Solar Array (Radiated/Non-Radiated): Materials Characterization and Cryogenic Thermal Cycling Qualification for the planned Europa Clipper Mission (ECM)

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Two special instruments were custom built for our critical study and manufactured and employed to test the SA materials of interest to cryogenic temperature conditions. We have procured custom manufactured two independent systems such as Thermo-Mechanical Analyzer (TMA) with Three Point Bend Probe (TPBP) module and Dilatometer. TMA can be used to measure Young's modulus or elastic modulus (e-modulus). Dilatometer can be used to measure Co-efficient of Thermal Expansion (CTE). We have optimized the materials configuration to measure physical properties of radiated and non-radiated materials for CTE and e-modulus, which will be useful to assess materials and processes reliability for cryogenic temperature applications. We have successfully implemented for some materials that are of interest to solar panels for the planned ECM project to measure CTE and Young's modulus.

Also a separate study was undertaken to thermal cycle qualify SAs for ECM project. One can do thermal cycling to temperatures of 50 K and 133 K using liquid Helium (Lq He). This is in reality exorbitantly too expensive and is also inefficient. Furthermore, this is not technically controllable test to 133 K and 50 K temperatures. This is also too expensive to accomplish. Therefore, a vacuum set-up was made along with a cryostat successfully. This is a closed loop system where we do not lose the Helium gas. We were able to get to 35 K for a given test coupon size. These temperatures are lower than what we would intend to qualify the solar array technologies. This will allow to have some margin at cold temperatures. We successfully completed the qualification of solar array technologies down to 50 K temperatures. This is the first time we are reporting this accomplishment.

In this paper, we will present the solar array materials properties for cryogenic temperatures down to 20 K temperatures and the thermal cycling qualification test results from 133 K to 50 K for three times the mission life of 120 thermal cycles to meet JPL Design
Keywords: Extreme temperatures, qualification, cryogenic thermal cycling, CTE, Young's modulus, solar array materials, TMA, dilatometer, etc.

Nomenclature

ΔL	=	change in thickness
μm	=	micrometer
CTE	=	co-efficient of thermal expansion
e/cm²	=	flux and accumulated fluence
FM73	=	adhesive material selected for this test
GPa	=	Giga Pascal
He	=	helium
K	=	Kelvin

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LqHe	=	liquid helium
mm	=	millimeters
MPa	=	Mega Pascal or modulus of elasticity?
MeV	=	Mega Electronic Volts
ppm	=	parts per million
Torr	=	Pressure units

I. Introduction

This paper provides the experimental test results of radiated and non-radiated solar array (SA) test coupons at temperatures ranging from cryogenic temperatures to room temperatures. These tests were performed using custom built LinSeis's Dilatometer (DIL) and Thermo-Mechanical Analyzer (TMA)/Three Point Bend Probe (TPBP) instruments. These instruments were used to characterize the thermo-mechanical properties of materials of interest (Young's modulus or elastic modulus, and Co-efficient of Thermal Expansion, CTE) for the first time down to cryogenic temperatures.

Solar array (SA) cell test coupon materials have previously been characterized down to only 93 K in earlier studies. There has been no characterization of SA test coupons (radiated or non-radiated) to Jovian cryogenic temperatures. This paper presents some preliminary thermal cycling and physical characterization of the solar array materials to cryogenic temperatures. Solar arrays consist of face sheets, adhesive materials, and honeycomb materials. A variety of SA test coupons (radiated and non-radiated) using FM73 (adhesive materials), honeycomb solar array cell, and face sheet materials were evaluated.

A. TMA and Dilatometer

Figure 1 shows the (a) TMA and (b) Dilatometer instrument custom built units. The TMA and Dilatometer consists of independent measuring head, the furnace lift control, a cryostat, and the computer-controlled power supply for the furnace.

1. TMA and Dilatometer Descriptions

The LinSeis TMA/TPBP was used to measure the change in deflection of non-radiated and radiated materials of FM73 adhesive bonding material, aluminum honeycomb, and graphite composite face sheet materials. This test data can be used to estimate Young's modulus of materials of interest to assess their reliability. The LinSeis Dilatometer was used to measure the change in thickness of radiated and non-radiated materials of FM73 adhesive bonding and graphite composite face sheet material. This test data can be used to estimate the CTE of materials which can be used to assess their reliability under cryogenic conditions.

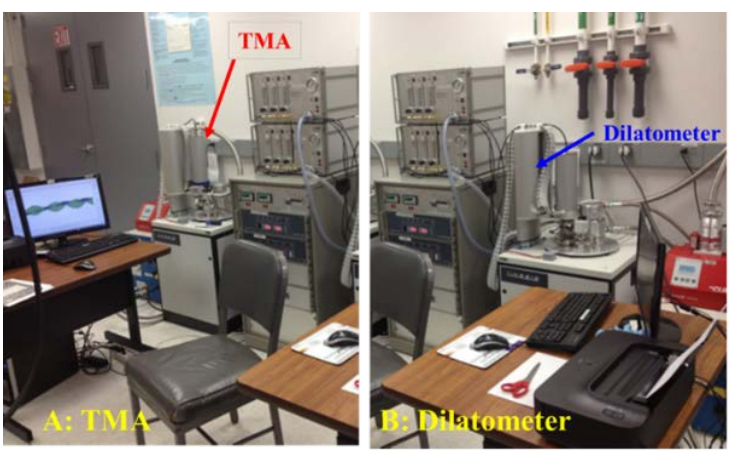

Figure 1. LinSeis: (a) TMA and (b) Dilatometer

The TMA measures the deflection of a thin test sample under load by means of a special sample holder set-up and a knife-edge piston called TPBP. The sample was placed in the holder horizontally and the change in deflection can be transferred to the inductive traveling sensor (Linear Variable Differential Transducer, LVDT) by means of a quartz piston rod.

Dilatometers measure the change in thickness of a test coupon as a function of temperature. The change in thickness is transmitted by means of a push rod from the furnace on a LVDT. The sample temperature was recorded by a diode temperature sensor for cryogenic temperature applications. Measurements were carried out under partial vacuum of Helium (He) inert gas to enhance the thermal equilibrium process of the hardware. The Dilatometer is a completely custom-designed system for measuring change of length, coefficient of linear expansion using appropriate special testing module.

II. Test Coupons/Samples

A. Sample Preparation Guidelines

The diameter of the test samples cannot exceed the inner diameter of the sample holder. The sample diameter should be 12 mm or less so that it can fit in the sample holder. The standard Dilatometer has a transducer with a maximum linear travel of ± 2.5 mm. The anticipated height change of the test sample should be kept well within this range. Use of small samples results in the best temperature accuracy and repeatability while large samples often report better dimensional accuracy.

B. Details of the Test Sample Matrix

Table 1 shows the test sample matrix of 19 samples. One needs a significant load capability to see any deflection or height or thickness change with aluminum honeycomb structures. Figure 2a shows one of the test coupons used in this effort. Configurations tested include Stack of FM73, FM73 Single Sample, Single Honeycomb Cell, and FS/FM73/FS (see Figure 2b).

			Temperature				Dilatmeter for CTE	TMA-TPBP for e-modulus
Test Coupon	No. of Samples	No. of Thermal Cycles	Room Temperature	133K	77K	50K	Test Status	Test Status
Stack FM73	3	5	Yes	Yes	Yes	Yes	Completed	-
FM73 Single Sample	4	5	Yes	Yes	Yes	Yes		Completed
Radiated FM73 Stack	3	5	Yes	Yes	Yes	Yes	Completed	-
Radiated FM73 single sample	5	5	Yes	Yes	Yes	Yes	-	Completed
Single Honeycomb Cell	1	5	Yes	Yes	Yes	Yes	Completed	Not possible
FS/FM73/FS	3	5	Yes	Yes	Yes	Yes	Completed	-
Total test samples completed	19							

Table 1: Test matrix of all the test coupons (analyzed) using Dilatometer and TPBP/TMA.

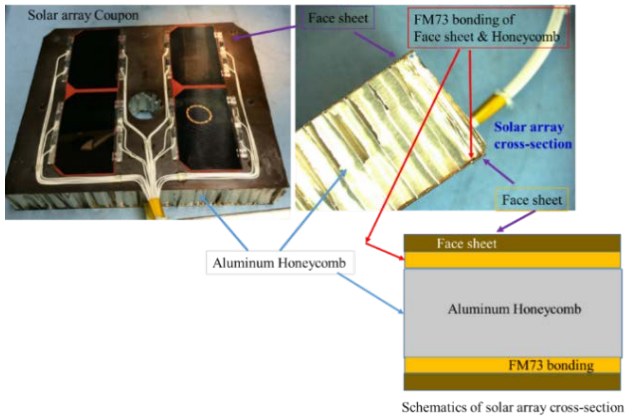

Figure 2a: Solar array coupon with a face sheet, FM73 bonding or adhesive material, and aluminum honeycomb.

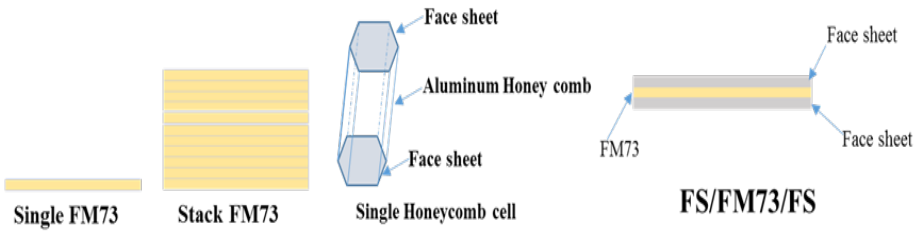

Figure 2b: Solar array test coupon configurations.

C. Special Precautions for Test Coupons

Solar array test coupons were handled with extreme care so they were not damaged or contaminated during handling and characterization. The test coupons were inspected visually prior to their installation in the test chamber while the unit was in its test fixture. Mounting of the test coupons in dilatometer and TPBP/TMA is shown in Figure 2c. Solar-array test coupons were cleaned appropriately with a lint-free wipe prior to installation of the test coupon in the high vacuum cryogenic thermal vacuum test chamber as shown in Figure 2c.

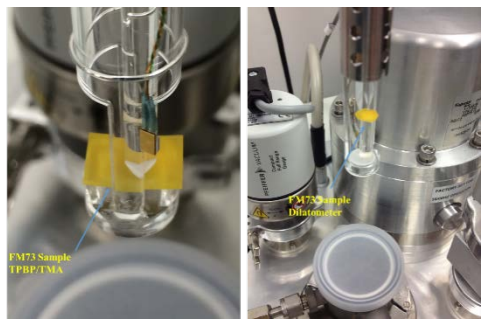

Figure 2c: Mounting of the test coupons in the TPBP/TMA and dilatometer.

D. Temperature Excess

The solar array test coupons were tested down to cryogenic sample temperatures from room temperature. A diode temperature sensor was mounted very closely to the solar-array test coupon in a thermal vacuum test chamber, and the test coupon's temperature was monitored continuously using the software package associated with the Dilatometer and TMA/TPBP instruments.

III. Test Procedure

The TMA/TPBP and Dilatometer instruments are controlled by a custom-built vendor software package, computer-interfaced temperature controller, electronic latching temperature custom-built thermal vacuum chamber, test coupon hoist system, vacuum isolation chamber, and temperature fail-safes. Temperature levels were attained by heating or cooling the heat exchanger/cryostat and chamber shroud. Dry He gas (ultra-high purity) was used to enhance the thermal equilibration process to obtain the cryogenic temperatures level.

