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CRYOGENIC RADIATION DAMAGE IN

STRUCTURAL POLYMERS

A PAPER FOR PRESENTATION AT
THE AMERICAN NUCLEAR SOCIETY
1966 ANNUAL MEETING
NOVEMBER 1966

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CRYOGENIC RADIATION DAMAGE IN STRUCTURAL POLYMERS

C. E. Dixon and C. W. Funk

ABSTRACT

The useful service limitations of polymers and polymer-bonded laminates used for bearing retainer materials needed to be established to determine their suitability for the NERVA system. Materials investigated included two forms of Teflon-bonded glass cloth laminate (Armalon), a polyimide formulation filled with 15% MoS₂ and FEP Teflon. Tests were conducted with quadruplicate 0.125 inch thick tensile specimens in the General Dynamics Ground Test Reactor at doses of 1.1, 5.4 and 27×10^9 ergs/gm(C). Exposure was conducted in liquid hydrogen (-423°F) with tensile tests being performed at -423°F before and after warm up to room temperature. Room temperature tensile tests after warm-up were also made.

The ultimate strength and ultimate elongation of the polyimide is not changed by a gamma dose of 27×10^9 ergs/gm(C) when exposed in liquid hydrogen. Teflon of the FEP grade reaches a radiation threshold at 1.2×10^9 ergs/gm(C) in liquid hydrogen, suffers a 30% strength loss at 5.4×10^9 ergs/gm(C) and becomes too brittle to test after 27×10^9 ergs/gm(C). A comparison of these results with ambient temperature data indicates the radiation resistance of Teflon is greatly enhanced in a liquid hydrogen environment over an ambient air environment. Armalon suffers severe strength loss and delamination after exposure to 27×10^9 ergs/gm(C) with some strength loss at 5.4×10^9 ergs/gm(C), due to deterioration of the Teflon bonding. Annealing polymers irradiated at liquid hydrogen temperature to room temperature indicated no significant trend of properties that could be attributed to oxidation mechanisms.

I. INTRODUCTION

The polymers, polytetrafluoroethylene (TFE Teflon) and fluorinated ethylene propylene (FEP Teflon), are frequently used in cryogenic applications either in pure form, with additives or as a bonding agent for laminates. Thus, in the NERVA engine in which many components operate in liquid or gaseous hydrogen at temperatures as low as -423°F the use of Teflon and Teflon-bonded laminates is desirable. Since in the NERVA engine most parts are subjected to nuclear radiation in addition to cryogenic temperatures, this study was undertaken to obtain structural property design data for Teflon, Armalon and another candidate material, polypromellitimide (Superpolymer SP-3) when irradiated and tensile tested in liquid hydrogen (-423°F). The latter material is reported to have excellent radiation(1) resistance at room temperature, whereas, Teflon is known to have low radiation resistance at room temperature. Very limited data on cryogenic radiation testing are available.

It is desirable to know not only the effect of irradiation temperature upon properties but the effects of post-irradiation heat treatment in different environments. Post-irradiation heating (above cryogenic temperatures) can permit internal molecular structure modifications by internal atom migration or by permitting free radical reaction with an oxygen environment. Various test temperatures and intermediate annealing temperatures were chosen to answer the following questions with respect to the effect of radiation on mechanical properties:

What is the effect of irradiation temperature? (80°F vs -423°F)

What is the effect of post irradiation annealing at 80°F in the absence of oxygen?

What are the effects of post irradiation annealing at 80°F and 300°F in air?

I, Introduction (cont.)

The inherent difficulties, safety hazards and high costs associated with radiation testing in liquid hydrogen have prevented the inclusion of sufficient material and test variables to definitively answer all the above questions, however, design data were obtained as well as partial answers to the basic mechanisms involved.

II. EXPERIMENTAL PROCEDURE

A. MATERIALS

1. FEP Teflon (fluorinated ethylene propylene) is a thermoplastic resin which can be processed by conventional extrusion or molding. The material used in this study was a standard grade molded 0.25 inch sheet produced by the Raybestos Manhattan Co. The average density was 2.13 gm/cm^2 . Prior to fabrication the sheet stock was annealed for 1 hour at 200°F. This resulted in slight dimensional changes but no density change.

2. Armalon FEP 510-L-128

This is a commercial product of the E. I. du Pont Co. This laminate is made by hot pressing layers of FEP Teflon-impregnated No. 128 glass fabric. The single layers of glass cloth are 0.010 inch thick. The glass fabric has a square weave with a thread count of 31 warp and 41 fill. The material was purchased as 0.125 inch thick sheets 13 inch x 17 inch. All specimens were fabricated with their long dimension parallel to the 17 inch dimension to eliminate orientation effects as a variable. The sheets were produced at the same time to minimize variations of properties between sheets.

3. Armalon TFE 405-CL-116

This is a commercial product of the E. I. du Pont Co. The laminate is made by hot pressing layers of TFE Teflon-impregnated No. 112 glass fabric.

II, A, Materials (cont.)

The single layers are 0.005 inch thick. The glass fabric has a square weave with a thread count of 57 warp and 59 fill. The material was purchased as 0.125 inch sheets, 13 inch x 17 inch. All specimens were fabricated with their long dimension parallel to the 17 inch dimension to eliminate orientation effects as a variable. The sheets were produced at the same time to minimize variations of properties between sheets.

4. Superpolymer SP-3 (Polypyromellitimide)

This proprietary product of the E. I. du Pont Co. is an aromatic polyimide filled uniformly with 15 weight percent MoS_2 . The added MoS_2 improves the friction properties. The matrix material was reported to be unchanged in strength and elongation after irradiation to 1.4×10^{10} ergs/gm(C) at -320°F . (1) The material was purchased as fabricated specimens from the du Pont Co. The billets from which the specimens were machined were heated to 480°F in three hours, held at 480°F for two hours and furnace cooled.

