SPACE ENVIRONMENT EXPOSURE RESULTS FROM THE MISSE 5 POLYMER FILM THERMAL CONTROL EXPERIMENT ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

It is known that polymer films can degrade in space due to exposure to the environment, but the magnitude of the mechanical property degradation and the degree to which the different environmental factors play a role in it is not well understood. This paper describes the results of an experiment flown on the Materials International Space Station Experiment (MISSE) 5 to determine the change in tensile strength and % elongation of some typical polymer films exposed in a nadir facing environment on the International Space Station and where possible compare to similar ram and wake facing experiments flown on MISSE 1 to get a better indication of the role the different environments play in mechanical property change.

1. INTRODUCTION

Thin film polymers are used in many spacecraft applications for thermal control (multi-layer insulation and sunshields), as lightweight structural members (solar array blankets, inflatable/deployable structures), and have been proposed for propulsion (solar sails). Polymers in these applications are exposed to the space environment and are vulnerable to degradation by solar ultraviolet radiation, solar flare X-rays, solar wind electrons and protons trapped in Earth's magnetic field, temperature and orbital thermal cycling, micrometeroids and orbital debris, and low Earth orbit atomic oxygen [1]. In applications where the polymer film is unsupported or is the structural member, it is important that the mechanical properties are not degraded beyond the limits set for its intended application. The Polymer Film Thermal Control Experiment (PFTC), first flown as one of many experiments on the Materials International Space Station Experiment (MISSE) 1, was designed to expose tensile specimens of a small selection of polymer films on ram facing and non-ram facing surfaces of MISSE 1 [2]. A more complete description of the NASA Glenn Resarch Center MISSE 1-7 experiments is contained in a publication by Kim de Groh et al [3]. The PFTC was expanded and flown as one of the experiments on the nadir facing side of MISSE 5 in order to examine the long term effects of the space environment on the mechanical properties of a wider variety of typical spacecraft polymers exposed to the anti-solar or nadir facing space environment. A total of 33 tensile specimen samples (11 different types of 3 samples each) were flown on the MISSE 5 PFTC Experiment. The results of the post flight testing of these samples are described in this paper.

2. MISSE 5 ENVIRONMENT DESCRIPTION

MISSE 5 was placed on the aft P6 Trunion Pin Handrail of the International Space Station (ISS) by the crew of STS-114 on August 3rd, 2005. The experiment was retrieved by the crew of STS-115 on September 15th, 2006 after 13 months in space. Figure 1 shows a photo of the position of MISSE 5 on the ISS. Estimated environmental conditions provided by G. Pippin and M. Finckenor [4] for the nadir side of MISSE 5 during deployment are given in Table 1. The estimated number of thermal cycles for MISSE 5 was about 6400. Temperature range was estimated from the experiment deck temperature for the Forward Technology Solar Cell Experiment on the solar facing side of MISSE 5 [5].

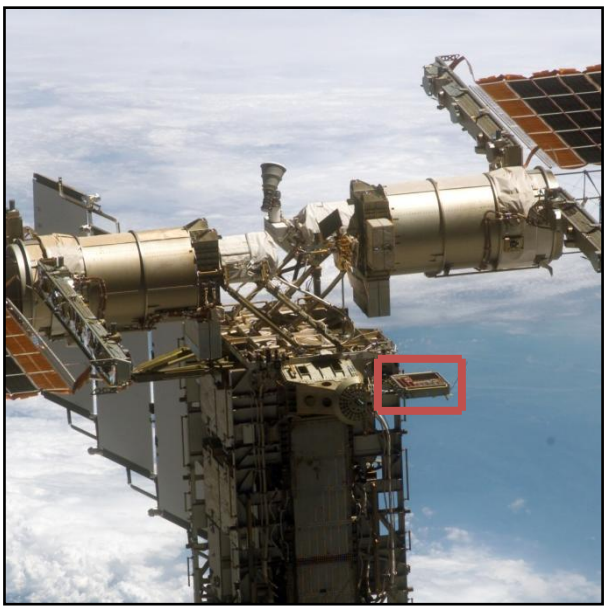

Figure 1. Photograph of MISSE 5 location on the ISS taken by the STS-114 crew (MISSE 5 can be seen inside the boxed-in area).

Table 1. Summary of estimated environmental conditions for nadir side of MISSE 5.