IV. Experimental Results

A. Dilatometer Testing of FM73 Adhesive Materials (Non-Radiated)

1. FM73 Test Sample #1—Dilatometer

A stack of the polymer FM73 adhesive sheet material was placed in a dilatometer test chamber (Figure 2c) to determine CTE and the change in thickness (ΔL) of the material. The material was subjected to cryogenic temperatures or below liquid nitrogen temperatures. The temperatures were linearly increased and decreased based on the direction of temperature ramp during the test. The FM73 test sample was run for a total of five thermal cycles to understand the consistency and reproducibility of the test data. The ΔL was measured continuously for all the five thermal cycles to measure CTE of the FM73 material. Testing of sample #1 of the FM73 polymer adhesive (used in bonding of face sheet and Aluminum Honeycomb in SA, Figures 2a and 2b) was conducted. All the test set-up materials were made up of quartz materials in this study. Therefore, a correction to the test data was made with quartz material. It is to be

noted that the first thermal cycle for test sample #1 was anomalous data since there was no quartz correction made. It can be seen in Figures 3 and 4 that the CTE value continuously decreased (for cycle 1 data), showing that there was some apparent error in the instrumentation or data correction. This was corrected after the first thermal cycle as soon as it was observed. Sample #1 has a larger spread in the data, possibly due to the lack of the quartz correction. The maximum average ΔL values range from 25 to 33 µm in length in the Europa project temperature range (50 K to 133 K). The CTE allows us to know how vulnerable the material is to changing in length due to the change in temperature of the sample. Our test data show that the CTE will increase linearly as temperature increases, meaning that as the temperature increases, the value of ΔL also increases linearly. This is in agreement with the test data that we collected for the ΔL vs. temperature. For the CTE, we focused on the test data in the "Critical Zone or Mission" temperature range. These are the temperatures the SA hardware would experience the most during the Europa mission. The minimum average CTE value is 41 E-06/K, and the CTE ranges from 41 to 55 E-06/K in the Europa project temperature range as shown in Figures 3 and 4.

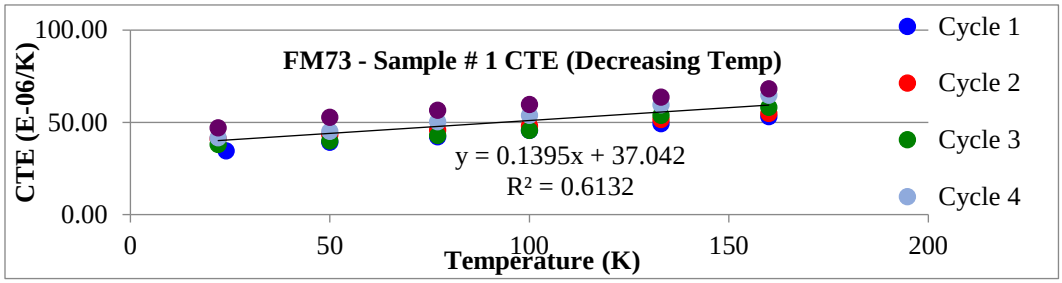

Figure 3: FM73 Stack sample #1. Variation of CTE as temperature decreases.

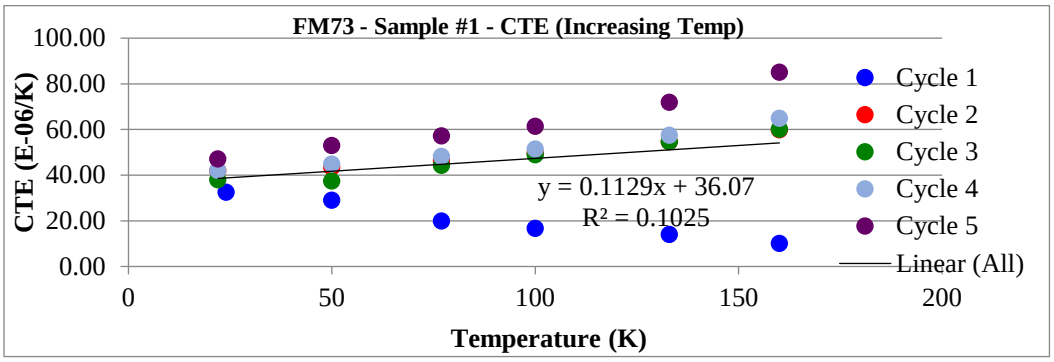

Figure 4: FM73 Stack sample #1. Variation of CTE as temperature increases.

2. FM73 Test Sample #2—Dilatometer

For the test data shown in Figures 5 and 6, a stack of the polymeric FM73 adhesive was placed in a dilatometer instrument to determine CTE. The data show that the average coefficient of thermal expansion in critical zone will change in a range of 49–58 E-06/K (49–58 ppm).

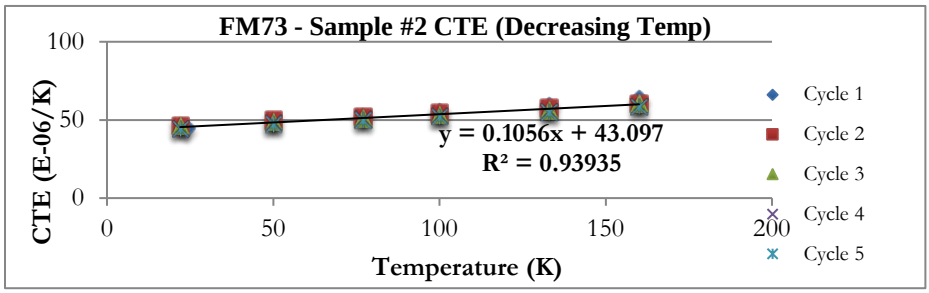

Figure 5: FM73 Stack sample #2. Variation of CTE as temperature decreases.

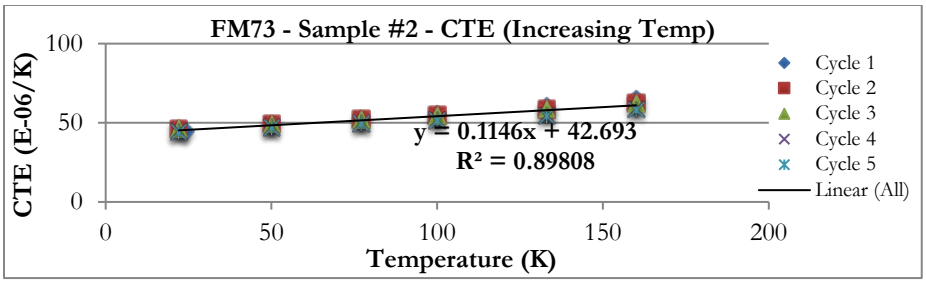

Figure 6: FM73 Stack sample #2. Variation of CTE as temperature increases.

3. FM73 Test Sample #3—Dilatometer

Figures 7 and 8 show dilatometer test data for FM73 sample #3. The observed test data show that the average coefficient is in the range of 48–58 E-06/K (48 ppm to 58 ppm) for the "Critical Zone."

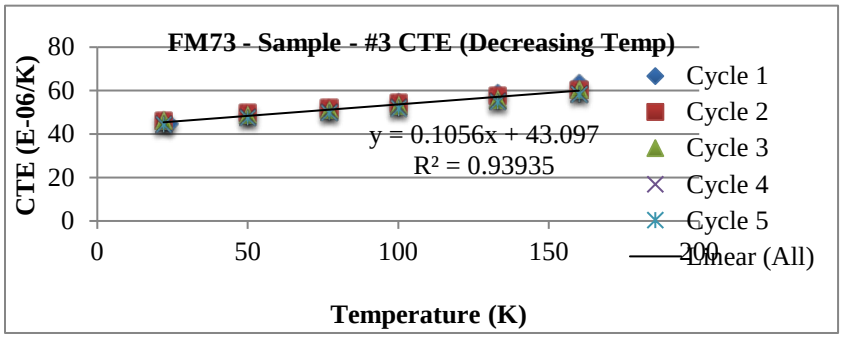

Figure 7: FM73 Stack sample #3. Variation of CTE as temperature decreases.

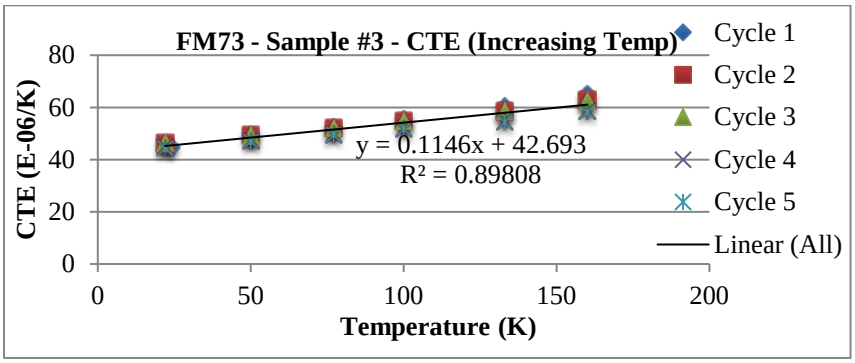

Figure 8: FM73 Stack sample #3. Variation of CTE as temperature increases.

B. TPBP/TMA Testing of FM73 Adhesive Materials (Non-Radiated)

1. FM73 Test Sample #1—TPBP/TMA

Test sample #1 of the polymer FM73 adhesive material (single sheet) underwent the TPBP measurements using TMA test set-up to cryogenic temperatures. Figures 9 and 10 show the test data for sample #1 of the polymer FM73 adhesive to determine the Young's modulus by using TPBP/TMA. From the test data we were able to determine the Young's modulus or elastic modulus (e-modulus) of the FM73 material test sample as the temperature changes. The data expected were that the temperature decreases as the Young's modulus would increase. Sample #1 was repeated through the five thermal cycles to verify its reproducibility. It should be noted that the e-modulus data estimated from cycles 4 and 5 are rather high during the last half (increasing temperature) of each cycle. This was due to a disturbance in test set-up during the test, which caused a large spike in the data. When the bump in the test data was removed using the software tool, the accuracy of the data increased greatly. For this reason, the data from cycles 4 and 5 have been

presented in the figures but will be disregarded due to the obvious anomalies. The measured Young's modulus is in the range of 3.3 to 9.1 GPa (average) in the temperatures of interest for Europa project (50 K to 133 K).

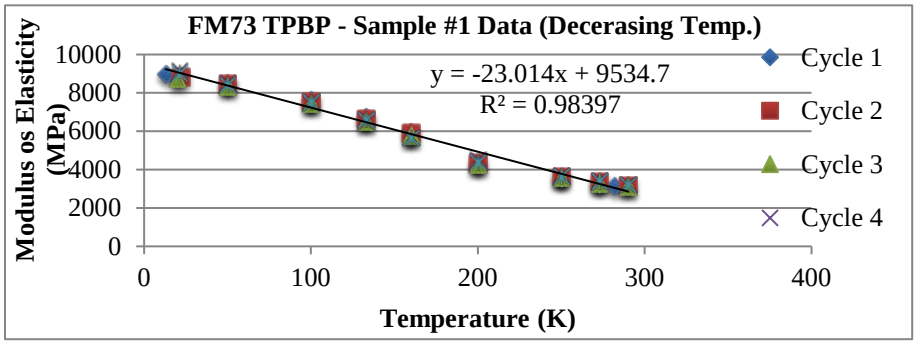

Figure 9: Young's Modulus of FM73 materials vs. decreasing temperatures; trend line excludes cycle 5.

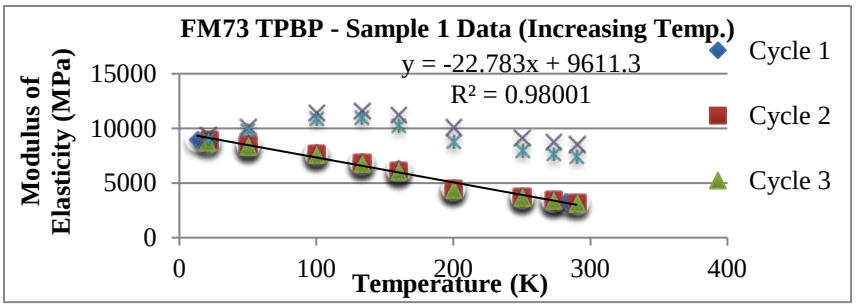

Figure 10: Young's Modulus of FM73 materials vs. increasing temperatures; trend line excludes cycles 4 and 5.