B. SPECIMEN DESIGN

All specimens had a 0.500 inch width and a nominal 0.125 inch thickness; the gage length was 2.00 inch; a shoulder radius of 1.0 inch was used to match the full 3.00 inch width of the specimen ends. Aluminum doublers .062 inch thick were riveted and bonded on the specimen ends to minimize tearing or deformation outside the gage section. In many cases during liquid hydrogen testing the adhesive would break at high loads and preclude obtaining accurate strain data from the crosshead movement. In these instances, the total strain was estimated by extrapolating the good portion of the curve to the breaking load. In spite

(1) General Dynamics/Fort Worth Report FZK 188 (1965)

II, B, Specimen Design (cont.)

of the 1.0 inch radius beyond the reduced gage section, nearly all of the Armalon specimens broke at the point of tangency between the gage length and the radius. The consistency of the data within each Armalon grade indicates the relative changes due to irradiation are correct; however, it is possible that a different specimen design with a larger radius could result in higher absolute strength values. In the few instances where the breaks were in the gage sections, the strength and elongation were identical with those similar specimens which broke at the point of tangency. Therefore, we believe all of the data closely represents the true absolute tensile properties. The SP-3 specimens were the same dimensions as the others, however they were machined from 0.25 inch stock and doublers were not required. Nearly all the specimens broke within the reduced gage section. Most specimens lost small fragments of material in the region of the fractured surface indicating poor impact properties.

C. TEST FACILITIES

1. Radiation Facilities

These tests were performed at the General Dynamics/Fort Worth Ground Test Reactor (GTR). One of the major advantages of this reactor is the dry test cell configuration. Three faces of the reactor are accessible for large size test fixtures without being submerged in water. Gamma dose rates are the order of 10^8 ergs/gm(C)-hr near the reactor faces.

Remotely operated hydraulic tensile test equipment was utilized for the irradiation in liquid hydrogen (-423°F) and post-irradiation testing. The irradiations in liquid hydrogen involved safety hazards and very costly facilities and procedures. The dewar, shown in Figure 1 is basically a

Figure 1
 LH₂ DEWAR CROSS - SECTION

II, C, Test Facilities (cont.)

double-walled cylindrical vessel made of aluminum. A vacuum is maintained between the two walls for insulation. Welded to the top of the flange are stainless steel tubes containing pull rods, concentric tubes for extensometer devices, cryogen supply lines, gaseous relief lines, and an electrical harness. When the dewar is operated with liquid hydrogen, it is completely enclosed with an aluminum shroud. Gaseous helium is circulated within the shroud to eliminate the possibility of fires on or around the assembly.

2. Instrumentation

Applied Load Measurement. The applied load to each specimen in the liquid hydrogen remote pulling assembly is measured by a four-arm strain-gage load cell and recorded on a Sanborn millivolt recorder. The strain gages used are BLH type and were applied with the Rokide process for optimum radiation resistance. Each load cell was calibrated utilizing the millivolt recorder for data acquisition. Calibration data were obtained in representative increments up to 10,000 lb. All room temperature specimens were tested directly on an Instron tensile machine.

Strain Measurement. A mechanism is provided at each pull position to measure the specimen pull-rod displacement. This measurement is continuous for the total rod movement. A Helipot potentiometer (50,000 ohm, 360° rotation) is geared through a rack and pinion to the specimen pull rods. The potentiometers have nine equally spaced taps. Selection of gear ratio and potentiometer tap spacing was made to give 360° of potentiometer rotation per 0.050 inch of rod movement. With the nine tap potentiometer, this provides full scale deflection of the recorder for each 0.050 inch of rod movement. This gives a resolution of from 0.5 to 1.0 mil. Each position is calibrated in 0.025 inch increments for 2 inch of rod movement.

II, C, Test Facilities (cont.)

An extensometer mechanism is activated at one position of one assembly to measure the strain between the shoulders of a selected group of 12 control specimens. Tabs are secured to the upper and lower shoulders with a 2.00 inch spacing between. Fingers are positioned relative to the tabs and connected to concentric tubes which are in turn connected to a displacement transducer. The transducer used is a Physical Sciences variable permeance type with a ± 1.00 inch range. The cryogen gas seal around the concentric tubes is effected by a cylinder-and-piston arrangement utilizing Teflon "bal seals." The extensometer mechanism is indexed from one specimen to another by means of a combination hydraulic and pneumatic indexing system. Each extensometer mechanism is calibrated to 0.800 inch in representative progressive increments.

A 2 inch gage length clip-on extensometer is used to measure the strain within the elastic region of all specimens tested at ambient temperature. This extensometer has high resolution with a travel of 0.040 inch. The transducer was calibrated in representative increments to the limit of its travel.

3. Correction and Correlation of Data

The specimens tested at 80°F were pulled to fracture in the Instron tensile test machine. The strain for all materials, with the exception of Teflon, was measured by a 2 inch gage-length clip on extensometer. The strain recorded when testing the three types of Armalon material was always within the operating range of the extensometer. However, some extrapolation was necessary with the strain data recorded from testing of the Superpolymer SP-3 specimens, and because of the extremely high elongation of Teflon, cross-head travel was used as an indication of strain for this material.

II, C, Test Facilities (cont.)

The specimens tested in liquid hydrogen were pulled to fracture in the remotely operated cryogenic tensile test assemblies. The strain was measured by the rod-movement mechanism. These devices measure not just the strain that occurs within the gage length, but the total, or gross, strain that occurs in the system. For this reason, it was necessary to consider two correction factors to determine the approximate true strain that occurred within the reduced cross section of the specimens. These two strain correction factors were applied to the data from all specimens tested at -423°F .

As previously mentioned, the rod-movement mechanism measures the total, or gross, strain that occurs in the complete pull-rod train. To eliminate the deflection that occurred outside the specimen shoulders, the following correlation was made. Extensometer tabs were attached to the upper and lower grip sections of 12 specimens (all materials except SP-3). These specimens were tested at -423°F using the same equipment and instrumentation previously used for the irradiated and control specimens. One extensometer mechanism, described previously was activated and used in the testing of these 12 specimens. This mechanism measures, essentially, the elongation that occurs between the specimen shoulders. Average stress-elongation curves were drawn from both rod-movement and extensometer strain-measurement values, for the various materials. From a comparison of these curves, it was found that the ratio of extensometer elongation to rod movement is reasonably linear and consistent. The average ratio was found to be 0.665. The rod movement strain data were multiplied by 0.665 to correct for the system error. This correlation was used for all materials.

II, C, Test Facilities (cont.)

The previous section explains the method used to correct for measured strain that occurs outside the specimen. We now describe the method used to correct for strain that occurs within the specimen but outside the reduced cross section. The greater portion of this strain error occurs in the specimen between the point of tangency at the reduced cross section and the shoulder at each end. This error is significant and must be eliminated to find the approximate true strain within the 2.00 inch gage length section.

