COLUMBIA

ACCIDENT INVESTIGATION BOARD

Note: Volumes II – VI contain a number of conclusions and recommendations, several of which were adopted by the Board in Volume I. The other conclusions and recommendations drawn in Volumes II – VI do not necessarily reflect the opinion of the Board, but are included for the record. When there is conflict, Volume I takes precedence.

REPORT VOLUME IV
OCTOBER 2003

On the Front Cover

This was the crew patch for STS-107. The central element of the patch was the microgravity symbol, µg, flowing into the rays of the Astronaut symbol. The orbital inclination was portrayed by the 39-degree angle of the Earth's horizon to the Astronaut symbol. The sunrise was representative of the numerous science experiments that were the dawn of a new era for continued microgravity research on the International Space Station and beyond. The breadth of science conducted on this mission had widespread benefits to life on Earth and the continued exploration of space, illustrated by the Earth and stars. The constellation Columba (the dove) was chosen to symbolize peace on Earth and the Space Shuttle Columbia. In addition, the seven stars represent the STS-107 crew members, as well as honoring the original Mercury 7 astronauts who paved the way to make research in space possible. The Israeli flag represented the first person from that country to fly on the Space Shuttle.

On the Back Cover

This emblem memorializes the three U.S. human space flight accidents – Apollo 1, Challenger, and Columbia. The words across the top translate to: "To The Stars, Despite Adversity – Always Explore"

The Board would like to acknowledge the hard work and effort of the following individuals in the production of Volumes II – VI.

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Chapter 2	*Columbia*'s Final Flight
Chapter 3	Accident Analysis
Chapter 4	Other Factors Considered
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Chapter 5	From *Challenger* to *Columbia*
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Reader's Guide to Volume IV

Volume III of the Report contains appendices that were not cited in Volume I. These consist of documents produced by NASA and other organizations, which were provided to the Columbia Accident Investigation Board in support of its inquiry into the February 1, 2003 destruction of the Space Shuttle *Columbia*. The documents are compiled in this volume in the interest of establishing a complete record, but they do not necessarily represent the views of the Board. Volume I contains the Board's findings, analysis, and recommendations. The documents in Volume III through V are also contained in their original color format on the DVD disc in the back of Volume II.

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Volume IV
Appendix F.1
Water Absorption by Foam

The CAIB requested these data be included in this Appendix. This Appendix is a summary of present and past efforts that were initiated to characterize the moisture absorption capability of sprayed-on-foam-insulation (SOFI) and specifically, BX-250.

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Preliminary Evaluation of Water vapor transmission and Liquid Water Absorption in ET Foam Samples

Leon R. Glicksman
June 1, 2003

I have examined the report of May 15 on water vapor transmission testing of BX 250 foam by Jeff Kolodziejczak and the report by Palmer Peters on water absorption by external tank foam. Although I have corresponded with both of them, because of my academic schedule I have been unable to visit the Marshall Center. I hope to do that in the next few weeks so that I can gain further insight into the details of their work and allow me to submit a final report.

The tests described in the reports appear to yield the property data that was initially requested by the Board. The test results of both water vapor permeability and liquid water absorption of polyurethane foams agree with previous tests reported in the literature as well as personal communications I have with people in industry and government labs knowledgeable about foams.

The test results by Palmer Peters raises some intriguing questions about the possibility of liquid water penetrating through wormholes or in knit lines that extend from the surface to the interior of the foam. If this is substantiated, it could represent a mechanism by which liquid water is trapped near the surface and is subsequently vaporized to initiate a crack in the foam. I would suggest further tests to investigate this possibility. Other means of detecting water within the foam sample should be explored.

The role of long voids within the foam needs to be examined in terms of permeability enhancement and possible sites for water accumulation.
Tests should also be undertaken to determine water vapor permeation and liquid or solid water accumulation within the foam when a substantial temperature gradient exists through the foam.

Although the test results raise the possibility of water ingress into the foam and subsequent vaporization and possible crack formation, the amount of water would not cause a substantial increase in the foam density by water or ice formation.

The test results need to be integrated into a mechanistic, quantitative model of possible failure modes to determine if any are possible.