2. FM73 Test Sample #2—TPBP/TMA

Figures 11 and 12 show the test data for sample #2 of the polymeric FM73 adhesive to determine the Young's modulus. The test sample underwent five thermal cycles during the experiment. Sample #2 showed e-modulus values that were inconsistent with the values obtained with sample #1. We observed e-modulus values on the scale of nearly three times less than those observed from sample #1. Based on these results it was determined that we would test a fourth sample so that we could be certain of the test results. We were unsure why there was such discrepancy in the data between the samples #1 and #2 tested. It could have been an error in the initial start of the test, such as the piston not being calibrated completely. The average e-modulus values for SA materials in a temperature range (50–133 K) varied from ~2.8 to 3.4 GPa (2,787 MPa to 3,436 MPa).

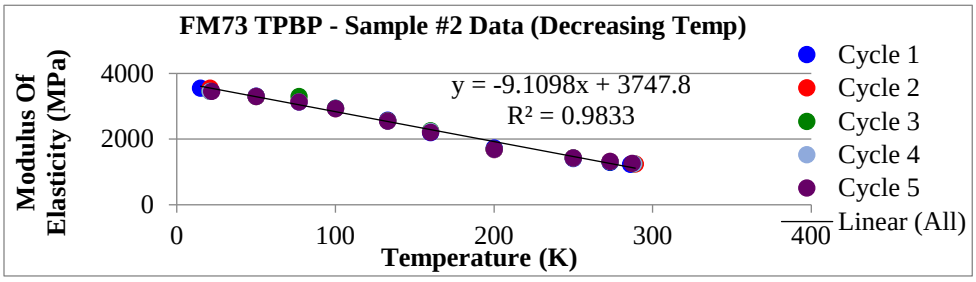

Figure 11: Young's Modulus of FM73 materials vs. decreasing temperatures.

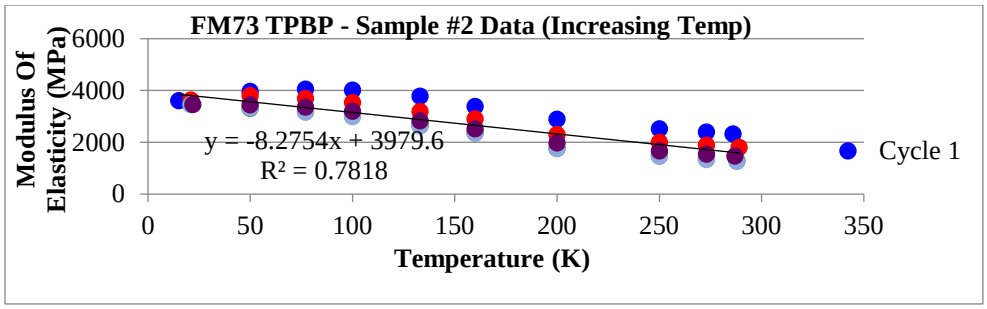

Figure 12: Young's Modulus of FM73 materials vs. increasing temperatures.

3. FM73 Test Sample #3—TPBP/TMA

Figures 13 and 14 show the test data for FM73 polymeric adhesive material sample #3 obtained using TPBP/thermomechanical analysis. From this test data we were able to determine the Young's modulus of the test sample vs. temperature. The test data are very much consistent with the anticipated trend of decrease in temperature vs. increase in the Young's modulus. The sample #3 data are more consistent with the sample #2 data in terms of its elastic modulus properties. The e-modulus for sample #2 and sample #3 are in good agreement; therefore, it has been determined that the data collected from sample #1 may have some unknown error. One thing that is apparent from both sample #2 and sample #3 is that each cycle shares a similar characteristic after reaching the lowest temperature. The Young's modulus appears to stay higher at the end of each cycle than at the beginning. The value of the Young's modulus of the sample at the beginning of the cycle was less than the value at the end, even at the same temperature readings. The average e-modulus values for the solar array materials for the Europa project temperature range (50–133 K) varies from ~2.6 to 3.3 GPa (2637 MPa to 3314 MPa).

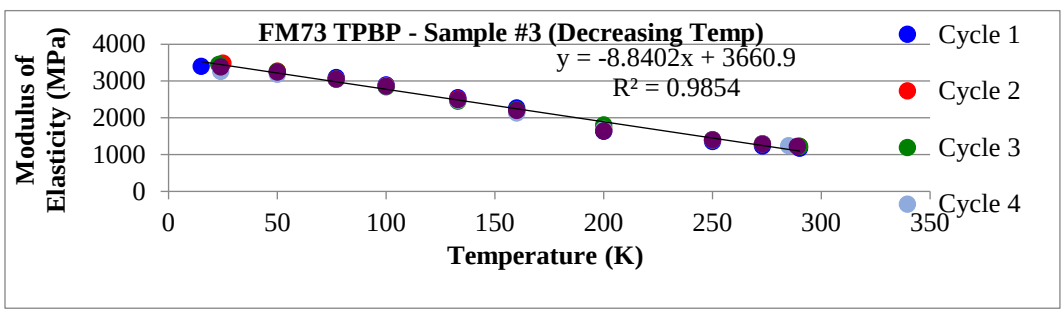

Figure 13: Young's Modulus of FM73 materials vs. decreasing temperatures.

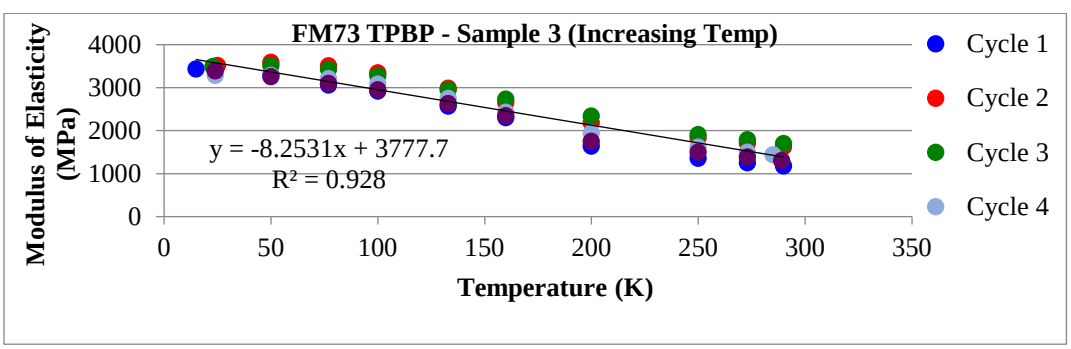

Figure 14: Young's Modulus of FM73 materials vs. increasing temperatures.

4. FM73 Test Sample #4—TPBP/TMA

Figures 15 and 16 show the test data FM73 adhesive polymeric sample #4 using TPBP/TMA to determine the elastic modulus of the material. The sample underwent five thermal cycles during the experiment. FM73 sample (#4) was tested due to the discrepancies in data obtained with sample #1 and samples #2 and #3. Sample #4 data show that the Young's modulus increased as the temperature of the sample decreased. The average value of the modulus ranged

from 2509 to 3151 MPa in the Europa temperature range (50–133 K). The maximum and minimum values of the modulus for the sample are rather low but consistent with data obtained with sample #2 and #3.

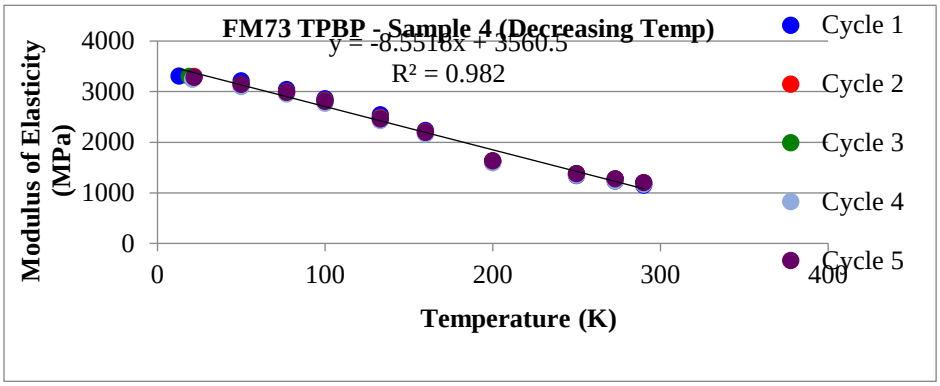

Figure 15: Young's Modulus of FM73 materials vs. decrease in temperatures.

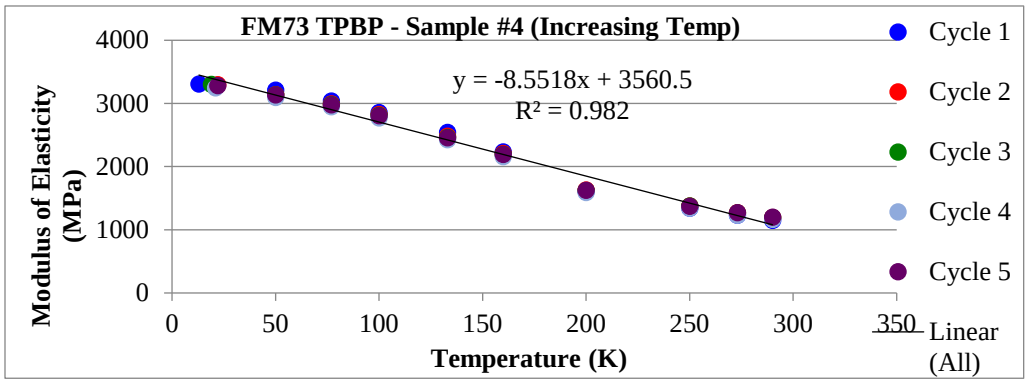

Figure 16: Young's Modulus of FM73 materials vs. increase in temperatures.

C. Dilatometer Study of Radiated FM73 Samples

1. Radiated FM73 Stack Sample #1—Dilatometer

Radiation exposure parameters: The following test parameters were used to radiate the sample employed in this assessment study. (Table 2)

Test Parameter	Magnitude	Units
Energy	1	MeV
Flux	4.00E+09	P/CM^2/S
Fluence	3.60E+15	P/CM^2
Temperature	-140	° C
Vacuum	<=10E-4	TORR

Table 2: Radiation Exposure Parameters.

Stacked radiated FM73 polymeric adhesive materials using dilatometer to measure the CTE. The sample underwent five thermal cycles during the experiment. The values of the ΔL in Europa project temperature range vary between 28 and 37 µm in length, which is very similar to the non-radiated samples of FM73. It seems that the test data show that there is little or no difference in the change of length between the radiated FM73 sample and the non-radiated FM73 sample when subjected to temperature. Figures 17 and 18 show the CTE vs. temperature data. This is in agreement with the data that we collected for the CTE. The data show that the average CTE will change in a range of 47–57 E-06/K for the Europa temperature range.

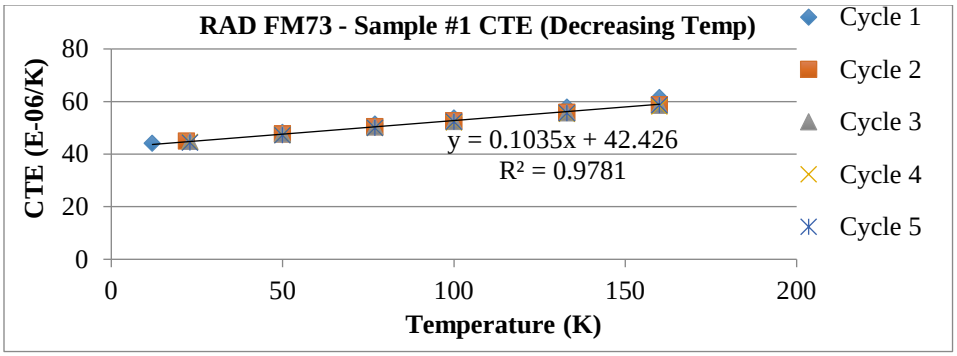

Figure 17: CTE of radiated FM73 (sample #1) vs. decreasing temperature.

