NASA / CR-2000-210101

Simulated Space Environmental Testing on Thin Films

Dennis A. Russell, Larry B. Fogdall, and Gail Bohnhoff-Hlavacek
The Boeing Company, Seattle, Washington

April 2000

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at *http://www.sti.nasa.gov*

- Email your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Telephone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076-1320

NASA / CR-2000-210101

Simulated Space Environmental Testing on Thin Films

Dennis A. Russell, Larry B. Fogdall, and Gail Bohnhoff-Hlavacek
The Boeing Company, Seattle, Washington

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
under Purchase Order L-9162

April 2000

Available from:

NASA Center for AeroSpace Information (CASI)
7121 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

TABLE OF CONTENTS

ABSTRACT

An exploratory program has been conducted, to irradiate some mature commercial and some experimental polymer films with radiation simulating certain Earth orbits, and to obtain data about the response of each test film's reflective and tensile properties. Protocols to conduct optimized tests were considered and developed to a "prototype" level during the program.

A test fixture to provide a particular configuration for the films during irradiation, was designed and custom-manufactured. This fixture featured controlled exposure areas, and protected the ends of the samples for later gripping in tensile tests. Fifteen polymer film specimens were then arranged on this fixture, and installed in a clean vacuum chamber where protons, electrons, and solar ultraviolet radiation could simultaneously irradiate the films. Near-realtime UV rates were used, whereas proton and electron rates were accelerated appreciably to simulate 5 years in orbit during a planned 2-month test. Periodically, the spectral reflectance of each film was measured *in situ*. After the end of the irradiation, final reflectance measurements were made *in situ*, and solar absorptance values were derived for each specimen. The samples were then measured in air for thermal emittance and for tensile strength.

Most specimens withstood irradiation intact, but with reduced reflectance (increased solar absorptance). Thermal emittance changed slightly in several materials, as did their tensile strength and elongation at break. Conclusions are drawn about the performance of the various test films, and some recommendations are made for future consideration.

ACKNOWLEDGMENTS

The authors wish to thank Dr. John Connell of NASA for discussions that guided this program, Dr. M. J. Meshishnek for his helpful discussions including the environment depth-dose calculations, and Mr. W. Blackwell for valuable discussions on his preliminary environment definition study.

The authors also thank Dr. Werner Winkler of Bonn, Germany for the opportunity to hold complementary discussions on methodologies for property measurements. Dr. Winkler, then of the German Space Agency GfW (Gesellschaft fur Weltraumforschung), collaborated with NASA and industry in the formulation of technical approaches to the successful execution and outcomes of the near-Sun Helios spacecraft missions of the 1970s. This program benefited from Dr. Winkler's review of several principles and approaches utilized then, and factors that could be considered in programs of various scopes. These discussions are reflected in some of the content of the Introduction, and the Experimental Approach.

The authors appreciate the contributions of the following individuals during the course of this program. Loren D. Milliman for scientific data programming, James Beymer for fixture design and CAD support, Douglas Franich for test setup and monitoring, Jerry Hobson and staff for tensile strength measurements and analysis, and Robert Duby for emittance measurement support.

INTRODUCTION

As NASA's space programs become more and more advanced it is necessary to consider, and in appropriate cases to incorporate, more advanced test techniques and methods in the evaluation of candidate materials. The orbital environment, however simple or complicated, demands test approaches that are truly applicable to the situation. Research performed with sufficient sophistication and accuracy, and which utilizes proven test techniques, speeds adoption of the best materials and subsystems for new missions and programs.

The materials evaluation program being reported herein takes advantage of several concepts previously developed. In the USA, the flexibility and availability of ground facilities that simulate space well, while certainly not ubiquitous or all-encompassing, is still diverse enough that some judicious choices can be made in selecting the exact ways in which test results will be acquired. There is diversity in the kinds of space radiation that can be simulated. There are selections that can be made regarding the ways in which candidate materials can be prepared, irradiated and evaluated. Consideration can be given to how those materials would actually be used, or contemplated for use, in space.

The materials being evaluated in the program reported here are, in some cases, derivatives of earlier work. Several earlier programs investigated materials and applications bearing some resemblance to the films of current interest. Just prior to several appendices for this report, some previous concepts and developments are referred to, or briefly described, in a References list.

SUMMARY

This program, "Simulated Space Environmental Testing on Thin Films," has evaluated certain key properties of flexible polymer films in radiation environments simulating space. NASA seeks advanced materials, including such films, for future missions where the performance of present materials is unknown or is in doubt. In general, materials on spacecraft will be subjected to the deleterious effects from protons, electrons, and solar ultraviolet radiation. In some cases there will be additional adverse kinds or levels of radiation.

In this program, Boeing undertook the radiation testing of a variety of polymer films supplied by NASA-Langley Research Center. The films range from experimental polymers available only in small quantities, to polymers similar to those commercially developed and available. Thickness of the test films was nominally 13 micrometers (0.5-mil). Boeing utilized its main radiation facility in which protons, electrons, and ultraviolet radiation can be beamed together onto an array of test specimens for combined, simultaneous evaluation of their response to radiation. The radiation exposure levels were the combined beams of 40-keV protons to a fluence of $1x10^{15}$ p/cm^2, 40-keV electrons to a fluence of $8x10^{15}$ e/cm^2, and 1000 equivalent UV sun hours.

Special efforts were made to irradiate the supplied films in a manner that would achieve an overall evaluation that simulated space optimally. We needed control over the configuration of each sample to define its orientation with respect to the irradiation beam direction(s), and its

orientation with respect to an optical beam performing measurements of spectral reflectance *in situ.* We needed to provide for both a central test-section that would be irradiated, while also providing for significantly long end-sections that were not to be irradiated. These end-sections were kept shielded and intact for gripping during tensile property tests later. They also provided unaltered comparison sections of the test materials during post-test emittance measurements.

In space, a film's application might dictate that it not be in contact with any other structure or material. That would define or affect thermal contact and/or electrostatic control. We approached this situation by draping each film sample over a nearly flat mandrel section, and securing the ends of each sample behind its mandrel. We partially decoupled the mandrel thermally from the chamber's baseplate cooling. We then formed 3 such mandrels into a compact array for 15 specimens to be irradiated (except for their protected ends) within an available 75 mm by 75 mm (3" x 3") space located centrally in the test chamber. All sections of the test fixture were at chamber electrical ground throughout the test.

Given the test objectives and the films' physical arrangement, the relevant properties of solar absorptance, thermal emittance, and tensile strength with its related parameters of modulus and elongation under stress, were the most critical to study. Table 1 and the following paragraphs summarize the experimental results obtained:

Table 1. Summary of Results

Measurements / **Materials**	**Solar Absorptance**	**Thermal Emittance**	**Apparent Modulus**	**Failure Stress**	**Failure Strain**
Kapton E	Small change	Small Change	Slight Change	Decrease	Large Decrease
Kapton HN	Small change	Small Change	Slight Change	Decrease	Large Decrease
Upilex S	Small change	Small Change	Slight Change	Decrease	Some Decrease
CP-1	Doubled	Some change	Slight Change	Decrease	Decrease
CP-2	Doubled	Small Change	Slight Change	Decrease	Decrease
TOR - RC	Doubled	Small Change	Slight Change	Decrease	No change
TOR - LMBP	Samples Disintegrated				

<u>**Solar Absorptance**</u>: We computed coefficients of this basic parameter, based upon spectral measurements of sample reflectance made *in situ.* The reflectance of all test-film specimens decreased after exposure to simulated space radiation. Thus the computed values of each sample's solar absorptance increased as exposure to radiation continued, to the end of the test without saturation. Certain films that were colorless prior to irradiation became considerably more absorptive (a "bronze" color) during irradiation. All the quantitative values obtained *in situ* are given in the Experimental Results section (page 12). In summary, the polymers that originally were colorless, more than doubled their solar absorptance (from about 0.2 to nearly 0.5). Five Kapton specimens increased about 0.07 in solar absorptance, from base values of about 0.3. Upilex S was slightly more stable for solar absorptance, increasing about 0.06 (from base values of about 0.35).

Two specimens of TOR-RC nearly tripled in solar absorptance by the end of the test (from base values approximately 0.2). Two specimens of another TOR film, namely TOR-LMBP, distorted and then disintegrated during the first quarter or so of the test period. Consequently, TOR-LMBP could not be tested for reflectance/absorptance during the remainder of the irradiation test, nor for emittance or tensile properties following irradiation. Early results on TOR-LMBP indicated it might be slightly more reflectance-stable than TOR-RC.

Figure 1 summarizes the solar absorptance data obtained on each of the irradiated polymer films. The solar absorptance values computed on individual specimens of each type of film were averaged for presentation in Figure 1. The experimental data divide into two principal "performance zones," one of them based on much more stable reflectance after irradiation, as described in the text above. The <u>changes</u> in solar absorptance from Kapton and Upilex samples remain less than 0.1, whereas the solar absorptance <u>changes</u> in TOR and CP film samples rise to more than 0.3 without saturating.

In Figure 1 the exposure values have been stated in terms of number of months in Earth orbit. The exposure parameters are discussed in detail in the Radiation Environment section. Figure 1 also indicates the approximate amount of experimental uncertainty, namely about ±0.01; this uncertainty is shown as "error bars" along the uppermost data series. The same uncertainty applies to every data series. The appearance of temporary "plateauing" of degradation in the more stable films partway through the test is within the band of experimental uncertainty.

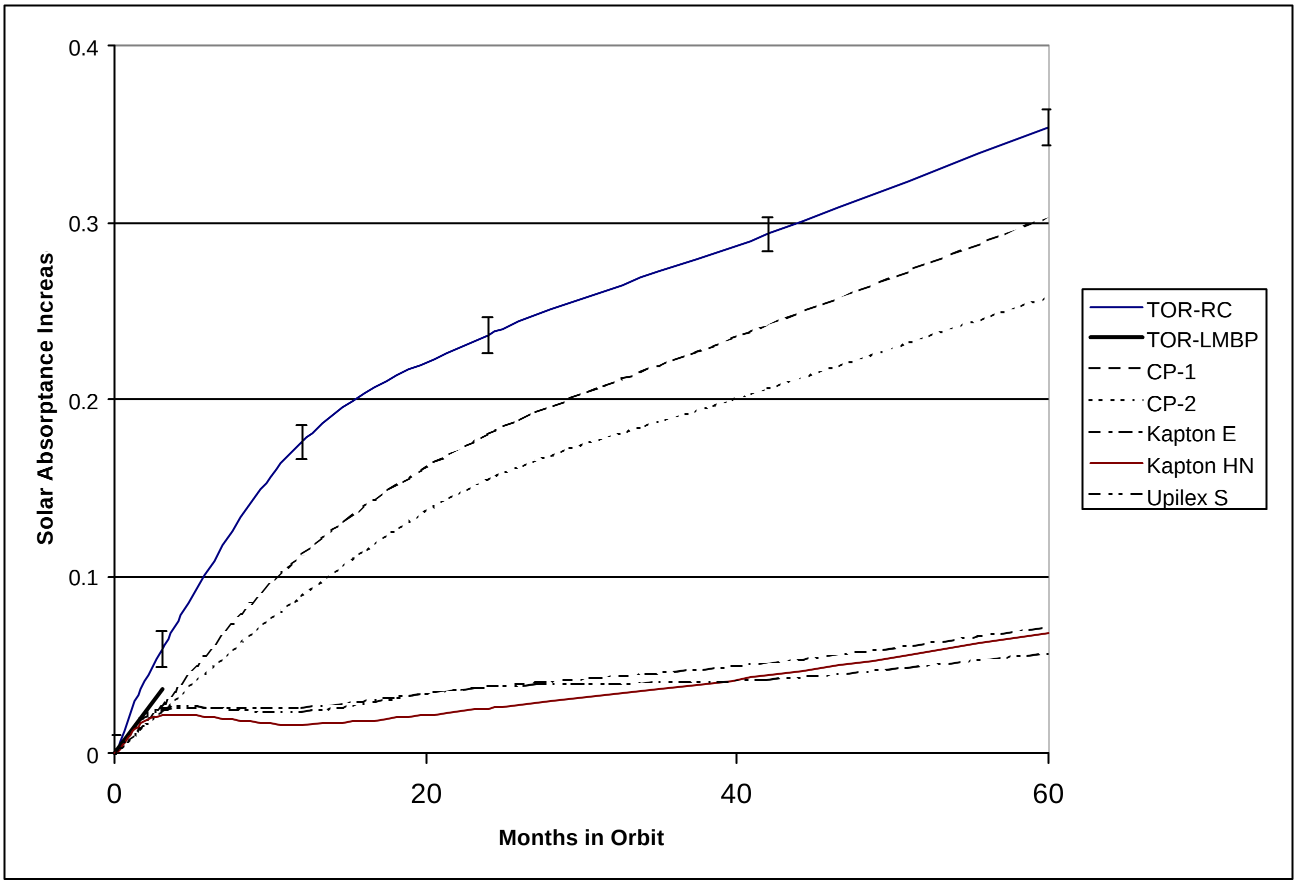


Figure 1. Increase in the Solar Absorptance of Metalized Polymer Films Due to Irradiation

Thermal Emittance: Several films indicated small changes in thermal emittance as a result of irradiation, according to measurements made in air following the test. We performed one "batch" or run of emittance measurements, during which we measured exposed specimens alternately with unexposed comparison samples and traceable reference-standard samples. This approach, along with continually correcting for small amounts of "drift" displayed by the measuring apparatus, assured that experimental uncertainty was small, on the order of 0.01, during the measurements.

The thermal emittance of polymer CP-1 increased about ten percent in air (from about 0.47 to about 0.51 decimally) as a result of the combined UV/proton/electron irradiation performed. The emittance of CP-2 and TOR-RC increased perhaps half as much. The emittance values measured on Kapton remained essentially unchanged within experimental uncertainty. The thermal emittance values measured on one Upilex-S sample are "borderline" as to whether they are real changes, or within experimental limits. All exact quantitative values obtained in these measurements are displayed in the Experimental Results section (page 13).

Tensile strength: Based on tensile property measurements made in air following the test, the failure stress of every type of polymer film decreased as a result of being irradiated. (For Upilex and TOR-RC, the preceding statement applies to the average values of several unirradiated specimens and several irradiated specimens.)

The apparent failure strain (as a percent of original gage length) of every type of polymer film except TOR-RC, decreased as a result of irradiation. The decrease was "dramatic" in Kapton. Apparent modulus generally decreased (but only slightly) due to irradiation. Specific values are in the Experimental Results section (page 14).

Photographs of all the tested films show varying amounts of visual change, such as curling or other distortion, due to irradiation. Some of the photos (Appendix A) also show that some end sections were altered by manipulation of the fragile films prior to the irradiation test. Nevertheless, all the end-sections on the films that survived irradiation were adequate for the intended purposes.

There was apparent shrinkage in the lengths of the TOR-RC films. The Experimental Results section of this report details all quantitative values obtained.

EXPERIMENTAL APPROACH

Radiation environment. It was the goal of the program to provide a 5-year simulation of two regions of space, the environment at 0.98 astronomical units (AU) where the Geostorm satellite will orbit, and the environment at the second Lagrangian point (L2) where the Next Generation Space Telescope (NGST) will be positioned. The Geostorm location between the Sun and the Earth is far beyond the influence of the Earth's magnetic field, making the environment of interest that of the solar wind and solar events. The L2 position, on the other hand, is located on the far side of the Earth away from the Sun. At this position, a spacecraft would pass through the Earth's geotail created by the interaction of the geomagnetic field with the solar wind. It was found that by far the major contribution to both environments was from the solar wind.

The electron and proton fluence levels were determined by first generating a dose depth profile for a representative material (Kapton in this case) for the solar wind at L1. The goal then is to approximate this profile with the beam energies available in the chamber. This was accomplished by generating a test protocol that used 40-keV protons with a range of 0.52 micrometers (0.02 mils) to deliver the very high dose indicated near the surface, which is the region that most influences optical measurements. Electrons of 40-keV energy with a much deeper dose depth profile were used to deliver the bulk dose, which is the region most influencing the material properties. Figure 2 shows the dose depth curves for both the environment and the simulation.

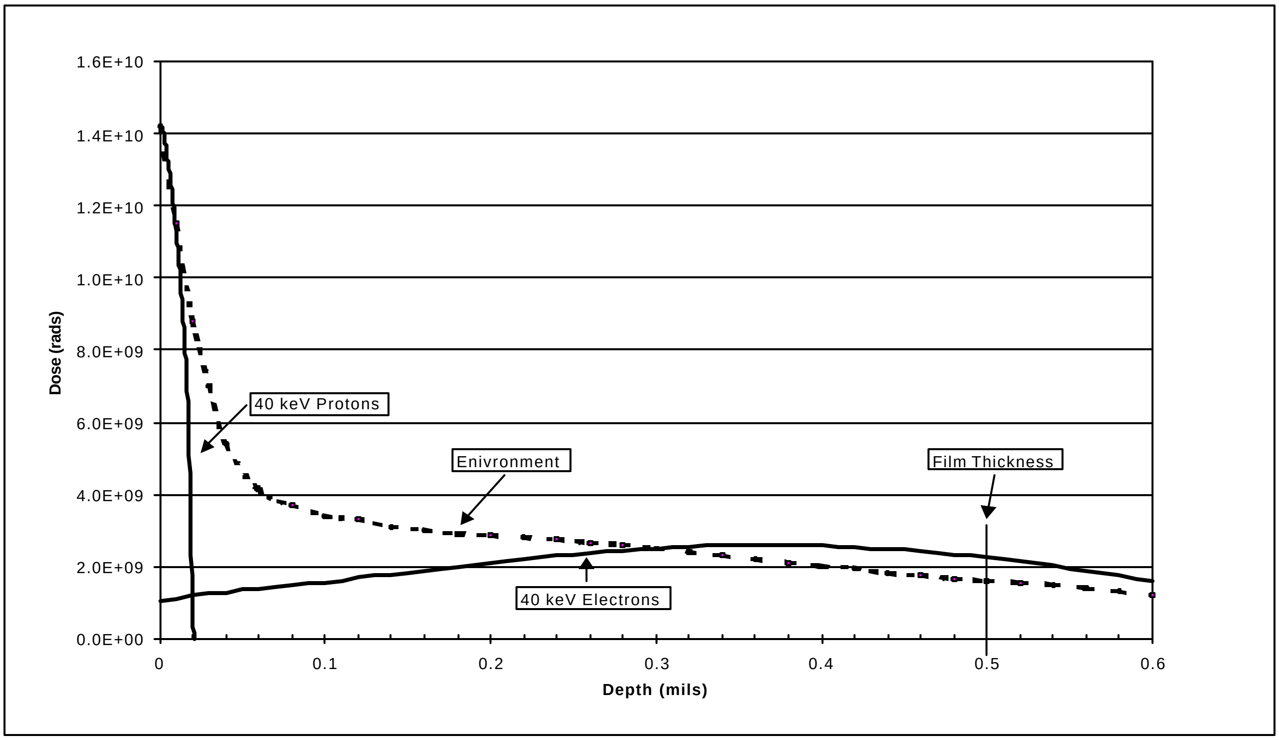


Figure 2. Depth - Dose Profile – 5-Year Environment and Simulation

Experimental apparatus. Boeing's main simulation facility for space radiation with selected *in situ* measurement capabilities is the Combined Radiation Effects Test Chamber (CRETC) located at the Boeing Radiation Effects Laboratory in Seattle. It has been utilized in many programs similar to this one, including cases reported in the literature and others not reported. CRETC has "clean" vacuum with cryopumping, and it features the ability to combine UV (and longer wavelength light) with protons and/or electrons. The UV is continuum radiation from a xenon arc that closely simulates the Sun's output between 200 and 400 nm. CRETC proton and electron fluxes are available between energies of about 10 keV and 50 keV.

Figure 3 is a top view of the chamber showing the positioning of the proton, electron, and UV sources relative to the sample array as well as the position and travel direction of the integrating sphere.

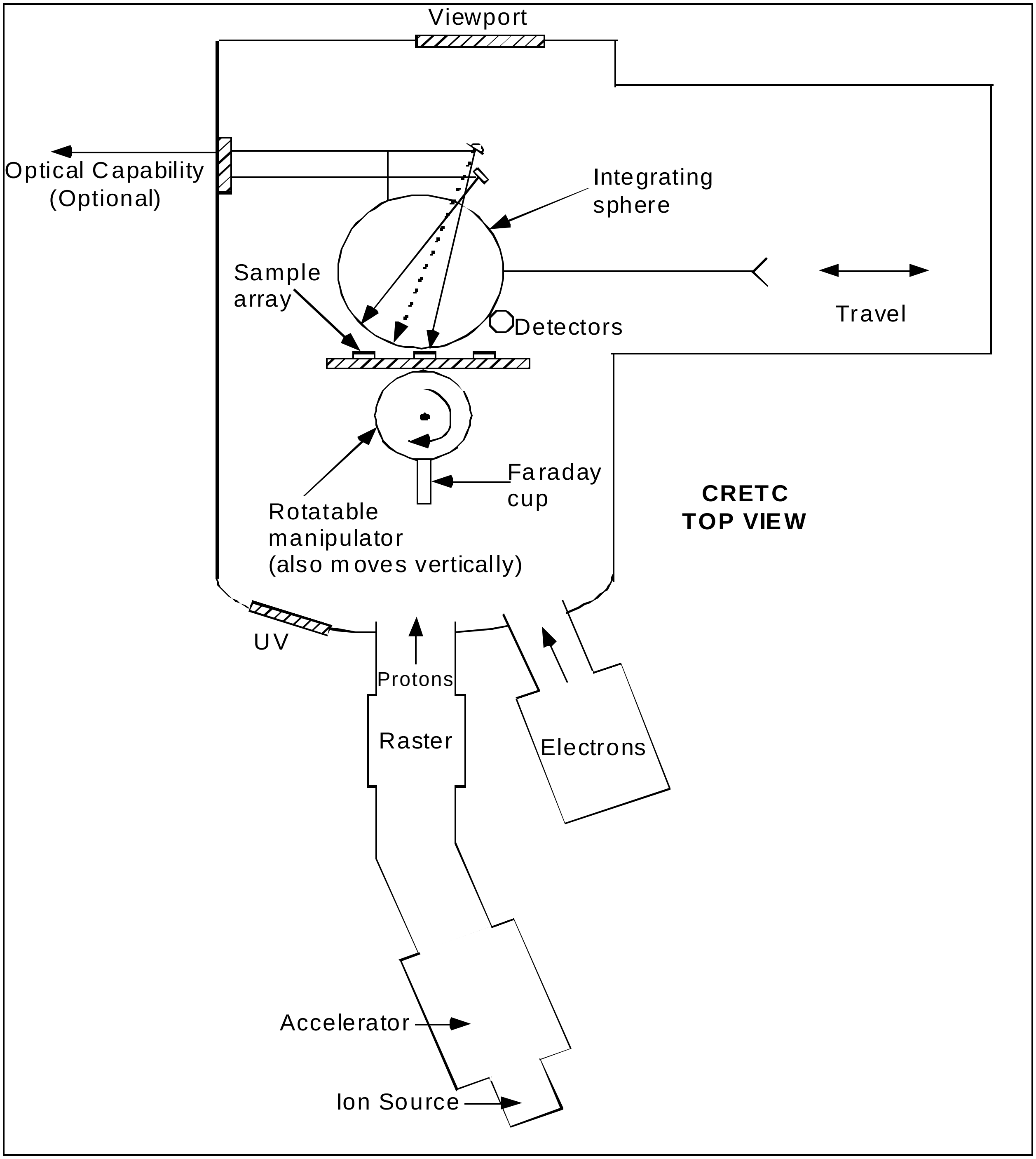


Figure 3. Combined Radiation Effects Test Chamber

When preparing this apparatus for this test, Boeing measured UV intensity across the overall beam-space that the specimen array would occupy. We found that UV intensity would be uniform within ±10 percent across the array of specimens when using a UV intensity approximately 1.5 UV suns. (One total sun is approximately 0.135 watt/cm^2; the sun's UV content is approximately 9.1% of its overall output, for a value of approximately 0.12

watt/cm^2/UV-sun.) The areas of lowest UV intensity are small portions of the four corners of the array-space.

Characteristics of the proton and electron beams were determined with Faraday cups that track the chamber horizontal and vertical centerlines (bisecting the array of specimens). We determined that the 40-keV electrons were quite uniform to ±5%. The 40-keV proton beam, which is rastered with significant overlaps to provide uniformity along with a larger beam size, was uniform to ±15 percent over the sample array. See the Discussion section (page 15) for further comments regarding off-axis beam characteristics.

Test materials. Boeing irradiated government-supplied test materials in this program. The polymer films were received inside transparent plastic protective sheets. We inspected each type of polymer film, partly in order to estimate how much material we had to work with – how many spares and comparison samples we could fabricate and have available. For the experimental polymers, only a limited amount of film was available, nominally 50 to 80 square inches, but in some cases irregular in shape. We considered along with this, how to develop the most effective use of specimen exposure area(s) in the available combined radiation beam area. These mutual considerations helped establish a central exposure zone for each specimen with an area of approximately 16 mm wide and 20 mm long.

Test-sample fixturing. Boeing designed a custom test fixture sized for specimens approximately 75 mm (3 inches) long and 16 mm (0.65 inch) wide, with a central exposure and test section about 20 mm (0.8 inch) long. A computer-aided design approach was utilized. Many iterative steps to optimize all features were taken prior to fabrication in our shop.

One such feature was a thin shield between the rows of test specimens, to provide for a definite location for the ends of each central irradiation section. We considered simply letting the wrap-around areas of each specimen, leading to the protected end/grip areas, be the means to define graduated edges for the exposed sections, but adverse experience in previous programs indicated that a design with an effective shield, defining an abrupt edge, is preferable.

Figure 4 is an "exploded" view of the custom test fixture. The thin shield is the uppermost piece shown in the diagram. The features that appear in Figure 4 like stair-steps are the mandrel-like devices that secured each test specimen in place during irradiation.

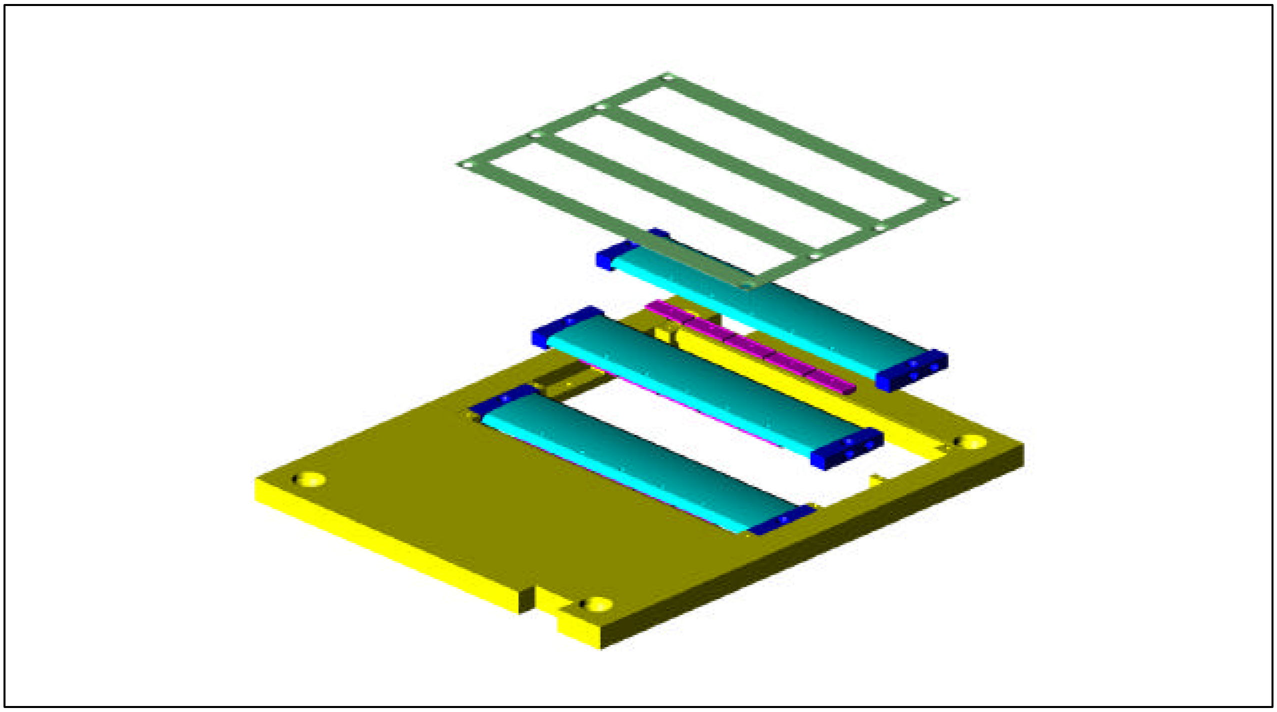


Figure 4. Exploded View of Sample Fixture

Specimen preparation and installation. As received, the films were not identified as to machine direction, nor with any indication of preference for orientation. Some, but not all of the polymers showed extrusion lines or other indications of directionality. The metalized side of the films was not indicated. For the colorless polymers it was difficult to discern which was the metalized side. Microscopy was used to determine machining direction as well as to assure that the films would be exposed as second-surface mirrors.

Microscopy also revealed pinholes and other defects in the experimental films. The commercial films appeared to have very good quality.

The preparation of individual specimens began with experiments in film-cutting methods. Many fresh, cleaned scalpels and a mask-like tool were used. The more fragile experimental polymer films were the most difficult to cut. Samples that developed ragged edges or tears were not used for irradiation, but were saved as extra controls. Successful test specimens and good control samples were stored in a container on a clean bench with laminar airflow control until needed for sample integration onto the sample plate.

The fabricated test fixture was wiped with isopropyl alcohol, then ultrasonically cleaned in a detergent wash and rinse, and finally given an ethanol solvent rinse and dry.

Sample integration was performed using cleanroom gloves inside a clean laminar flow bench. The first step of the integration was to attach the cut specimens to their holding bars (each bar is described elsewhere as like a section of a very slightly curved mandrel). Small pieces of Kapton tape were used as needed to aid the initial securing of specimen ends behind their hold-down metal strips. One at a time, each specimen was then wrapped "down" and over the front surface of its mandrel, then looped over the top and back of the mandrel, whereupon small weights were attached to each sample's bottom grip area, to keep each specimen in mild tensile stress, but with freedom to shrink or elongate in response to radiation. See Appendix A. The front cover shield was then attached, to define the overall exposure area of each specimen exactly. The result was an array of 5 samples in each of 3 horizontal rows on mandrel bars. After integration, the samples were photographed and transferred to the irradiation facility.

Property measurement description. Reflectance. The Boeing CRETC has a double-beam spectrophotometer in air that is optically coupled to the locations of test samples in the vacuum chamber. With appropriate measuring light sources (UV to near-IR), and with light detectors *in situ*, the value of a test surface's spectral reflectance, as modified by radiation or perhaps other stresses, is determined during measurements and retained for computer analysis. In Boeing's facility, an integrating sphere in the test chamber, between the detector and a sample being measured, produces a measurement of hemispherical reflectance. The spectral range is 250 nm to about 2500 nm. A sample is illuminated spectrally since the spectrophotometer optical path includes the monochromator after the light source(s). The spectral illumination begins with longest wavelength light (lowest eV value), and the measurement proceeds to shorter wavelengths. This is a non-destructive measurement. With opaque samples, solar absorptance is derived by simple subtraction (using the appropriate solar wavelength weighting).

Emittance. A non-destructive measurement using near-infrared radiation can be given to a film sample by laying it over an aperture provided in a Gier-Dunkle Emittance Inspection Device (DB100). Boeing performed a series of these measurements as part of this program, in air following the *in situ* irradiation. All measurements were made at room temperature. We had cached a number of unirradiated comparison samples cut from the same polymer sheets, and all specimens were measured in the same run. The measuring device illuminates each sample with polychromatic radiation, and the apparatus circuitry computes a weighted infrared reflectance value internally. With opaque specimens as in this program, the values of thermal emittance coefficients were derived by simple subtraction from the measured reflectance values.

Tensile. After completion of the emittance measurements on all exposed samples as well as on selected "comparison" or non-exposed samples, measurements for this program proceeded to the mechanical property testing apparatus. The test machine used for the property testing was a MII-50 UD Satec universal test machine with a 440-kg (1000-pound) load cell. The cell is calibrated down to 2 pounds with a resolution down to 0.001 pounds. Instron hydraulic grips with rubber pads were used to clamp each test film in turn. All measurements were made at room temperature.

Ideally, film samples would be given mechanical property tests when in a known state as to uniformity or variability of physical stress across and through the specimen, perhaps with sophisticated lighting techniques to display such state. In this exploratory program, each specimen was carefully aligned and taped to the rubber pads. The gage length (unclamped length of film between the grips) was approximately 20 mm (0.80 inch), matching the exposure length. Each specimen was loaded in turn into the top grip and clamped there, allowing the bottom to hang free. The bottom grip was then clamped. This technique allowed the samples to be gripped without any uneven stress of twisting being imposed.

EXPERIMENTAL RESULTS

This section describes the results obtained on the array of 15 polymer film test specimens that were irradiated with UV, electrons, and protons simulating a 5-year mission in an Earth-related orbit. (Details of the orbit and radiation were discussed in the previous section.)

The simultaneous exposure of protons, electrons and UV simulating a 5-year (60 month) mission at L1/L2 was divided into 5 exposure segments. Table 2 lists the proton and electron fluences and the equivalent UV exposure hours for each segment. While the total proton and electron fluences were simulated the entire 60-month mission it was not possible to provide a UV exposure that simulated the full mission within the scope of this contract. Therefore, the highest amount of UV possible was accumulated dictated by the exposure times of the protons and electrons.

Table 2. Exposure Summary

Exposure Segments	Equivalent Mission Duration	Proton Fluence	Electron Fluence	UV Exposure
	(months)	(p/cm^2)	(e/cm^2)	(hours)
1	~3	3.6E+13	5.0E+14	90
2	12	2.0E+14	1.6E+15	330
3	24	3.9E+14	3.2E+15	480
4	42	7.1E+14	5.7E+15	685
5	60	1.0E+15	8.0E+15	1000

Table 3 lists the test parameters of particle flux, UV sun rate and chamber pressure for each exposure segment.

Table 3. Test Parameters

Exposure Segments	Ave. Proton Flux	Ave. Electron Flux	Ave. UV Sun Rate	Chamber Vacuum Pressure
	(p/cm^2-s)	(e/cm^2-s)		(torr)
1	7.1E+08	9.8E+09	1.31	9.6E-7 to 4.2E-7
2	6.9E+08	5.2E+09	1.37	4.2E-7 to 2.9E-7
3	5.3E+08	5.0E+09	1.52	2.9E-7 to 2.9E-7
4	6.4E+08	5.0E+09	1.48	2.9E-7 to 2.5E-7
5	3.9E+08	3.3E+09	1.64	2.5E-7 to 2.2E-7

Spectral reflectance *in situ*. During this program, charts of hemispherical spectral reflectance were obtained on the opaque specimens by interrupting exposure and securing a dark in-chamber environment. Vacuum remained about $2x10^{-7}$ torr. The specimens did not have to be moved out of their holders or mandrels for each measurement, so each measurement is truly an *in situ* type of measurement. The spectrophotometer and *in situ* reflectometer combination produced “traditional” spectral charts and, via encoders on the wavelength and percent reflectance shafts, simultaneously produced a digital record of each spectral scan.

The times of measurements were selected to represent certain numbers of equivalent months in orbit. Dosimetry values relating to each such point were expressed in terms of percent of “full-term” or 60-month orbital period. The total number of UV equivalent sun hours (ESH) reached 1000 during the overall test. The measurement times of 90, 330, 480, 685, and 1000 ESH represent a progression from about 10 percent to half, to two-thirds, and finally the full amount of the intended 1000 ESH UV exposure.

The spectral reflectance data are plotted in 15 graphs, one for each specimen, derived from a master Excel workbook. Since this data is an extensive body, the 15 graphs are grouped in Appendix B. The spectral reflectance results can be summarized as solar absorptance coefficients that are derived from the spectral scans of sample surface reflectance. The solar absorptance values obtained on the 15 test specimens are presented in the next sub-section.