Environment	Dose
Atomic Oxygen (atoms/cm^2)	~1.8x10^{20}
Solar Exposure (equivalent sun hours, ESH)	165 ± 25 (direct) 360 ± 50 (Earth reflected) ~ 525 (total)
Temperature (^{o}C)	~+40 to ~-10 ~6400 thermal cycles
Ionizing Radiation (krads(Si))	~2.75 dose through 127 μm Kapton

Table 2. MISSE 5 PTFC Samples

Sample description and overall thickness	Polymer description	Polymer manufacturer
Teflon FEP (50.8 μm)	fluorinated ethylene propylene	DuPont
8% PTFE-SiO$_x$/ Teflon FEP (50.8 μm)	fluorinated ethylene propylene	DuPont
8% PTFE-SiO$_x$/ Upilex S (25.4 μm)	aromatic polyimide	UBE Industries, Ltd.
8% PTFE-SiO$_x$/ CP1 (25.4 μm)	fluorinated polyimide	SRS Technologies
Kapton E (50.8 μm)	aromatic polyimide	DuPont
Si/Kapton E/VDA (50.8 μm)	aromatic polyimide	DuPont
PTFE Teflon (76.2 μm)	Polytetrafluoro-ethylene	Saint-Gobain
8% PTFE-SiO$_x$/ PTFE Teflon (76.2 μm)	Polytetrafluoro-ethylene	Saint-Gobain
Kapton HN (50.8 μm)	aromatic polyimide	DuPont
8% PTFE-SiO$_x$/ Kapton HN (50.8 μm)	aromatic polyimide	DuPont
TOR LM (50.8 μm)	polyarylene ether benzimidazole	Triton Systems Inc.

3. PFTC EXPERIMENT DESCRIPTION, APPARATUS, AND PROCEDURE

3.1 Description of samples

The polymers that were exposed on MISSE 5 and evaluated for changes in mechanical properties are described in Table 2. Coated samples are indicated by a "/" separating each layer. The layers are listed in order from closest to farthest from the space-facing surface.

The 8% PTFE-SiO$_x$ (8% polytetrafluoroethylene-silicon oxide) coating is an ion beam co-sputter deposited coating approximately 100 nm in thickness that was applied at NASA Glenn Research Center [6]. It was deposited from a silicon dioxide target with a PTFE wedge sized to give an 8% volume fraction of PTFE with the remainder silicon oxide. The coating was added to provide protection from the atomic oxygen environment in order to filter out this environmental factor for better comparison. The coated Kapton E sample was received from the manufacturer with a vapor deposited aluminum (VDA) coating on the back of the sample of approximately 100 nm thickness for simulation of a back-side surface reflective layer. It also had an Si coating of unknown thickness on the front side.

Tensile test specimens for flight and backup were fabricated from the polymer materials described in Table 2 using a die manufactured according to specimen "Type V" under the American Society for Testing and Materials (ASTM) Standard D-638 [7]. The dog-bone-shaped die had a gage length of 7.62 mm and an average gage width of 3.21 ± 0.02 mm. Three dog-bone-shaped tensile test samples of each polymer type were selected to be the flight samples and these were taped to a polyimide Kapton blanket that comprised the nadir viewing side of MISSE 5 along

with other samples using alumium tape at the edge of each grip end. The samples were then stitched to the blanket through the tape to firmly hold the samples in place for flight. A photograph of the samples on the blanket is shown in Figure 2. After retrieval, the tensile samples were carefully cut from the blanket near the tape line to remove them from the blanket but leave enough grip length for testing.

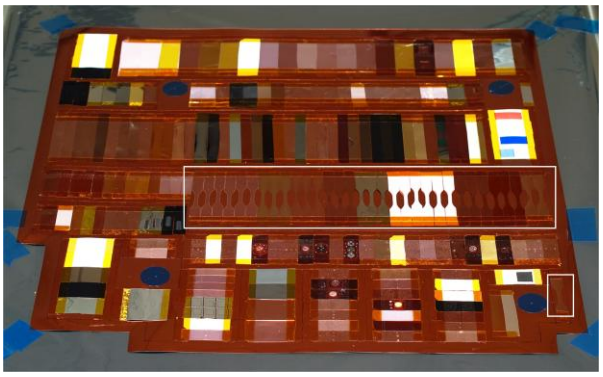

Figure 2. Kapton blanket with samples exposed on nadir side of MISSE 5. PFTC experiment samples are outlined in white