A relationship can be determined for specimens of a given configuration by considering the specimen geometry and assuming Hooke's law behavior. A complete and detailed explanation of the mathematical mechanics for determination of this factor is presented in Appendix B of General Dynamics/Forth Worth, Report FZK 263-1, October 20, 1965. In the present test specimens of two basic configurations were used, necessitating two sets of calculations:

- (a) The three Armalon materials and Teflon specimens were fabricated from 0.125 inch sheet with 0.0625 inch aluminum doublers bonded and riveted to each side of the grip sections. The correction factor for this configuration was found to be 0.6283.
- (b) The Superpolymer specimens were machined to a 0.125 x 0.500 inch reduced cross section from 0.25 inch thick specimen blank. The correction factor for this configuration was found to be 0.6539.

II, C, Test Facilities (cont.)

4. Test Description and Procedures

The test consisted of the irradiation and subsequent testing of approximately 250 tensile specimens made from the following organic materials:

1. Teflon FEP
2. Armalon FEP-510-L-128
3. Armalon TFE-405-CL-116
4. Superpolymer SP-3

The specimens were irradiated in liquid hydrogen in the three cryogenic test assemblies. Each assembly was exposed to a different gamma dose, each dose approximating one of the three design exposures. The average gamma dose and integrated fast-neutron flux ($E \geq 2.9$ Mev) achieved for each assembly are as follows:

<u>Dose</u>	<u>Assembly Location</u>	<u>Run Time (hr)</u>	<u>Assembly-to-Closet Spacing</u>	<u>Exposure</u>	
				<u>Gamma [ergs/gm(C)]</u>	<u>Neutrons (n/cm²)</u>
High	North	25	Normal	2.7×10^{10}	5×10^{15}
Intermediate	East	25	19 in.	5.4×10^9	7.8×10^{14}
Low	North	1	Normal	1.1×10^9	2.0×10^{14}

Postirradiation testing was accomplished at several different environmental conditions. For comparison, nonirradiated control specimens were tested at conditions nearly parallel to those of the irradiated specimens. An explanation of each test condition and the symbolic representation of that condition are given below:

Condition 1: LH_2

After irradiation, specimens were tested in liquid hydrogen (LH_2) with no intervening warmup.

II, C, Test Facilities (cont.)

Condition 2: $\text{LH}_2 \rightarrow \text{GHe} \rightarrow \text{LH}_2$

After irradiation, the specimens were warmed up to ambient temperature in gaseous helium (GHe). The specimens were held for 4 days in GHe, then returned to and tested in LH_2 . The control specimens at this condition were warmed up and held in air rather than GHe, since oxidation is not considered relevant for nonirradiated specimens.

Condition 3: $\text{LH}_2 \rightarrow \text{GHe} \rightarrow \text{LH}_2 \rightarrow \text{Air} \rightarrow \text{LH}_2$

These specimens were subjected to the same GHe hold and then returned to LH_2 , as described in Condition 2. The specimens were then warmed to ambient temperature, held in air for 4 days, then returned to and tested in LH_2 . No control specimens were tested at this condition.

Condition 4: $\text{LH}_2 \rightarrow \text{GHe} \rightarrow \text{LH}_2 \rightarrow \text{Air}$

The specimens tested at this condition were subjected to the same environmental sequence as Condition 3, except that the specimens were tested at ambient temperature following the 4-day hold in air.

Condition 5: $\text{LH}_2 \rightarrow \text{GHe} \rightarrow \text{LH}_2 \rightarrow \text{Air} \rightarrow 300^\circ\text{F} \rightarrow \text{RT}$

The specimens tested at this condition were subjected to the same environmental sequence as Condition 4. After the 4-day hold in air, the specimens were placed in an oven and subjected to a $+300^\circ\text{F}$ temperature for 8 hr. The specimens were then cooled and tested in

II, C, Test Facilities (cont.)

air at room temperature (RT). No control specimens were tested at this condition since available literature data indicate this 300°F hold does not change the properties.

Condition 6: RT as received

Only control specimens were tested in this condition for a temperature cycling comparison. These specimens were tested in air at ambient temperature in the as-received form.

A summary of the specimens tested at the various conditions is shown in Table 1.

III. TEST RESULTS

All irradiation specimens were submerged in liquid hydrogen during the irradiation period, then tested at the five different environmental conditions. Control specimens were tested at environmental conditions nearly parallel to those of the irradiation specimens. A description of these conditions is given in the previous section. This section presents and discusses the mechanical-property and X-ray diffraction data.

The mechanical property data are presented in several forms: stress-strain curves, averaged-data plots of ultimate tensile strength and ultimate strain,* and tabulated detail data. All data in this section are categorized by material and are tabulated in accordance with dose and environmental condition.

*Ultimate strain or elongation in organic materials is normally defined as the total strain at fracture. It includes elastic strain unlike the common metallurgical practice.

Table I
Summary Schedule of Test Specimens

Material	Environmental Condition					
	1	2	3	4	5	6
Test Temp	-423°F	-423°F	<u>Control Specimens</u>		-423°F	80°F
Armalon 405-L-112	4	4	-	4	-	4
Armalon 510-L-128	4	4	-	4	-	4
Teflon FEP	4	4	-	4	-	4
Superpolymer SP-3	4	4	-	4	-	4
			<u>Irradiated Specimens</u>			
			<u>All Specimens Irradiated in LH₂</u>			
Armalon 405-L-112	4	4	4	4	4 ^(a)	-
Armalon 510-L-128	4	4	4	4	4	-
Teflon	4	4	4	4	4	-
Superpolymer SP-3	4	-	4	4	4	-

(a) Omitted from low- and intermediate-dose assemblies.

- (1) LH₂
- (2) LH₂ → GHe → LH₂
- (3) LH₂ → GHe → LH₂ → Air → LH₂
- (4) LH₂ → GH₂ → LH₂ → Air
- (5) LH₂ → GH₂ → LH₂ → 300°F → Air
- (6) As Received

III, Test Results (cont.)

