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**Air Force Small Business Innovation
Research Program
(Phase II)**

**Air Force Research Laboratory
Contract FA8650-04-C-2468
Data Item A006**

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GLOSSARY

ACT	Advanced Concept Technology
AFFTC	Air Force Flight Test Center
AFRL	Air Force Research Laboratory
AO	atomic oxygen
BATC	Ball Aerospace & Technologies Corporation
CE	cyanate ester
CE SMP	cyanate ester-based SMP
CNF	carbon nanofibers
COP	Condensed Outgassing Product
CO ₂	carbon dioxide
CRG	Cornerstone Research Group Inc.
CTE	coefficient of thermal expansion
DMA	Dynamic Mechanical Analyzer
DoD	Department of Defense
DSC	differential scanning calorimeter
FTIR	Fourier transform infrared
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IR&D	Independent Research and Development
JPL	Jet Propulsion Laboratory
MDA	Missile Defense Agency
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NMR	nuclear magnetic resonance
NRO	National Reconnaissance Office
RF	radio frequency
RMS	root mean square
SBIR	Small Business Innovation Research
SMP	shape memory polymer
SOTA	state-of-the-art
T _g	glass transition temperature
TML	total mass loss

UAH	The University of Alabama in Huntsville
VARTM	vacuum assisted resin transfer molding
VEN	vacuum exposure nephelometer
zero-G	zero-Gravity
1-G	one-gravity
<	less than
<<	much less than
>	greater than

1.0 INTRODUCTION

CRG succeeded in developing self-deploying membrane reflector technology to readiness for transition to use in system development by a major spacecraft prime contractor, Ball Aerospace & Technologies Corporation (BATC), and BATC commenced Phase III application of the technology.

This excerpt of the project Final Report summarizes results Cornerstone Research Group Inc. (CRG) achieved under Air Force Research Laboratory (AFRL) contract FA8650-04-C-2468 for an Air Force Small Business Innovation Research (SBIR) Phase II project entitled, "Shape Memory Polymer Self-Deploying Membrane Reflectors." AFRL awarded this contract under Department of Defense (DoD) SBIR 2003.1 Topic AF03-182, "Deployable, Membrane Optical or RF Reflector." CRG conducted Phase I effort under Air Force Flight Test Center (AFFTC) contract F04611-03-M-3107.

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Recipients of this report needing further information are invited to contact the Principal Investigator, Stephen D. Vining (viningsd@crgrp.net, (937) 320-1877 extension 108).

The following subsections, primarily excerpted from the original contract proposal, provide context for the technical objectives and results presented in the body of this report.

1.1 Problem Definition

Current materials and fabrication processes for space-based mirrors have serious drawbacks severely limiting the size and therefore the performance of optical systems. Major drawbacks fall in the areas of mass properties, structural properties, and fabrication costs:

- Conventional mirror materials (i.e., glass and metals) have a relatively high areal density, thereby limiting the size of mirrors that fall within the lift capacity of available space launch systems (Space Transportation System and expendable vehicles). Even approaches involving segmented mirrors are highly constrained by the lift capacity of current launch systems.
- The high mass density of conventional mirrors also presents challenges for supporting the mirrors in order for them to survive inertial and vibration loads during launch and spacecraft deployment. The need for extra structure to support mirror mass during launch adds to the overall system mass problem and complicates the design challenge for optical spacecraft systems.
- Conventional mirror fabrication processes are highly complex, time consuming, and expensive. Facilities and equipment required for fabricating the mirror structure and grinding and polishing the optical surface involve large capital investment for a low-rate production process. This results in a very high per-unit mirror cost. A mirror material requiring simpler, faster fabrication processes with less expensive facility requirements would dramatically reduce mirror costs.

A radically different mirror approach--deployable membranes--holds the potential for mitigating conventional mirrors' drawbacks, enabling increased mirror size while accommodating lift capacity limitations. This approach would enable mirrors with greatly reduced areal density. Further, by launching the mirror in a folded configuration and deploying it into the optical figure on orbit, the membrane approach eliminates much of the mirror support structure that becomes nonperforming "scar" mass after orbital deployment. Finally, membrane-based mirrors would employ simpler, faster fabrication processes with less expensive facility requirements, thereby reducing mirror costs.

Air Force Research Laboratory's (AFRL's) investigation of this new approach has revealed that membrane mirrors present new challenges: (a) the spacecraft must employ a practical, mass-effective means to deploy the membrane on orbit and achieve the required optical figure, (b) the system requires a means to maintain the membrane's figure, and (c) the system requires a support structure that does not detract from the mass and deployability benefits of the membrane reflector¹.

Technology enabling membrane optics for imaging systems would also find application in optical reflectors for solar thermal propulsion and large reflectors for radio frequency (RF) or optical communications systems¹. Solar thermal propulsion systems would have the least stringent optical performance requirements. While imaging systems would have the most stringent requirements.

1.2 Opportunity

Phase I results (summarized below, Section 1.5) demonstrated feasibility of new materials and fabrication processes enabling an innovative approach for producing dramatically lighter, less expensive mirrors for space-based optical systems:

Shape Memory Polymer Self-Deploying Membrane Reflectors

CRG's high-performance shape memory polymer (SMP) materials and related fabrication processes enable very large (>20 m diameter), ultra-lightweight (<0.5 kg/m² areal density) membrane mirrors whose material inherently self-deploys to the optical figure on orbit. SMP membrane mirrors will employ simpler fabrication processes with less expensive facilities than conventional mirrors, thereby reducing mirror costs.

Founded in CRG's demonstrated expertise in SMP materials (background provided in Appendix A) and process technologies, SMP self-deploying membrane reflector technology (concept described in next section) presents the space imaging community with the opportunity to obtain a revolutionary improvement in the physical properties of space-based mirrors and a dramatic reduction in the cost of mirror fabrication. CRG proposed Phase II effort to exploit Phase I results and CRG's other extensive R&D in SMP and space-based reflectors and bring the SMP self-deploying membrane reflector technology to readiness for transition to operational use.

1.3 Concept for SMP Self-Deploying Membrane Reflectors

SMP as membrane mirror material will enable innovative deployment concepts for large, ultra-lightweight space-based reflector systems. This section describes one potential concept. The Phase II project was proposed to provide material and fabrication techniques as a foundation for this and many other concepts that could exploit SMP properties for deployable membrane mirrors.

In this concept (Figure 1, optical figure exaggerated to aid visualization), thin SMP membrane mirrors are attached to an articulated positioning structure composed of conventional lightweight composites. The structure and mirrors are folded into a compressed package for launch stowage (Figure 1a). On orbit, the structure deploys by simple hinge mechanisms to place the mirrors' attach points at their final location (Figure 1b). Then the mirrors are heated to the glass transition temperature (T_g) of the membranes, allowing them to become pliable and begin unfurling (Figure 1c). The membranes will express their shape memory and autonomously self-deploy to achieve their original shape--the mirrors' parabolic optical figure (Figure 1d). When the membranes cool to space ambient temperature, they will stiffen and permanently retain the mirrors' optical figure.

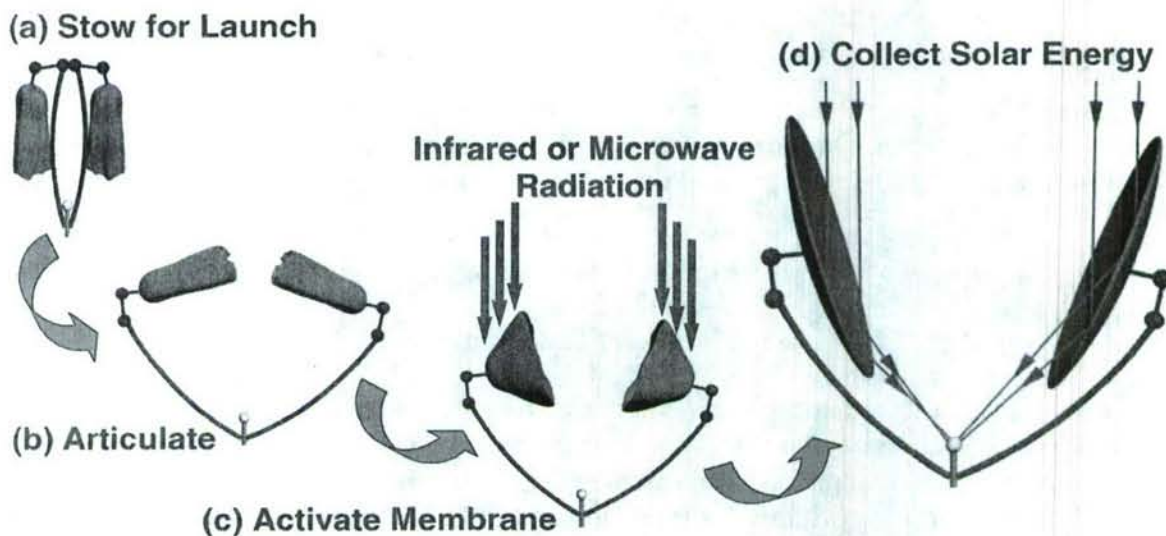


Figure 1. Concept -- SMP Self-Deploying Membrane Reflectors

Heating of the SMP could be accomplished by means of small on-board energy transmission devices (either carbon dioxide (CO_2) laser or microwave RF magnetron) or ground-based CO_2 lasers. An off-board CO_2 laser energy source would provide for greatly reduced spacecraft mass and complexity. Infrastructure for this approach is already available at several sites.

In this concept, the membrane is composed of SMP with high stiffness at operational temperatures (well below T_g). The membrane is self-supporting except for its single attach point on the positioning structure. This provides for a simpler system design than that of a compliant membrane reflector supported by a surrounding rigid structure (which must have three-dimensional articulation mechanisms and energy sources) or supported by an inflatable structure (e.g., Figure 2) (which must incorporate close tolerances in mounting and tensioning provisions in order to prevent figure distortion in the membrane).

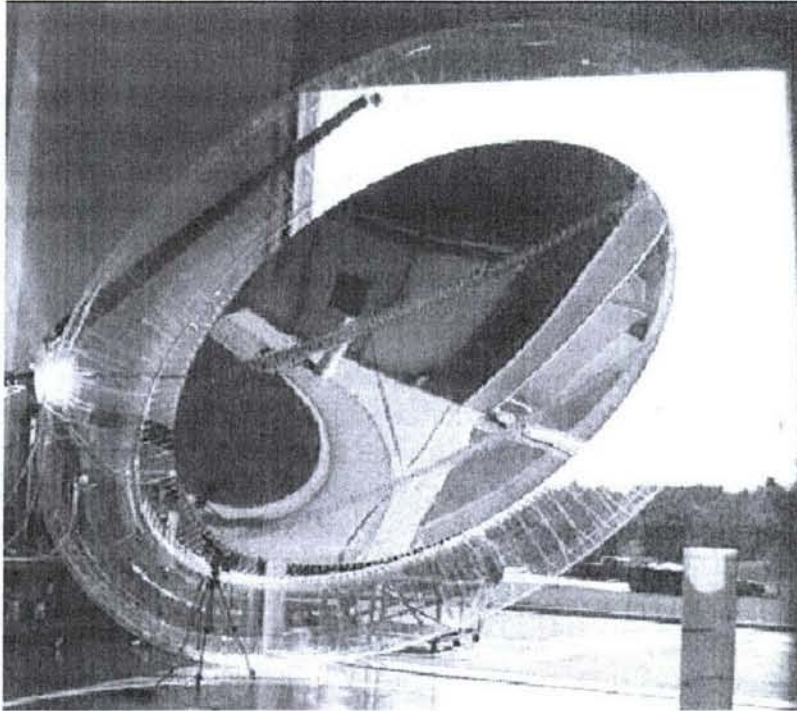


Figure 2. Compliant Membrane Reflector with Inflatable Support Structure²

If required to meet optical requirements, the membrane's reflective surface could then be manipulated ... to correct minor local surface distortions. This correction technique could employ a mechanism CRG developed and demonstrated under [another government R&D contract].

Figure 3. [Reserved]

Figure 4. [Reserved]

The above concept would apply to reflectors for space-based imaging, RF or optical communication, or solar thermal propulsion. Due to lower optical performance requirements, the propulsion application, depicted in a presentation by this topic's author (Figure 5), would be the lowest risk near-term opportunity for transitioning this SMP-based technology to operational use. The simple positioning structure and self-supporting SMP membrane would replace the inflatable support structure and compliant membrane shown in that drawing.

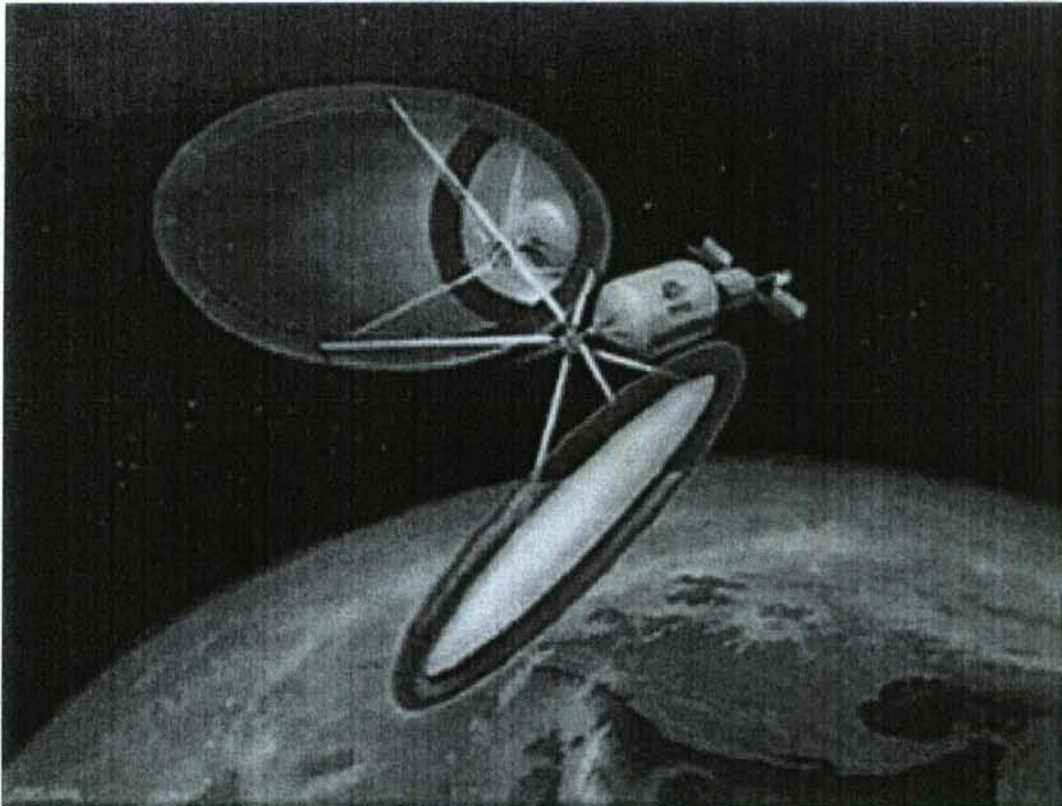


Figure 5. Solar Thermal Propulsion System²

1.4 Program Goal

Based on innovations demonstrated feasible in Phase I (Section 1.5) and brought to fruition in Phases II and III, this program will develop space-qualifiable SMP materials and fabrication processes and demonstrate their application in self-deploying membrane reflectors for solar-thermal space propulsion systems. The resulting material system will provide major reduction in mirror areal density compared with current conventional rigid mirrors and increased mechanical and optical stability compared with current membrane mirrors while also achieving self-deployment performance. The resulting fabrication processes will significantly reduce the cost for producing mirrors.

1.5 Highlights of Phase I Results & Related R&D

In the Phase I effort, development in related programs, and supporting Independent R&D, CRG demonstrated feasibility of material and process technologies enabling SMP self-deploying membrane reflectors. Those results are summarized here, while details are presented in AFRL technical report AFRL-PR-ED-TR-2004-0036, Shape Memory Polymer Self-Deploying Membrane, 27 March 2004 (CRG Report CRG-AFTC3107-004Z).

- **Space-qualifiable cyanate ester SMP material for membrane mirrors**
 - Full strain recovery to "memory" shape after repeated deformation
 - Operationally relevant glass transition temperature at which shape recovery occurs (160 °C)
 - Mechanical strength consistent with self-supporting membrane structures
 - Compatibility with space environment (radiation, atomic oxygen, low outgassing in vacuum)
 - Compatibility with achieving optical-quality reflective surfaces durable through deployment
 - Compatibility with carbon reinforcement for lightweight composite membranes
- **Viable Fabrication Technology for SMP Membranes**
 - "Neat" (unreinforced) SMP resin
 - Carbon nanofiber-reinforced SMP composite
 - Carbon fabric-reinforced SMP composite
- **Coatings to Establish Reflective Surface on SMP Membranes**
 - Adhesion compatibility between cyanate ester SMP and coatings materials
 - Retention of SMP's optical-quality surface during coating process
- **Membrane Mirror Self-Deployment Technologies**
 - IR-induced self-deployment of carbon fabric reinforced and carbon nanofiber-reinforced membranes
 - Microwave RF-induced self-deployment of carbon nanofiber-reinforced membranes

2.0 PHASE II TECHNICAL OBJECTIVES

Phase II research and development was guided by the following objectives documented in the original proposal.

Top level objectives (e.g., 2.1) are structured with sub-objectives for clarity in guiding development effort.

2.1 To Develop Mature Materials

2.1.1 To Optimize Cyanate Ester SMP and Related Composites

Materials meeting this sub-objective will have properties specifically tailored for the self-deploying membrane reflector application, achieving the following attributes for space-based membrane mirrors and support structures while enabling optical surfaces equivalent to current mirrors (relative terms (e.g., "lower") refer to improvement over conventional mirror materials):

- a. Lower areal density ($\ll 0.5 \text{ kg/m}^2$)
- b. Equivalent optical surface quality (especially figure and finish)
- c. Compatibility with the self-deployable membrane mirror concept
- d. Space compatibility: Radiation hardened (space ambient), atomic oxygen (AO) resistant (either inherent or practical to protect with coating), and resistant to outgassing in a vacuum
- e. Structural integrity under mechanical and thermal loads representative of operational employment
- f. Provide acceptable optical surface throughout thermal and mechanical excursions representative of operational use (i. e., will coefficient of thermal expansion (CTE) mismatches or mechanical loads (e. g., stretching and bending) degrade the reflective surface's final figure or finish?)

2.1.2 To Fully Characterize Cyanate Ester SMP and Related Composites

Materials meeting this sub-objective will have documented material properties in all parameters relevant to designing self-deploying membrane reflector for space applications. Those parameters will include, but not be limited to, structural and mechanical properties, mass properties, optical properties, and process behavior properties (e.g., cure shrinkage, mold release compatibility, etc.).

2.2 To Develop Mature Full-scale Fabrication Processes

2.2.1 To Increase SMP Material Production Processes to Relevant Batch Sizes

Meeting this sub-objective requires demonstrating the capacity to produce cyanate ester SMP resin on a scale relevant to full-scale membrane mirrors, with physical demonstration of batch

sizes supporting fabrication of a mirror of at least 1 meter diameter. Quantitative analysis will confirm the processes are scalable for membrane mirrors of at least 20 meters in diameter.

2.2.2 To Increase Structure Fabrication Processes to Relevant Sizes and Shapes

Meeting this sub-objective requires demonstrating the capability to fabricate neat resin or composite membrane mirror structures on a scale and in shapes relevant to full-scale membrane mirrors, with physical demonstration accomplished with a mirror of at least 1 meter diameter. Quantitative analysis will confirm the processes are scalable for membrane mirrors at least 20 meters in diameter.

2.2.3 To Increase Coatings Processes to Relevant Sizes & Performance

Meeting this sub-objective requires demonstrating the capability to apply reflective and protective coatings to neat resin or composite membrane mirror structures on a scale and in shapes relevant to full-scale membrane mirrors, with physical demonstration accomplished with a mirror of at least 1 meter diameter. Coatings meeting this objective must also remain conformal to the membrane during the stow and self-deployment cycle and retain acceptable post deployment optical performance. Quantitative analysis will confirm the processes are scalable for membrane mirrors at least 20 meters in diameter.

2.3 To Develop Membrane & Interface Design Methodology

Meeting this objective requires demonstrating use of material properties data and fabrication process information to reliably define the material compositions; mold shapes, materials, and finishes; and fabrication steps which repeatably yield a membrane mirror of specified aperture, figure, and finish within acceptable tolerances and the physical interface for its attachment to the host spacecraft.

2.4 To Develop Full-Scale Self-Deployment Technology

Meeting this objective requires demonstrating repeatable, controlled self-deployment by a prototype membrane mirror yielding achievement of a specified final figure and finish within defined tolerances, with physical demonstration accomplished in 1-G simulation with a mirror of at least 1 meter diameter. Quantitative analysis will confirm the self-deployment technology approach is scalable for membrane mirrors at least 20 meters in diameter.

2.5 To Demonstrate Relevant Optical Performance by a Full-Scale Prototype Self-Deploying Membrane Mirror

Meeting this objective requires demonstrating the design and production of a 1 meter diameter membrane mirror which employs the materials and fabrication processes and design methodology resulting from achieving Objectives 2.1 through 2.4 and which achieves operationally relevant mirror performance (specifications to be determined by the government program technical monitor).

3.0 TECHNICAL RESULTS

Highlights of Phase II results (details presented in the following sections):

- **An optimized cyanate ester-based SMP (CE SMP) achieved the strength, strain recovery, and other properties required for self-deploying space-based membrane reflectors. A provisional patent application was filed for this new material.**
- **CE SMP-based composites achieved strength, strain recovery, and mass properties relevant for self-deploying space-based membrane reflectors.**
- **Fabrication process development demonstrated meter-scale self-deploying membranes using processes scalable to multi-meter diameter membranes and achieved membranes with 0.59 kg/m² areal density.**
- **In a simulated zero-G environment, a 0.5 m diameter membrane that had been “stowed” by accomplishing severe deformation from its original shape subsequently self-deployed with approximately 99.7% accurate recovery of its original shape.**

In the Phase II effort under this contract, development in related programs, and supporting Independent Research and Development (IR&D), CRG matured the material and process technologies enabling SMP self-deploying membrane reflectors. As noted in Section 6, development in related programs or IR&D provided results originally proposed to be achieved by direct Phase II contract effort. As a result, less contract effort needed to be expended in those areas, enabling more emphasis in areas that presented greater challenges, especially formulation of the space-compatible shape memory polymer on which the self-deploying membrane is critically dependent. The net effect was that this project obtained substantial leverage from external funding sources in achieving the Phase II objectives.

For simplicity of narrative, results are presented according to the contract Statement of Work task structure, but were not necessarily achieved in that sequence. Correlation to Technical Objectives (Section 2) is addressed in Section 4, Assessment of Results.

3.1 Task 1: Optimize Materials

Extending the Phase I development of cyanate ester SMP, CRG optimized materials (neat resin and composites) for application in self-deploying membrane reflectors.

CRG investigated optimization of two SMP-based material systems as candidate materials for implementing self-deploying membrane structures: (a) nanoparticle-reinforced composites and (b) fiber-reinforced composites. Due to anticipated advantages in mass density and fabrication simplicity, CRG intended to use the nanoparticle-reinforced composites as its primary membrane material, but pursued the conventional fiber-reinforced composites as a risk mitigation back-up.

For both material systems, effort focused on achieving Technical Objective 2.1, modifying a broad range of formulation and process factors to improve upon the Phase I materials in the following parameters:

- Inherent material mass density and areal density of resultant membranes
- Stiffness at temperatures below T_g
- Maximum allowable strain above T_g with full strain recovery (shape memory)
- Coefficient of thermal expansion (CTE) and thermal conductivity
- Compatibility with achieving a high-performance reflective surface

3.1.1 Cyanate Ester SMP Resin

The program was critically dependent on optimizing the cyanate ester SMP (CE SMP) as the functionally active component enabling membrane self-deployment. CE SMP was the matrix resin for both membrane material systems, nanoparticle-reinforced composites and fiber-reinforced composites. Resin optimization focused on the following:

- Increasing the degree of mechanical strain that the material can undergo and then fully recover spontaneously when heated above its T_g
- Increasing the inherent stiffness of the resin

CRG completed its investigation of a wide variety of cyanate ester-related SMP formulations by varying both the types and proportions of the constituent monomers, activators, and other chemical components. While Phase I development demonstrated the technical feasibility of achieving shape memory properties in a cyanate ester-based polymer system, the Phase I strain recovery performance was inadequate for the membrane reflector concept. The Phase I SMP achieved repeatable full recovery from approximately 10% elongation, but greater strain recovery was needed to enable a practical stowage configuration for the membrane reflector.

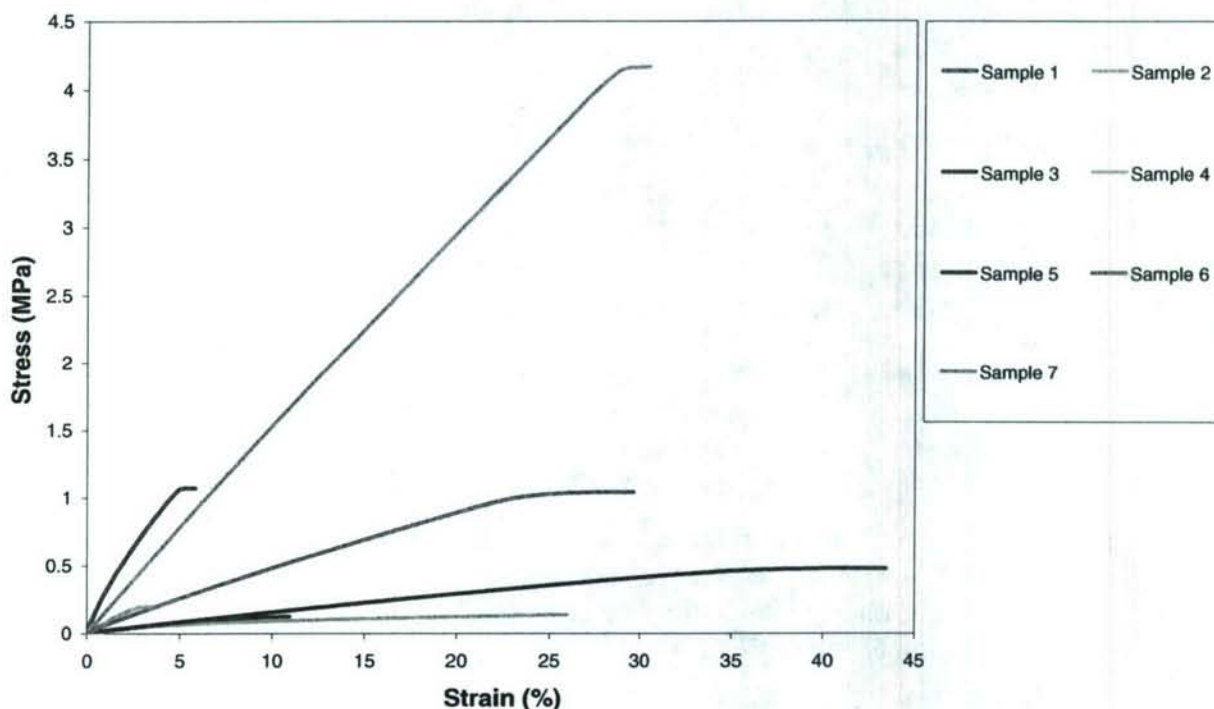
CRG initially investigated tailoring the original cyanate ester formulation to improve its material properties for the membrane reflector application. While this approach yielded some improvement in elongation and strain recovery capacity, the degree of improvement and repeatability were not promising for achieving required performance.

CRG therefore investigated formulating cyanate ester with other classes of resins to obtain space-compatible SMP. CRG hypothesized that enhanced performance from incorporating the alternative resins would be achieved through lengthening of the cyanate ester polymer segments between crosslinking points, thereby increasing strain capability of the network. CRG investigated cyanate ester-related SMP (CE SMP) formulations in [three candidate] areas:

- [Candidate A]
- [Candidate B]
- [Candidate C]

Figure 6 and Table 1 show the broad range of material properties resulting from CRG's SMP resin development investigations.

30 January 2007

CRG Cyanate Ester SMP Formulations**Figure 6. Stress-Strain Performance Data Showing Progress During Resin Development****Table 1. Overall Progress in Resin Development**

Sample	Maximum % Elongation
[Sample 1]	5.0%
[Sample 2]	4.5%
[Sample 3]	10.8%
[Sample 4]	24.7%
[Sample 5]	25.4%
[Sample 6]	41.9%
[Sample 7]	30.4%

In the investigation of [Candidate C], results yielded an SMP with acceptable performance for application in self-deploying membrane reflectors. Formulations of [a Candidate C] CE SMP achieved T_g in the range of 190 °C to 230 °C. Further CRG development funded by BATC (as a part of its Phase III effort with this material, see Section 7.1) demonstrated T_g as low as 130 °C, and that experience indicates this formulation approach could achieve T_g as low as 25 °C. [Candidate C] CE SMP has achieved elongations above T_g in the range of 30-35%. Vacuum outgassing tests (conducted by BATC) demonstrated a Total Mass Loss of 0.094% to 0.288% (values below 1.0% are acceptable) and Condensed Outgassing Product of 0.004% to 0.020% (values below 0.1% are acceptable).

Based on the results achieved with the [Candidate C] cyanate ester SMP, and its suitability for the Phase III effort by a commercial customer, CRG selected it as the resin system for both the nanoparticle-reinforced and the fiber-reinforced membrane materials. Future references to "CE SMP" in this report will therefore pertain exclusively to [Candidate C] cyanate ester SMP unless identified otherwise (especially Sections 3.1.1.1 through 3.1.1.3, which describe the alternative resin investigations).

[CRG has a patent pending for the cyanate ester SMP resulting from this effort.]

The following subsections present a summary of the investigations of candidate formulations which led to the final results described above.

3.1.1.1 Tailored Baseline Cyanate Ester SMP Formulation

The baseline cyanate ester-based SMP resulting from Phase I development was composed primarily of ... constituent monomers plus activators and other chemical components. The initial Phase II resin development focused on tailoring this formulation to provide improved properties, especially capacity for degree of elongation above T_g and repeatable strain recovery.

One initial candidate formulation achieved repeatable recovery from 43% strain (Figure 7) -- approaching the 50% target. However, the recovery was not uniform among all strain cycles, and the 43% recovery was not repeatable from batch to batch of the material. That formulation exhibited a glass transition temperature (T_g) of 166 °C.