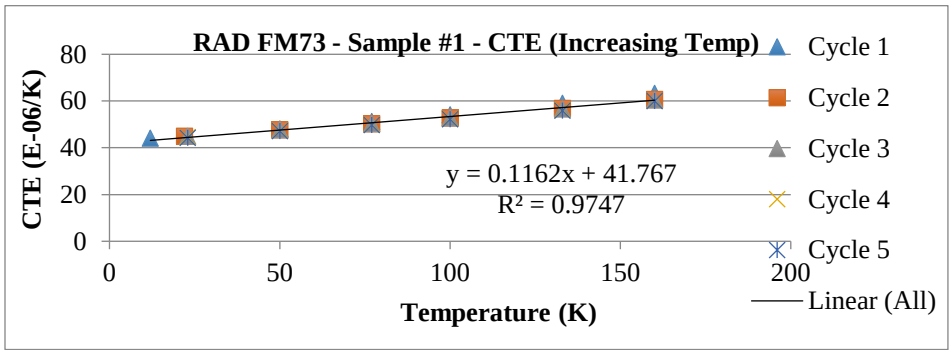

Figure 18: CTE of radiated FM73 (sample #1) vs. increasing temperature.

D. Radiated FM73 Stack Sample #2—Dilatometer

The data of stacked radiated FM73 polymeric adhesive materials using dilatometer to measure the CTE. It seems that the test data show that there is little or no difference in the change of length between the radiated FM73 sample and the non-radiated FM73 sample when subjected to temperature. Figures 19 and 20 show the CTE vs. temperature data. The data show that the average coefficient of thermal expansion will change in a range of 44–54 E-06/K for the Europa temperature range.

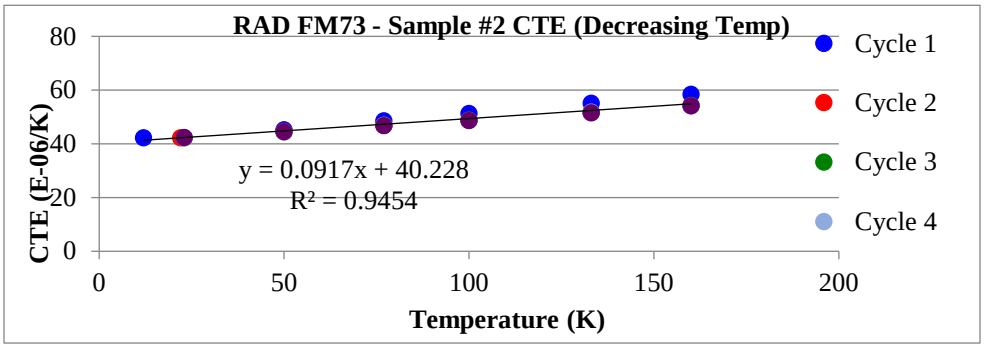

Figure 19: CTE of radiated FM73 vs. decreasing temperature.

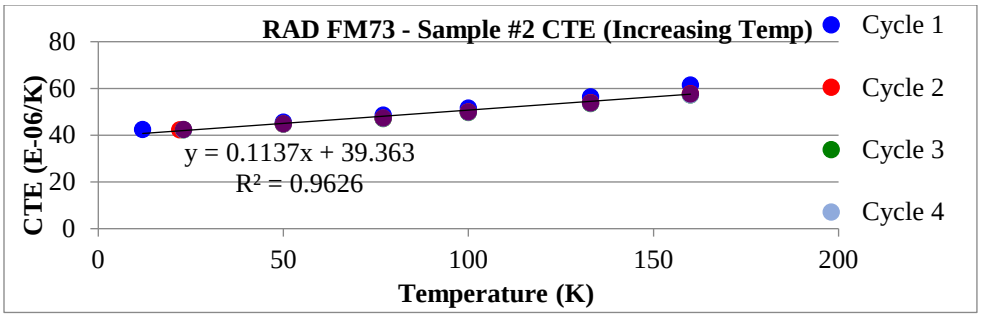

Figure 20: CTE of radiated FM73 vs. increasing temperature.

1. Radiated FM73 Stack Sample #3—Dilatometer

Figures 21 and 22 show the test data of a stack of radiated polymer FM73 obtained in a dilatometer to measure the CTE. The sample underwent five thermal cycles of the experiment. The values of the ΔL in Europa temperature range vary between 39 and 48 µm in length, which is very similar to the non-radiated samples of FM73. Figures 21 and 22 show the CTE vs. temperature data. The data shows that the average coefficient of thermal expansion will change in a range of 50–60 E-06/K for the Europa temperature range.

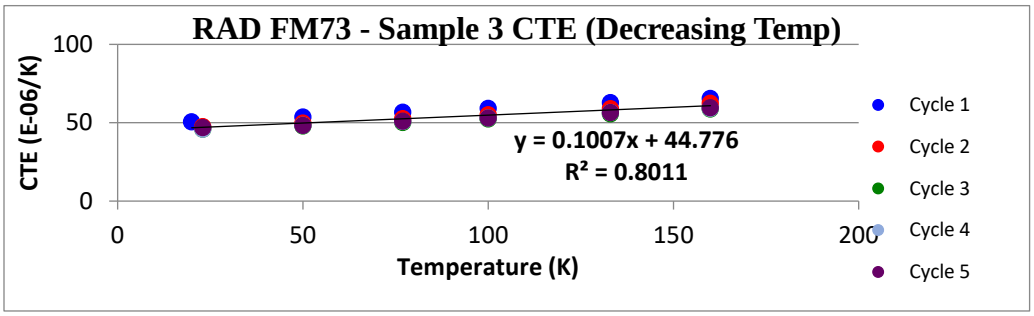

Figure 21: CTE of radiated FM73 vs. decreasing temperature.

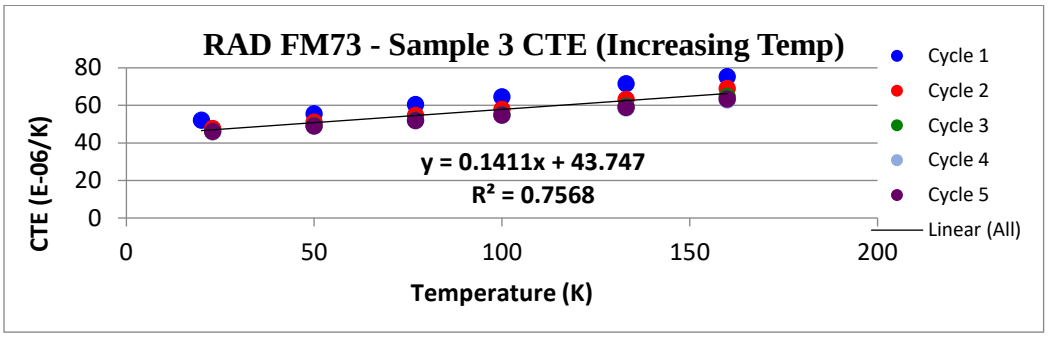

Figure 22: CTE of radiated FM73 vs. increasing temperature.

E. TPBP/TMA Study of Radiated FM73 Samples

1. Radiated FM73 Stack Sample #1—TPBP/TMA

Figures 23 and 24 show the elastic modulus of radiated polymer FM73 sample #1, which was determined using TPBP/thermomechanical analysis. The material was subjected to cryogenic temperatures for five thermal cycles. Sample #1 of the radiated FM73 polymeric adhesive material resulted in values for the modulus of elasticity that were higher than the non-radiated samples, on the order of 3–4 times higher in the temperature range tested. This seems to be a good observation because the radiation would not play a significant role in the elastic modulus; however, the test data showed otherwise. The reason could be that the samples (radiated) resulted in a high value of modulus of elasticity since the radiated material samples became more brittle and dense. To confirm these results, several tests were repeated

with a few more radiated samples. Average e-modulus for radiated FM73 material has been observed to be from 9519 MPa to 11955 MPa (9.519 GPa to 11.955 GPa).

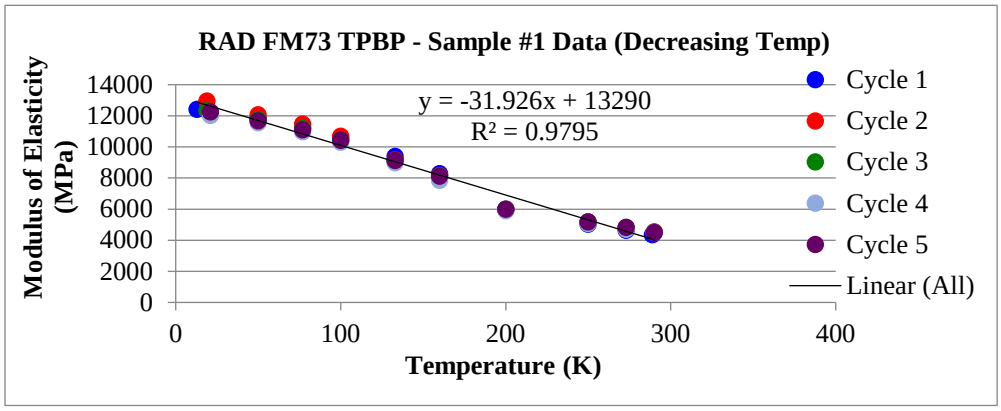

Figure 23: Elastic Modulus of radiated FM73 vs. decreasing temperature.

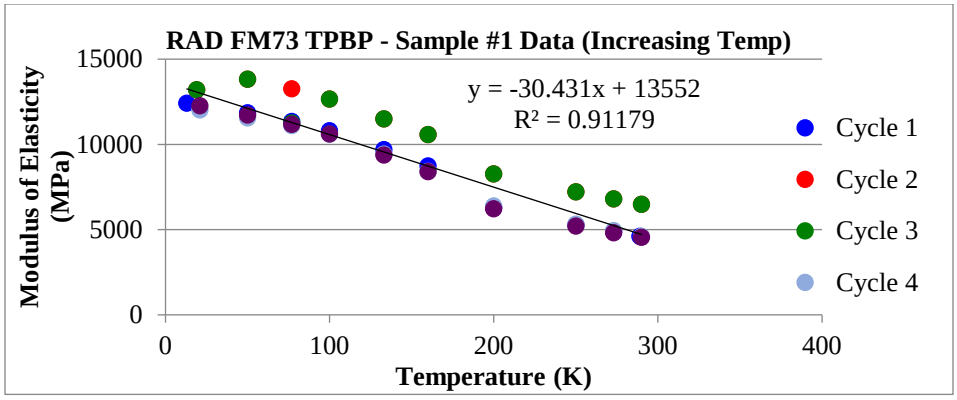

Figure 24: Elastic Modulus of radiated FM73 vs. increasing temperature.

2. Radiated FM73 Stack Sample #2—TPBP/TMA

Figures 25 and 26 show the test data for sample #2 of the radiated FM73 polymer, which was determined using TPBP/thermomechanical analysis to estimate the Young's modulus of the material. The test sample #2 underwent five thermal cycles of the experiment. Sample #2 of the radiated FM73 showed values that were significantly less than those determined from the radiated sample #1. Sample #1 had results three times that of the non-radiated samples, which was higher than we expected. The discrepancy between the two radiated FM73 samples could be due to the radiated face of sample #2 not being placed up during the test. At this time, we are uncertain as to the cause of the discrepancies, and it may be warranted to test a new sample to make sure our findings are correct. The average maximum values for the e-modulus is ~4388 at the lowest temperatures measured. The observed e-modulus range from 4388 to 5467 MPa (4.388 to 5.467 GPa) during the Europa temperature range for SA materials. The change in modulus of elasticity in the test temperature range is approximately 2.5 times.

