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**RESILIENCE AND PERFORMANCE OF DEPLOYABLE SPACE STRUCTURES BASED ON A  
SHAPE MEMORY POLYMER BUS**

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**ABSTRACT**

*We seek to advance the topic of large-scale space structures for low-frequency radio interferometry enabled by self-folding shape memory polymers (SMPs). Large-scale space structures, greater than 1 km in diameter, are necessary to unlock the secrets of the cosmological dark ages. Two important considerations in developing such large structures are their ability to deploy to the desired configuration in space and their resilience to harsh space environments, which include UV radiation, atomic oxygen, and thermal cycling under vacuum. These environments lead to long-term degradation and erosion of even the most resilient materials. Degradation of SMPs in space applications has potential to affect both material properties and shape-memory performance. Although a plethora of materials have been evaluated in space conditions, the coupled effects of simultaneous space environments on the properties and shape memory performance of polymers has not been evaluated sufficiently. In this study, we evaluate the effects of relevant space environments on the thermomechanical properties of candidate SMPs using laboratory-based experiments. Representative SMP samples are subjected to UV-Oxygen for varying durations. The effects of these environments on material properties for various amounts of exposure are evaluated using differential scanning calorimetry and dynamic mechanical analysis. Knowledge gained from this study includes how the shape recovery required for in-space deployment is affected by space environments and the resilience of these structures to long-term space exposure. Through improved understanding of the effects of space environments on SMP properties and performance, we can*

*advance the field of low-cost, lightweight, self-deploying space structures.*

Keywords: Self-folding; Origami; Space Environments; Shape memory polymer

**NOMENCLATURE**

AO	atomic oxygen
DMA	dynamic mechanical analysis
DSC	differential scanning calorimetry
ESH	equivalent sun hours
IR	Infrared
SMP	shape memory polymer
TTS	time temperature superposition
UV	ultraviolet radiation
UVO	ultraviolet and ozone treatment

**1. INTRODUCTION**

With the current advancements in technology, space exploration can be accounted as a milestone in human history [1]. Simplification of space mission designs and economical components has driven short duration missions over the last decade. CubeSat missions have proved to be promising from operational as well as engineering perspectives [2]. Polymers have been integrated into space vehicles, rockets, coatings, adhesives, thermal blankets, insulating blankets and many more [1, 3]. High elasticity and toughness, low density, easy molding process and good insulation of polymers make the material useful for application in space industry [3]. The space environment consists of harsh conditions manifesting an

exceptional challenge to evolving space missions [4]. Materials exposed to space are subjected to several environmental threats including solar ultraviolet radiation (UV), vacuum, charged particle (ionizing) radiation, surface charging, plasma, thermal cycling, and environment induced contamination [5]. These environments cause degradation of the structure and pose a risk to mission success. The level of degradation depends on the material composition, thickness, and stress levels [6]. The degradation of material is also a function of mission duration and environment including orbital parameters, solar events, solar cycle, and orientation of space system surface. Vacuum ultraviolet radiation (VUV) originated in space environment with wavelength in the range of 115 - 200nm causes deterioration of polymer films. The exposure to VUV produces changes in chemical, mechanical and optical properties of a polymer [7]. In low earth orbit, atomic oxygen is a considerable factor in the degradation of spacecraft components eventually threatening mission success [8]. Preliminary studies to quantify the erosion yield of common polymers in low earth orbit (LEO) were performed as part of the Materials International Space Station Experiment (MISSE) [8]. The Polymer Erosion and Contamination Experiment (PEACE) included assorted polymers in a sample tray that were exposed to atomic oxygen (AO). Polystyrene with density 1.0503g/cm<sup>3</sup> reported mass loss of 0.115 g for an exposed area of 3.5043 cm<sup>2</sup> and erosion yield of 3.74E-24 cm<sup>3</sup>/atom over the span of four years. Mass loss should be under 1% for a material to qualify for spacecraft materials [8]. The study of atomic oxygen combined with UV degradation is crucial in selecting materials for space missions.