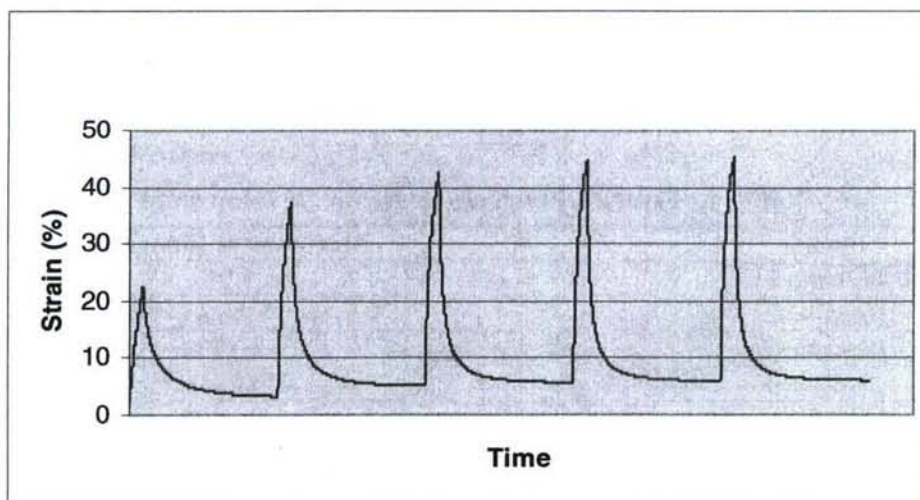


Figure 7. 43% Strain Recovery of a Candidate Optimized Cyanate Ester SMP Formulation

Another initial candidate formulation achieved repeatable recovery from 23% strain (Figure 8) and exhibited the required uniform strain recovery among all strain cycles. However, the 23% recovery performance was not reliably repeatable from batch to batch of the material. That formulation exhibited a T_g of 174 °C.

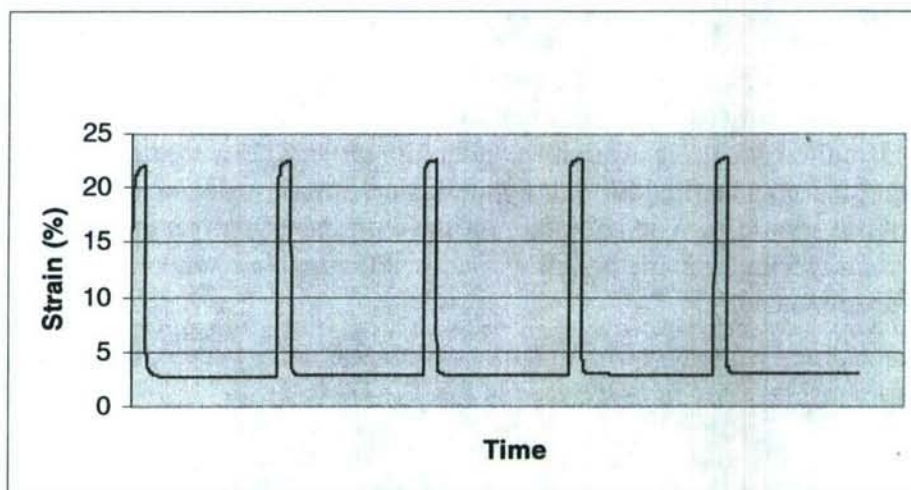
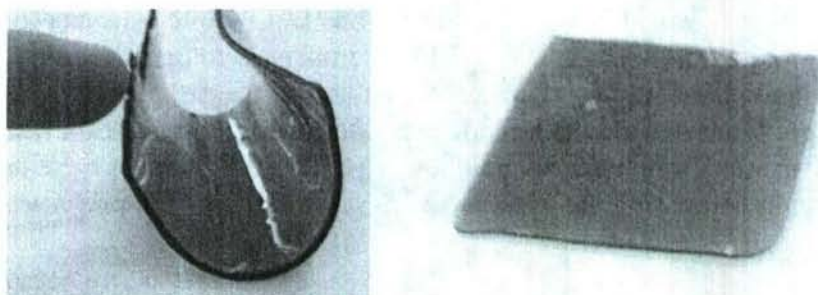


Figure 8. 23% Strain Recovery of a Candidate Optimized Cyanate Ester SMP Formulation

TA506-051 | Figure 9 illustrates the radius of curvature achievable within the recoverable strain threshold of another candidate SMP formulation. This early result provides a positive qualitative indication that a practical stowage configuration should be achievable with the eventual optimized CE SMP formulation. However, further investigation with this formulation approach did not yield substantial progress towards greater elongation and strain recovery properties and better repeatability.



PA506-051 | **Figure 9. Maximum Recoverable Deformation (L) and Memory Shape (R) of a Coupon Membrane of a Candidate Optimized Cyanate Ester SMP**

CRG obtained BATC testing (see Section 3.6.2) for vacuum outgassing characteristics (Total Mass Loss (TML) and Condensed Outgassing Product (COP)) of this type of CE SMP and carbon fiber-reinforced composites using it as the matrix. The neat resin exhibited 0.147% TML and 0.006% COP. One composite exhibited 0.292% TML and 0.027% COP while another using a different type of carbon fabric and lay-up configuration exhibited 0.059% TML and 0.012% COP. When compared with NASA's acceptance criteria of TML <1% and COP <0.1%, these results confirm that CRG's baseline CE SMP exhibits outgassing performance compatible with space qualification.

3.1.1.2 [Candidate A]

This methodology involved the reaction of [a type of constituent] with cyanate ester Initial studies were performed using [commercially available constituents]. This material was chosen for initial studies due to its availability and high potential for significant modification of mechanical properties such as flexibility, toughness, and impact resistance. The [candidate constituent] material should give an indication of the extreme effects on mechanical properties that might be obtained using this methodology while allowing the chemistry of the reactions taking place to be evaluated.

Dynamic mechanical analyzer (DMA) data showed that, as expected, the presence of the [candidate constituent] resulted in a decrease in the T_g (Table 2).

Table 2. Effect of [Candidate Constituent] on T_g and Ultimate Elongation of [Cyanate Ester-Based] SMP

% [Candidate Constituent]	T_g ($^{\circ}\text{C}$)	Maximum Elongation
0% [A1]	188	4.5%
10% [A2]	171	6.3%
15% [A3]	165	5.0%

Reducing the crosslink density in combination with the addition of [candidate constituent] resulted in an observable increase in maximum elongation, Table 3. There was approximately a 100% increase in maximum elongation in going from 0% [candidate constituent] to 30% [candidate constituent]. There was an observable trend in the increase in maximum elongation with [candidate constituent] from 10-30%. However, the 10% sample warrants further investigation. It is important to note the 0% and 15% samples were performed by a different person than the 10% and 30% samples. Differences in sample preparation may account for the 10% sample seemingly lying outside the trend if the differences in preparation result in one persons data being systematically lower than the other persons. There was a greater than 300% increase in elongation in comparing the 10% and 30% samples that were prepared and measured by the same person.

Table 3. Effect of [Candidate Constituent] on Ultimate Elongation of [Cyanate Ester-Based] SMP

% [candidate constituent]	Avg. Maximum % Elongation	Std. Deviation
0% [A4]	10.8%	0.77
10% [A5]	5.9%	1.05
15% [A6]	15.7%	0.67
20% [A7]	24.7%	1.55
30% [A8]	20.4%	2.71

The DMA data presented in Figure 10 show the stress-strain curves for three of the samples from Table 3. The 20% [candidate constituent] shows an approximate 100% increase in strain and very large increase in toughness while breaking at the same applied stress as the 0%

[candidate constituent] sample. The 10 % [candidate constituent] sample appears much stiffer and breaks at a much lower strain than the 0% [candidate constituent] sample. The increased stiffness in the material and its deviation from the trend indicate the 10% [candidate constituent] sample warrants additional investigation. It seems most likely the difference in the stress-strain curve is due to a variation in sample preparation.

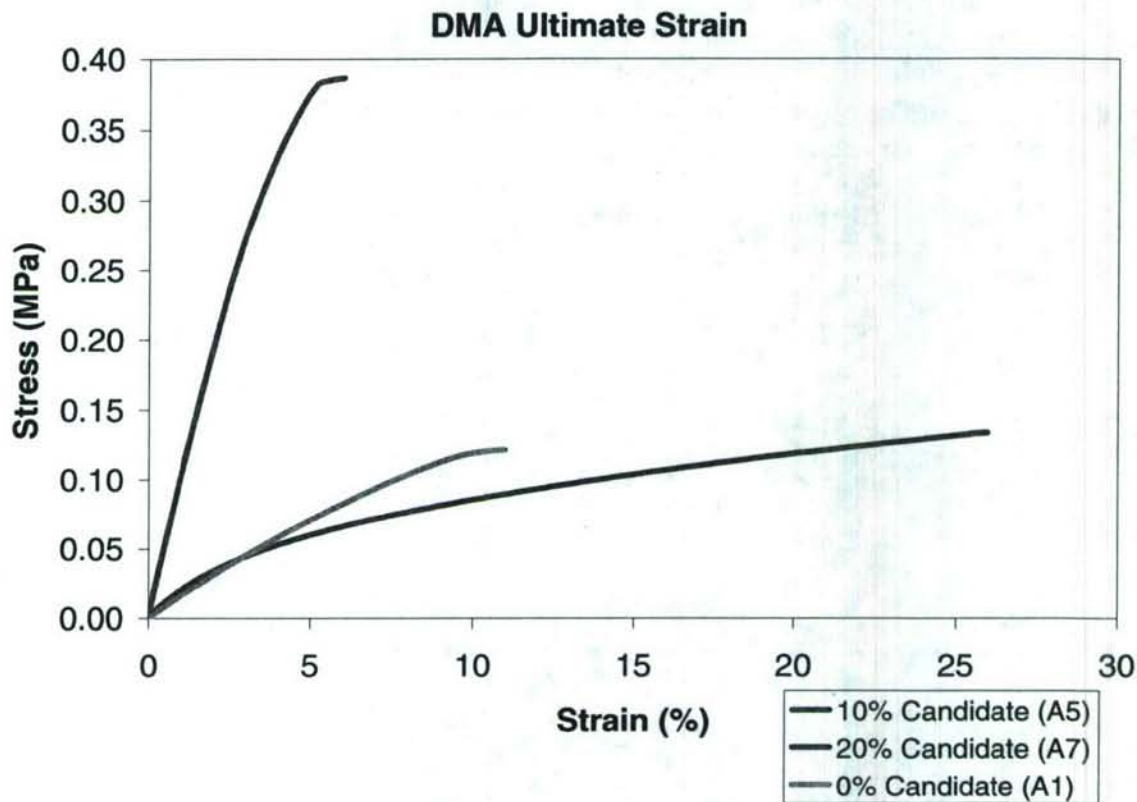


Figure 10. Stress-Strain Performance for Candidate SMP Formulations

BATC tested two CRG specimens of this type of SMP for vacuum outgassing characteristics (see Section 3.6.2). One specimen exhibited 0.302% TML and 0.013% COP. The other exhibited 0.122% TML and 0.002% COP. When compared with NASA's acceptance criteria of TML <1% and COP <0.1%, these results confirm that this type of CE SMP exhibits outgassing performance compatible with space qualification.

3.1.1.3 [Candidate B]

The synthesis of cyanate ester monomers having [Candidate B] incorporated was also investigated. CRG hypothesized that it should be possible to vary the T_g of a [Candidate B] cyanate ester homopolymer from -100 °C to well above 200 °C

Figure 11. [Reserved]

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The entire synthesis was completed, the desired product isolated, and its structure confirmed by nuclear magnetic resonance (NMR) and Fourier transform infrared (FTIR) spectroscopy.

Initial investigations of the mechanical properties of some preliminary formulations were conducted. The [candidate formulation] resulted in a tough room temperature elastomer that could be repeatedly folded or rolled on itself. A material having such a low T_g was unexpected. The [candidate formulation], however did demonstrate as much as a 64% maximum elongation with samples routinely and repeatedly having elongations of 42%. As might be expected, formulation with [another constituent] can be used to increase the T_g , the modulus, and the force of retraction. The addition of [that constituent], however, also results in a decrease in the maximum elongation. The effect of [that constituent] on T_g and % elongation can be seen in Table 4, while the mechanical properties are presented as DMA stress-strain plots in Figure 12.

Table 4. Effect of [a Constituent] on [Candidate B Formulation]

% [Constituent]	T_g ($^{\circ}\text{C}$)	% Elongation	Std. Deviation
0 [B1]	10.7	41.9	1.2
10 [B2]	37.4	19.6	0.6
20 [B3]	52.5	25.4	1.7

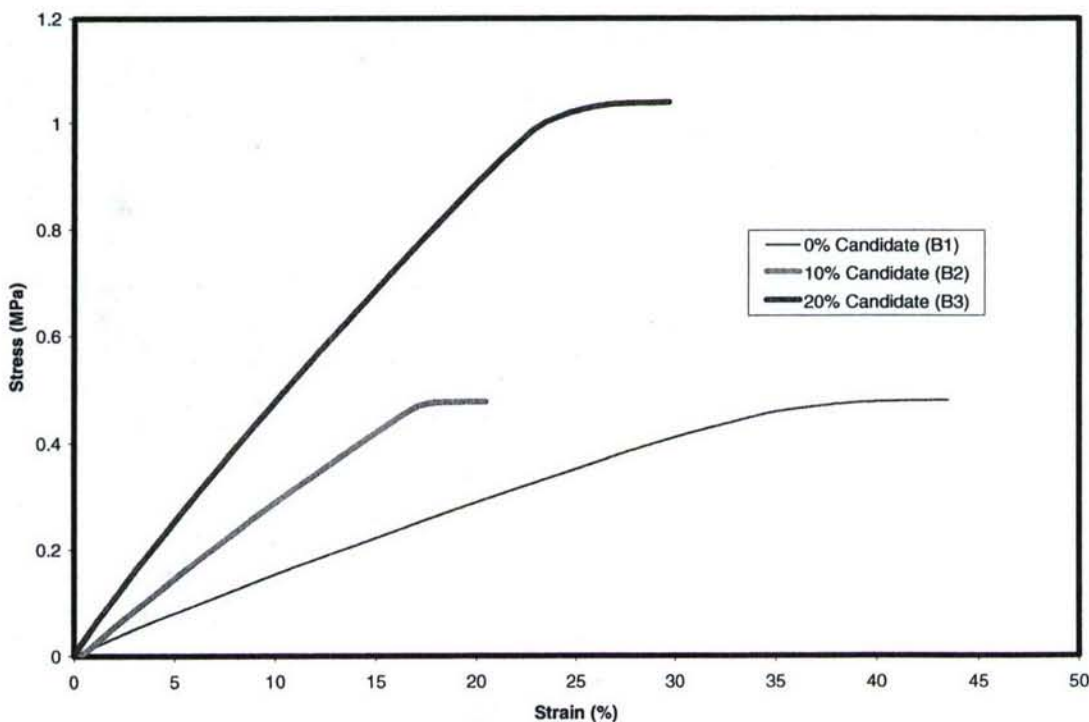


Figure 12. Stress-Strain Performance for Preliminary [Candidate B] Formulations

Although no quantitative data is available at this time, some initial formulations of [Candidate B] with [another constituent] have shown an increase in the T_g . This, along with what CRG has shown with the baseline CE SMP formulations, would indicate that the ultimate elongation of the material may be further increased while the glass transition temperature is also increased. Additionally, larger increases in T_g can be accomplished by the addition of [a particular constituent] and any decrease in ultimate elongation associated with this can potentially be countered by the addition of [another constituent].

While one of the key selection criteria in material evaluation has been ultimate elongation, this property is certainly not the only criteria and is perhaps not the best suited to indicate how the material will perform in its desired application. The toughness (defined as the area under the stress/strain curve) may be a better indicator. The series of photos in Figure 13 shows [a Candidate B formulation] returning to its memory shape after being wrapped in a 360° spiral. This sample was able to be repeatedly deformed to this configuration, stowed (cooled below T_g), and then deployed to its memory configuration (flat) by heating. While the maximum elongation of this sample is similar to that of a [Candidate A formulation], clearly the toughness of this material makes it potentially suitable for the desired application.

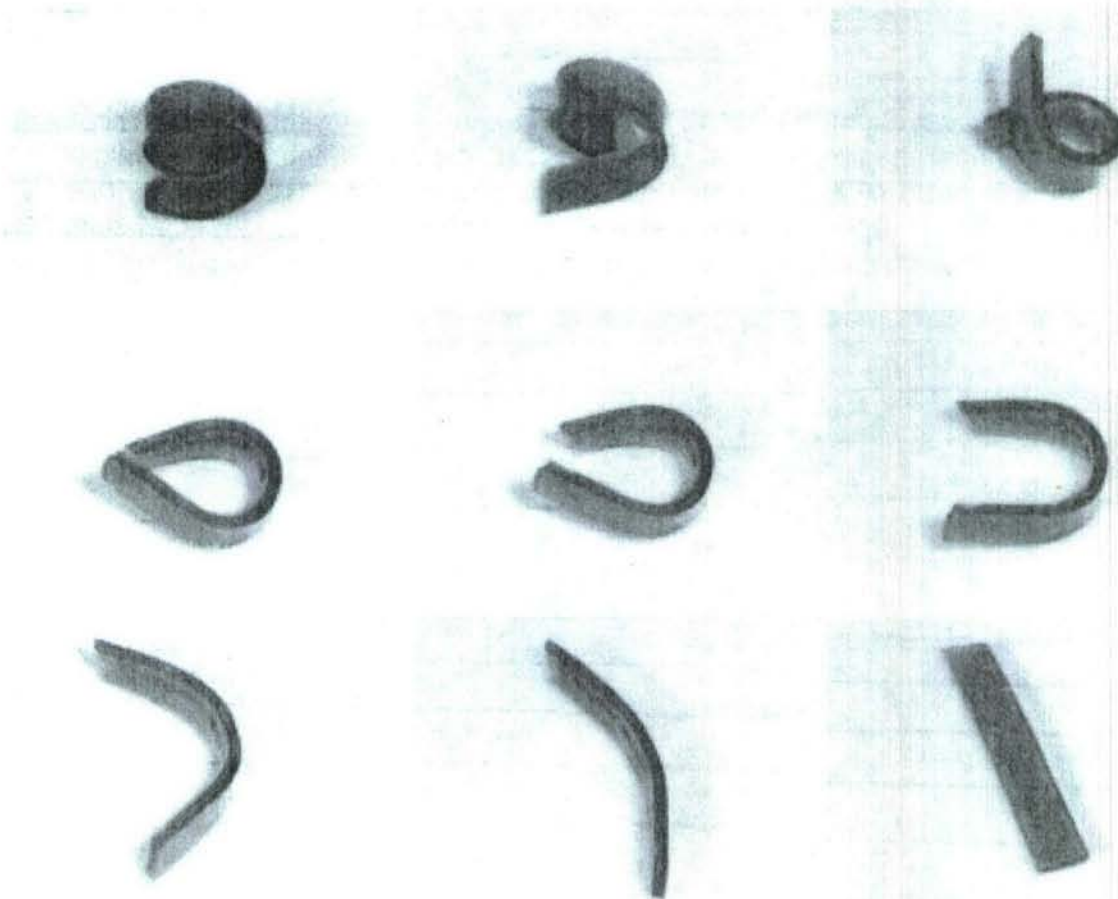


Figure 13. [Candidate B] CE SMP Self-Deploying from Stowed Configuration (Upper Left) to Memory Configuration (Lower Right)

Due to the relative high expense of this material, CRG did not obtain vacuum outgassing tests in the manner described for the types of SMP formulations.

3.1.1.4 [Candidate C]

Additional elastomeric materials having [another candidate] functionality were acquired. Both of these functional groups also have the capability to co-react with cyanate ester. CRG expected the ability to utilize these different functional groups would allow a broader range of commercially available polymers to be incorporated in the cyanate ester matrix. The first of these materials to be examined was based on [a particular constituent].

This investigation was an extension of the [Candidate A] work (above). [This particular constituent is from a class of materials] that have been used in space applications. CRG hypothesized their incorporation in the CE SMP should result in a space-qualifiable material. The presence of [this constituent] should also lead to greater flexibility in the cyanate ester SMP than [Candidate A]. Additionally, [Candidate C formulations based on these] materials should have better temperature stability relative to their [Candidate A] counterparts and very low moisture uptake. Initial attempts to incorporate [this particular constituent] were unsuccessful.

Figure 14. [Reserved]

CRG developed a novel process that allows for the controlled incorporation and reaction of [a related constituent] with cyanate esters. Results for the [modified Candidate C formulation (right-most bar in Figure 15)] showed considerable increases in toughness and T_g over the previous baseline cyanate ester SMP formulation ([left-most bar in] Figure 15). Formulations of the [modified Candidate C] CE SMP investigated under this contract had T_g in the range of 130 °C to 230 °C and elongations above T_g in the range of 30-35%.

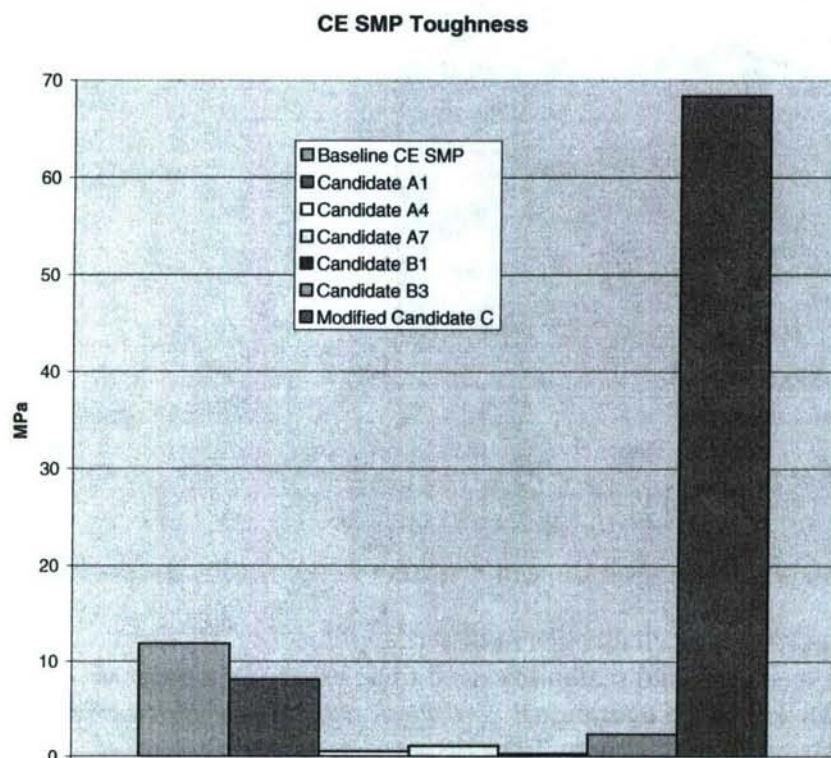


Figure 15. Toughness of Several CE SMP Formulations (Tested 20 °C above T_g)

CRG obtained BATC testing (see Section 3.6.2) for vacuum outgassing characteristics (TML and COP) of this type of CE SMP. The five specimens exhibited TML ranging from 0.094% to 0.288% and COP ranging from 0.003% to 0.0049%. When compared with NASA's acceptance criteria of TML <1% and COP <0.1%, these results confirm that this new type of CE SMP exhibits outgassing performance compatible with space qualification.

3.1.2 Materials for Nanoparticle-Reinforced SMP Membranes

In this effort, CRG investigated optimizing the Phase I material formulation for CE SMP reinforced with carbon nanofibers (CNF) and scaling up the related fabrication processes to enable implementation of a self-deploying membrane reflector using this material system.

The Phase I investigation of this material system was limited to a single 2.5 cm x 2.5 cm coupon of CE SMP-CNf composite membrane (Figure 16). The membrane had an areal density of 0.47 kg/m². The 0.4 mm thick material exhibited self-supporting structural integrity and had a storage modulus of approximately 2700 MPa, representing approximately a 17% increase in stiffness compared with the Phase I baseline cyanate ester SMP (approximately 2300 MPa).

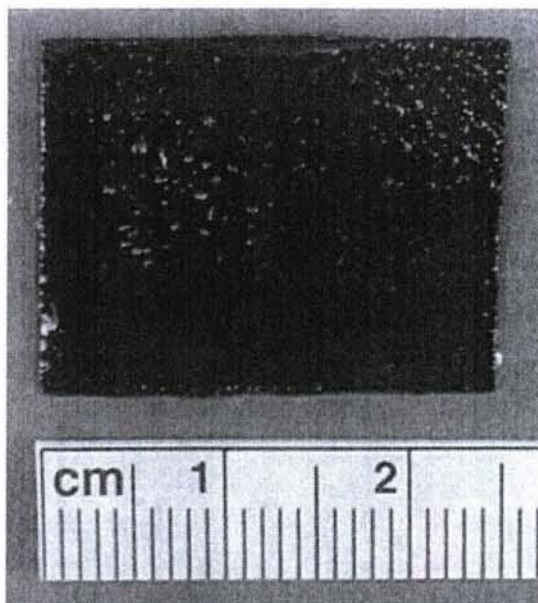


Figure 16. Phase I Carbon Nanofiber-Reinforced Cyanate Ester SMP Composite

The Phase II effort addressed processing challenges in material uniformity, material performance (strength and shape memory), and scalability need to be resolved in order to consider this a viable candidate for use in the operational prototype. As the size of a membrane structure increases, difficulty in controlling thickness, filler dispersion, and uniformity of resin/filler ratio increase significantly. Processing methods used for small scale coupons do not necessarily work on a larger scale.

3.1.2.1 Carbon Nanofiber Treatment Process

During Phase I effort, the as-delivered CNF component required in-house treatment to remove contaminants and functionalize the nanofibers to enhance the nanofiber-resin interface in the composite. During Phase I, this treatment process accommodated batch sizes of 6 g. At the time of the Phase II proposal, CRG anticipated the need for scaling up its in-house CNF treatment process to accommodate batch sizes compatible with fabricating the much larger membranes planned for prototype demonstrations.

Early in the Phase II effort, CRG scaled up its CNF treatment batch size by 50% (to 9 g) which was adequate for initial small coupons, but would have required further scale-up to accommodate meter-scale membranes.

However, shortly after Phase II effort commenced, the CNF source significantly improved the quality of the bulk CNF material. The new CNF component proved ready for use in CE SMP without the need for CRG's in-house treatment. CRG discontinued further scale-up of the CNF treatment process.

3.1.2.2 Composite Development

CRG made significant progress improving and scaling up fabrication processes for carbon nanofiber-reinforced composites using CE SMP as the resin matrix. While initial Phase I effort confirmed the feasibility of incorporating carbon nanofibers (CNF) in a CE SMP matrix to fabricate a CNF-reinforced composite, that effort involved only a very few small trial coupons on which no attempt was made to obtain an optical surface (Figure 16). Figure 17 shows the specular reflection from a CNF-reinforced composite membrane coupon with an area approximately 900% greater than the area of the Phase I coupons.

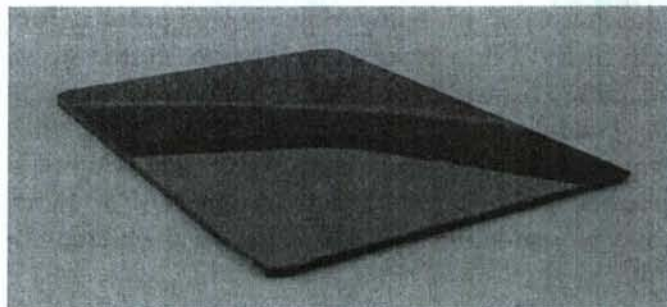


Figure 17. Current Phase II CNF-Reinforced CE SMP Composite Membrane Coupon (Approximately 7.5 cm Square)

Achievement of the high-quality surface and uniform structural integrity shown in the Figure 17 coupon represent a significant breakthrough in fabrication process development. Early CE SMP coupons often shattered during cure, and initial attempts at scaling up from the Phase I size for CNF-reinforced composites resulted in irregular surfaces unsuitable for membrane reflectors (Figure 18).

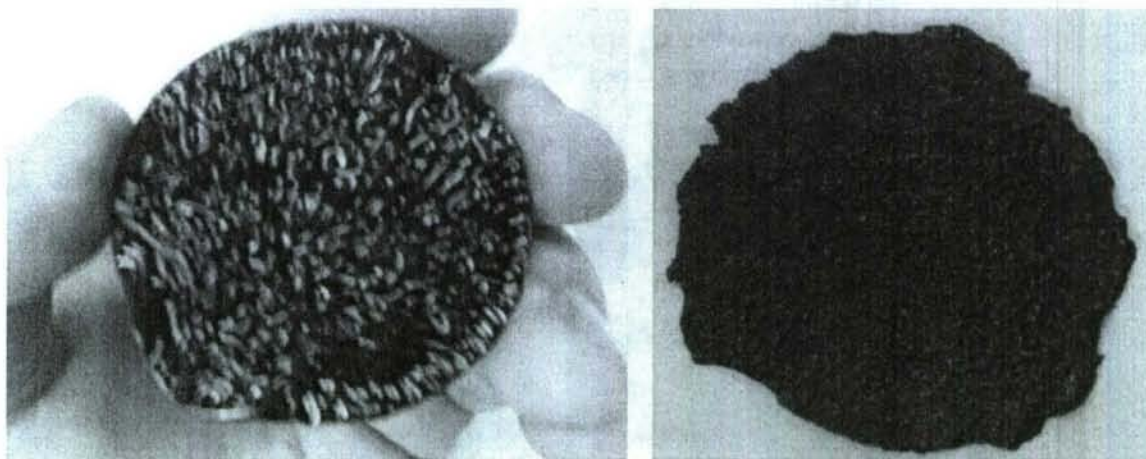


Figure 18. Early Phase II CNF-Reinforced CE SMP Composite Membrane Coupons (Examples Illustrating Process Issues Overcome to Achieve the Figure 17 Quality)

CRG developed a process to reduce the void content and non-uniformity experienced in CE SMP/CNF composites using earlier techniques. This new process succeeded in yielding a uniform CE SMP/CNF composite with high CNF loading.

The benefit of this process is its versatility in design. The process can be followed while slightly changing the design to meet specific requirements such to allow for complex shapes (e.g., parabolic reflectors). Another benefit of this process is the potential to achieve consistent high filler loadings.

Composites using CNF as the filler yielded a material mass density of 1.25 g/cc with an areal density of 1.73 kg/m² for a coupon structure of 0.14 cm thickness. This thickness was required to maintain acceptable stiffness below T_g . Further tailoring of this composite material was needed increase its inherent stiffness and thereby allow thinner structures with resulting lower areal density.

Initial coupon-scale qualitative stow/deploy trials showed promise for the feasibility of this process in a deployable CE SMP/CNF composite membrane. Initial stow/deploy cycles were conducted by cutting a specimen from a flat coupon. The specimen was heated using a heat gun and “stowed” by manually bending the specimen (Figure 19). The sample was then reheated and “deployed” (Figure 20) while being held with the bend axis oriented vertically such that gravity did not have a significant effect on the specimen’s deployment. The sample displayed some hysteresis (not a full recovery) visible in Figure 20 due to the localized high strains induced using the manual technique.