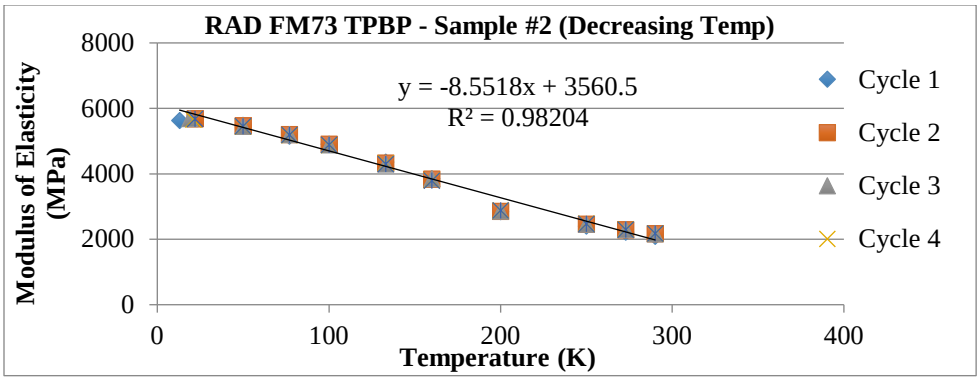

Figure 25: Elastic Modulus of radiated FM73 vs. decreasing temperature.

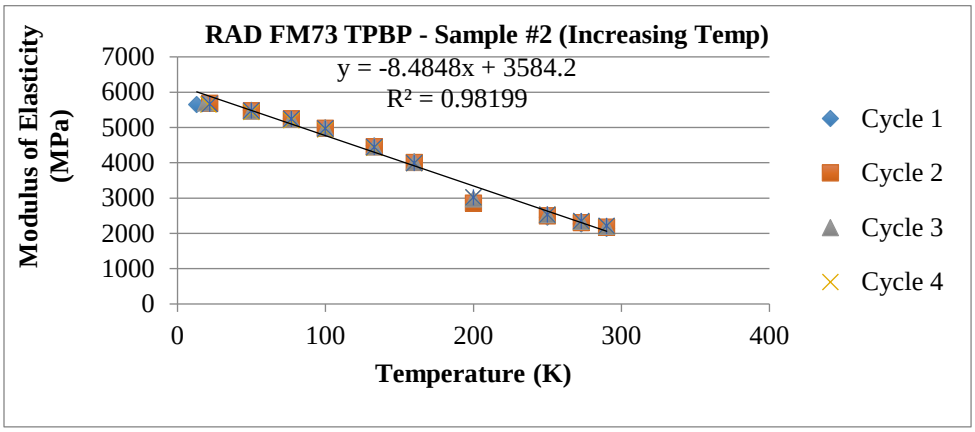

Figure 26: Elastic Modulus of radiated FM73 vs. increasing temperature.

3. Radiated FM73 Stack Sample #3—TPBP/TMA

Figures 27 and 28 show the test data for the FM73 polymeric sample #3, using TPBP/thermomechanical analysis to determine the Young's modulus of the material. The sample underwent five thermal cycles. Elastic modulus of the sample was estimated at various temperatures. The radiated polymer FM73 sample #3 shows similar values to sample #2; however, the values are less than the values of sample #1 by nearly a factor of 2. It is for this reason a fourth sample was tested to ensure a statistical certainty in the observed values. We believed that the values could vary because of the orientation of the sample: whether the radiated side of the sample is exposed to the knife edge of the TPBP. The data from sample #3 show that the Young's modulus will increase as the temperature of the sample decreases. The average e-modulus range for the Europa temperatures of 50 K–133K is 4774–5984 MPa (4.774 GPa to 5.984 GPa).

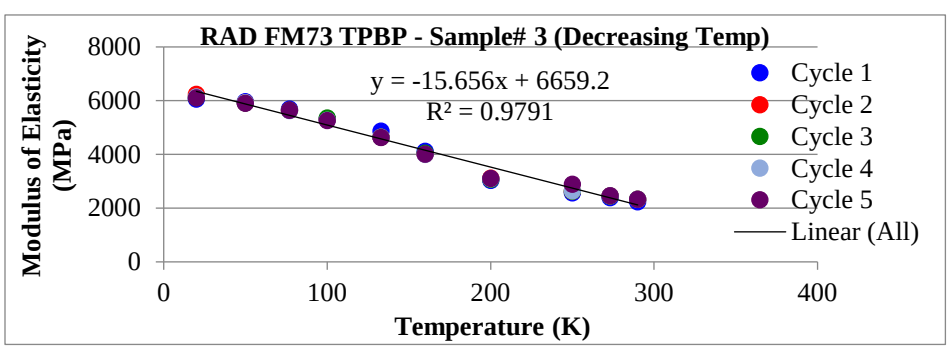

Figure 27: Elastic Modulus of radiated FM73 sample #3 vs. decreasing temperature.

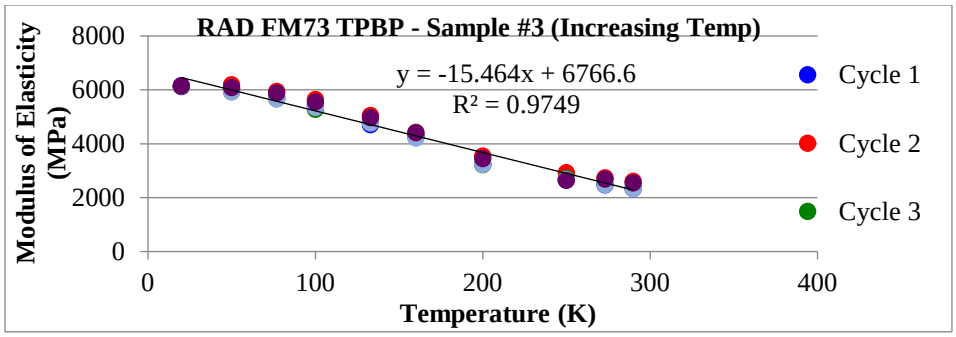

Figure 28: Elastic Modulus of radiated FM73 sample #3 vs. increasing temperature.

4. Radiated FM73 Stack Sample #4—TPBP/TMA

Figures 29 and 30 show the test data for the radiated FM73 polymeric adhesive sample #4 where TPBP/thermomechanical analysis was used to determine the Young's modulus of the material. The temperature was linearly increased or decreased for five thermal cycles. Because of the discrepancies between the values of the first three samples tested, we opted to test a sample #4 of the radiated FM73 material. For this test, we made sure to mark which side of the sample had been exposed to direct radiation. This is because we expected the side exposed directly to radiation would have larger values of elastic modulus than the side that was not exposed directly. This was what we believed caused the difference in values from the first three samples. The results for sample #4 of the radiated FM73 resembled those of the values measured from the first tested sample. This means that our theory about the directly radiated sides could hold true, but a fifth sample needed to be tested to be sure. The average e-modulus ranged from 8285 MPa to 10198 MPa during testing at the Europa project temperature range.

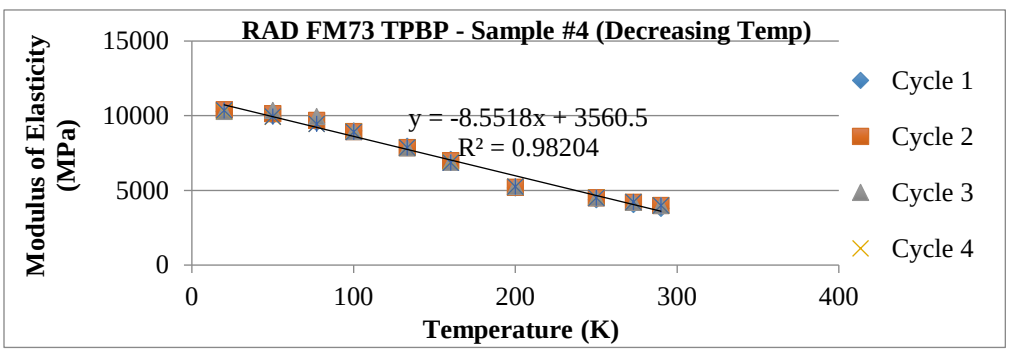

Figure 29: Elastic Modulus of radiated FM73 sample #4 vs. decreasing temperature.

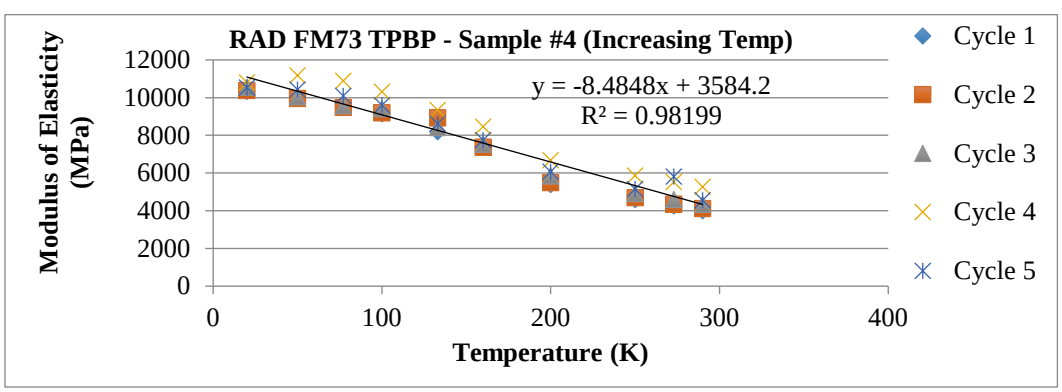

Figure 30: Elastic Modulus of radiated FM73 sample #4 vs. increasing temperature.

5. Radiated FM73 Stack Sample #5—TPBP/TMA

Figures 31 and 32 show the test data for FM73 polymeric radiated adhesive sample #5 material where elastic modulus was determined by using TPBP/thermomechanical analysis. After testing sample #4 and analyzing its data, it was decided to test a sample #5 of the radiated FM73 so that we could obtain three tests with consistent data. For sample #5, we again marked which side of the sample had been exposed to radiation. If our theory was true, the side exposed directly to the radiation would have a larger modulus of elasticity. This side was facing upwards during testing using TPBP/TMA. For sample #5, we received values resembling test sample #4, which gave us enough data to conclude that the orientation of the sample does matter and that the values found from samples #1, #4, and #5 are indeed the correct values that we were expecting. The modulus ranges from 7304 MPa to 9148 MPa (7.304 GPa to 9.148 GPa) during testing at the Europa temperature range.

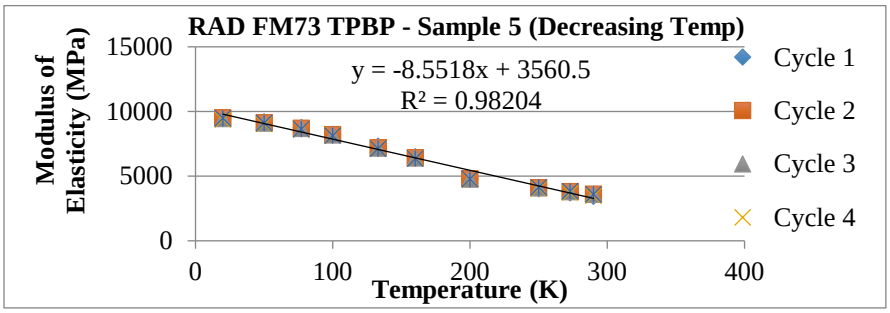

Figure 31: Elastic Modulus of radiated FM73 sample #5 vs. decreasing temperature.

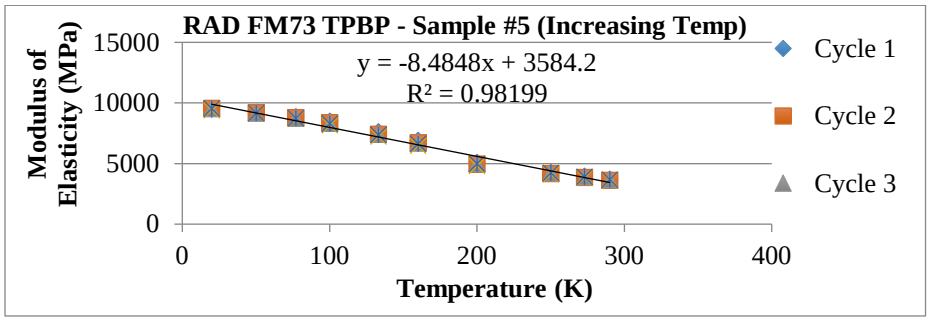

Figure 32: Elastic Modulus of radiated FM73 sample #5 vs. increasing temperature.