Solar absorptance. Values of the coefficient generally known as solar absorptance were derived from the spectral reflectance scans. Of the 240 or so specific wavelengths available from each scan, 100 wavelengths that represent the relative spectral weighting of the Sun’s radiance curve were used in the calculation of solar absorptance.

Table 4 displays the solar absorptance data obtained on every test specimen. The physical failure of the two TOR-LMBP samples early in the test precluded obtaining further data from them.

Table 4. Solar Absorptance of Each Test Specimen *in Situ*, Before and After Irradiation

Measurement Point	Kapton HN		Kapton E			Upilex S	
Time in orbit	1	8	2	7	15	4	11
In vac, pre-expos	0.318	0.314	0.300	0.304	0.304	0.351	0.355
~3 months	0.337	0.339	0.326	0.326	0.329	0.376	0.381
12 months	0.329	0.337	0.328	0.328	0.330	0.370	0.383
24 months	0.335	0.349	0.335	0.340	0.346	0.383	0.398
42 months	0.356	0.365	0.352	0.352	0.356	0.392	0.399
60 months, in vac	0.380	0.389	0.373	0.373	0.375	0.407	0.413

Measurement Point	C P - 1		C P - 2		TOR-RC		TOR-LMBP	
Time in orbit	9	14	3	6	10	13	5	12
In vac, pre-expos	0.213	0.217	0.215	0.211	0.194	0.193	0.233	0.227
~3 months	0.246	0.238	0.241	0.233	0.258	0.246	0.252	0.280
12 months	0.339	0.316	0.315	0.289	0.374	0.365		
24 months	0.409	0.382	0.376	0.360	0.440	0.421		
42 months	0.473	0.441	0.432	0.406	0.496	0.478		
60 months, in vac	0.546	0.491	0.484	0.458	0.560	0.536		

Figure 1 (page 4) showed the relative stability of the polymer films that survived to the end of the irradiation. That figure showed changes in solar absorptance, without considering the different baseline solar absorptance values of the various films. Table 4 above shows the individual initial values of solar absorptance, sample by sample.

Thermal emittance. Data were obtained in air, as previously described, and are presented in Table 5 below. The third digit is included to indicate trends.

Table 5. Thermal Emittance Results

Test Material	Sample No.	Pre Exposure Emittance, *note 1*	Post Exposure Emittance (vacuum only) *note 2*	Post Exposure Emittance (combined beams) *note 3*
Kapton E		0.530		
	2		0.526	0.538
	7		0.529	0.542
	15		0.528	0.537
Kapton HN		0.512		
	1		0.508	0.518
	8		0.509	0.520
CP-1		0.473		
	9		0.479	0.512
	14		0.475	0.510
CP-2		0.550		
	3		0.545	0.579
	6		0.543	0.574
Upilex S		0.511		
	4		0.508	0.518
	11		0.524	0.534
TOR RC		0.593		
	10		0.588	0.628
	13		0.577	0.618
TOR LMBP				
	5			note 4
	12			note 4

Note 1: Measurement taken on unnumbered samples kept out of vacuum chamber
Note 2: Measurement taken on surface that was kept behind sample holder
Note 3: Measurement taken on exposed surface
Note 4: Measurement not possible due to sample failure during irradiation test

Mechanical properties. Data were obtained in air on fresh and on irradiated specimens.

Table 6. Mechanical Properties of Tested Polymer Films

Material Description	Sample ID	Thickness (mil)	Apparent Modulus (ksi)	Failure Stress (ksi)	Apparent Failure Strain (%)	Failure Decription	Sample Description	Test Rate (in/min)
Kapton E	Kapton E UN-3	0.5	590	47.1	101.3	Grip	Control	0.5
	Kapton E UN-4	0.5	530	46.2	101.0	Gage	Control	0.5
	Kapton E EX-2	0.5	530	32.4	24.4	Gage		0.5
	Kapton E EX-7	0.5	580	30.7	18.7	Grip		0.5
	Kapton E EX-15	0.5	550	38.2	53.0	Gage		0.5
Kapton HN	Kapton HN UN-1	0.5	390	36.3	85.8	Grip	Control	0.5
	Kapton HN UN-2	0.5	420	34.5	76.9	Grip	Control	0.5
	Kapton HN UN-3	0.5	360	36.0	82.7	Grip	Control	0.5
	Kapton HN UN-4	0.5	370	35.5	83.1	Grip	Control	0.5
	Kapton HN EX-1	0.5	310	29.0	44.0	Grip		0.5
	Kapton HN EX-8	0.5	440	23.1	17.9	Grip		0.5
CP-1	CP-1 UN-1	0.5	320	13.5	7.4	Grip	Control	0.5
	CP-1 UN-2	0.5	300	13.2	7.4	Grip	Control	0.5
	CP-1 UN-3	0.5	350	14.7	9.5	Gage	Control	0.02
	CP-1 UN-4	0.5	340	13.9	8.4	Grip	Control	0.02
	CP-1 UN-5	0.5	320	11.9	6.3	Gage	Control	0.02
	CP-1 EX-9	0.5	300	10.2	3.5	Gage		0.02
	CP-1 EX-14	0.5	300	5.9	2.8	Gage		0.02
CP-2	CP-2 UN-1	0.5	450	19.8	5.8	Grip	Control	0.02
	CP-2 UN-2	0.5	450	22.4	6.5	Grip	Control	0.02
	CP-2 UN-3	0.5	450	22.7	7.8	Grip	Control	0.01
	CP-2 UN-4	0.5	460	22.9	8.0	Grip	Control	0.01
	CP-2 EX-6	0.5	410	8.0	2.5	Gage		0.01
	CP-2 EX-3	0.5	400	11.5	3.8	Gage		0.01
Upilex S	Upilex S UN-1	0.5	820	52.0	34.4	Gage	Control	0.01
	Upilex S UN-2	0.5	820	55.5	46.0	Grip	Control	0.5
	Upilex S UN-3	0.5	830	53.4	39.3	Grip	Control	0.5
	Upilex S EX-11	0.5	870	53.9	31.0	Gage		0.02
	Upilex S EX-4	0.5	800	43.5	14.8	Gage		0.02
TOR-RC	TOR-RC UN-1	0.5	420	8.1	3.4	Gage	Control	0.02
	TOR-RC UN-2	0.5	380	5.1	2.0	Grip	Control	0.01
	TOR-RC UN-3	0.5	410	7.7	2.9	Gage	Control	0.01
	TOR-RC UN-4	0.5	360	6.1	2.5	Grip	Control	0.01
	TOR-RC EX-13	0.5	360	7.3	3.3	Gage		0.01
	TOR-RC EX-10	0.5	360	3.2	2.0	Gage		0.01

UN = Unexposed EX = Exposed

Table 6 summarizes experimental results obtained in air on all types of tested polymer film specimens. The table includes the name of each test material, sample identifications including "UN"exposed (a control) or "EX"posed (irradiated), apparent modulus values for each film (derived from the test apparatus), the stress value at failure, apparent failure strain, nomenclature describing the type of failure (grip or gage), specimen history (exposed or control), and an indication of mechanical test or pull rate in inches per minute.

Irradiation weakened the tensile strength of most of the test specimens. This result is readily apparent in Table 6 for most of the films, but in the cases of Upilex and TOR-RC, the result is true only in one irradiated specimen of each type. Within the scope of this program, we elected not to perform any rigorous statistical analyses of the mechanical property results data we obtained.

Sixteen specimens failed in the gage section, and nineteen specimens failed in the grip section. Each type of material had gage failures except for Kapton HN. In general, the values determined for failure strains in the case of grip failures were similar to the values obtained for the failure strains in the case of gage failures.

Specimens that were irradiated showed a reduction in strain at failure. The only exception was TOR-RC, where failure strains were extremely low (less than 3.5% for all specimens). The CP-1, CP-2, and TOR-RC specimens showed small decreases in apparent modulus. Overall, however, the apparent modulus values of the test films did not seem to be affected *appreciably* by radiation exposure.

DISCUSSION

One “artifact” that should be considered further is the possibility that the four samples in the corners of the exposure array may have received a slightly reduced “dose;” or at least they may not have responded in quite the same way as other samples, judging by their mechanical property values. These four samples are numbers 1, 5, 11, and 15. Number 5 failed physically prior to the end of the irradiation. The other three corner samples can be identified in Table 6 by parts of their names, “EX-1,” “EX-11,” and “EX-15.” The values of apparent failure strain in each of these three specimens *are appreciably greater* than the values for failure strain in the specimens of like types, located elsewhere in the exposure array. The greatest measured spread in mechanical property values is found in the portion(s) of Table 6 where strain failure is indicated for these samples. Also, these three samples seem to have survived in tension until higher stress values were reached, compared to specimens of like types that were located elsewhere in the test array.

Dosimetry measurements tend to indicate that the electron beam is the most uniform of the three kinds of radiation beams. The electron scattering foil causes the electron beam to be circular in shape, and to be the largest beam of the three. UV dosimetry suggests the four corners are about ten percent lower in UV (and overall light) intensity, compared to the center. As indicated previously, protons are detected by Faraday cups directly along the horizontal and vertical centerlines of the chamber, and their intensity is inferred elsewhere. The proton raster circuitry should provide a truly rectangular beam, fully filled out at the corners; but being objective, there is no absolute guarantee of that.

The reflectance and emittance results do not tend to show any edge or corner effect (unless one makes a speculative case for the measured emittance values of sample number 11, Upilex S).

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Irradiation decreased the spectral reflectance, and therefore increased the solar absorptance, of every test specimen. Some changes were moderate, whereas others were quite large (doubling or even nearly tripling). One type of polymer failed physically during irradiation.

Irradiation may have induced moderate changes in the thermal emittance of some test samples, but most indicated emittance values were unchanged within experimental uncertainty.

Irradiation decreased the tensile strength of most of the polymer films tested. Nearly every irradiated test specimen had less elongation at failure than the unirradiated specimens did.

Recommendations

The test protocols outlined in Appendix D are recommended for further study, development, and use in future experimental work in this field.

Further refinement of the radiation environment in the regions of L1 and L2 around Earth is required to improve test fidelity.

Since the solar absorptance data does not show a leveling out or saturation at the exposure levels of this contract, testing to higher values of UV appears to be justified during future experimental evaluations, and testing to greater charged-particle fluences is justified for longer missions.

<u>References</u> – Related and Background Programs and Principles

Solar Sailing – Studies of Thin Polymer Films for Spacecraft Control and Acceleration

Solar Power Satellites – Systems and Supporting Materials for Light Concentrators

Development of Flexible Polymers for Space Applications

Evaluation Methods for Polymers:

Dynamic Mechanical Analysis

Tensile and Modulus Properties…("static" measurements for JPL *in situ*)

Reflectance of Films…("framing" samples during exposure or measurement.

Durability of Flexible Polymers in Radiation Environments:

Survival of Polymers Exposed to Elevated Levels of Solar Radiation:

JPL Program HF 525908, 1970… "Experimental *in Situ* Investigation of the Effects of Protons, Ultraviolet Radiation, and Temperature on Thermophysical Properties of Solar Cell Filters and Other Spacecraft Materials," by Lawrence B. Fogdall and Sheridan S. Cannaday, The Boeing Company, February 1971.

JPL Contract 954701, 1977… NASA CR-157322, "Simulation of Space Radiation Effects on Polyimide Film Materials for High Temperature Applications," by Lawrence B. Fogdall and Sheridan S. Cannaday, The Boeing Company, November 1977.

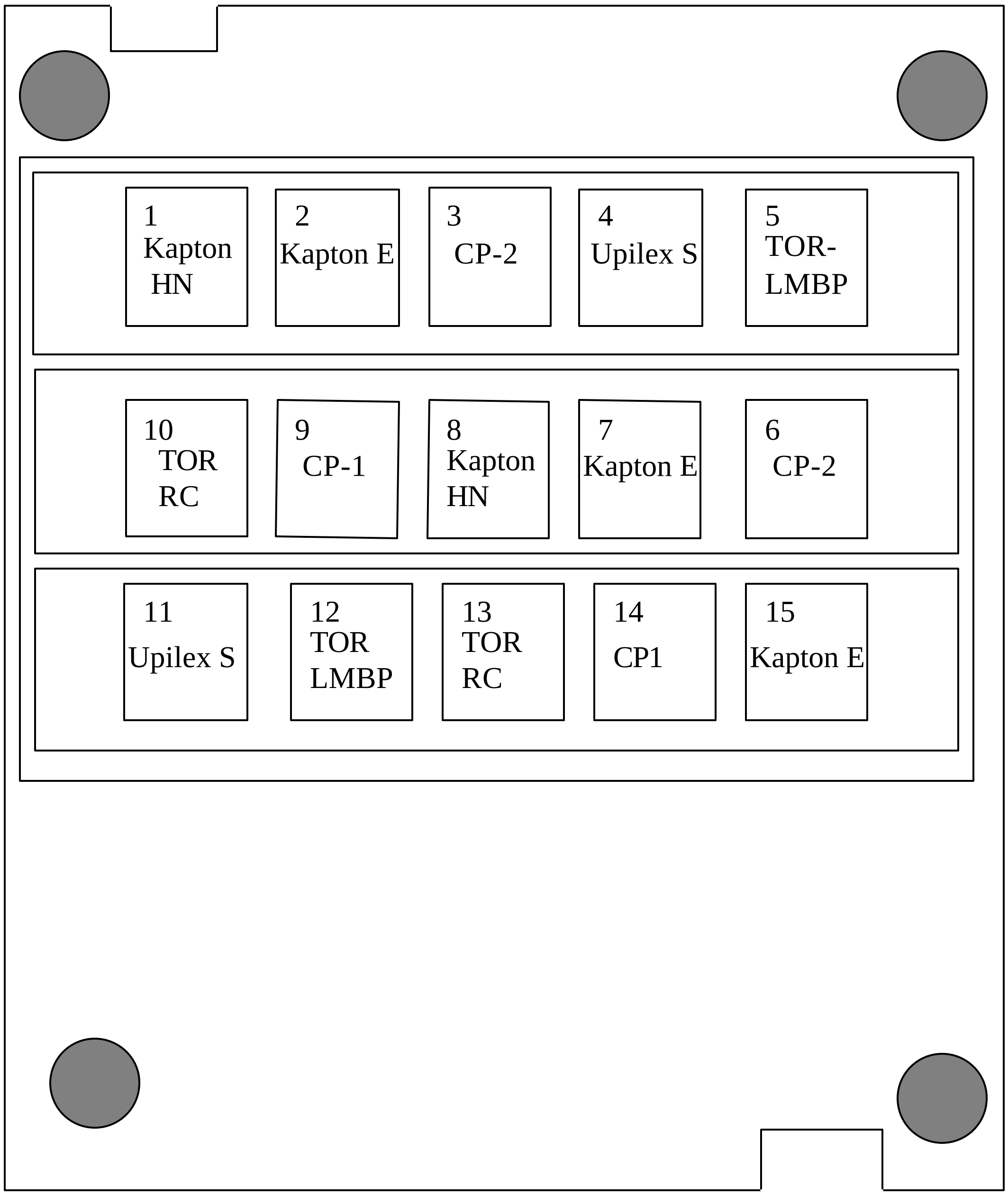
Stability of Reflective Polymers in Simulated Earth Orbit:

Boeing IR&D report, 1978…"Study of Front-Surface Aluminized Kapton Films Under Combined Electron, Proton, and Ultraviolet Radiation," by L. B. Fogdall and S. S. Cannaday, The Boeing Company.

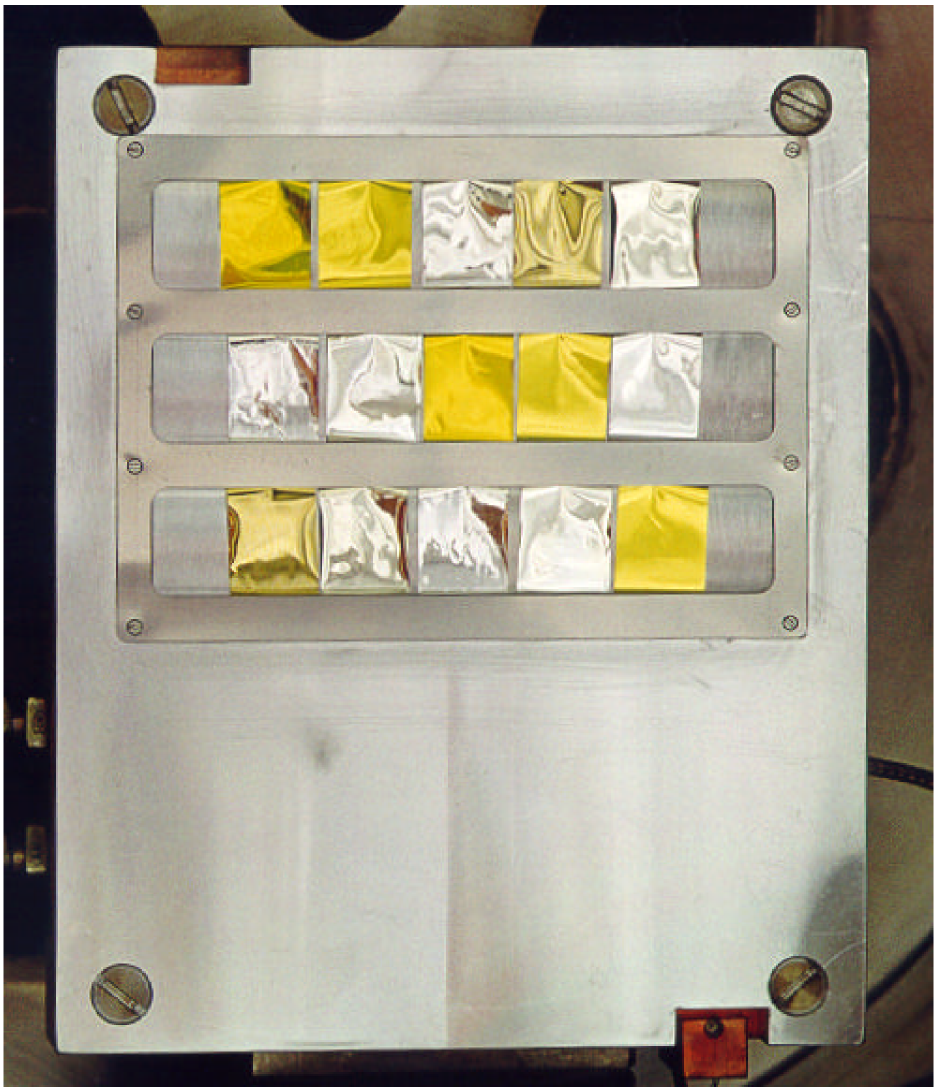
Appendix A

Photographic Documentation

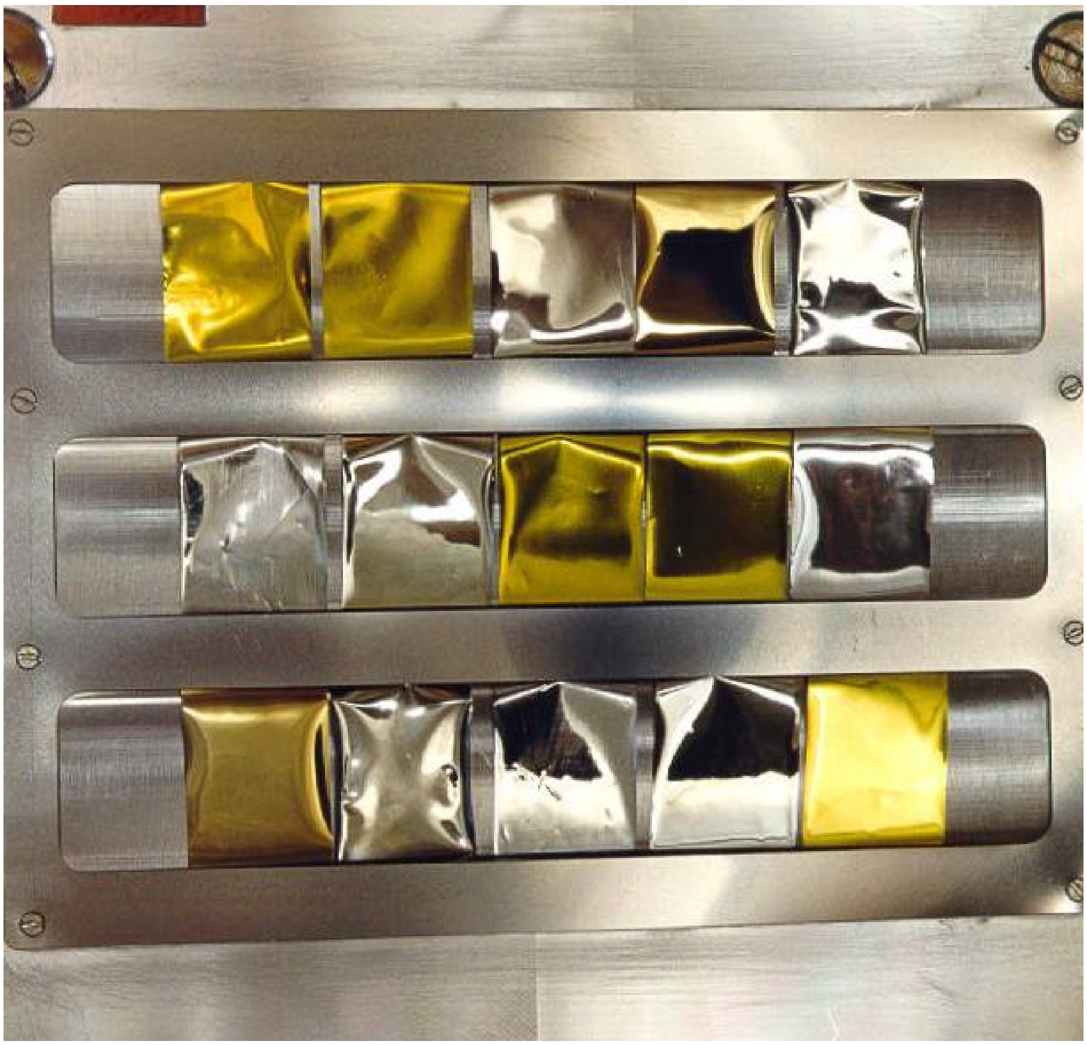
Sample Layout



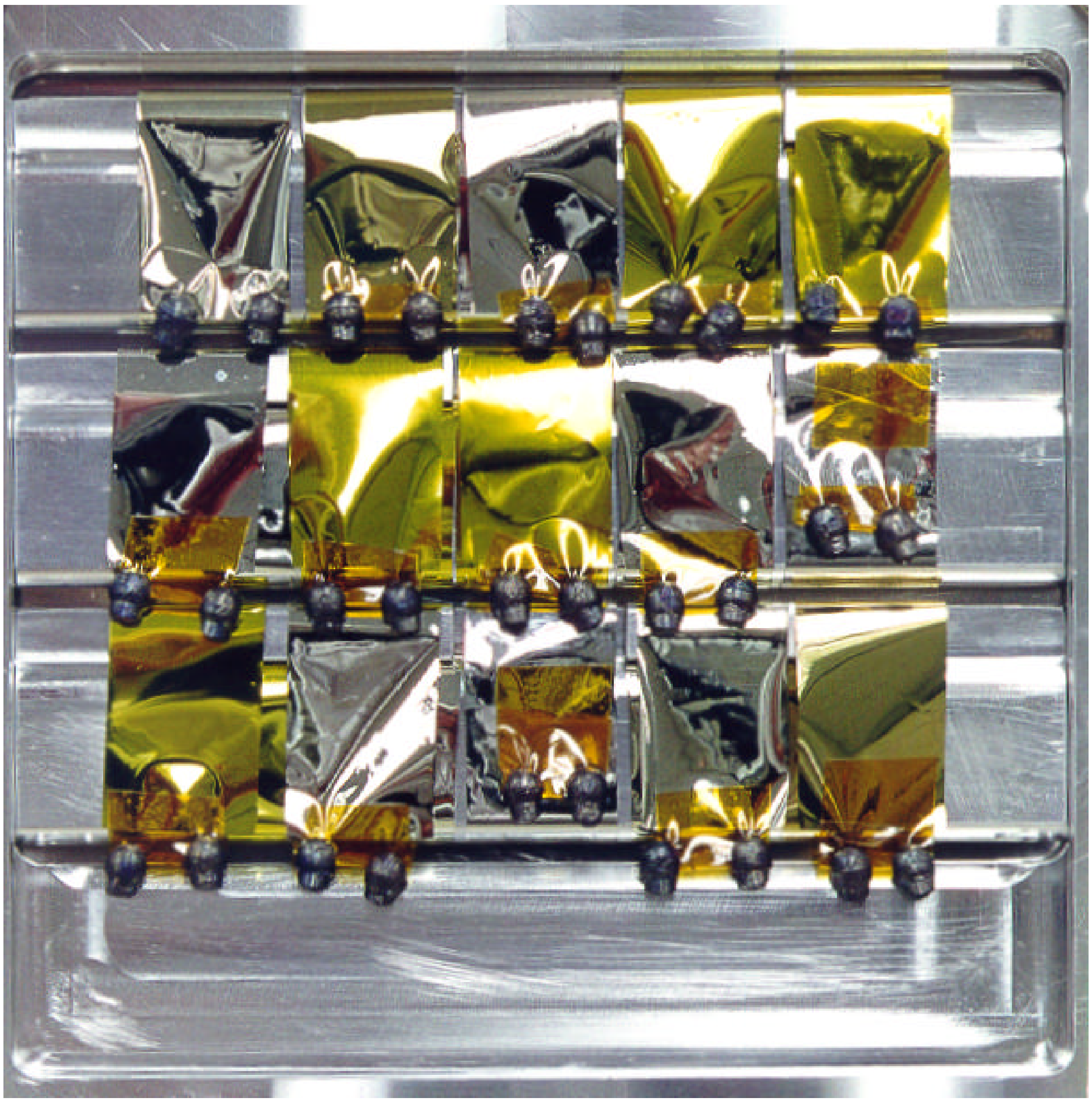
Samples mounted in CRETC



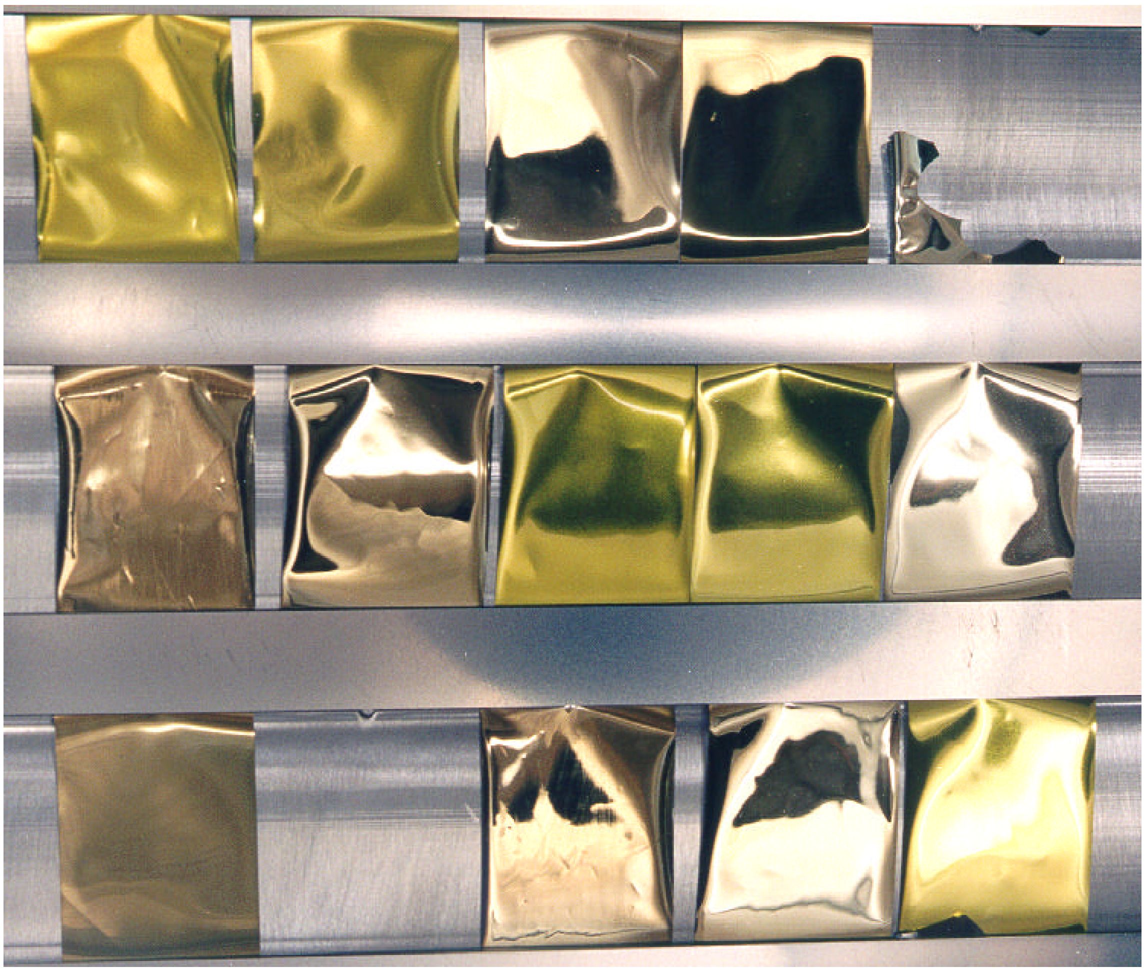
Close-up of mounted samples



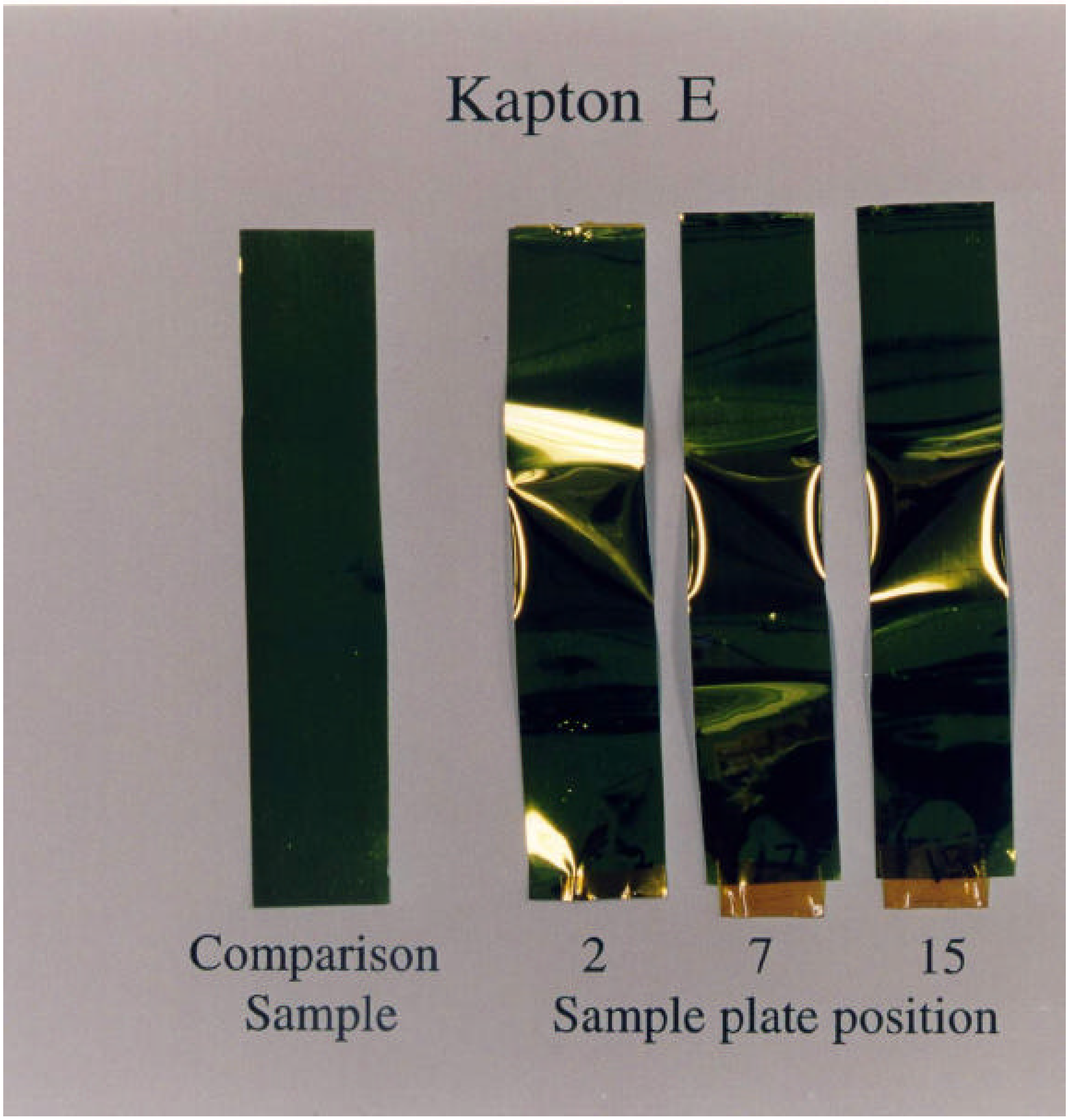
Backside of Sample Plate showing sample mounting and weights