Shape memory polymers (SMPs) are a specific class of material that has not been fully investigated in relevant space environments. SMPs can change shape in response to external stimuli, such as heat, which enables them to be used as actuators in deployable space structures. SMPs are polymers to which a thermomechanical prestrain sequence has been applied to retain a temporary (pre-strained) shape. By heating an SMP above its glass transition temperature, large changes in shape may be realized as the material returns towards its original (shape-recovered) state. Further, heating can be localized in the SMP sheet to induce self-folding, as demonstrated by Liu *et al* [9]. In their approach, the SMP is patterned with black ink lines, or hinges. When the material is exposed to IR light, the black ink absorbs radiant energy and heats, thus creating a gradient in temperature through the thickness of the sheet. The gradient in temperature produces a gradient in shrinking as the polymer heats above its glass transition temperature, and the material folds along the hinge. The folded shape is retained when the material is cooled below its glass transition temperature. This self-folding behavior relies on the viscoelastic properties of the material, which can be affected by space environments, in particular UV radiation and atomic oxygen.

Various polymers exhibit different responses to ultraviolet and infrared (IR) radiation in space environment. Additionally, a limited number of polymers have been shown to exhibit the shape memory effect in ideal laboratory conditions. Thus, it is hard to predict the behavior of shape memory polymers (SMPs)

after exposure to space environments. Based on the literature survey, several experiments have been performed by placing the polymer in various levels of UV-ozone treatment, but the effects of long-term exposure to UV radiation have not been explored in an intensive manner yet for a range of SMPs. In a related study, a Cyanate based SMP was exposed to UV radiation for 3000 equivalent sun hours (ESH) and a change of molecular structure was recorded, which lead to degradation of the polymer via breaking of weak bonds. Samples exposed to UV radiation for 3000 ESH indicated no adverse effects on mechanical properties, thermal stability, and shape memory properties [10,11].

The present study focuses on analyzing the aging process and thermomechanical properties of UVO treated SMP. A series of polystyrene samples are exposed to varying durations of UV radiation. Two scenarios were considered. In the first scenario, samples are exposed to UVO treatment before inducing shape recovery. In the second scenario, shape recovery is induced prior to UVO treatment. The difference in the order of the procedure produces diverse results in terms of morphological evaluation. Changes to the viscoelastic properties of UVO treated samples are evaluated using temperature sweep in DMA. Impact of UV exposure on thermomechanical properties is inferred in discussion and conclusion. These experiments help in gaining better understanding about the viscoelastic behavior of SMP when exposed to space environments.

## 2. MATERIALS AND METHODS

In this study we will evaluate the effects of prestrain state and ultraviolet-ozone (UVO) treatment on the behavior of a polystyrene based SMP. Samples are subjected to UVO treatment, in either the pre-strained or shape-recovered state, for varying durations and then evaluated using differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA).

### 2.1 Material Preparation

The material used in our study is a pre-strained polystyrene sheet, which is commercially available as Graftix® Shrink Film. This material shrinks ~ 55% in each planar direction when heated above the glass transition temperature,  $T_g = 103^\circ\text{C}$  [9]. The shrinking behavior results from a thermomechanical pre-straining sequence (heat-deform-cool) performed by the manufacturer. We use the material in the as received state, and tests are initiated in one of two ways: (1) the material is exposed to UVO treatment then shape recovered (shrunk) for evaluation or (2) the material is shrunk then exposed to UVO treatment. Shrinking of the material is required to prevent shape recovery from occurring during dynamic mechanical analysis.

### 2.2 UV Radiation

UV-Oxygen treatment of SMP samples is performed using a Jelight Model 18 UVO cleaner (Figure 1). UV radiation is generated by using low pressure mercury (Hg) vapor lamp. The UVO cleaner is operated at 253.7 nm with an average intensity of 28-32 mW/cm<sup>2</sup> [12]. UV-C region (<280 nm) is eliminated by stratospheric layer and is not experienced on earth. Short wavelength of 253.7 nm is highly energetic and one of the most damaging type of UV radiation [13]. The sample tray is placed 3-5 mm from the bulb. Four durations of UVO treatment were considered: 0 hours (baseline), 1 hour, 2 hours, and 3 hours.

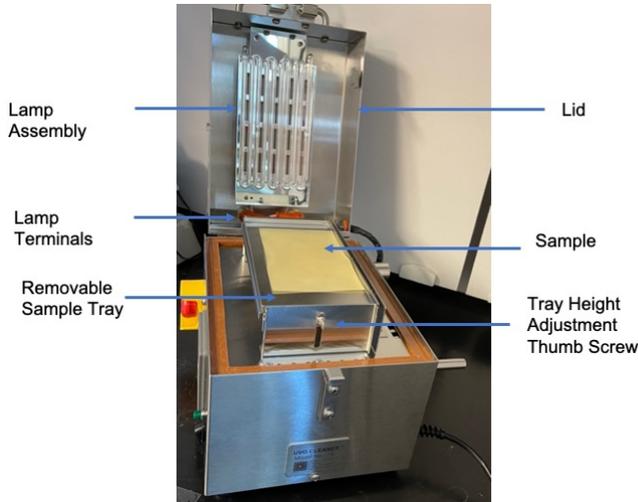


Figure 1: UVO cleaner with open lid and sample in sample tray.

