

# **DIMENSIONAL STABILITY OF METALLIZED AND NO METALLIZED POLYMERIC COMPOSITES**

**Tim O'Donnell, Don Lewis, Michael Clark\*, Ben Dolgin  
and Witold Sokolowski**

**Jet Propulsion Laboratory/California Institute of Technology  
Mechanical Systems Engineering and Research Division  
Pasadena, California**

## **ABSTRACT**

### **KEY WORDS - COMPOSITES, COATINGS, AND DIMENSIONAL STABILITY**

The effects of various time, temperature, vacuum, and moisture environments on four types of metallized and bare graphite/epoxy, bare graphite/PEEK samples, and a coated graphite/cyanate ester sample were evaluated. Moisture weight gain or loss and isothermal dimensional changes as a function of time in vacuum were experimentally determined. Thirty-one 2.5 cm by 10 cm by 2 mm thick P75/934 flat coupons, fourteen 25 cm by 25 cm by 2-3 mm thick IM7/977-2 plates, and three 30 cm long 6.26 cm diameter and 2 mm thick IM7/977-2 tubes were used in the gravimetric studies. Most samples were coated with a proprietary activation or impregnation layer, followed by nominally 25 microns of electroplated copper, and either 5 or 12.5 microns of electroplated nickel. Representative samples were left bare. Sample weights were recorded as a function of humidity and temperature conditions ranging from 0.13 Pascals or  $1.3 \times 10^{-4}$  Pascals/100 C to 100%RH/30°C to 80%RH/30°C to 0%RH/20°C to vacuum at 20°C and long term ambient conditions. Statistical results are presented. In addition, a metallized graphite/epoxy and graphite/cyanate ester tube, 10 cm long by 2.5 cm diameter and three unmetallized P75/PEEK 10 cm by 2 cm samples were measured for length changes at 38 and 25°C over a period of 112 days. A Fabry-Perot interferometer was used to measure daily length changes to accuracies of about +/- 0.02 parts per million/month. Temporal length measurements are reported.

•Presently at Massachusetts Institute of Technology

# 1. INTRODUCTION

Future NASA missions in astrophysics, Earth observation, and solar system exploration that require optical communication, optical/infrared imaging, or high precision astrometric measurements impose very stringent demands for dimensional stability (DS) of precision structures and science instrument components. JPL has conducted a survey of future NASA applications and has described many of the DS technology issues in a recent publication (Ref. 1).

Missions/instruments such as the Cassini spacecraft imaging science camera, the Advanced X-ray Astronomical Facility (AXAF) and future concepts such as the Orbiting Stellar Interferometer require knowledge of material stability in the ranges of 1, 0.1 and 0.01 Part Per Million (PPM) strain per year, respectively. However, to meet these needs the temporal stability database for optomechanical materials of interest is very sparse (except for good old Invar). In particular, temporal DS data on composites is nearly nonexistent.

One example of on-orbit material instability (successfully predicted and dealt with) was contraction of the Hubble Space Telescope (HST) composite metering truss structure (Ref. 2). Strut length contracted about 250 microns within the first year on-orbit which caused a change of focal distance of over 25 mm (Ref 3). The average rate of this contraction at the end of 1991, was 0.06  $\mu\text{in}/\text{day}$ . While active focus capabilities were successfully used on HST and other composite optical benches such as JPL's Wide Field Planetary Camera 1, these focus mechanisms can be costly and present a risky single point failure. Hopes for passively stabilizing hydroscopic composites primarily lie with prelaunch environment control (including bakeouts), "low" moisture absorbing matrices, and "hermetic" coatings (the subject of this paper).

Over the last fifteen years moisture DS effects on composite space structures has been a topic of interest. Representative work can be found in References 4-17. However, we are aware of only three papers addressing the issue of experimental long term, e.g. > 1 month, length stability of coated composites (Refs. 4, 8, and 17). Most of these three efforts involved eutectic coatings of either In/Sn or Bi/Sn. These efforts demonstrated significant improvements in long term composite DS (approximately one order of magnitude over bare composites) for small sample sets.

Two potentially significant driving forces for dimensional instability of polymeric composites are moisture absorption/desorption and thermal expansion. However, the DS of composites is considerably more complex depending on the application (Refs. 1, 13, 18- 22). In addition, the basic integrity, with respect to DS, of coated or uncoated composites for optomechanical spaceflight application can be evaluated by a variety of experimental methods (Ref. 23), with varying degrees of accuracies (Ref. 1 ). The two experimental methods used in this effort were: 1 ) weight loss/gain as a function of various humidity/thermal/vacuum conditions and 2) isothermal temporal length changes in a vacuum using laser interferometry. The gravimetric (weight scale) technique was used for moisture loss/gain evaluation. A Fabry-Perot laser interferometer/thermal vacuum chamber at the

University of Arizona was utilized by Professor Steve Jacob for the temporal length change studies.

The work reported on here was conducted in four phases over an approximate two and one half year period, 7/89 to 1/93. Phase Zero: Coating feasibility assessment. Phase one: Small coupon fabrication and gravimetric assessment. Phase two: Large coupon gravimetric assessment. Phase three: Temporal dimensional stability. Note: All samples were fabricated by Katema Composites.

## 2. Material Description

**2.1 Phase zero - Coating feasibility - Seven samples, 2.5 cm by 10 cm by 5 mm thick** were used. All samples were P75/934. The layup was  $[[0/45/90/135]_s]_2$ , where there was a bulk reduction of each sublaminar. Four samples were produced with a coarse peel ply surface while the other three samples were made with a fine peel ply surface finish. Two samples (one coarse and one fine peel ply surface) were left bare, two samples (one coarse, one fine) received only the initial nonmetallic impregnation (or activation) coating, and the remaining three samples (two coarse, one fine) received nominally 25 microns Cu and 10 microns Ni electroplating. As-delivered coating adhesion was excellent. These samples were subjected to various temperatures, humidities and vacuum for up to 147 hours.

**2.2 Phase one - Small coupon fabrication and gravimetric assessment** - Twenty-four samples, 2.5 cm by 10 cm by 5 mm thick, were used. All samples were P75/934. The layup was  $[[0/45/90/135]_s]_2$ , where there was a bulk reduction of each sublaminar. Three lots, six to nine samples each lot, were manufactured with fabrication platen pressures as a process variable. Platen pressures 0.34, 0.69, and 1.03 MPa (50, 100 and 150 psi) were used and were considered Lots 1, 2, and 3, respectively. Subsequently, all samples from each lot except one (left bare) were metallized within a week of fabrication. Metallization was conducted under the auspices of Katema Composites and was specified to first consist of a couple hour bakeout in air at about 100°C. Bake-out was followed by a proprietary activation layer, followed by nominally 25 microns electroplated copper, with a final coating of from 5 to 12.5 microns of electroplated nickel. Note: No stringent processing parameters were enforced to ensure a "dry" coated sample prior to testing at JPL. As-delivered coating adhesion was excellent. Samples were stored in an ambient lab environment until the start of testing, which was within two months of fabrication/plating.