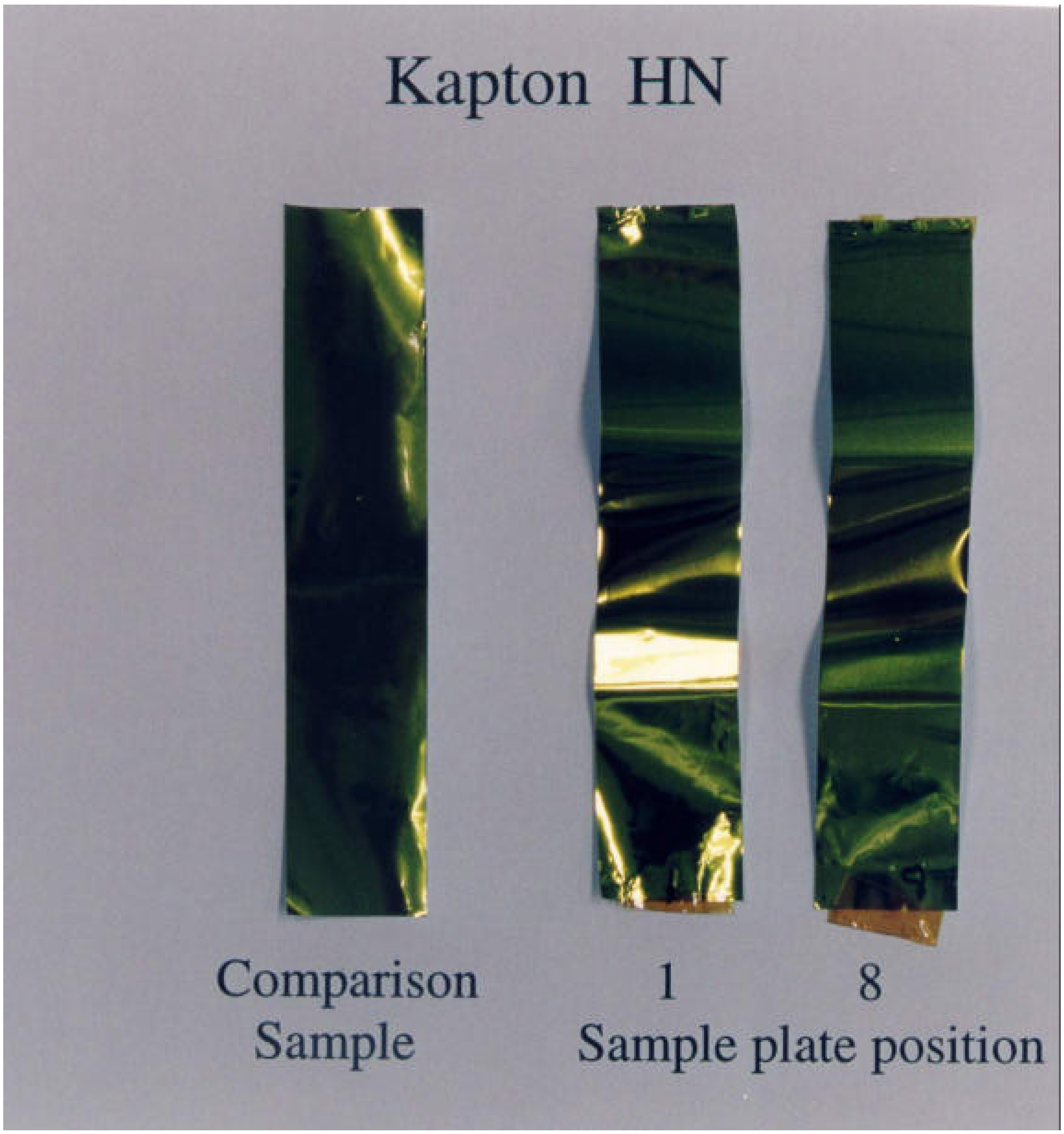


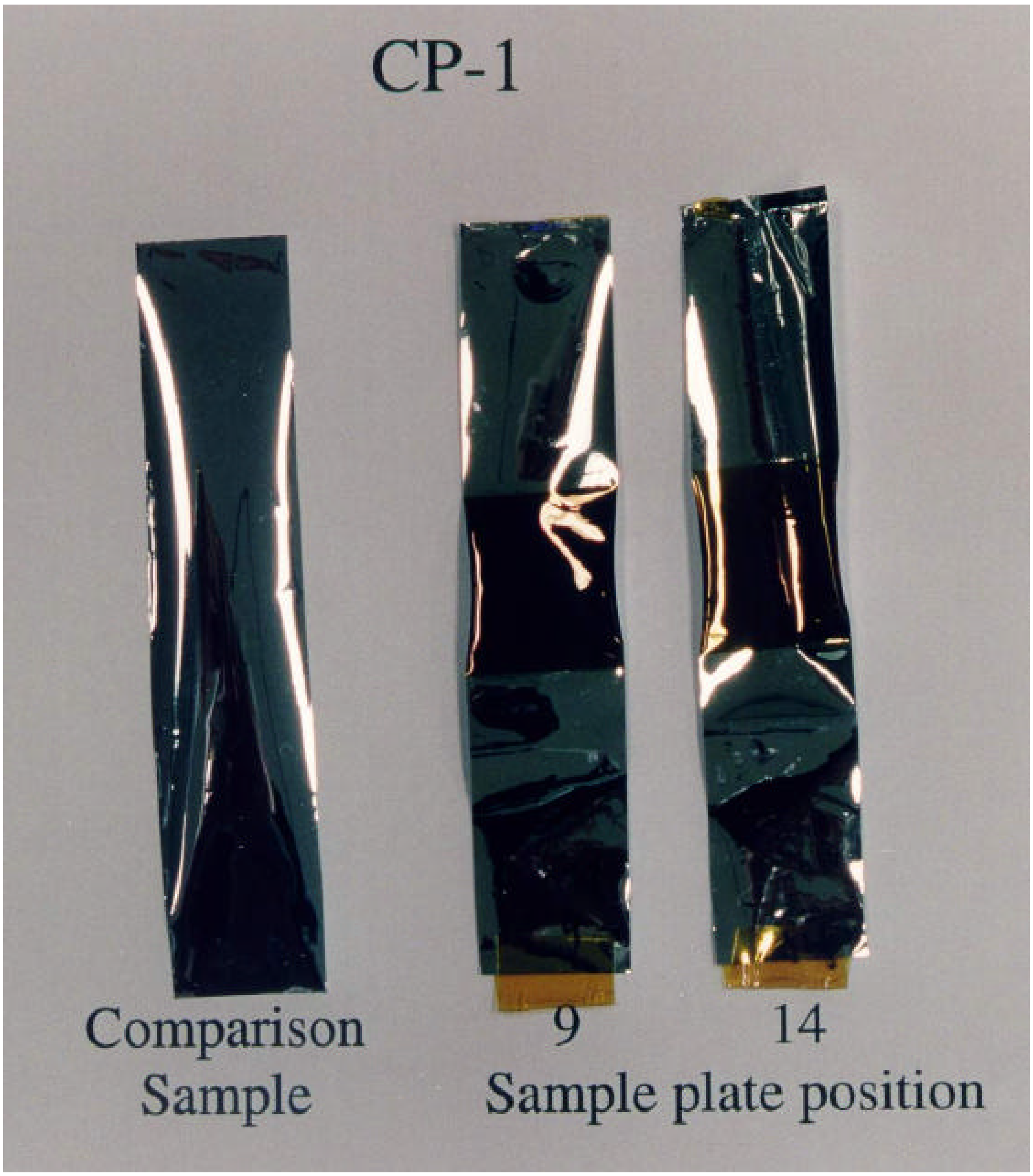
Post test view of Samples on plate
(note TOR-LMBP samples missing)

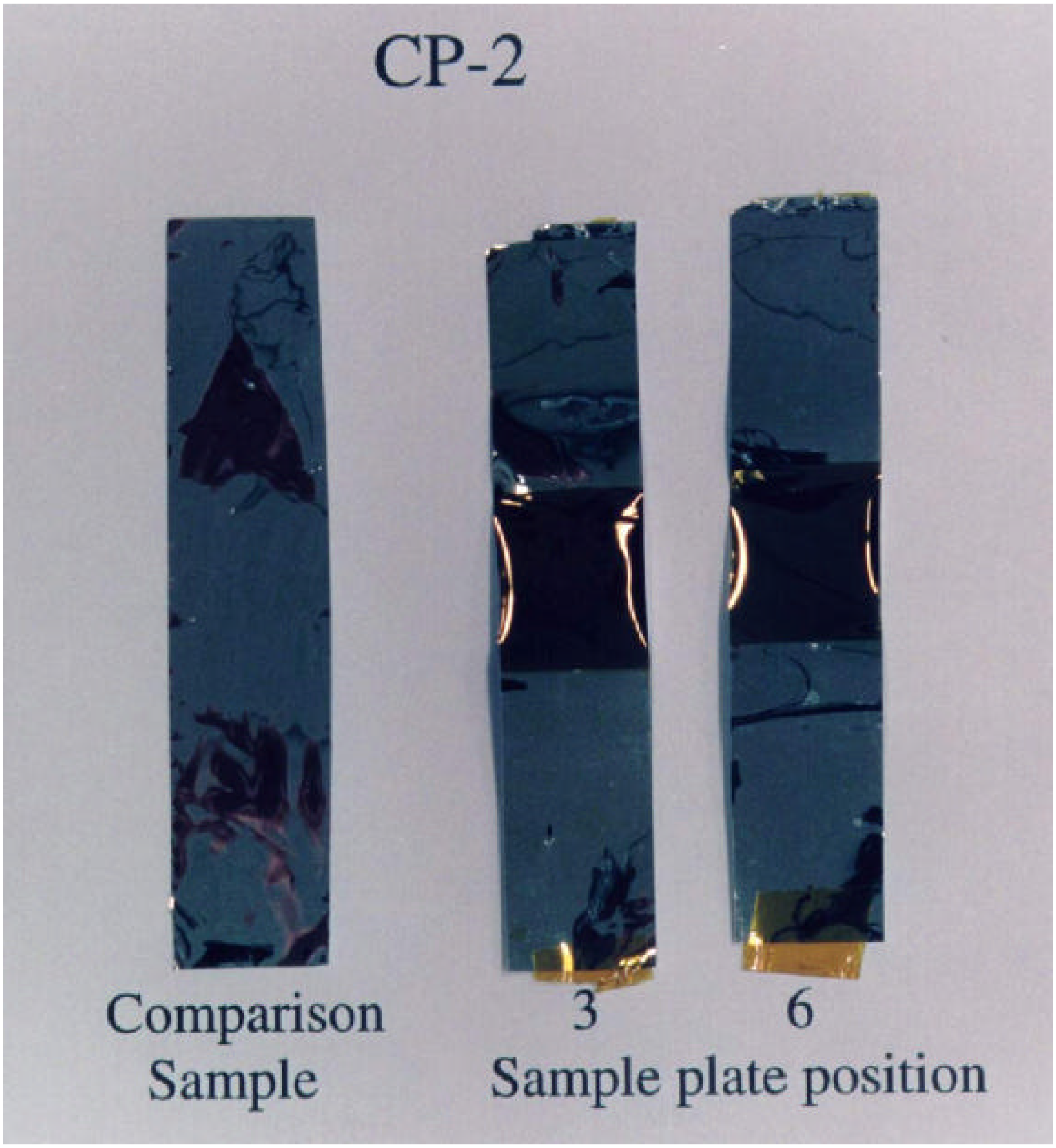


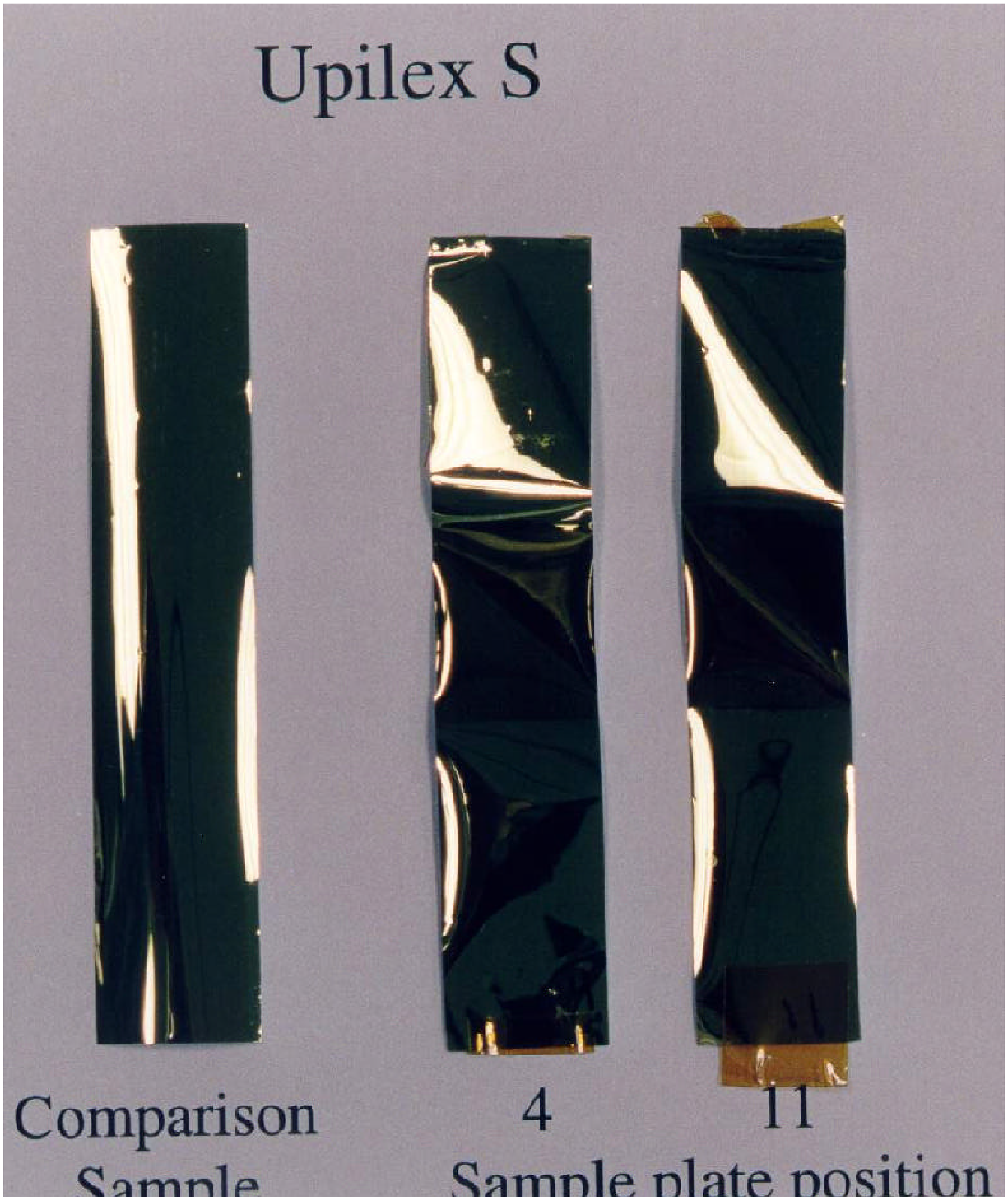
The following 6 photos compare an un-irradiated sample with the irradiated samples of the same material.

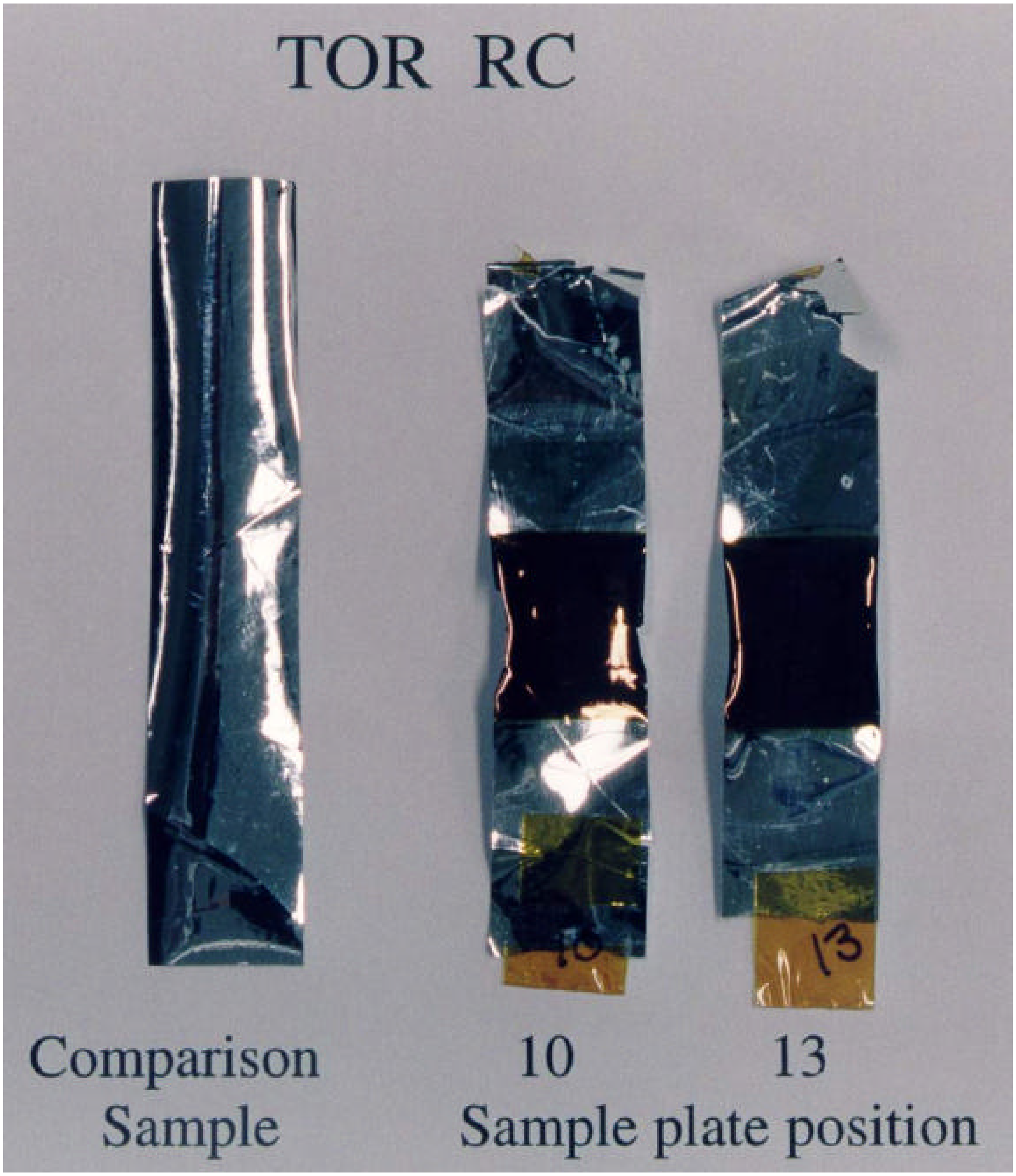



Kapton HN
Comparison
Sample
1
8
Sample plate position

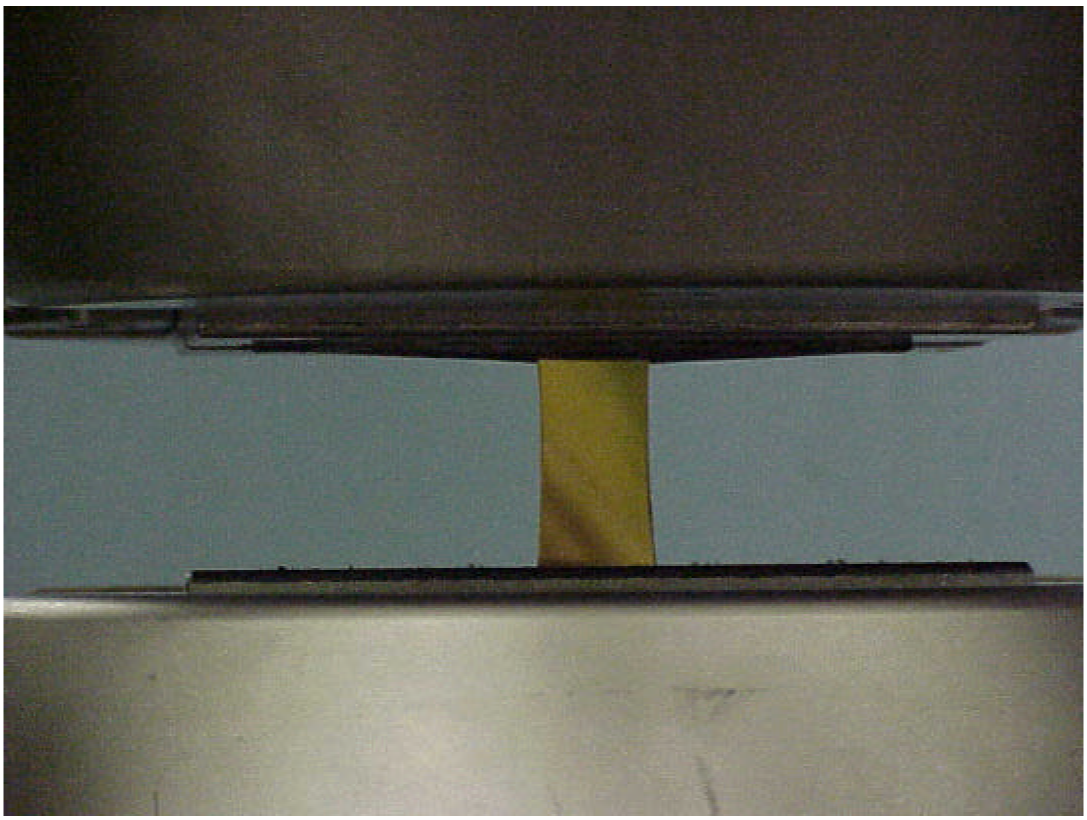

CP-1
Comparison
Sample
9
14
Sample plate position

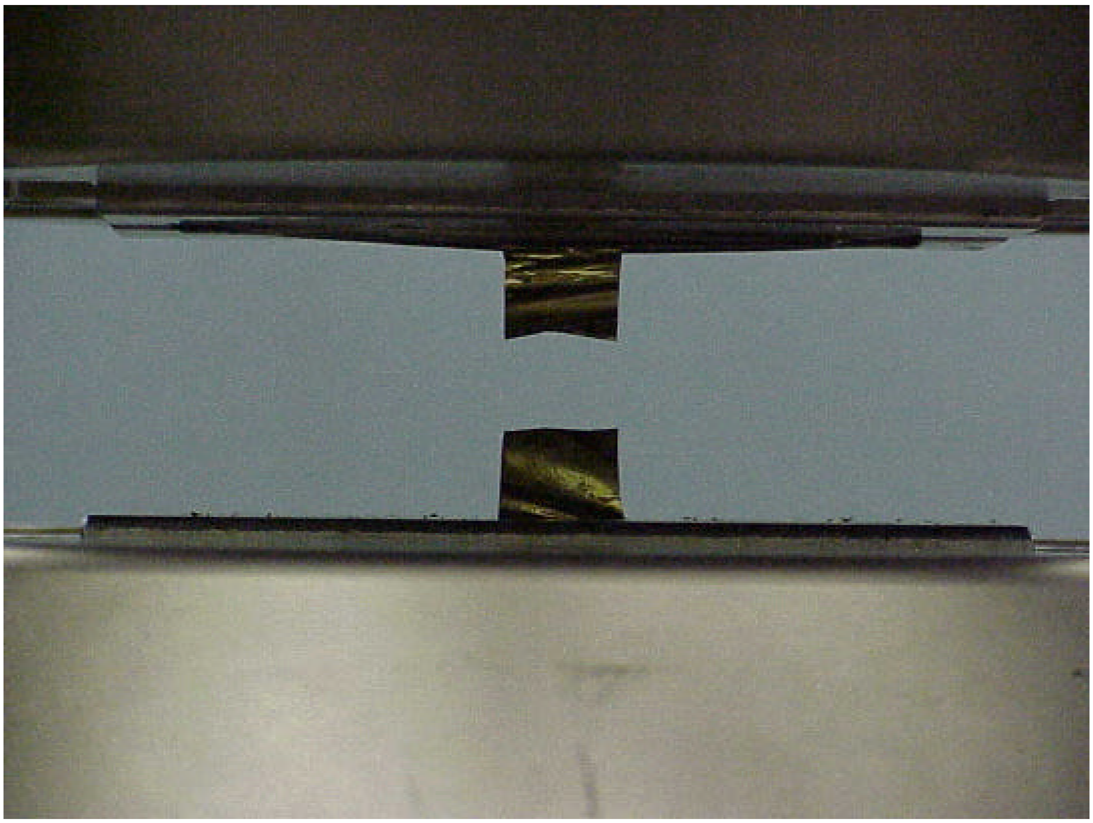

CP-2
Comparison
Sample
3
6
Sample plate position


Upilex S
Comparison
Sample
4
11
Sample plate position


TOR RC
10
13
Comparison Sample
10
13
Sample plate position

Tensile Measurement Apparatus

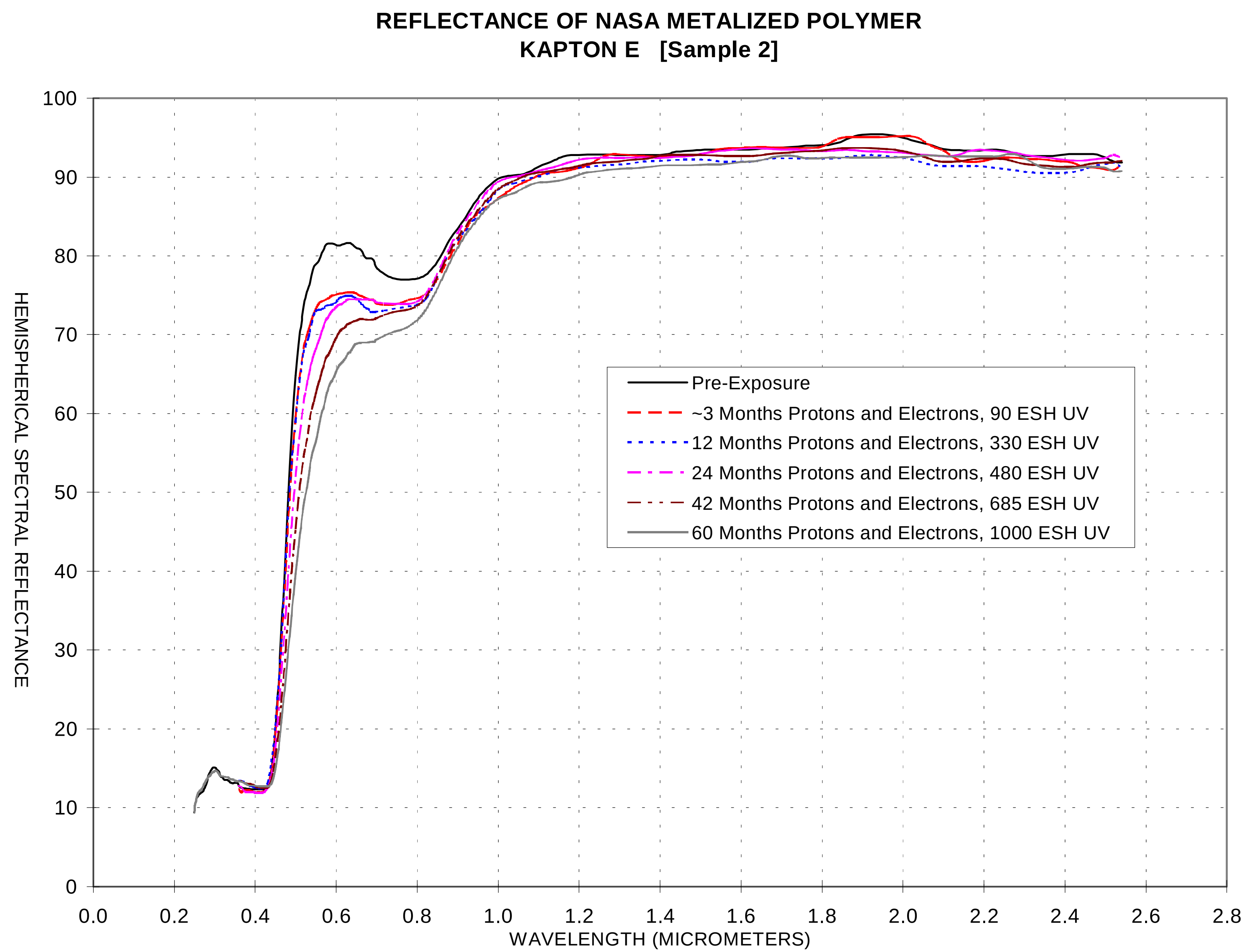




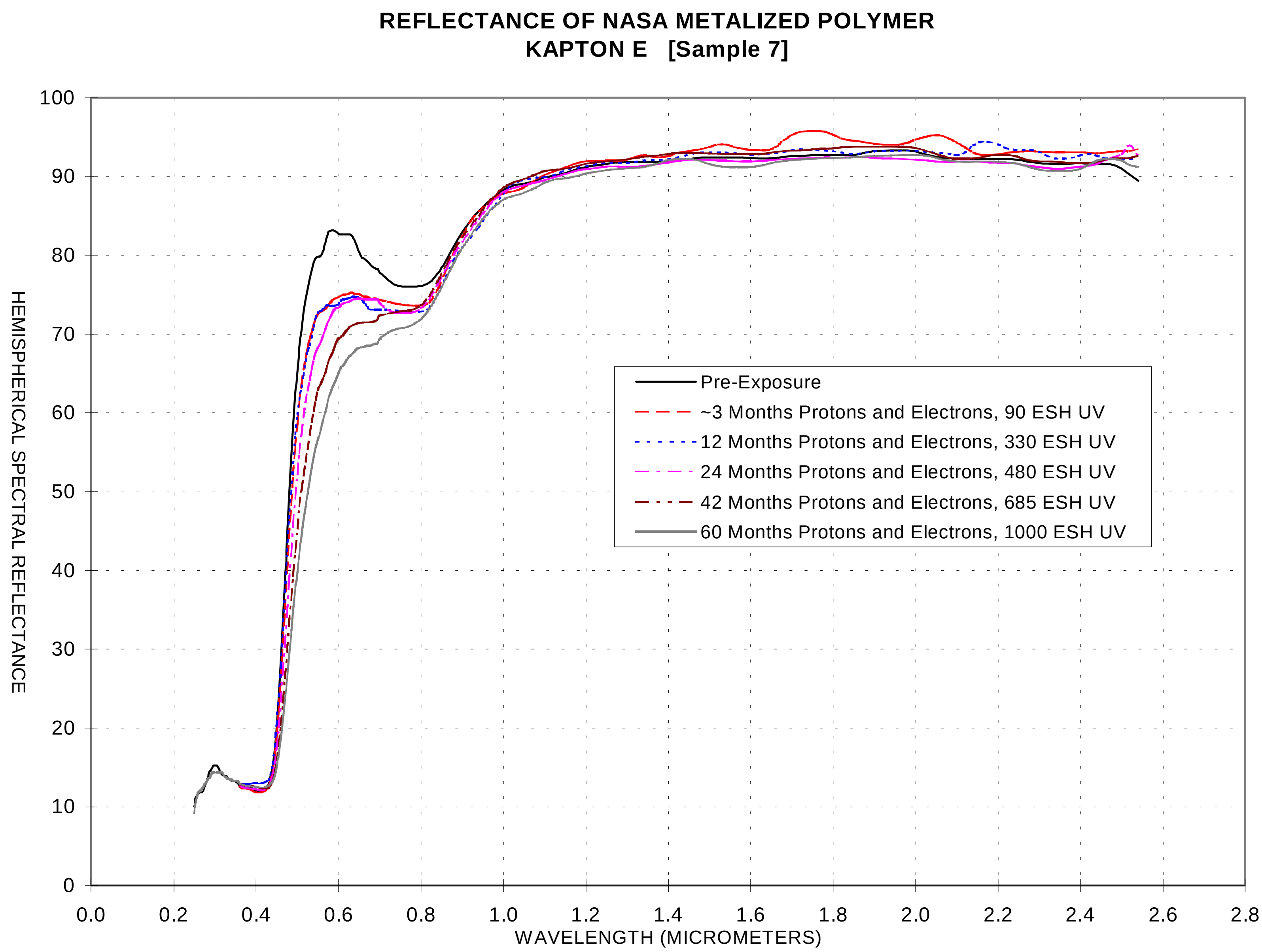
Appendix B

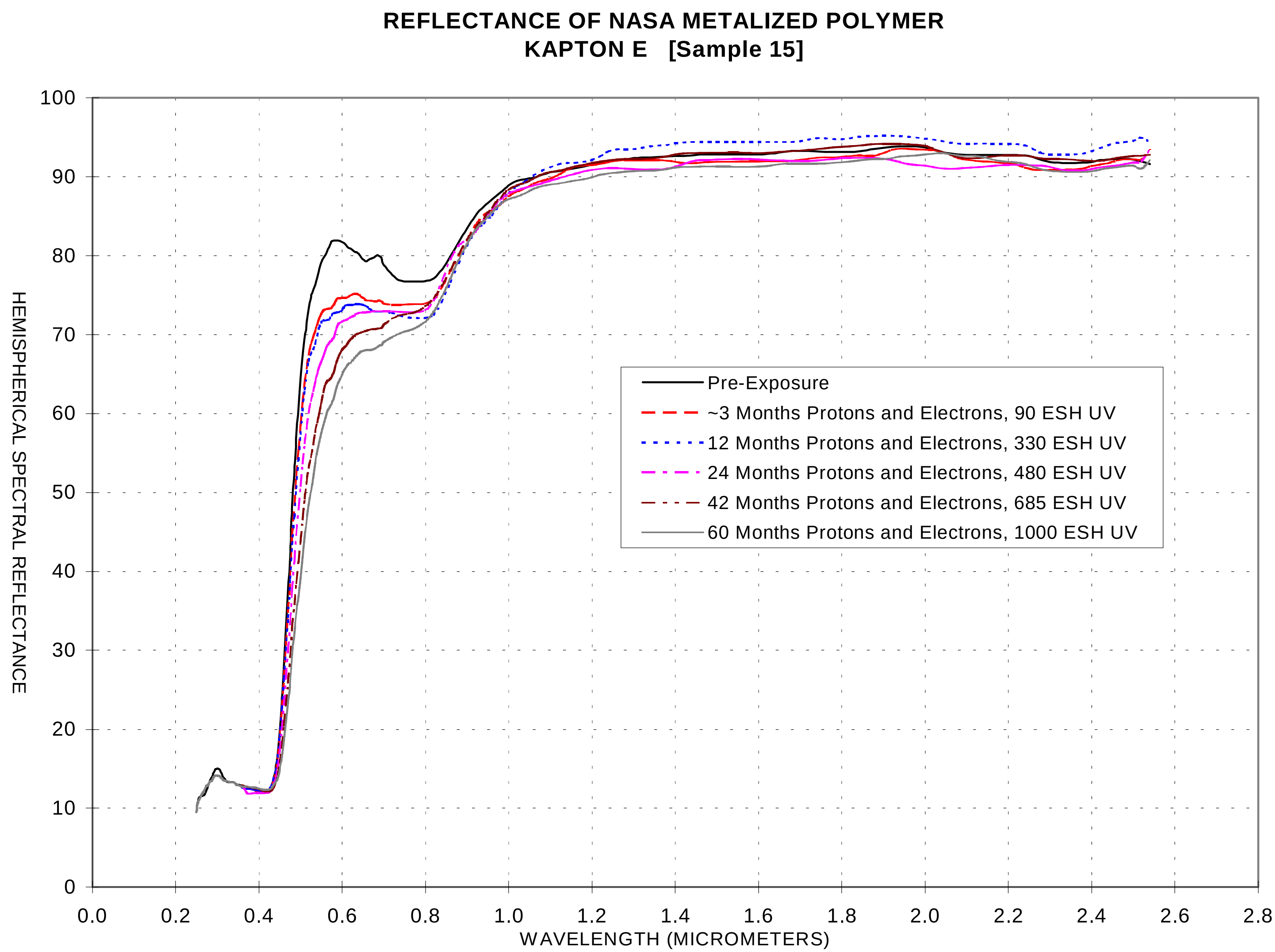
Spectral Reflectance Experimental Results