### 2.3 Thermomechanical testing

Differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) are used to evaluate the thermomechanical behavior of the SMPs exposed to varying amounts of UVO treatment. A TA instruments DSC 25 is used to measure specific heat capacity and glass transition temperature of the SMP. A typical heat-cool-heat cycle is applied to the polymer samples, and  $T_g$  values are reported from the second heating cycle. A TA Instruments DHR-20 Hybrid rheometer with DMA mode and environmental test chamber is used to evaluate the viscoelastic properties of the polymer. DMA experiments were conducted using a rectangular solid torsion fixture.

A portion of the polymer samples were cut to fit into Tzero aluminum pans with Hermetic lids for DSC evaluation. Samples of varying mass 8-10 mg were subjected to heat-cool-heat cycle with heating rates of 10 °C/min and a cooling rate of 5 °C/min, and a nitrogen purge flow was used. The temperature range for this experiment was 50 – 200 °C. DSC was used to calculate glass transition temperature ( $T_g$ ) of the polymer.

For evaluation of polystyrene SMP samples in the DMA, two different types of experiments were conducted. In the first experiment type, pre-strained polystyrene was exposed to UV radiation for the amounts of time prescribed earlier and thereafter, heated to 110°C for 30 minutes to remove the thermomechanical prestrain (i.e., shrinking the sample). The second experiment type was performed by first shrinking the sample using the above heating conditions, and then exposing it to UVO treatment. The resulting samples were placed in the DMA to evaluate changes to the thermo-mechanical properties. DMA test conditions were an oscillatory strain of 0.1% with angular frequency of 100 rad/s to 1 rad/s over a temperature range of 80°C to 130°C were defined as pre-conditions for DMA.

## 3. RESULTS

### 3.1 Morphological analysis

Pre-strained polystyrene samples were clear and transparent before exposure to UV radiation, but samples became yellow upon exposure to UVO treatment (Figure 3). An increase in the UV radiation duration is directly proportional to yellowing of the

exposed surface of sample. We also observe that samples that are UVO treated then shape recovered (Figure 3, left) are a darker yellow than the samples that were shape recovered then UVO treated (Figure 3, right). The samples that were shape recovered after exposure to UV as shown in Figure 3 (right) have flat and even surfaces and can be positioned in DMA. However, samples treated with UV radiation first and then shrunk, took on a curved shape during shape recovery, as shown in Figure 2. Based on observations, UVO reduces shrinking on the exposed side of the sample causing the sample to curve during shape recovery.

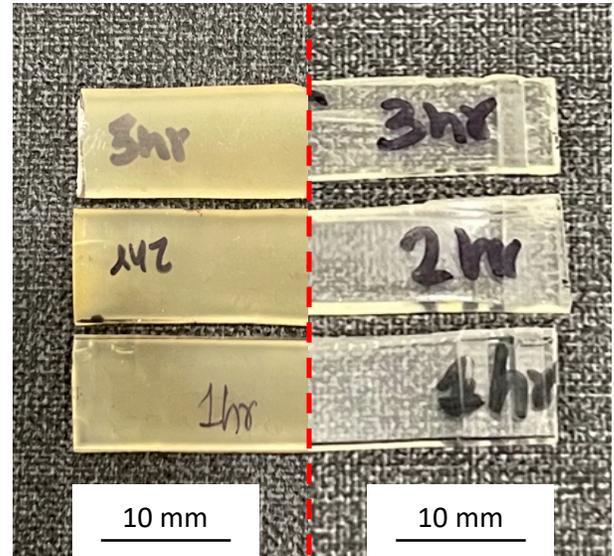


Figure 3: Images showing samples that were UVO treated and then shape recovered (left) and shape recovered before UVO treatment (right). Cropped images are shown side by side to emphasize difference in sample appearance.



Figure 2 UVO treated sample after shape recovery develops curvature on the end.

A similar effect of yellowness and discoloration was demonstrated by epoxies when exposed to UV radiation [14]. Long exposure of sample to UV radiation results in aging of the SMP. Polystyrene samples were smooth and uniform in nature before treatment with UV radiation. Surface roughness and brittleness increase with prolonged exposure to UV radiation due to oxidation of the polymer. With the increase in radiation exposure, degradation of surface becomes more visible.