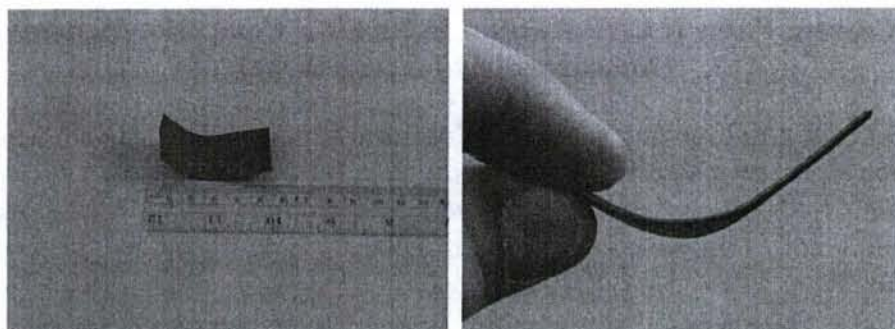


Figure 19. Stowing Cyanate Ester SMP/CNF Composite
(Left and Right Images Are Different Views of Same Coupon)

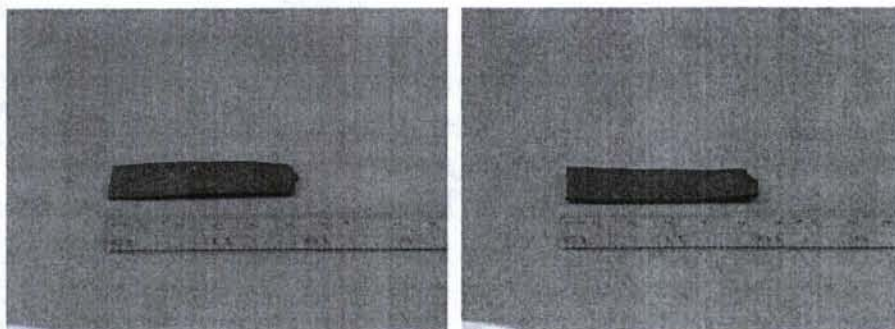


Figure 20. Deployment of Cyanate Ester SMP/CNF Composite
(Left and Right Images Are Different Views of Same Coupon)

CRG improved its coupon-scale fabrication process sufficiently to yield uniform material of approximately 0.64 mm thickness with areal density of approximately 0.75 kg/m². While this membrane had a higher areal density than that of the Phase I coupon, the increase was strictly due to the increased thickness, not an increase in the inherent mass density of the material. The

Figure 21 shows an untrimmed, as-cast coupon of the improved material. This development represented a scale-up of approximately ten times the membrane area of the Phase I coupon, but scale-up of six times greater area is required to fabricate a meter-scale membrane.

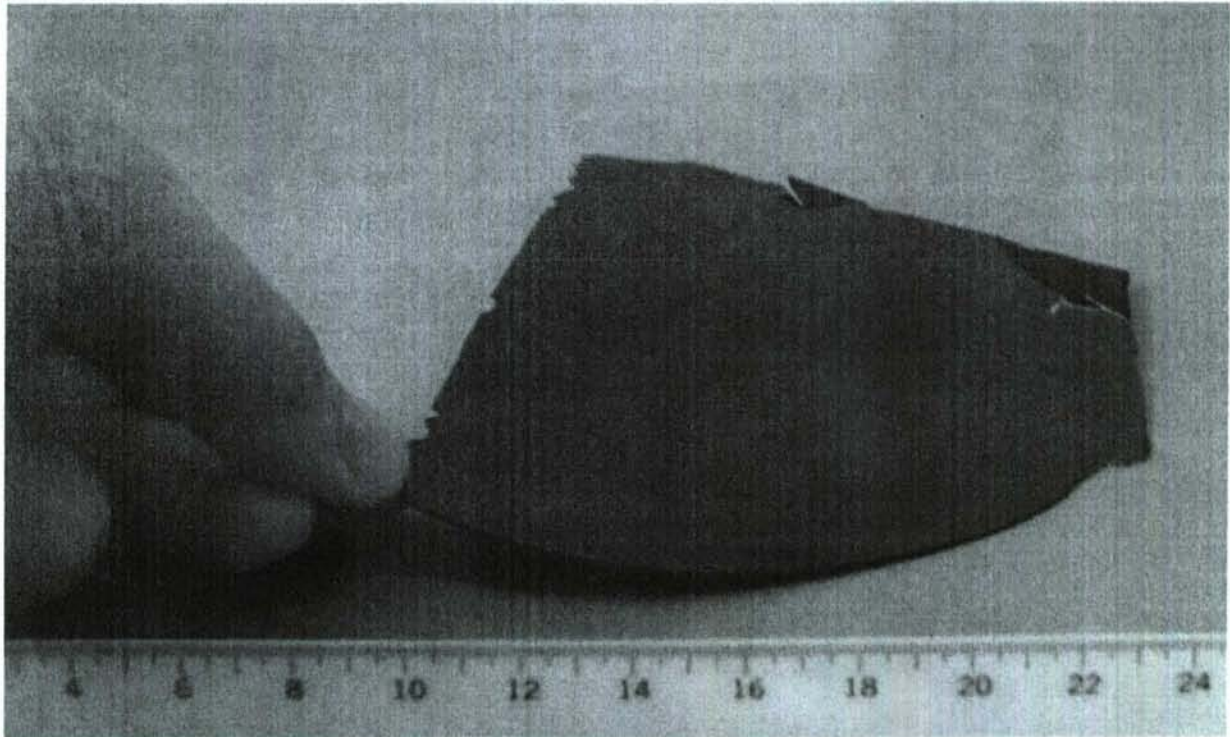


Figure 21. As-Cast Coupon of SMP/CNF Composite with 0.75 kg/m^2 Areal Density

CRG conducted additional process modifications intended to further reduce the areal density below 0.5 kg/m^2 . Extending the previously successful technique for reducing membrane thickness yielded a membrane of approximately 0.36 mm thickness and 0.3 kg/m^2 . However, as shown in Figure 22, the resulting material no longer achieved the uniform CNF dispersion required to exhibit predictable and repeatable deployment characteristics.

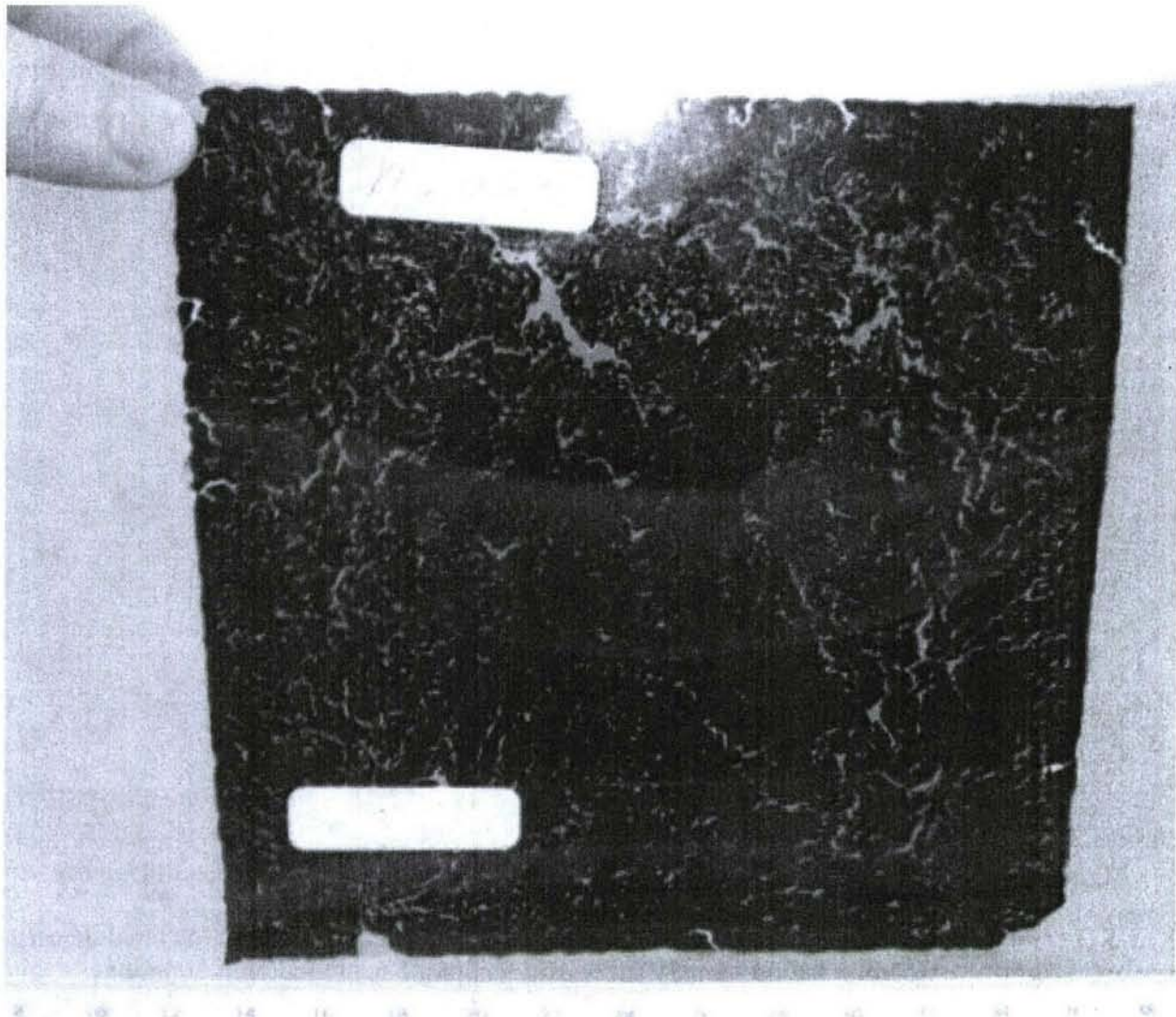


Figure 22. As-Cast Coupon of SMP/CNF Composite with 0.30 kg/m² Areal Density

In parallel with this project, CRG was engaged in another AFRL-funded SBIR Phase II project developing SMP/CNF composites for a different application (AFRL/ML contract FA8650-05-C-5047, "Hierarchical Shape Recovery Polymer Nanocomposites (PNCs) for Next-Generation Aerosystem Applications"). Since that program was engaged in a detailed investigation of techniques for uniform dispersion of CNF in SMP, CRG suspended SMP/CNF composite development in this project in order to leverage results from the parallel project (and avoid contractually prohibited "essentially equivalent work").

Also, by this stage of the project, BATC had engaged CRG in Phase III effort to exploit the fiber-reinforced membrane approach (see Section 7.1). CRG therefore focused the remainder of this contract effort on the fiber-reinforced material (Section 3.1.3), conducting parallel mutually supporting (but not overlapping) development under BATC Phase III purchase orders and this Phase II contract.

3.1.3 Materials for Fiber-Reinforced SMP Membranes

CRG conducted initial process development for fabricating fabric-reinforced composites based on CE SMP. Figure 23 presents early coupons incorporating carbon fabric in a CNF-loaded CE SMP matrix. While these coupons demonstrated the composite is feasible from a structural perspective, and specular reflection was achieved, significant development was still required to achieve an acceptable optical surface.

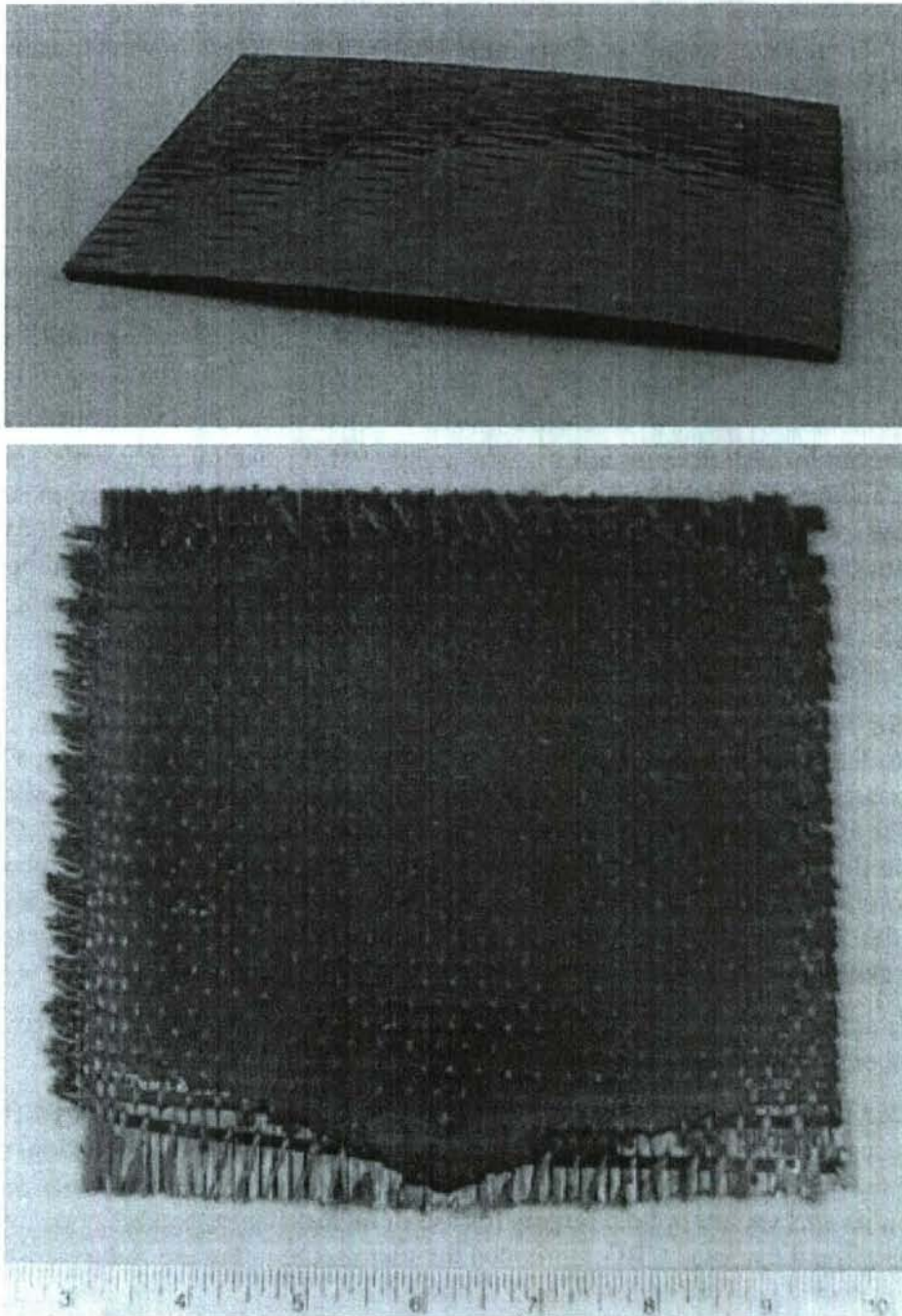


Figure 23. Early Phase II CNF- and Carbon Fabric-Reinforced CE SMP Composite Membrane Coupons (Left Coupon Approx. 7.5 cm Square)

CRG accomplished significant directly related development of CE SMP-based composite materials and fabrication process under CRG subcontract to a BATC NASA prime contract for a different space-based deployable membrane application. The BATC effort is leveraging the Air Force investment in the Task 1 CE SMP development in this SBIR Phase II program while this SBIR program leveraged composite development from the BATC subcontract effort. As a result of this cross-leveraging between parallel Phase III and Phase II development efforts, this SBIR project deferred further expenditure on fiber-reinforced material development and applied the savings to the challenging CE SMP development described in Section 3.1.1.

Section 7.1 summarizes results of the parallel Phase III BATC effort which were directly relevant to this program's Technical Objectives.

3.2 Task 2: Develop Meter-Scale Mirror Fabrication Processes

Although addressed as a separate task for the purposes of describing Statement of Work content, material process development was conducted in parallel with and integral to material formulation effort for Task 1. This approach precluded pursuing material formulations that would later prove impractical for scale-up to production of membranes of operationally relevant size.

CRG implemented a quantitative computational tool which predicts appropriate cure cycle profiles for specific formulation variations. The success of this technique greatly accelerated the evaluation of candidate formulations. In Phase I, the iterative process to determine an appropriate cure cycle for a new candidate formulation was a primary pacing factor in the development timeline. The new computational tool dramatically reduced the number of iterations required to obtain the first properly cured specimen of a new formulation. Achieving that result was the critical first step to enable repeatable fabrication of coupons for evaluating the material properties of that formulation.

As noted for Task 1 (see Section 3.1.3), CRG accomplished significant directly related development of CE SMP-based composite materials and fabrication process under CRG subcontracts to a BATC NASA prime contract for a different space-based deployable membrane application. The BATC effort is leveraging the Air Force investment in the Task 1 CE SMP development in this SBIR Phase II program while this SBIR program leveraged fabrication process development from the BATC subcontract effort. As a result of this cross-leveraging, this SBIR project deferred further expenditure on fabrication process development and applied the savings to the challenging CE SMP development described in Section 3.1.1.

Section 7.1 summarizes results of the parallel Phase III BATC effort which were directly relevant to this program's Technical Objectives.

CRG applied the results of the streamlined cure process development and the BATC fabrication process development to demonstrate fabrication of a prototype self-deploying membrane for use in the Task 4 deployment demonstration. Figure 24 shows that membrane (silver spots on its surface are optical targets for use in measuring repeatability of figure recovery after stow-deployment cycles). CRG fabricated the membrane using the material design and fabrication processes described in Sections 3.2.2 and 3.2.3.

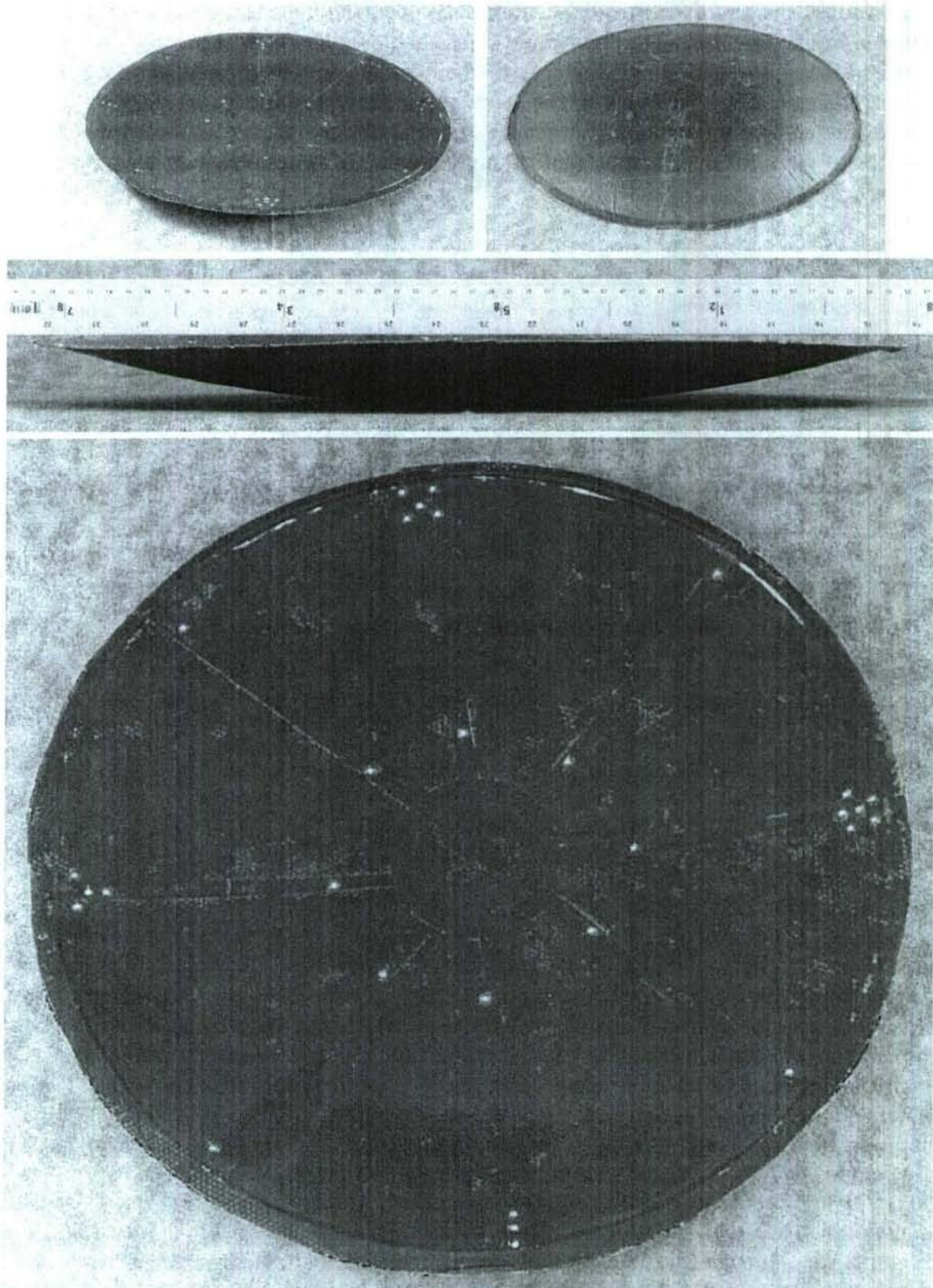


**Figure 24. Prototype Membrane for Self-Deployment Demonstration,
Carbon Fiber-Reinforced Cyanate Ester Shape Memory Polymer
(45 cm diameter, 2.1 kg/m² areal density)**

CRG limited this prototype membrane to half the planned diameter due to the expense encountered in building the neutral buoyancy tank in which it would be demonstrated. Building a tank large enough for deploying a meter-scale membrane would have been significantly more expensive than anticipated during proposal preparation. However, the same materials and processes were applied in fabricating the meter-scale membranes shown in the Appendix C presentation of work for BATC, thus confirming scalability to meter diameter and larger membranes.

3.2.1 Reflector Coatings

The BATC Phase III effort (Section 7.1) indicated that a thin layer of nickel is a practical reflective coating for deployable carbon fiber-reinforced CE SMP membranes.

Based on the BATC results, CRG concluded that the nickel coating will probably meet the basic requirements for a self-deploying membrane reflector for the solar thermal propulsion application:

- Flexibility to remain conformal to the host membrane during stow and deployment cycles
- Surface durability to retain required optical quality following membrane deployment
- Full compatibility with the space environment
- Scalability to 20-meter diameter mirrors

As a result of this cross-leveraging, this SBIR project deferred expenditure on coatings development and applied the savings to the challenging CE SMP development described in Section 3.1.1.

3.2.2 Mirror Design

CRG selected materials based on the composite design parameters investigated in Task 1 (and complementary Phase III effort for BATC, Section 7.1) and for the best match to the selected oil medium for the neutral buoyancy tank (see Section 3.6.1.5). While design methodologies for conventional mirrors are mature, design for this composite membrane reflector took the dynamic effects of deployment into consideration. A material was selected to achieve the appropriate matching density with the tank oil, surface finish, and reinforcement mobility. The composite lay-up was optimized to achieve an acceptable surface roughness while minimizing the stowing bend radius. Based on the maturity of the woven reinforcement materials, processability, scalability, and stiffness of the fabric reinforced composites, carbon nanofiber-reinforced materials were not selected for the prototype demonstration. (Further development in the processing of those materials will lead to more mature and lower areal density composites.) Through development and lessons learned in collaboration with BATC funding, structures consisting of these materials require a stiffening ring to reduce out-of-plane bending modes. The prototype reflector was fabricated on a low cost spherical security mirror which contains a flattened lip at the circumference. This feature in the resulting composite membrane provides added stiffening without significantly increasing mass. There are stowability tradeoffs, however, involved in selection of the reinforcement fiber. The design can

be tailored for applicability to specific mission requirements, weighing stow volume versus the structural stability of the reflector.

Based on these factors, CRG finalized the prototype membrane material design as the Phase II optimized CE SMP (Section 3.1.1.4) reinforced with carbon fiber. The reinforcement layer is sandwiched top and bottom with a layer of random carbon fiber scrim to reduce surface print-through of the reinforcement fibers. The scrim layer opposite the reflective surface provides symmetry for structural stability.

In a configuration tailored to optimize the balance of strength, strain recovery, and areal density, CRG achieved a membrane of 0.5 mm thickness with an areal density of 0.59 kg/m^2 .

3.2.3 Mirror Fabrication

CRG developed and demonstrated two fabrication processes for fiber-reinforced self-deploying membranes: (a) vacuum assisted resin transfer molding (VARTM), and (b) [a proprietary process]. CRG accomplished this development under Phase III subcontracts to BATC (see Section 7.1). Under that Phase III effort, CRG fabricated 1 m diameter membranes using the VARTM process and a 1/3 m diameter membrane using the [proprietary] process.

To fabricate the demonstration prototype membrane for this SBIR Phase II effort, CRG applied the VARTM results.

Figure 48 in Section 7.1.1 shows a composite lay-up in progress for a 1 m deployable membrane using the [VARTM] process.

3.3 Task 3: Develop Mirror-to-Spacecraft Attachment Interface

CRG designed, fabricated, and experimentally demonstrated a means for attaching a self-deploying membrane reflector to a host spacecraft. However, due to the unanticipated long duration and high cost of the Task 1 SMP development effort, CRG constrained this interface task to simply accommodating the mounting requirements of the Task 4 deployment demonstrations. More sophisticated design effort was deferred to eventual Phase III development with a spacecraft integrator. Such a spacecraft-specific design will address a number of specific issues, including but not limited to:

- Minimizing occlusion of reflective surface area
- Minimizing thermally induced optical distortion during operational cycles
- Minimizing optical distortion induced by inertial loads during operational use
- Accommodating position control by the host spacecraft
- Simplifying the fabrication process for integrating the interface structure with the membrane
- Scalability to 20-meter class membranes

Addressing the physical interface element of Technical Objective 2.3, CRG selected materials compatible with its membrane composition and the temperature to which the membrane would be exposed during the deployment demonstration (160°C) and applied them in a simple design for the attachment interface structure. Exploiting the self-supporting structural

integrity (in zero-G) of the planned membranes, CRG's design concept was a single attach point at the apex of the optical figure's curvature as shown in the system concept schematic at the outset of this proposal (Figure 1). As shown in Figure 25, a stainless steel bolt to carry structural loads passes through the center of the membrane, holding a pair of stainless steel washers above and below the attach point to stabilize the membrane.

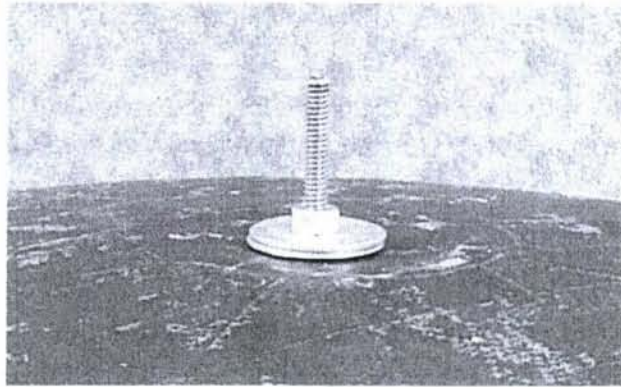


Figure 25. Mounting Interface for the Deployment Demonstration Membrane

3.4 Task 4: Develop & Demonstrate Full-Scale Self-Deployment Technology

CRG accomplished two subtasks addressing the self-deployment function of CE SMP-based membranes for spacecraft applications.

3.4.1 Trade Study -- Energy Source for Self-Deployment Heating

While Phase I investigation indicated both IR and microwave RF radiation are plausible energy transmission mechanisms for heating membrane mirrors' SMP for self-deployment, system level considerations not yet investigated might dictate a preference for one mechanism over the other. To avoid developing component-level technology that would not be viable for system-level spacecraft integration or would be significantly less effective than the alternative, Phase II effort conducted an initial engineering trade study evaluating the relative merits of the IR and RF energy transmission mechanisms. CRG used the following factors in the trade study:

- Minimizing the mass penalty of on-board components whose only function is to support the self-deployment sequence (e.g., batteries would be multifunctional without a mass penalty, while an on-board CO₂ laser may not have any postdeployment function)
- Minimizing host spacecraft energy demand (i.e., minimizing diversion of energy from other spacecraft subsystems to accommodate energy required for heating the membrane to T_g)
- Minimizing total energy required for self-deployment
- Subsystem level simplicity and reliability for the membrane and related deployment components
- Spacecraft level simplicity and reliability
- Launch environment tolerance

- Hazard to host spacecraft systems (i.e., level of exposure and effect of transmitted energy)
- Cost

This investigation revealed that using microwave radiation is inefficient and not feasible, while infrared is a better choice to use as an energy transfer mechanism in the heating of membrane mirrors' SMP for deployment. Additionally, other options such as using sunlight or strip heaters were found to be even better sources of energy for this application.

The main drawback to microwave radiation is its source inefficiency. With only 30-40% of energy input being transmitted to the target, the total power necessary for self-deployment is unreasonable. This then affects the cost of the mechanism. Furthermore, the reflected beam that isn't absorbed by the composite could affect other sensitive areas of the spacecraft. Also, microwave heating has a better chance of causing noise, interference, or even damage in electrical circuits, due to proximity and high power. Overall, using microwave radiation would yield a combination of unacceptable negative characteristics.

On the other hand, an infrared source has acceptable source efficiency. It is somewhat cheaper than microwave and less likely to cause problems to other systems. Another alternative is using energy from sunlight (infrared and visible), which has been proven to expose similar materials to a temperature greater than 200 °C (more than enough heating for deployment of the structures based on the Phase II CE SMP with T_g of 130 °C). There are multiple possible coatings to apply to the back of the mirror for this method of heating. During deployment, the spacecraft would be pointed in the necessary direction to expose the coated surface and collect the energy needed. Also heating doesn't have to be uniform as the mirror can be deployed in sections. A thermal shield would prevent solar heating after deployment.

The most attractive option researched in this trade study was using strip heaters on the back of the mirror, coupled with solar heating. This is a mature and reliable technology, which can use redundancy for ruggedness without much of a mass penalty. The strip heaters can be produced on thin films or directly on the composite, ensuring that induced stresses on the reflective surface are negligible. This approach would be efficient, cost effective, and safer for sensitive optical areas. It is the approach BATC has baselined for their deployable membrane structures using CRG's technology resulting from this project.

3.4.2 Full-Scale Self-Deployment Demonstration

Using the prototype self-deploying membrane (Figure 24) resulting from Task 2 effort and the neutral buoyancy tank described in Section 3.6.1.5, CRG demonstrated the stow-deployment functional cycle on which this project's operational concept is based (see Section 1.3).

CRG took digital photographs of the membrane as baseline data for photogrammetry (see Section 3.6.1.6) as the means to quantitatively compare the membrane's as-fabricated figure to its figure after undergoing a stow-deploy cycle. Figure 26 shows the photogrammetry set-up.