Leon R. Glicksman
Consultant

Summary of Water Absorption Data of BX-250 to Address CAIB Action B1-00194

Scotty Sparks/NASA/MSFC/ED34
27 May 2003

The following is a summary of present and past efforts that were initiated to characterize the moisture absorption capability of sprayed-on-foam-insulation (SOFI) and, specifically, BX-250. Recent efforts to characterize moisture absorption were conducted by Drs. Palmer Peters/NASA-MSFC and Jeff Kolodziejczak/NASA-MSFC. Peters investigated the ability of foam to absorb liquid water and Kolodziejczak characterized the water vapor transmissibility of foam. Their work enjoyed the oversight of Dr. Leon Glicksman/MIT who helped coordinate test plans, review data, and offer expert analysis of the data. Other efforts, which include accelerated moisture absorption and on-pad rainfall significance, are two different sets of data that lend understanding to the moisture-to-foam relationship.

The Columbia Accident Investigation Board (CAIB) initiated the following request (CAIB Action B1-00194) to compile data to support their investigation:

> *"Request that MSFC: 1) plan and conduct moisture absorption testing on foam exposed to low (less than 100 °F) ambient temperatures, 2) use Prof. Leon Glicksman of MIT as an outside expert for planning tests and analyzing the results, and 3) report results obtained from these tests and from previous moisture absorption tests to the CAIB."*

Moisture Absorption (Peters, Kolodziejczak, Sharpe)

- Liquid Phase Absorption
    - Date: May 2003
    - Test Conductor: Dr. Palmer Peters/MSFC
    - Scope: To characterize the moisture absorption of BX-250 via submersion in dyed liquid water
    - Procedure:
        - NCFI 24-124 and BX-250 as two small, 1-inch-cube specimens referred to as Foam1 (NCFI 24-124) and Foam 2 (BX-250). Water-mass gain was measured when these specimens were submerged 2 ½ inches below distilled, de-aired water surfaces for 3,765 minutes. See Figure 1.
    - Conclusions:
        - "Water absorbed by submersion can be accounted for primarily by liquid in open surface cells resulting from machining or removing the outer skin, or rind."
        - "… indicate limited penetration of water into submerged foam surfaces. This agrees with prior reported studies and expert opinions, which indicate most absorption occurs through water vapor permeating foam having a temperature gradient"
            - Sectioning of foam after submersion indicated only absorption in thin layer around the machined foam. This layer characterized to be less than or equivalent to broken cells on surface. See Figure 2.
        - "The amount of increased mass from submersion is equivalent to a thickness of water comparable to the cell dimensions, as shown in Table 1, suggesting that damaged (open) cells at the surface and surface connected voids absorb most, if not all, of the water."
    - Reference:
        - Investigation of Water Absorption by External-Tank-Types of Foam, Palmer N. Peters, SD46, Marshall Space Flight Center, May 2003.
- Vapor Phase Transmission
    - Date: May 2003
    - Test Conductor: Dr. Jeff Kolodziejczak/MSFC

- Scope: These tests are specifically designed to study the transmission of water vapor through BX-250 foam in the context of evaluation of the probability of external tank foam loss scenarios and determination of foam debris properties as they relate to the Columbia Accident Investigation.
- Conclusions:
  - All specimens exhibited water vapor transmission at a level consistent published polyurethane foam values, for example a web summary of BASF Walltite foam quotes values from 30 to 125 ng/Pa-s-m^2 as typical for tests of 25mm thick commercial foam samples. See Figure 3.
    - This level of transmission deemed to be insignificant in terms of producing detrimental effects *(still pending concurrence from additional experts-ss)*
      - Low level of moisture absorption
      - Limited time (from tanking to launch) with imposed thermal gradient
  - All of the permeability values are within ±25% of the mean. Local effects in the test chamber, differences among the test specimens and differences among the test dishes may contribute uncertainty to the values at the 25% level.
- Reference: Procedure for Testing Water Vapor Transmission of BX-250 Foam Under Thermal and Pressure Gradient Conditions, Jeff Kolodziejczak, Marshall Space Flight Center, May 2003.