### 3.2 DSC analysis

DSC samples prepared from each level of UVO treatment were exposed to similar heat-cool-heat cycles. A representative heat flow curve is shown in Figure 4 for a baseline sample. A glass transition temperature ( $T_g$ ) of 103.54°C was computed based on the midpoint of the transition in the heat capacity curve. No significant variation in  $T_g$  was measured for the levels of UV exposure performed in these experiments. With the long exposure of polymer under UV environment in other studies, oxidative degradation was encountered which weakened chemical bonds resulting in a breaking of the crosslinked structure on the exposed surface [15]. We anticipate that increased UVO exposure would have a similar effect on our polystyrene SMP and cause a shift in the glass transition temperature.

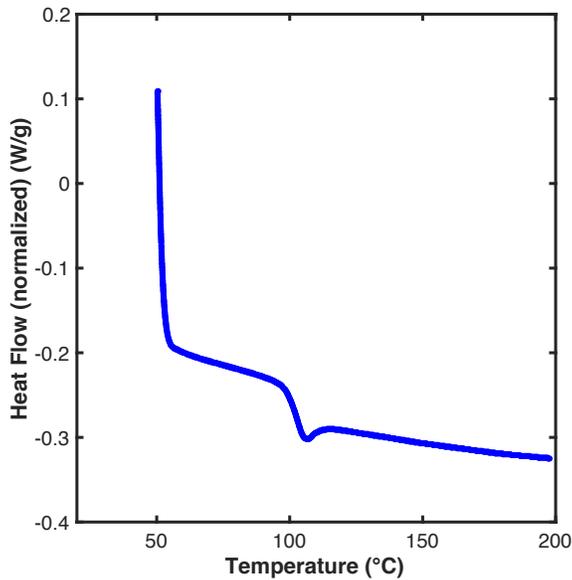


Figure 4 Representative heat flow curve for UVO exposed SMP.

### 3.3 Dynamical Mechanical Analysis

The process of shrinking the UVO treated sample for testing (relieving the pre-strain) resulted in undesired curvature and an increase in brittleness of the sample (Figure 2). This ultimately led to cracking of the sample upon loading in the DMA, as shown in Figure 5. This brittleness indicates the degradation of polymer in UV environment. Hence, these first experiment type samples were excluded from DMA testing.

For the second set of samples (shrink then UVO), thermomechanical properties such as storage modulus, loss

modulus and phase angle were evaluated using DMA in a torsion mode. The rectangular profiles of 8.30 mm wide and 1.50 mm thick samples were used for the experiment. Temperature sweep experiments were conducted from 80°C to 130°C in 5°C increments, and the angular frequency ranged from 100 rad/s to 1 rad/s with a strain of 0.1%. The soak time at the beginning of the experiment was 180 seconds and axial conditioning force of 2 N was applied.

The viscoelastic master curves are shown in Figure 6 (0 hour exposure), Figure 7 (1-hour exposure) and Figure 8 (2-hour exposure) and Figure 9 (3-hour exposure), which was obtained by shifting the experimental data using the time-temperature superposition principle. Above  $T_g$ , the curves are shifted using the Williams-Landel-Ferry (WLF) equation, given in Eq. (1).

$$\log a_T = \frac{-C_1(T-T_0)}{C_2+(T-T_0)} \quad (1)$$

Here,  $C_1$  and  $C_2$  are empirical constants,  $T$  is the temperature during testing, and  $T_0 = 100^\circ\text{C}$ . When reference temperature is equal to glass transition temperature, the values of constants were calculated by the TA Instruments Trios software [16] and are shown in Table 1. These coefficients indicate very small



Figure 5 UVO exposed then shape recovered sample broken after loading in DMA.

changes for the various UVO exposure times considered herein.

Table 1: WLF constants for UVO exposed samples.