X-ray diffraction studies were accomplished on a selected number of specimens - one specimen from each dose level (including Control) of five materials at environmental conditions 1, 2, and 3. All samples for analysis were taken from the reduced cross section of the specimens, with the exception of the high-dose Armalon specimens, in which case the samples were taken from the grip areas. These studies indicated that there was no significant change in lattice spacing or apparent crystallinity from either dose or environmental condition for any of the materials tested.

III, Test Results (cont.)

A. TEFLON FEP

A difficulty was encountered in the testing of this material in that all specimens subjected to the high dose, and some at the intermediate dose, were so embrittled by the irradiation they could not be tested. These specimens fractured in the doubler section prior to testing. Typical specimens are shown in Figure 2. The damage is considered to have been caused by stress concentrations resulting from the riveted aluminum doublers. Therefore, no high-dose data are available for this material. Representative fractures of this material, tested at both 80°F and -423°F, are presented in Figures 3 and 4.

A comparison of the ultimate tensile strength at the different dose and environmental conditions is presented in Figure 5. Very little or no damage was detected in the low-dose specimens. Significant damage was detected at the intermediate level. As previously mentioned, the high-dose specimens could not be tested, but a visual inspection indicated severe damage.

A comparison of ultimate strain at the different test conditions is presented in Figure 6. These data indicate no change at the low-dose level but a very decided effect at the intermediate level. The greatest effect was noted in the specimens tested at room temperature. For condition 4 (80°F anneal and 80°F test) the strain decreased from 446% at the low-dose level to 161% at the intermediate-dose level. For condition 5 (300°F anneal and 80°F test) the damage was even greater, with a span of from 452% to 7.7%.

A tabulation of all detailed mechanical property data is presented in Table II. Average stress-strain relationships are presented in Figures 7 and 8 showing the effects of dose level on specimens tested at environmental conditions 1 through 5, respectively.

TFE Teflon has been reported to be the least radiation resistant of the polymers. Its threshold damage has been reported to be 1.7×10^6 ergs/gm(C)

Figure 2 Teflon FEP: Four Typical Specimens From the High-Dose Test Assembly, Showing Static Failure

Figure 3 Teflon FEP: Fractured Specimens Pulled at Room Temperature after Exposure to Low, Intermediate, and High Gamma Doses

Figure 4

Teflon FEP: Fractured Specimens Pulled at LH₂ Temperature after Exposure to Low, Intermediate, and High Gamma Doses

Figure 5 Teflon FEP: Effect of Gamma Dose and Postirradiation Environmental Sequence on Ultimate Tensile Strength

Figure 6

Teflon FEP: Effect of Gamma Dose and Postirradiation
Environmental Sequence on Ultimate Strain

Table II

Teflon FEP: Ultimate Tensile Strength and Elongation

Environmental Sequence	Test Temp	Control				Low Dose				Intermediate Dose				High Dose			
		Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)
<u>Condition 1</u> LH ₂	LH ₂	4-55	23.8	1	3.9	4-45	23.3	2	3.8	4-37		3		4-41		2	
		4-56	25.8	1	4.0	4-69	22.9	1	3.8	4-61	NO	3	NO	4-65	NO	3	NO
		4-79	23.6	1	3.8	4-47	22.3	2	3.3	4-39	DATA	3	DATA	4-43	DATA	3	DATA
		4-80	22.3	1	3.7	4-71	22.1	1	3.8	4-63		3		4-67		3	
		Avg/σ: 23.9/1.7 3.85/0.14				Avg/σ: 22.7/0.6 3.7/0.24											
<u>Condition 2</u> LH ₂ →GHe→LH ₂	LH ₂	4-57	23.9	1	4.1	4-46	22.9	1	3.6	4-38	12.3	3	1.8	4-42		2	
		4-58	24.1	1	3.9	4-48	20.6	2	3.3	4-40	17.6	3	2.6	4-66	NO	3	NO
		4-81	23.8	1	3.7	4-70	22.8	1	3.9	4-62	No Data	3	No Data	4-44	DATA	3	DATA
		4-82	24.2	1	3.8	4-72	22.8	1	3.8	4-64	15.6	3	2.4	4-68		3	
		Avg/σ: 24.0/0.2 3.9/0.19				Avg/σ: 22.3/1.1 3.6/0.15				Avg/σ: 15.2/3.1 2.3/0.47							
<u>Condition 3</u> LH ₂ →GHe→LH ₂ →Air→LH ₂	LH ₂	NOT TESTED				4-53	23.8	2	3.8	4-49	14.0	2	2.2	4-51		4	
						4-54	23.9	1	3.7	4-50	19.7	3	2.8	4-52	NO	4	NO
						4-77	25.3	1	3.8	4-73	22.3	3	3.3	4-75	DATA	4	DATA
						4-78	22.4	1	3.6	4-74	20.5	1	3.3	4-76		4	
						Avg/σ: 23.9/1.4 3.7/0.10				Avg/σ: 19.1/4.0 2.9/0.53							
<u>Condition 4</u> LH ₂ →GHe→LH ₂ →Air	Room Temp	4-28	3.8	1	468.7	4-9	2.8	1	452.7	4-1	1.77	1	147.8	4-5		4	
		4-29	3.4	1	437.8	4-10	3.2	1	471.7	4-2	1.45	1	136.6	4-6	NO	4	NO
		4-30	3.7	1	466.4	4-11	2.8	1	433.1	4-3	1.77	1	166.3	4-7	DATA	4	DATA
		4-31	3.5	1	448.0	4-12	3.0	1	425.5	4-4	1.78	1	192.9	4-8		4	
		Avg/σ: 3.6/0.20 455.2/15.0				Avg/σ: 3.0/0.18 445.8/22.4				Avg/σ: 1.69/0.16 160.9/27.3							
<u>Condition 5</u> LH ₂ →GHe→LH ₂ →Air→300°F→Air	Room Temp	NOT TESTED				4-21	2.9	1	427.7	4-13	1.37	1	5.0	4-17		4	
						4-22	3.2	1	468.2	4-14	2.27	1	10.5	4-18	NO	4	NO
						4-23	3.1	1	449.4	4-15	No Data	3	No Data	4-19	DATA	4	DATA
						4-24	3.2	1	464.5	4-16	No Data	3	No Data	4-20		4	
						Avg/σ: 3.1/0.15 452.2/17.9				Avg/σ: 1.82/0.8 7.7/4.9							
<u>Condition 6</u> As Received	Room Temp	4-32	3.6	1	498.7	NOT TESTED				NOT TESTED				NOT TESTED			
		4-33	3.9	1	473.2												
		4-34	4.0	1	489.0												
		4-35	4.3	1	519.8												
		Avg/σ: 4.0/0.34 495.2/22.2															