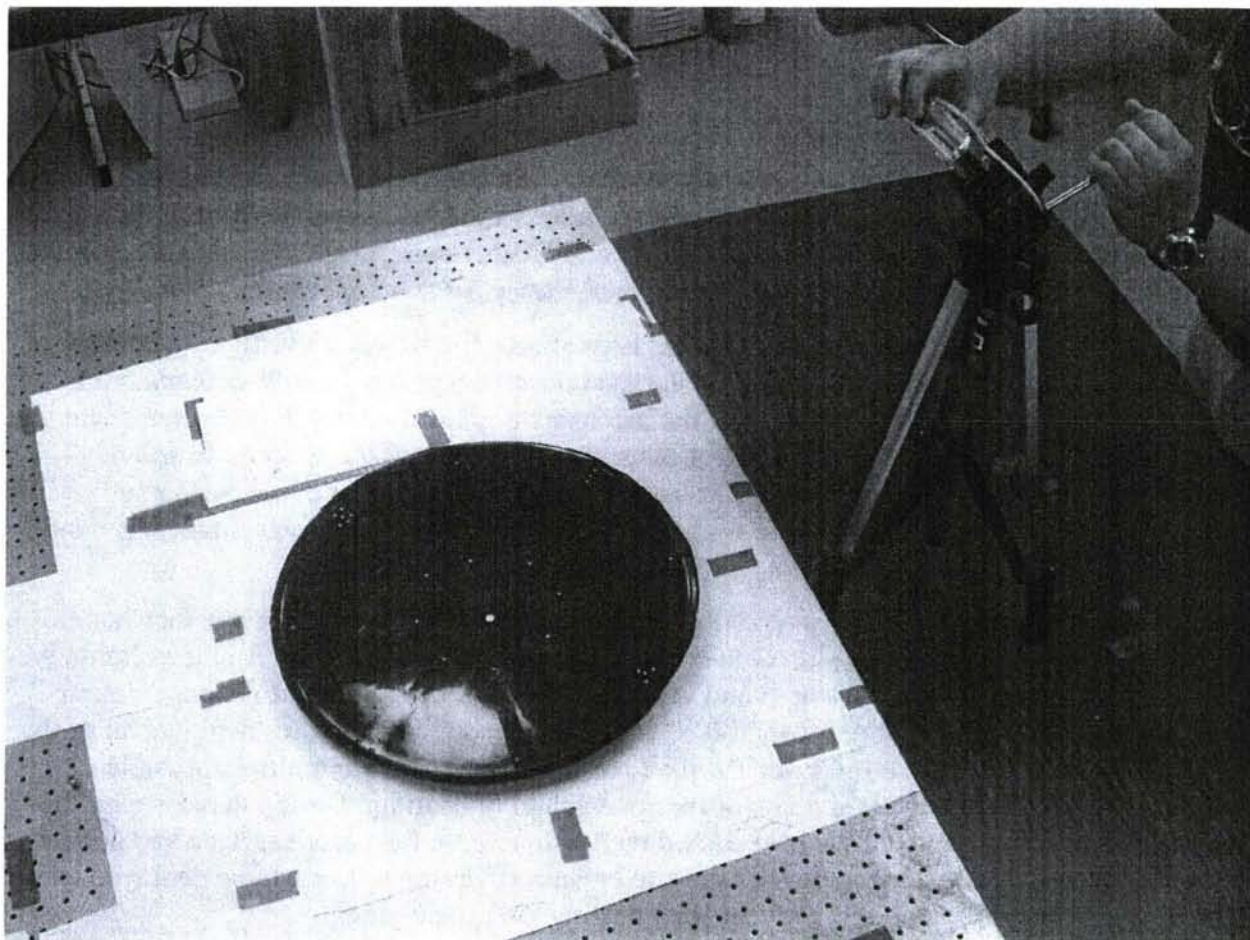


Figure 26. Photography for Photogrammetry Analysis of Deployment Prototype

CRG next mounted the membrane on a temporary pedestal (Figure 27) and heated it in an oven to 200 °C, well above the CE SMP's T_g of 130 °C. The membrane was then removed from the oven and manually deformed to the stowed configuration shown in Figure 28. The stowed configuration induced severe deformation of the membrane at several locations, representing a maximum challenge for the self-deployment capability of the membrane material. This stowed configuration reduced the structure's overall diameter from 45 cm to 30 cm.



Figure 27. Prototype Membrane on Temporary Mount for Stowing

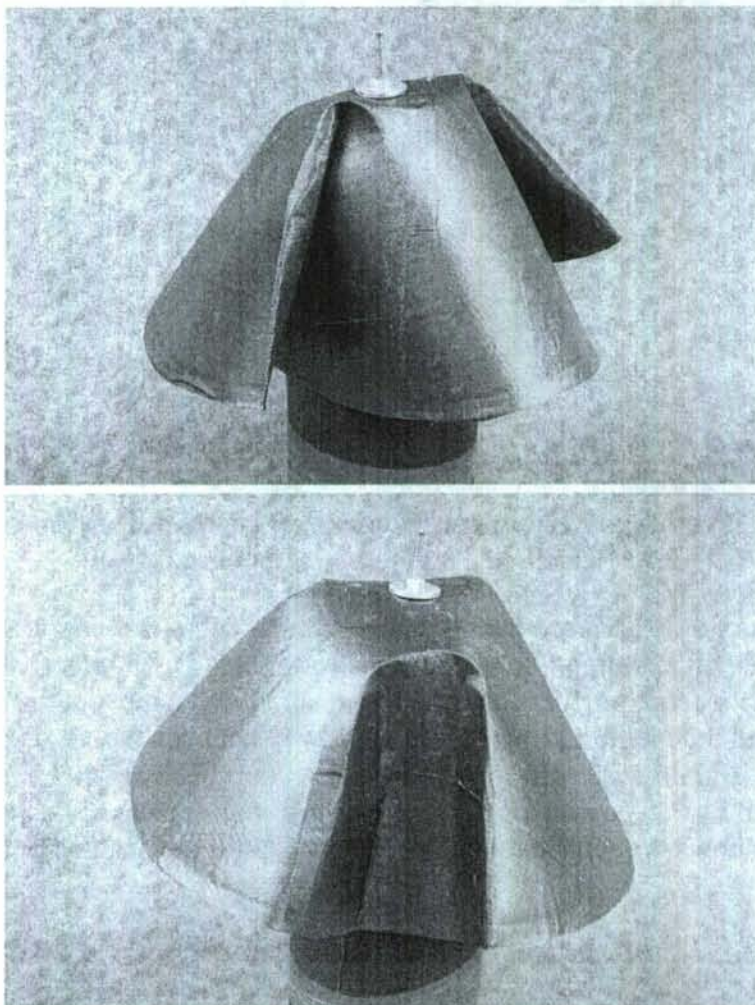


**Figure 28. Prototype Membrane in Stowed Configuration
(Front and Back Views of Same Membrane)**

Using the interface approach described in Section 3.3, CRG mounted the membrane in the neutral buoyancy tank. Figure 29 shows the membrane in the tank with the oil medium filled to a level just below the membrane.

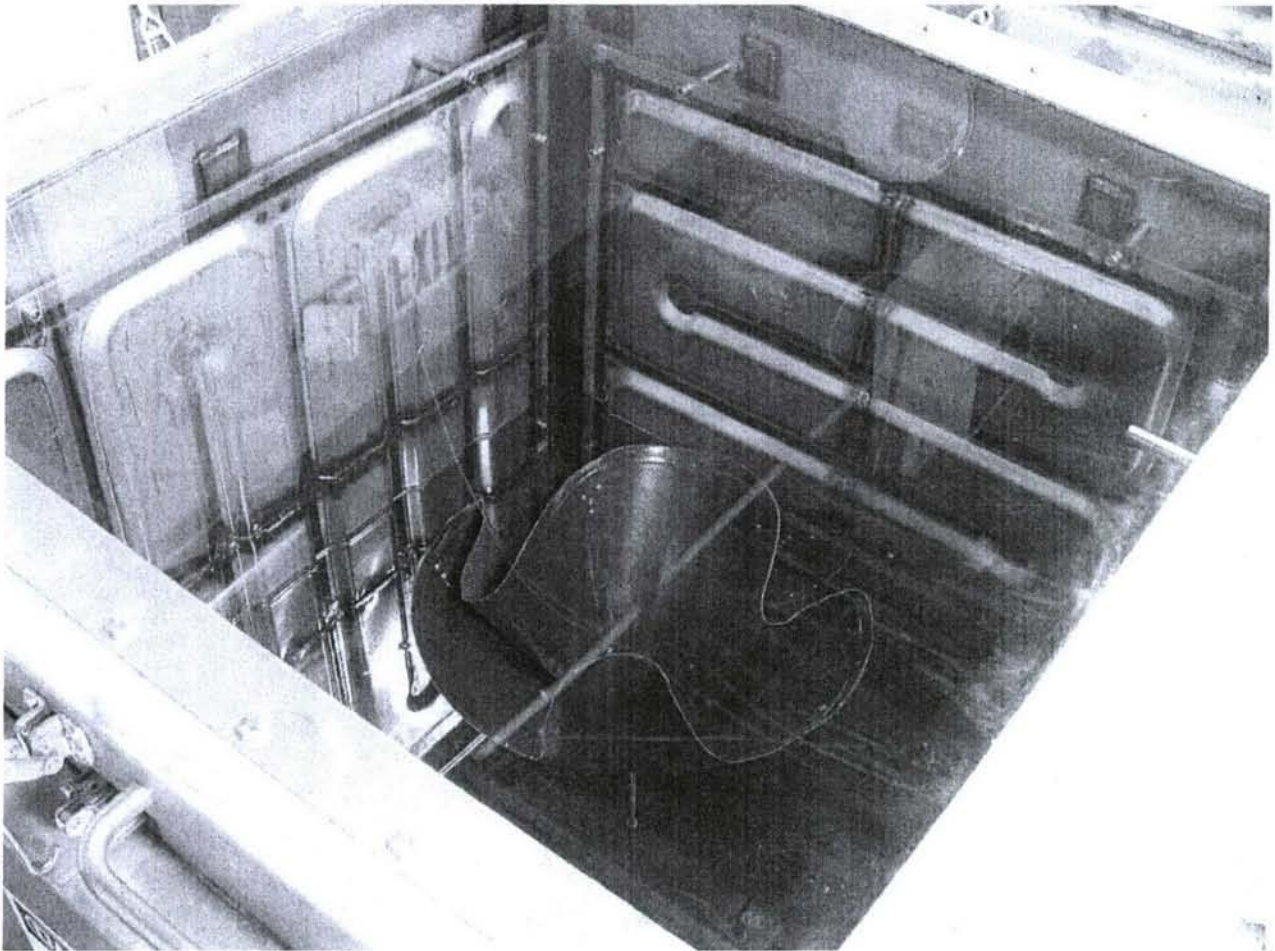


Figure 29. Prototype Membrane Mounted in Neutral Buoyancy Tank for Full-Scale Self-Deployment Demonstration

After filling the tank, CRG raised the oil temperature at approximately $1.4\text{ }^{\circ}\text{C}/\text{minute}$ until reaching a maximum temperature of approximately $160\text{ }^{\circ}\text{C}$. (The oil inlet temperature was $170\text{ }^{\circ}\text{C}$, the tank thermocouple-driven thermometer read $150\text{ }^{\circ}\text{C}$ at the coolest tank location opposite the inlet, and the membrane was located midway between those locations.) When the membrane was heated to its T_g , it self-deployed, fully recovering even the most severe deformations induced by the stowing operation. The self-deployment took approximately thirty minutes. Figure 30 shows the self-deployment sequence, with images at four minute intervals.

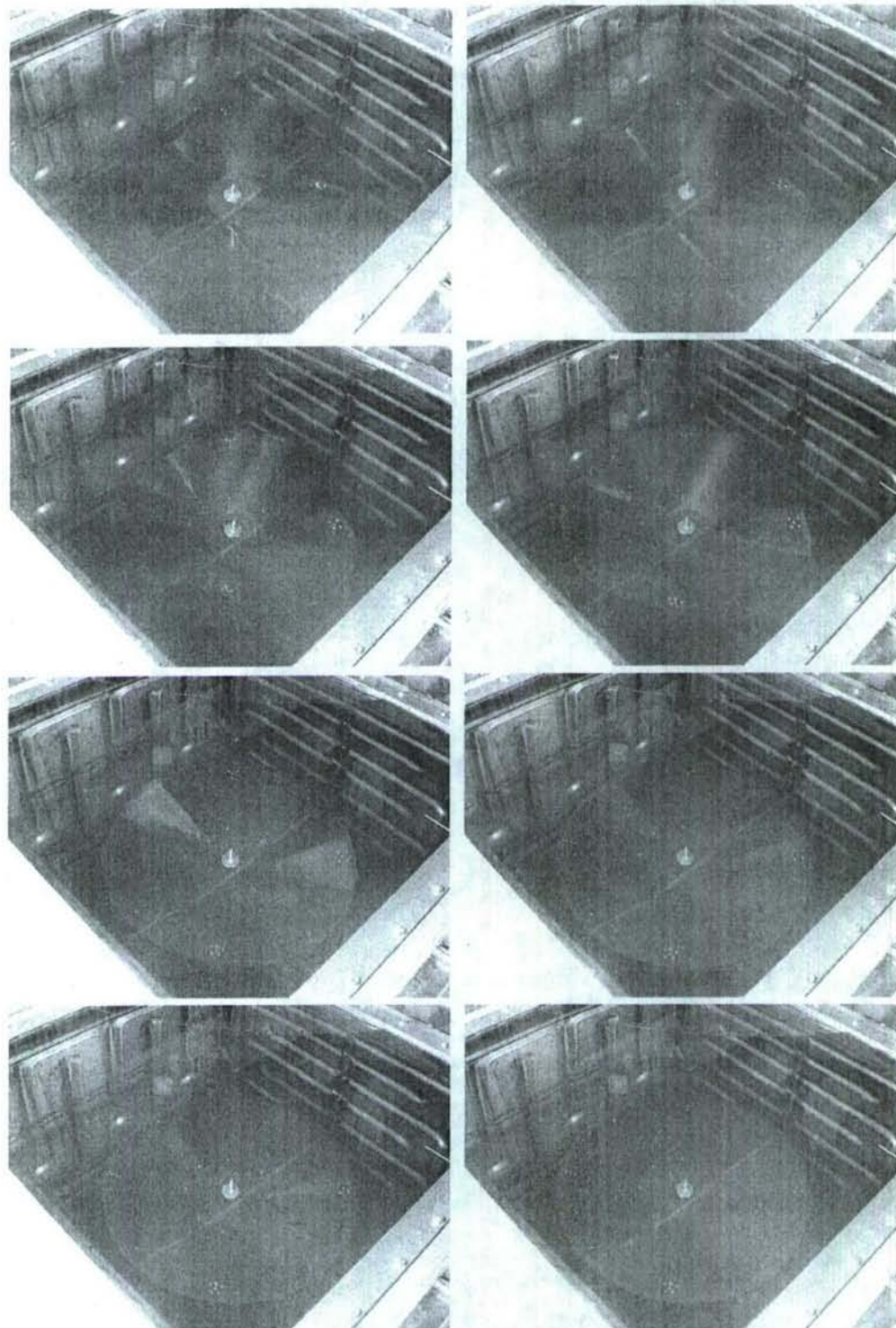


**Figure 30. Self-Deployment of Prototype Membrane in Neutral Buoyancy Tank
(Images at 4 Minute Intervals)**

Figure 31 shows the membrane after removal from the tank after a cool-down period of approximately 24 hours. Similar images (from Figure 24) of the membrane taken before stowing are presented for comparison. The membrane figure qualitatively appeared to have fully

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recovered from even the most severe deformation induced during the stow operation. However, the material experienced damage due to the prolonged exposure to the hot oil during the cool-down period after the demonstration. The center of Figure 32 shows a localized “blister” resulting from this damage. CRG also noted even after having been wiped of all visible oil immediately upon removal from the tank, the membrane still exuded oil 18 hours later after a subsequent wipe-down. This indicates the membrane absorbed significantly more oil than anticipated and precluded a planned second deployment demonstration to assess repeatability.

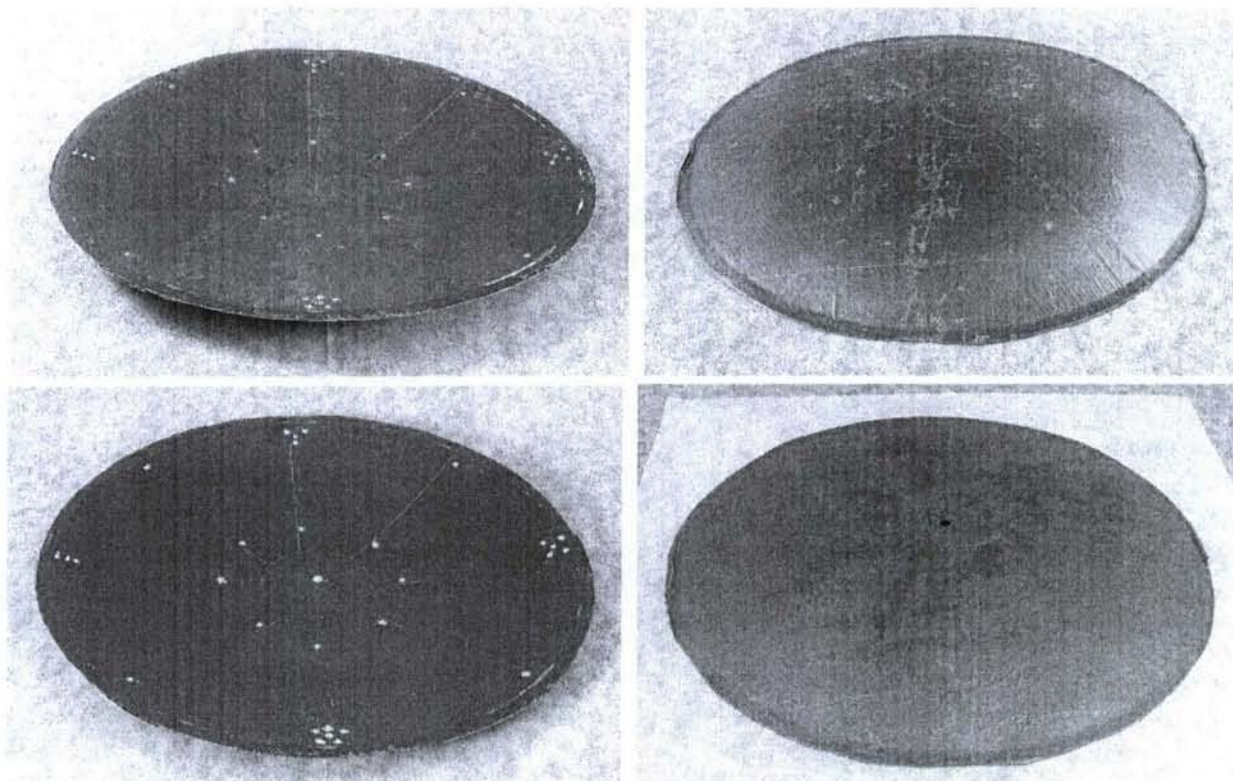


Figure 31. Prototype Membrane Before (Top) and After (Bottom) Self-Deployment Demonstration in Neutral Buoyancy Tank

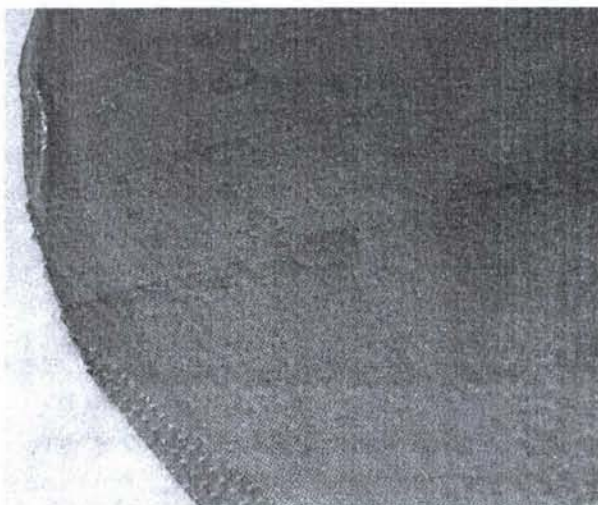


Figure 32. Close-Up of Delamination Caused by Prolonged Exposure to Hot Oil

Following the self-deployment demonstration, CRG again took digital photographs of the membrane for photogrammetry analysis. Figure 33 shows the photogrammetry application's display identifying the sixteen optical targets placed on the membrane to support this analysis. Each target is marked by an "X" in the display.

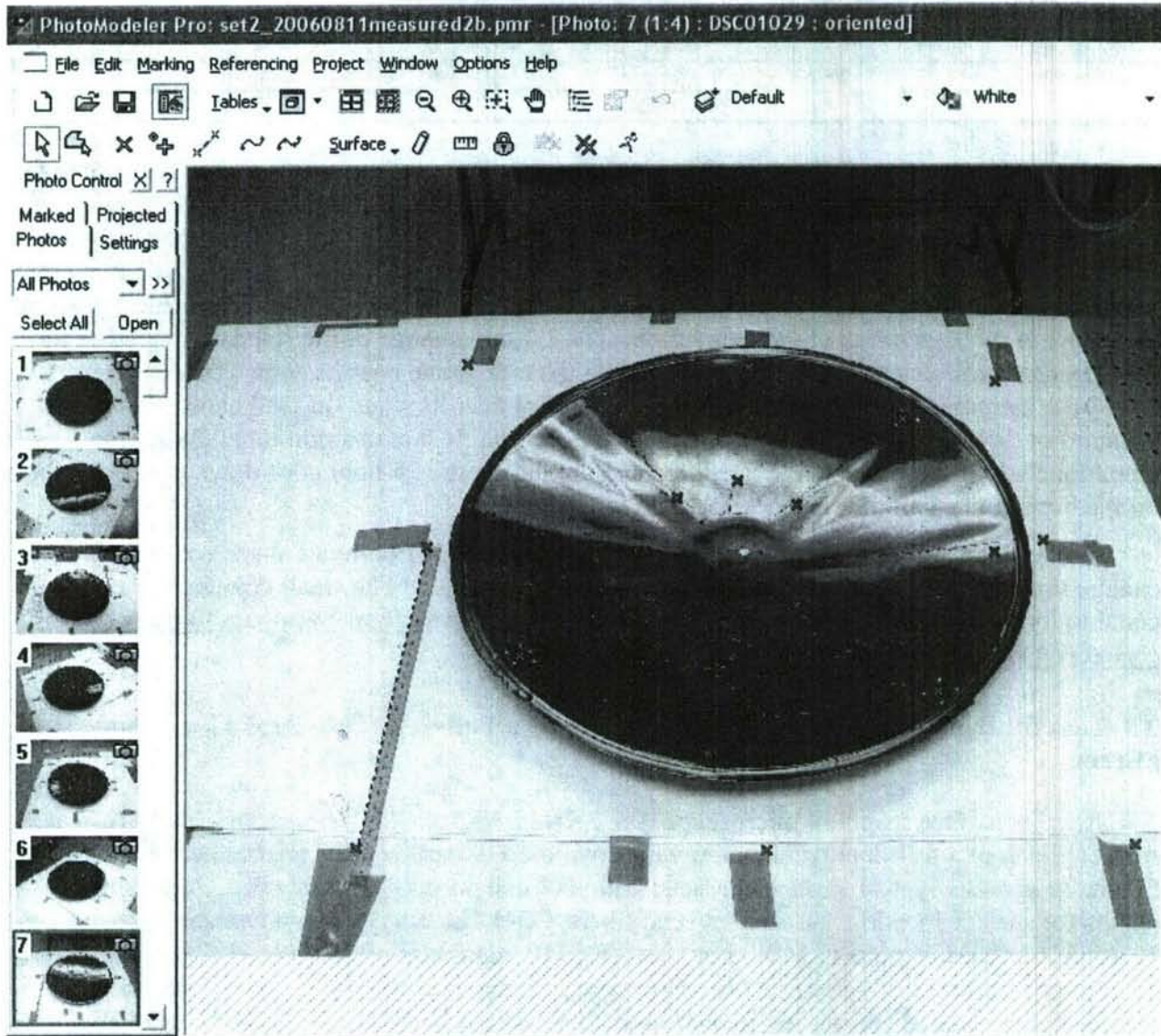


Figure 33. Photogrammetry Application During Analysis of Self-Deployment Results

While the photogrammetry application was not sophisticated enough to directly compare the pre- and post-deployment locations of individual target points on the membrane, it provided the means for comparison of their positions relative to each other. CRG used the targets' coordinates determined by photogrammetry as an input to a three-dimensional plotting and analysis software application (see Section 3.6.1.6) and calculated "best fit" planes encompassing the upper and lower sets of targets. Table 5 presents statistics resulting from that analysis.

Table 5. Photogrammetry Results for Pre- and Post-Deployment Figure of Prototype

Target Plane	Pre-Deployment		Post-Deployment		Distance Between Planes	
	Std Deviation of Target Distance from Plane (mm)	Distance Between Target Planes (mm)	Std Deviation of Target Distance from Plane (mm)	Distance Between Target Planes (mm)	Change	% Change
Upper Set	2.9		0.5			
Lower Set	0.9		0.6			
		32.2		32.1	-0.1	-0.3

The standard deviation of target distance from a plane gives an indication as to how much the surface may have been distorted by the stow-deployment cycle. If the surface had recovered to a figure significantly different from the original paraboloid, that distortion would necessarily force the standard deviation to change. Given the measurement accuracy of 0.1 mm for locating target positions, the 0.3 mm change of the standard deviation for the lower set indicates a small shift in the figure in the lower area of the membrane. The 2.4 mm change of the standard deviation for the upper set indicates a somewhat larger shift in the membrane near its edge. This is expected due to the increased mobility of the flexible membrane near its edge. In both cases, the smaller standard of deviation for the post-deployment figure is likely due to strain relief during the membrane's long exposure to elevated temperature during the 24-hour cool-down period for the oil medium in the neutral buoyancy tank.

Another indicator of the overall fidelity of the membrane's fidelity of shape recovery is the change in the vertical separation of the calculated target planes. The small change, 0.1 mm, is equal to the measurement accuracy. Therefore, **the membrane figure appears to have recovered with approximately 99.7% accuracy.**

3.5 Task 5: Demonstrate Optical Performance by a Full-Scale Self-Deploying Membrane Mirror

Using its surface mapping microscope (see Section 3.6.1.4), CRG characterized the typical surface finish of a self-deployable membrane composed of carbon fiber-reinforced CE SMP. Figure 34 shows a typical surface characterization of one point on a membrane. Averaging results for surface locations on and between fibers, CRG found a typical membrane roughness of 1230 nm root mean square (RMS). For neat CE SMP membranes, CRG found a typical membrane roughness of 440 nm RMS. However, in both cases relatively poor quality of the surface finish resulted from using industrial-quality security mirrors as fabrication mandrels, rather than optical-quality components. Use of an optical-quality mandrel for a fabricating a large-scale optical membrane was originally planned, but not implemented due to the need to cut costs and allocated the savings to CE SMP resin development. CRG is not aware of any fundamental differences between the final Phase II CE SMP resin and the Phase I resin that would preclude achieving CE SMP surface finishes as smooth as those obtained in Phase I (typically 20 nm - 40 nm RMS and a best surface of 6 nm RMS) when membrane fabrication is accomplished on an optical-quality mold. However, an empirical investigation is required to confirm this.

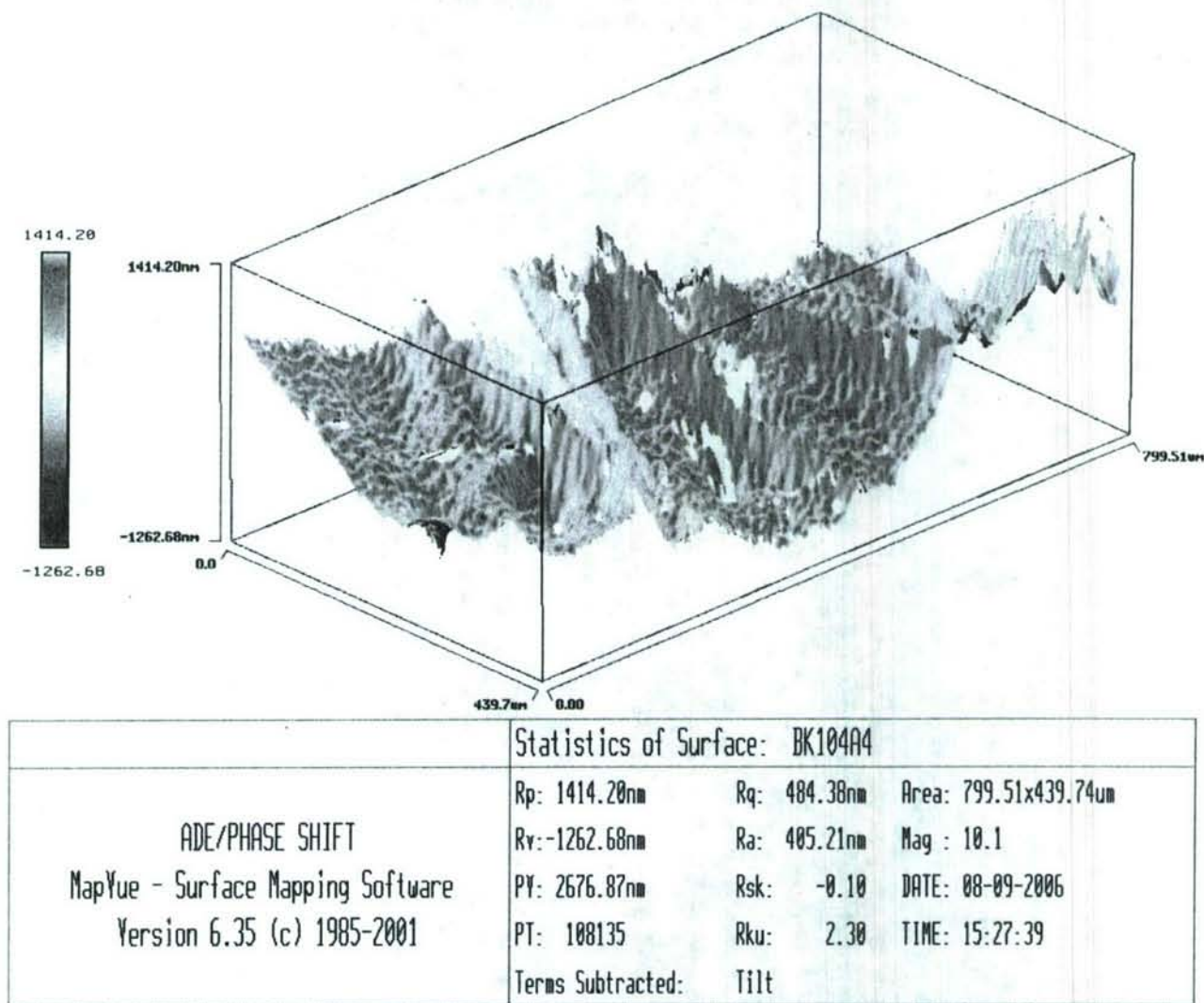


Figure 34. Surface Finish Characterization of CE SMP Membrane

Addressing this Technical Objective 2.5, CRG fabricated a 45 cm deployable membrane reflector composed of carbon fiber-reinforced CE SMP with an aluminum layer (applied by vapor deposition) as the reflective surface (Figure 35). **This prototype reflector has an areal density of 0.46 kg/m².** To save cost, CRG simply coated a membrane that had resulted from a Task 2 intermediate fabrication trial. As noted in the preceding paragraph, to avoid the expense of a more sophisticated optical mold, CRG had used a commercial security system mirror as the mandrel on which to fabricate this specimen. Its figure is roughly equivalent to an F/1 sphere. The membrane has significant surface “print-through” of the reinforcement fibers and lay-up overlaps. While the figure was not optimal for a solar concentrator, the fabrication and material technologies are fully traceable to a mirror designed specifically for the concentrator application. While surface of this particular specimen is not adequate for imaging applications, the surface quality is adequate for the intended solar concentrator application.