3.2 Tensile Testing

A DDL Inc. Model 200Q bench-top tensile tester manufactured by TestResources Inc. was used to test the MISSE 5 PFTC flight and control samples post retrieval. All of the samples were kept in the same controlled room environment with the tensile tester 48 hours prior to testing to eliminate variation due to change in the environment as recommended by ASTM Standard Test Method for Tensile Properties of Thin Plastic Sheeting D882-02 and ASTM D-638 [8 and 7]. Tensile tests were conducted according to ASTM D-638 [7], using a 444.8 N load cell and a strain rate of 12.7 mm/min. Each sample when loaded into the tensile holder was mounted in the grips with slack and then moved slightly with the motor drive to eliminate the slack without introducing initial tension on the sample. The initial grip separation was kept constant for all samples at 25.1 ± 0.9 mm.

Tests were conducted to obtain load-displacement data for each sample as well as the tensile (break at maximum load) or yield (yield at maximum load) strength (maximum load (N) divided by the original minimum cross sectional area (m^2) of the test sample) and the percent elongation at break (change in grip distance at break divided by the initial grip distance times 100).

4. RESULTS AND DISCUSSION

4.1 Initial observations

The PFTC flight samples were all intact with no evidence of tearing or breakage of the polymer post flight. There were, however differences in some of the flight samples in comparison to the controls. The uncoated polymer flight samples were more matte in appearance indicating some atomic oxygen erosion on the surface and the 8% PTFE-SiO_x coated CP1 showed evidence of surface cracking of the coating. Examples of both post flight conditions are shown in Figure 3. The remaining coated samples were very similar in appearance to their respective unflown control sample counterparts.

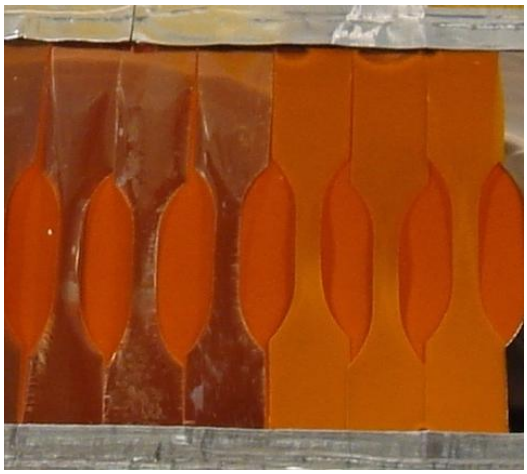

Figure 3. 8% PTFE-SiOx/CP1 (three samples on the left) showing evidence of cracking of the surface coating and uncoated Kapton E (3 samples on the right) showing matte surface post flight.

4.2 Load vs displacement

Load versus displacement data was measured on three flight samples and three controls for each of the 11 materials tested unless otherwise noted. The majority of the samples exhibited a region of Hookean behavior where the load vs displacement was linear. Most of these materials also exhibited a clean break at peak load. Both the coated and uncoated PTFE Teflon also had a fairly linear load vs displacement but failed by developing a v-notch on one side or the other within the gage length at a displacement near the point of failure which initiated a tear across the tensile specimen. Both the 8%PTFE-SiO_x coated CP1 and the TOR LM samples had non-linear load vs displacement curves with a yield point at maximum load. The load at

break was lower than the load at the yield point for these two materials.

For the majority of the samples the slope of the load vs displacement curves for the control and flight samples were very close to each other near the break point. Figures 4 and 5 illustrate typical load vs displacement curves for both linear and non-linear conditions respectively.

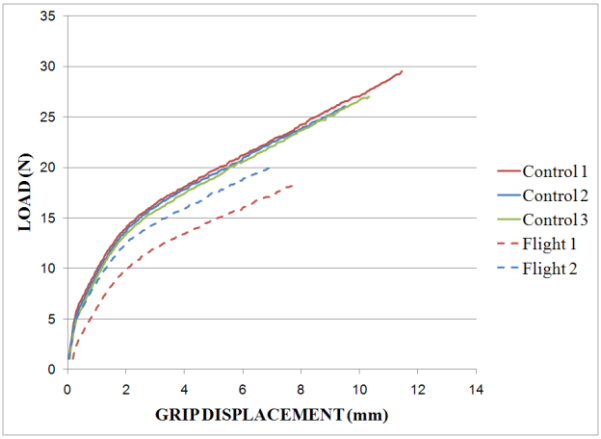

Figure 4. Load versus displacement for uncoated polyimide Kapton HN comparing control with flight exposed samples. Curve exhibits mostly linear behavior near break point.