UV Exposure duration (hrs)	C1	C2	Frequency of phase angle peak	Magnitude of phase angle
0	12.72	37.04	0.001949	4.306
1	13.86	44.71	0.001981	3.444
2	13.25	41.68	0.003140	3.261
3	13.34	43.16	0.007656	3.277

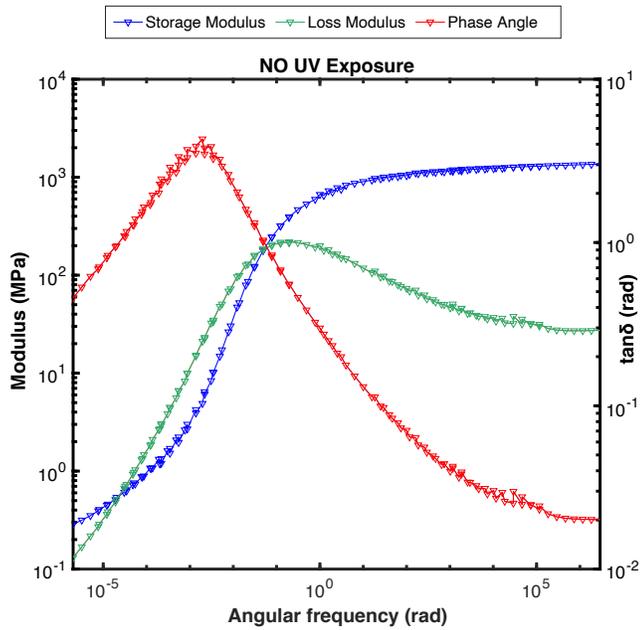


Figure 6 Viscoelastic master curve for sample with 0 hours of UVO treatment.

The storage modulus is around  $1000 \pm 70$ MPa for all three

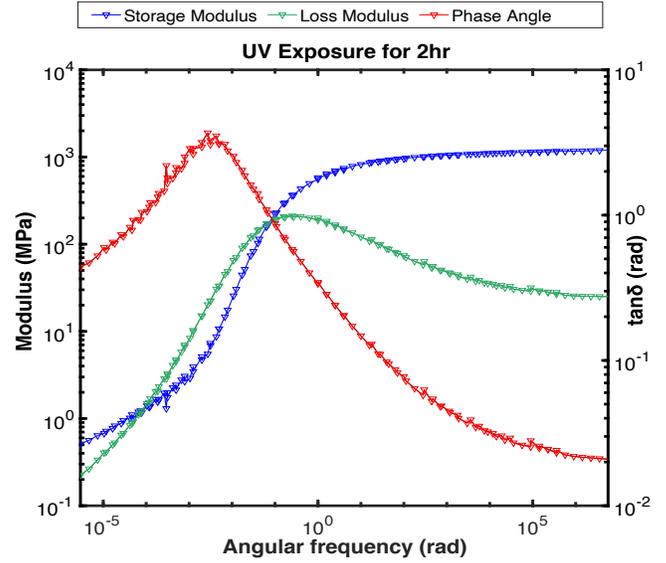


Figure 8 Viscoelastic master curve for sample with 2 hours of UVO treatment.

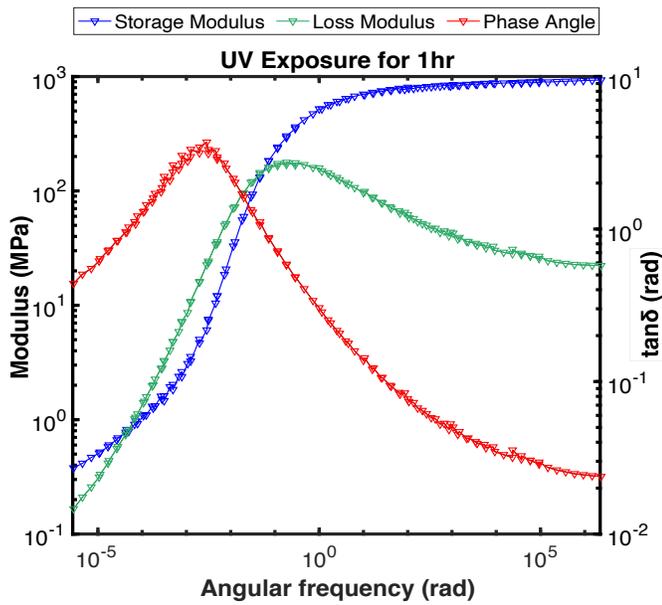


Figure 7 Viscoelastic master curve for sample with 1 hour of UVO treatment.