*Type of Break

1 - Gage length	4 - Static
2 - Point of tangency	5 - Combination of delamination, tangency, and/or shear
3 - Rivets and/or grip	

Figure 7 Teflon FEP: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 1

Figure 8 Teflon FEP: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 4

III, A, Teflon FEP (Cont.)

with a 25% damage level being 3.4×10^6 ergs/gm(C).^{*} These data are based on irradiation and testing at ambient temperatures in air. It has been established that in this environment an important contribution to the damage is a result of oxygen reaction with free radicals formed by the irradiation. This results in additional scissions of the original molecules. This conclusion is based on observations that thin specimens are damaged more readily than thick ones. This is because oxygen diffusion from the surface is required in order to complete the damaging reaction. Additional information leading to this conclusion is that Teflon is more radiation resistant by one or two orders of magnitude in a high vacuum or in certain oil or propellant fuel environments.

FEP Teflon is reported to be slightly more radiation resistant than TFE Teflon; however, the improvement achieved by irradiating in an oxygen free atmosphere is only slight; therefore, we estimate the liquid hydrogen environment improves the radiation resistance by one or two decades of exposures.

These irradiations have demonstrated that FEP Teflon when irradiated and tested in LH₂ (liquid hydrogen) is not damaged significantly by an exposure of 1.1×10^9 ergs/gm(C). No detrimental reactions which affect the -423°F mechanical properties occur on warming in a helium atmosphere for four days. (Condition 2) Similarly no detrimental reactions on the -423°F mechanical properties occur on subsequent holding in air at 80°F for four days. (Condition 3) However, the low dose irradiation plus a four day hold in air or helium (Condition 5) did cause a slight strength loss in the 80°F properties. (Strength decreased from 3.6 Ksi to 3.0 Ksi.) On irradiating in liquid hydrogen to an exposure of 5.4×10^9 ergs/gm(C) strength and ultimate elongation are reduced about 30% when tested at -423°F and about

^{*} Radiation Effects Information Center Report, REIC No. 21 Addendum, "Radiation Effects in Polymers and Elastomers" (1964)
R.O. Bolt and J.G. Carroll, Radiation Effects on Organic Materials (Academic Press 1963), p 172

50 % when tested at 80°F. Intermediate anneals at 80°F in helium or air do not affect the test results significantly.

The specimens irradiated to the high dose of 27×10^9 ergs/gm(C) are markedly embrittled and property measurements were not possible, due to fracture of the specimens within the aluminum doublers. The differential contraction between the aluminum doublers and the Teflon is about 1.4% between 80°F and -423°F. The resulting stresses in the doubler section were sufficient to fracture the specimens in this region after the high exposure. This indicates an additional loss of strength at this dose, as is expected, but more important is the evidence that very little, if any, stress relaxation occurs during irradiation at -423°F.

III, Test Results (Cont.)

B. ARMALON FEP-510-L-128

This material was tested satisfactorily at all conditions, and the data were found to be very consistent. The fractures for this type of Armalon were predominantly at the point of tangency for the specimens tested at both -423°F and 80°F . Representative fractures of this material are shown in Figures 9 and 10.

A comparison of the ultimate tensile strengths at the different dose is presented in Figure 11. From these data it can be seen that extreme damage was encountered in the specimens that were subjected to the high dose; some damage was detected at the intermediate-dose condition, but no radiation effect was noted at the low-dose condition. The specimens tested at room temperature exhibited a gradual decrease in strength with an increase in dose.

A comparison of ultimate strain at the different test conditions is presented in Figure 12. These data are not as clear-cut as the stress data, but some decrease is indicated at the high-dose level.

A tabulation of all mechanical-property data are presented in Table III.

Average stress-strain relationships are presented in Figure 13, showing the effects of dose level on specimens tested at environmental condition 1.

The parallel behavior between this FEP-Teflon bonded laminate (510-L-128) and the bonding material FEP Teflon suggests the primary damage in the laminate is to the Teflon rather than to the glass. The loss of strength in the laminate at the two higher dose levels is a result of the Teflon degradation which prevents it from performing its functions of distributing stress, and binding the fabric layers together to provide transverse stiffness.

After the intermediate dose of 5.4×10^9 ergs/gm(C) it was noted that the FEP Teflon suffered serious embrittlement between conditions 4 and 5; e.g., 300^o F anneal). The 510-L-128 Armalon, however, suffered only slight changes in strength or ultimate elongation. This indicates the laminate properties are not sensitive to the elongation of the bonding material, Teflon, provided the Teflon elongation exceeds about 5%.

Figure 9

Armalon 510-L-128: Fractured Specimens Pulled at LH_2 Temperature after Exposure to Low, Intermediate, and High Gamma Doses

Figure 10 Armalon 510-L-128: Fractured Specimens Pulled at Room Temperature after Exposure to Low, Intermediate, and High Gamma Doses

Figure 11 Armalon 510-L-128: Effect of Gamma Dose and Postirradiation Environmental Sequence on Ultimate Tensile Strength

Figure 12 Armalon 510-L-128: Effect of Gamma Dose and Post-irradiation Environmental Sequence on Ultimate Strain