After a total of 147 hours of gravimetric data/measurements, (reported later) three transverse sections were cut from the end of one sample per lot using a diamond band saw. Cutting was done at slow speeds and without water lubrication. The samples were mounted in a room temperature cured epoxy and polished using successively finer grit abrasives until a 0.05 µm surface finish was attained. The polished samples were examined under an optical microscope and Scanning Electron Microscope (SEM) for characteristics such as: a) coating thickness and uniformity, b) porosity, c) cracking, and d) other anomalies. Detailed metallography

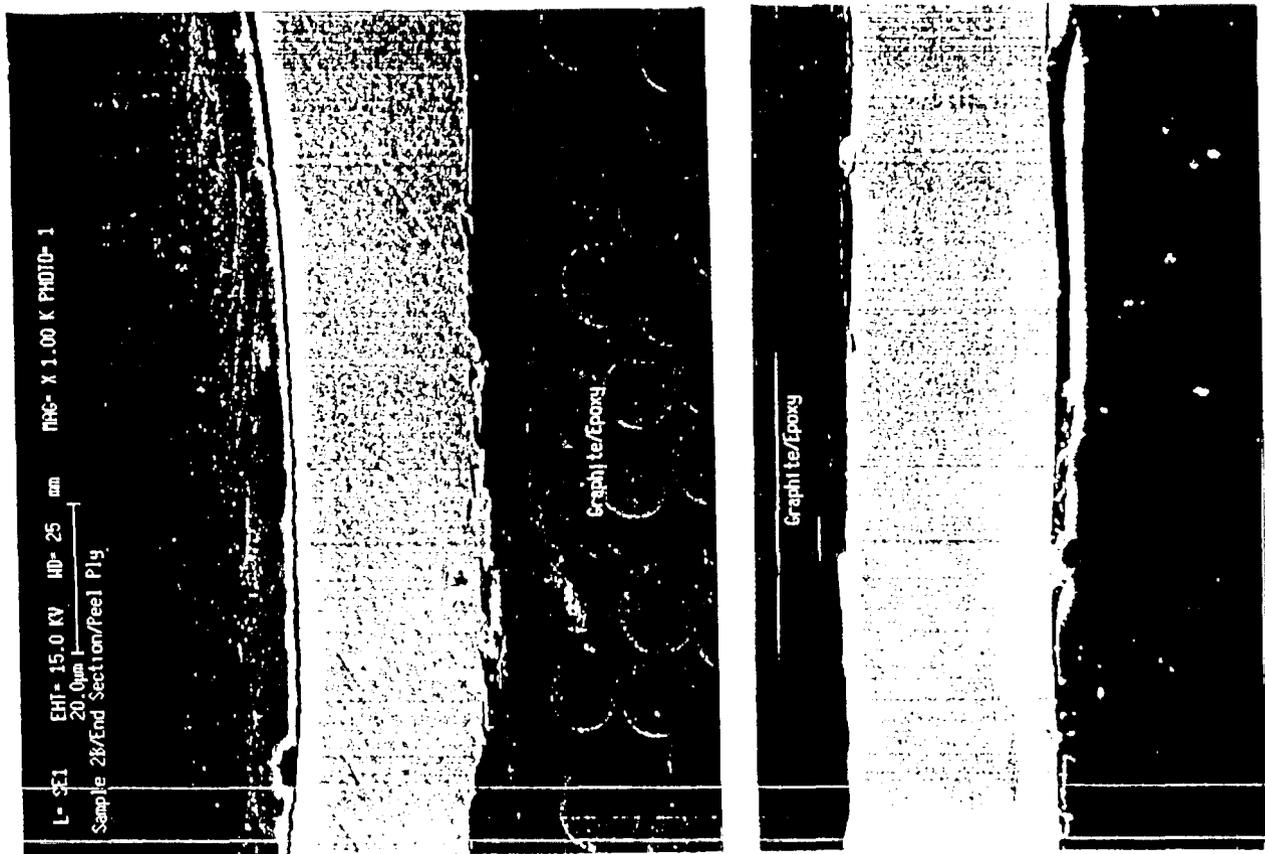


Figure 1. Cross section of a metallized graphite/epoxy plate that was used in Phase 1 of this study.

and thickness measurements to 500X revealed no porosity, cracking or other significant anomalies. See Figure 1 for two typical photographs of coating cross sections. However, up to 25% coating thickness variations in both Cu and Ni were noted from one side of a sample to the other.

Table 2 outlines the coating thicknesses. Average thickness values are based on the mean of three adjacent sections in each sample. In the table, the "left" side of each sample corresponds to the surface that was exposed to the caul plate during the curing process. As a result, the "left" side appears to have a smoother coating than the side which was exposed to peel ply. In addition, the average thickness of the metallic coating appears to be greater on the "left" side of each sample.

Also, following gravimetric measurements, three samples were thermally cycled 10 times between  $-120^{\circ}\text{C}$  and  $+120^{\circ}\text{C}$ . SE M was used up to 500X magnification to look for any evidence of surface cracking or other post cycling anomalies. No anomalies were discovered. Post-cycling adhesion tests indicated excellent adhesion remaining.

**2.3 Phase two - Large coupon gravimetric assessment** - Fourteen square plates 25 cm on a side by approximately 2 or 3 mm thick and three 6.25 cm diameter tubes 30 cm long with a wall thickness of 2 mm made of IM7/977-2 were used. See Figure 2. Tube layup was  $[28/0_3/-28/0_2]_s$  and was made using ply thicknesses of nominally 140 microns. Resin content was specified to be 35% by weight with a final nominal laminate fiber volume of 58%. One plate and one tube



Figure 2a. Photograph of one of the metallized IM7/977-2 tubes. The tubes are 30 cm long and 6.25 cm in diameter with a wall thickness of 2 mm.