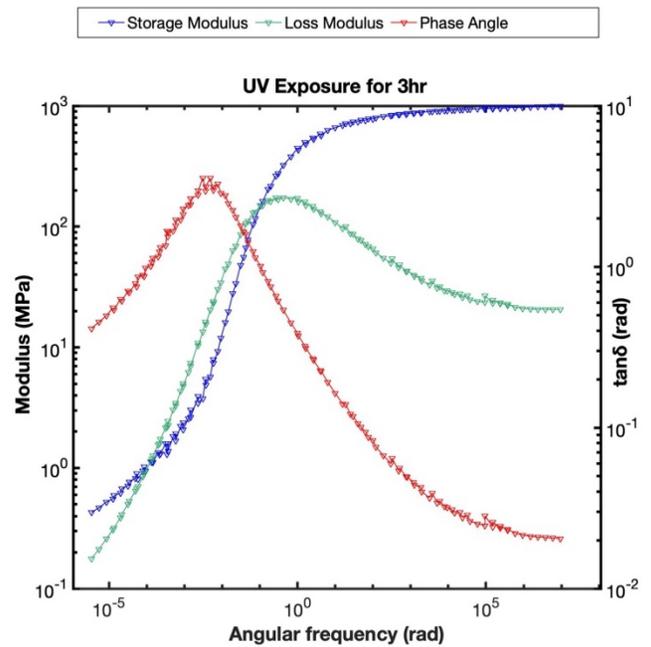


Figure 9 Viscoelastic master curve for sample with 3 hours of UVO treatment.

It can be seen from Figure 6, Figure 7, Figure 8, and Figure 9, the storage modulus gradually increases up to the point of glass transition before suddenly increasing to the glassy state, as expected for a viscoelastic material. The storage modulus differs by approximately two orders of magnitude and reach a constant value at high frequencies. Thereafter gaining a stable response for magnitudes of angular frequency in the order of  $10^4$  to  $10^6$ .

samples. Loss modulus follows the same pattern and start achieving constant value towards higher frequency in the range of 10-100 MPa. Due to the viscous nature of the polystyrene, a phase shift between the stress and strain exists known as damping factor ( $\tan \delta$ ). The damping factor reaches a peak during the glass transition. Frequency and magnitude of the peak values of the damping factor are reported in Table 1.

#### 4.0 DISCUSSION

It was shown in Figure 2 that longer exposure of polystyrene to UVO treatment leads to yellowing of the surface. This results from oxidation and possible degradation of the material. Furthermore, UVO treatment results in an increased brittleness and surface roughness of the sample. The order of shape recovery and UVO treatment plays a pivotal role in evaluating the viscoelastic properties of the SMP. UVO limits the shrinking on the side of the sample directly exposed to UV radiation, hence producing a curvature on the sample. Samples exposed to UV radiation after shrinking do not have any curvature on the surface of sample and are less brittle in nature. This is contrary to the results observed for samples that are UVO treated before shrinking. Viscoelastic curves for samples that were shape recovered then UVO treated with varying amounts of UV exposure were evaluated in the DMA. Viscoelastic response is almost similar at three different instants of exposure. However, a slight shift in frequency for the maximum  $\tan \delta$  is observed. Hence, the amount of UV exposure evaluated for 3 hours does not have a significant impact on mechanical properties of polystyrene. Degradation of material can result in dysfunction of components and lead to spacecraft failure. These experiments support in analyzing the viscoelastic behavior of polystyrene which can further be utilized as a material in designing space system

#### 4. CONCLUSION

Pre-strained polystyrene was exposed to UV radiation for replicating relevant space environments. Exposure of samples to UVO treatment results in yellowing of sample. When the material first treated with UVO and then heated to recover the prestrain, it loses its flexibility and the brittleness increases. Additionally, the sample curves due to reduced shape recovery of the UVO exposed surface. However, when the pre-strain is recovered first, and then exposed to UVO treatment, the sample becomes less yellow and does not curve upon shrinking. Temperature sweep experiments were performed in DMA to evaluate the effects of UVO treatment on the mechanical properties of the samples. Limited changed in viscoelastic properties were found during experiments. A part of each sample is tested in DSC to measure  $T_g$  of the material, and a negligible change in  $T_g$  was observed. For varying durations of UVO treatment, the evolution of mechanical properties was investigated using DMA. A slight shift in the peak damping factor was observed, which scaled with UVO treatment time. These experiments become instrumental in analyzing polymer behavior and serve in material research for space missions.

#### 5. FUTURE SCOPE

To replicate the space environment more accurately, specimen on ground can be tested under simultaneous vacuum and controlled temperature in UV exposure. Longer duration testing can provide better insight into the effects of long-term service in space. Since polystyrene is non-hygroscopic in nature, mass loss calculations can help in computing atomic oxygen erosion yield. Testing of certain polymers performed under controlled conditions will contribute to preventing space craft degradation.

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