Table III

Armalon 510-L-128: Ultimate Tensile Strength and Elongation

Environmental Sequence	Test Temp	Control				Low Dose				Intermediate Dose				High Dose			
		Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)
<u>Condition 1</u> LH ₂	LH ₂	3-55	87.9	1	4.7	3-45	84.4	2	4.8	3-37	69.3	2	4.7	3-41	33.8	5	No Data
		3-56	85.6	2	4.8	3-69	84.5	2	5.2	3-61	69.7	2	5.3	3-65	40.4	5	No Data
		3-79	86.9	2	6.0	3-47	88.7	2	4.7	3-39	66.6	2	4.8	3-43	21.0	5	No Data
		3-80	85.8	2	6.2	3-71	80.4	2	4.0	3-63	68.0	2	4.6	3-67	34.5	5	No Data
		Avg/σ: 86.5/0.6 5.4/0.68				Avg/σ: 84.5/4.0 4.7/0.58				Avg/σ: 68.4/1.5 4.8/0.34				Avg/σ: 32.4/9.4			
<u>Condition 2</u> LH ₂ -GHe-LH ₂	LH ₂	3-57	85.9	2	5.0	3-46	87.7	2	4.6	3-38	79.1	2	4.9	3-42	21.6	5	No Data
		3-58	84.0	2	4.8	3-48	87.4	2	4.6	3-40	73.8	2	4.6	3-66	39.6	5	No Data
		3-81	89.5	2	5.4	3-70	89.7	2	5.2	3-62	74.2	2	4.4	3-44	24.4	5	2.4
		3-82	88.0	2	5.9	3-72	88.4	2	4.6	3-64	73.9	2	4.3	3-68	52.2	5	No Data
		Avg/σ: 86.9/2.7 5.3/0.53				Avg/σ: 88.3/1.1 4.8/0.29				Avg/σ: 75.3/2.6 4.6/0.29				Avg/σ: 34.5/14.9 2.4			
<u>Condition 3</u> LH ₂ +GHe-LH ₂ +Air-LH ₂	LH ₂	NOT TESTED				3-53	85.7	2	4.5	3-49	77.4	2	5.2	3-51	18.1	2	1.8
						3-54	85.2	2	4.4	3-50	74.4	2	4.4	3-52	15.1	2	1.9
						3-77	88.6	2	5.9	3-73	79.1	2	5.3	3-75	11.7	2	2.1
						3-78	88.3	2	6.1	3-74	80.4	2	5.8	3-76	21.3	2	1.9
						Avg/σ: 86.9/1.5 5.2/0.82				Avg/σ: 77.8/2.9 5.2/0.68				Avg/σ: 16.6/4.7 1.9/0.14			
<u>Condition 4</u> LH ₂ +GHe-LH ₂ +Air	Room Temp	3-28	26.5	2	1.4	3-9	23.7	2	1.4	3-1	19.0	5	1.6	3-5	9.3	5	1.5
		3-29	26.2	2	1.5	3-10	24.1	2	1.1	3-2	18.1	2	No Data	3-6	9.9	5	1.5
		3-30	26.8	3	1.3	3-11	22.3	2	1.2	3-3	18.2	5	1.3	3-7	10.1	5	1.0
		3-31	27.7	3	1.5	3-12	24.1	2	1.5	3-4	18.6	5	1.3	3-8	11.8	5	1.2
		Avg/σ: 26.8/0.7 1.4/0.1				Avg/σ: 23.5/0.9 1.3/0.14				Avg/σ: 18.5/0.4 1.4/0.18				Avg/σ: 10.5/1.2 1.3/0.24			
<u>Condition 5</u> LH ₂ -GHe-LH ₂ +Air-300°F-Air	Room Temp	NOT TESTED				3-21	25.0	2	No Data	3-13	13.3	2	1.0	3-17	9.2	5	1.6
						3-22	24.9	2	1.3	3-14	15.3	2	0.9	3-18	8.5	5	1.6
						3-23	24.8	2	No Data	3-15	15.2	2	0.8	3-19	9.0	5	1.6
						3-24	24.5	2	1.0	3-16	14.9	2	1.2	3-20	9.0	5	0.6
						Avg/σ: 24.8/0.13 1.2/0.27				Avg/σ: 14.7/1.0 1.0/0.19				Avg/σ: 8.9/0.4 1.4/0.49			
<u>Condition 6</u> As Received	Room Temp	3-32	26.0	2	1.5	NOT TESTED				NOT TESTED				NOT TESTED			
		3-33	26.9	2	1.6												
		3-34	26.8	2	1.7												
		3-35	27.3	2	1.6												
		Avg/σ: 26.8/0.6 1.6/0.1															

*Type of Break

1 - Gage length	4 - Static
2 - Point of tangency	5 - Combination of delamination, tangency, and/or shear
3 - Rivets and/or grip	

Figure 13 Armalon 510-L-128: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 1

III, Test Results (cont.)

C. ARMALON TFE-405-CL-116

This material was tested without difficulty at all test conditions. In general, the specimens of this material did not fail within the 2.00 inch gage length but fractured at approximately the point of tangency of the reduced section. This was true of the specimens tested at both 80°F and -423°F temperatures. Representative fractures can be seen in Figure 14.

A comparison of the ultimate tensile strength at the different dose and environmental conditions is presented in Figure 15. From these data it can be seen that a high degree of damage was detected in the specimens subjected to the high dose. The specimens tested at room temperature exhibited a gradual decrease in strength with an increase in dose.

A comparison of ultimate strain at the different dose and environmental conditions is presented in Figure 16. These data indicate a trend similar to the ultimate-stress data for specimens tested at -423°F. For those specimens tested at 80°F, there is very little or no radiation-induced ultimate strain variation.

A tabulation of all detailed mechanical-property data is presented in Table IV.

Average stress-strain relationships are presented in Figures 17 and 18. There appears to be a definite decrease in ultimate strain with thermal cycling but no effect on ultimate stress.

Most curves are linear to the fracture load; however in some cases at high loads discontinuities and apparent curvature was observed. This is attributed to failure of the adhesive bonding the doublers to the specimen and subsequent bending in the specimen shoulders.

Figure 14 Armalon 405-CL-116: Fractured Specimens Pulled at LH_2 Temperature after Exposure to Low, Intermediate, and H_2 High Gamma Doses

Figure 15 Armalon 405-CL-116: Effect of Gamma Dose and Postirradiation Environmental Sequence on Ultimate Tensile Strength

Figure 16 Armalon 405-CL-116: Effect of Gamma Dose and Post-irradiation Environmental Sequence on Ultimate Strain