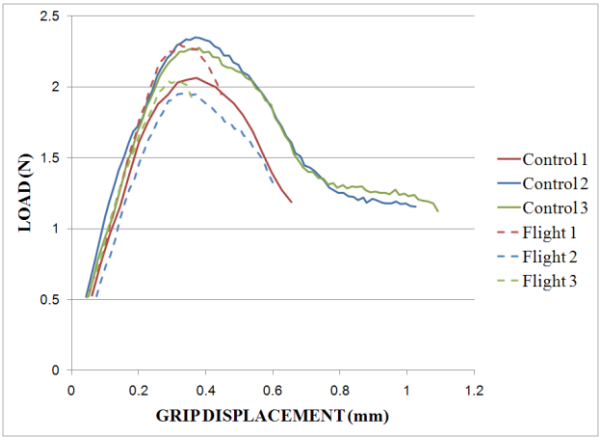

Figure 5. Load versus displacement for TOR LM comparing control with flight exposed samples. Curve exhibits mostly non-linear behavior near yield point.

The flight exposed uncoated and coated PTFE Teflon samples were the only samples to show a significant change in the slope of the load vs displacement curves. Figure 6 contains the load versus displacement curves for uncoated PTFE Teflon comparing flight and control samples. The curves for the coated PTFE Teflon were nearly identical. All of the PTFE Teflon samples failed by tearing from one edge to the other across the width of the narrowest part of the test sample. The other polymer samples appeared to fail more by breaking uniformly across the narrowest part of the test sample.

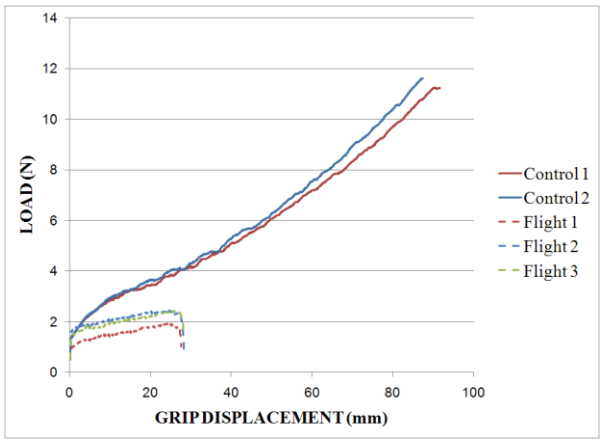

Figure 6. Load versus displacement for uncoated PTFE Teflon comparing control with flight exposed samples illustrating a change in slope of the curve for the flight samples compared to the controls.

4.3 Tensile strength and % elongation

Control and flight comparison data (tensile or yield strength and % elongation to break) for all sample types are contained in Tables 3 and 4. Both coated and uncoated FEP Teflon experienced a reduction in tensile strength (~30% and 45% respectively) and % elongation (~24% and 33% respectively) . It is difficult to know if shielding of the FEP Teflon from atomic oxygen by the thin film coating reduced the loss, however, because the difference between the values for the coated and uncoated FEP Teflon were within the error of the measurement as shown in Tables 3 and 4.

Coated and uncoated Kapton HN also experienced a loss in tensile strength (~18% and 41% respectively) as a result of exposure with the error being much less than the difference between the tensile strength values. One of the uncoated Kapton flight samples experienced uneven loading during testing and was not used in the data average. The data for the samples that were properly loaded indicates that the coating provided some protection to the surface which reduced the loss in tensile strength. Both the coated and uncoated Kapton HN experienced about the same level of reduction in % elongation (21% and 29% respectively).

Table 3. Tensile or Yield Strength comparison for samples flown on MISSE 5 and those kept on the ground as controls. *Denotes samples with yield point before break.