By Sample

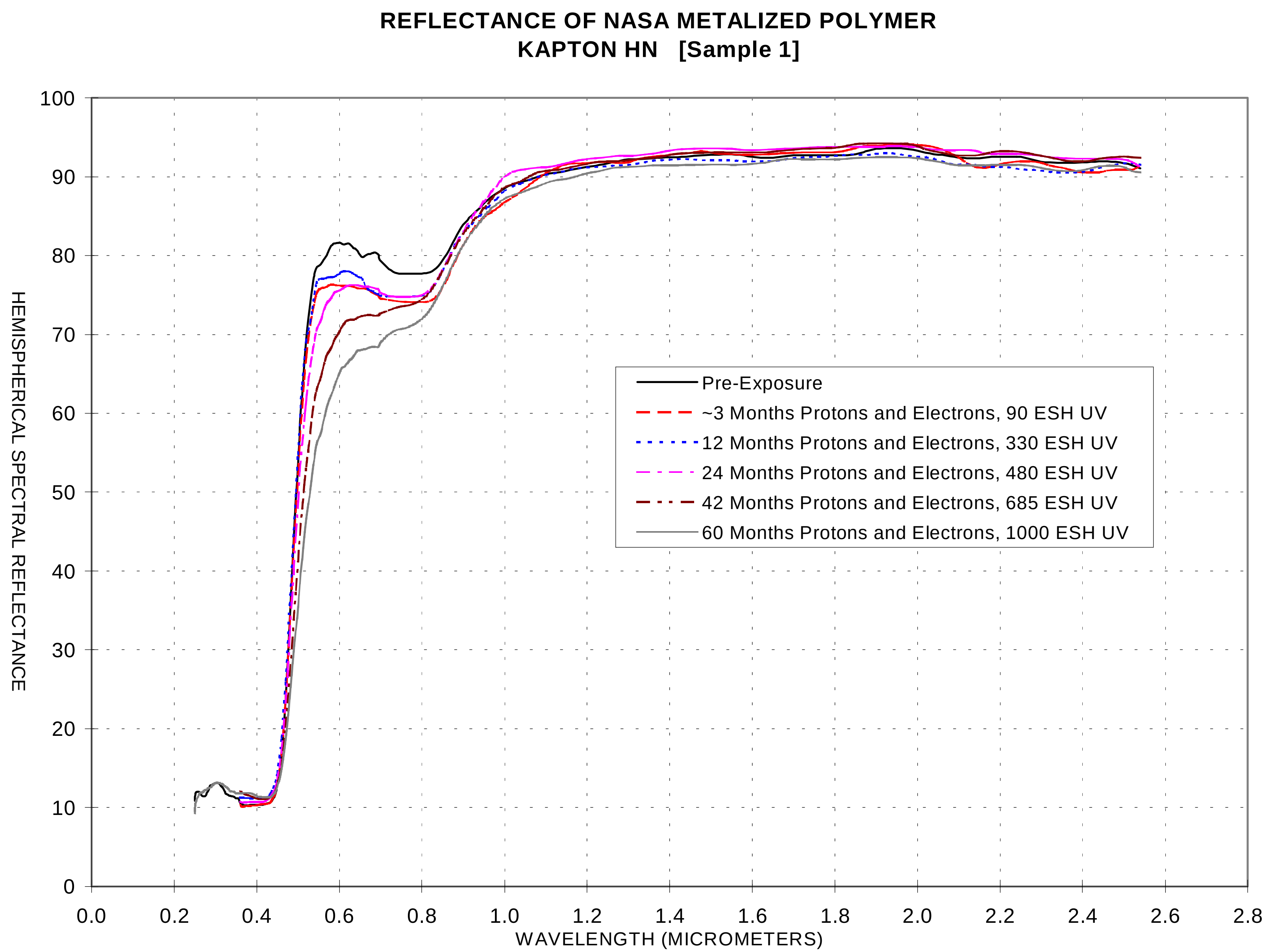


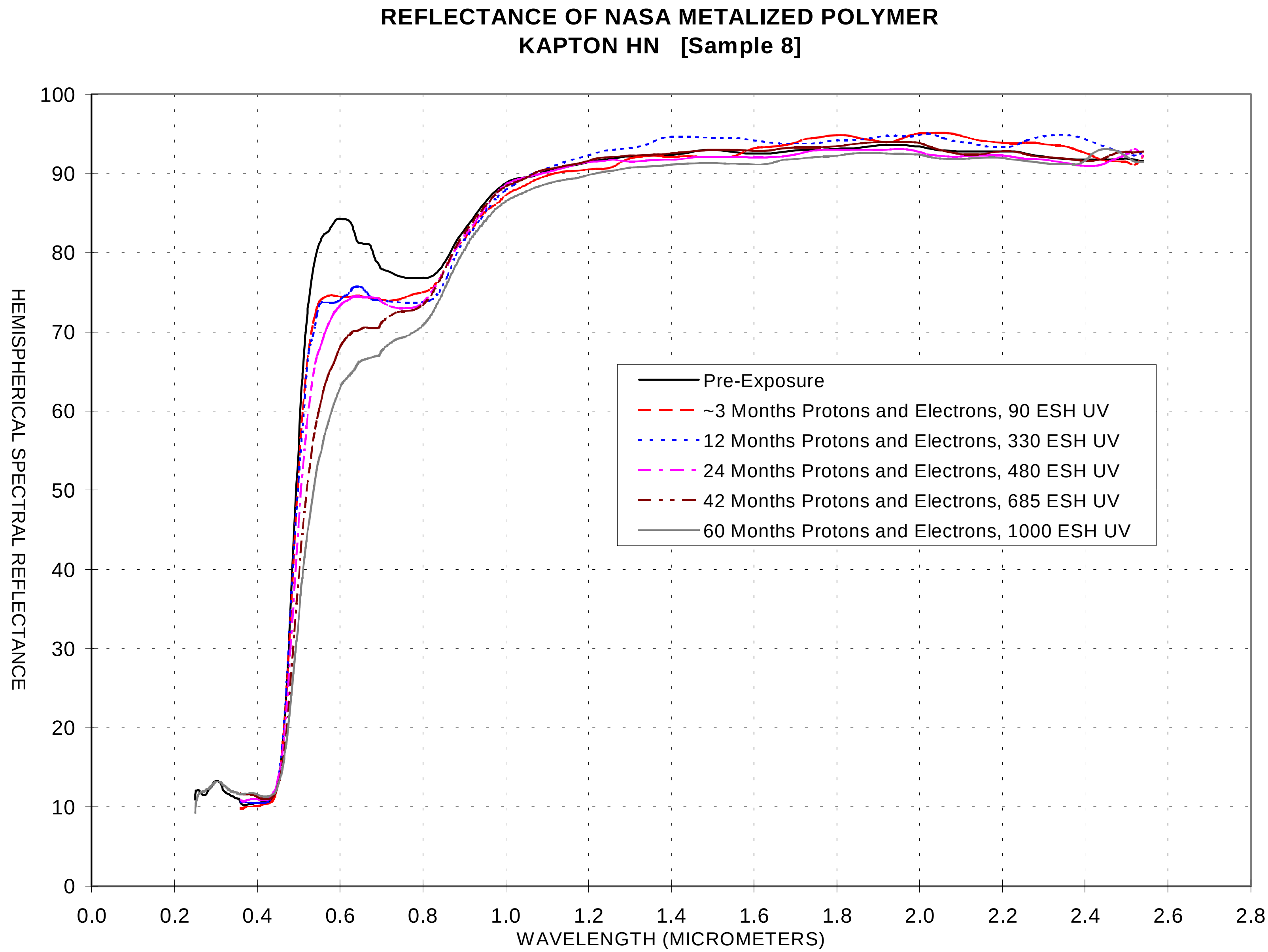
REFLECTANCE OF NASA METALIZED POLYMER
KAPTON E [Sample 2]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV

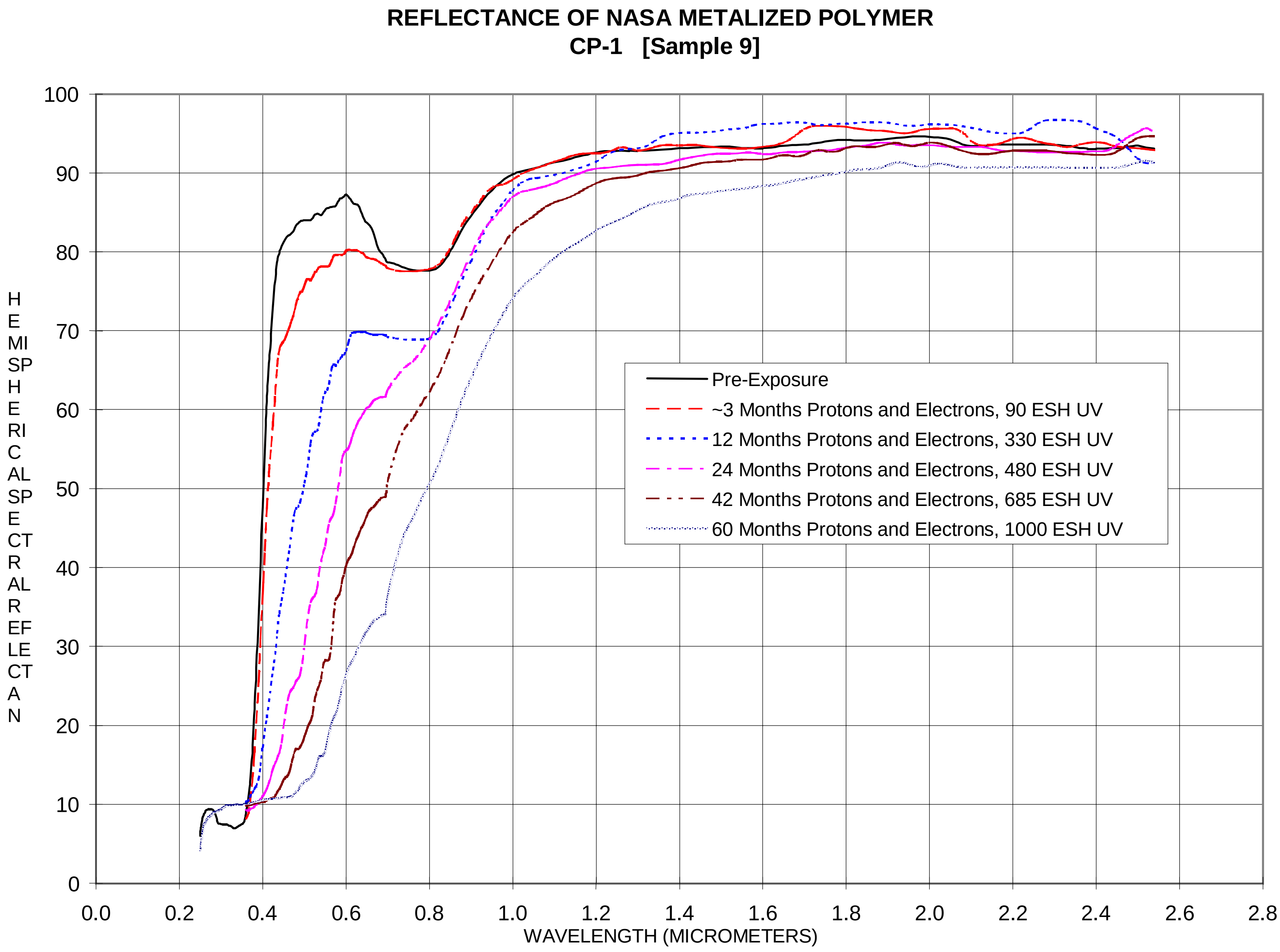

REFLECTANCE OF NASA METALIZED POLYMER
KAPTON E [Sample 7]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV

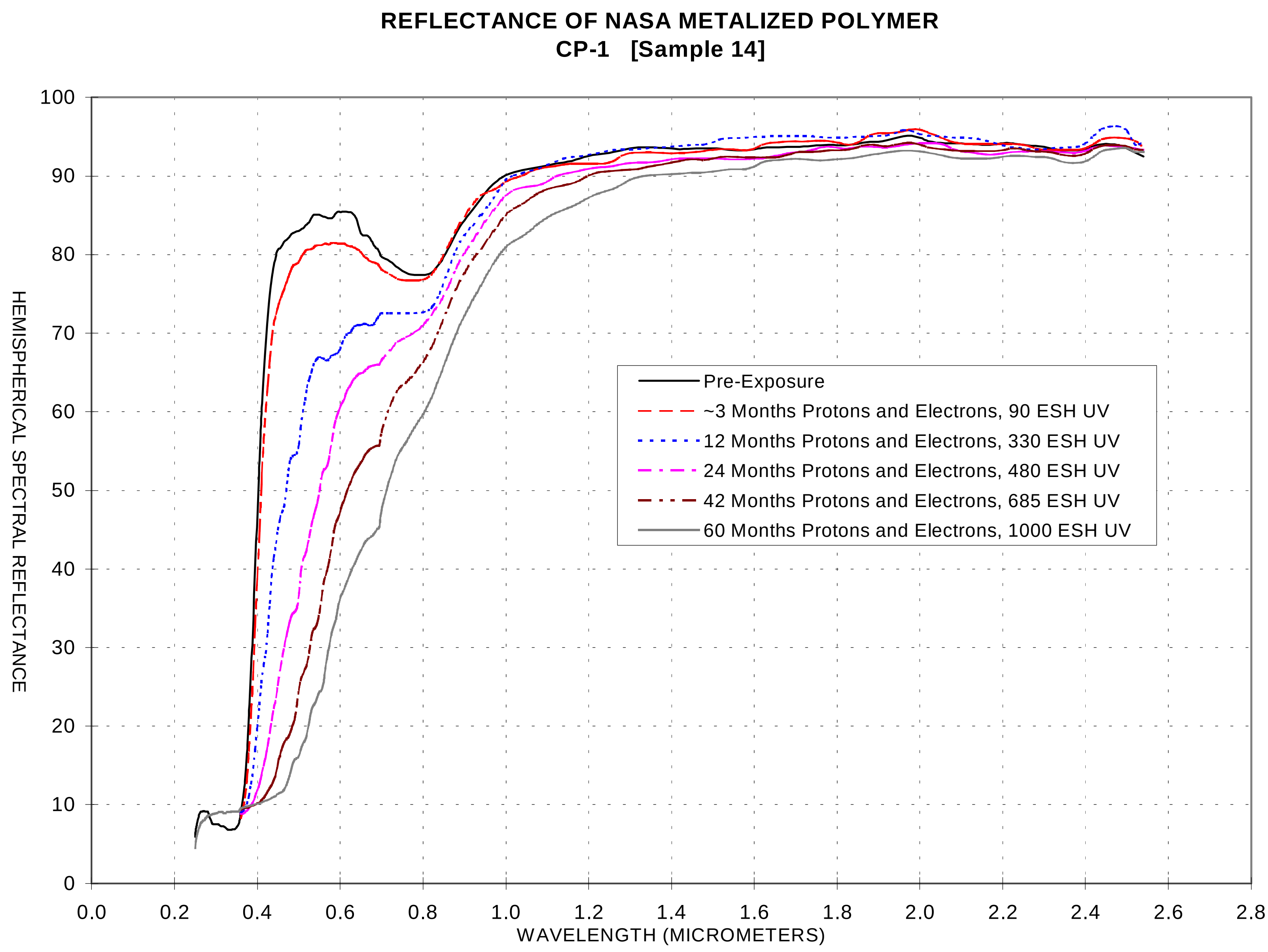


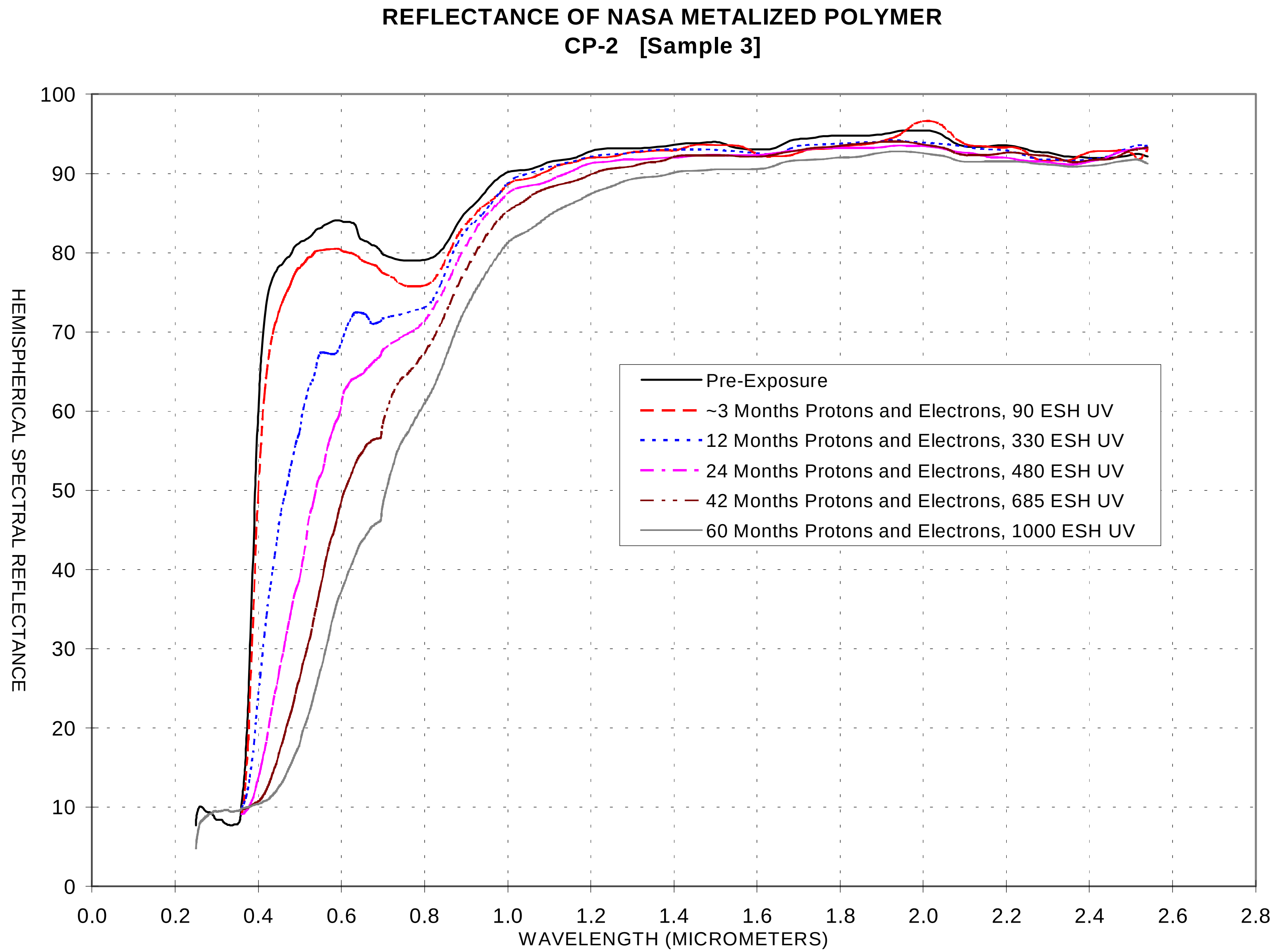
REFLECTANCE OF NASA METALIZED POLYMER
KAPTON E [Sample 15]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV


REFLECTANCE OF NASA METALIZED POLYMER
KAPTON HN [Sample 1]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

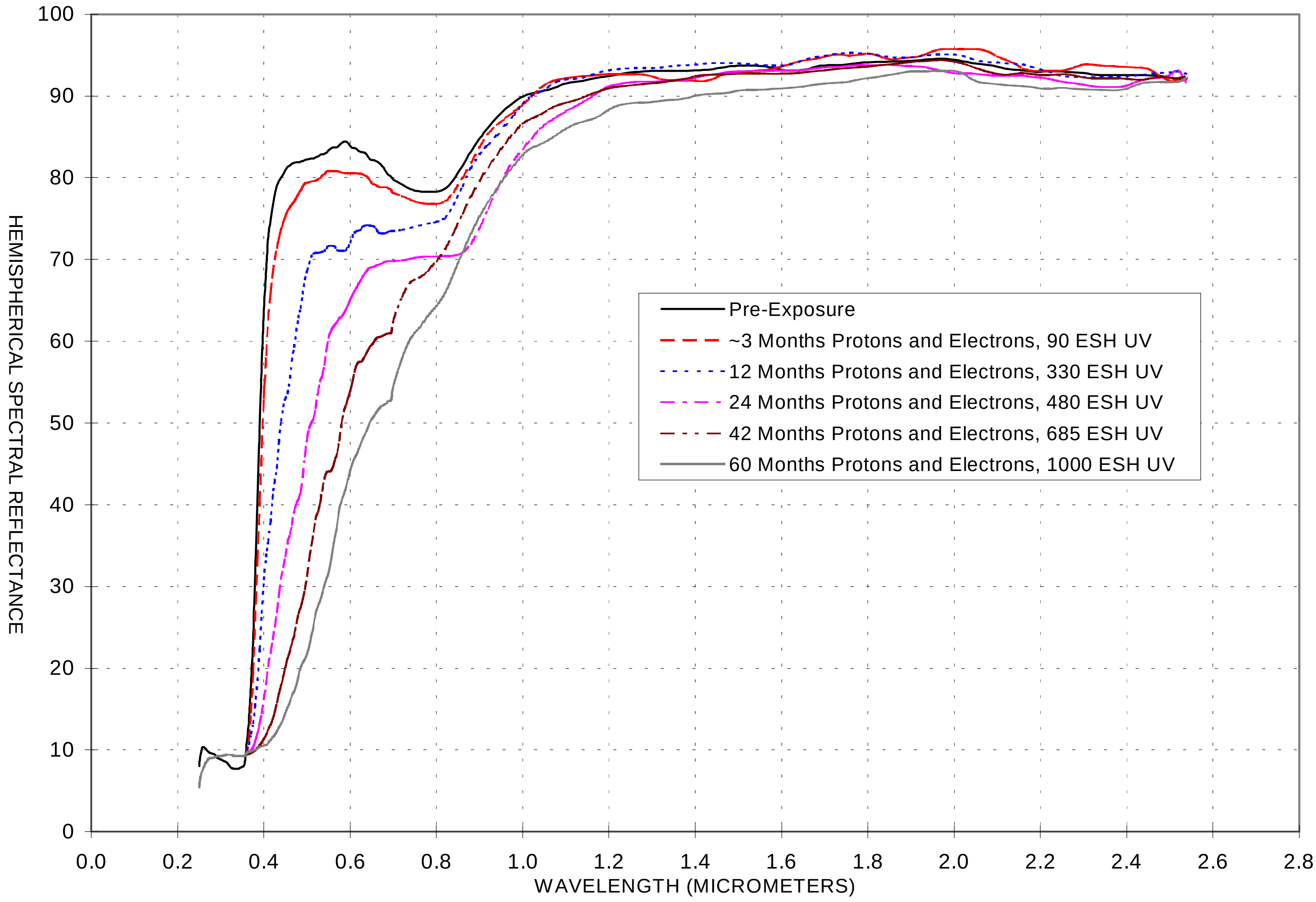

REFLECTANCE OF NASA METALIZED POLYMER
KAPTON HN [Sample 8]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV

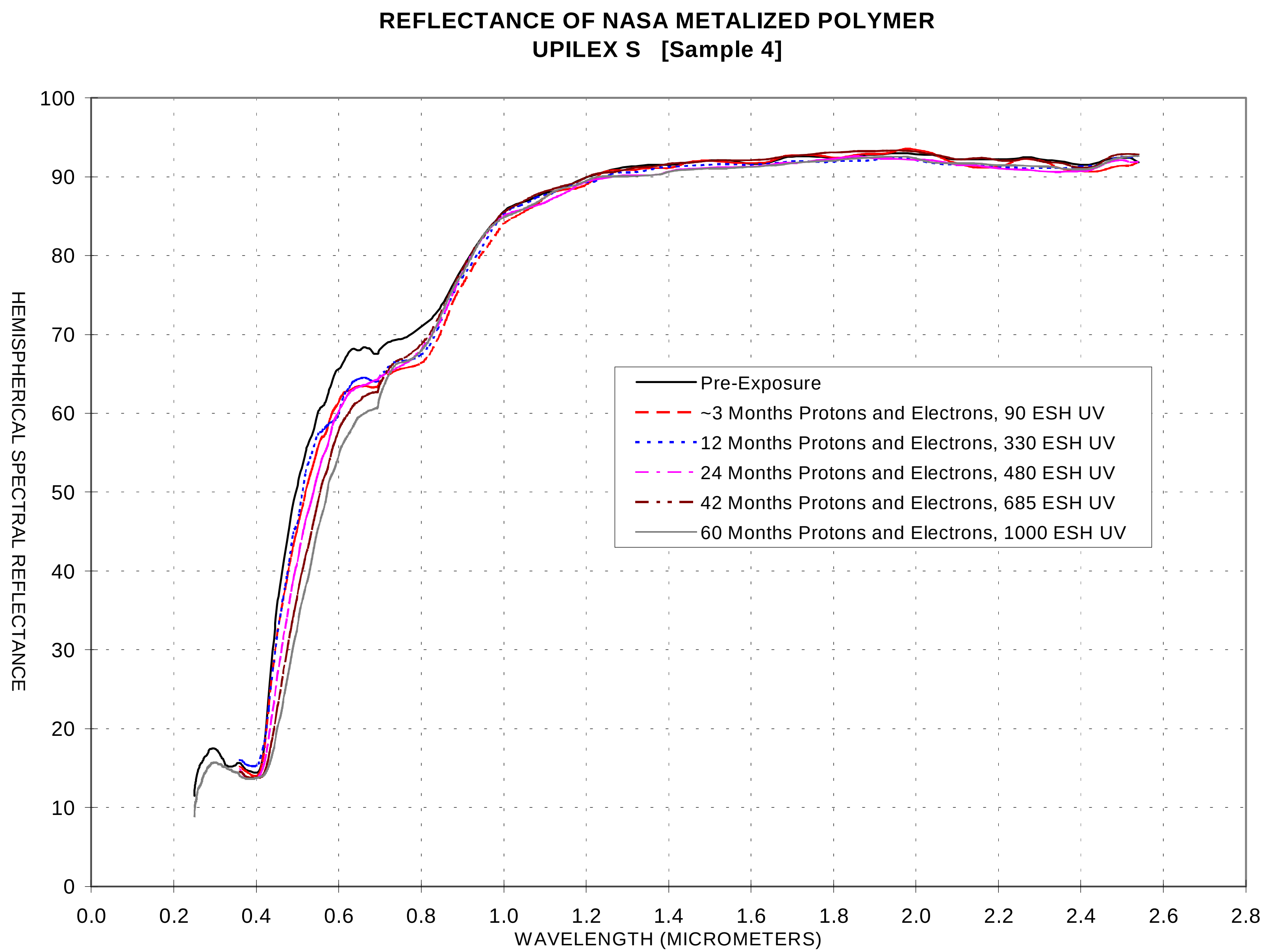

REFLECTANCE OF NASA METALIZED POLYMER
CP-1 [Sample 9]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV


REFLECTANCE OF NASA METALIZED POLYMER
CP-1 [Sample 14]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8

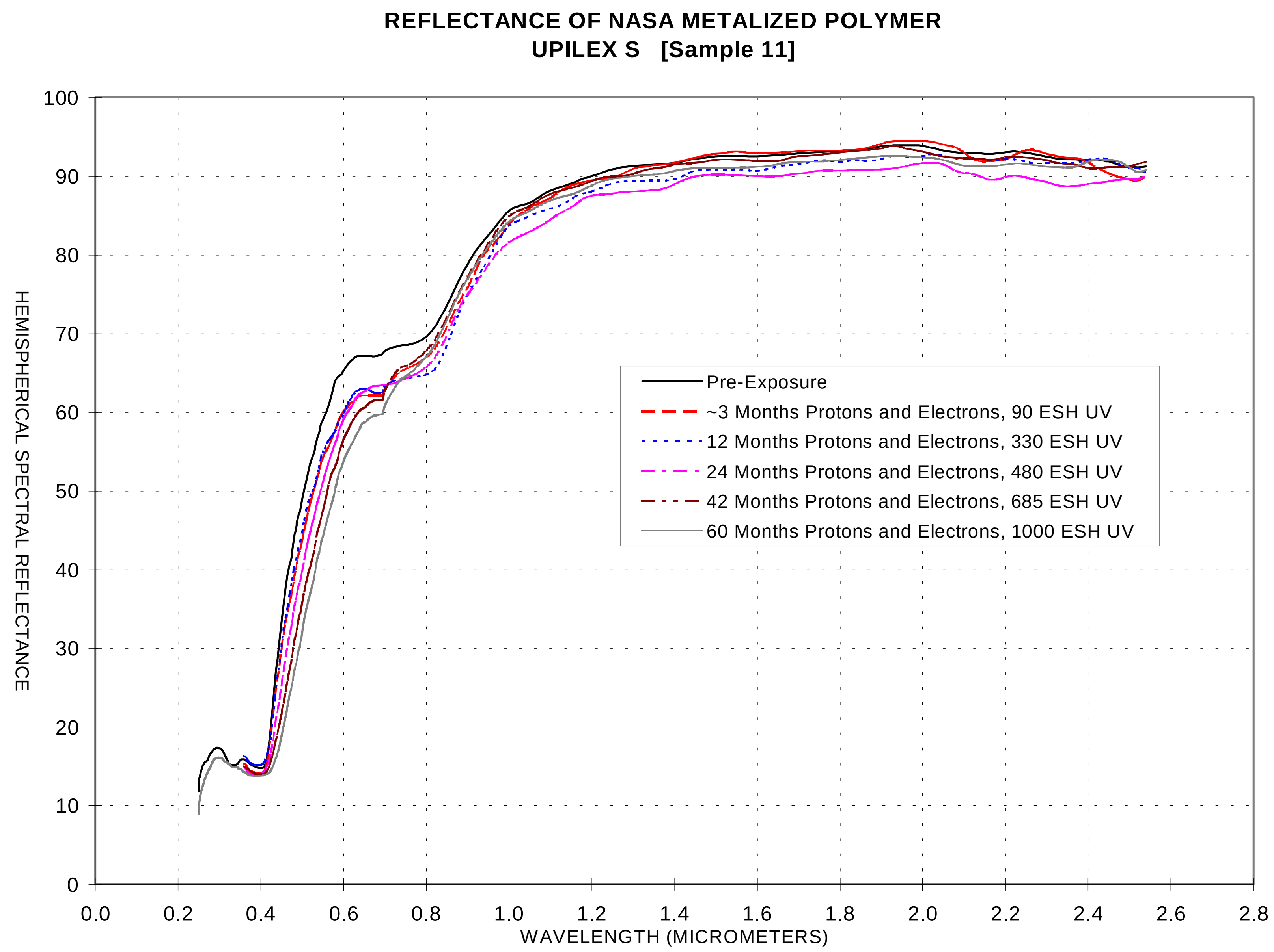

REFLECTANCE OF NASA METALIZED POLYMER
CP-2 [Sample 3]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV

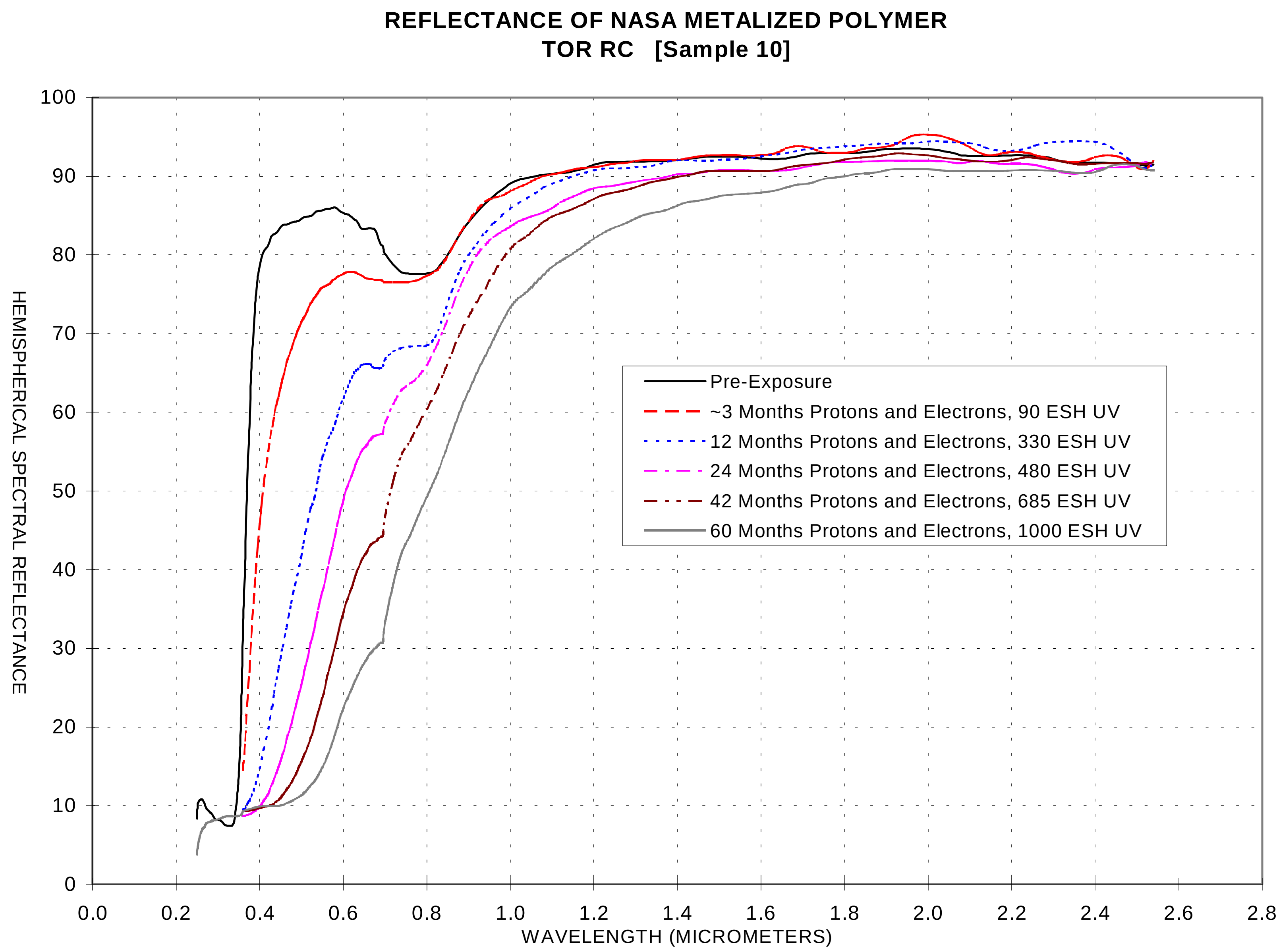
REFLECTANCE OF NASA METALIZED POLYMER
CP-2 [Sample 6]