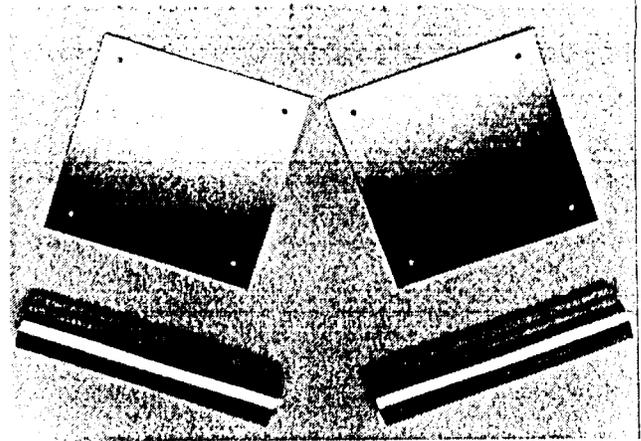


Figure 2b. Photograph of metallized IM7/977-2 plates and tubes. The plates are 25 cm by 25 cm by 2-3 mm and the tubes are 30 cm long by 6.25 cm in diameter with a wall thickness of 2 mm.

tube were maintained bare (the bare plate was 20.3 cm by 7.6 cm by 3mm thick). All other samples were metallized as was described in phase one materials (above). The 5 micron Ni thickness was utilized. Prior to metallization of the plates, four 0.7 cm diameter through holes were drilled near the four plate corners. Holes were used as both a test of the plating process as well as for hooking the samples.

The final weight measurements were made 2/2/93 after almost 13,000 hours of tracking moisture uptake and loss. Material property data for the tubes, based on the average of two laminates, is the result of acid digestion experiments performed to ASTM STD D3171 -A by Katema, Programmed Composites Inc. See Table 2.

**2.4 Phase three - Temporal dimensional stability - Four 2.5 cm diameter tubes 10 cm long with a wall thickness of about 2 mm were obtained. The tube layups were [0/+60/-60]s. Table 3 provides further information.**

### 3. EXPERIMENTAL - TESTS AND ENVIRONMENTS

Aluminum control samples were used in all phases of gravimetric measurements

**3.1 Phase zero and one - Outlined** below is the 147 hour environmental exposure schedule used for the thirty one Phase zero and Phase one samples:

From ambient room temperature conditions:

- 1) 24 hrs. in vacuum at 100°C
- 2) 72 hrs. in 100% relative humidity at room temperature
- 3) 30 hrs. in 80% relative humidity at room temperature
- 4) 21 hrs. in vacuum at 100°C
- 5) Phase zero samples were then exposed to an additional 146 hrs in vacuum at 100°C.

Weight measurements were at each point above. This schedule allowed us to compare directly with early GD Convair data on eutectic tin coatings.

**3.2 Phase two - Outlined** below is the 12,800 hour environmental exposure schedule used in Phase two large plate and tube testing:

From ambient room temperature conditions weight measurement were made after:

- 1) 380 hours, 10<sup>-6</sup> torr, 100 C
- 2) 120 hours, ambient pressure and temperature, 100% RH
- 3) 24 hours, ambient pressure and temperature, 80% RH
- 4) 40 hours, 10<sup>-6</sup> torr, 40 C
- 5) 2900 hours, ambient pressure and temperature, 100% RH
- 6) 9380 hours, ambient pressure, temperature and humidity (JPL office)

**3.3 Phase three - Length measurements were made daily over a 112 day time period in the University of Arizona's Dimensional Stability Lab** per established interferometric technology and procedures (Fiefs. 24 and 25). Prior to insertion into the interferometric thermal vacuum (0.13 Pascal) apparatus the samples were weighed, vacuum desiccated for nine days and reweighed to the nearest tenth of a mg. At the end of the 112 day testing the samples were weighed again.

Samples were initially held at 38 C +/- 0.02 C for 10 weeks of daily length measurements. Subsequently, the test chamber was reduced to 27.5 C +/- 0.02 C for 6 weeks of testing. Copper, Homosil (fused quartz) and Invar samples were being measured concurrently and served as reference samples. We evaluated and estimated system drift to be less than 0.04 PPM/month. We consider the dimensional strain data reported here in PPM/month to be accurate to better than +/- 0.04 PPM.

## 4. TEST RESULTS AND DISCUSSION

**4.1 Phase zero - Although the sample population was very small several factors emerged:**

- 1 ) the proprietary impregnation coating alone (no Cu or Ni electroplating) provided moisture uptake or loss retardations of only 10- 20% over uncoated samples,
- 2) the coated fine peel ply weave surface samples exhibited a high degree of moisture retardation during the 147 hour exposure schedule. Results on these two samples were encouraging enough for us to proceed to Phase one testing.
- 3) coated coarse peel ply surface samples exhibited little resistance to moisture

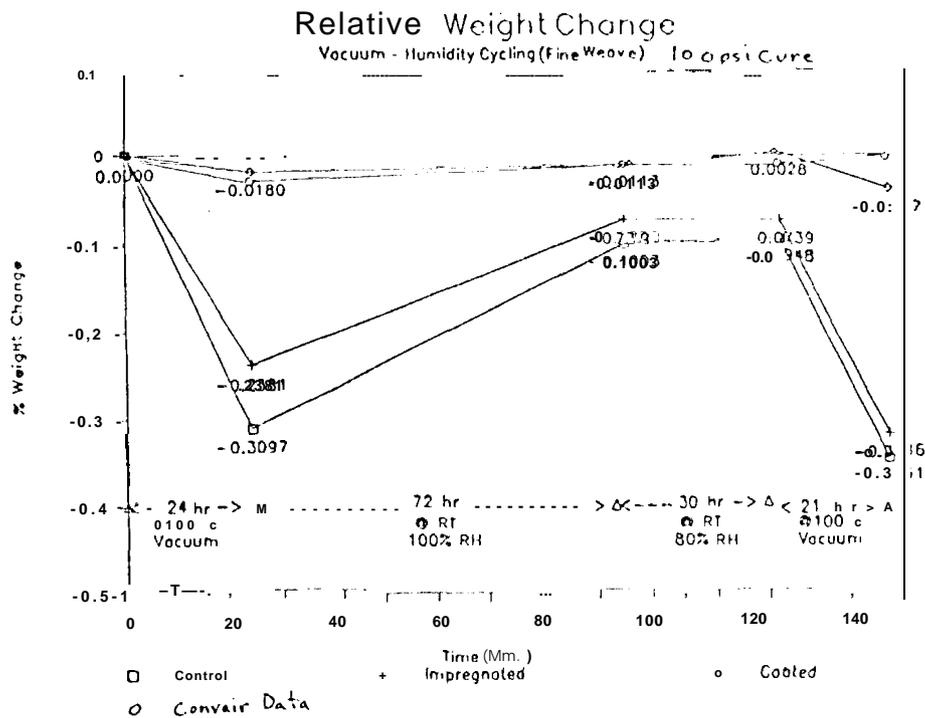


Figure 3. Relative Weight Change over time of a fine weave composite in several different environments.

ingress and egress,

4) Figure 3 curves are representative of the weight change for the three fine weave surface samples (bare or control, impregnated, and coated). Over one order of magnitude reduction in weight response is indicated by the coated sample versus the uncoated. Results comparable to eutectic tin coatings is also observed.