Table IV

Armalon 405-CL-116: Ultimate Tensile Strength and Elongation

Environmental Sequence	Test Temp	Control				Low Dose				Intermediate Dose				High Dose			
		Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)
Condition 1 LH ₂	LH ₂	1-55	43.9	2	3.1	1-45	56.8	2	4.1	1-37	48.2	2	2.9	1-41	19.1	5	1.9
		1-56	46.1	2	3.0	1-69	49.9	2	4.1	1-61	54.0	2	3.2	1-65	25.0	5	No Data
		1-79	46.3	2	2.9	1-47	58.2	2	3.3	1-39	48.5	2	3.2	1-43	14.5	5	1.8
		1-80	50.8	2	3.4	1-71	51.3	2	3.8	1-63	51.1	2	3.2	1-67	18.4	5	No Data
		Avg/σ: 46.8/3.4				Avg/σ: 54.1/4.0				Avg/σ: 50.5/2.8				Avg/σ: 19.3/5.1			
Condition 2 LH ₂ →GHe→LH ₂	LH ₂	1-57	61.2	2	3.7	1-46	58.3	2	3.8	1-38	51.2	2	3.3	1-42	22.6	2	2.6
		1-58	63.7	2	4.7	1-48	60.7	2	4.0	1-40	50.9	2	3.4	1-66	21.8	2	2.6
		1-81	64.5	2	4.9	1-70	51.9	2	3.8	1-62	56.5	2	3.6	1-44	26.8	2	2.4
		1-82	61.4	2	4.6	1-72	50.6	2	3.8	1-64	55.6	2	4.2	1-68	27.6	2	2.7
		Avg/σ: 62.7/2.1				Avg/σ: 55.4/4.9				Avg/σ: 53.5/2.7				Avg/σ: 24.7/2.8			
Condition 3 LH ₂ →GHe→LH ₂ →Air→LH ₂	LH ₂	NOT TESTED				1-53	52.6	2	3.7	1-49	57.6	2	4.1	1-51	30.6	2	3.1
						1-54	49.7	2	3.3	1-50	60.0	2	3.8	1-52	23.1	2	2.3
						1-77	36.1	1&2	3.5	1-73	50.1	2	3.7	1-75	20.6	2	1.9
						1-78	49.3	2	3.4	1-74	46.7	2	4.5	1-76	30.3	2	2.7
						Avg/σ: 46.9/8.0				Avg/σ: 53.6/6.5				Avg/σ: 26.2/4.9			
Condition 4 LH ₂ →GHe→LH ₂ →Air	Room Temp	1-25	16.3	2	0.66	1-9	15.9	2	0.70	1-1	14.2	5	0.66	1-5	11.4	5	0.92
		1-26	16.2	2	0.72	1-10	14.7	2	0.60	1-2	13.4	2	0.64	1-6	10.7	5	0.79
		1-27	17.6	2	0.68	1-11	13.4	2	0.61	1-3	12.2	2	0.54	1-7	9.2	5	1.00
		1-28	17.9	2	0.89	1-12	15.2	2	0.74	1-4	12.3	5	0.58	1-8	11.3	5	0.86
		Avg/σ: 17.0/0.8				Avg/σ: 15.2/1.2				Avg/σ: 13.0/1.0				Avg/σ: 10.6/1.1			
Condition 5 LH ₂ →GHe→LH ₂ →Air→300°F→Air	Room Temp	NOT TESTED				1-21	15.3	2	0.67	1-13	10.9	5	No Data	NOT TESTED			
						1-22	14.4	2&3	0.69	1-14	12.1	5	0.77				
						1-23	14.2	2	No Data	1-15	12.3	2	0.70				
						1-24	13.1	2	No Data	1-16	12.3	2	0.64				
						Avg/σ: 14.2/1.1				Avg/σ: 11.9/0.7							
Condition 6 As Received	Room Temp	1-17	17.6	2	1.01	NOT TESTED				NOT TESTED				NOT TESTED			
		1-18	19.2	2	1.15												
		1-19	16.0	2	1.04												
		1-20	15.5	2	1.13												
		Avg/σ: 17.1/1.8															

*Type of Break

1 - Gage length	4 - Static
2 - Point of tangency	5 - Combination of delamination, tangency, and/or shear
3 - Rivets and/or grip	

Figure 17 Armalon 405-CL-116: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 1

Figure 18 Armalon 405-CL-116: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 4

III, Test Results (cont.)

D. SUPERPOLYMER SP-3

All specimens of this material were tested satisfactorily with good results. The data were found to be very consistent. This material was found to exhibit an increase in strength when tested at LH_2 temperature relative to room temperature.

Representative fractures of this material, tested at -423°F are presented in Figure 19.

Comparisons of ultimate tensile strength at the different environmental conditions are presented in Figure 20. From these data and similar ultimate strain data it can be seen that the SP-3 material was not damaged at the dose levels achieved in this test. A tabulation of detailed data is shown as Table V.

Average stress-strain relationships are presented in Figures 21 and 22 showing the effects of dose level. The -423°F stress-strain data indicate no permanent deformation prior to fracture; whereas, the curvature in the room temperature curve indicates a possible permanent deformation.

Figure 19 Superpolymer SP-3: Fractured Specimens Pulled at LH_2 Temperature after Exposure to Low, Intermediate, and High Gamma Doses

Figure 20 Superpolymer SP-3: Effect of Gamma Dose and Postirradiation Environmental Sequence on Ultimate Tensile Strength