Figure 35 shows the prototype reflector in use in a qualitative demonstration as a solar concentrator. CRG used ambient sunlight as the light source for this demonstration. The photograph was taken at approximately 1 second after achieving maximum focus, at which time

the reflected energy scorched the target grid, thereby recording the reflection's spot size. The reflection's brightness overwhelmed the digital camera, resulting in the image showing a spot much larger than the actual focused reflection. The scorched spot was approximately 3 cm in diameter, indicating a concentration ratio of approximately 230:1.

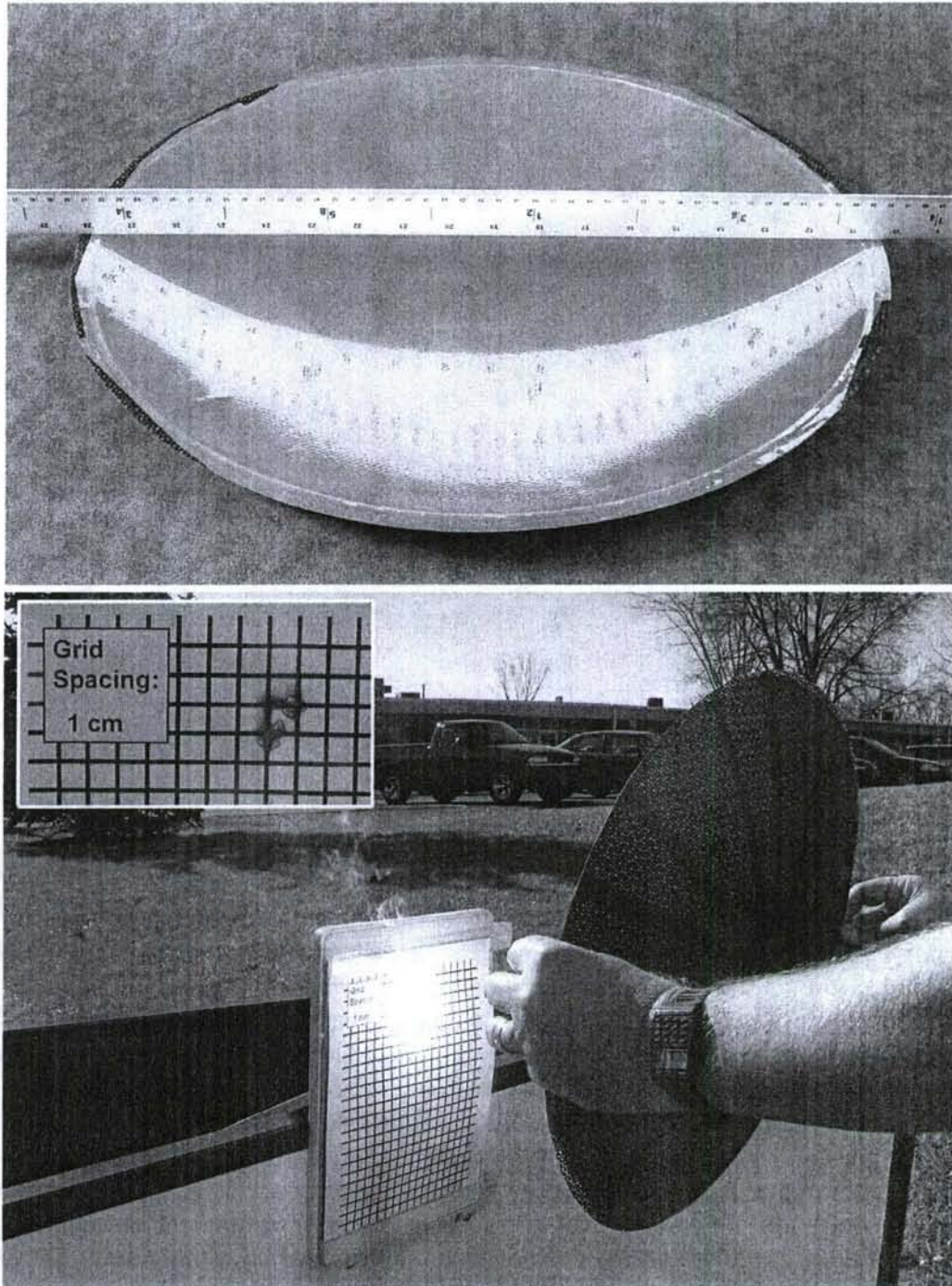


**Figure 35. Aluminum-Coated Carbon Fiber-Reinforced Deployable Membrane Reflector Demonstrated as a Solar Concentrator (45 cm diameter, 0.46 kg/m² areal density)
(Top: Prototype Reflector; Bottom: Concentrated Reflection on 1 cm Grid, with Inset Close-Up of Scorched Area Showing Reflection Spot Size)**

3.6 Task 6: Characterize Materials & Mirrors

With the exception of the outsourced support described in Section 3.6.2, CRG used in-house capability to accomplish the testing required to support material development and characterize the properties or performance of resulting materials and structures.

3.6.1 CRG In-House Characterization

This section describes the instruments and apparatus CRG used to accomplish characterization effort, presented in the approximate sequence in which they were first used during Phase II effort. The results are presented in the narratives for the tasks they supported.

3.6.1.1 Modulated Differential Scanning Calorimeter (DSC)

Characterization by the differential scanning calorimeter (DSC) (TA Instruments Q100) determines the heat flow into or out of a sample as it is exposed to a controlled thermal profile. DSC analysis provides both qualitative and quantitative information about material transitions, such as glass transition, crystallization, curing, melting, and decomposition. Modulated DSC is an added feature on this instrument that enables the separate measurement of reversible and irreversible transitions by overlaying a sinusoidal temperature oscillation on a traditional linear ramp. Figure 36 shows the DSC instrument and a typical DSC plot.

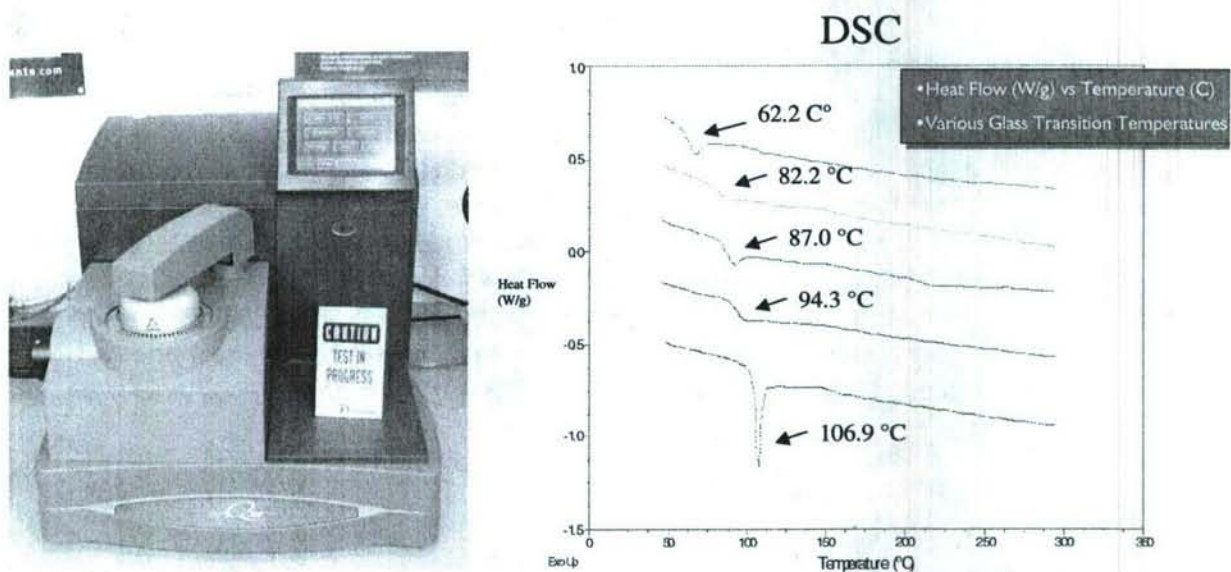


**Figure 36. Modulated Differential Scanning Calorimeter and Typical Plot
(Captions Added)**

3.6.1.2 Dynamic Mechanical Analyzer (DMA)

The dynamic mechanical analyzer (DMA) (TA Instruments Q800) quantitatively measures a material's response under load while varying temperature, thereby determining temperature-dependent strength characteristics. A variety of deformation modes are available, including

tension, compression, and cantilever (bending). In addition to temperature, CRG also has the ability to control the relative humidity within the test chamber, through the use of an integrated vapor generation unit. This unique configuration enables the characterization of materials' mechanical response to humidity variation. CRG's instrument and a typical output are presented in Figure 37.

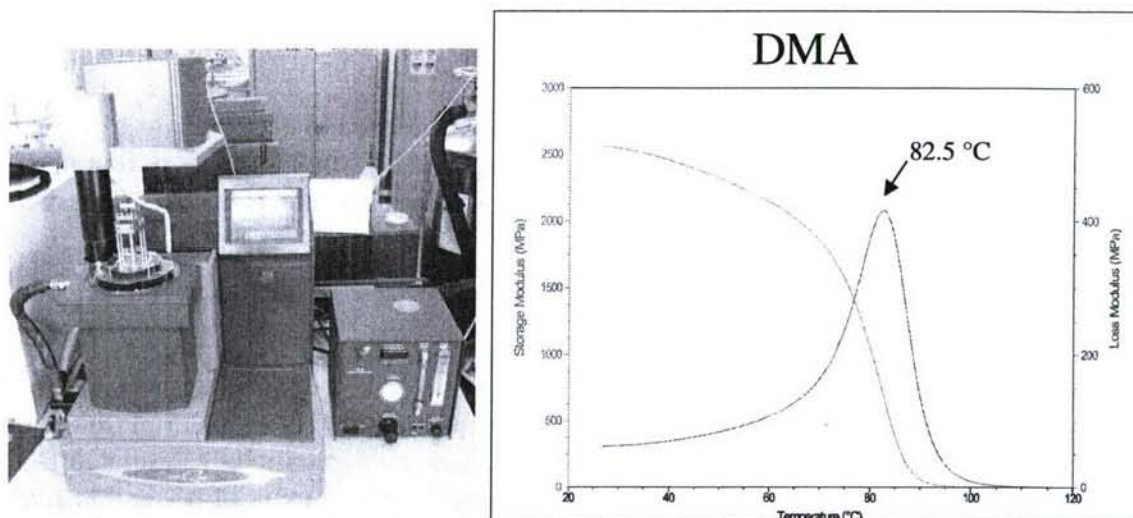


Figure 37. Dynamic Mechanical Analyzer (DMA) and Typical Graphic Output (Captions Added)

3.6.1.3 Fourier Transform Infrared (FTIR) Spectroscopy

The FTIR spectrometer (Nicolet™ 4700) (Figure 38) characterizes infrared spectra of materials for chemical analysis. As with conventional infrared (IR) spectroscopy, chemical bonds are identified by their vibrational resonance frequencies. However, FTIR analysis employs an interferometer to generate an interferogram, thereby allowing all frequencies to be collected at once. This enables more accurate measurements at higher efficiency compared with conventional IR spectroscopy. CRG's instrument includes a 10-meter path-length gas cell and a diamond attenuated total reflectance fixture, which enable accurate measurement of gasses, liquids, and both transparent and opaque solids. Figure 38 also presents a typical FTIR spectrometer output.

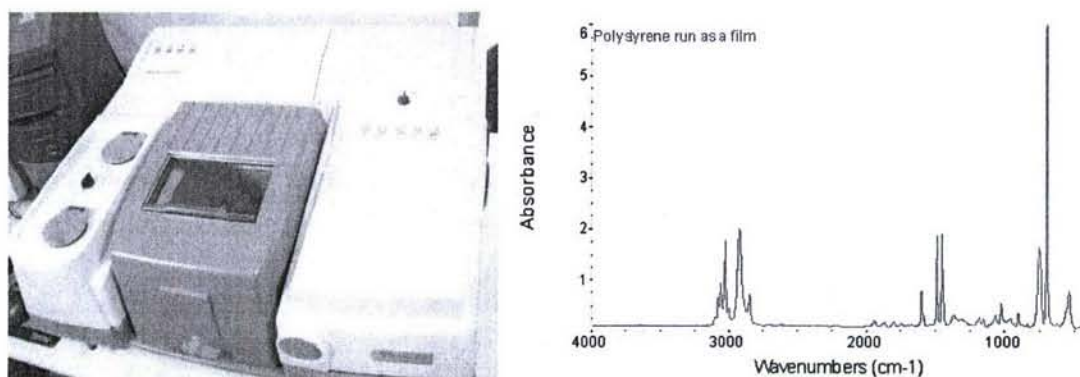


Figure 38. Nicolet™ 4700 FTIR Spectrometer and Typical Output

3.6.1.4 Interferometric Surface Mapping Microscope

The interferometric surface mapping microscope (MicroXAM (ADE Phase Shift)) provides quantitative characterization of surface topography with sub-nanometer resolution. Its digital output provides graphic representation of the results. Figure 39 shows this instrument and an excerpt of a typical output.

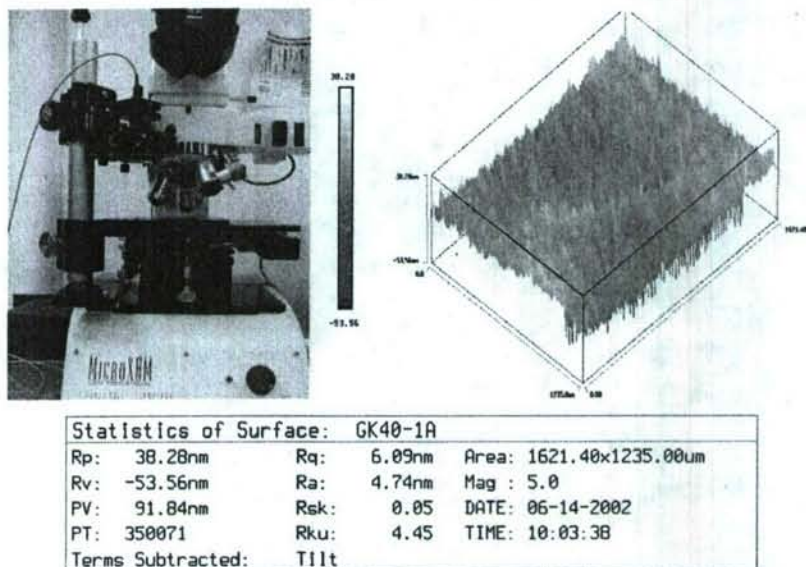


Figure 39. Surface Mapping Microscope and Excerpt of Typical Output

3.6.1.5 Neutral Buoyancy Tank

In order to simulate “zero-G” self-deployment of an operationally representative membrane, CRG needed a means to minimize gravity-induced deformation. This was accomplished by means of a tank filled with an oil medium with a mass density approximately matching that of the membrane material. With this close density match, the immersed membrane experiences neutral buoyancy simulating the microgravity condition of on-orbit deployment. The oil medium is heated to the T_g of the membrane material to activate self-deployment.

3.6.1.5.1 Tank Design

The neutral buoyancy tank is based on a heat transfer system using a prime surface plate heat exchanger situated at the bottom of an insulated, double-walled tank beneath an aluminum plate. The system has a separate reservoir from which the neutral buoyancy medium is pumped into and out of the deployment tank. For observing deployment tests, the tank has a glass panel in one of its vertical sides as well as a transparent lid. The tank is a closed system with argon purge in order to reduce oxidation and fire hazard of the neutral buoyancy media while it is at elevated temperatures.

Figure 40 shows a close-up view of the tank. Figure 41 shows the tank with its associated oil heater, oil supply reservoir, pump, and controls.

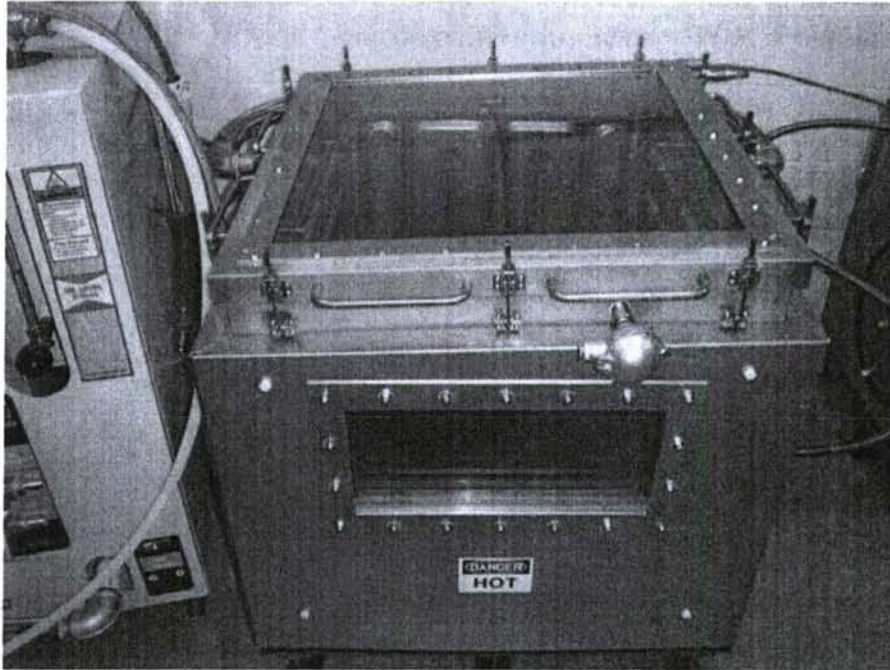


Figure 40. Neutral Buoyancy Tank



Figure 41. Neutral Buoyancy Tank with Support Equipment
(Left of the Tank Is the Oil Heater; To the Right Are the Reservoir, Pump, and Controls)

3.6.1.5.2 Oil Medium

CRG surveyed a wide variety of potential oil media. In addition to optical transmission characteristics (transmission and refractive index), candidate materials were evaluated based on flash and boiling points, auto-ignition temperature, reactivity with the membrane material, cost,

and potential for modification of density to match that of test article composites. The survey results identified 22 suitable candidate media.

Upon finalization of the membrane material development, CRG selected the oil medium with acceptable properties and the closest density match to the membrane, a synthetic hydrocarbon with a mass density of 982 kg/m^3 at the tank's operating temperature of 170°C . (CRG found silicone oils with better properties and densities, but at a prohibitively high cost.)

CRG had originally intended to try to use additives to adjust the medium's density to match that of the membrane material. However, that approach proved impractical, so CRG instead adjusted the material formulation for the self-deployment demonstrator to match the density of the selected oil medium. This adjustment was accomplished by changing the volume-fraction of fiber versus resin matrix, a straightforward modification that did not significantly compromise the strength and shape recovery properties of the material optimized for minimum practical areal density. The optimized material achieved 0.59 kg/m^2 areal density, while the deployment demonstrator membrane had an areal density of 2.1 kg/m^2 (1120 kg/m^3 mass density).

Using a free body diagram representing the expected forces in the neutral buoyancy tank (see Figure 42 and its accompanying equation), CRG estimated the net gravity-induced load the membrane should experience during the deployment demonstration as 0.12 G .

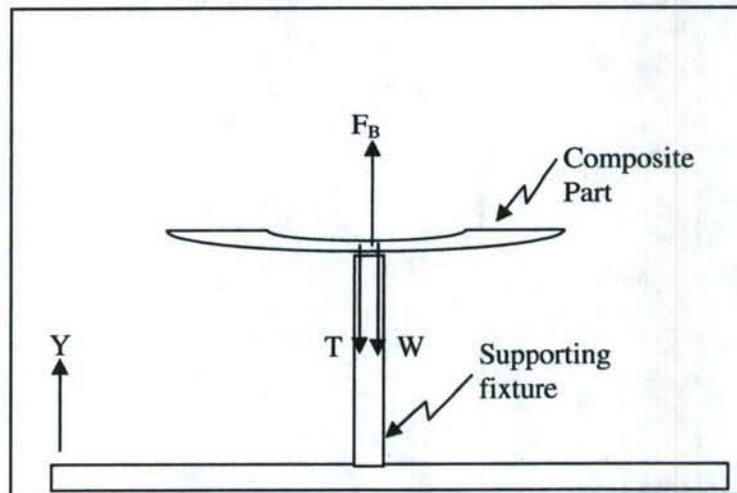


Figure 42. Free Body Diagram for Estimating G-Loading for Oil-Immersed Membrane

$$\sum F_y = F_B - W - T \quad (1)$$

where,

W = weight of the composite part

T = Reaction force of supporting fixture acting on the composite part

$F_B = \rho g V$ = force of buoyancy acting on the composite

ρ = density of the heat transfer fluid

g = acceleration due to gravity

V = composite part density

3.6.1.6 Photogrammetry

CRG used the PhotoModeler Pro 5 (EOS Systems Inc) photogrammetry software application to analyze digital photographs to characterize changes, if any, of the prototype membrane's shape from its pre-deployment to its post-deployment configuration. This application calculates in the relative positions, in three-dimensional space, of physical locations identified in a digital photograph. In conjunction with that application, CRG used SigmaPlot 9.0 (Systat) to calculate "best fit" planes encompassing the positions calculated by the photogrammetry application.

3.6.2 Outsourced Characterization

Using a vacuum exposure nephelometer (VEN) procedure, BATC performed vacuum outgassing tests on CRG's CE SMP and CE SMP-based composites to evaluate compatibility with space qualification requirements for Total Mass Loss (TML) and Condensed Outgassing Product (COP).

3.7 Task 7: Assess Technology Results

CRG used the results of Tasks 1 through 6 to assess the degree to which the Phase II effort achieved the Technical Objectives defined in Section 2. Section 4 presents that assessment.

4.0 ASSESSMENT OF RESULTS

Using the results summarized in Section 3 to address the Phase II Technical Objectives defined in Section 2, CRG assessed the feasibility of implementing the self-deploying membrane mirror concept and presents the following conclusions.

OVERALL ASSESSMENT: While CRG did not achieve all sub-objectives, this project succeeded in developing self-deploying membrane reflector technology to readiness for transition to operational use by a major spacecraft prime contractor, Ball Aerospace & Technologies Corporation (BATC), and BATC commenced Phase III application of the technology.

NOTE: Significant portions of the Phase II technical objectives were achieved by the CRG Phase III effort funded by BATC described in Section 7.1. This parallel effort enabled CRG to apply more effort to the SMP resin development than was originally planned. Achievement of Phase II objectives by Phase III effort represented a significant leverage effect without which CRG would not have had sufficient resources to address all Phase II objectives. Phase III contributions to achieving Phase II objectives are specifically acknowledged where they apply.

4.1 Technical Objective 1: To Develop Mature Materials

This objective had two key sub-objectives, addressed by the Phase II Task 1 effort and complementary Phase III effort for BATC.

4.1.1 To Optimize Cyanate Ester SMP and Related Composites

CRG achieved most of this sub-objective.

The new cyanate ester-based shape memory polymer (CE SMP) invented in Phase II, and carbon-reinforced composites based on it as the matrix, provide the mechanical strength and shape recovery performance required for implementing the self-deploying space-based membrane reflectors conceived for this program.

While full qualification testing is still needed, the new CE SMP is an inherently space-compatible material. Empirical testing confirmed the CE SMP has acceptable vacuum outgassing characteristics. Its chemistry is based on formulations known to be inherently compatible with exposure to the space radiation environment. The fully cross-linked nature of the polymer should also make it resistant to atomic oxygen.

The new CE SMP exhibits the thermal characteristics required for orbital self-deploying membrane applications. Its available range of glass transition temperatures (130 °C - 230 °C) can accommodate a wide variety of application-specific deployment architectures in a wide variety of orbital conditions.

Based on the Phase III results, at least one reflective coating approach (nickel) is compatible with the thermal, flexural, and optical requirements of deployable reflectors.

The Phase II materials achieved an areal density of 0.59 kg/m^2 . While this did not meet the target of an areal density below 0.50 kg/m^2 , it still represents a significant improvement over the areal density of conventional space-based reflector materials.

4.1.2 To Fully Characterize Cyanate Ester SMP and Related Composites

CRG achieved most of this sub-objective.

The structural and shape recovery properties documented in this report were directly relevant to Phase III exploitation by BATC in support of their development of a space-based deployable reflector system for NASA.

However, Phase II resource limitations precluded a full investigation of the ability of the new CE SMP to achieve optical-quality surfaces by direct replication of an optical-quality mold. The BATC Phase III approach involves a relatively thick nickel layer which serves as the polished reflective surface. While effective from an optical stand point, the nickel impacts areal density. In the original CRG membrane reflector concept, the CE SMP surface is fabricated directly with an optical-quality finish requiring only a few angstroms of metal (e.g., gold) to be applied to achieve the desired reflectance. Phase I results indicated the feasibility of this approach with the earlier CE SMP formulation, but a follow-up investigation is still required to confirm its feasibility with the new Phase II CE SMP formulation. CRG anticipates there is very low risk that the new CE SMP would not be compatible with achieving high-quality surface finishes.

4.2 To Develop Mature Full-scale Fabrication Processes

This objective had three key sub-objectives, addressed by the Phase II Task 2 effort and complementary Phase III effort for BATC.

4.2.1 To Increase SMP Material Production Processes to Relevant Batch Sizes

CRG achieved this sub-objective.

CRG produced several 1.0 m and 0.5 m diameter carbon fiber-reinforced CE SMP composite membranes using the new CE SMP resin developed in Phase II. There are no inherent availability of processing issues preventing its application in multi-meter scale membranes.

4.2.2 To Increase Structure Fabrication Processes to Relevant Sizes and Shapes

CRG achieved this sub-objective.

The complementary BATC Phase III effort demonstrated fabrication of several 1.0 m diameter carbon fiber-reinforced CE SMP composite membranes with a spherical figure. The VARTM fabrication employed is inherently scaleable to multi-meter scale membranes. The mandrel in which the lay-up is accomplished is limited only by the size of grinding and polishing able to achieve the required figure and finish. Since the mandrel does not need to be free-standing, it can be constructed of segments in order to achieve apertures larger than can be achieved with a monolithic structure. Also, since the vacuum enclosure also is not free-standing, it can be scaled up to any arbitrary size. Finally, while the curing process for the composite was accomplished in an oven for Phase II and Phase III effort, it is not limited to that approach.

Other practical heating technologies could be adapted to accommodate a multi-meter diameter lay-up.

4.2.3 To Increase Coatings Processes to Relevant Sizes & Performance

CRG did not achieve this sub-objective.

The Phase III effort for BATC demonstrated a nickel reflective coating on a 0.5 m deployable membrane with coating process technology scaleable to at least 2.0 m. However, that technology is not likely to be practical for achieving 20 m diameter membranes.

For 20 m diameter self-deploying membranes, a vapor or spray deposition coating process will be required. However, the greater than expected expenditures required to achieve the optimized new CE SMP precluded the planned investigation of conformal coatings and the processes required to apply them to 20 m scale membranes.

4.3 To Develop Membrane & Interface Design Methodology

Phase II effort in Tasks 1 and 3 addressed this objective.

CRG achieved part of this objective.

CRG demonstrated that self-deployable CE SMP-based membranes of 0.59 kg/m^2 with full self-deployment capability are achievable with the technology resulting from Phase II and the complementary Phase III development. However, follow-on development is still required to achieve the desired 0.50 kg/m^2 or lower density.

Demonstration of a 0.5 m membrane in a simulated zero-G operating environment indicated that a simple single-point attachment at the vertex of the membrane's optical figure is a practical design approach for providing an interface to the host spacecraft.

4.4 To Develop Full-Scale Self-Deployment Technology

Phase II effort in Task 4 and complementary Phase III effort for BATC addressed this objective.

CRG achieved most of this objective.

Phase III demonstration of a 1.0 m diameter deployable membrane fabricated with CRG's materials and processes resulting from this SBIR project achieved acceptable deployment performance after repeated stow-deploy cycles in a 1-G evaluation.

CRG's simulated zero-G demonstration of 0.5 m diameter membrane achieved approximately 99% accurate self-deployment in recovery from a stowed position with severe deformation. Demonstration of repeated stow-deploy cycles was precluded by membrane damage caused by the oil medium used to provide neutral buoyancy for the zero-G simulation.

4.5 To Demonstrate Relevant Optical Performance by a Full-Scale Prototype Self-Deploying Membrane Mirror

Phase II effort in Task 5 addressed this objective.

CRG achieved this objective.

Using fabrication processes and materials scaleable to 20 meter-class membranes, CRG demonstrated an aluminum-coated CE SMP-based membrane which exhibited optical performance adequate for a solar concentrator application.

Phase II use of an optical-quality mandrel for fabricating a meter-scale optical membrane was originally planned, but not implemented due to the need to cut costs and allocated the savings to CE SMP resin development. CRG is not aware of any fundamental differences between the final Phase II CE SMP resin and the Phase I resin that would preclude achieving CE SMP surface finishes as smooth as those obtained in Phase I (typically 20 nm - 40 nm RMS and a best surface of 6 nm RMS) when membrane fabrication is accomplished on an optical-quality mold. However, an empirical investigation is required to confirm this.

5.0 KEY R&D ISSUES INDICATED BY PHASE II RESULTS

While assessment of Phase II results indicates feasibility of the technologies required to implement the self-deploying membrane mirror concept, further R&D is required in key areas to enable achievement of the program goal:

- Carbon nanofiber composites based on cyanate ester SMP still show potential for achieving self-deploying membrane reflectors with areal density below 0.5 kg/m^2 . However, further process development is needed in order to achieve the required uniformity of nanofiber dispersion and membrane thickness in processes scalable to multi-meter apertures. Phase II effort in this project was suspended in deference to another AFRL-funded SBIR Phase II project in which this challenge is being addressed (AFRL/ML contract FA8650-05-C-5047, "Hierarchical Shape Recovery Polymer Nanocomposites (PNCs) for Next-Generation Aerosystem Applications").
- Effort is still required to develop conformal reflective coatings. That planned Phase II investigation had to be abandoned in favor of the higher risk, more critical SMP resin optimization.
- Development of operationally relevant designs for the membrane-to-spacecraft mounting interface will need to be accomplished to meet specific host spacecraft requirements.
- Based on specific host spacecraft deployment and power requirements, a detailed design will need to be accomplished to implement heat transmission into the membrane by means of electrical resistive elements and energy absorbing coatings on the back side of the membrane.
- Capacity of the new CE SMP resin for high-fidelity replication of a mold's optical-quality surface needs to be empirically confirmed.