**4.2 Phase one - With considerably** more samples and three lots to consider several factors became apparent:

- 1) The average weight loss of lot three coated material (1 .03 MPa or 150 psi platen pressure) bettered a) the best results obtained in Phase zero testing and b) early GD Convair data on eutectic tin coated graphite/epoxy.
- 2) Figure 4 illustrates the response of the three lots of bare samples versus the coated lot three material. **A** thirty to sixty fold retardation in moisture (weight) changes is noted.
- 3) Even the worst performing coating (lot *one*) provided about a factor of four retardation over bare. The comparative weight changes of the three lots of materials and a Old GD Convair curve are shown in Figure 5.
- 4) In step 2 of the schedule, the samples were exposed to 100 % relative humidity at room temperature for 72 hrs. The uncoated samples showed weight gain at equivalent linear rates of 0.0043 %/hr. for Lot 1, 0.0055 %/hr. for Lot 2, and 0.0047 %/hr. for Lot 3. The coated samples, however showed significantly lower absorption rates such as 0.0004 %/hr. for Lot 1, 0.0002 %/hr. for Lot 2, and 0.0001 %/hr. for Lot 3.
- 3) Scatter in data was relatively high. For example, the standard deviations for the four lot three coated sample data points (see Figure 5) was 0.0056, 0.0043, 0.0043, and 0.0114 % weight change, respectively.

**As** with Phase zero results we were encouraged with some of the Phase one results. We decided to increase both sample size and complexity as we moved into Phase two.

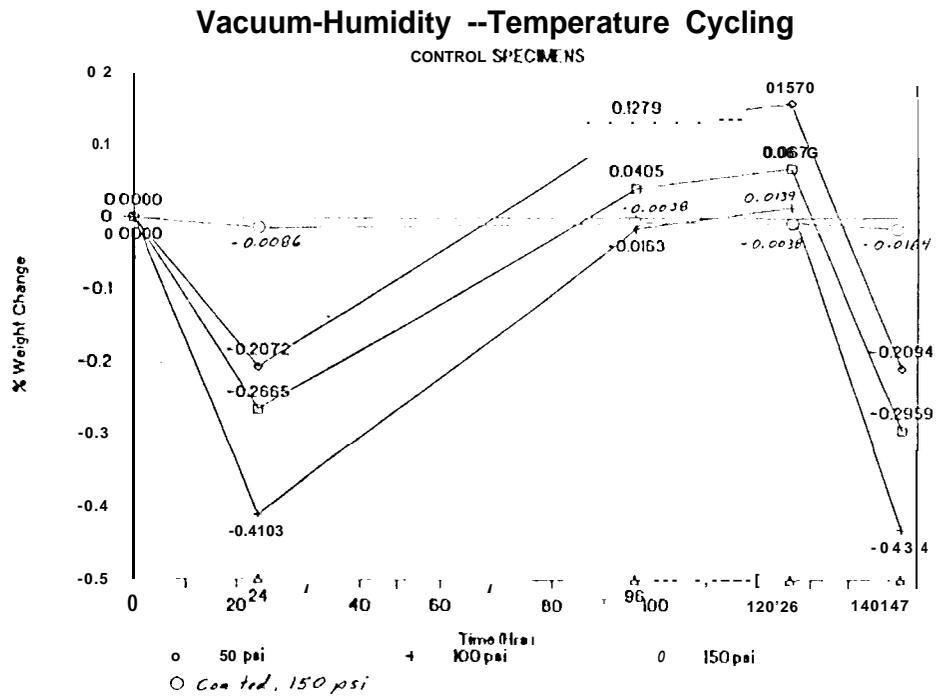


Figure 4. Percent Weight Change vs Time of the uncoated specimens, Phase 1.

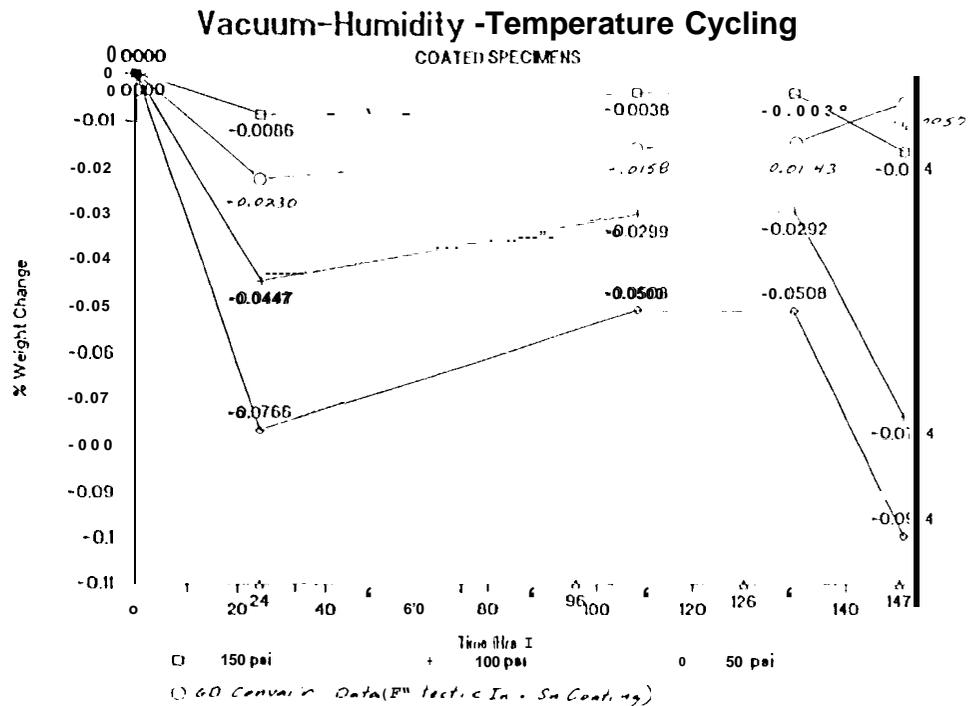


Figure 5. Percent Weight Change vs Time of the coated specimens, Phase 1.