Sample Description	Tensile or Yield Strength (MPa)		
	Flight	Control	% Loss
Teflon FEP (50.8 μm)	7.9 ± 1.2	14 ± 1	45 ± 10
8% PTFE-SiO_x/Teflon FEP (50.8 μm)	10 ± 3	15 ± 2	30 ± 27
8% PTFE-SiO_x/Upilex S (25.4 μm)	280 ± 100	220 ± 80	-31 ± 61
*8% PTFE-SiO_x/CP1 (25.4 μm)	7.7 ± 11	21 ± 4	64 ± 57
Kapton E (50.8 μm)	120 ± 7	160 ± 8	22 ± 7
Si/Kapton E/VDA (50.8 μm)	150 ± 18	140 ± 12	-8.5 ± 15
Teflon PTFE (76.2 μm)	9.3 ± 1.3	47 ± 2	80 ± 6
8% PTFE-SiO_x/Teflon PTFE (76.2 μm)	11 ± 0.5	41 ± 6	74 ± 17
Kapton HN (50.8 μm)	120 ± 9	170 ± 14	41 ± 4
8% PTFE-SiO_x/Kapton HN (50.8 μm)	140 ± 10	170 ± 10	18 ± 8
*TOR LM (50.8 μm)	13 ± 1	14 ± 1	6 ± 12

Uncoated Kapton E also experienced a loss in tensile strength but the loss was about half the amount experienced by Kapton HN. The reduction in % elongation for the uncoated Kapton E, however, was within error of that for uncoated Kapton HN. The Si/Kapton E/VDA samples did not show a statistically significant change in tensile strength or elongation indicating that the coating protected the Kapton E from being affected by the environment.

There was a great deal of variation in the coated Upilex S samples. The error was much larger than the change in tensile strength or the change in % elongation for these samples so it is difficult to draw any meaningful conclusions. The samples had a mottled appearance as

Table 4. % Elongation comparison for samples flown on MISSE 5 and those kept on the ground as controls.

Sample Description	% Elongation		
	Flight	Control	% Loss
Teflon FEP (50.8 μm)	150 ± 15	220 ± 7	33 ± 8
8% PTFE-SiO_x/Teflon FEP (50.8 μm)	170 ± 31	230 ± 4	24 ± 14
8% PTFE-SiO_x/Upilex S (25.4 μm)	13 ± 1	13 ± 2	-4 ± 15
8% PTFE-SiO_x/CP1 (25.4 μm)	1.6 ± 2.2	3.3 ± 1.0	53 ± 75
Kapton E (50.8 μm)	22 ± 2	27 ± 0.9	20 ± 8
Si/Kapton E/VDA (50.8 μm)	20 ± 3	18 ± 2	-13 ± 21
Teflon PTFE (76.2 μm)	110 ± 2	350 ± 12	68 ± 4
8% PTFE-SiO_x/Teflon PTFE (76.2 μm)	110 ± 7	310 ± 28	63 ± 11
Kapton HN (50.8 μm)	29 ± 3	41 ± 4	29 ± 12
8% PTFE-SiO_x/Kapton HN (50.8 μm)	34 ± 3	44 ± 3	21 ± 10
TOR LM (50.8 μm)	1.9 ± 0.5	3.7 ± 0.9	49 ± 30

if the polymer were a mixture rather than a uniform polymer film. The coated CP1 samples and the TOR LM samples both broke at lower stress than their yield points. These samples were again mottled in appearance and had wide variation in the data. Both the CP1 and TOR LM samples had very low % elongation to break. Two of the CP1 flight samples broke while in the grips just before the load was applied. The TOR LM % elongation was reduced upon flight exposure but the yield strength change was within the error of the measurement. The opposite is true for the coated CP1 sample. That data indicated a reduction in yield strength but the error in the measurement for the % elongation was larger than the change.

Coated and uncoated PTFE Teflon experienced the greatest loss in tensile strength (~74% and ~80% respectively) and elongation (~63% and ~68% respectively). The presence of a coating did not appear to play a significant role in the change indicating that atomic oxygen did not play a large role in the loss in mechanical properties. In fact, for the majority of the samples where there was a comparison between a coated and uncoated polymer sample of the same type, atomic oxygen did not appear to play a great role in the reduction of bulk mechanical properties such as % elongation. The tensile strength however did appear to be reduced for many of the uncoated counterparts although the thickness loss was insignificant for these calculations. The loss in tensile strength may be due more to a change in surface texture as a result of atomic oxygen erosion causing uneven stress on the surface leading to the polymer breaking at lower overall loads.