6.0 RELATED WORK

This program leverages over \$4.1 M in precursor or supporting R&D by CRG in the following related projects.

6.1 Shape Memory Polymers

Independent Research and Development (IR&D) (1999 through present). CRG conducts ongoing in-house R&D to advance the state-of-the-art in high-performance SMP materials. That effort extends shape memory properties into polymeric material systems not generally recognized as accommodating that functional behavior. This in-house effort also establishes material design methodology for optimizing SMP formulations to meet specific performance requirements (e.g., T_g , strength and modulus of elasticity above and below T_g , % strain recovery).

6.2 "Laser Processing of a Net-Shape Polymeric Reflector Using Shape Memory Polymers"

National Aeronautics and Space Administration, STTR Phase I Contract NAS1-00002 (October 1999 through September 2000). This effort in conjunction with the University of Connecticut experimentally demonstrated the feasibility of fabricating high-performance shape memory polymer (SMP) films. Test results indicated their strong potential for application in low-cost, near-net-shape polymer reflectors, null correctors for optical systems, and other deployable applications exploiting SMPs' unique properties of controlled strain recovery.

6.3 "Deployable Electromagnetic Reflectors"

National Reconnaissance Office, Director's Innovative Initiative Contract NRO000-01-C-0213 (February 2001 through November 2001). This collaborative research effort with the University of Connecticut and the Air Force Institute of Technology demonstrated conceptual feasibility for deployable reflectors based on shape memory polymers (SMP) for space applications. Using styrene-based polymers as an analog for space-qualifiable SMP, CRG fabricated successful coupon-scale test articles of SMP-based reflectors and SMP honeycomb support structures integral to the reflector surface.

6.4 "SMP Development for [a] Manufacturing Process"

Commercial Contract (February 2001 through December 2005). This effort was targeted toward a specific commercial product line of a *Fortune 500* company (a nondisclosure agreement precludes identifying the company or describing the product). SMP materials offer a unique set of characteristics suitable for manufacturing small quantities of complex or precise parts, which makes them ideal for manufacturing the current and next-generation product currently marketed and sold by the company. CRG demonstrated SMP materials' potential to improve the manufacturing yield of the company's existing products and their potential as enabling technology for the customer's next-generation product line. CRG tailored SMP formulations to meet specific strength, thermal, and other requirements and demonstrated the

new material's application in a functional prototype. CRG also designed and implemented sophisticated demonstration fabrication apparatus, with automated controls, scalable to ISO 9000-series manufacturing quality standards.

6.5 "Composite Replica Mirrors for Lightweight Space Optics"

Air Force Research Laboratory, SBIR Phase I Contract F33615-02-M-5027 (April 2002 through November 2002) and Phase II Contract F33615-03-C-5013 (June 2003 through October 2006). This program is demonstrating new composites applied in lightweight rigid replica mirrors for space-based imaging systems. The resulting materials will provide reduction in mirror areal density (compared with conventional mirrors) while achieving strength and thermal properties required for space applications. The fabrication technology development will culminate in an operationally relevant prototype demonstration of a composite replica mirror. In this project's approach, replica mirrors are cast directly on an optical-quality mold and a coating provides the reflective surface. The program's results with cast cyanate ester optical surfaces and cyanate ester composites are directly applicable to the development of membrane mirrors.

6.6 "Oriented Nanofiber Film Adhesives"

Air Force Research Laboratory, SBIR Phase I Contract F33615-02-M-5614 (April 2002 through January 2003) and Phase II Contract F33615-03-C-5603 (July 2003 through October 2006). This program is developing a toughened adhesive system for damage tolerant joints. The initial approach was based on next-generation materials exhibiting increased bond durability and toughness and on alignment of nanofibers in a film adhesive. The nanofibers would be aligned in the film manufacturing process, not at joint bonding. Early Phase I results indicated the processing necessary to accomplish nanofiber orientation would not be cost effective. However, a secondary proposed approach yielded good results using a random mat-type carbon nanofabric to replace polymer or glass scrim in the bond line. CRG developed a surface treatment process to increase matrix adhesion and dispersion properties of the carbon nanofibers; developed a fabrication process yielding 1 ft² pieces of nanofabric (world class state-of-the-art (SOTA) scale for nanofabric); and demonstrated that composites fabricated with carbon nanofabric exhibit increased fracture toughness. Phase II effort is extending and completing this development to implement the Phase I breakthroughs in a mature adhesive system. Loctite Aerospace, a leading manufacturer of high-performance adhesive, is a program partner.

6.7 "Production Technology for Replica Seeker Mirrors"

Air Force Research Laboratory, SBIR Phase I Contract F33615-03-M-5725 (August 2003 through February 2004). In this Missile Defense Agency (MDA) funded program, CRG integrated advanced materials and processes into a fabrication technology system addressing the producibility and affordability drawbacks of conventional mirrors used in seeker optics for interceptor missiles. In this approach, a mirror's final figure and finish is achieved by thermoforming a thin layer of SMP at the surface of a structure composed of other advanced material (e.g., metal matrix composite). Grinding and polishing to achieve optical figure and finish are accomplished on a mold rather than individual mirrors. However, in this project, a

thermoformed SMP layer replicates the mold's figure and finish, rather than the casting approach in the current program for membrane mirrors.

6.8 "Lightweight Composite Metal Optics for ACT [Advanced Concept Technology]"

CRG Subcontract to Ball Aerospace & Technologies Corporation (BATC) NASA Prime Contract NAS1-03007 (August 2003 through July 2005) and supporting Purchase Order funded by BATC IR&D. Two complementary CRG efforts for BATC investigated application of cyanate ester shape memory polymer (SMP) composite material to implement BATC's approach for deployable lightweight mirrors for space-based reflector systems. These efforts constituted SBIR Phase III application of this SBIR Phase II project. Results, summarized in Section 7.1 and Appendix C, demonstrated CRG's ability to tailor its SMP-based composite materials for the BATC application. BATC presented their contract results to NASA as Final Report ACT 02-0096, Development of High Performance Laminated Electroformed Shape Memory Composite Materials for Lightweight and Deployable Optics.

6.9 "Hierarchical Shape Recovery Polymer Nanocomposites (PNCs) for Next-Generation Aerosystem Applications"

Air Force Research Laboratory, SBIR Phase I Contract FA8650-04-M-5017 (March 2004 through November 2004) and Phase II Contract FA8650-05-C-5047 (June 2005 - June 2007). CRG's Phase I effort demonstrated feasibility of employing nanomaterials to enhance shape recovery performance and enable alternative triggering mechanisms in next-generation shape recovery materials. The resulting nanocomposites showed significant improvement in thermal and mechanical properties over current shape memory polymers. The alternative triggering mechanisms improved response time, increased energy efficiency, and alleviated drawbacks associated with the current, direct heating mechanism. Phase II effort is improving on the Phase I materials through alternative nanocomponents and optimized formulations and processes. The resulting advanced shape recovery nanocomposites will provide compatibility with aerospace systems. These advanced materials will enable new design concepts that significantly reduce conventional designs' need for trade-offs between vehicle configuration alternatives (e.g., wing and fuselage shapes, control surfaces, etc.) to accommodate varying mission profiles.

7.0 PHASE III COMMERCIALIZATION TO DATE

This project has already generated \$419,500 in Phase III commercial investment in the materials and fabrication processes it developed. The bulk of that Phase III effort represents direct transition of these technologies to a commercial prime contractor for application in space-based membrane reflectors.

7.1 Ball Aerospace & Technologies Corporation -- Space-Based Membrane Reflectors

This Phase III effort is a direct technology transition of this Air Force SBIR program's technology to a major aerospace prime contractor.

In Phase III effort funded by Ball Aerospace & Technologies Corporation (BATC) as a subcontract to BATC for a NASA program (NASA prime contract NAS1-03007, "Lightweight Composite Metal Optics for ACT [Advanced Concept Technology]"), and a supporting IR&D-funded purchase order, CRG accomplished significant development effort in self-deploying membrane reflectors composed of carbon fiber-reinforced CE SMP. The BATC design approach for a microwave reflector applies a nickel reflective surface (using technology developed by Northwestern University) to a fiber-reinforced CE SMP structure using CRG's material and process technologies.

The BATC effort leveraged the Air Force investment in the Task 1 CE SMP resin development in this SBIR program while this SBIR program leveraged fabrication process and composite material development from the BATC subcontract effort. This section summarizes results of the parallel BATC effort which are directly relevant to this project's Technical Objectives. CRG presents this nonproprietary summary with permission from the BATC technical manager, Steven Varlese. CRG expresses appreciation to BATC for allowing inclusion of its Phase III results in this report.

BATC presented their overall contract results to NASA as Final Report ACT 02-0096, "Development of High Performance Laminated Electroformed Shape Memory Composite Materials for Lightweight and Deployable Optics."

7.1.1 Material and Process Development for CE SMP-Based Composites

CRG developed a vacuum assisted resin transfer molding (VARTM) process to fabricate a void free, resin-rich convex composite with a uniform, smooth surface as the reflective face of a self-deploying membrane mirror. This process eliminates the need for a large autoclave for fabricating meter-scale optics.

The VARTM technique uses a negative pressure gradient to transport resin into an evacuated system. The uncured composite material is laid up in contact with a mold against which the vacuum-induced pressure differential presses the composite as it cures. As air is removed from the vacuum bag, the resin fills any voids, resulting in an air bubble-free composite which replicates the molds shape and surface. The resin transfer duration depends on four variables: the pressure differential, resin viscosity, permeability or porosity of the reinforcement material, and the distance the resin has to travel.

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CRG conducted an iterative investigation to develop a practical VARTM fabrication process relevant to meter-scale self-deploying membrane reflectors. Only one process variable was changed in each consecutive trial, thereby allowing controlled iteration as the development proceeded. The initial process definition process was based on CRG's past experience with similar materials and processes. Results presented here represent a subset of trials, provided to illustrate the iterative progression rather than a comprehensive account of the investigation.

Figure 43 shows a coupon fabricated with the baseline material and process. This component used baseline CE SMP reinforced with 3D weave fiberglass. The resulting component had a few random voids on the convex side and approximately twice as many voids on the concave side.

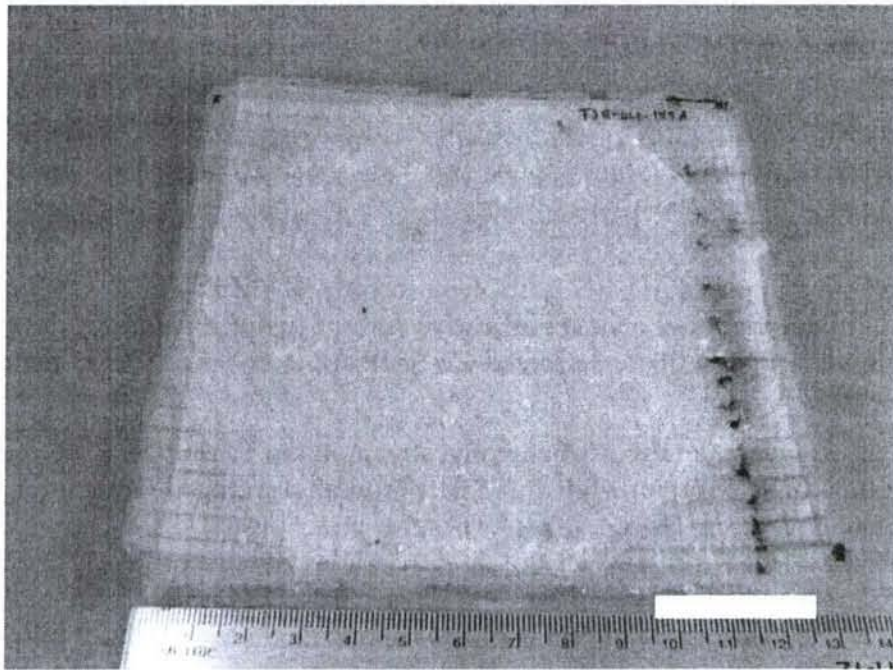


Figure 43. Baseline VARTM Trial with CE SMP-Fiberglass Composite

Figure 44 shows a coupon fabricated with the same baseline material and process except the set-up omitted one component designed to enhance resin transfer. As expected, the resulting component had more and larger voids.

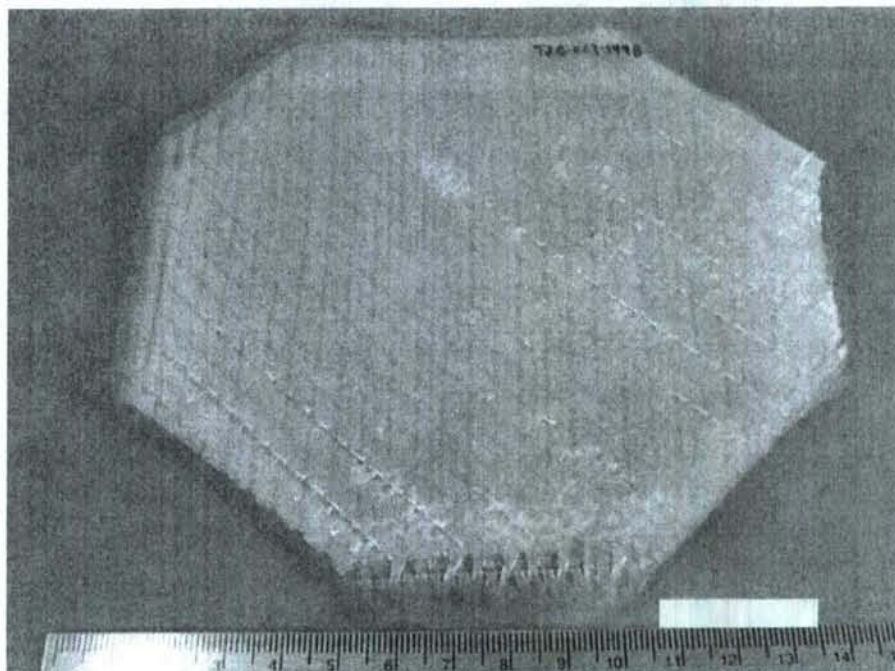


Figure 44. VARTM Trial with CE SMP-Fiberglass Composite, Process without Scrim

Figure 45 shows a coupon fabricated with the baseline material and process except the resin formulation included an additive expected to enhance resin transfer. The cure material exhibited voids along fabric grooves, which CRG attributed to the additive acting as a catalyst and causing an excessive exothermic reaction.

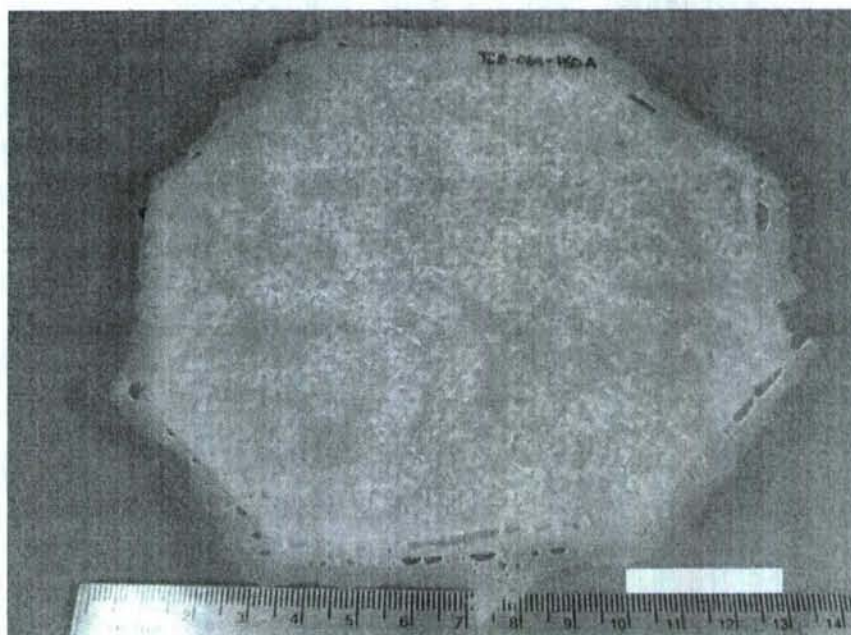


Figure 45. VARTM Trial with CE SMP-Fiberglass Composite, Resin Additive for Surface Tension

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Figure 46 shows a coupon fabricated with the baseline material and process and a modified cure cycle. The modified cure process significantly reduced the voids in frequency and size.

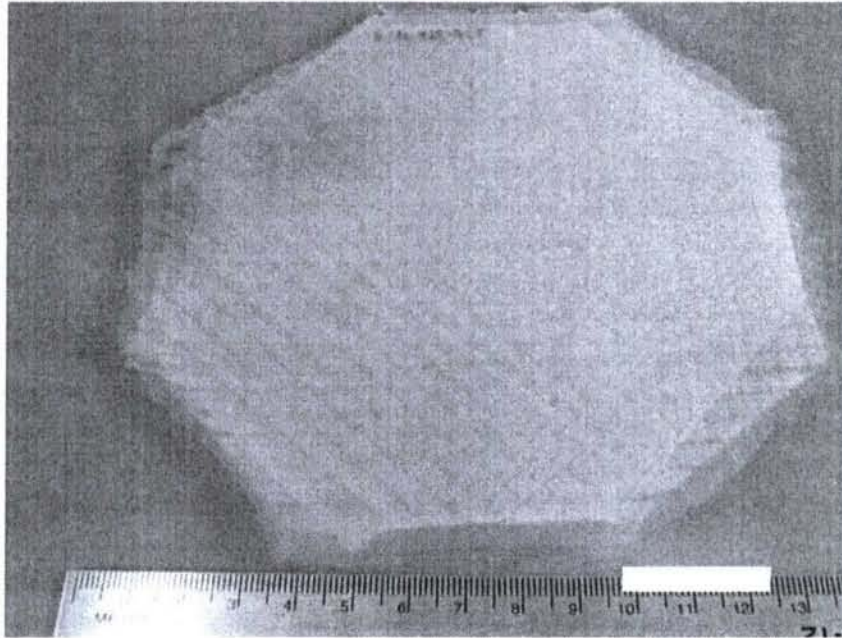


Figure 46. VARTM Trial with CE SMP-Fiberglass Composite, Modified Cure Cycle

Figure 47 shows a coupon fabricated with the baseline material used for the Figure 46 coupon, but with the process modified further to change the resin infusion method. The modified process provided another incremental reduction in voids.

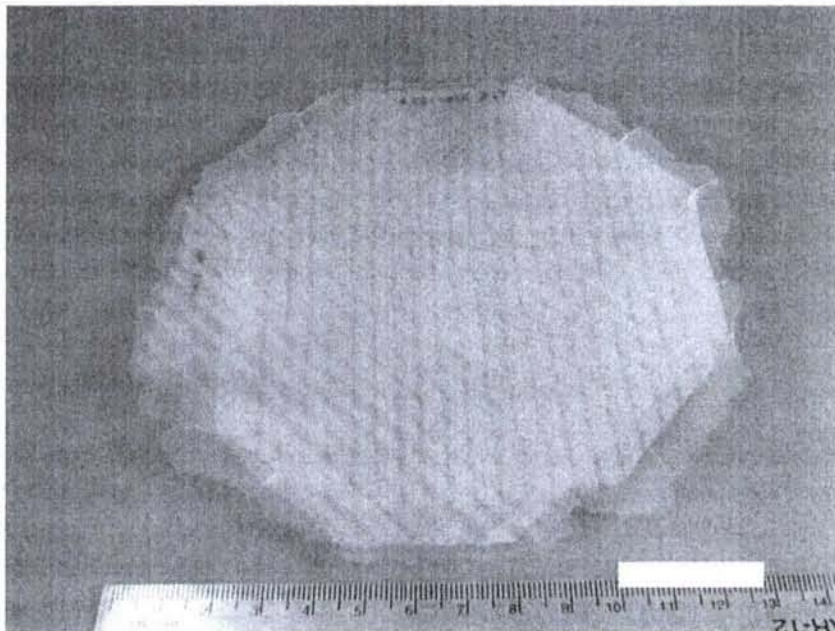


Figure 47. VARTM Trial with CE SMP-Fiberglass Composite, Modified Resin Infusion Method

Through further development, CRG optimized this process to yield a void-free surface at the intended optical face of the composite structure.

Figure 48 shows a meter-scale membrane being laid up on the mandrel during the VARTM process, Figure 49 shows the finished structure, and Figure 50 shows the membrane in its stowed configuration during BATC testing.



Figure 48. Prototype Self-Deploying Membrane Microwave Reflector (1.0 m diameter), Carbon Fiber-Reinforced Cyanate Ester Shape Memory Polymer, on Lay-Up Mandrel



Figure 49. Prototype Self-Deploying Membrane Microwave Reflector (1.0 m diameter), Carbon Fiber-Reinforced Cyanate Ester Shape Memory Polymer, Finished Structure

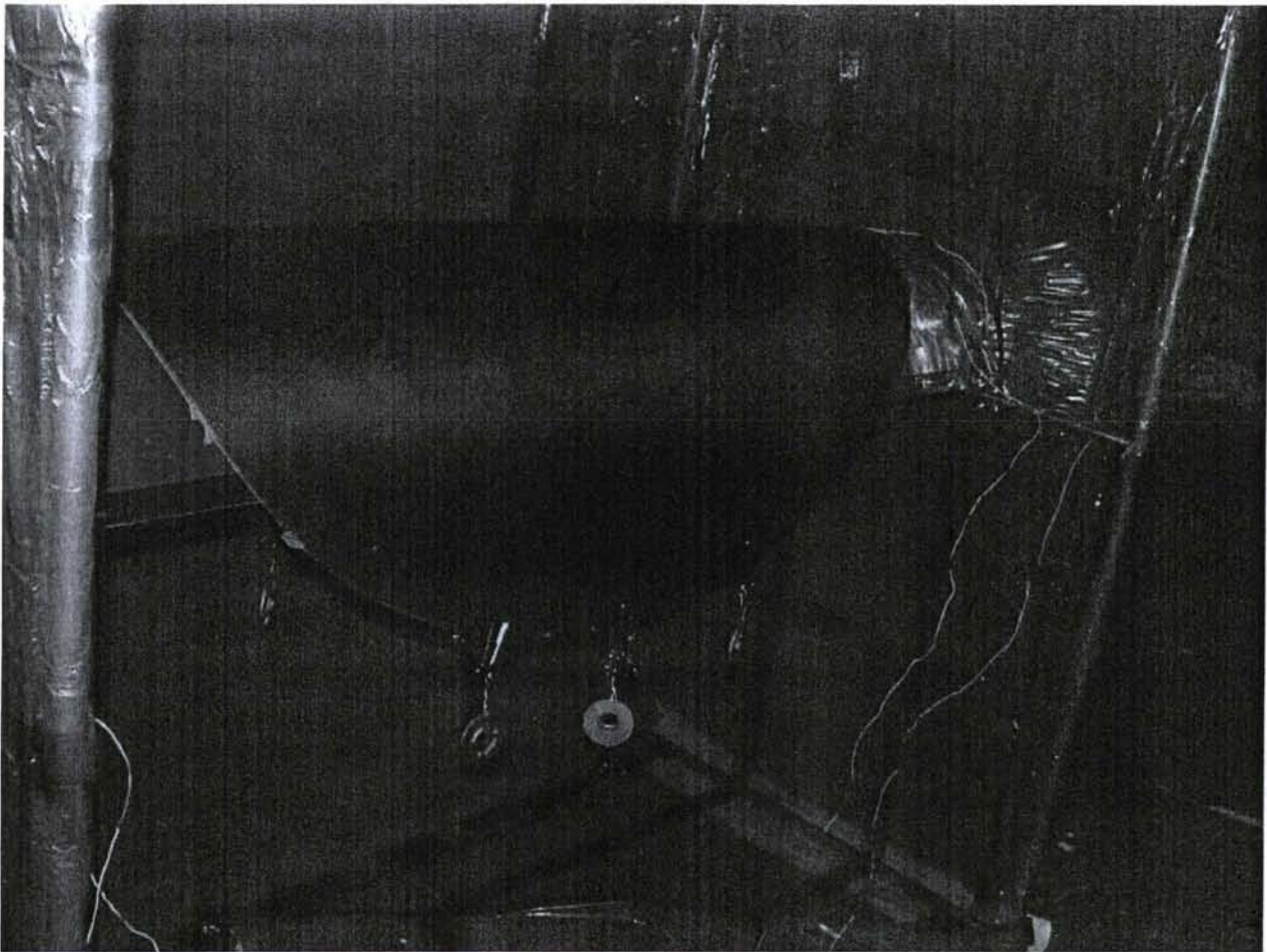


Figure 50. Prototype Self-Deploying Membrane Microwave Reflector (1.0 m diameter), Carbon Fiber-Reinforced Cyanate Ester Shape Memory Polymer, Stowed

Figure 51 shows the final prototype reflector resulting from the Phase III effort. This self-deploying membrane reflector met BATC's figure and surface quality requirements for a microwave reflector.

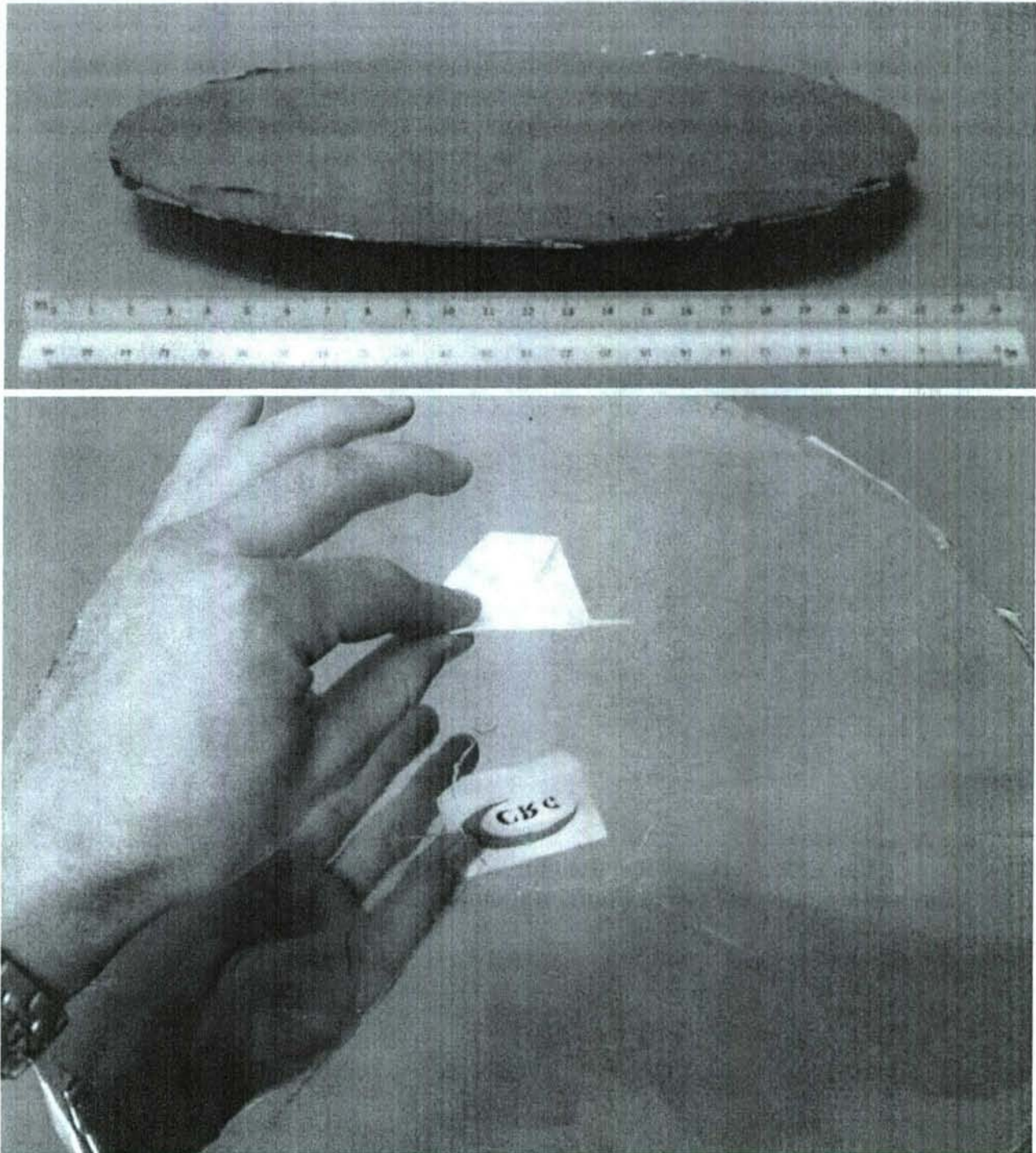


Figure 51. Prototype Self-Deploying Membrane Microwave Reflector (45 cm diameter)

Appendix C provides a BATC presentation of their results applying CRG technology for their NASA program's deployable microwave reflectors. BATC's principal investigator, Steven Varlese, gave this presentation at the joint NASA-DoD "Mirror Technology Days 2006" conference at Kirtland Air Force Base, New Mexico, 18-20 September 2006 (see NASA's web site for the conference: http://optics.nasa.gov/tech_days/index.html).

7.1.2 Sub-Scale Deployment Tests

Early in this effort, CRG conducted qualitative demonstrations using coupons of carbon fiber-reinforced baseline CE SMP. Figures 52 through 54 show one such coupon before deformation to a hypothetical stowed position, during heat-activated deployment (in which the CE SMP matrix reaches T_g and accomplishes strain recovery to its original pre-deformation shape), and after deployment. In this demonstration, the membrane was heated by placing the coupon in a conventional laboratory oven. The photographs of the deployment sequence were taken by periodically opening the oven door to take a picture. The deployment sequence took approximately 30 minutes.

These results have validated the approach in the SBIR Phase I project in which demonstrations were conducted using a styrene-based SMP as an analog for CE SMP, thereby enabling parallel effort during initial development of CE SMP rather than having to delay SMP-dependent development until a CE SMP was in hand.