4.3 Phase two - Gravimetric results are summarized in Figures 6, 7, and 8. Duplicate weight readings were always taken at scheduled measurement time. The three graphs in Figures 6 and 7 depict different time scales. The top graph covers the first 575 hours of scheduled exposure, while the middle and bottom extend the time scales out to 3500 and 12,800 hours, respectively. Please note that the environmental exposure for Phase two is different than previously discussed gravimetric test results.

Based on the percentage weight change, an absorption rate for each exposure cycle was calculated and they are listed in Table 4. Rates are in units of % wt. change per hour.

Some general comments:

- 1 ) The short term (hours) retardation effect is not as strong for the large tubes and plates in phase two as compared to the small coupons in phases zero and one. For example, a nominal retardation of about three times reduction in weight change is noted for the large tubes/plates.
- 2) The long term integrity and retardation effect from the coating appears high. Note the high degree of stability in weight for both tubes and plates after the initial 0-600 hour environment schedule. The coated samples are within 0.05% of their starting weights at 3500 hours while the uncoated samples are approaching a C 5% weight change from their starting condition.
- 3) One of the tubes developed a delamination of the coating on an inside diameter and exhibited lower retardation than the undelamed tube.
- 4) Except for the one tube noted above, adhesion of coatings on all other samples remained strong throughout the testing schedule.
- 5) An aluminum control sample weight values is included in Figure 8 for reference purposes.

4.4 **Phase three** - Notes on the two coated tubes weight study:

<u>Date</u>	<u>s/n 001</u>	<u>s/n 003</u>	<u>note</u>
3/3/92	18.75964 grns	20.44308 gins,	initial weights
3/1 2/92	18.75958	20.44308	after 9 days in vacuum desiccator
9/16/92	18.75955	20.44316	after 6 months in 0.13 Pascal vacuum

Extremely small changes in weight values are noted.

Figures 9-11 illustrate preliminary temporal dimensional strain data over a 112 day period. Samples were measured daily over a 10 week period at 38C and subsequently 27.5 C for 6 weeks. Nominal stability of the cyanate ester and epoxy matrix P75 fiber coated tubes was 2 PPM/month. The two P75/PEEK (uni and 0/90) samples exhibited nominally -0.5 to + 1 PPM/month temporal strain.

Two mechanisms that may be involved in the ester and epoxy temporal data are

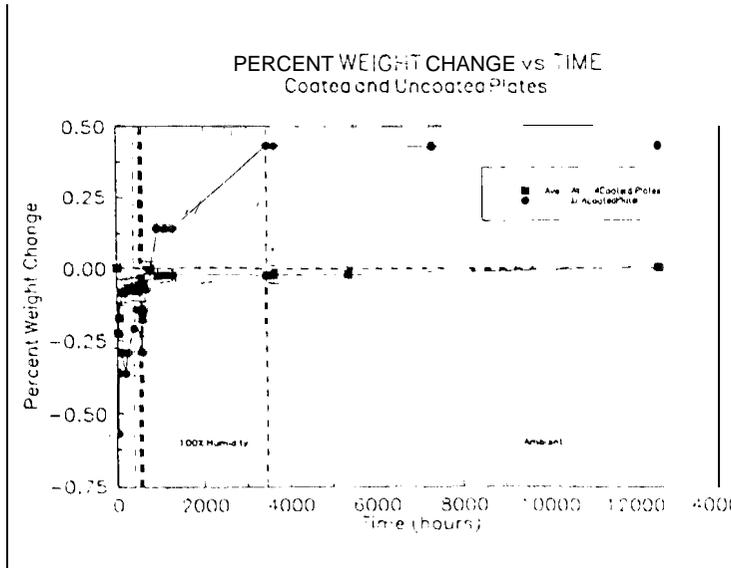
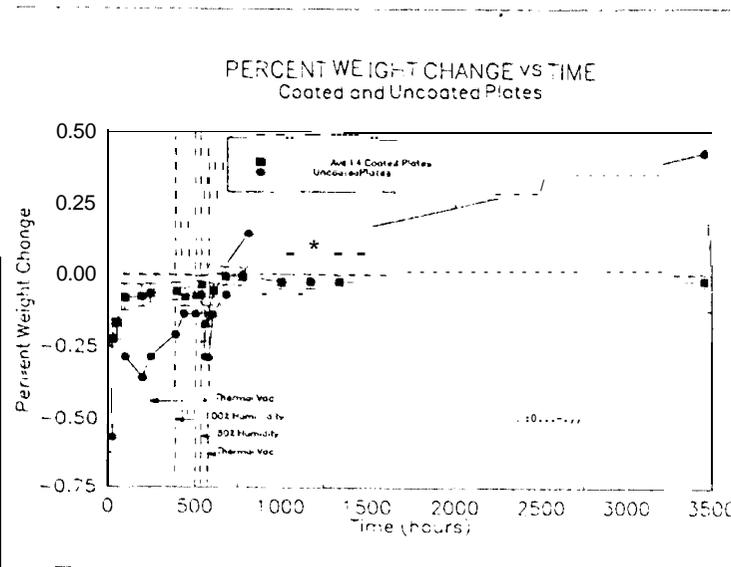
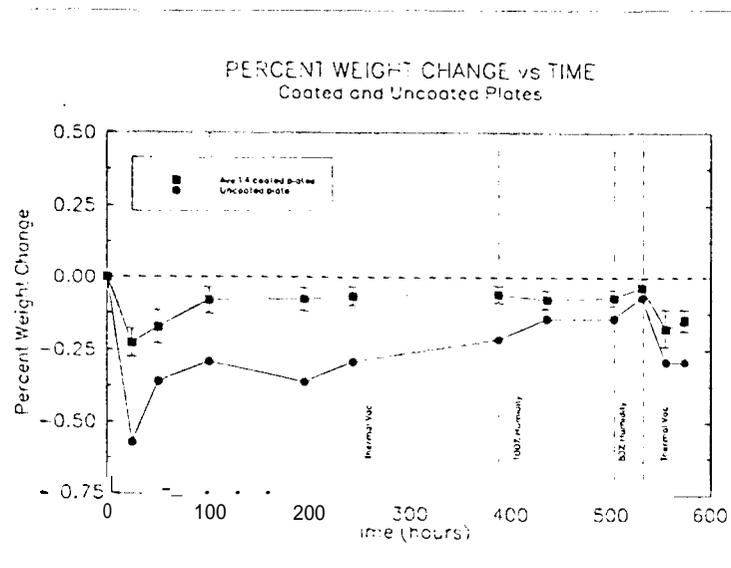


Figure 6. Percent Weight Change vs Time of the coated and uncoated plates, Phase 2.