4.4 Comparison with MISSE 1 data

MISSE 1 experienced nearly 4x more thermal cycles over roughly the same temperature range and nearly a 4x higher radiation dose than MISSE 5 [2]. There was also ~11x more equivalent sun hours (ESH) of vacuum ultraviolet radiation (VUV) on the ram side of MISSE 1 and ~9.6x more ESH of VUV radiation on the wake side of MISSE 1 than on the MISSE 5 nadir viewing side [2].

Unfortunately not too many of the tensile samples flown on MISSE 1 could be compared with those flown on MISSE 5 because of sample breakage on MISSE 1 and some differences in the types of samples flown. CP1 was flown on both experiments but the polymer was from different lots and the initial (control) yield strength and % elongation were very different (about 4x and 2x higher for the MISSE 1 control than the MISSE 5 control respectively) so it was difficult to make direct comparisons.

Upilex S flown on the ram side of MISSE 1 experienced a 36% loss in tensile strength and a 68% loss in elongation [2]. The spread in the MISSE 5 tensile strength data is very large so it could be similar to the MISSE 1 results. The control mechanical properties are within error of each other. The % elongation data for MISSE 5, however, had less variation and experienced a negligible change in comparison to the 68% loss on MISSE 1.

The only other sample type flown on MISSE 1 and MISSE 5 that could be compared was coated FEP Teflon flown on the ram side of MISSE 1. The control data for the mechanical properties between MISSE 1 and MISSE 5 were again within error of each other. The % loss in tensile strength for the MISSE 1 sample was 30% [2] in comparison to ~30% on MISSE 5. So essentially there was no difference in loss of tensile strength between the two very different environments. It may be that the environment affects the tensile strength for FEP Teflon up to a limit and beyond the limit, there are no further changes. There was however a difference in % elongation between the MISSE 5 and MISSE 1 samples. The MISSE 1 coated FEP sample had a 73% loss in elongation [2] compared to the ~24% loss on MISSE 5 which is about a factor of 3 difference. It is interesting to note that the uncoated FEP Teflon flown on the wake side of MISSE 1 had very similar values for loss in tensile strength and % elongation (23% and 85% respectively) [2] in spite of the difference in VUV illumination. MISSE 5 had a much lower VUV radiation dose, but it also had a lower number of thermal cycles and less ionizing radiation than MISSE 1. Either there is a VUV damage limit or the other environmental factors play a larger role in the loss in mechanical properties. Further testing separating out each environmental factor is needed in order to determine which constituent of the environment or combination is causing the greatest damage.

5. CONCLUSIONS

The majority of the samples flown on MISSE 5 experienced some loss in tensile or yield strength and % elongation as a result of exposure to the environment except for Si/Kapton E/VDA and 8% PTFE-SiO_x/Upilex S which had larger variation in the sample measurements than the % loss that was calcuated. Protected Kapton HN, Kapton E and FEP Teflon all had similar losses in % elongation to their uncoated counterparts. All of these coated samples however had less of a loss in tensile strength than their uncoated counterparts, although for FEP Teflon it was within the error of the measurement. Since the Kapton samples had noticeable surface texture due to atomic oxygen

erosion but no significant thickness loss, it is possible that the texture may give rise to stress points on the surface that cause the samples to break at a lower peak load. The greatest loss in tensile strength and elongation was exhibited by the uncoated and coated PTFE Teflon samples. In this case, failure was dominated by some other component of the environment than atomic oxygen since both the coated and uncoated PTFE experienced nearly the same losses. Comparing MISSE 1 and MISSE 5 test results indicated that the loss in tensile strength for the coated FEP Teflon samples was independent of the VUV and radiation levels or number of thermal cycles indicating that there may be a damage limit which MISSE 1 and 5 both exceeded for this property. The % loss in elongation, however was greater for coated Upilex S and coated FEP Teflon flown on MISSE 1 showing that there is an environmental exposure dependence for this property. The levels at which changes occur, and which environment factor or combination of factors causes these changes is unclear and needs further investigation in experiments where these factors can be controlled or eliminated independently.

6.0 ACKNOWLEDGEMENTS

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