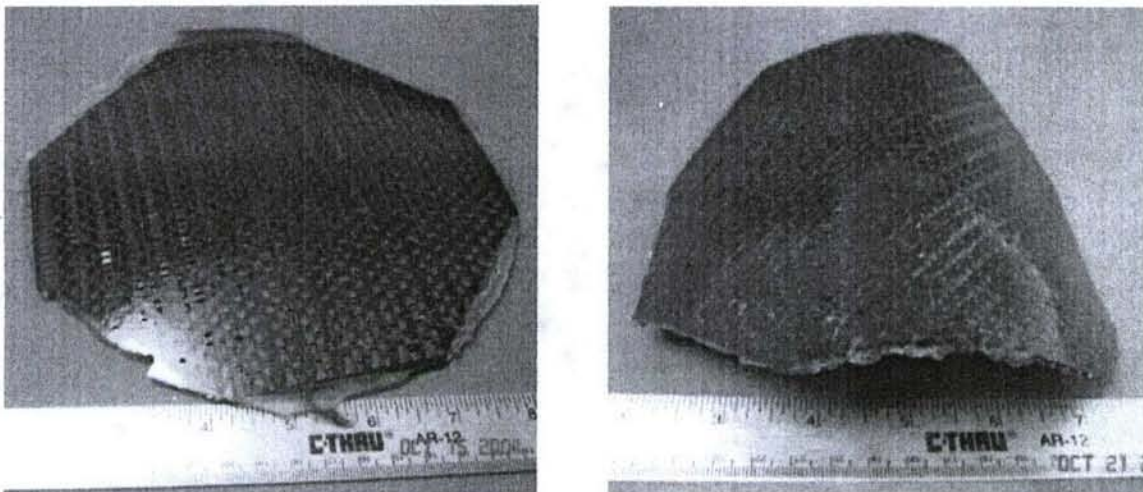


Figure 52. Carbon Fiber-Reinforced CE SMP Composite Coupon before Deformation to Stowed Configuration (L) and in Stowed Configuration (R)

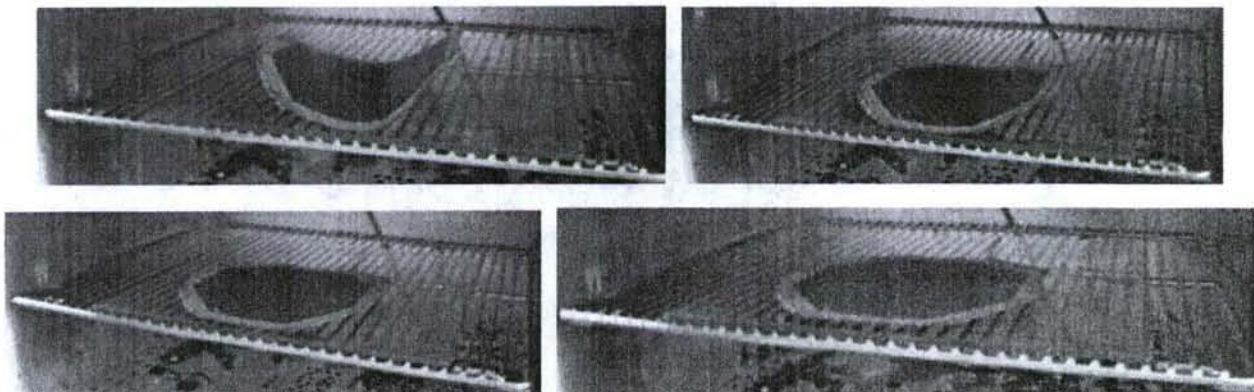


Figure 53. Carbon Fiber-Reinforced CE SMP Composite Coupon during Deployment (Approx. 30 Minutes Total Sequence: (1) Top L, (2) Top R, (3) Bottom L, (4) Bottom R)

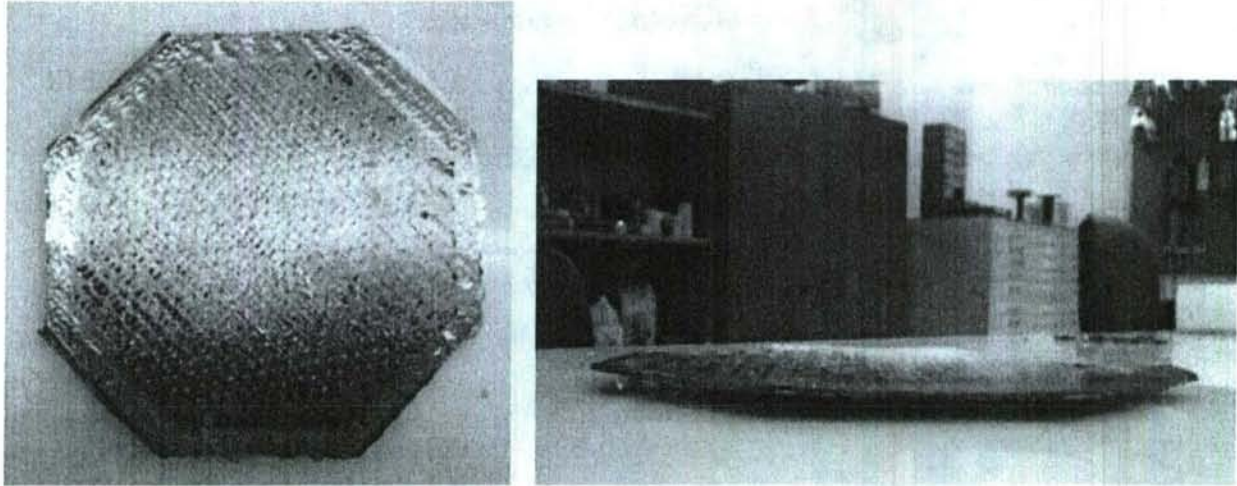


Figure 54. Carbon Fiber-Reinforced CE SMP Composite Coupon after Stow-Deploy Cycle

7.2 Commercial Investment for Terrestrial Applications

Nondisclosure agreements preclude identifying the commercial customers and specific applications involved in the following Phase III efforts resulting from this SBIR project.

A major aircraft manufacturing corporation invested in CRG evaluation of this project's shape memory composite materials for use as a tailorable mandrel for lay-up of composite aircraft structural members.

An industrial polymer material supplier invested in CRG applying the SMP optimization methodology developed in this project to improve the material properties of their polyurethane material.

REFERENCES

1. Michael R. Holmes, "Deployable, Membrane Optical or RF Reflector," DoD 2003.1 SBIR Solicitation, Topic No. AF03-182 (<http://www.acq.osd.mil/osbp/sbir/solicitations/sbir031/index.htm>).
2. Michael R. Holmes (AFRL/PRSS), "Solar-Thermal Propulsion IHPRT Program," NASA JPL/MSFC/UAH 12th Annual Advanced Space Propulsion Workshop, Huntsville AL, 3-5 April 2001 (http://www.spacetransportation.com/ast/abstracts/4D_Holmes.html).

APPENDIX A

BACKGROUND ON SHAPE MEMORY POLYMERS

Shape memory polymers (SMPs) are unique materials with the ability to recover from deformations by releasing stored mechanical energy. If one takes an unstressed SMP structure; deforms it while above its glass transition temperature, T_g (temperature at which it softens); and then quenches it to below T_g ; the material "locks" the strain as stored mechanical energy and retains the new shape. At a later time, this mechanical energy is released by reheating above T_g . The SMP structure then relaxes back to a zero-stress state and recovers the original "memory shape."

CRG's SMP materials exhibit higher strain recovery performance -- speed, energy, and shape fidelity -- than that which is commonly associated with commercially available SMP materials (typically polyurethane). This high-performance results from CRG's ability to design the polymer molecule for specific SMP properties and control the fabrication process to achieve that design.

Figure A-1 shows the shape memory process schematically at the molecular level. SMP is a collection of polymer chains attached at cross-link sites. These cross-links can be physical (molecular entanglement) or chemical (molecular bonding). The SMP characteristics are determined by the choice of polymer chains and cross-linking method. T_g as well as modulus of elasticity (stiffness) both above and below T_g can be controlled through design of the composition and the formulation process. In previous MDA, Air Force, and commercial contracts, CRG has demonstrated ability to control these parameters and design SMPs to meet customer requirements.

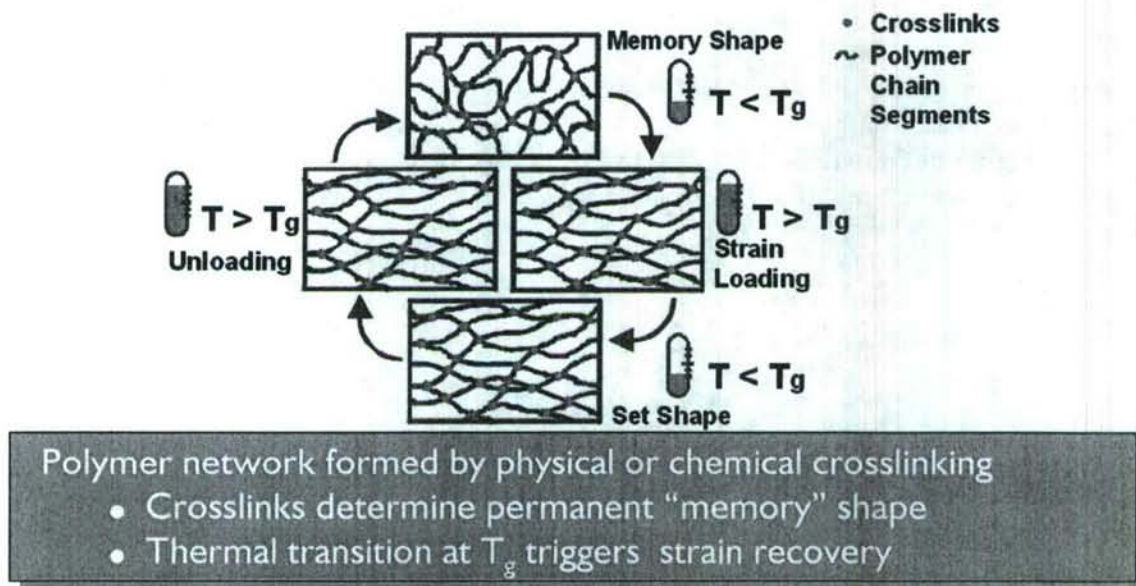


Figure A-1. Schematic of SMP Molecular Configuration with Change in Temperature and Load

Figure A-2 shows a shape recovery sequence with a sub-scale notional mirror shape composed of an early physically cross-linked SMP.

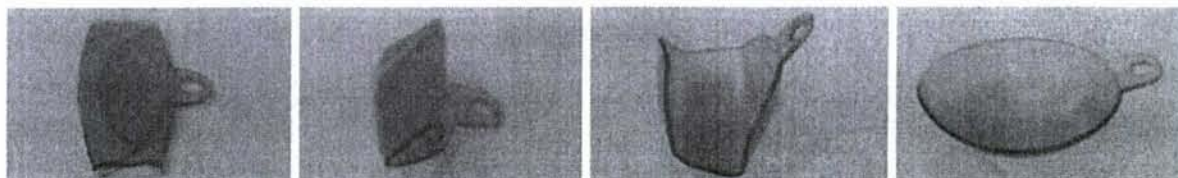


Figure A-2. Shape Memory Polymer Recovery Sequence (5 seconds)

The essential functional characteristic of SMP is its autonomous shape recovery. This shape recovery occurs when the SMP's modulus of elasticity changes at its T_g , allowing the material to shift under the self-induced loads of strain recovery. Further, an SMP's modulus change is repeatable without loss of other material properties even after multiple cycles. Figure A-3 presents a typical SMP glass transition curve (modulus of elasticity as a function of temperature).

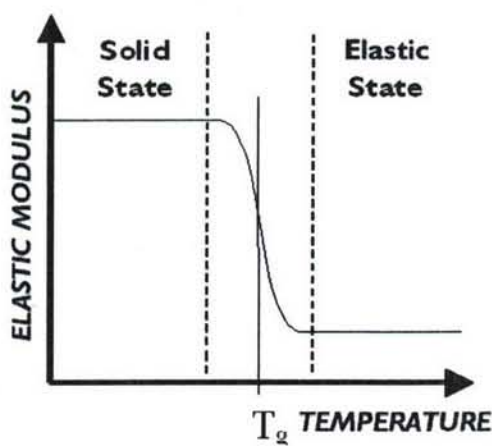


Figure A-3. SMP Modulus of Elasticity versus Temperature

CRG has demonstrated the ability to design SMPs with specific T_g , enabling applications that exploit a controlled shift in the materials' modulus to accomplish design functions. Figure A-4 presents characteristics for a family of SMPs whose range of T_g was produced by varying a key component in the formulation of a styrene-based material system investigated for a commercial application.

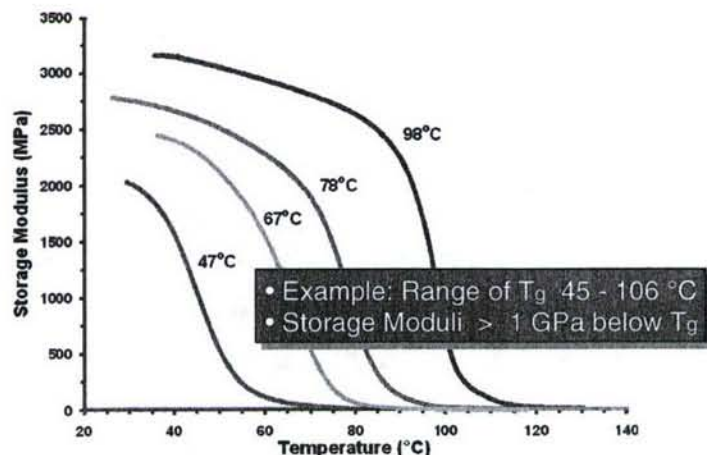


Figure A-4. Tailored SMP T_g

APPENDIX B

[RESERVED]

APPENDIX C

PHASE III EFFORT FOR BALL AEROSPACE & TECHNOLOGIES CORPORATION (BATC)

This Phase III effort is a direct technology transition of this Air Force SBIR program's technology to a major aerospace prime contractor.

This presentation summarizes BATC results for a NASA program to demonstrate enabling technology for deployable microwave reflectors (NASA prime contract NAS1-03007, "Lightweight Composite Metal Optics for ACT [Advanced Concept Technology]"). The BATC design approach for a microwave reflector applies a nickel reflective surface (using technology developed by Northwestern University) to a fiber-reinforced CE SMP membrane structure using CRG's material and process technologies. In a subcontract constituting a direct Phase III application of this AFRL SBIR Phase II project's technology, CRG accomplished significant development effort in self-deploying membrane reflectors composed of carbon fiber-reinforced CE SMP. Section 7.1 in the body of this report provides further information regarding the CRG effort presented in these BATC charts.

BATC's principal investigator, Steven Varlese, gave this presentation at the joint NASA-DoD "Mirror Technology Days 2006" conference at Kirtland Air Force Base, New Mexico, 18-20 September 2006 (see NASA's web site for the conference: http://optics.nasa.gov/tech_days/index.html).



Shape Memory Composite Applications for Deployable Membrane Reflectors

Steven J. Varlese
Ball Aerospace & Technologies Corp.

Mirror Technology Days 2006

Mirror Technology Days: September 18, 2006



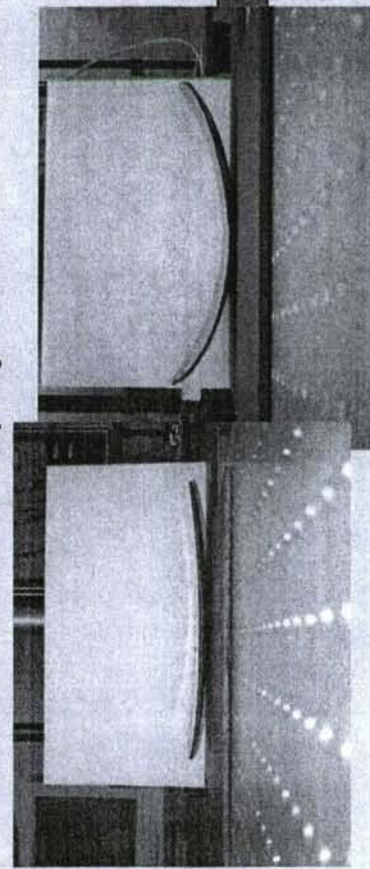
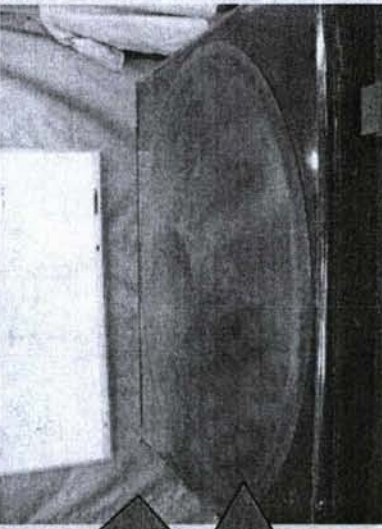
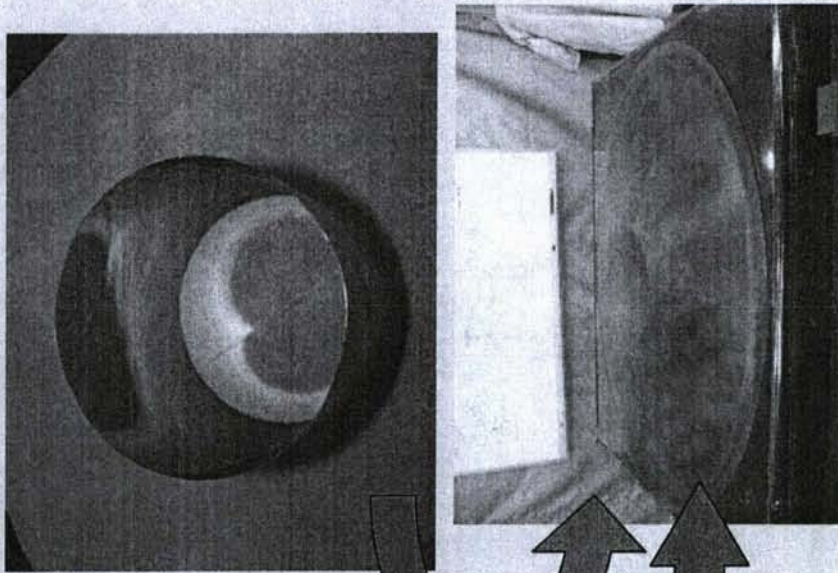


Laminated Deployable Optics

The Best of Two Technologies

Nickel electroformed replica:
Smooth, accurate optical
surfaces

Shape memory polymer- carbon
fiber reinforced, for light weight
and controllable deployment



Deployable, lightweight reflectors

Mirror Technology Days: September 18, 2006



NORTHWESTERN
UNIVERSITY





NASA Needs for Deployable Reflectors

- **ESTO Workshop (2003) identified multiple mission needs for deployable imaging systems requiring apertures of 1 to 5 meters and larger**
 - Microwave- soil moisture, temp radiometry, cloud heights
 - IR- temperature measurement, radiometry
 - SAR
 - Visible- Lasercom, LIDAR
- **Deployable reflectors are an enabling technology for many missions**
 - Lighter weight and stiffer optics
 - Instrument capabilities enhanced at larger apertures
 - Cross enterprise value to OSS, Exploration missions



Primary Objective of Shape Memory Optics Technology Demonstration

Goal: Make deployable, stiff, lightweight reflectors for earth science space applications

Result: Shape Memory Composite material allows deployable microwave reflectors with performance comparable to rigid reflectors, but optical applications initially considered will require more development. Nickel surface development is mature enough for VU-VIS-IR applications

Applications:

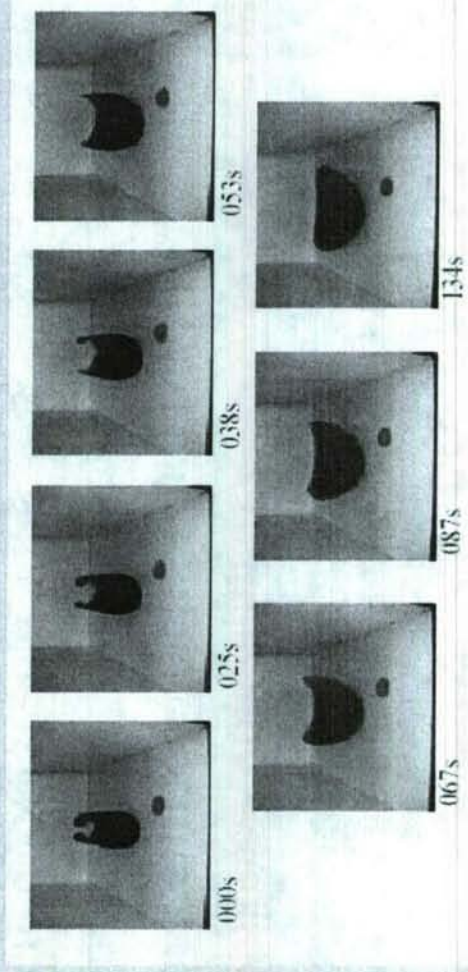
- Use shape memory composites to provide deployable RF band reflectors with better surface accuracy and finish than the current metal mesh reflectors
- Light bucket type optical systems where light collection aperture is more important than surface accuracy
- GEO LIDAR and LaserCom applications





Why Consider Shape Memory Composite Reflectors?

- **Replication – Reduced production time and cost**
- **Larger design parameter space; low mass, compact packing, high stiffness, segmented or monolithic**
- **Adaptable to simple in-space deployment and active control**
- **Better surface accuracy than mesh and inflatable**



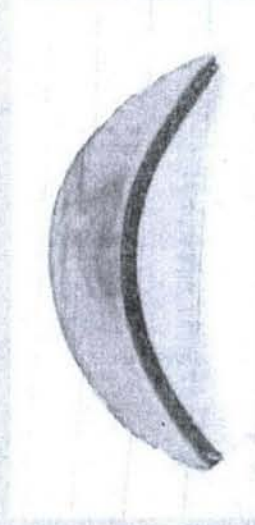
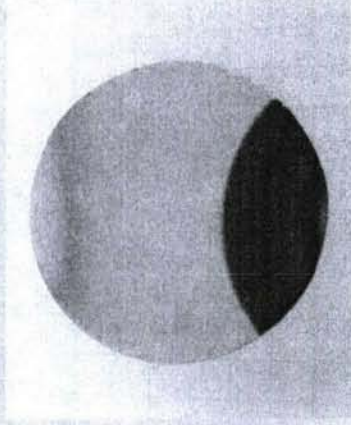
Mirror Technology Days: September 18, 2006





Laminated Reflector Concept Replicated Nickel/Composite

- **Surface Replication: low stress nickel**
 - Replicates optical figure
 - Good surface finish ($< 2\text{nm RMS}$)
 - Tough, flexible, established processes
 - Etched for reliable adhesion
- **Shape memory resin composite**
 - High stiffness, low mass ($1\text{-}5\text{ kg/m}^2$)
 - Replicated Production
 - Low outgassing ($< 0.16\% \text{ TML}$)
 - Deployable
 - Composite adjusted to match nickel CTE





Detailed Modeling Goals

- **Update material constructions**
 - Symmetric laminations for stability and uniformity
- **Comparison with strain measurements made on samples**
 - New constructions fabricated and tested
- **Scalability**
 - Utilize scaling methods developed for other large space structures
- **Thermal deformations**
 - Balanced constructions minimize thermal deformation level
- **Resonant Frequency**
 - Mass / size are drivers for fibers, thickness, # layers, deployability
- **Thermal actuation**
 - Analysis demonstrated feasibility of deployment via solar heating, with appropriate thermal coatings

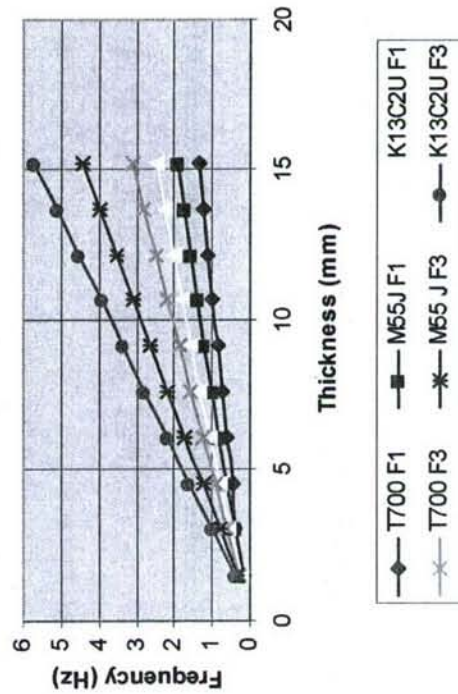


Resonant Frequency for a 5m Mirror

Using the same
(0.060 in) thickness:

Material	F1 (Hz)	F2 (Hz)	F3 (Hz)	F4 (Hz)
T700	0.145	0.290	0.268	0.399
M55J	0.191	0.298	0.338	0.565
K13C2U	0.239	0.386	0.415	0.736

Frequency vs Thickness for a 5m Mirror

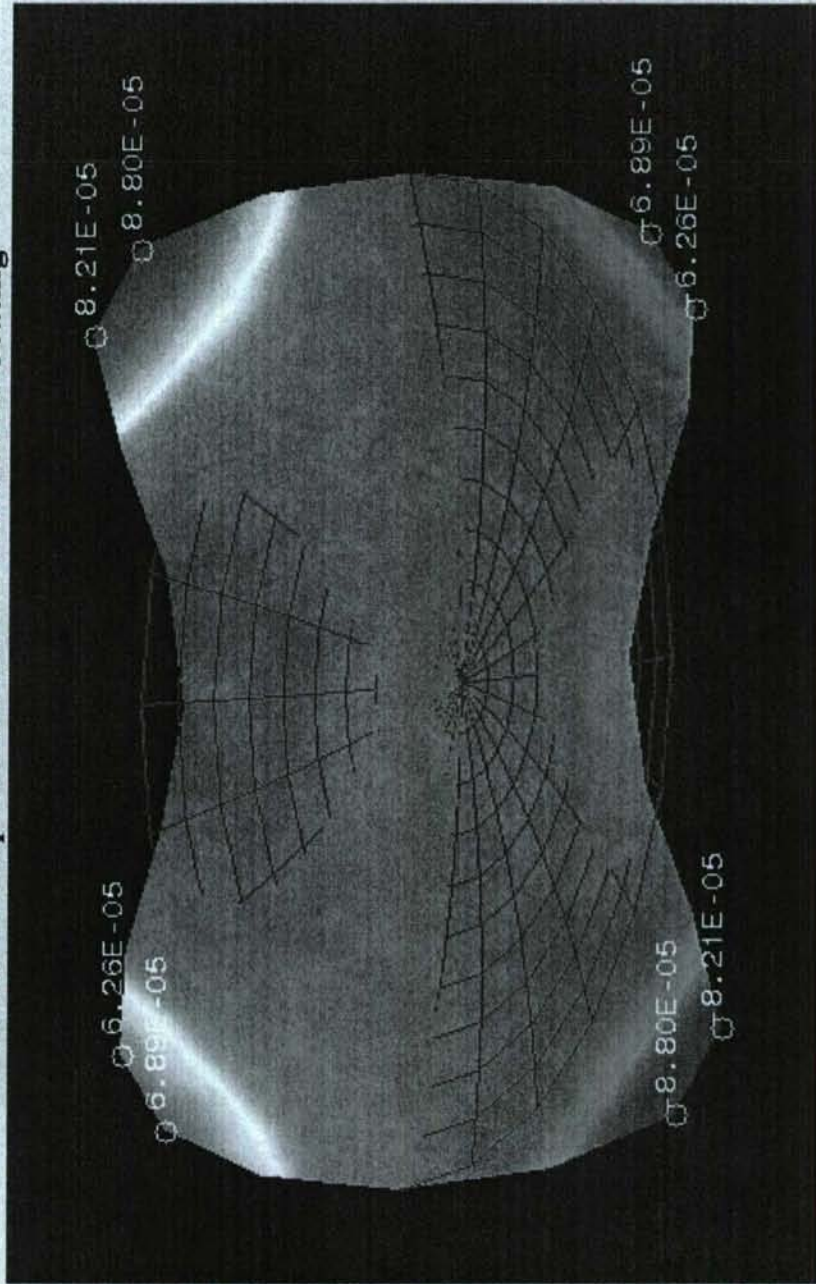


5m Mirror Mass:
(from NASTRAN FEM)
1.5 mm thick: 58 kg
7.6 mm thick: 274 kg
15 mm thick: 544 kg



Shape Change for a $\pm 1^\circ$ Side to Side Gradient are minor effect

Deformed Shape for a T700 Mirror with Ni Coating



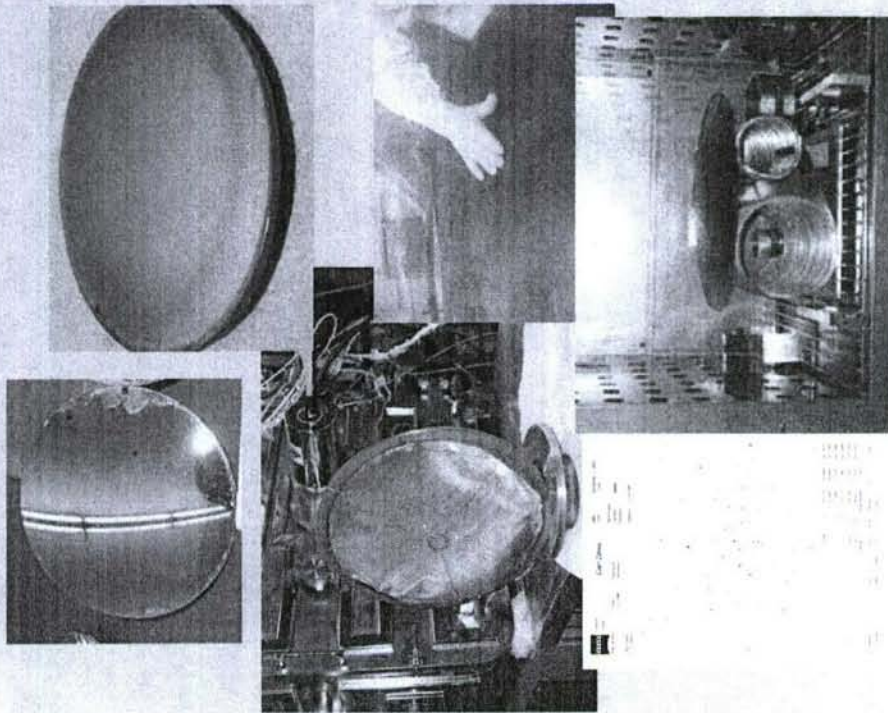
Mirror Technology Days: September 18, 2006