V. Summary of the CTE and e-modulus Data for the Materials Studied

Figure 33 shows all the CTE test data obtained for the non-radiated FM73 polymeric material. CTE of the least square fit data is around 44 ppm at cold temperatures studied and around 61 ppm at 160 K. One test sample's data deviated from the least square fit.

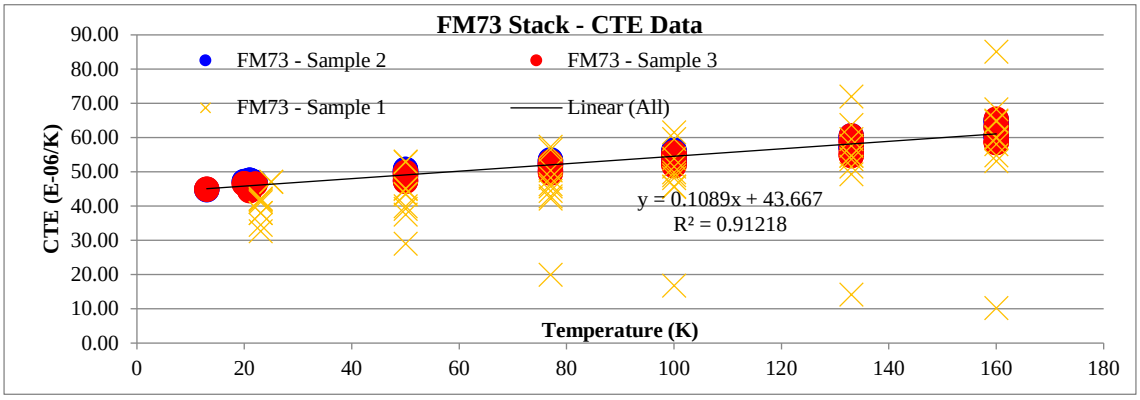

Figure 33: CTE of FM73 stack material samples #1, #2, and #3.

Figure 34 shows all the CTE test data obtained for the radiated FM73 polymeric material. CTE of the least square fit data is around 44 ppm at cold temperatures studied and around 59 ppm at 160 K. One sample's data deviated slightly from the least square fit of the other samples. The CTE obtained experimentally for the radiated and non-radiated FM73 sample are almost same. Radiation of the FM73 adhesive material sample did not change the CTE properties significantly from the non-radiated FM73 sample. This is a very good result for the Europa project since the change in temperature may have a small impact on the mechanical CTE properties of SA materials assemblies.

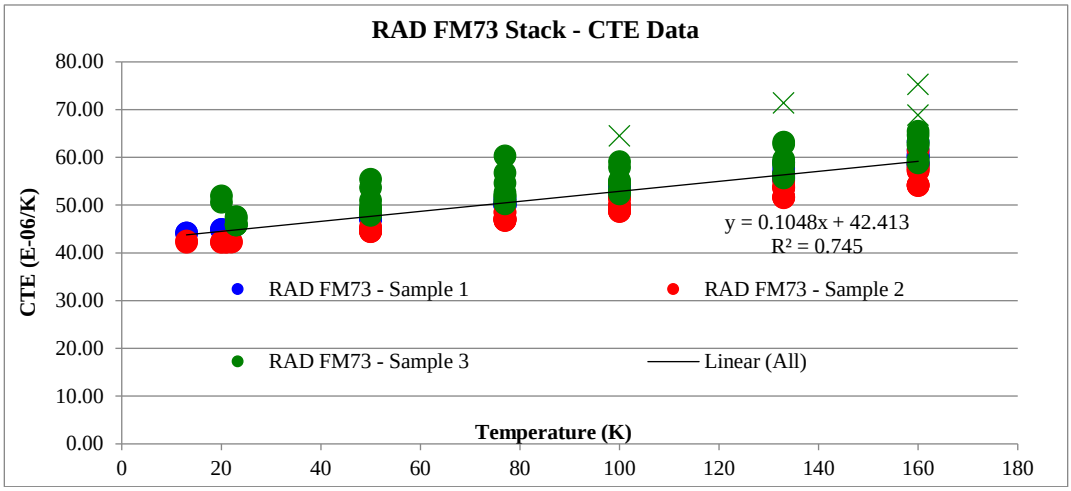

Figure 34: CTE of radiated FM73 stack material samples #1, #2, and #3.

Figure 35 shows all the CTE test data obtained for the non-radiated graphite face sheet material. CTE of the least square fit data is around 33 ppm at cold temperatures and around 43 ppm at 160 K. One sample deviated from the least square fit of the other test data.

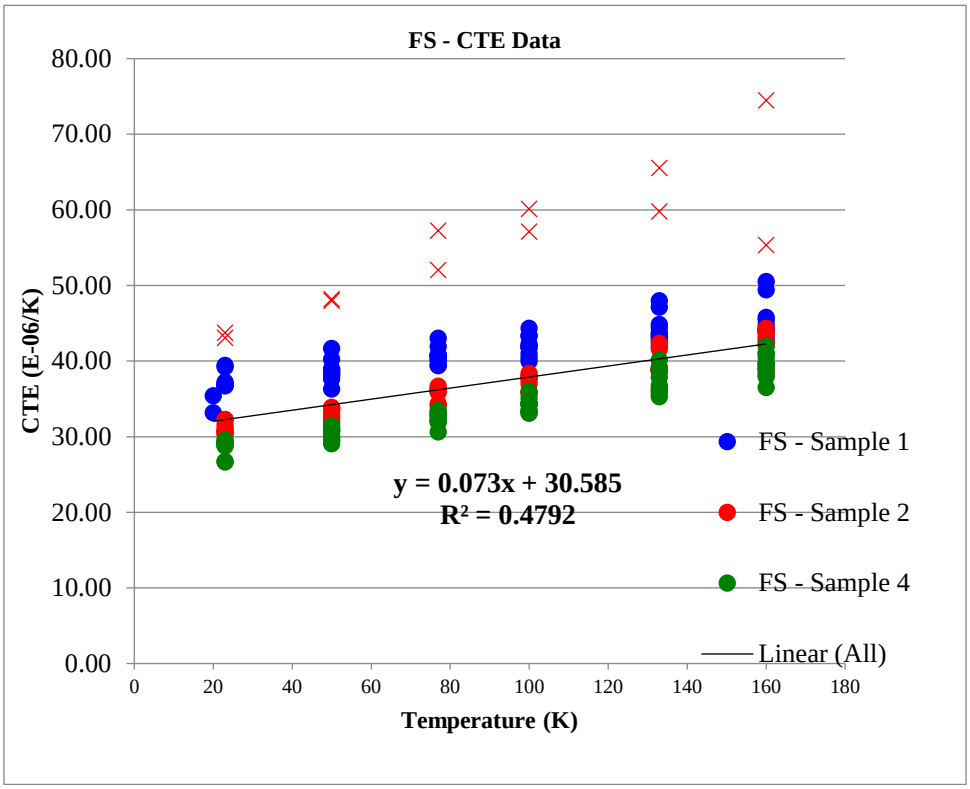

Figure 35: CTE of graphite face sheet material samples #1, #2, #3, and #4.

Figure 36 shows the Young's modulus or elastic modulus test data obtained for the non-radiated FM73 polymeric material. E-modulus of the least square fit data is around 3800 MPa (or 3.8 GPa) at cold temperatures and around 1600 MPa (1.6 GPa) at hot temperatures as shown in Figure 69. One sample's modulus data deviated from the least square fit of the tested samples' data.

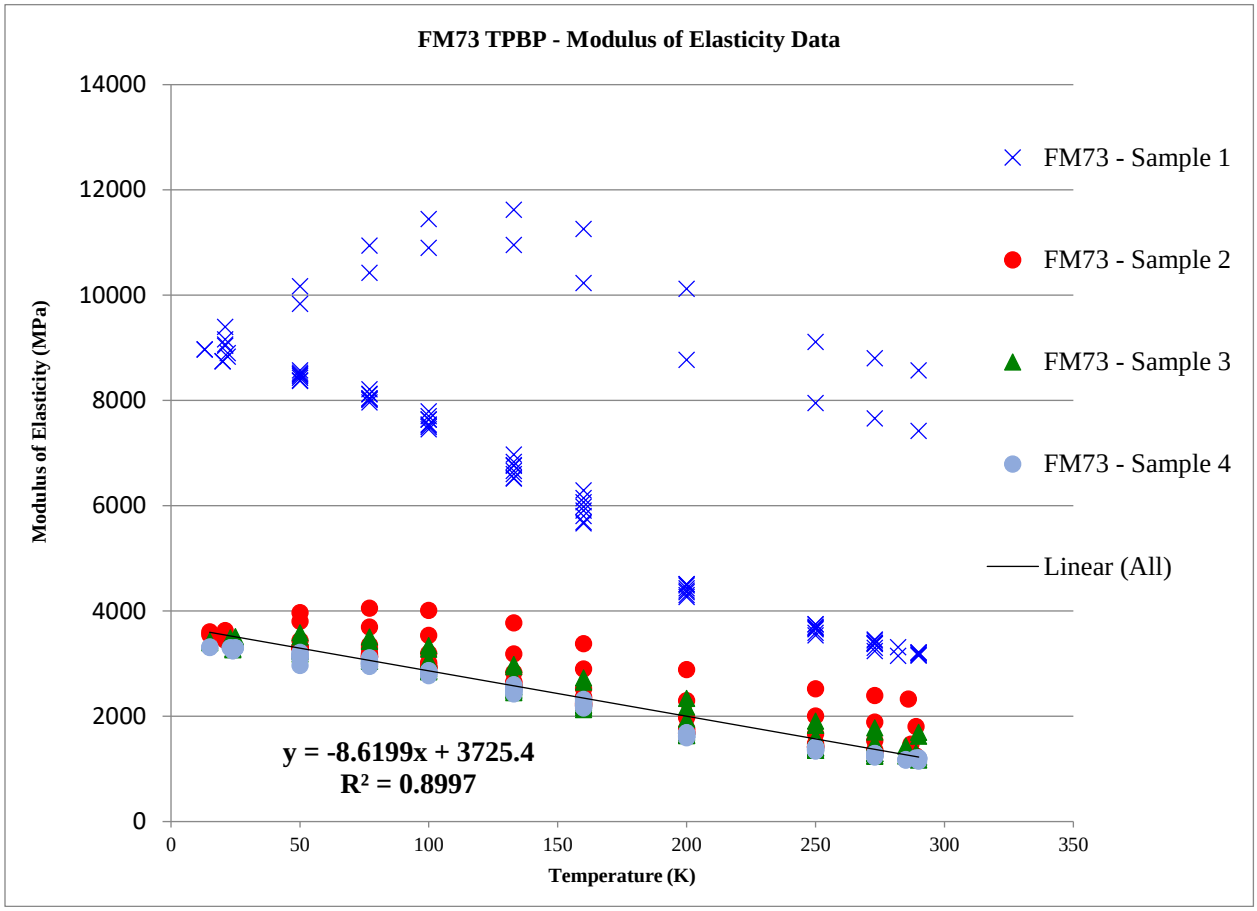

Figure 36: e-modulus of non-radiated FM73 material samples #1, #2, #3, and #4.

Figure 37 shows the Young's modulus or elastic modulus test data obtained for the radiated FM73 polymeric material. The e-modulus of the least square fit data is around 11,200 MPa (11.2 GPa) at cold temperatures and around 3800 MPa (3.8 GPa) at warm temperatures. The modulus data from three samples deviated slightly from the least square fit of the tested samples' data. The elastic modulus obtained experimentally for the radiated and non-radiated FM73 sample is not the same. Radiation of the FM73 sample did change the elastic modulus by three times (increase in e-modulus or decrease in elasticity) from the non-radiated FM73 sample. This is a very good result for the Europa project. Solar array panels experience extremely cold temperature swings besides radiation during the mission life during which the solar array could get stiffer, which could have a stress impact on the SA assemblies.