Table V

Superpolymer SP-3: Ultimate Tensile Strength and Elongation

Environmental Sequence	Test Temp	Control				Low Dose				Intermediate Dose				High Dose			
		Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)	Specimen No.	Stress (ksi)	Type of Break*	Strain (%)
<u>Condition 1</u> LH ₂	LH ₂	5-25	15.8	1	2.4	5-9	14.5	1	2.2	5-1	20.6	1	2.8	5-5	15.0	1	1.9
		5-26	15.5	1	2.2	5-10	18.0	1	2.9	5-2	13.6	1	1.9	5-6	17.3	1	2.6
		5-27	17.1	1	2.4	5-11	15.9	1	2.4	5-3	17.3	1	2.3	5-7	14.6	1	2.1
		5-28	17.1	2	2.6	5-12	16.0	1	2.3	5-4	20.0	2	2.8	5-8	18.1	2	2.4
		Avg/σ: 16.3/0.8 2.4/0.19				Avg/σ: 16.1/1.7 2.4/0.34				Avg/σ: 17.9/3.4 2.5/0.44				Avg/σ: 16.3/1.7 2.2/0.34			
<u>Condition 2</u> LH ₂ →GHe→LH ₂	LH ₂	5-29	16.9	2	3.8	NOT TESTED				NOT TESTED				NOT TESTED			
		5-30	17.4	2	3.7												
		5-31	11.5	1	2.5												
		5-32	16.2	1	3.3												
		Avg/σ: 15.5/2.9 3.3/0.63															
<u>Condition 3</u> LH ₂ →GHe→LH ₂ →Air→LH ₂	LH ₂	NOT TESTED				5-21	15.4	1	No Data	5-13	18.6	1	2.9	5-17	16.8	1	2.2
						5-22	17.4	1	2.3	5-14	15.1	2	2.3	5-18	15.6	1	2.4
						5-23	18.3	1	2.2	5-15	15.5	1	2.2	5-19	15.1	1	2.8
						5-24	15.9	1	2.3	5-16	19.5	2	2.9	5-20	16.4	1	2.0
		Avg/σ: 16.8/1.4 2.2 /0.12				Avg/σ: 17.2/2.1 2.5 /0.44				Avg/σ: 16.0/0.8 2.4 /0.58							
<u>Condition 4</u> LH ₂ →GHe→LH ₂ →Air	Room Temp	5-36	10.0	1	4.2	5-52	10.7	1	4.6	5-44	12.4	1	6.7	5-48	13.1	1	7.2
		5-37	10.5	1	4.4	5-53	12.1	1	5.8	5-45	9.96	1	3.8	5-49	10.8	2	4.6
		5-38	10.3	1	4.5	5-54	12.3	1	6.5	5-46	12.9	1	7.4	5-50	8.8	1	3.0
		5-39	11.0	1	4.5	5-55	12.3	1	6.0	5-47	11.3	1	5.1	5-51	11.9	1	5.6
		Avg/σ: 10.5/0.5 4.4/0.15				Avg/σ: 11.9/0.8 5.7/0.92				Avg/σ: 11.6/1.4 5.8/1.7				Avg/σ: 11.5/2.1 5.1/2.0			
<u>Condition 5</u> LH ₂ →GHe→LH ₂ →Air→300°F→Air	Room Temp	NOT TESTED				5-60	10.9	1	4.2	5-56	13.1	1	6.4	5-64	12.7	1	6.4
						5-61	11.7	1	5.0	5-57	11.7	1	5.0	5-56	11.4	2	4.8
						5-62	12.8	1	6.4	5-58	12.1	1	4.9	5-66	8.8	2	2.9
						5-63	11.5	1	5.0	5-59	10.1	1	3.7	5-67	12.0	1	3.7
		Avg/σ: 11.7/0.9 5.2/0.11				Avg/σ: 11.8/1.5 5.0/1.3				Avg/σ: 11.2/1.9 5.0/1.7							
<u>Condition 6</u> As Received	Room Temp	5-40	10.2	1	4.0	NOT TESTED				NOT TESTED				NOT TESTED			
		5-41	10.7	1	4.6												
		5-42	12.3	1	6.6												
		5-43	10.6	1	4.5												
		Avg/σ: 11.0/1.2 4.6/1.3															

*Type of Break

1 - Gage length	4 - Static
2 - Point of tangency	5 - Combination of delamination, tangency, and/or shear
3 - Rivets and/or grip	

Figure 21 Superpolymer SP-3: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 1

Figure 22 Superpolymer SP-3: Stress-Strain Curves Showing Effect of Dose Level on Specimens Tested at Environmental Condition 4

IV. GENERAL DISCUSSION AND CONCLUSIONS

These test results demonstrate the temperature dependence and the effects of thermal cycling on the tensile properties of Teflon, Armalon and SP-3 both in the irradiated and unirradiated conditions. It was thought that temperature cycling could affect properties especially in the Armalon laminate since the expansion coefficients of Teflon and glass are greatly different. Teflon has the largest percentage increase (600%) in strength at -423°F (133%). The ratios of strength at -423°F to strength at 80°F for all materials in the unirradiated condition are listed in Table IV. Comparable ratios were observed following irradiation except for the highest dose.

Only the Armalon 405-CL-116 showed evidence of significant property change due to thermal cycling in the unirradiated condition. The control specimens appeared to increase the -423°F strength from 46.8 Ksi to 62.7 Ksi between the third and fourth thermal cycles to -423°F although no change was observed in 80° strength due to this cycling. Since no thermal cycling effects were observed in the Armalon 510-L-128 and a similar material Armalon 405-L-112, we speculate this may be either a result of an unknown experimental error or an extreme statistical fluctuation.

The stress-strain data for all these materials at -423°F indicate nearly all the strain is elastic and it is not safe in design to assume that any permanent deformation can take place without fracture.

The SP-3 polymer can be safely used within its unirradiated property limits in a cryogenic radiation environment at least up to the highest exposure in this test of 27×10^9 ergs/gm(C).

TABLE VI

Temperature Dependence of Ultimate Tensile Strength

Material	-423°F Control Condition 1 KSI	80°F As Received KSI	Ratio $\frac{\text{UTS } (-423^{\circ}\text{F})}{\text{UTS } (80^{\circ}\text{F})}$
FEP Teflon	23.9	4.0	6.0
Armalon 510-L-128	86.5	26.8	3.2
Armalon 405-CL-116	54.7(A)	17.1	3.2
SP-3	16.3	11.0	1.5

(A) Average of Condition 1 (after 2 thermal cycles) and Condition 2 (after 3 thermal cycles).

The two Armalons 510-L-128 and 405-CL-116 retain useful tensile strengths up to an exposure of 5.4×10^9 ergs/gm(C) but their strength is degraded too much at an exposure of 27×10^9 ergs/gm(C) to be useful for most structural applications. It should be noted that tensile tests are not a good indicator of flexural rigidity and, in the absence of direct test data, design with Armalon in a cryogenic radiation environment involving bending should be very conservative.

FEP Teflon in a cryogenic radiation environment can tolerate one or two orders of magnitude greater gamma exposure than when irradiated in ambient air. It is degraded in strength slightly at 1.1×10^9 ergs/gm(C), 25% to 50% at 5.4×10^9 ergs/gm(C) and suffers extreme embrittlement at 27×10^9 ergs/gm(C). Strength data were not obtained at this highest dose. At this highest dose glass-like breaks occurred in regions of stress concentrations which indicates very little, if any, radiation-induced stress relaxation occurs at -423°F .

Annealing Teflon, Armalon and SP-3 to room temperature subsequent to irradiation at -423°F does not cause oxidation or other reactions which are significantly detrimental to mechanical properties. However, annealing Teflon for 8 hours at 300°F seriously embrittles it although the ultimate tensile strength is not affected.

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