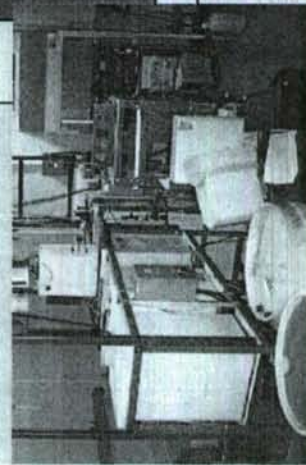
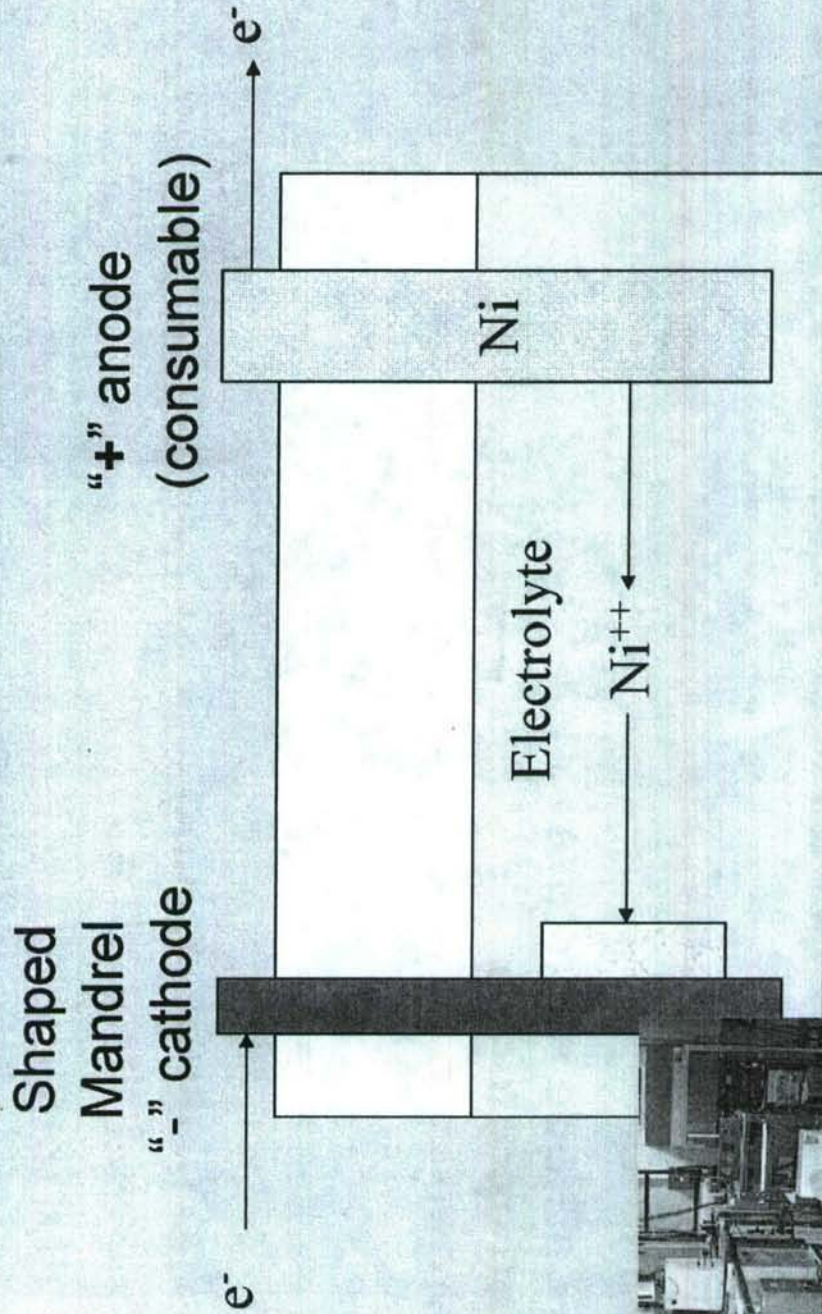
Replication process

- Polish and prepare mandrel
- Electroplate Nickel
- Etch Nickel for adhesion
- Lay-up and cure composite
- Remove from Mandrel
- Characterize surface
- Prepare for stow and deploy testing and further measurement





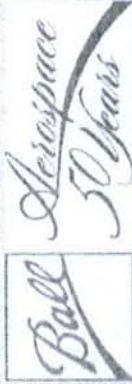
Low Stress Electroplating Forms the Reflective Surface



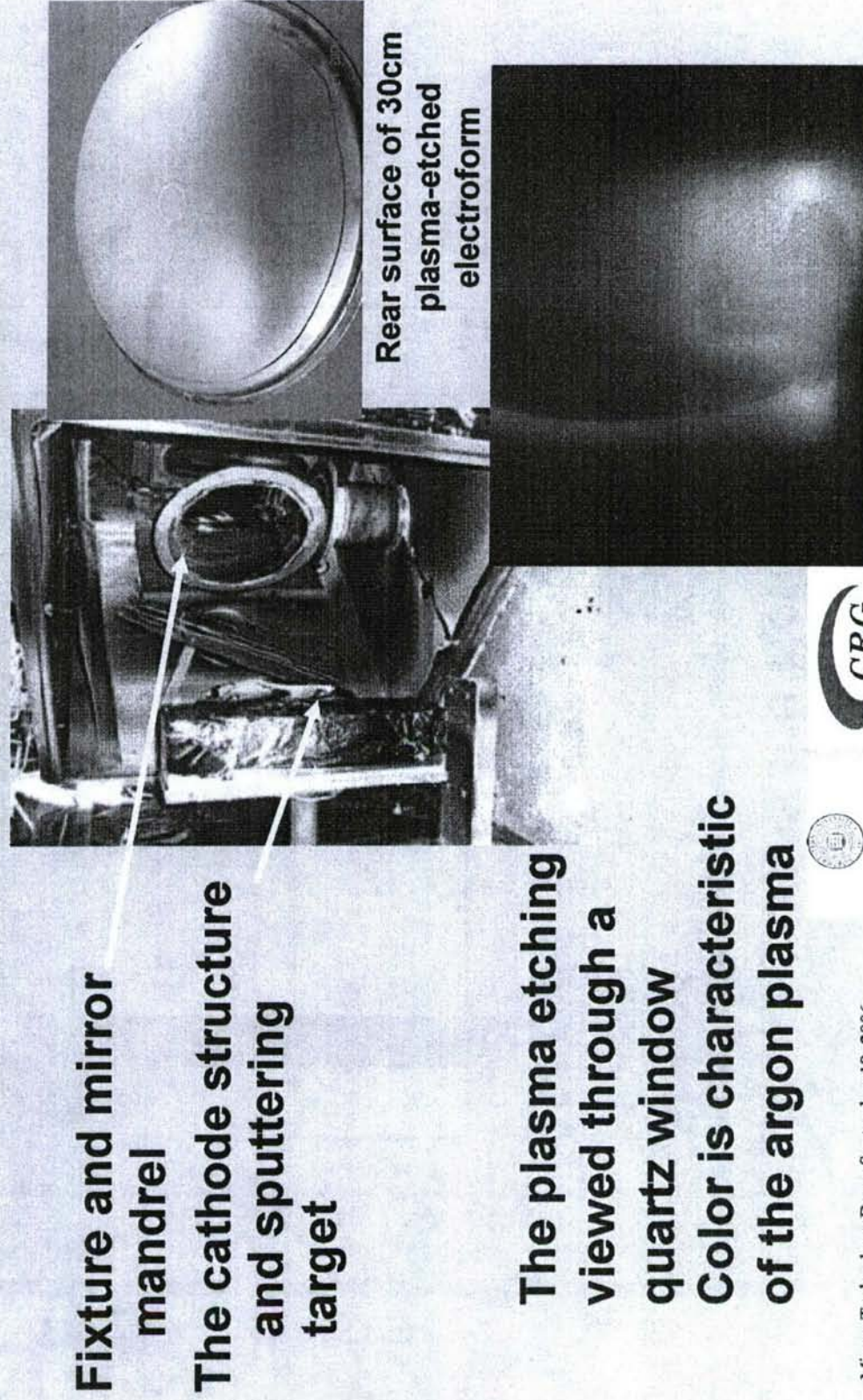
Process adapted from fabrication of Wolter X-Ray optics

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Plasma Etching Prepares Nickel Electroforms for Composite



Fixture and mirror
mandrel

The cathode structure
and sputtering
target

Rear surface of 30cm
plasma-etched
electroform

The plasma etching
viewed through a
quartz window
Color is characteristic
of the argon plasma

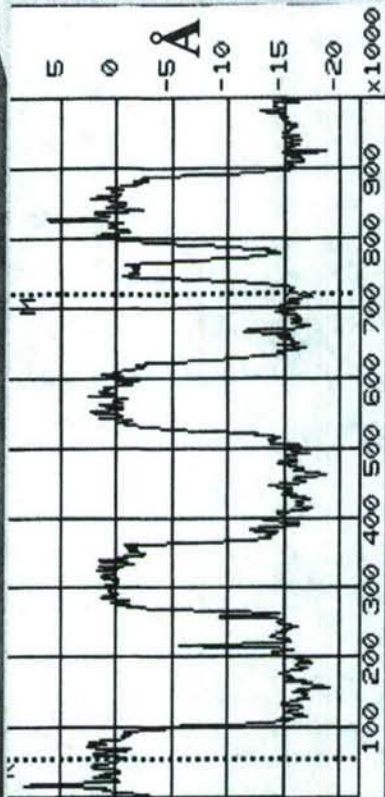


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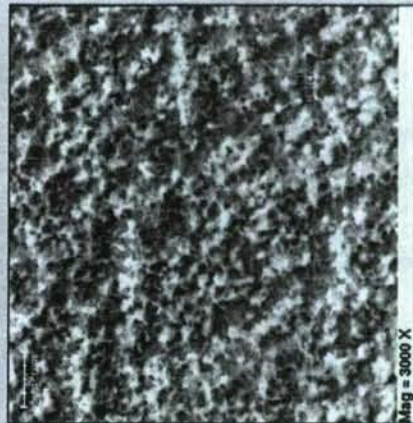
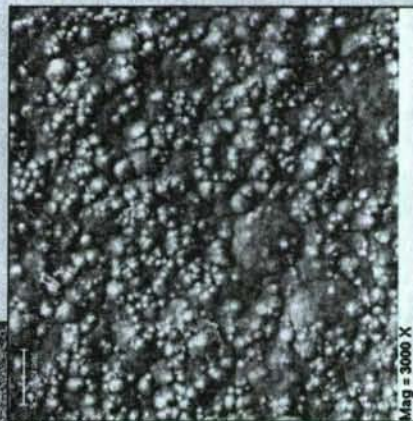
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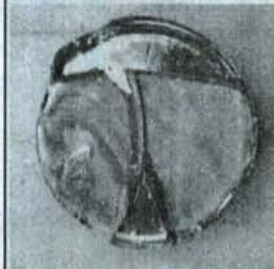
Etching of Nickel Increases Roughness Profile and Improves Adhesion



Mesh Profile (microns)



**Resin fails before
nickel adhesion**



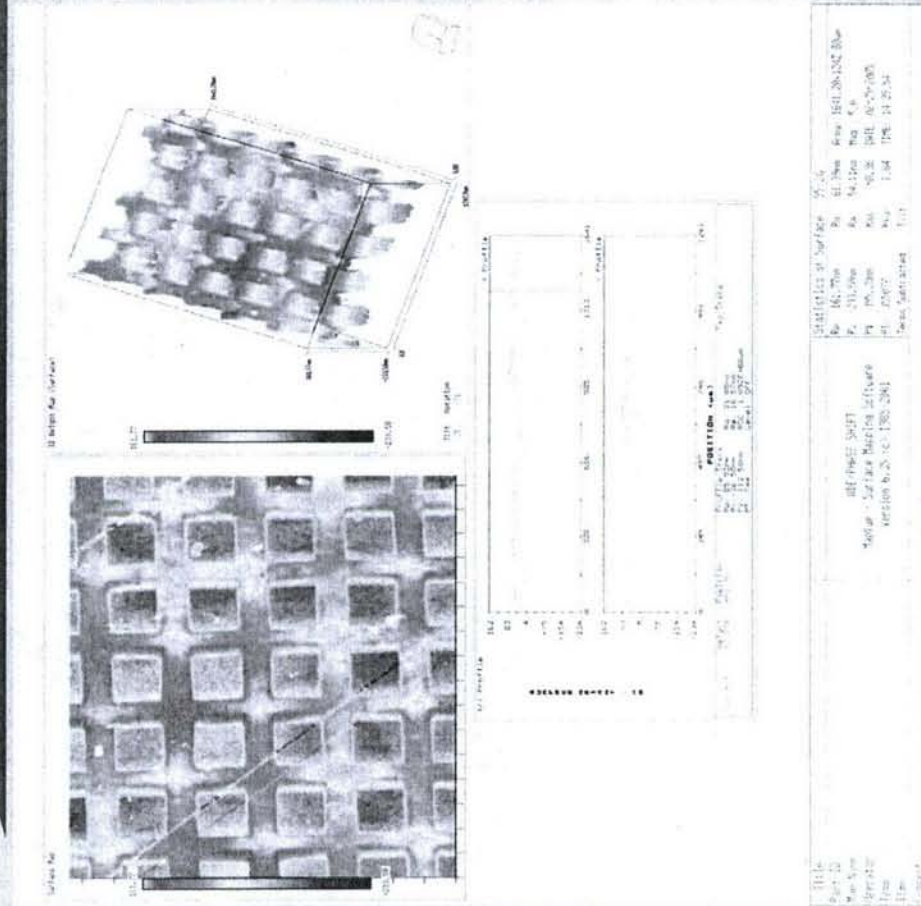
As-plated 3000 X Etched



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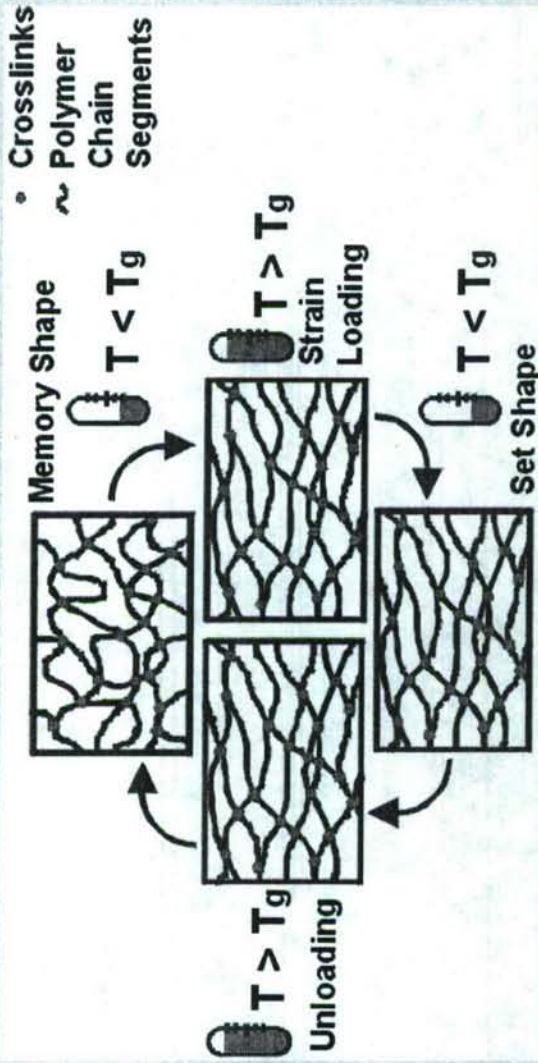


Etched profile of nickel surface





Shape Memory Polymers Application



Cured shape---

**Stow/Deploy
actuation--**

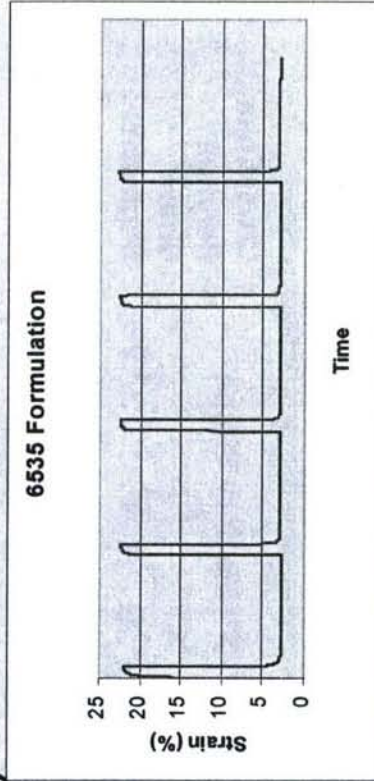
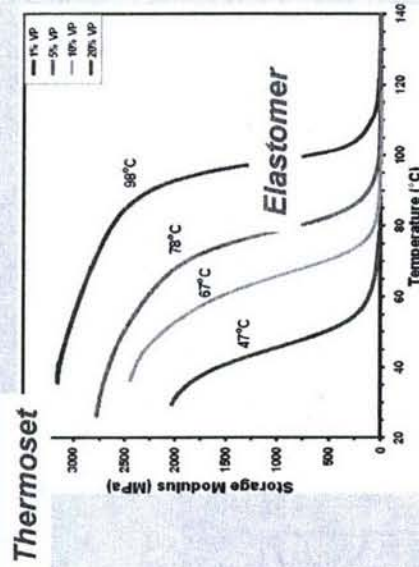
Stowed ---

- **Replication**
 - Replicate surface from master in manufacturing processes
- **Actuation**
 - Store and release mechanical energy
- **Reconfiguration**
 - Temporary modulus reduction to enable shape change



SMP Development - Cyanate Ester

- **CE polymers are already used in space**
- **Conventional CE transformed to SMP**
 - Fully cured, cross-linked for stability
 - Required new polymer design
- **CE shape memory polymer results:**
 - Deformation-recovery cycle demonstrated
 - Activation temperature of 160°C
- **Improvements Continuing**
 - Enhanced strain recovery
 - Increased toughness



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Cyanate Ester Shape Memory Resins- Acceptable Outgassing

- Total Mass Loss (TML) and Condensed Outgassing Product (COP) tests on cyanate ester SMP and composites found them to be space-qualifiable

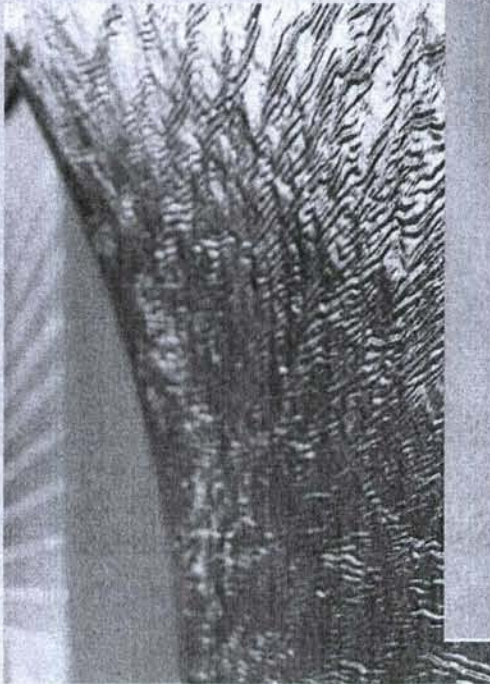
Log #	Material	TML %	COP %
58	SynLam TM with 3D Carbon Fabric	0.292	0.027
59	Triaxial weave Carbon Composite	0.059	0.012
66	Neat CE SMP Resin	0.147	0.006
-	Acceptable levels	1.0	0.1



Deployed Mirror surface undamaged by deployment

- Buckling was observed only where delaminated
- Remains smooth after several heat cycles
- Underlying fibers and resin undamaged

Surface remains a good reflector after several heating and deformation cycles



Surface damaged by deployment
only where delaminated



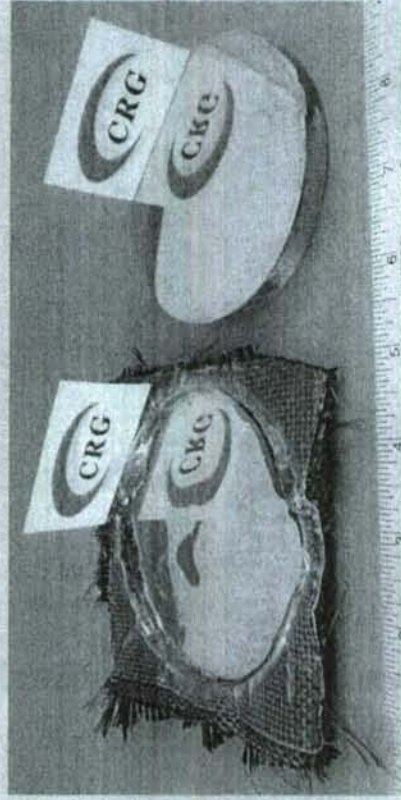
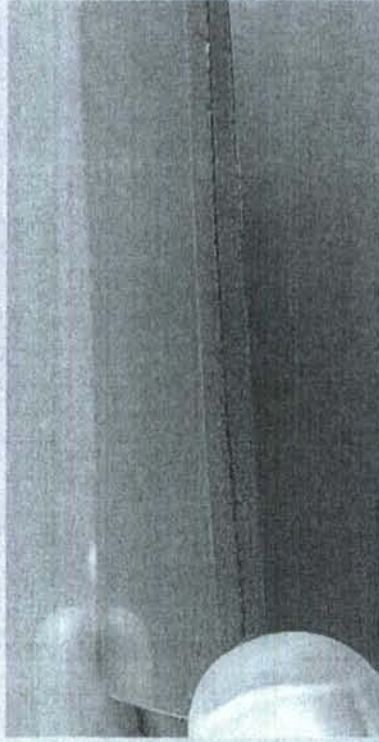
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Print through remains a challenge, but is significantly reduced

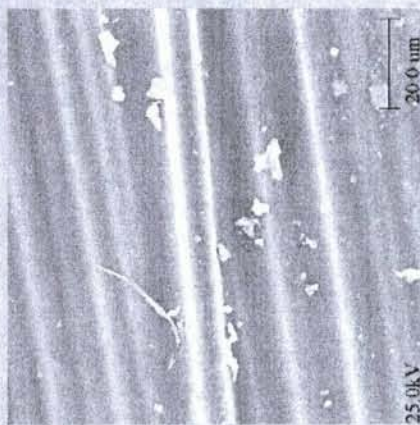


- Fiber-resin CTE mismatch produces print through
- Sandwich approach is improvement, without fibers near surface
- Neat (resin rich) layer surrounds fiber reinforcement
- Nanofibers and alternate filler reinforcement being investigated
- Neat resin layer reduces fiber print-through effect, but nickel-thermal mismatch caused waviness

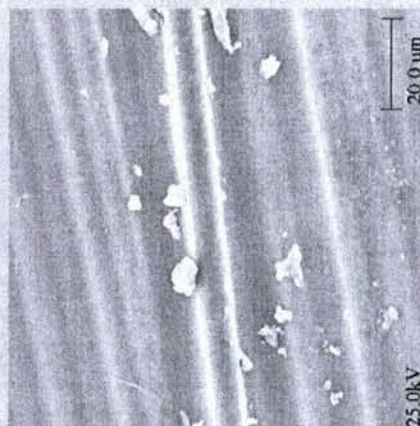


Composite Thermal & Bending Fatigue Test

- Thermal Cycling showed no damage or changes
- Samples of composite have been temperature cycled 10x between -20C to +50C.



1000x SEM before cycling



1000x SEM after cycling

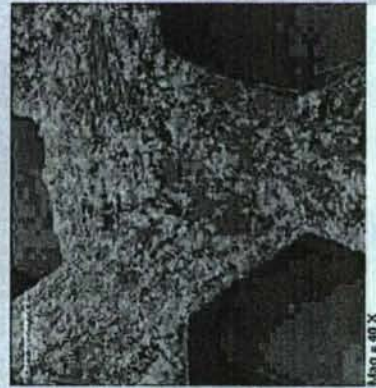
SEM photos before and after from 25x to 3000x show no change or microcracking in the resin or fibers. Microscope inspection of composite samples subjected to repeated cycling from room temperature to +200C have not shown evidence of resin or fiber cracking.



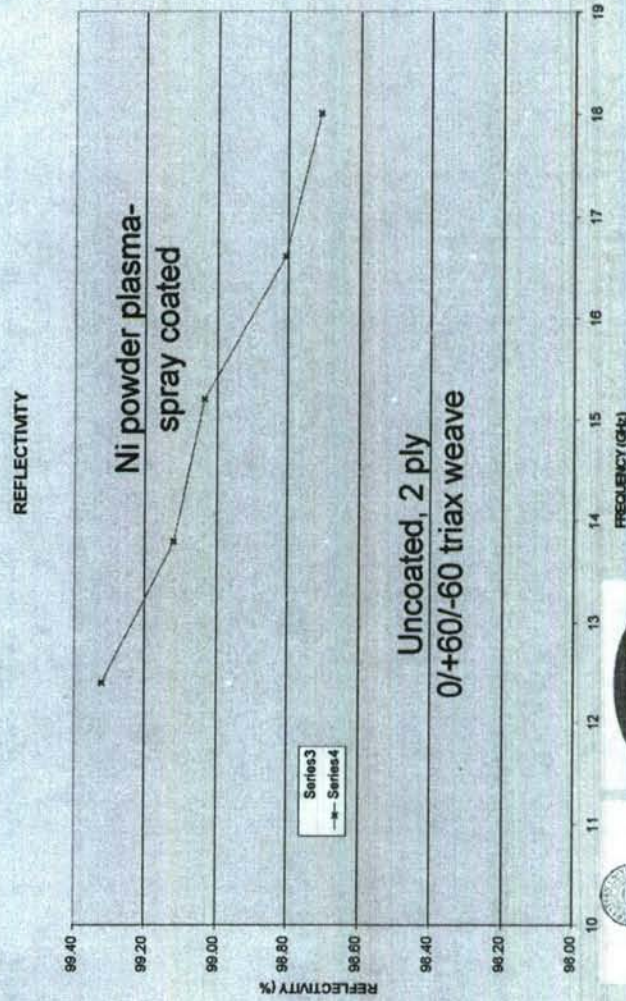


High Microwave Reflectivity

- Several sample constructions tested between 12-26.5 GHz
- Reflectivities uncoated are 94.5-97.5%
- Durable Plasma spray or plated coatings improve reflectivity to 99.5-97.5%, and adhere through multiple deployments



Ni powder
plasma-spray coated



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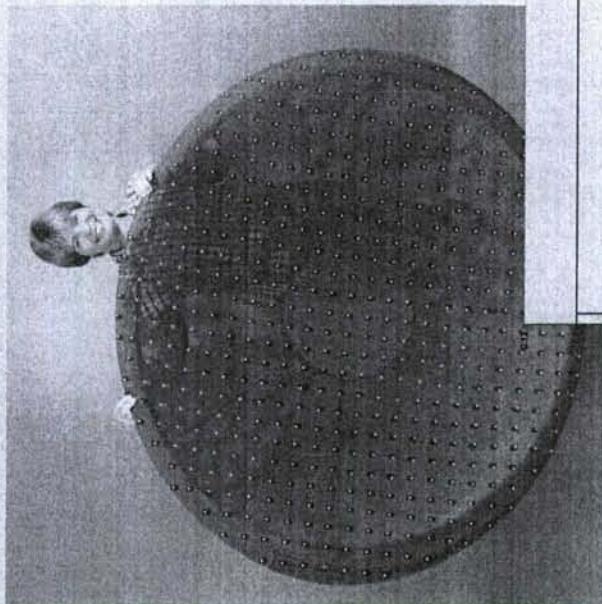
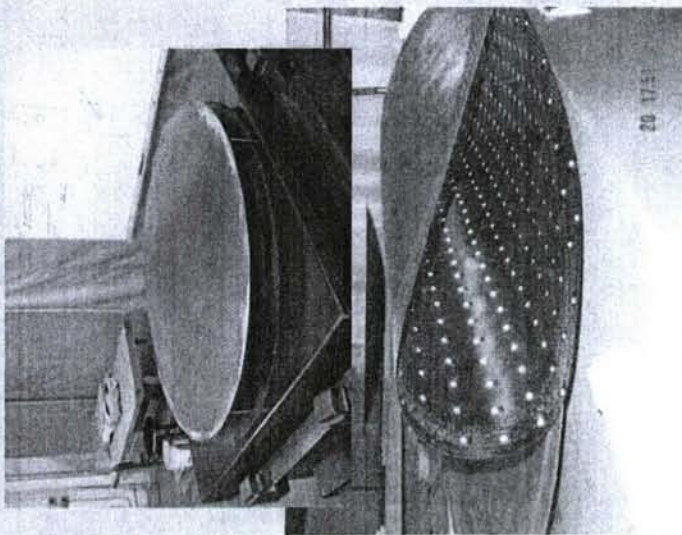


Reflectivity increased with Ni coating
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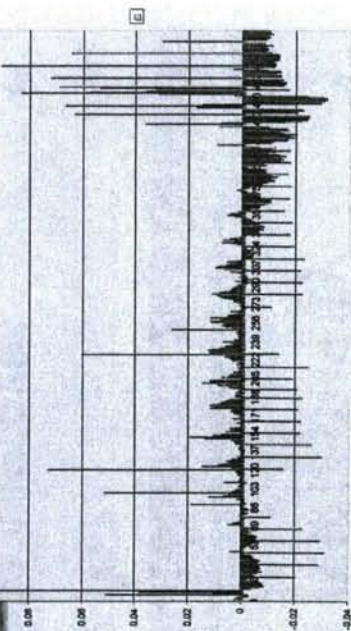
1m deployable reflector surface

Areal Density 0.4 kg/m²
Carbon fiber Triax Weave
Surfaces < 1mm RMS



**Stow-deploy
repeatability
+/- 0.5 mm**

1 mm



1 meter



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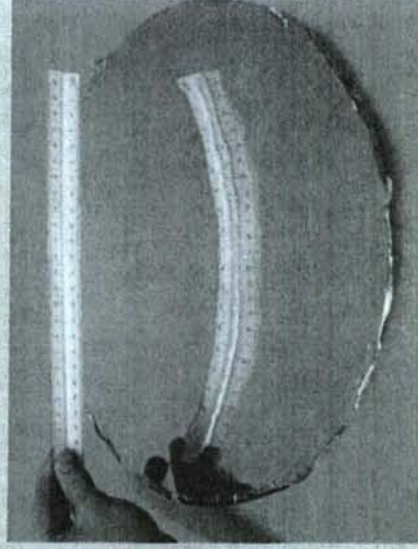
Current deployable reflector status

We have manufactured several test items of increasing size (up to 1.0 meter)

- Materials are low outgassing and space-stable
- Adhesion of metallization coatings demonstrated
- Figure accuracy as good as current rigid membrane reflectors, better than mesh

We are looking at other applications

- Deployable structures, beams
- Active shaping controls, metrology, dynamics & damping
- Heater/deployment implementation





Conclusions

- **Laminated nickel – composite optics can provide deployable, highly reflective surfaces without delamination or deterioration of metal surface and substrate**
- **Typical deployment accuracy is consistent with needs for 15GHz microwave reflectors of 1-2 meter diameter, and further development for surface accuracy adequate at higher frequencies**
- **Additional work needs to be done in:**
 - Resin chemistry (greater elongation, low CTE, low temp cure)
 - Structures (optimizing deployment, modeling in stow condition)
 - Durability verification in the space environment



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