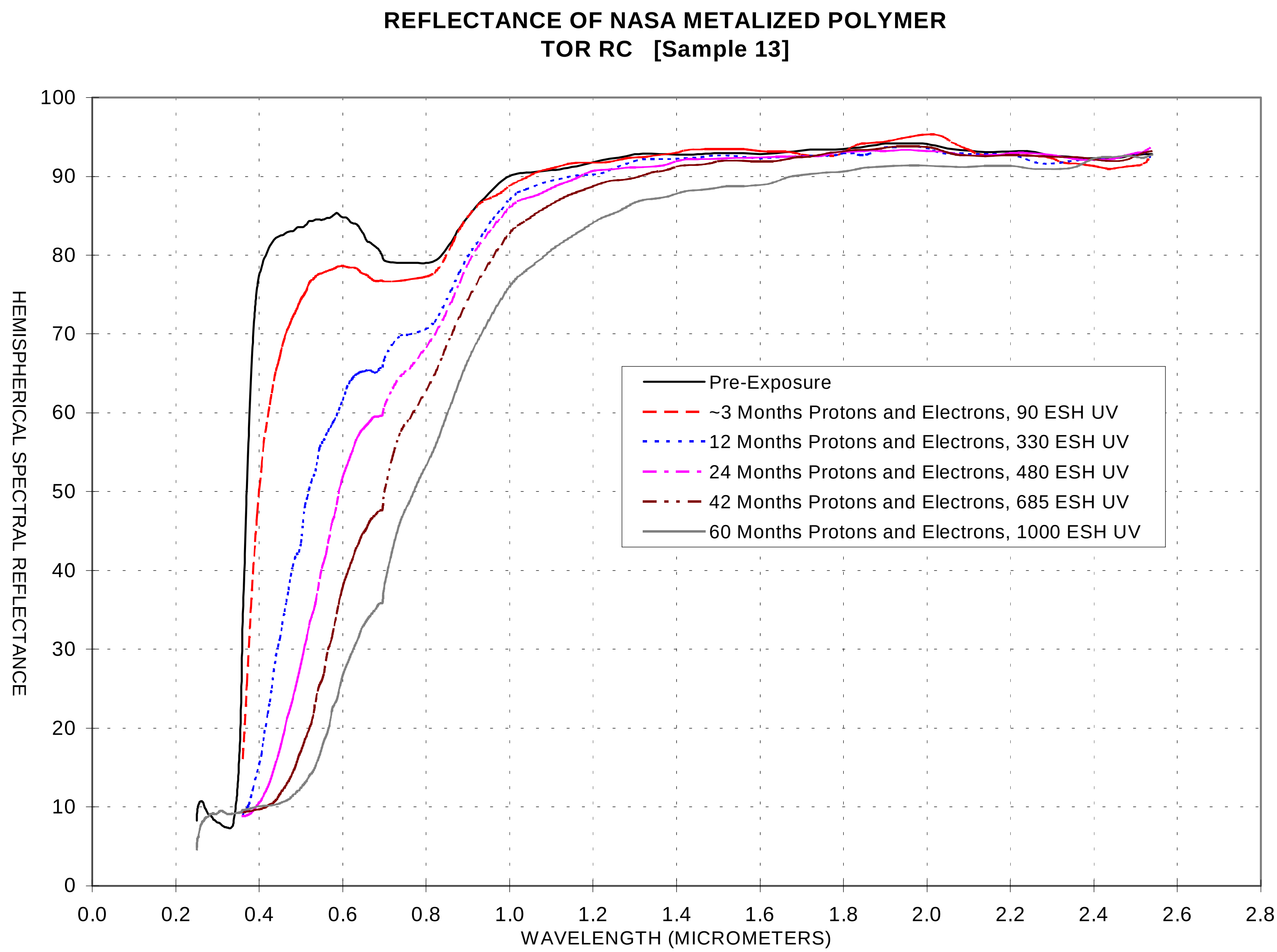


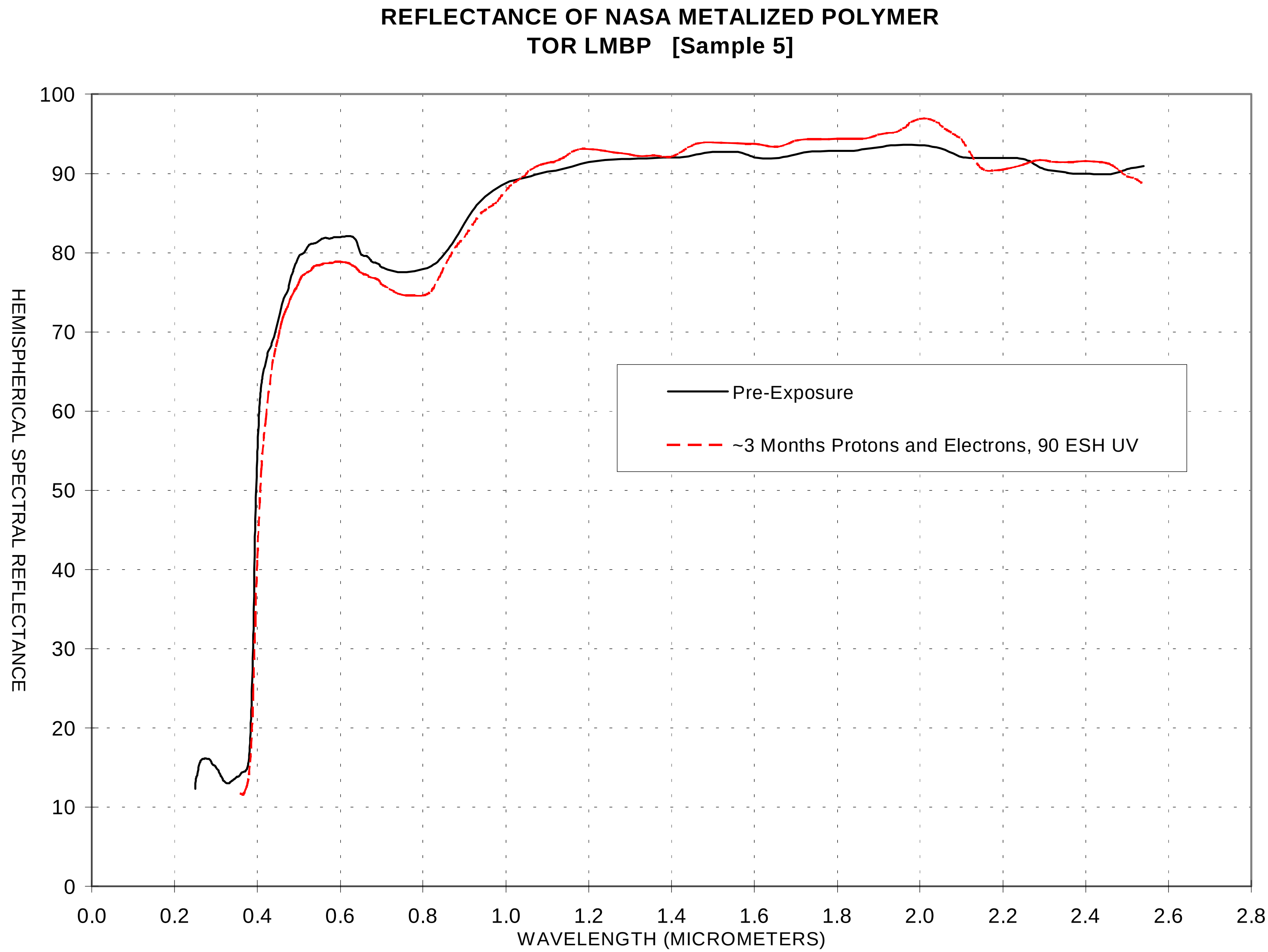


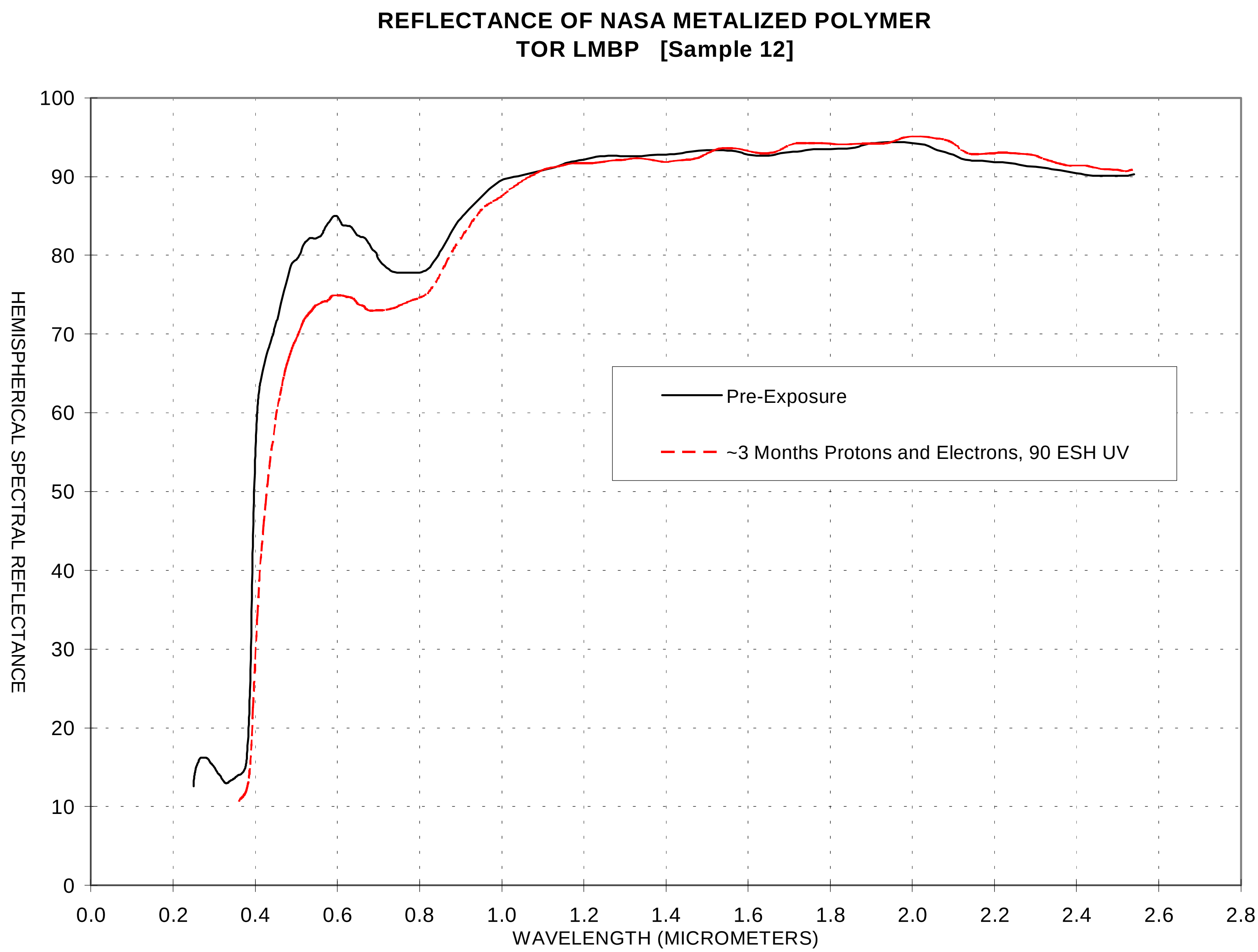
REFLECTANCE OF NASA METALIZED POLYMER
UPILEX S [Sample 4]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8


REFLECTANCE OF NASA METALIZED POLYMER
UPILEX S [Sample 11]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV

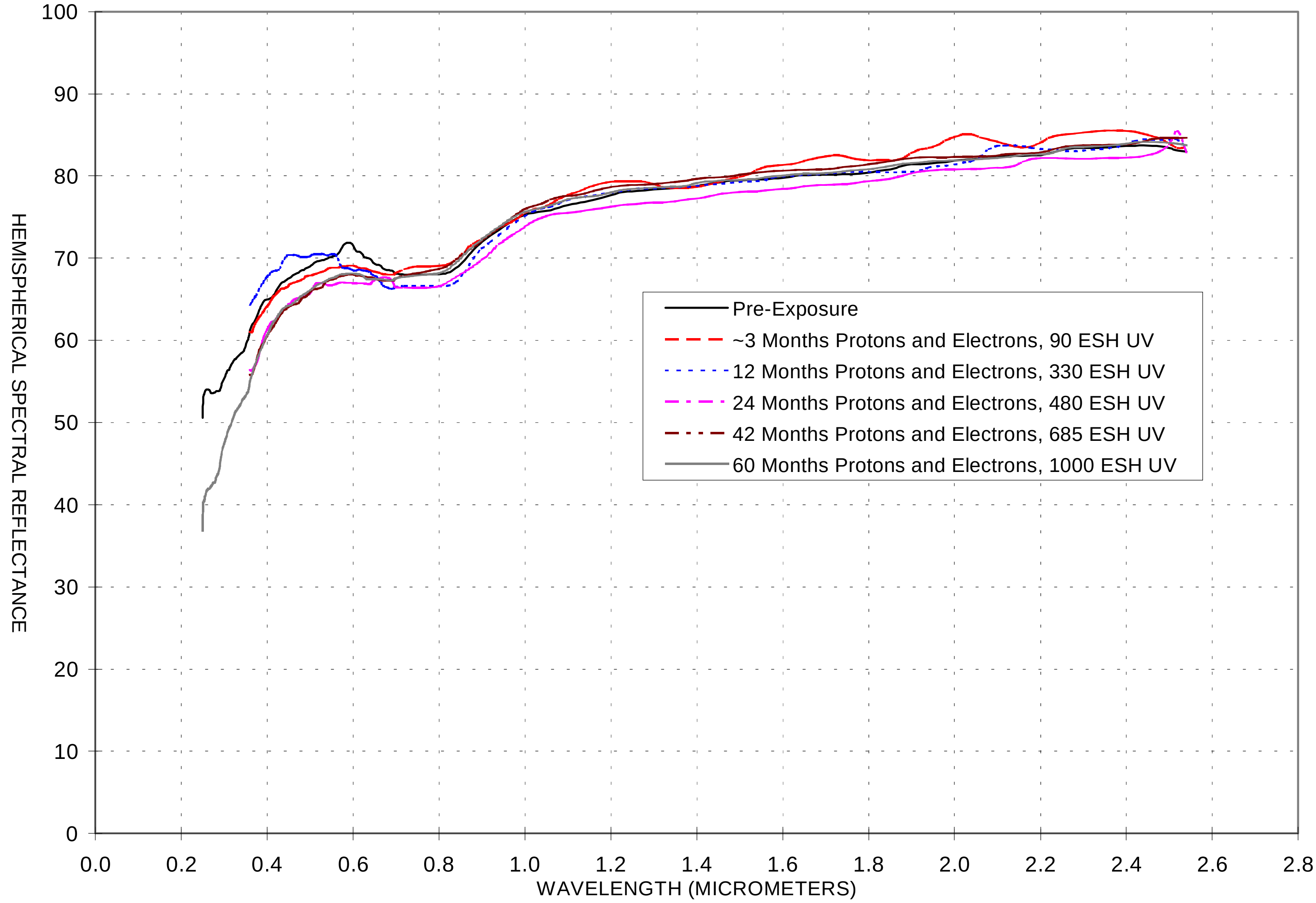

REFLECTANCE OF NASA METALIZED POLYMER
TOR RC [Sample 10]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV


REFLECTANCE OF NASA METALIZED POLYMER
TOR RC [Sample 13]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
12 Months Protons and Electrons, 330 ESH UV
24 Months Protons and Electrons, 480 ESH UV
42 Months Protons and Electrons, 685 ESH UV
60 Months Protons and Electrons, 1000 ESH UV


REFLECTANCE OF NASA METALIZED POLYMER
TOR LMBP [Sample 5]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8


REFLECTANCE OF NASA METALIZED POLYMER
TOR LMBP [Sample 12]
HEMISPHERICAL SPECTRAL REFLECTANCE
WAVELENGTH (MICROMETERS)
0
10
20
30
40
50
60
70
80
90
100
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Pre-Exposure
~3 Months Protons and Electrons, 90 ESH UV

REFLECTANCE OF NASA METALIZED POLYMER ALUMINUM SAMPLE HOLDER [Sample 1022]

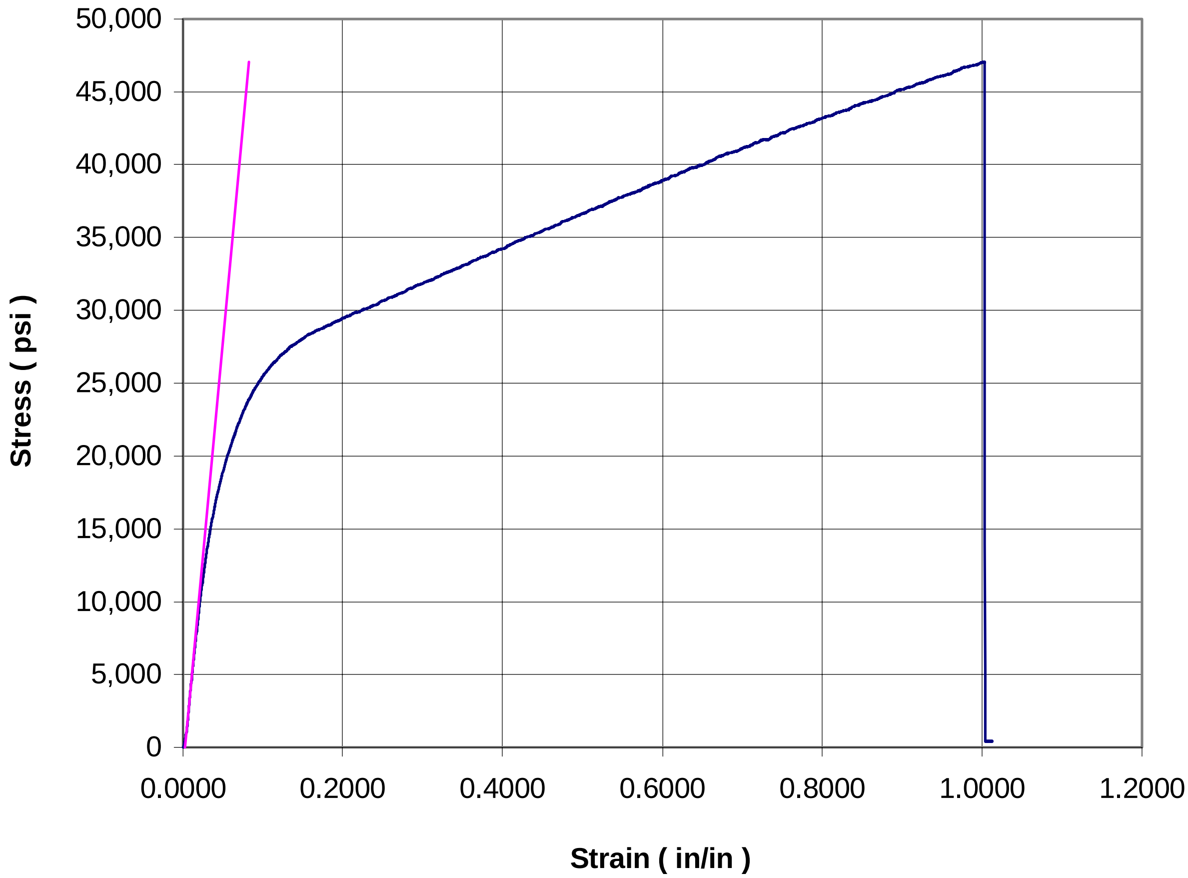


Appendix C

Tensile Properties Experimental Results

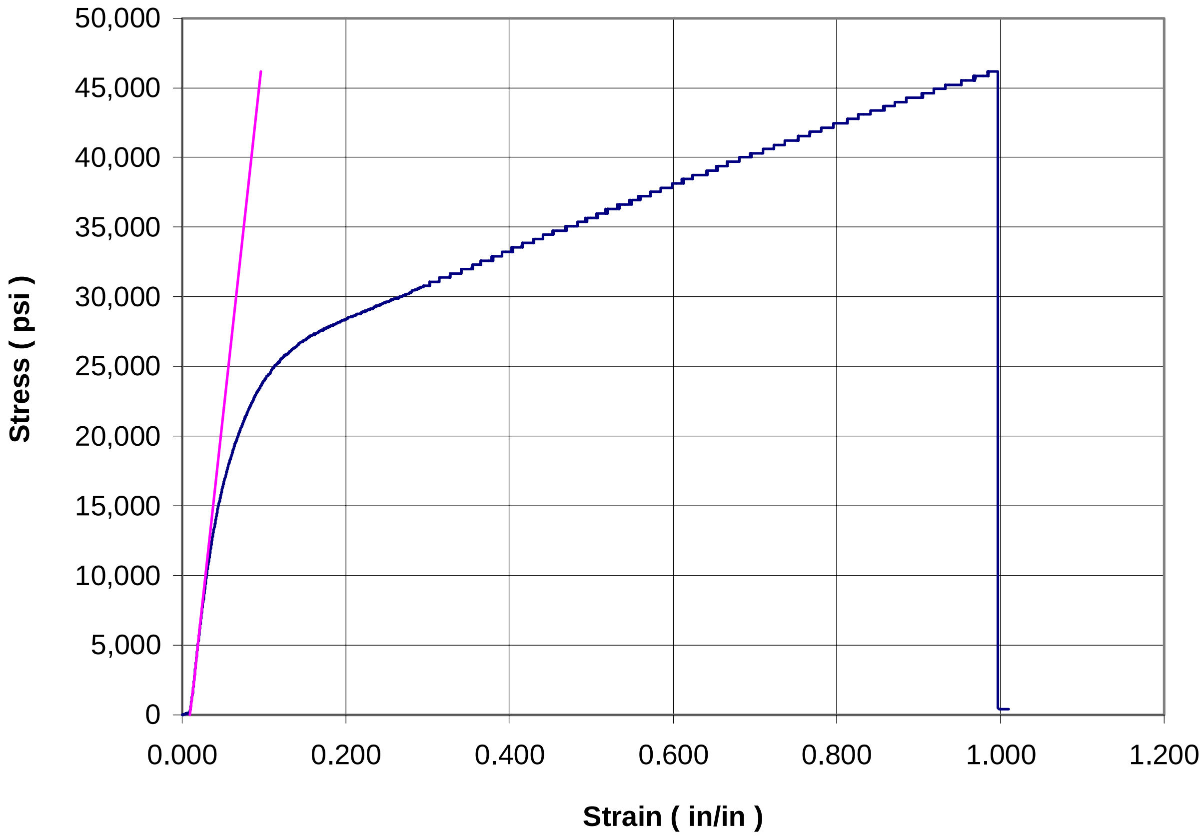
By Sample

Kapton E UN-3



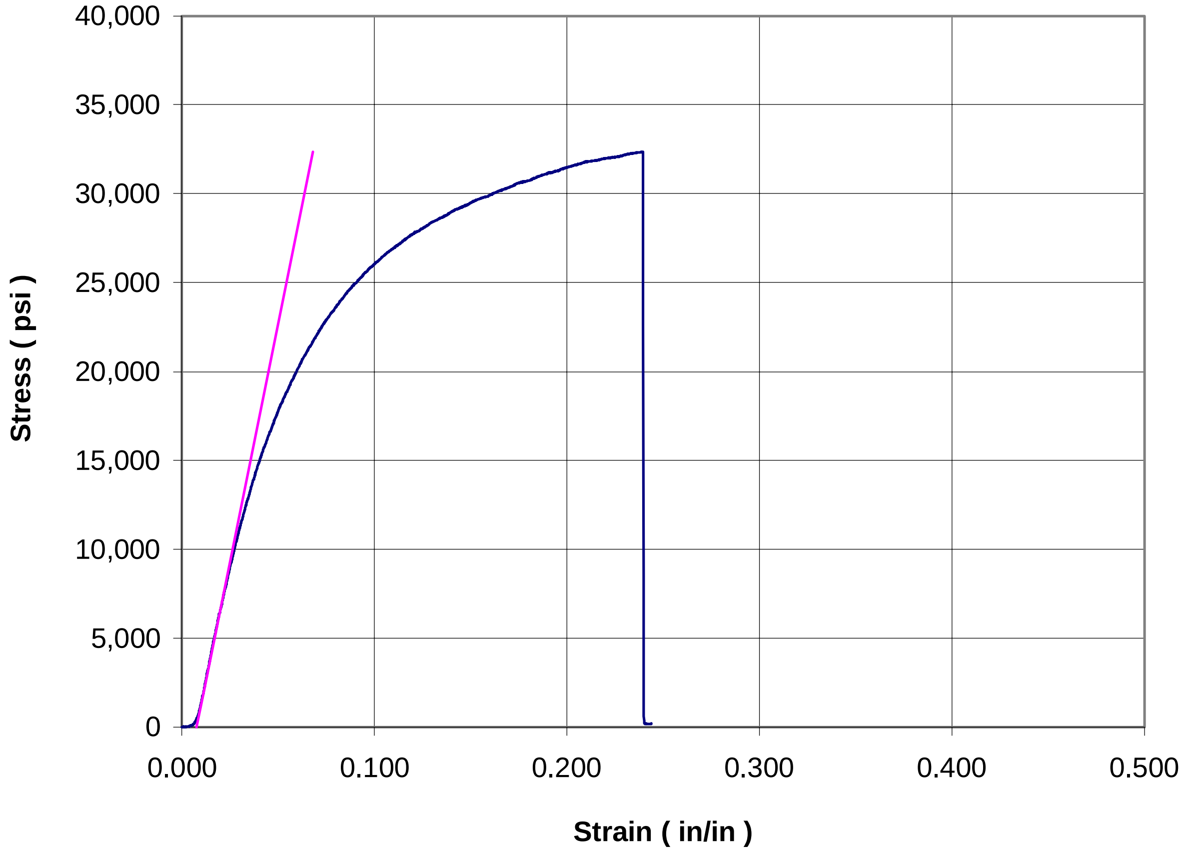
Operator:	S. McKean	Modulus:	590,600 (psi)
Engineer:	J. Hobson	Ult. Load:	15.29 (lbs)
Test Date:	10/04/99	Ult. Stress:	47,052 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	101.3 %

Kapton E UN-4



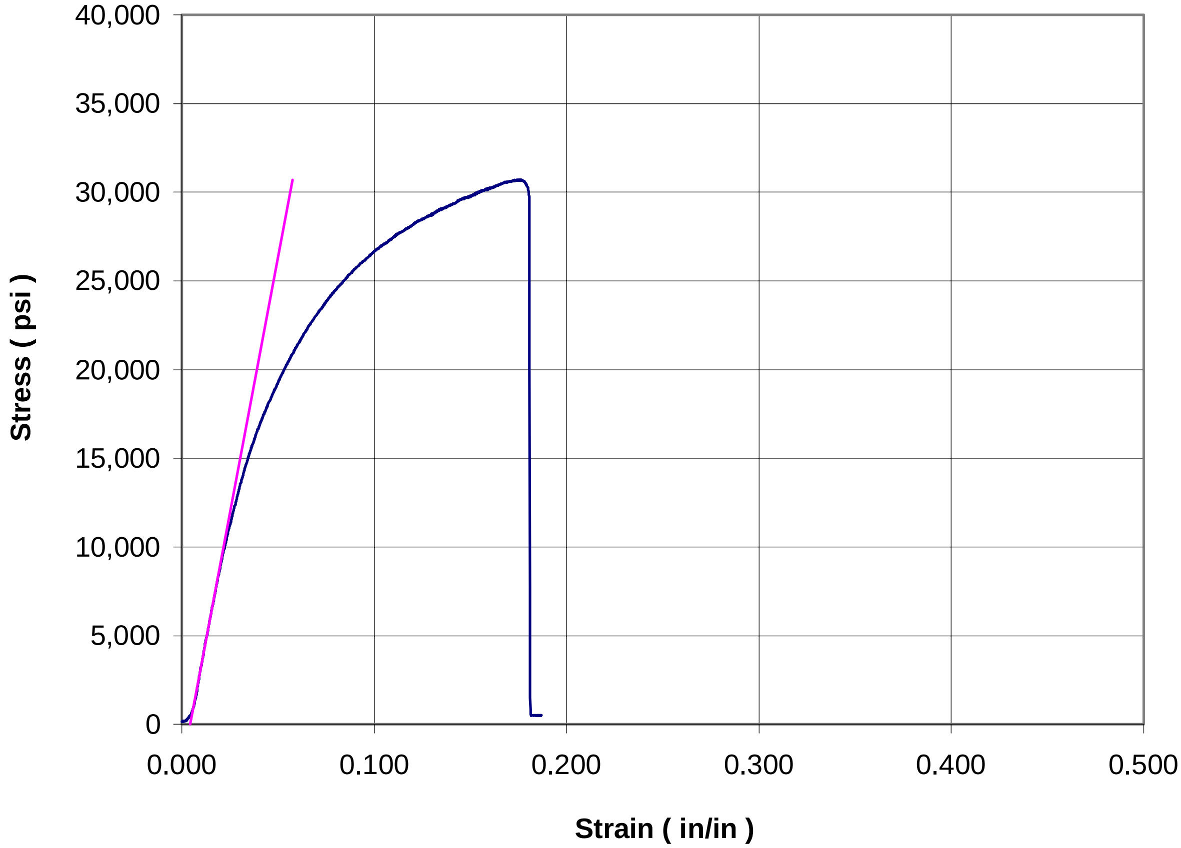
Operator:	S. McKean	Modulus:	531,692 (psi)
Engineer:	J. Hobson	Ult. Load:	15 (lbs)
Test Date:	10/04/99	Ult. Stress:	46,154 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	101.0 %

Kapton E EX-2



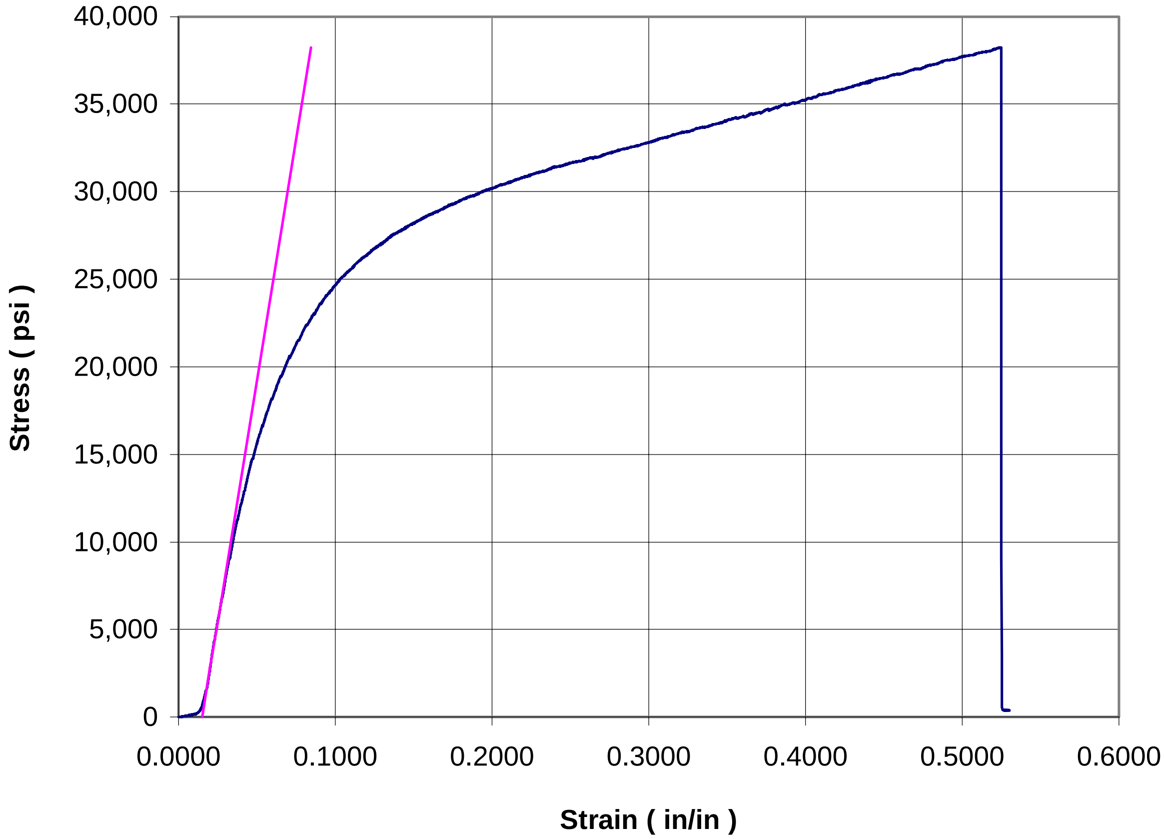
Operator:	S. McKean	Modulus:	534,021 (psi)
Engineer:	J. Hobson	Ult. Load:	10.52 (lbs)
Test Date:	10/05/99	Ult. Stress:	32,369 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	24.4 %

Kapton E EX-7



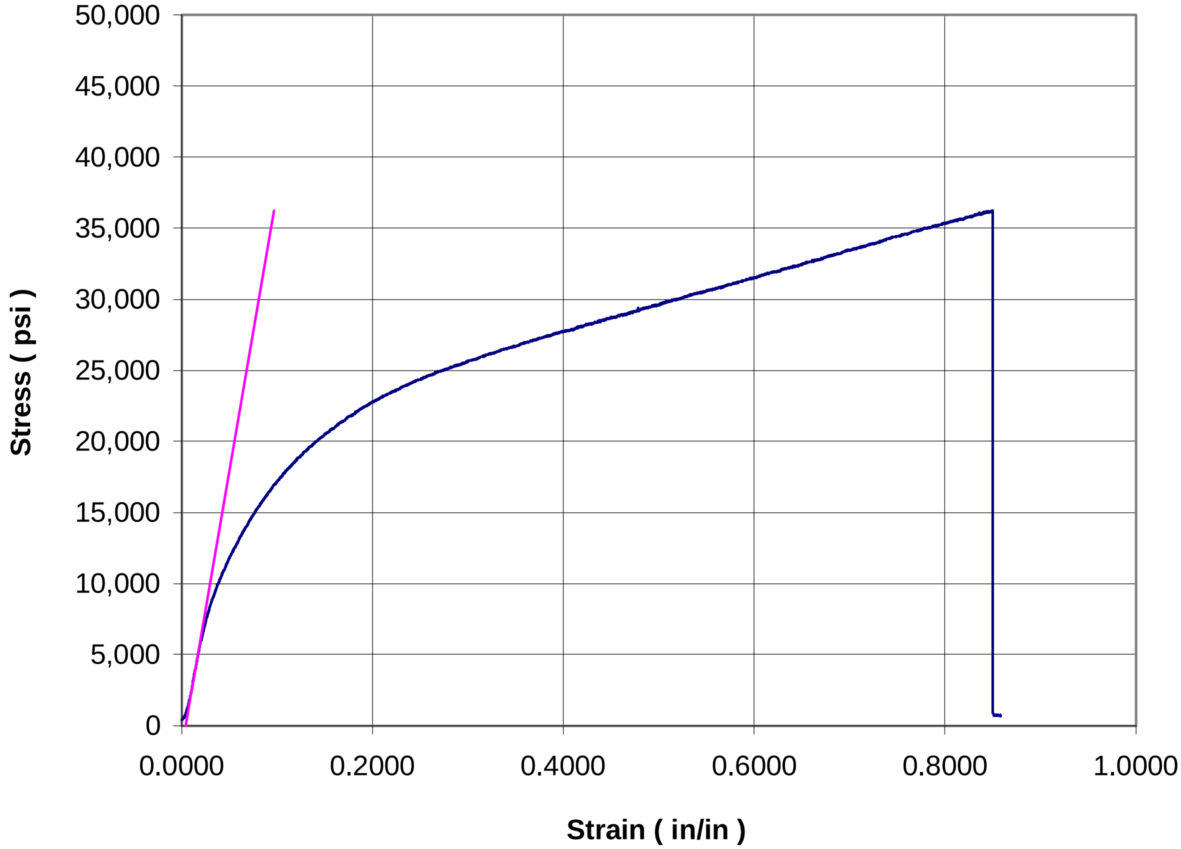
Operator:	S. McKean	Modulus:	576,000 (psi)
Engineer:	J. Hobson	Ult. Load:	9.98 (lbs)
Test Date:	10/05/99	Ult. Stress:	30,695 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	18.7 %

Kapton E EX-15



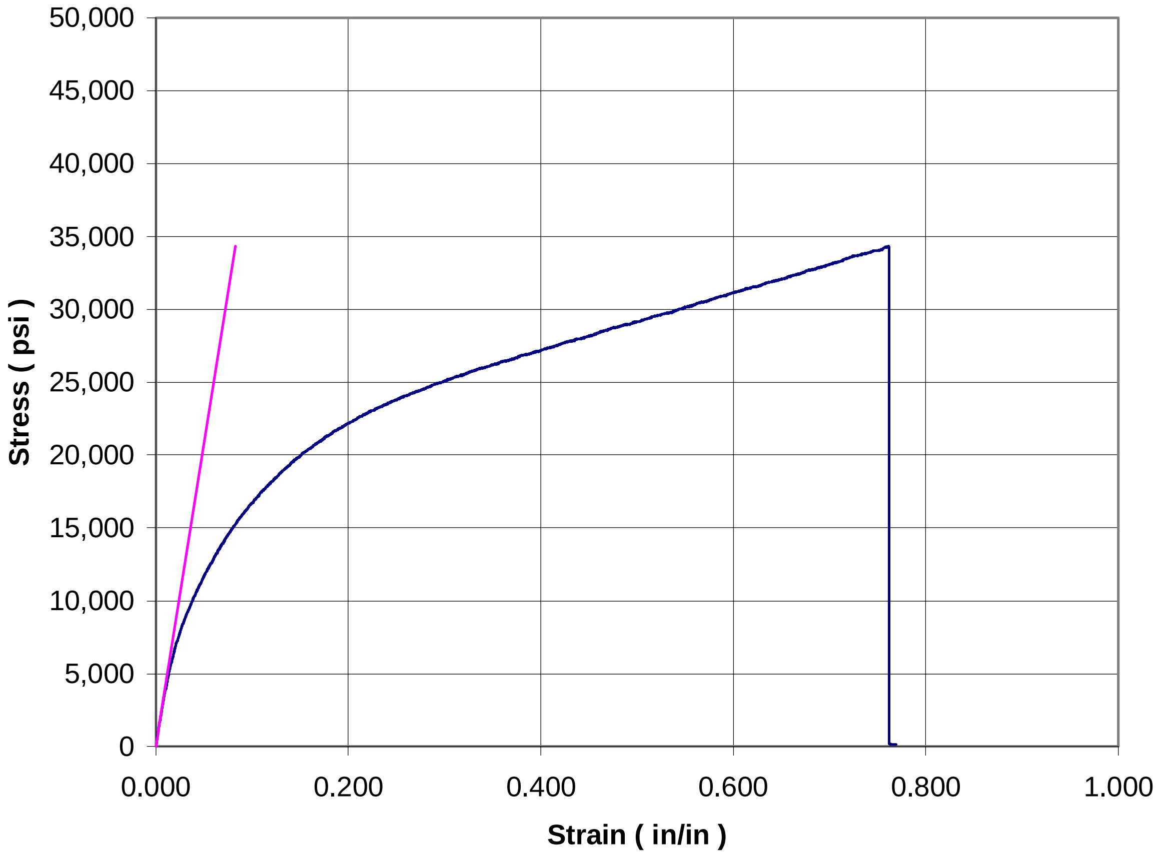
Operator:	S. McKean	Modulus:	549,676 (psi)
Engineer:	J. Hobson	Ult. Load:	12.43 (lbs)
Test Date:	10/05/99	Ult. Stress:	38,249 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	53.0 %