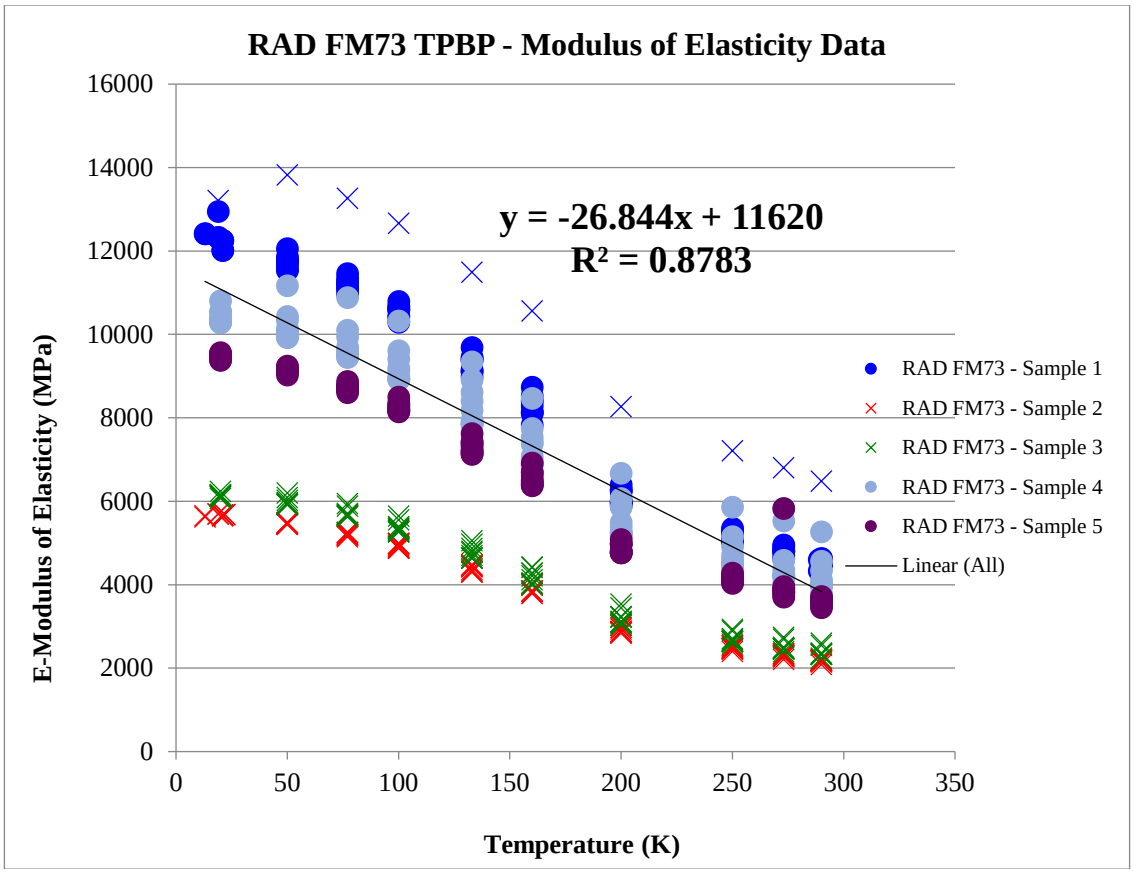

Figure 37: e-modulus of radiated FM73 material samples #1, #2, #3, #4, and #5.

VI. Part I: Conclusions

We worked with LinSeis to develop and build a custom dilatometer and thermomechanical analyzer (TMA) to test Europa solar array coupons to cryogenic temperatures as low as 15 K. Significant progress has been made in physical characterization of solar array (SA) materials for the Europa project. A summary of some of the salient experimental test results that were obtained under this risk reduction effort is as follows:

- Coefficient of Thermal Expansion of *non-radiated* FM73 adhesive materials has been measured for various test samples to cryogenic temperatures. The CTE has been measured to be from 45 ppm to 62 ppm in the temperature range studied (15 K to 293 K).
- Coefficient of Thermal Expansion of *radiated* FM73 adhesive materials has been measured for various samples to cryogenic temperatures. The CTE has been measured to be from 44 ppm to 59 ppm (15 K to 293 K).
- E-Modulus of *non-radiated* FM73 adhesive materials has been measured for various samples vs. temperature down to cryogenic temperatures. The e-modulus/Young's modulus of SA material has been determined to be 1 GPa (300 K) to 3 GPa (~20 K).
- E-Modulus of *radiated* FM73 adhesive materials has been measured for various samples vs. temperature down to cryogenic temperatures. The e-modulus of the material has been determined to be ~4 GPa (300 K) to 11 GPa (~20 K).
- Coefficient of Thermal Expansion of single solar panel honeycomb cell (non-radiated) has been measured for various samples vs. temperature down cryogenic temperatures. The CTE varies with reference to each sample. However, they are within 5–20 ppm over the range of the Europa project's solar array temperature requirements of 40 K to 133 K.
- Coefficient of Thermal Expansion of graphite face sheet (non-radiated) has been measured for various samples vs. temperature down to 15 K. The CTE has been measured to be from 32 ppm (~20 K) to 42 ppm (~300 K).

Part II: Conclusions

Thermal Cycling Qualification test plan of Non-Radiated (S/N-001) and Radiated (S/N-002) Solar Array (SA) Test Coupons from 50 K to 133 K is described is shown in Figure 38. .

The objective of this study was to determine the effects of thermal cycling and radiation exposure on carbon composite flat panel solar arrays. Thermal cycles are from 50 K to 133 K and the radiation levels are equivalent to the levels that will be achieved at the end of life of the planned Europa Clipper Mission (ECM).

Test Coupons: We had chosen two test coupons in this evaluation studies:

- Non-Radiated Solar Array (SA) test coupon (S/N-001 or Coupon A)
- Radiated Solar Array (SA) test coupon (S/N-002 or Coupon B)

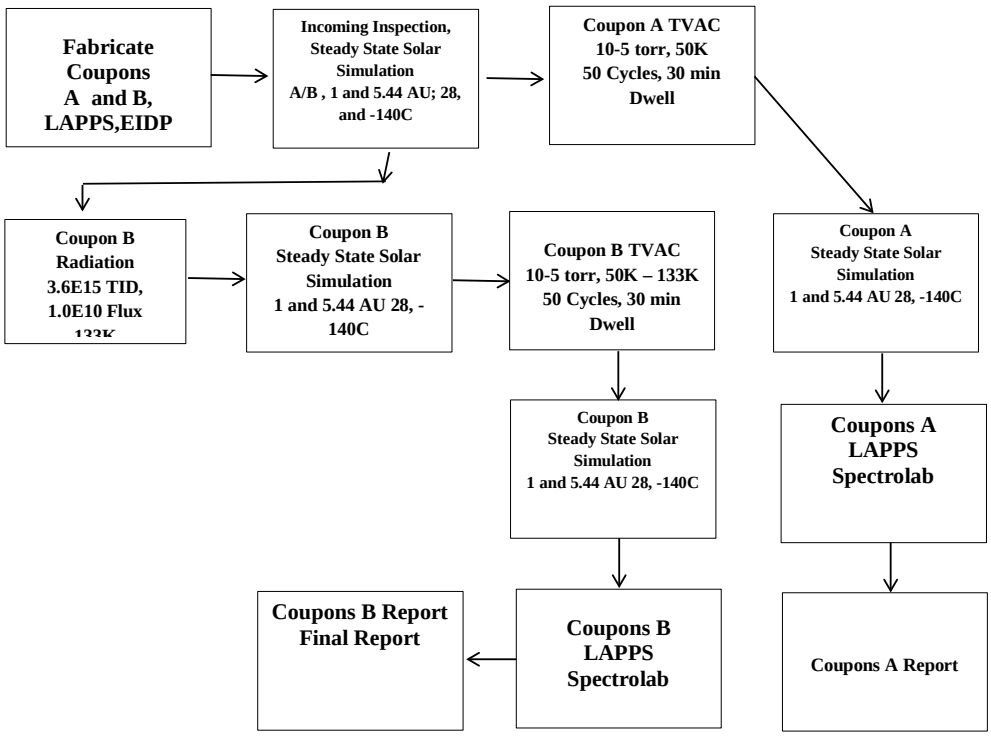

Figure 38: Schematic of Low Temperature Test Flow for Coupons A: S/N 001 and Coupon B: S/N 002

Figure 39 shows and Optical photograph of the Test Article Solar Array (S/N 002) Coupon with four solar cells. All the diodes have been continuously monitored during thermal cycling.

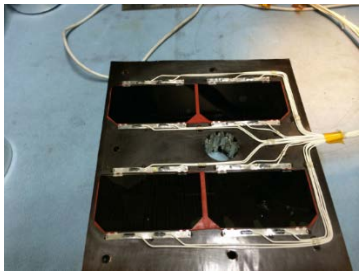

Figure 39. Optical photograph of the non-radiated SA test coupon.

This reliability study has been divided into two efforts. Part 1 is to assess the reliability of the non-radiated solar array test coupon after120 thermal cycles from 50 K to 133 K. The part II is to assess the reliability of the radiated solar array test coupon after 120 thermal cycles from 50 K to 133 K. Part 1 of SA Survival Assessment using S/N test coupon #001. This is non-radiated SA test coupon. Inspect the test coupon and documented as a base line. Thermal cycling of SA S/N 001 from 50 K to 133 K for 120 thermal cycles.

Technical issues experienced during S/N 001 Thermal Cycling Spectrolab SA test coupon. SA test coupon (SN: #001) had been inspected and documented. Qualification testing was accomplished using thermal cycling for long duration thermal cycling. Mounted the test coupons in thermal vacuum chamber for thermal cycling. Demonstrated 50 K to 133 K with test coupon in vacuum. Completed 23 thermal cycles from 133 K to 40 K. Temperature was monitored autonomously and remotely using diode temperature sensors. Test configuration allowed a maximum of three to four thermal cycles per day. Fabricated the copper plates and mounted over the test coupon with excellent thermal couplings to achieve 133 K to 40 K. (Figures 40 and 41)

Figure 40: Solar array coupon has been mounted in a high thermal vacuum chamber.

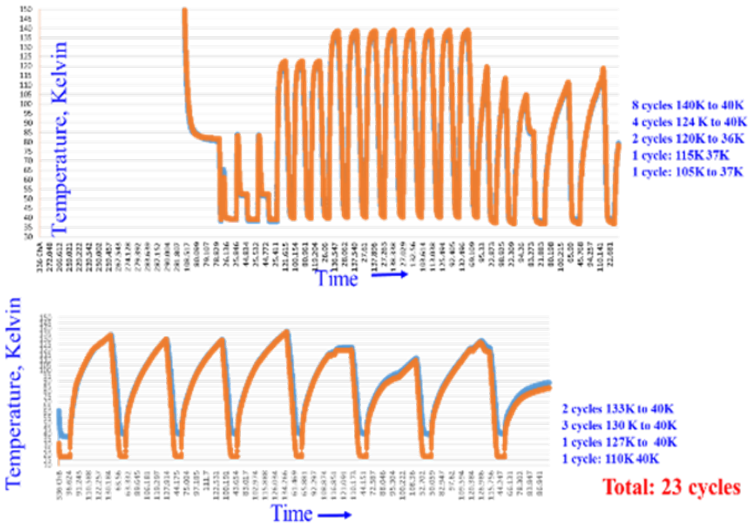

Figure 41: SA thermal cycles: temperature vs. time.

Experienced several issues during the thermal cycling. One can see the temperature cycles vary over 23 thermal cycles. They distinctly vary over number of thermal cycles. Then, the test was stopped the test due to technical issues of the heater during thermal cycling. Experienced an issue with the chiller water lines where the compressor was shutting down frequently. Not able to perform thermal cycling for long periods of time. Problems were solved by cooling the chiller water lines using ice and it was performed manually. Heater failed during thermal cycle test of S/N 001. Stopped the test after 23 cycles. Procured new heaters and installed. Built a cold plate with Dale Ohm resistors set-up. The dry run thermal cycles was completed. The test set-up was demonstrated for 12 thermal cycles with a new heater set-up.

