92 - '01
Mechanical Noise Prediction	HST	Accurate Prediction of Mechanical Noise Transmission and Dynamic Response in a 0-g Environment	'02	'92 - '06
Deployment/Erection Dimensional Repeatability (Room Temp.)	Technology is in Infancy	Prediction and Test Verification of Dimensional Repeatability to Optical Tolerances	'97 Components '99 System Level	'92 - '10
Deployment/Erection Dimensional Repeatability (Cooled Structures)	Technology is in Infancy	Dimensional Changes and Repeatability of Ensemble Structures With Temperature : 293 K to 100 K, ± 10 K Around 100 K	'98 Small Scale '02 Full Systems	'92 - '06
Structural Materials for Substrates	150 kg/m^2 With External Bending Control	25 – 35 kg/m^2 Substrates, 2 – 4 m in Diameter $\Delta r/r$ Stability : 3 ppm Over All Environments	'00	'92 - '06
Substrate Automatic Deployment and Alignment	None	Deploy/Erection of Two-Segment Mirror to Within Alignment Sensor Capture Range	'02	'92 - '98
Systems Engineering	N/A	Analyze Mission and System Requirements and Define Tech. Dev. Required, Coord. w/ Optics, Controls, etc.	'94	'92 - '94