Kapton HN UN-1



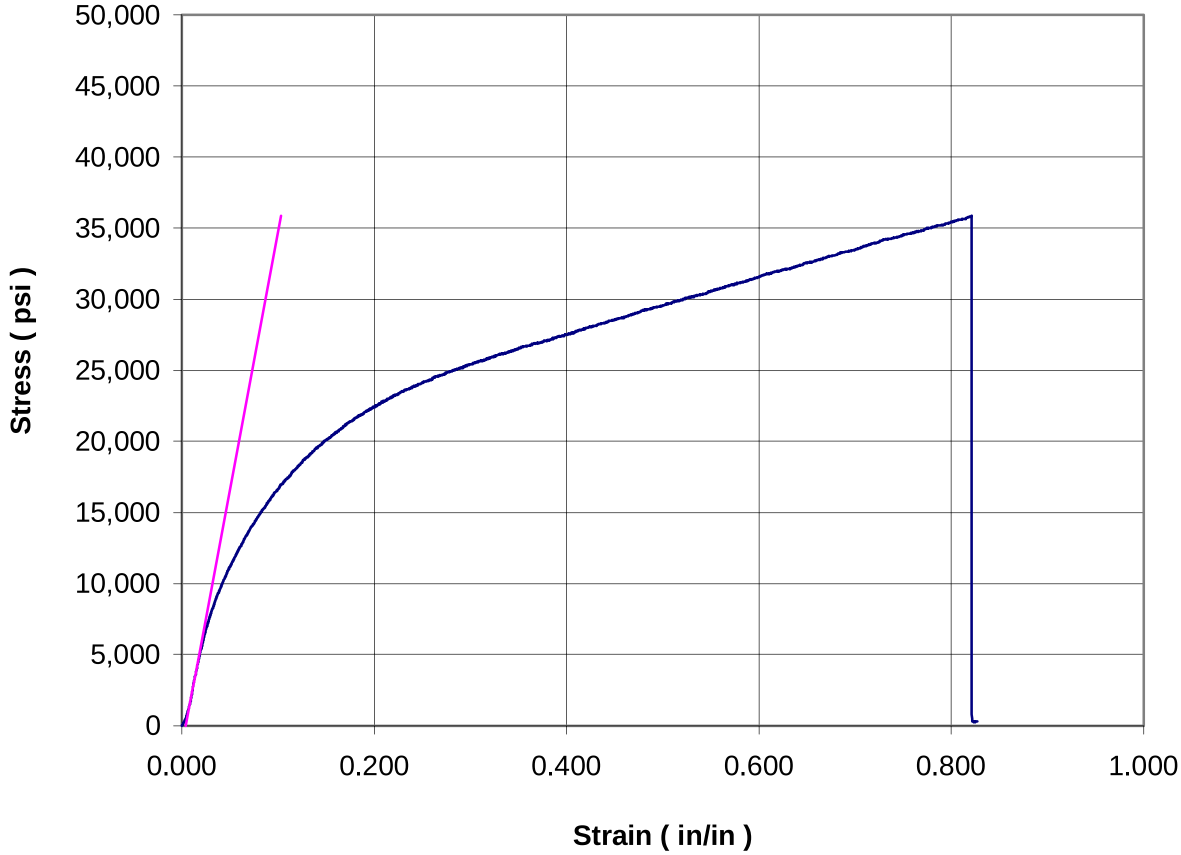
Operator:	S. McKean	Modulus:	390,769 (psi)
Engineer:	J. Hobson	Ult. Load:	11.80 (lbs)
Test Date:	10/05/99	Ult. Stress:	36,308 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	85.8 %

Kapton HN UN-2

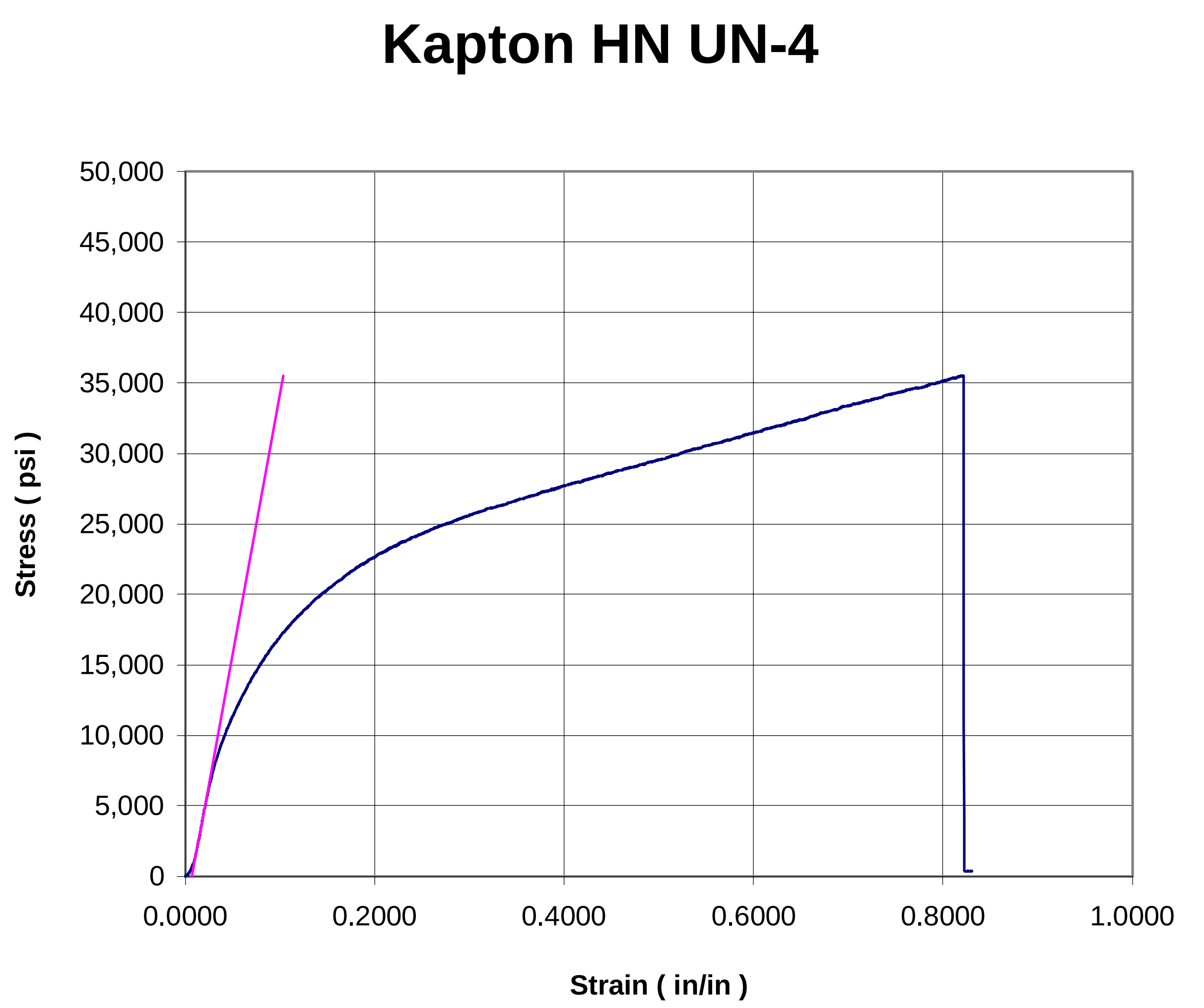


Operator:	S. McKean	Modulus:	417,163 (psi)
Engineer:	J. Hobson	Ult. Load:	11.20 (lbs)
Test Date:	10/05/99	Ult. Stress:	34,462 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	76.9 %

Kapton HN UN-3

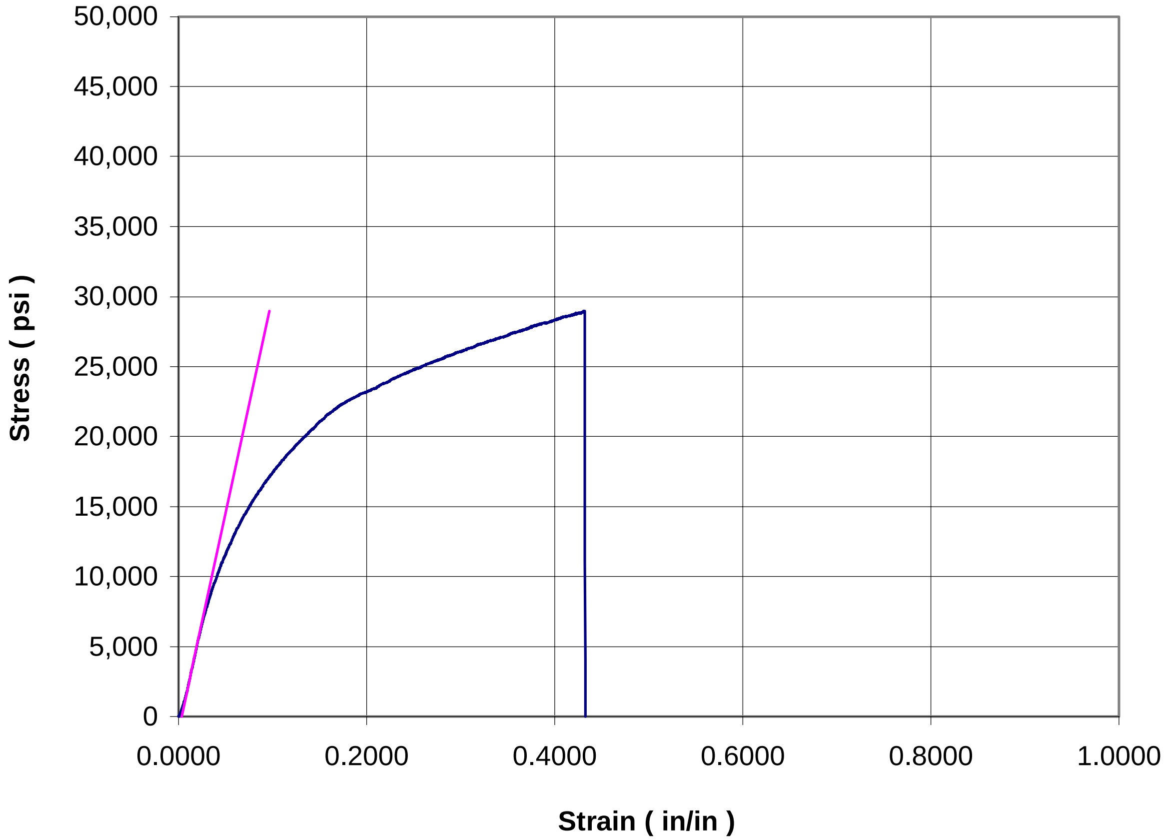


Operator:	S. McKean	Modulus:	361,979 (psi)
Engineer:	J. Hobson	Ult. Load:	11.70 (lbs)
Test Date:	10/05/99	Ult. Stress:	36,000 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	82.7 %



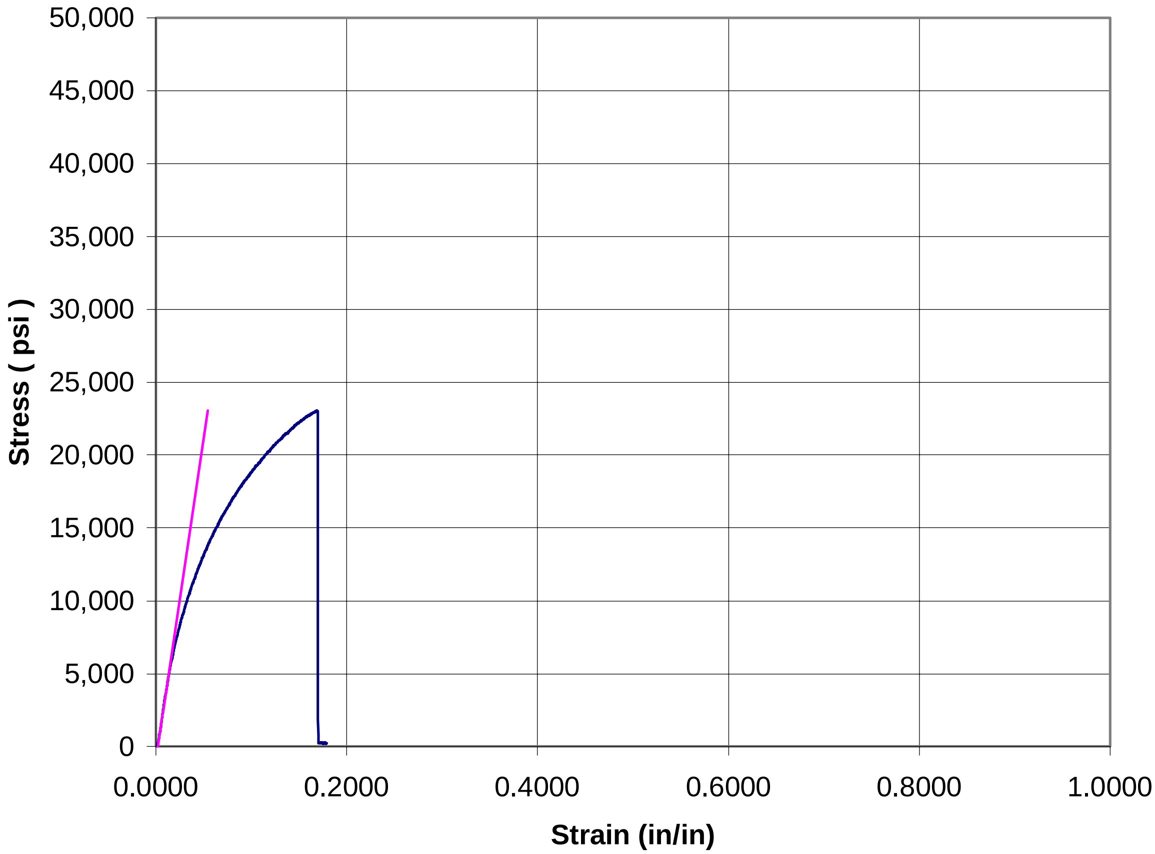
Operator:	S. McKean	Modulus:	368,950 (psi)
Engineer:	J. Hobson	Ult. Load:	11.55 (lbs)
Test Date:	10/06/99	Ult. Stress:	35,532 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	83.1 %

Kapton HN EX-1



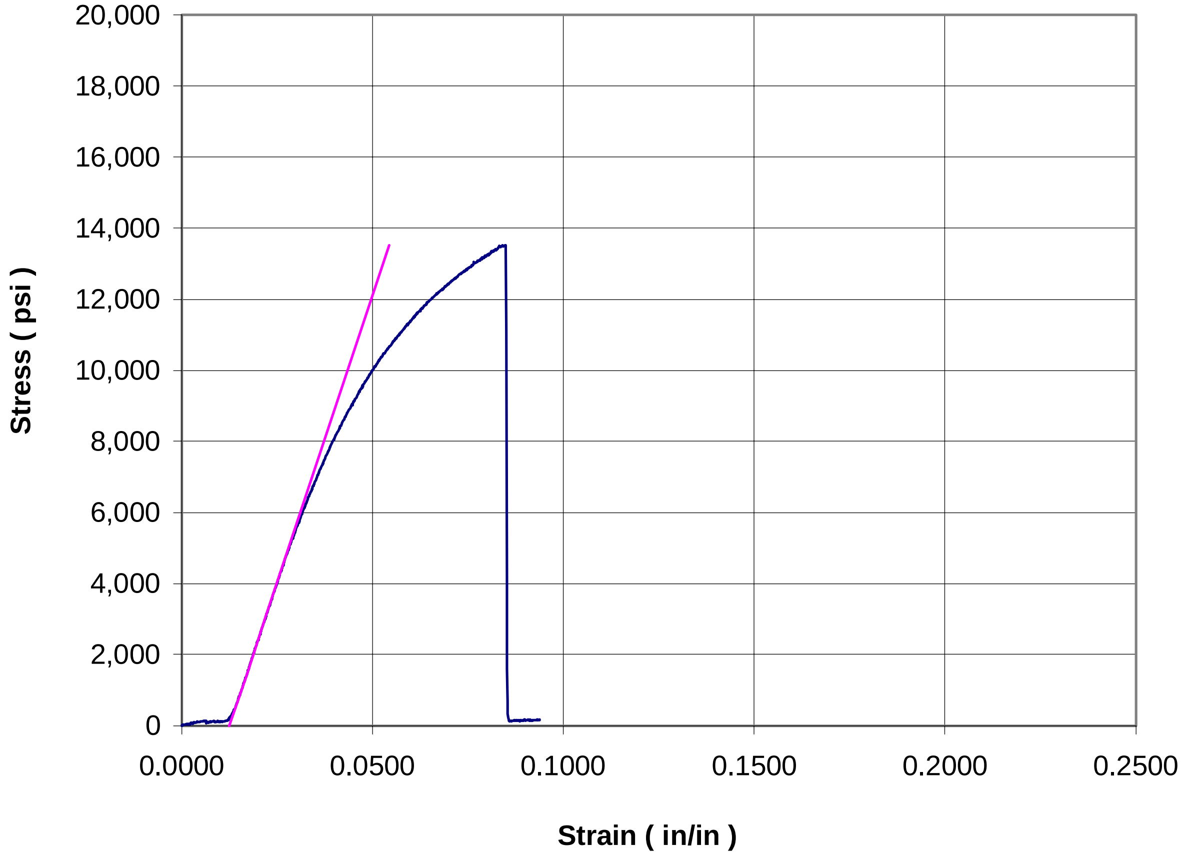
Operator:	S. McKean	Modulus:	310,555 (psi)
Engineer:	J. Hobson	Ult. Load:	9.42 (lbs)
Test Date:	10/06/99	Ult. Stress:	28,975 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	44.0 %

Kapton HN EX-8



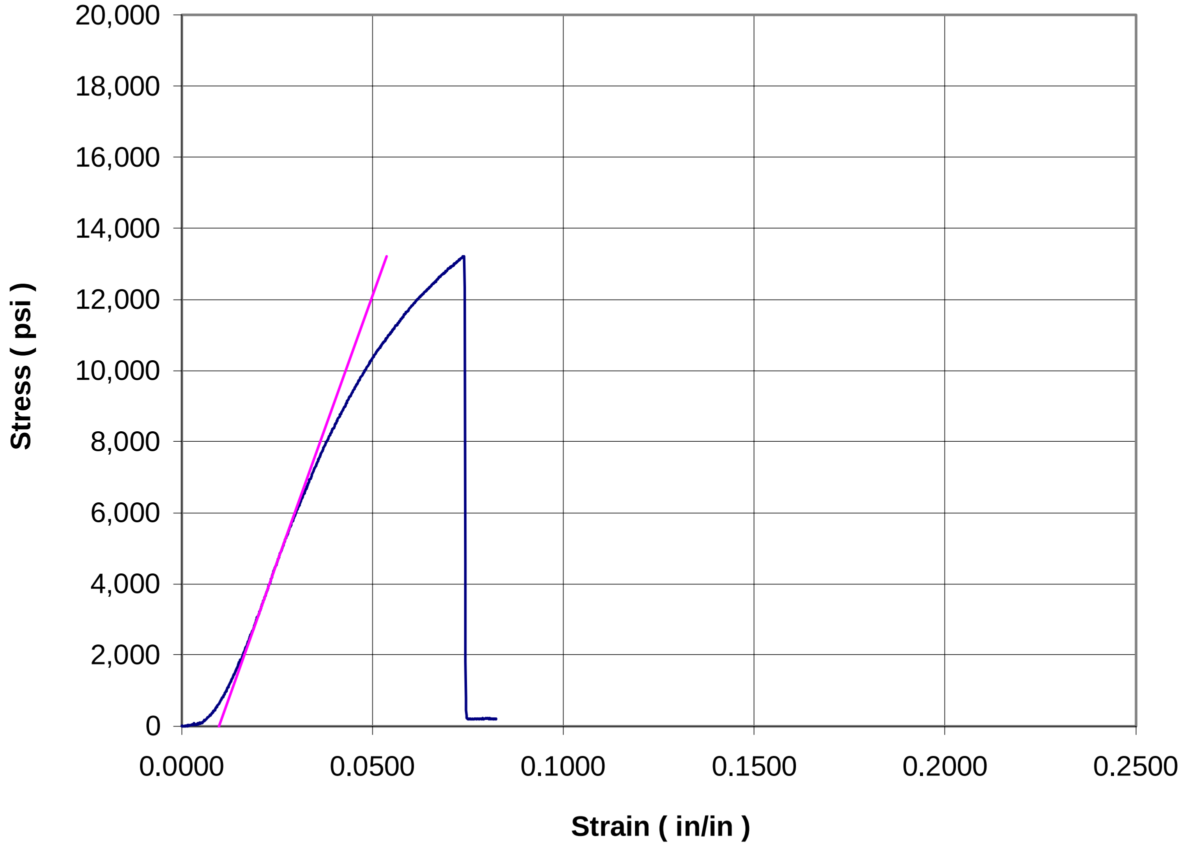
Operator:	S. McKean	Modulus:	437,446 (psi)
Engineer:	J. Hobson	Ult. Load:	7.50 (lbs)
Test Date:	10/06/99	Ult. Stress:	23,066 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	17.9 %

CP-1 UN-1



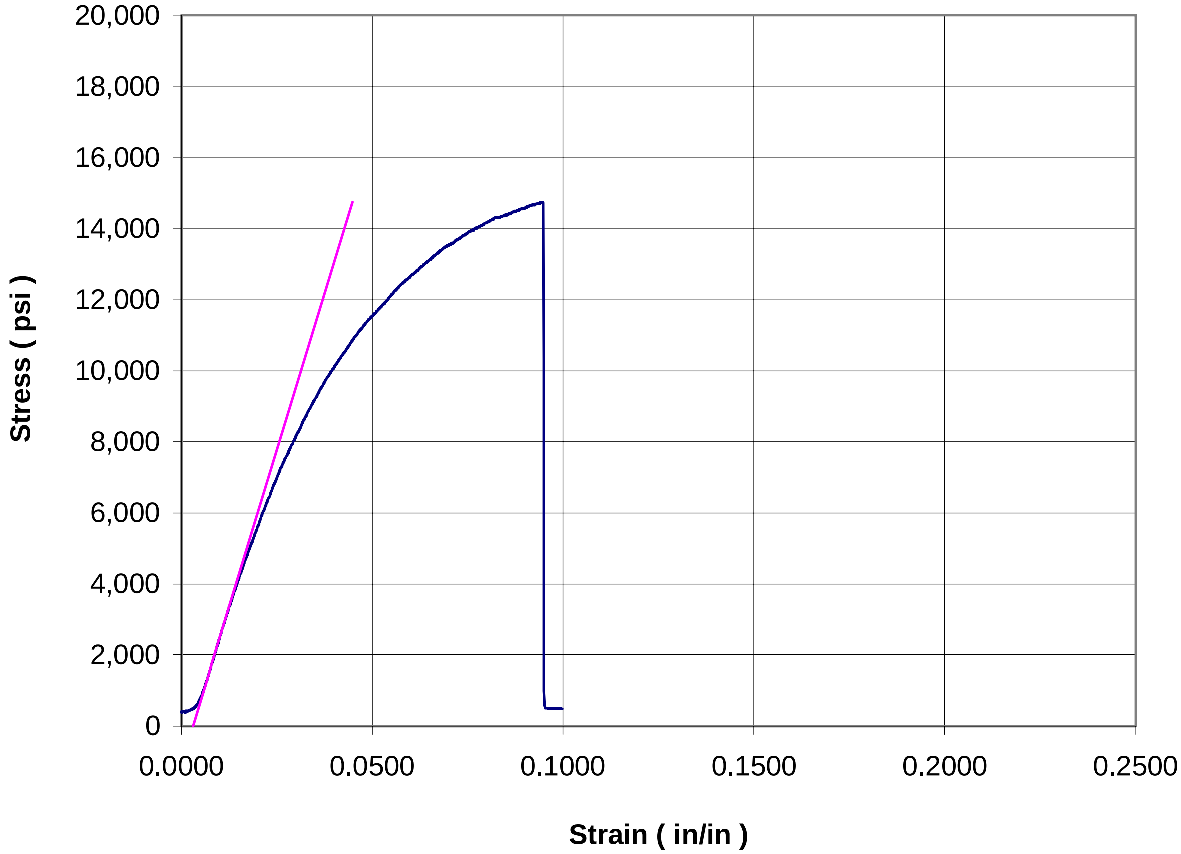
Operator:	S. McKean	Modulus:	323,834 (psi)
Engineer:	J. Hobson	Ult. Load:	4.40 (lbs)
Test Date:	10/06/99	Ult. Stress:	13,524 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	7.4 %

CP-1 UN-2



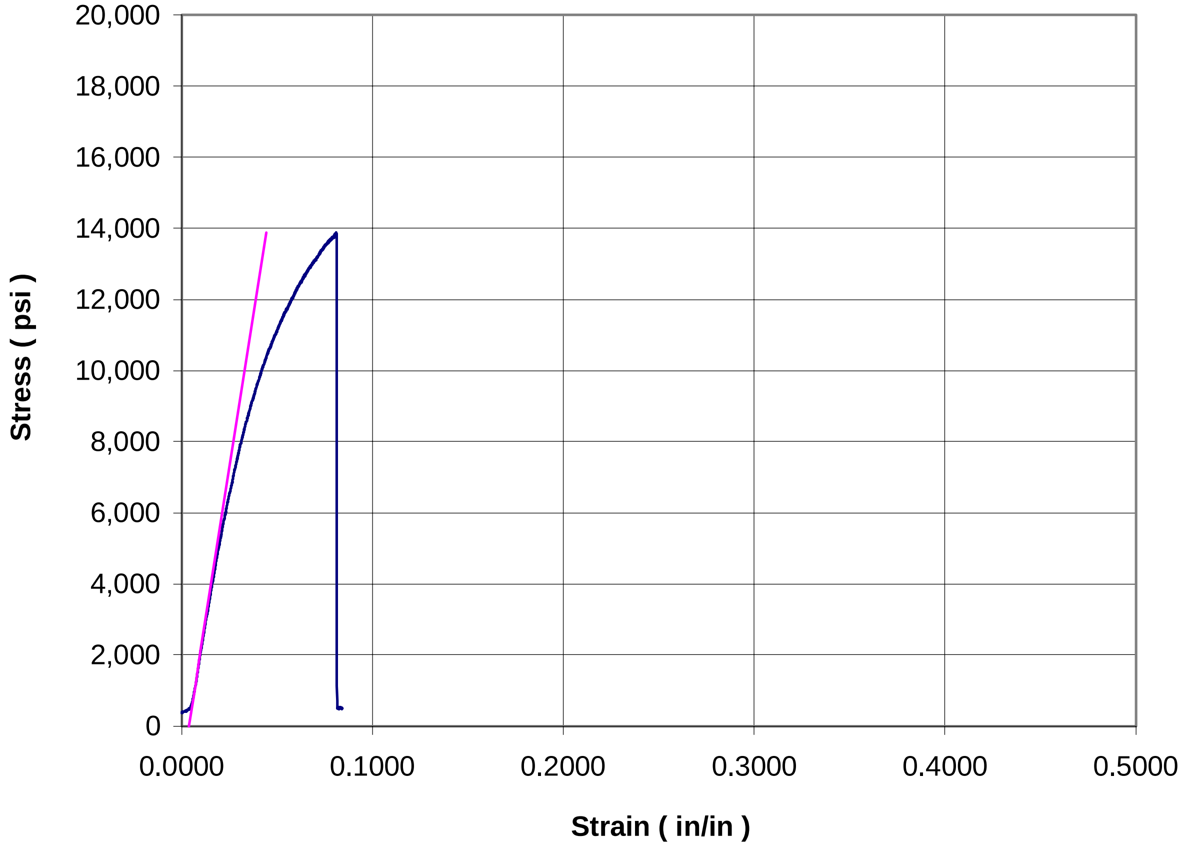
Operator:	S. McKean	Modulus:	300,198 (psi)
Engineer:	J. Hobson	Ult. Load:	4.30 (lbs)
Test Date:	10/06/99	Ult. Stress:	13,221 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	7.4 %

CP-1 UN-3



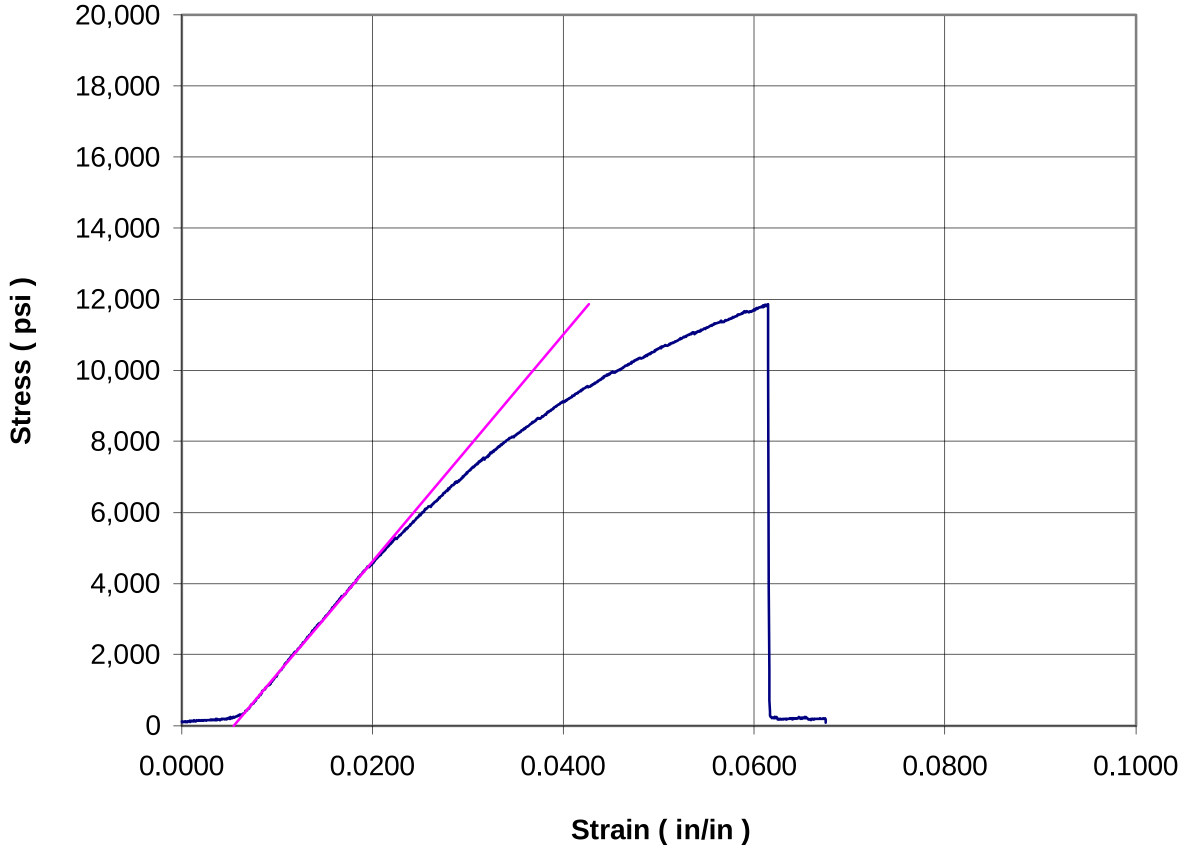
Operator:	S. McKean	Modulus:	352,277 (psi)
Engineer:	J. Hobson	Ult. Load:	4.79 (lbs)
Test Date:	10/07/99	Ult. Stress:	14,745 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	9.5 %

CP-1 UN-4



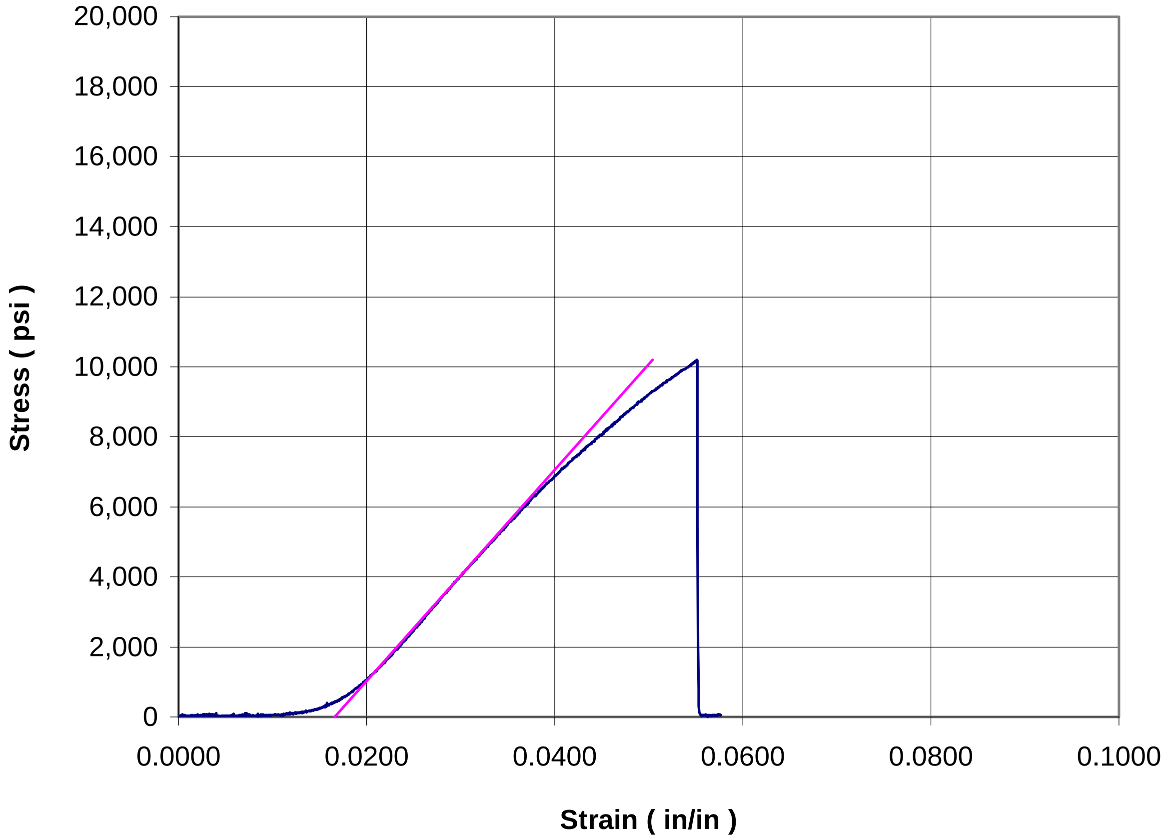
Operator:	S. McKean	Modulus:	343,333 (psi)
Engineer:	J. Hobson	Ult. Load:	4.51 (lbs)
Test Date:	10/07/99	Ult. Stress:	13,880 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	8.4 %