S/N 001 SA Test Coupon Summary: Successfully completed only 23 thermal cycles from ~50 K to 133 K. It was taking more time per cycle after the heater break down, with the chiller malfunctioning and vacuum pump breakdown. Started concentrating on mitigating the problems for testing radiated test coupon. In fact, thermal cycling of the radiated test coupon is more important and valuable to the project over the non-radiated test coupon.

Part II of SA Survival Assessment using S/N test coupon #002. This is radiated SA test coupon in Dynamitron Laboratory of JPL. Inspected the test coupon and documented as a base line. Thermal Cycling of SA S/N 002 from 50 K to 133 K for 120 Thermal cycles with suitable dwell times at the extreme temperatures.

Radiation Requirements: Fluency of 3.6E+15 P/CM2, 1MeV electrons at 5.0E+9 P/CM2/S flux rate in Dynamitron laboratory. (Table 3)

TEST ARTICLE		
QTY	DESCRIPTION	S/N
1	JPL EUROPA COUPON QCHR 14-118	2
TEST SPECIFICATION		
ENERGY	1	MeV
FLUX	4.00E+09	P/CM^2/S
FLUENCE	3.60E+15	P/CM^2
TEMP	-140	° C
VACUUM	<=10E-4	TORR
TEST FACILITY	JPL DYNAMITRON	
SCHEDULE		
REQUIRED BY DATE	6/12/2014	
ESTIMATED TEST TIME	250.00	HRS
RAD START DATE	5/28/2014	
RAD END DATE	6/9/2014	

Table 3: Radiation Test Parameters

Test Procedure and Set-Up: The test coupon was specially designed for mounting in the Dynamitron target cold plate in the zero degree vacuum chamber. Device Under Test (DUT's) were mounted on a honeycomb structure with copper cold fingers used to improve thermal transfer to the cells mounting surface. Accommodation was made in the center of the coupon for the Faraday cup to have clearance with cells closely positioned to it. The positive leads of each of the 4 DUT's were tied to through a 10 ohm resistor to ground. The negative leads of each of the 4 DUT's were tied to ground. Test articles were maintained under vacuum at low temperature using LN2 at all times during electron exposure, as well as during sample cool down and warm-up. Electron flux was measured at the center of the test article cluster with a Faraday cup of 0.624 cm2. The flux and accumulated fluence (e/cm2) were monitored in real time. The dose at the surface of the cells was presumed to be 5% greater than the measured value due to the set back of the Faraday cup.

A. Radiation Summary of Test Results

The solar cell test coupon (S/N 002) was exposed to 1 MeV electrons to the target fluence of 3.6E15 e/cm2, at a nominal flux rate of 4E9 e/cm2/s. This was achieved after 244 hours of exposure runtime over a period of thirteen days. The test article was observed to show no signs of physical change to the cells throughout exposure to the target fluence of 3.6E+15 P/CM2. Some darkening of the electrical wires was observed, which is to be expected. As the chamber began to gradually warm-up, the first indication of physical change in the cell structure was observed at -80°C. The test articles began to show signs of void like structures which had developed below the cover glass. These symptoms appeared to increase with the rise in temperature. Upon achieving ambient temperature, the chamber was slowly brought to atmosphere. No noticeable effects to the test article were observed during the venting process.

S/N-002 went through radiation exposure (Figure . This test coupon went through 122 thermal cycles from 50 K to (Figure 43) 133 K. In view of the physical effects seen through the cover glass, the potential delamination appears to be dependent on dose and the temperature.

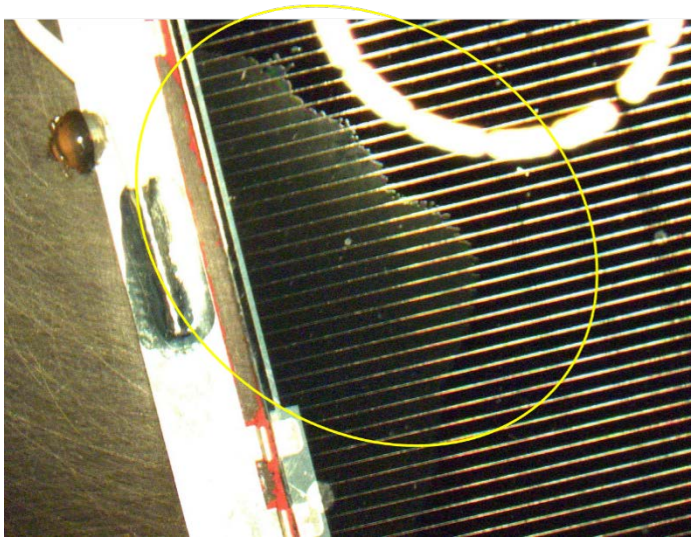

Figure 41: Optical image of some sort of bubble found in the solar cell test coupon (before thermal cycling), S/N 002 after radiation exposure.

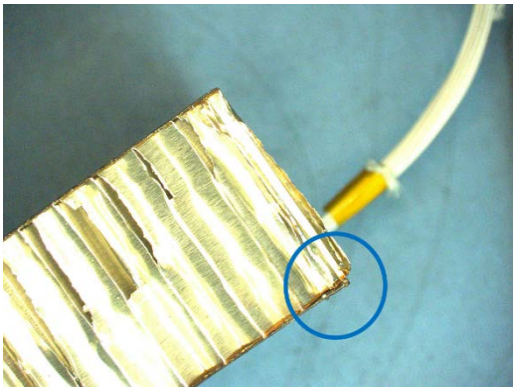

Figure 42: Optical image of the phase sheet separation from the corner of the test coupon prior to the thermal cycling (S/N 002).

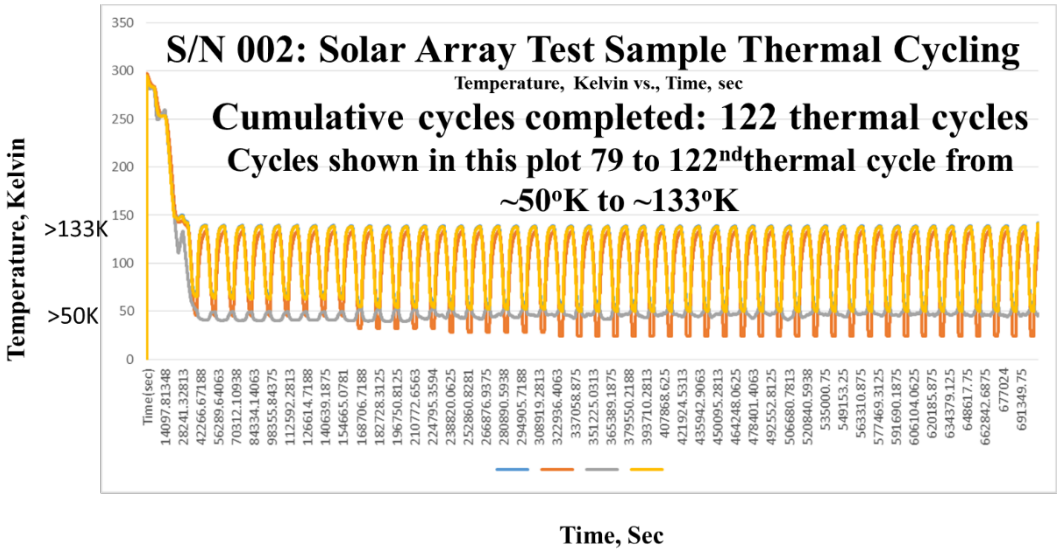

Figure 43: S/N 002: Solar Array Test Sample Thermal Cycling
Cumulative cycles completed: 122 thermal cycles

Thermal cycling was performed from 50 K to133 K successfully. Low and high temperature limits were adjusted during the thermal cycling to cover entire temperature range that the project is interested. (Figure 44)

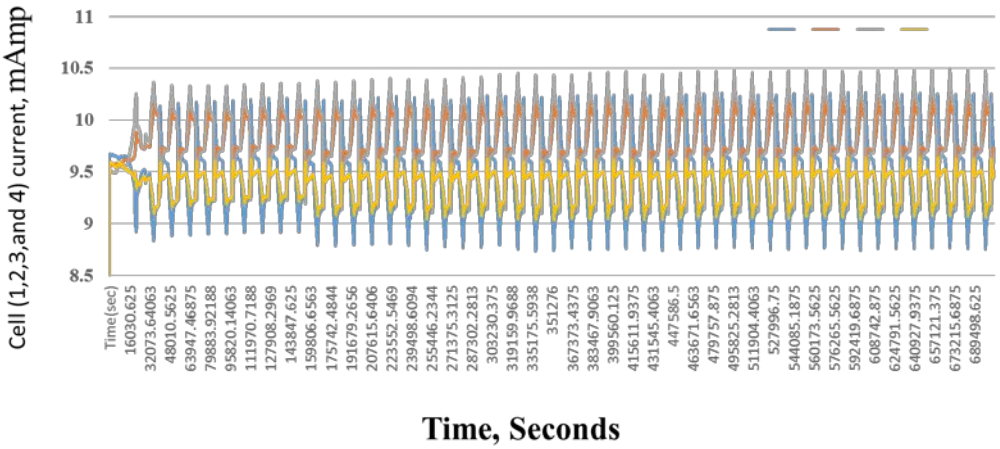

Figure 44: S/N 002: Solar Array Test Sample Thermal Cycling
Cumulative cycles completed: 122 thermal cycles
Cell current 1-4 from 79th cycle to 122nd cycle

Bubbles were present on the sample prior to thermal cycling but after radiation exposure. The solar array cell current was unchanged as a result of extreme temperature thermal cycling for 40 K to 133 K. Cell current was within the cell current limits at each temperature. Completed the thermal cycle testing of test S/N 002 for 122 thermal cycles. This is an indication that the solar cells are intact from the performance point of view. There was no degradation found in cell current.

There was no further expansion of bubbles observed after 122 extreme temperature thermal cycles. Furthermore, there was no new delamination observed as a result of cryogenic thermal cycling. No electrical continuity failures were observed as a result of thermal cycling. Interconnects were intact as a result of thermal cycling. No cracking of solder joints and interconnects was observed. Adhesive materials were intact after thermal cycling. The materials have survived three times ECM project life thermal cycles. The condition of solar panels after radiation and thermal cycles is considered as qualified. The bubbles were formed as a result of long time radiation exposure. Fortunately, those bubbles did not expand as a result of thermal cycling and the cell current did not show any anomaly. The formed bubble did not have any adverse effect on the cell performance as a result of thermal cycling

Acknowledgments

The research work described in this report was carried out at the Jet Propulsion Laboratory, Caltech, Pasadena, CA. The Europa Clipper Mission is highly appreciated for supporting us to work on this risk mitigation task. Thanks are due to Barry Goldstein, Ray Crum, Naomi Palmer, Richard Ewell, Genji Arakaki, Karla Clark, Thuy C. Nguyen-Onstott, Valerie Thomas, Greg Cordell, David Brinza, Mark Boyles, Angel Garnica, Cynthia Kingery, John Forgrave, Kin Man, Ryan Ross, Mohammad Mojarradi, and Jeremy Bonnell for their keen interest and constant support. Thanks are due to Timothy A. Mccann, Michael Errico for their timely unwavering support in accomplishing this effort. Radiation team member, Dennis Thorbourn (section 514) is acknowledged for his decisive support in preparing the radiated sample for this project.

Thanks are due to Ryan Pickard, a summer intern who assisted in processing the experimental test data. Thanks are also due to Michelle Tran (high school intern, 2015) who supported a literature survey of solar array qualification methodologies for extreme thermal environments. Thanks to Charles Rhoades for his help in preparing test samples and characterization-related effort/support. Radiation team members (section 514, section 513, and others) are acknowledged for their support in preparing the radiated samples for this risk reduction effort. Thanks are due to Michael Gregory for his help in review, format and editorial support.