- Accelerated Moisture Conditioning
  - Date: April 2003
  - Test Conductor: Jon Sharpe/LMC
  - Scope: Observe accelerated moisture absorption characteristics of BX-250 that was soon to undergo testing to support the investigation and corrective action for IFA-87.

    Variables such as conditions (120 °F/93% RH and 32 °F/76% RH), cure state (freshly sprayed vs. two-week cured), and surface preparation (rind vs. machined) were included in the testing.
  - Conclusions:
    - Data confounded by the measurement of combined mass of aluminum substrate and foam
    - Approximately no absorption observed in 32 °F/76% RH conditioning for both just-sprayed and two-week cured materials. See Figure 4.
    - Just-sprayed material arrived to maximum moisture absorption in 48 hours in 120 °F/93% RH conditioning. See Figure 5.
    - Two-week cured material absorbed very little moisture at 120 °F/93% RH conditioning
  - Reference: Lockheed-Martin Job Order 9266 – BX-250 Moisture Absorption

<u>On-Pad Rainfall Significance (Bourgeois)</u>

- Date: April 1999
- Test Conductor: Chris Bourgeois/LMC
- Scope: Analyze the correlation of on-pad rainfall to orbiter hit count to support investigation and corrective action of IFA-87.
- Conclusions:
  - Limited positive correlation between KSC Prelaunch Dew Point and Bipod foam loss from STS-108 to STS-107 (7 flights spanning 12/01 to 1/03). See Table 2.
  - Limited absence of correlation between on-pad rainfall and orbiter lower-surface tile damage (>1") from STS-86 to STS-96 (8 flights spanning 9/97 to 5/99). See Figure 6.
- Reference:
  - "ET Weather Report 11", Jeff Kolodziejczak, February 2003.
  - "KSC ET Exposure Environments", Chris Bourgeois, April 1999.

- "KSC Environments vs. Orbiter Damage", Chris Bourgeois, April 1999.
- "KSC Rainfall Data vs. Orbiter Damage", Chris Bourgeois, April 1999.

Peters sums up well in his report data compiled to the present, "Water absorbed by submersion can be accounted for primarily by liquid in open surface cells resulting from machining or removing the outer skin, or rind….This agrees with prior reported studies and expert opinions, which indicate most absorption occurs through water vapor permeating foam having a temperature gradient". Furthermore, moisture absorption per vapor transmission under a temperature gradient was shown not to be significant due to the low permeability of the SOFI.