CP-1 UN-5



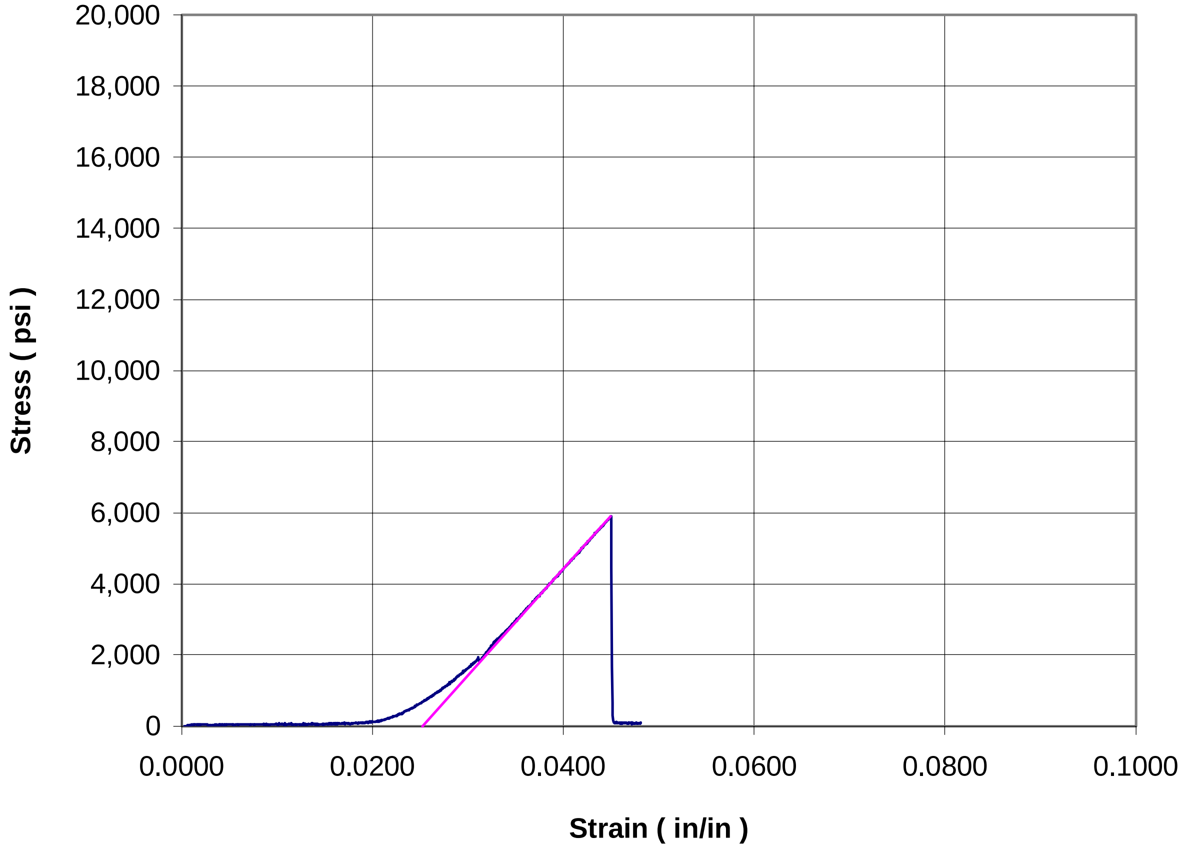
Operator:	S. McKean	Modulus:	319,071 (psi)
Engineer:	J. Hobson	Ult. Load:	3.86 (lbs)
Test Date:	10/07/99	Ult. Stress:	11,868 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	6.3 %

CP-1 EX-9



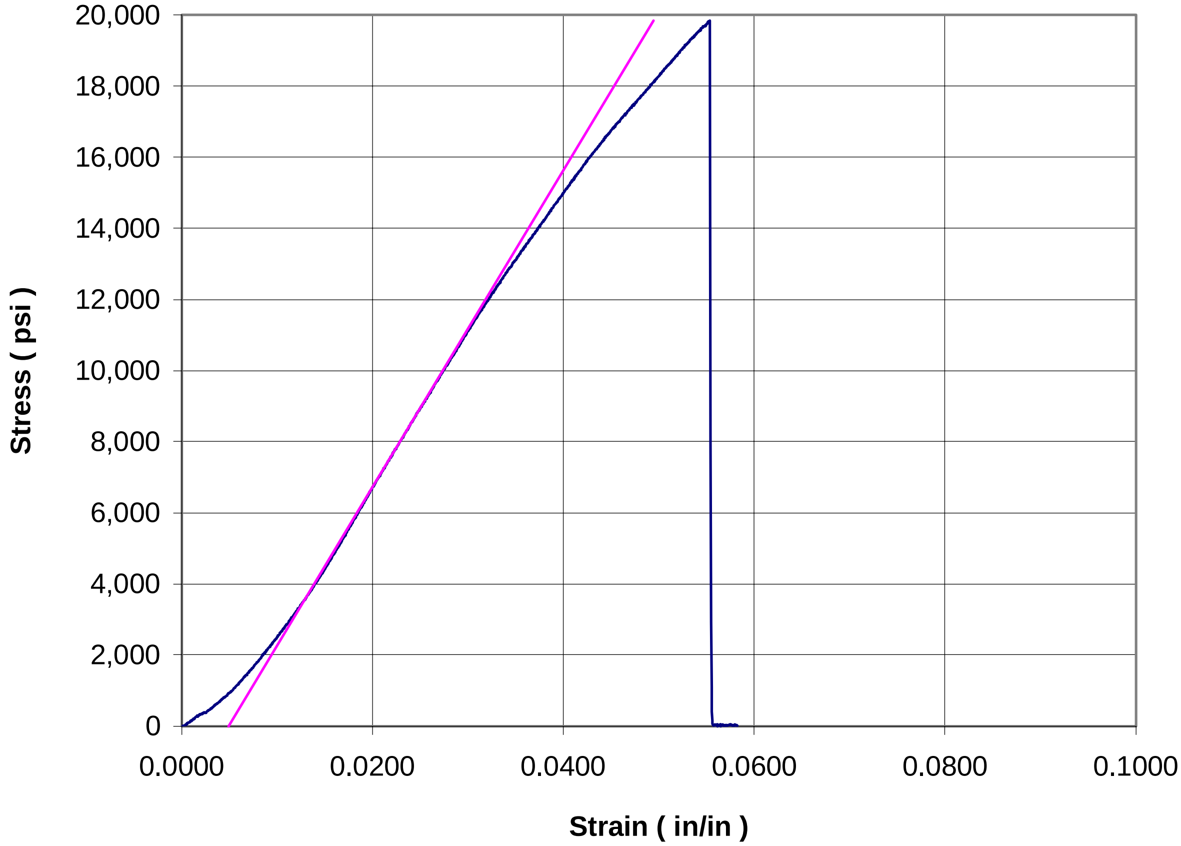
Operator:	S. McKean	Modulus:	301,502 (psi)
Engineer:	J. Hobson	Ult. Load:	3.31 (lbs)
Test Date:	10/07/99	Ult. Stress:	10,193 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	3.5 %

CP-1 EX-14



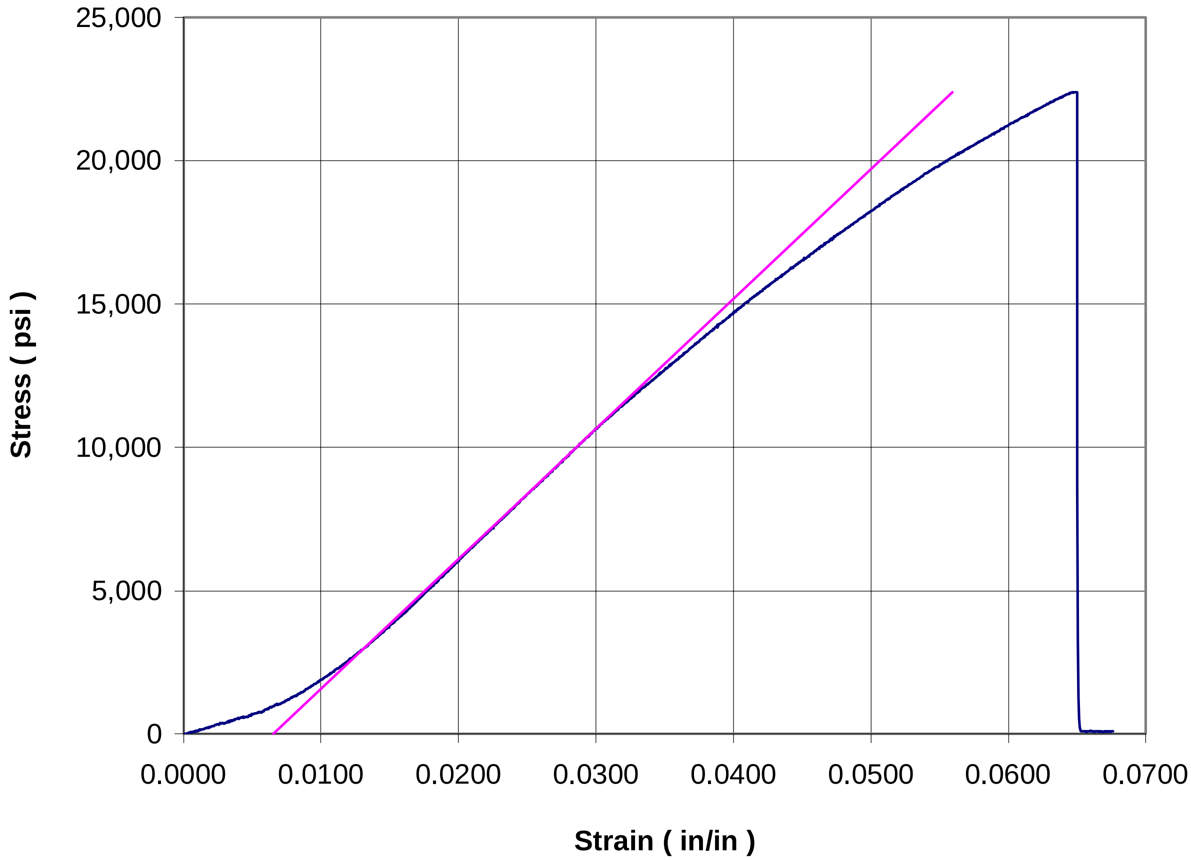
Operator:	S. McKean	Modulus:	299,579 (psi)
Engineer:	J. Hobson	Ult. Load:	1.92 (lbs)
Test Date:	10/07/99	Ult. Stress:	5,906 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.8 %

CP-2 UN-1



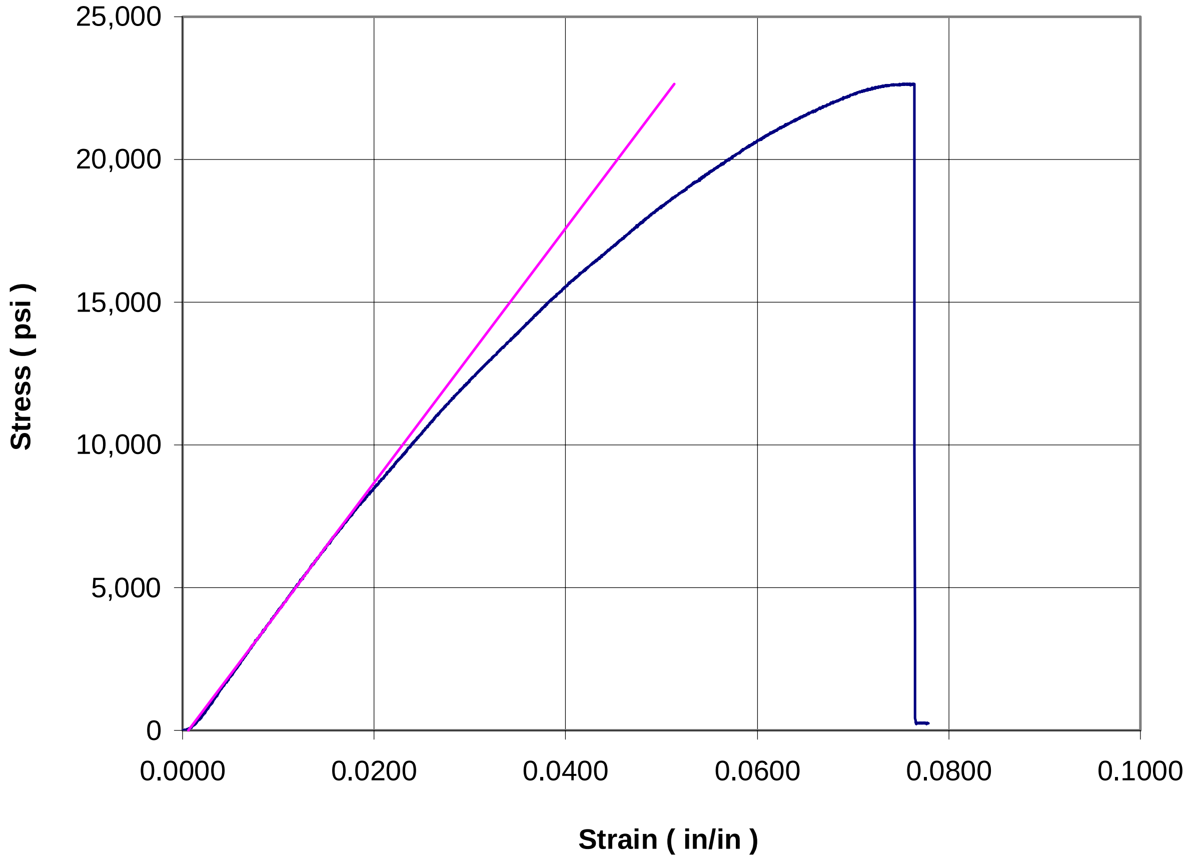
Operator:	S. McKean	Modulus:	446,241 (psi)
Engineer:	J. Hobson	Ult. Load:	6.45 (lbs)
Test Date:	10/07/99	Ult. Stress:	19,835 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	5.8 %

CP-2 UN-2

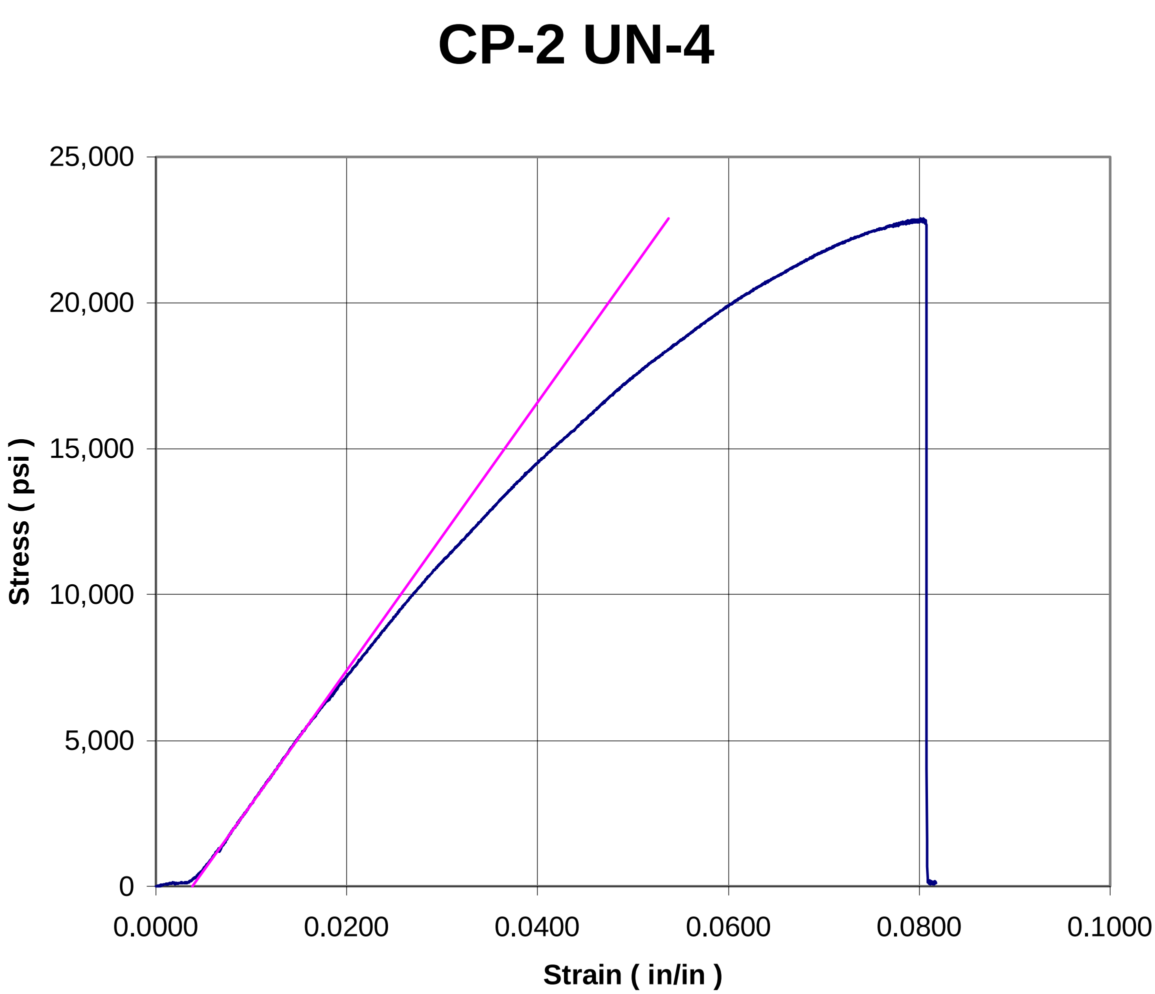


Operator:	S. McKean	Modulus:	453,895 (psi)
Engineer:	J. Hobson	Ult. Load:	7.28 (lbs)
Test Date:	10/07/99	Ult. Stress:	22,406 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	6.5 %

CP-2 UN-3

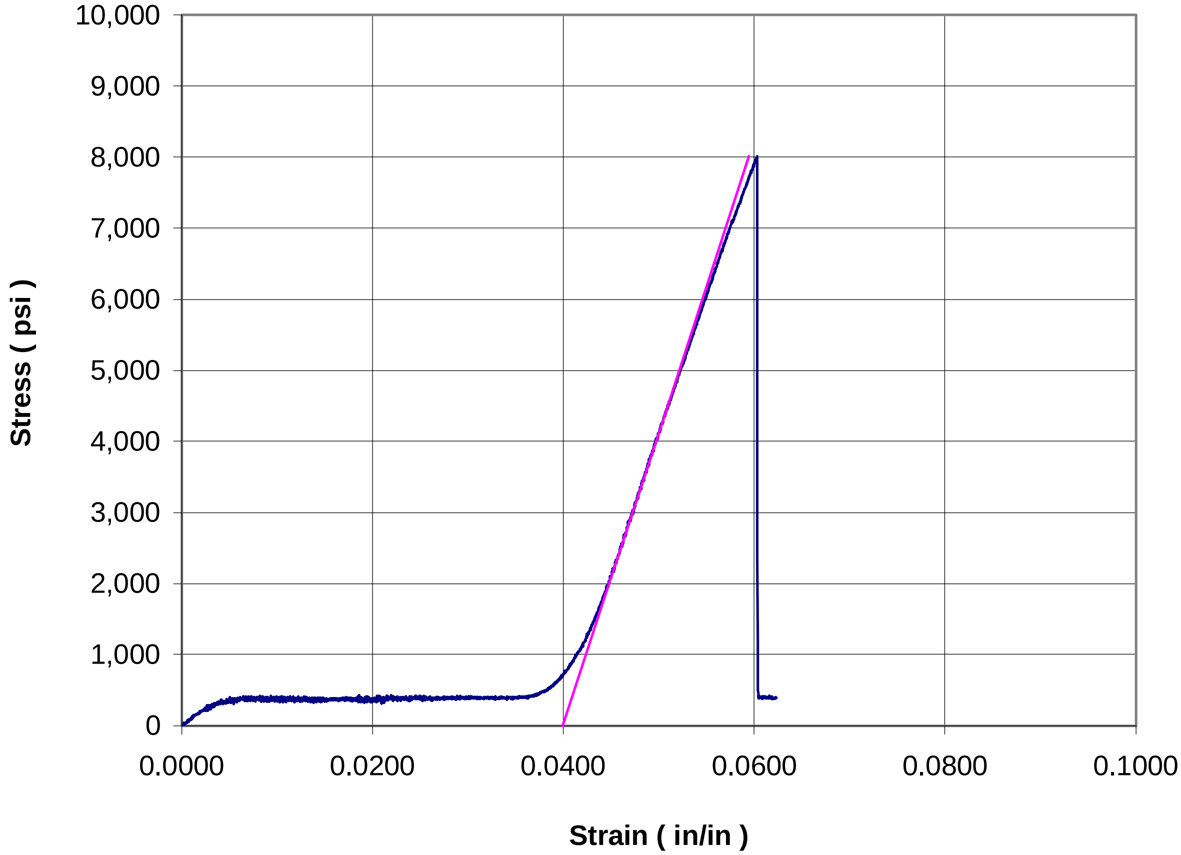


Operator:	S. McKean	Modulus:	446,382 (psi)
Engineer:	J. Hobson	Ult. Load:	7.36 (lbs)
Test Date:	10/07/99	Ult. Stress:	22,655 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	7.8 %



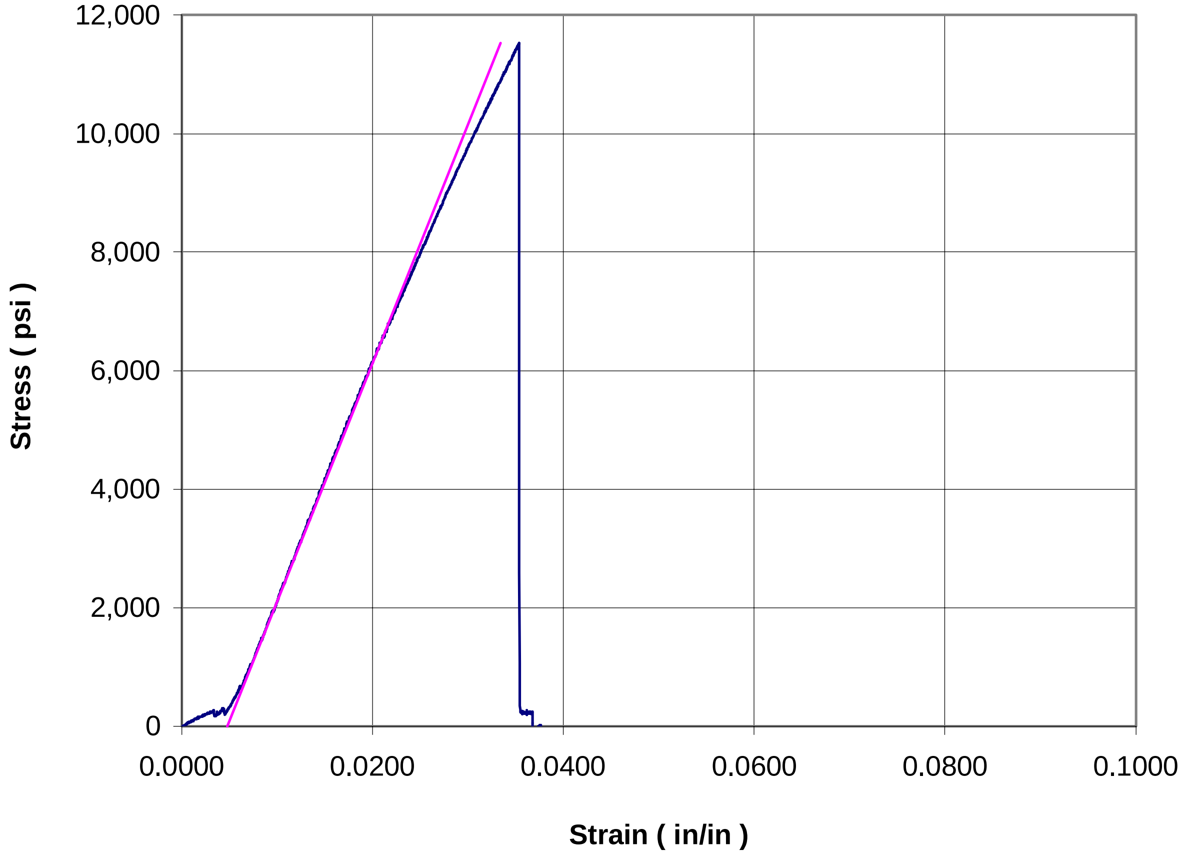
Operator:	S. McKean	Modulus:	459,056 (psi)
Engineer:	J. Hobson	Ult. Load:	7.44 (lbs)
Test Date:	10/08/99	Ult. Stress:	22,888 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	8.0 %

CP-2 EX-6



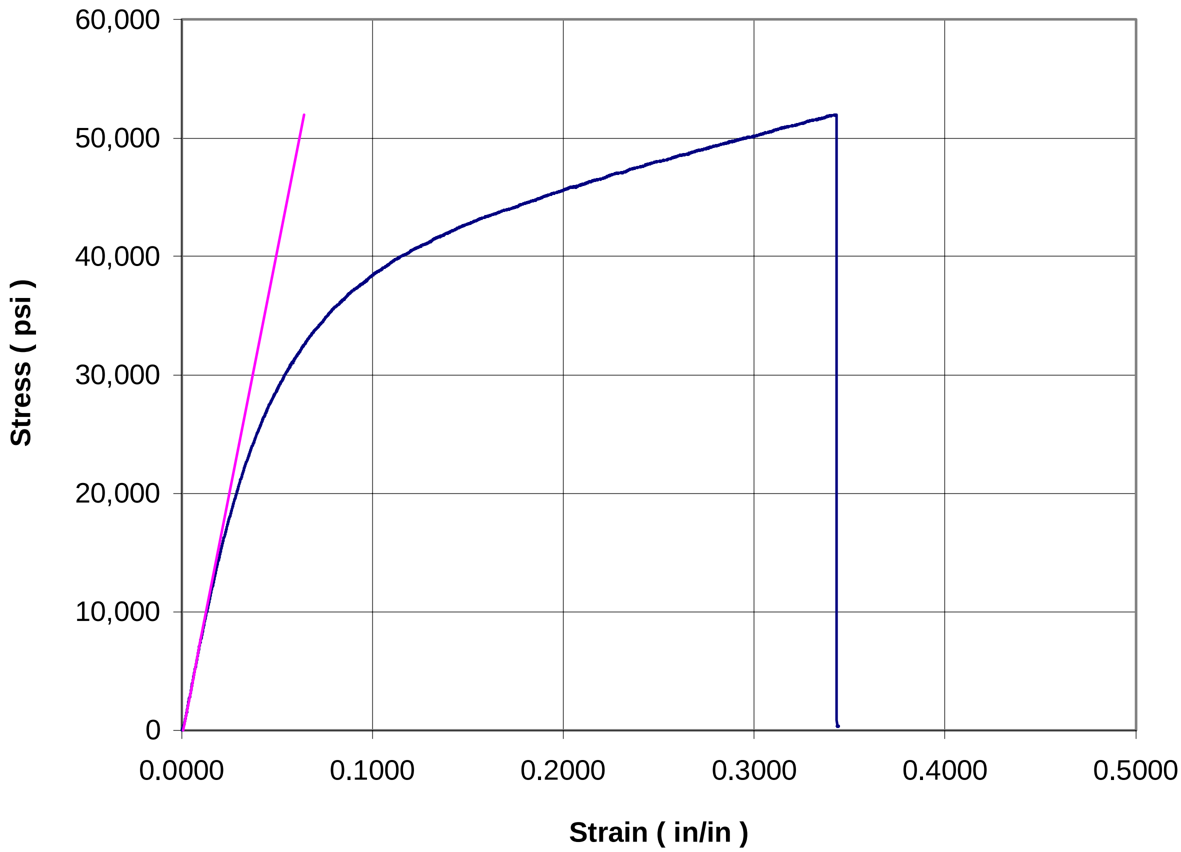
Operator:	S. McKean	Modulus:	408,847 (psi)
Engineer:	J. Hobson	Ult. Load:	2.60 (lbs)
Test Date:	10/08/99	Ult. Stress:	8,010 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.5 %

CP-2 EX-3

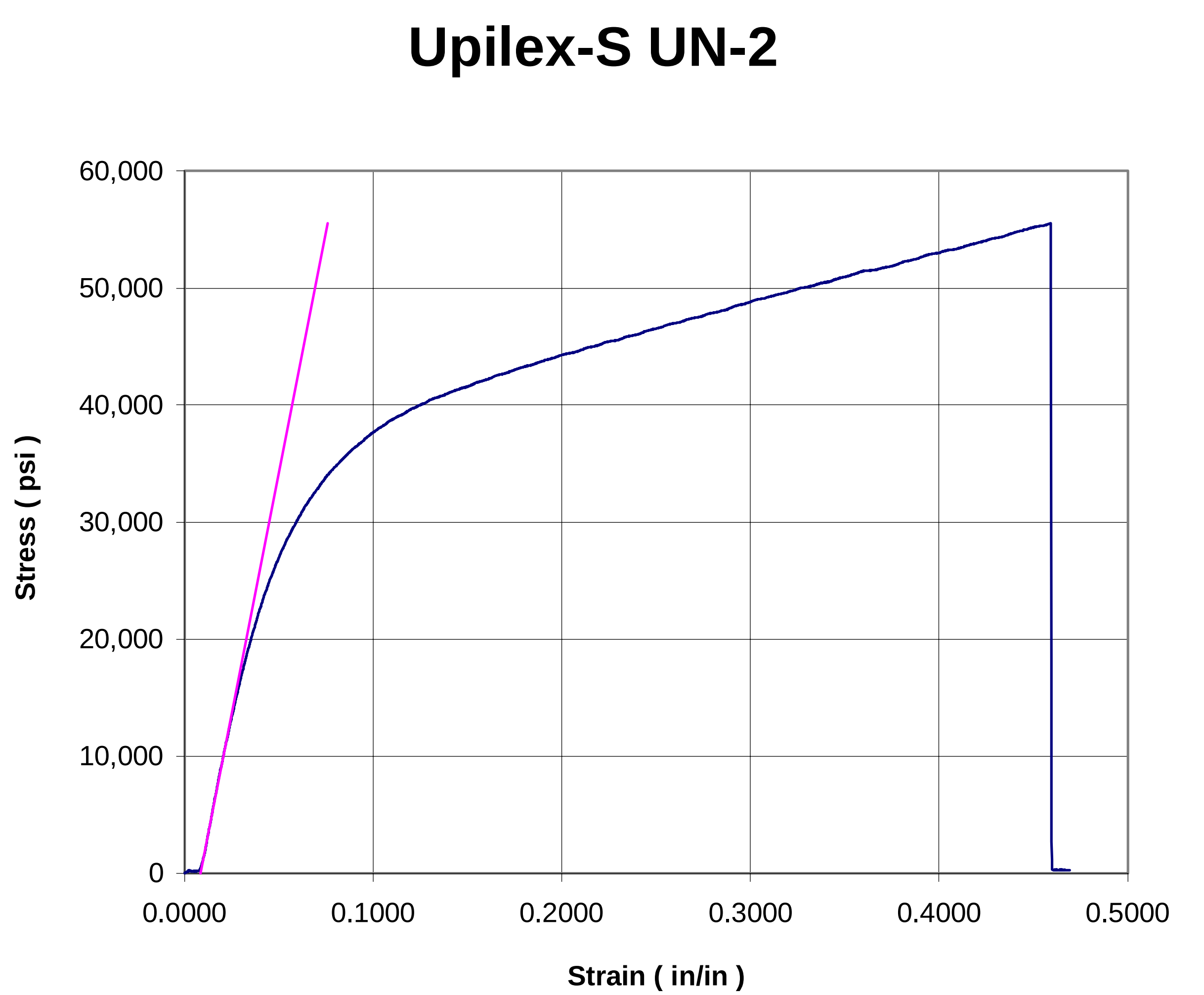


Operator:	S. McKean	Modulus:	402,438 (psi)
Engineer:	J. Hobson	Ult. Load:	3.75 (lbs)
Test Date:	10/08/99	Ult. Stress:	11,524 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	3.8 %

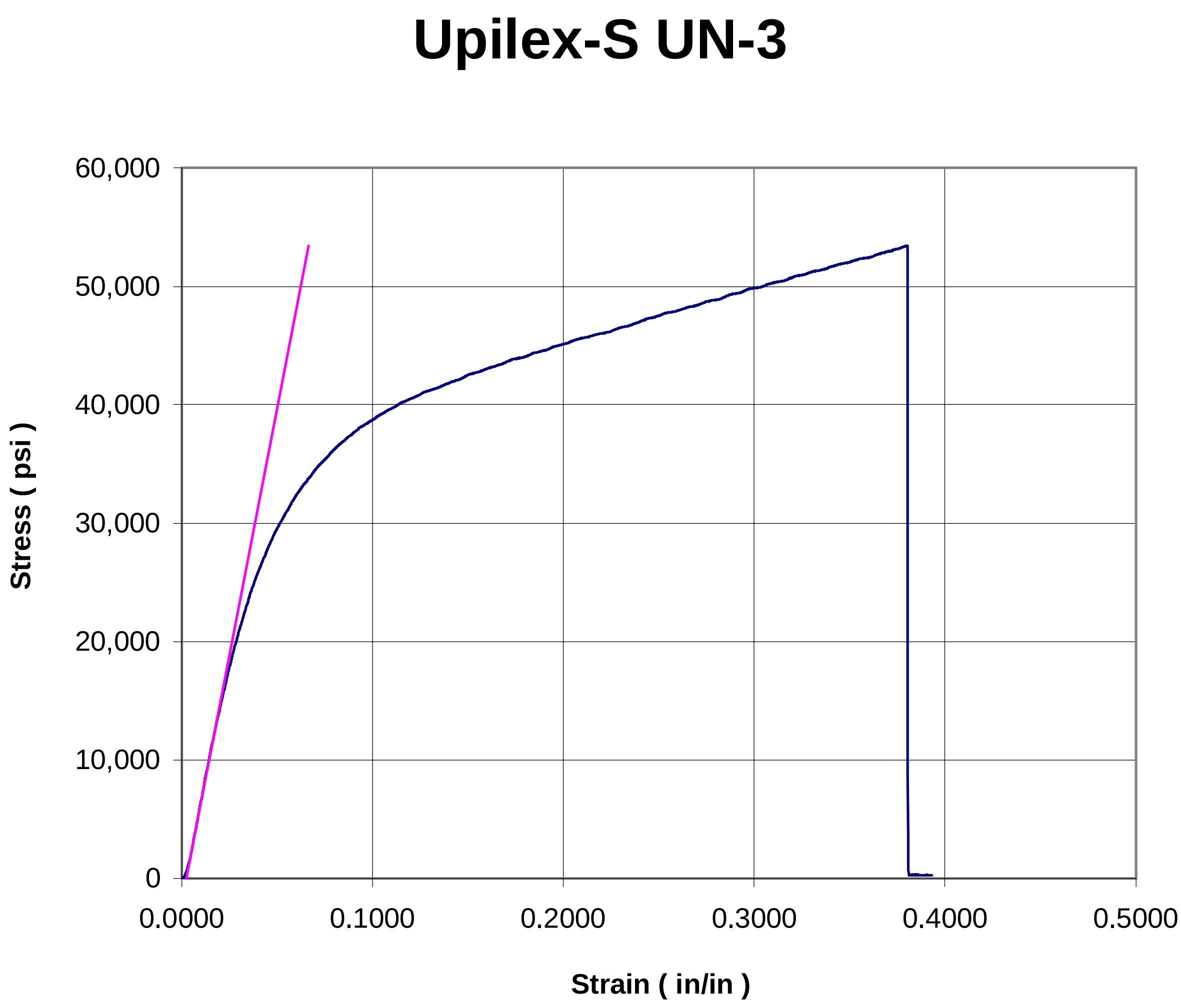
Upilex-S UN-1



Operator:	S. McKean	Modulus:	819,799 (psi)
Engineer:	J. Hobson	Ult. Load:	16.89 (lbs)
Test Date:	10/08/99	Ult. Stress:	51,974 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	34.4 %