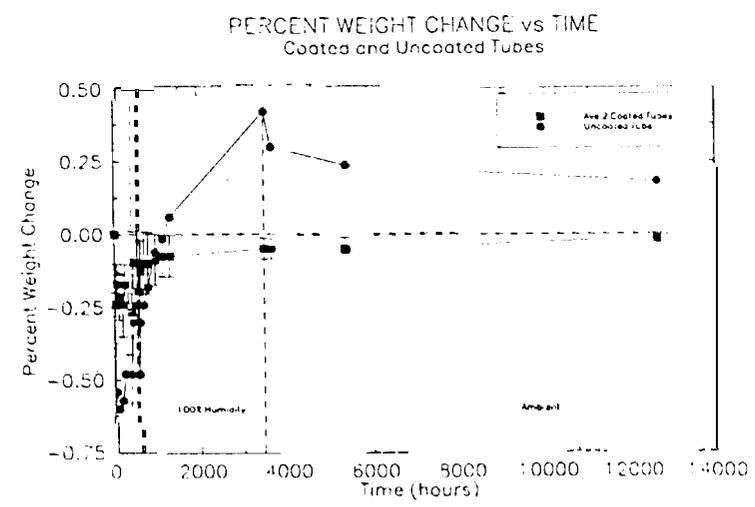
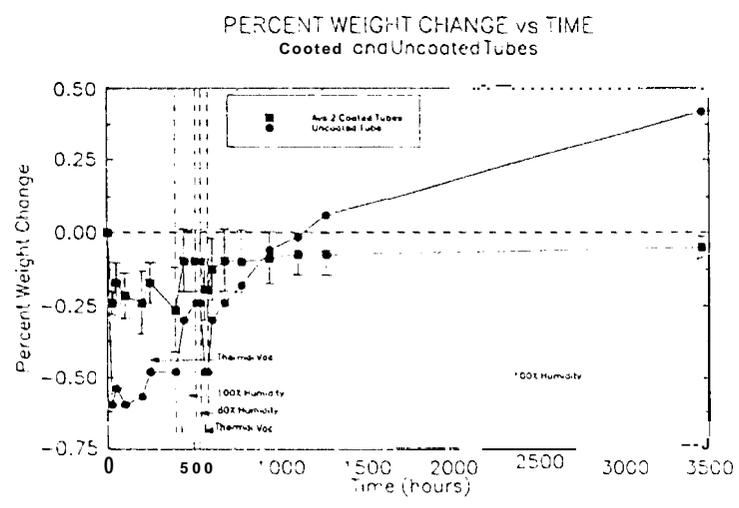
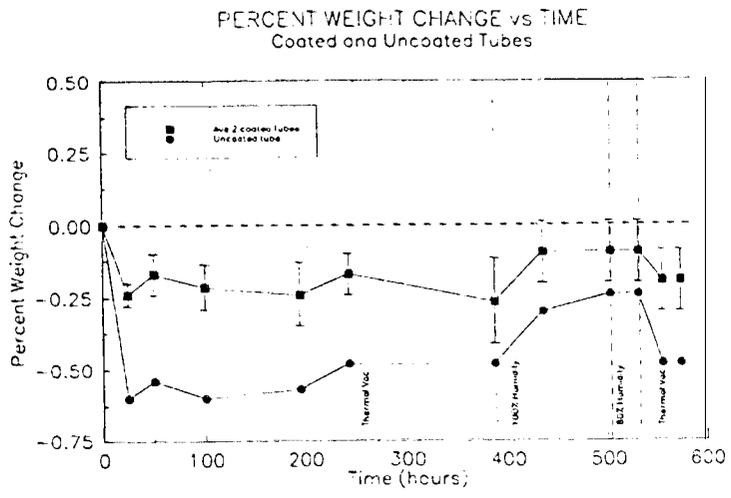


Figure 7. Percent Weight Change vs Time of coated and uncoated tubes, Phase 2.

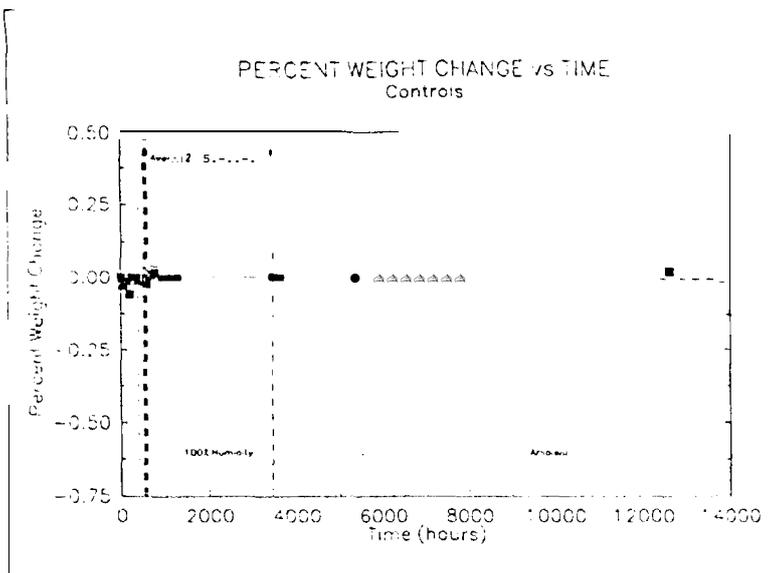


Figure 8. Percent Weight Change vs Time for aluminum control plates used in Phase 2.

thermal relaxation of the fiber/matrix interface or residual strain in the coatings.

**4.5 General - Qualitative assessment of moisture stability can be judged with an assumption of a coefficient of moisture expansion.** For psuedoisotropic P75/epoxy systems a nominal value of 1 PPM/0.01% moisture is considered. Total strain at saturation would be approximately 130 PPM. Based on these assumptions an approximate one order of magnitude reduction in strain can be realized with the type of electroplated coatings studied here. However, future applications may demand at least a two order of magnitude reduction in total strain, down to less than 2 PPM/year.

## 5. SUMMARY

Significant moisture retardation effects were demonstrated for several different types of Cu/Ni electroplated high modulus graphite fiber/epoxies. Over one order magnitude reductions in absorption/desorption were realized in several cases. In addition, unique, highly accurate temporal strain data was obtained. A reduction factor of about six over bare graphite/epoxy was exhibited for these temporal properties. Further progress is likely. Plans for additional testing are underway.

Neither the metrology nor the technology of dimensionally stable materials has been developed to the level required for future NASA missions. JPL advocates a research program in dimensional stability the main goals of which are: to develop a metrological technique capable of noncontact measurement of multi axial dimensional changes down to the nanometer level; to investigate causes for the instability of materials from the micron level down to the nanometer level; to characterize the stability of selected classes of materials; to understand the physical and chemical mechanisms of their instability; and to design and demonstrate dimensionally stable materials and components.

## 6. ACKNOWLEDGEMENTS

The testing and moral support from Professor Steve Jacobs and Dan Bass, University of Arizona is recognized. Material sample evaluation efforts were supported by Paul Jacoy and B. Blakkolb with valued oversight from Dan Coulter,

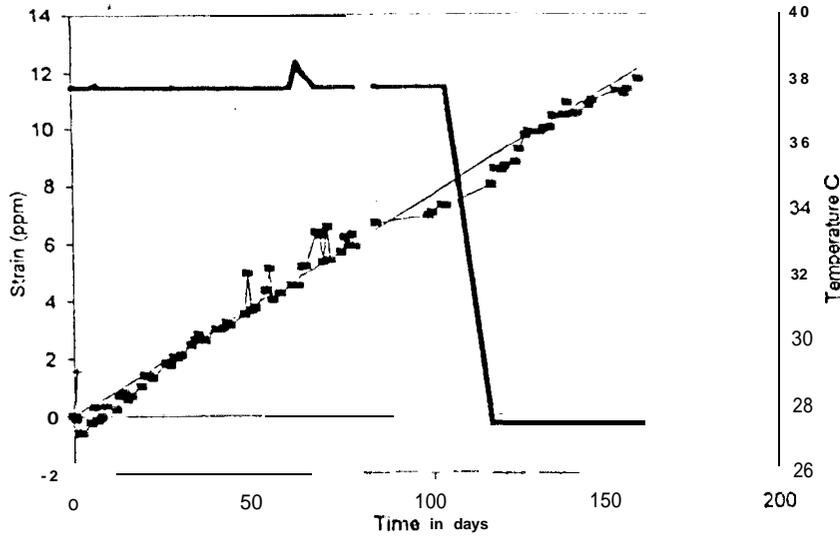


Figure 9. Strain vs Time for uncoated graphite epoxy tube.

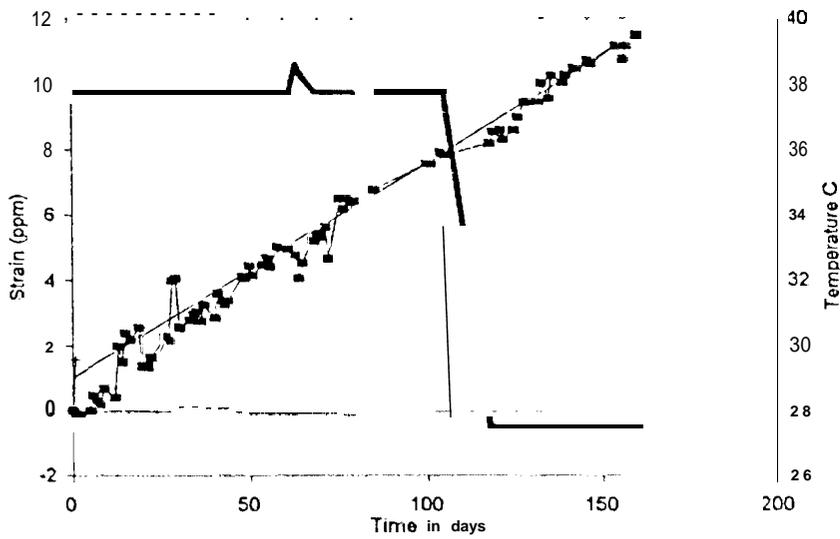


Figure 10. Strain vs Time for coated graphite epoxy tube.

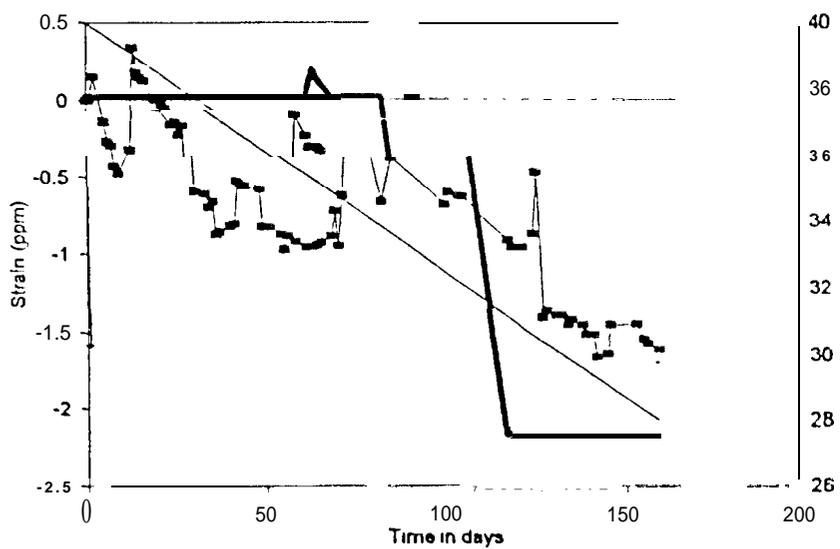


Figure 11. Strain vs Time for PEEK UN I tube.

all of JPL. Sample inputs from Katema PCI, Ed Orlowski, Dave Kwan and Don Guichard is gratefully acknowledged. Finally, last minute help from Patricia Hayes-Howe and Lisa Mchugh was very valuable.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

## 7'. REFERENCES

1. JPL Report D-9140, B. Dolgin, Assessment of Dimensional Stability Technology for Future NASA Missions, January 1992.
2. T. A. Facey, N. A. De Filippis, and P. J. Young, "Moisture Loss from Graphite Structures for the Hubble Space Telescope," AIAA Proc., 13-17, No. 85-6057 (1985).
3. T. Facey, M. Krim, C. Ftacfas, L Cermoch, G. Ruthven, R. Stoll, "On-Orbit Performance of the HST Optical Telescope Assembly, Proceedings of the "Space Optics for Astrophysics and Earth and Planetary Remote Sensing Topical Meeting, p.3-5, Williamsburg, Virginia, 1991.
4. Hertz, J., "Moisture Effects on Spacecraft Structures," The Enigma of the Eighties: Environment, Economics, Energy, SAMPE Volume 24, Book 2.
5. Walrath, D. E., and Adams, D. F., "Moisture Absorption Analysis of the Thematic Mapper Graphite/Epoxy Composite Structure," Modern Developments in composite Materials and Structure, ASME Winter Meeting, December, 1979.
6. E. G. Wolff, "Dimensional Stability of Carbon Fiber Reinforced Plastic Tubes," 29th National SAMPE Symposium, April 3-5, 1984, Reno, NV.
7. L. L. McMahan, "Space Telescope Optical Telescope Assembly Structural Materials Characterization," AIAA Proc., 127-136, (1 982)
8. D. J. Levy and C.R. Arnold, "Metal Moisture Barriers for Composites," 29th National SAMPE Symposium, April 3-5, 1984
9. E. G. Wolff, "Moisture and Viscoelastic Effects on the Dimensional Stability of Composites," 16th Northern California SAMPE Workshop, January 26, 1990.
10. E. G. Wolff, "Moisture and Viscoelastic Effects on the Dimensional Stability of Polymer Composites," SPIE 1990 Intl. Symp. on Optical and Optoelectronic Applications, San Diego, Ca, 1990.
11. A. R. Telcamp and E. A. Derby, "Design Considerations for Composite Materials Used in the Mars Observer Camera," SPIE Proceedings Advances in Optical Structural Systems, Vol. 1330, April 1990, Orlando, FL.
12. C. Blair and J. Zakreewski, "Coefficient of Thermal and Moisture Expansions

and Moisture Absorption for Dimensionally Stable Quasi-Isotropic High Modulus Graphite/Epoxy Composites," SPIE Proceedings, Advances in Optical Structural Systems, Vol. 1303, April 1990, Orlando, FL.

13. B. P. Dolgin, J. Moacanin, and T. O'Donnell, "Theoretical Limits of Dimensional Stability for Space Structures," Proc.SPIE, 1533, 229-239, (1991)
14. C. Hsieh, and T. P. O'Donnell, "Characterization of the Dimensional Stability of Advanced Metallic Materials using an Optical Test Bench Structure," Proc. SPIE, 1533, 240-251, (1991)
15. R. C. Tennyson, G.E.Mabson, W.D. Morison, and J. Kleiman, "LDEF Mission Update: Composites in Space", Advanced Materials and Processes, 33-36, May 91
16. G. C. Krumweide and R. A. Brand, "Attacking Dimensional Instability Problems in Graphite/Epoxy Structures, " SPIE, San Diego, 1992?
17. G. C. Krumweide, E. A. Derby and D. N. Chamberlain, "The Performance of Effective Moisture Barriers for Graphite/Epoxy Instrument Structure," Proc. of the international SAMPE Conference Series, v. 21, 614-625, September 1989
18. D. E. Bowles and D. R. Tenney, "Composite Tubes for the Space Station Truss Structure, SAMPE Journal, Vol. 23, No. 3, May - June 1987.
19. D. R. Tenney and D. E. Bowles, "Space Radiation Effects on Dimensional Stability of Composites", 4th International Space Environment Conference, 1988
20. C. T. Herakovich, D. J. Fox and G. F. Sykes, "Degradation of Graphite/Epoxy Due to Electron Radiation," ASME Transactions, Vol. 110, Apr. 1988, pp. 146-152.
- 21 S. S. Tompkins, "Thermal Expansion of Selected Graphite Reinforced Polyimide- Epoxy-, and Glass-Matrix Composites, International Journal of Thermophysical Properties, Vol. 8. No. 1, Jan. 1987, pp. 119-132.
22. JPL Report D-9920, B. Dolgin and S. W. Sirlin, "Tradeoffs of Passive and Active Means of Achieving Dimensional Stability", July, 1992.
23. JPL Report D-7667 (Revised), D. Rapp, "The Dimensional Stability of Materials", October 1990.
24. S. F. Jacobs, J. N. Bradford, and J. W. Berthold, "Ultraprecise Measurement of Thermal Coefficients of Expansion" Appl. Opt. 9, 2477 (1 970).
25. J. W. Berthold III and S. F. Jacobs, "Ultraprecise Thermal Expansion Measurements of Seven Low Expansion Materials," Appl. Optics, 15, No. 10, 2344 (1976).

Table I. Material data for control samples (Phase one).

Lot	Press. (psi)	F-V-F	% Resin	% Porosity	Density (g/cm <sup>3</sup> )
1	50	49.54	35.23	7.36	1.5905
2	100	48.02	34.96	10.71	1.5350
		47.1-7	35.64	11.05	1.5235
3	150	51.74	32.76	7.94	1.6005

Table 2. Average coating thickness of Phase one samples in inches.

Sample	Cu (left)	Ni(left)	Cu (right)	Ni(right)
1a	0.00057	0.00017	0.00068	0.00017
1c	0.00065	0.00016	0.00040	0.00011
1f	0.00085	0.00021	0.00062	0.00018
2b	0.00085	0.00017	0.00074	0.00017
2e	0.00085	0.00023	0.00068	0.00017
2f	0.00091	0.00023	0.00074	0.00023
3a	0.00074	0.00014	0.00051	0.00014
3b	0.00062	0.00011	0.00068	0.00014
3c	<b>0.00062</b>	0.00009	0.00068	0.00009

Table 3. Phase 3 Composite Tubes

SIN	MATERIAL	WEIGHT, gm (before coating)	WEIGHT, gm (after coating)	N C ) MINAI			
				FV%	VC%	Cu/Ni thk	
001	2054-3D	10.06	18.76	-	60	3	25/5
002	2054-3D	9.99	N/A		60	3	N/A
003	IM7/977-2	11.94	20.44		74	1.5	25/5
004	IM7/977-2	11.9	N/A		74	1.5	N/A

FV - Fiber Volume

VC - Void Content by volume

thk - thickness in microns

Table 4. Comparison of Absorption Rates of Phase One Samples

a) Control samples

Lot	Press. (psi)	Rate 1	Rate 2	Rate 3	Rate 4
1	50	-0.0111	0.0043	0.0009	-0.0173
2	100	-0.0171	0.0055	0.0010	-0.0212
3	150	-0.0086	0.0047	0.0010	-0.0174

b) Coated samples

Lot	Press. (psi)	Rate 1	Rate 2	Rate 3	Rate 4
1	50	-0.0032	0.0004	0	-0.0023
2	100	-0.0019	0.0002	9.7e-6	-0.0021
3	150	-0.0004	0.0001	0	-0.0006