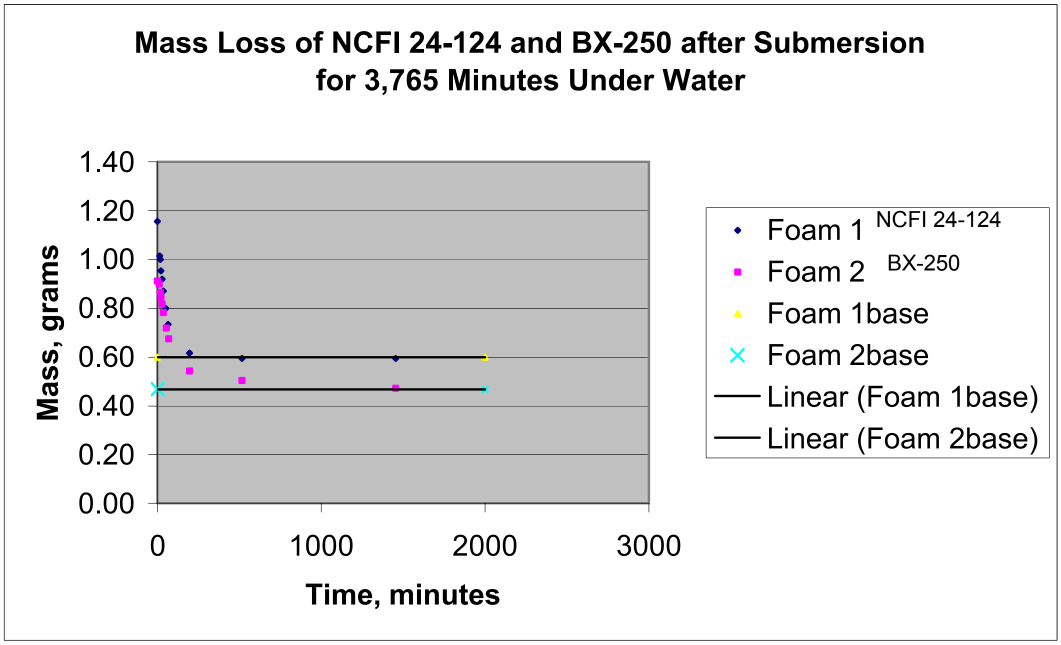

Figure 1. Plot of mass changes for NCFI 24-124 and BX-250 following submersion under 2.5 inches of distilled water for 3,765 minutes and blotting excess surface water before starting measurements.

Figure 2. (a) Shows blue dye decorating the surface of a BX-250 foam cube that was submerged 26.5 hours then sectioned, revealing the interior. (b) Shows a magnified image at the sectioned surface.

Table 1: Measured Water Absorption/De-Sorption Characteristics by Submersion.

Specimen	Size, cm	Initial Mass, g	*Submersion Data	+Mass After Submersion, g	++H_2O Liquid thickness, µm	Initial Evaporation Rate, mg/min	Comments
Foam 1, the only NSFI 24-124	2.54 cube	0.5990 ambient	6 cm; 21° C 62.8 hrs.	1.1560 increase=93%	143 (cell=80)	Not established	Lacking rapid, initial data
Foam 2, BX-250	2.54 cube	0.4673 ambient	6cm; 21° C 62.8 hrs.	0.9110 increase=95%	115 (cell~150)	Inaccurate; late aver. ~2.7	Late start
04/30/03 BX-250	2.86 aver, cube	0.8655 ambient	5 cm, 21° C 26.5 hrs. in blue dye	Shook instead of blotted, est. = 1.80	191 with dye error (cell ~150)	>3	Shaking left little excess puddle
05/07/03-1 BX-250	2.51 aver, cube	0.5204 ambient	5 cm; 21° C 21 hrs.	Not measured to speed up first IR image	Not determined	Not determined	IR image priority
05/07/03-2 BX-250	2.78 x2.54 x2.94	0.7710 ambient	5 cm; 21° C 20.8 hrs	Not measured to speed up IR image	Not determined	Not determined	IR image priority
05/08/03-1 BX-250	2.64 x2.7 x2.74	0.6412 baked @ 50° C	5 cm; 0.1° C 113 hrs. in blue dye	1.1516 increase=80%	117 with dye error (cell~150)	3.85 aver, 1st 10 min.	Blotted, weighed, IR imaged
05/08/03-2 BX-250	2.6 x2.65 x2.7	0.5985 baked @ 50° C	5 cm; 0.1° C 113 hrs	1.0937 increase=83%	118 (cell~150)	6.4 aver, 1st 26 min.	Blotted, weighed, repeatedly imaged, weighed
05/10/03-1 BX-250	2.60 x2.48 x2.60	0.5631 baked @ 50° C	5 cm; 52° C 148.8 hrs.	1.2258 increase=118%	168 (cell~150)	6.0	Blotted, Interior rind dark in image
05/10/03-2 BX-250	2.57 x2.70 x2.39	0.5855 baked @ 50° C	5 cm; 52° C 148.6 hrs. in blue dye	1.1543 increase=97%	146 (cell~150)	6.0	Blotted, Interior rind dark in image

Summary of Results

Specimen	Dimensions	Specific Gravity	ΔT	ΔP H20	Transmission g/hr-m^2	Permeance ng/s-Pa-m^2	Permeability ng/s-Pa-m
#1 (rind)	4"x4"x0.9"	0.03687	38°C	9 kPa	3.32	102.82	2.35
#2 (knit line)	4"x4"x1.0"	0.02975	38°C	9 kPa	2.44	75.51	1.92
#3 (bulk)	4"x4"x0.6"	0.0286	38°C	9 kPa	3.07	95.04	1.45

Discussion

- All specimens exhibited water vapor transmission at a level consistent published polyurethane foam values, for example a web summary of BASF Walltite foam quotes values from 30 to 125 ng/Pa-s-m^2 as typical for tests of 25mm thick commercial foam samples.

- The relative values did not exhibit expected behavior. The sample with rind exhibited the highest rate of transmission, while the purely bulk sample (no knit-line, no rind) exhibited the lowest permeability. The results do not correlate with density either.

- The specimens vary in the number of large elongated voids in the bulk material. These voids have diameters from 10 to 40 mil and extend in depth along the direction of rise as much as 0.5 inches.

- An unmodeled parameter such as the number and depth of large elongated voids may be a dominate permeability factor. So far, no attempt to characterize these voids has been made in this test set.

- All of the permeability values are within ±25% of the mean. Local effects in the test chamber, differences among the test specimens and differences among the test dishes may contribute uncertainty to the values at the 25% level.

Figure 3. Summary for "Procedure for Testing Water Vapor Transmission of BX-250 Foam Under Thermal and Pressure Gradient Conditions"

DRAFT

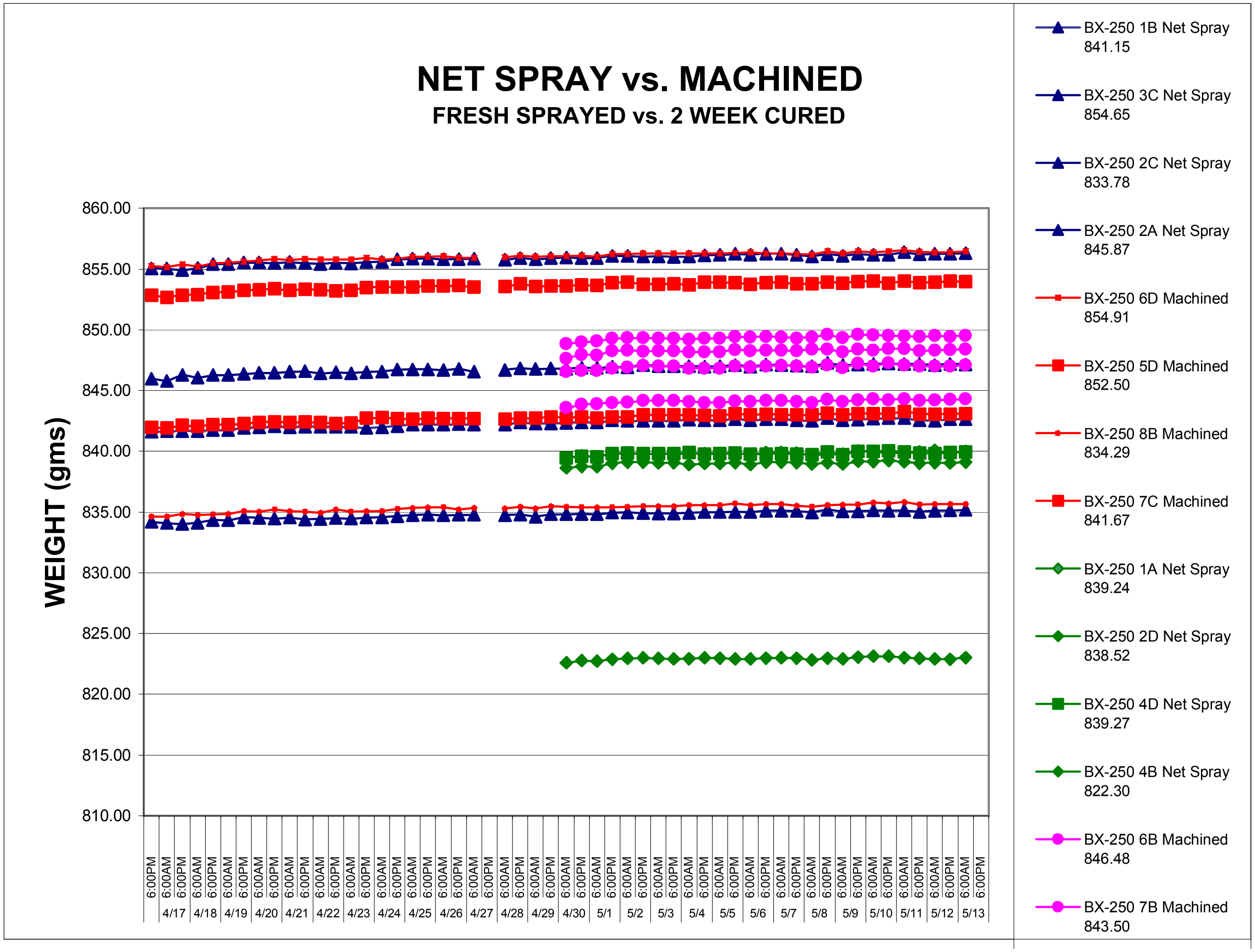

Figure 4. Accelerated Moisture Conditioning (32 °F/76% RH)

Sparks/Summary of Water Absorption Data of BX-250

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B1-000194

Summary of Water Absorption Data of BX rev3.doc

CTF059-0970

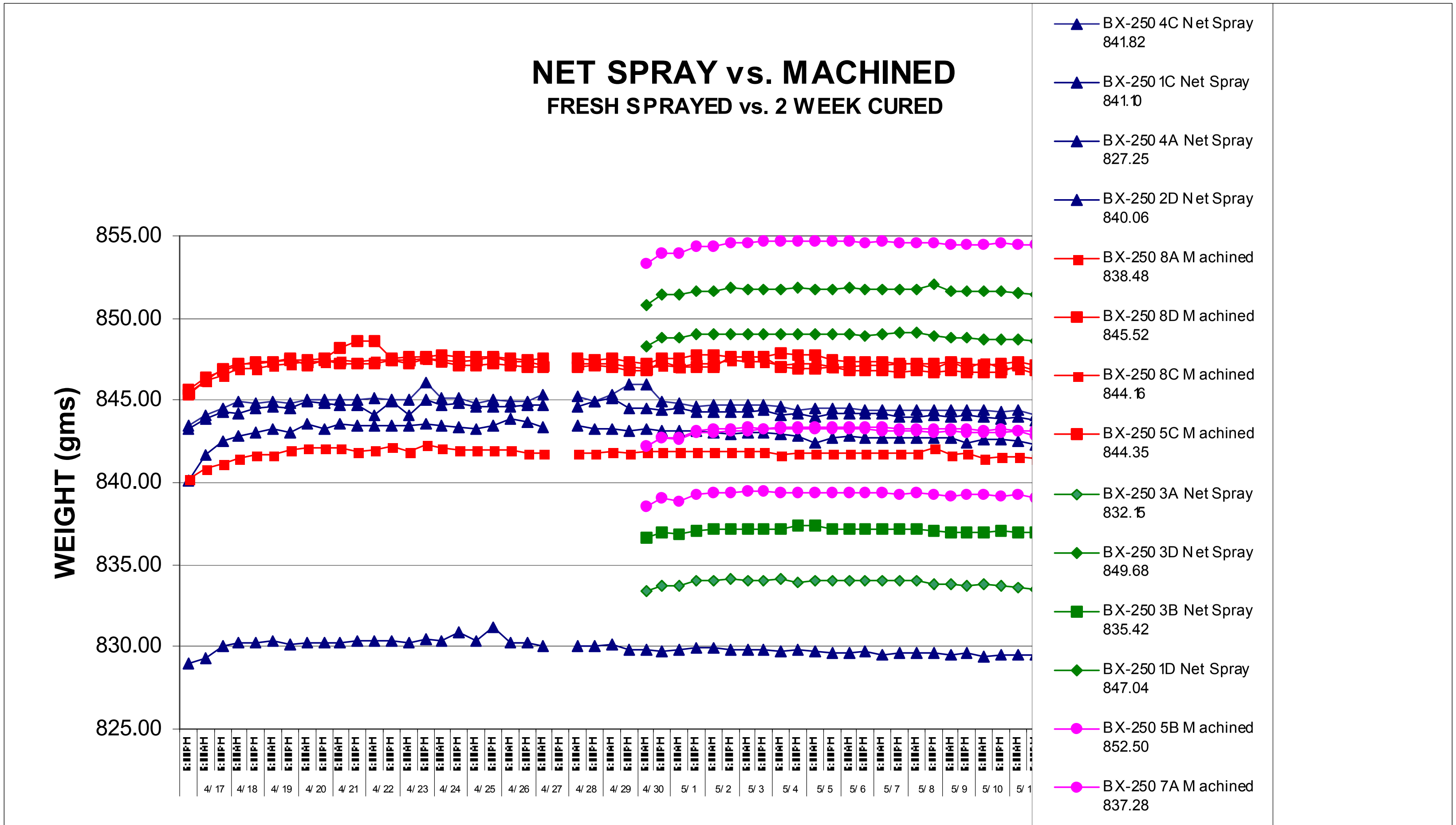

Figure 5. Accelerated Moisture Conditioning (120 °F/98% RH)

Date/EST	STS	Bipod Foam Loss?	Melbourne: (Temperature-Dew Point Temperature) @L-8hrs
01/16/03:10:39	107	Yes	1°F
11/23/02:19:49	113	No	22°F
10/07/02:15:45	112	Yes	0°F
06/05/02:17:22	111	No	10°F
04/08/02:16:44	110	No	16°F
03/01/02:06:22	109	No	14°F
12/05/01:17:19	108	No	11°F

Table 2. Preliminary analysis of environmental moisture conditions for launches with bipod foam loss vs. those without observed loss. (Melbourne, FL)

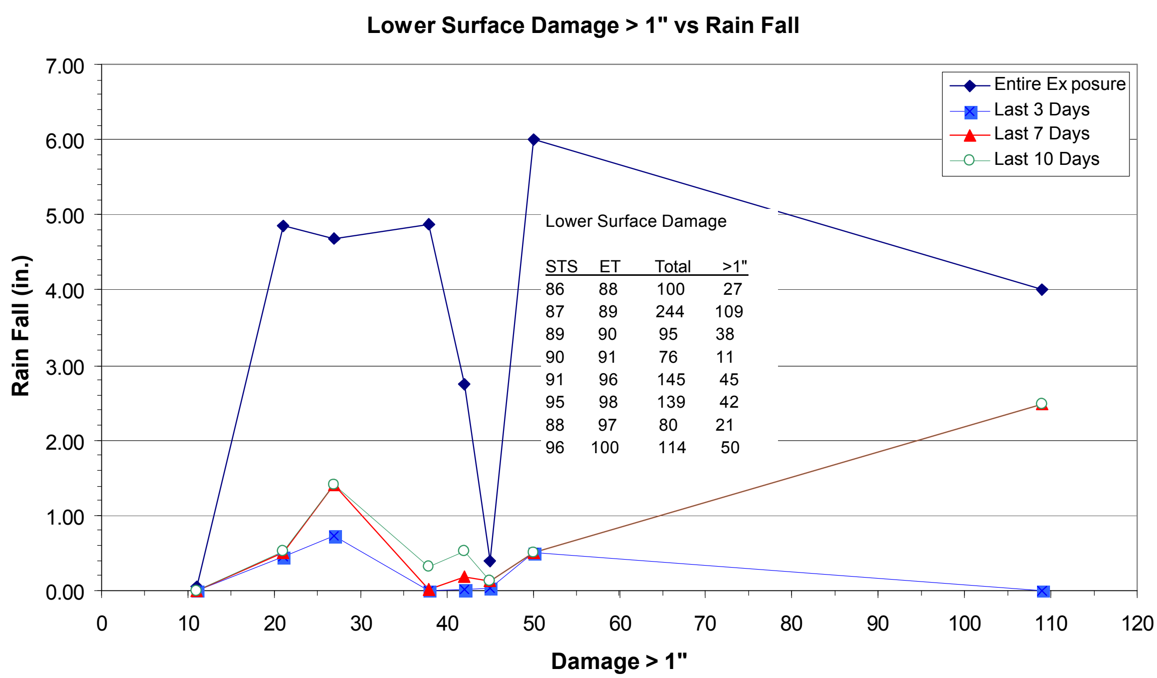

Figure 6. Correlation of On-Pad Rainfall to Orbiter Lower Surface Tile Damage.