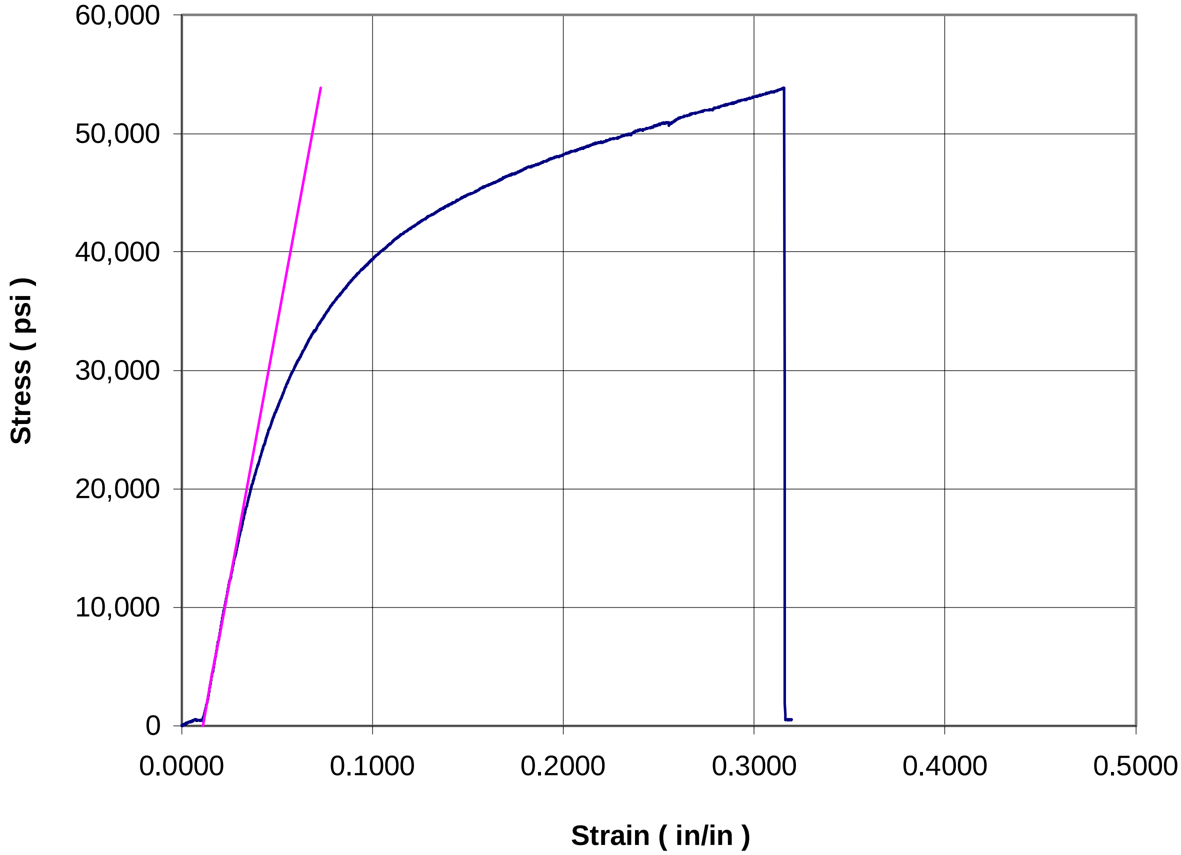


Operator:	S. McKean	Modulus:	819,448 (psi)
Engineer:	J. Hobson	Ult. Load:	18.04 (lbs)
Test Date:	10/08/99	Ult. Stress:	55,512 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	46.0 %



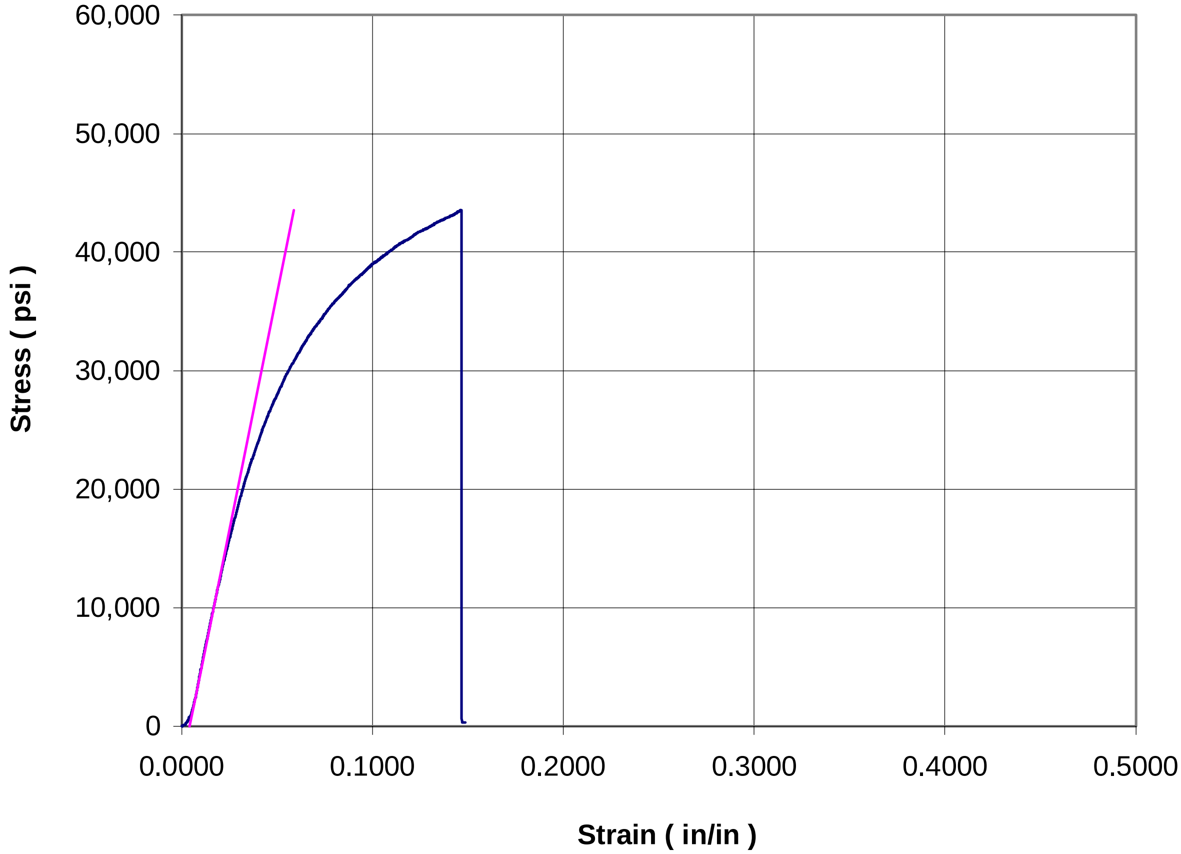
Operator:	S. McKean	Modulus:	833,974 (psi)
Engineer:	J. Hobson	Ult. Load:	17.37 (lbs)
Test Date:	10/08/99	Ult. Stress:	53,434 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	39.3 %

Upilex-S EX-11



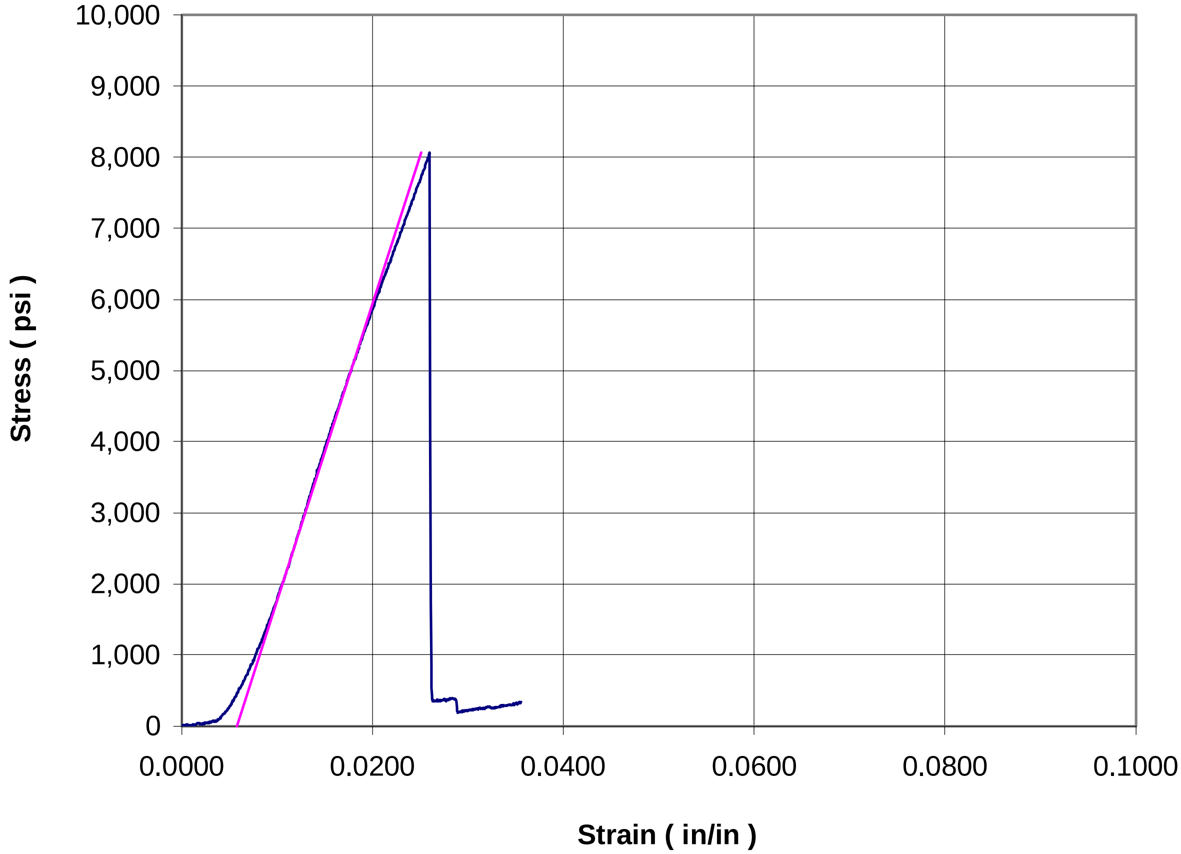
Operator:	S. McKean	Modulus:	870,031 (psi)
Engineer:	J. Hobson	Ult. Load:	17.51 (lbs)
Test Date:	10/08/99	Ult. Stress:	53,877 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	31.0 %

Upilex-S EX-4

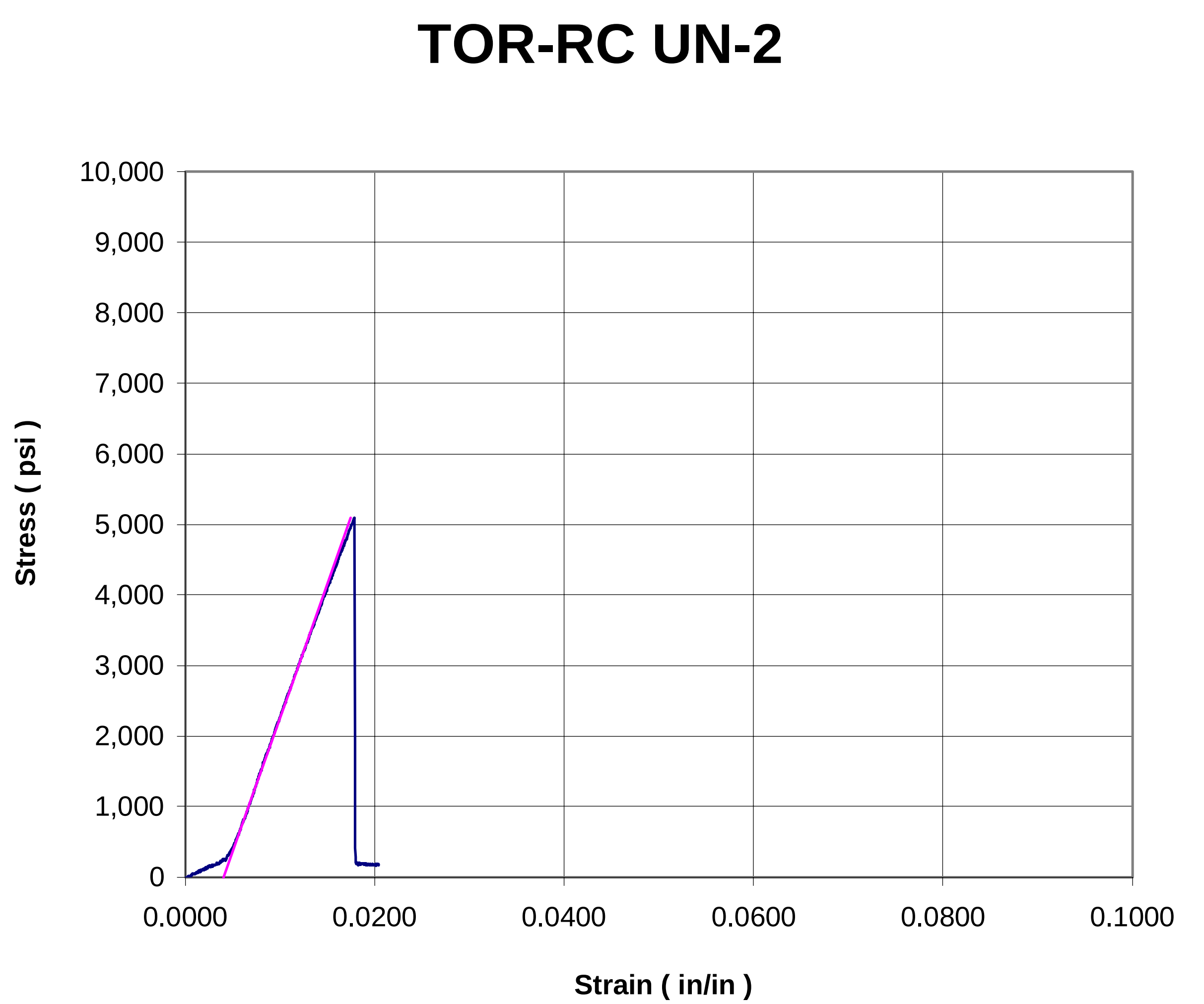


Operator:	S. McKean	Modulus:	798,471 (psi)
Engineer:	J. Hobson	Ult. Load:	14.15 (lbs)
Test Date:	10/08/99	Ult. Stress:	43,542 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	14.8 %

TOR-RC UN-1

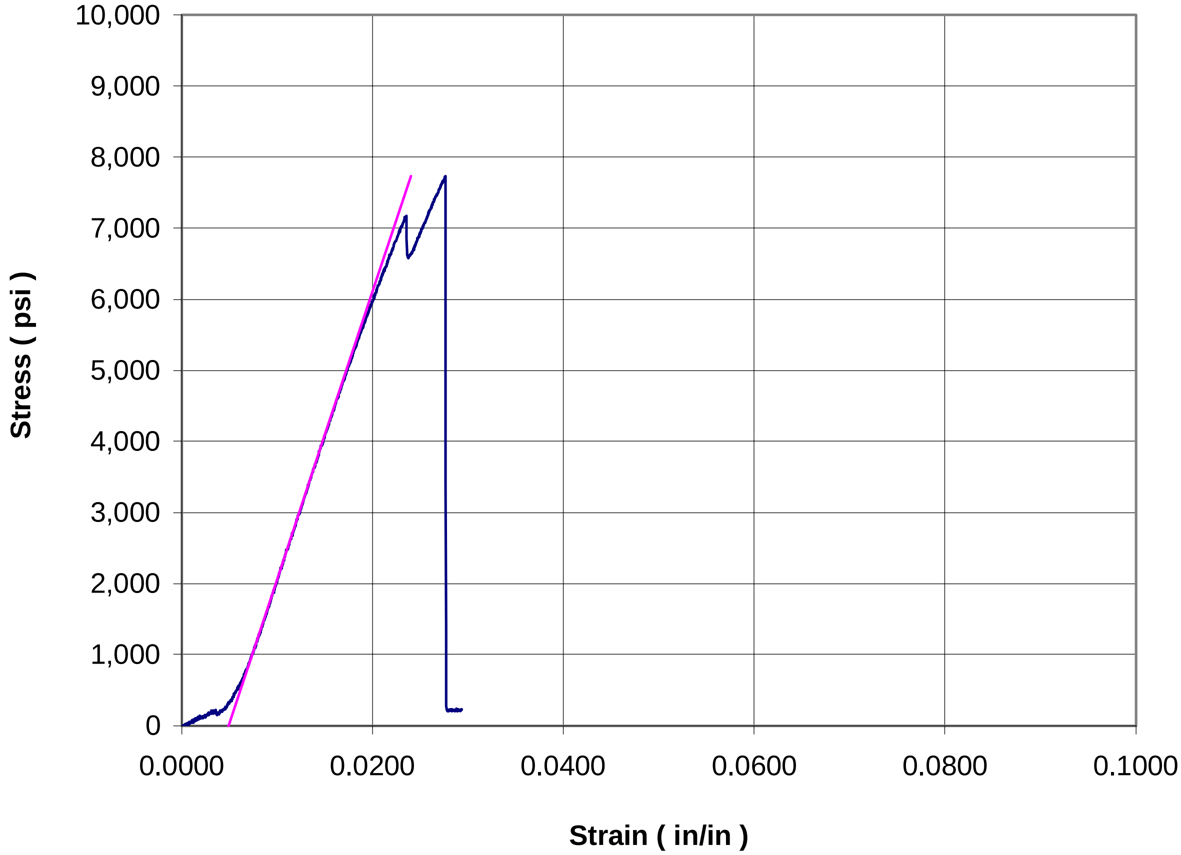


Operator:	S. McKean		Modulus:	416,466	(psi)
Engineer:	J. Hobson		Ult. Load:	2.62	(lbs)
Test Date:	10/08/99		Ult. Stress:	8,064	(psi)
Test Machine:	50 K Satec #1		Yield Load:		(lbs)
Spec. Width:	0.6500	(in)	Yield Stress:		(psi)
Spec. Thickness:	0.0005	(in)	Failure Strain:	3.4	%



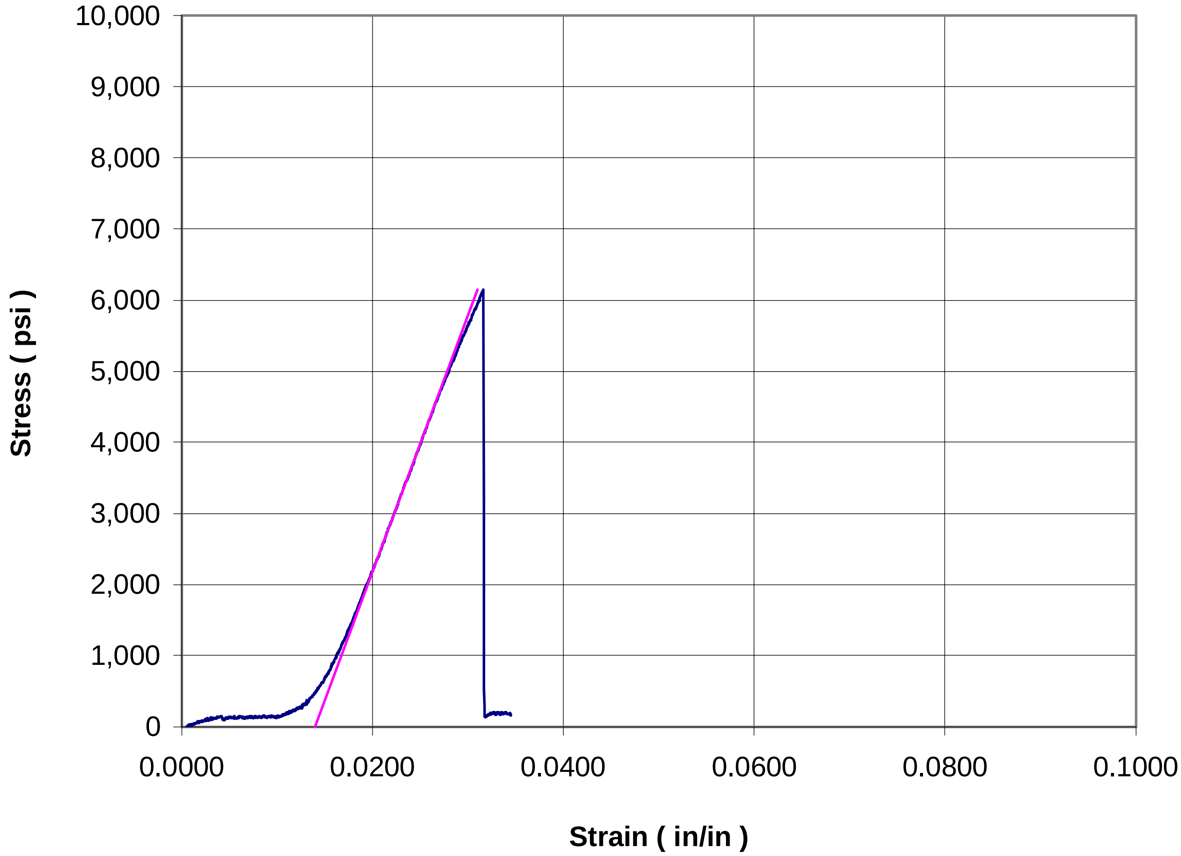
Operator:	S. McKean	Modulus:	379,357 (psi)
Engineer:	J. Hobson	Ult. Load:	1.66 (lbs)
Test Date:	10/08/99	Ult. Stress:	5,100 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.0 %

TOR-RC UN-3



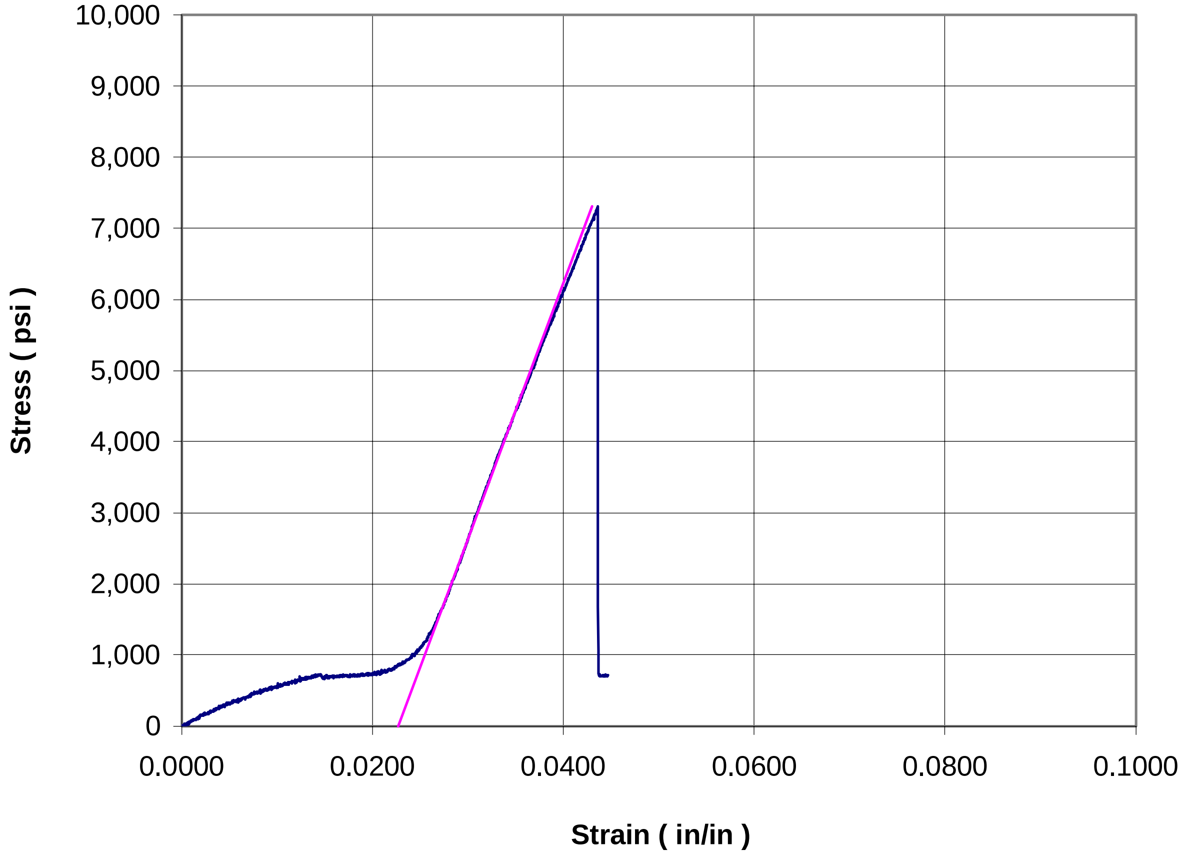
Operator:	S. McKean	Modulus:	405,067 (psi)
Engineer:	J. Hobson	Ult. Load:	2.51 (lbs)
Test Date:	10/08/99	Ult. Stress:	7,732 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.9 %

TOR-RC UN-4



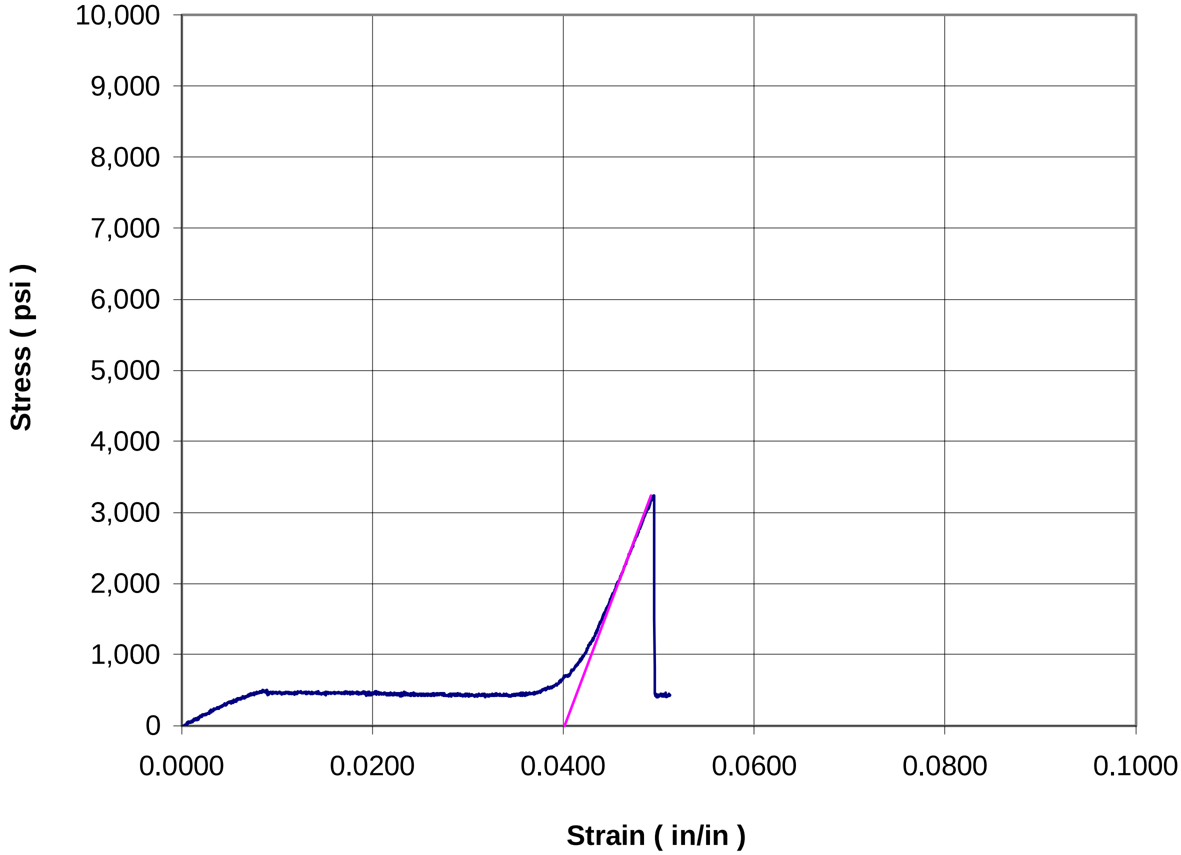
Operator:	S. McKean	Modulus:	361,800 (psi)
Engineer:	J. Hobson	Ult. Load:	2.00 (lbs)
Test Date:	10/08/99	Ult. Stress:	6,147 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.5 %

TOR-RC EX-13



Operator:	S. McKean	Modulus:	360,320 (psi)
Engineer:	J. Hobson	Ult. Load:	2.37 (lbs)
Test Date:	10/08/99	Ult. Stress:	7,304 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	3.3 %

TOR-RC EX-10



Operator:	S. McKean	Modulus:	356,585 (psi)
Engineer:	J. Hobson	Ult. Load:	1.05 (lbs)
Test Date:	10/08/99	Ult. Stress:	3,244 (psi)
Test Machine:	50 K Satec #1	Yield Load:	(lbs)
Spec. Width:	0.6500 (in)	Yield Stress:	(psi)
Spec. Thickness:	0.0005 (in)	Failure Strain:	2.0 %

Appendix D -- Test Procedures for NASA-Langley Contract L-9162

During the performance of this program, Boeing developed a set of preferred test methods or protocols to a "prototype" level. They are described below.

I. SAMPLE PREPARATION GUIDELINES, SAMPLE MOUNTING METHODS, AND INTERACTION WITH IRRADIATION CONFIGURATION. The preparation of test specimens must reflect all of the particular measurements required by the program.

A. Employ clean-room technologies including filtered laminar airflow and protection of test films from contamination during handling. Each test specimen will be cut from sheets of material supplied by NASA, using methods that result in closely controlled sample dimensions and other required features including smooth sample edges. Attention will be paid to any directional and other significant characteristics in all materials, and related instructions for their use. If any type of test material has been supplied in multiple sheets, any customer directions regarding use of such multiple resources is to be closely followed. Exploratory film-cutting with and without a die and/or other "high-technology" cutting methods should be tried prior to final sample preparation. The results of such exploratory efforts should be studied visually and by making exploratory tensile tests, using equipment and methods applicable to the program.

B. Each specimen will be sized to include both a central test/exposure section, and an adequate surrounding area for all planned measurements. Adequately sized grip areas will be provided at the top and bottom of each specimen in order to provide for tensile testing after the irradiation period. Each specimen will have a central section that:

is irradiated over an area (1) adequate for solar absorptance measurements *in situ* (approx. 6 mm by 6 mm or more), (2) adequate for thermal emittance measurements in air (circular, approx. 16 mm in diameter) after irradiation, and (3) appropriate for tensile testing. These requirements indicate a specimen width approximately 16 mm or more, and a central irradiated portion whose length is approximately 20 mm.

Each grip area will be nominally 16 mm wide by 25 mm long (at each end of specimens).

There will be provision for transition zones between grip areas and central sections.

The total length of each specimen is expected to be approximately 80 mm, including the allowances for transition zones, for grip areas, and for securing the ends of each specimen.

C. Specimens will be applied as flat as possible to maximize thermal contact with any provided substrate(s). Specimens will be arranged across the central 3-inch width portion of a machined plate, whose location is alignable with the test chamber's radiation beam zone(s). If "shingling" is feasible (to increase utilization of the available radiation beam zone), only "border" or "subsidiary" portions of samples will be shingled. Any available volume behind the machined plate will be designed to provide (i) "void" areas in which sample ends (grip ends) are secured, and (ii) solid areas in contact with the exposure chamber's cooled baseblock.

II. SAMPLE IRRADIATION PARAMETERS AND TEST PRACTICES

The planned irradiation zone must be defined relative to all specimens and test fixturing. In the Boeing CRETC the combined-beam irradiation zone is approximately square, roughly 3 inches (75 mm) by 3 inches (75 mm) in size, at a fixed location in the central vacuum chamber where radiation beams converge. (The radiation beams have border or fringe areas providing lower intensity levels.) Key parameters for the Boeing facility include the following:

All-metal chamber; vacuum better than 1×10^{-6} torr, using cryopumping and ionpumping.

Ultraviolet simulation using a xenon arc lamp for continuum 200-400 nm radiation;[1] accompanied by continuum radiation 400 to 1400 nm (not close-matched to Sun). Water-jacketed UV source provides IR control (minimal output to sample plane from 1400 to 2500 nm and longer wavelengths). UV intensity or acceleration factor approximately 1.5 Ultraviolet content of selected source strength determined from periodic dosimetry readings of radiation at sample plane or in equivalent, surrogate plane. (Dosimetry readings to be in spectral bands greater than and less than 400 nm.) See also the Comment below.

Monoenergetic protons simulating the near-surface dose encountered in the selected environment; simulator proton beam adjusted to provide $\sim 6 \times 10^{8}$ p/cm^2-s flux of 40-keV protons.

Monoenergetic electrons simulating the bulk dose encountered in the selected environment; simulator electron beam adjusted to provide $\sim 10^{9}$ e/cm^2-s flux of 40-keV electrons.

Test temperature nominally 20 °C, based on cold water circulating through base block, (upon which the sample plate is mounted during test).

<u>Comment:</u>

"On average, the Sun deposits 1371±5 W/m^2 of energy [per unit time] at the top of the Earth's atmosphere. This varies from a high of 1423 W/m^2 at Sun-Earth perigee to a low of 1321 W/m^2 at Sun-Earth apogee."[2] Moreover, the Sun's intensity varies very slightly over a solar cycle.

Boeing performed the testing described in this report using the average solar irradiance value indicated above, multiplied by the UV intensity acceleration factors indicated in Table 3.

---

[1] The "solar ultraviolet" waveband. The "vacuum ultraviolet" wavelengths < 200 nm are not included.

[2] A. C. Tribble, <u>The Space Environment</u>, p. 11. Princeton Univ. Press. This range is approximately plus and minus four percent above and below the average solar irradiance value.

III. SAMPLE PROPERTIES, MESUREMENTS AND TECHNIQUES

Solar absorptance – for opaque materials, solar absorptance is defined as one minus solar reflectance, and is based on accepted or refereed standard(s).

Computed on each sample from 100 spectral reflectance wavelengths.

Apparatus: double-beam spectrophotometer providing normalizing reference-beam, detectors and additional optics *in situ*. No measuring beam spillover beyond sample.

Each sample registered to X and Y locations provided for integrating sphere.

Measuring sequence: any order of the following three sub-sequences: (i) all samples in a reasonable X-Y order, 250-360 nm; (ii) all samples in a reasonable X-Y order, 710-2500 nm; and (iii) all samples in a reasonable X-Y order, 360-710 nm.

Measuring time-points: preirradiation; after 3, 12, 24, 42, and 60 simulated months in orbit.

Thermal emittance [in air]

Apparatus: Gier-Dunkle single-beam emittance inspection device; gold and black standard surfaces compared before, frequently during, and after each measuring sequence. Normal emittance calculated by apparatus' internal program.

Measuring sequence: all available specimens, alternating with unirradiated standards and comparison specimens of the same types of test materials.

Tensile strength, modulus, and elongation properties [in air]

Apparatus: Calibrated, traceable device with special load-cell for fine-gauge work.

Measuring rate: variable and controllable in inches per second or metric equivalent.

Test-points: preirradiation: advance configuration and methods check, using available spare, reference, and/or comparison samples, to ensure satisfactory performance of measuring techniques.

postirradiation: all available test specimens, preceded by a sufficient number of unirradiated and/or reference specimens to establish confidence in equipment performance, and a statistical base.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 2000	Contractor Report

4. TITLE AND SUBTITLE
Simulated Space Environmental Testing on Thin Films

5. FUNDING NUMBERS
PO L-9162
632-10-14-03

6. AUTHOR(S)
Dennis A. Russell, Larry B. Fogdall, and Gail Bohnhoff-Hlavacek

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Boeing Company
Seattle, Washington, 98124

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-2199

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA/CR-2000-210101

11. SUPPLEMENTARY NOTES
Langley Technical Monitor: John W. Connell

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified–Unlimited
Subject Category 27 Distribution: Standard
Availability: NASA CASI (301) 621-0390

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
An exploratory program has been conducted, to irradiate some mature commercial and some experimental polymer films with radiation simulating certain Earth orbits, and to obtain data about the response of each test film's reflective and tensile properties. Protocols to conduct optimized tests were considered and developed to a "prototype" level during this program. Fifteen polymer film specimens were arranged on a specially designed test fixture. The fixture featured controlled exposure areas, and protected the ends of the samples for later gripping in tensile tests. The fixture featured controlled exposure areas, and protected the ends of the samples for later gripping in tensile tests. The fixture containing the films was installed in a clean vacuum chamber where protons, electrons and solar ultraviolet (UV) radiation could simultaneously irradiate the specimens. Near realtime UV rates were used, whereas proton and electron rates were accelerated appreciably to simulate 5 years in orbit during a two month test. Periodically, the spectral reflectance of each film was measured in situ. After the end of the irradiation, final reflectance measurements were made in situ, and solar absorptance values were derived for each specimen. These samples were then measured in air for thermal emittance and for tensile strength. Most specimens withstood the irradiation intact, but with reduced reflectance (increased solar absorptance). Thermal emittance changed slightly in several materials, as did their tensile strength and elongation at break. Conclusions are drawn about the performance of the films. Simulated testing to an expected 5 year dose of electrons and protons consistent with those expected at L2 and 0.98 AU orbits and 100 equivalent solar hours exposure.

14. SUBJECT TERMS
Simulated space environmental effects, thin polymer films, low color polyimides
CP-1, CP-2, TOR materials

15. NUMBER OF PAGES
94

16. PRICE CODE
A05

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL