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Evaluation and Prediction of Long-Term Environmental Effects on Nonmetallic Materials

MARTIN MARIETTA

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EVALUATION AND PREDICTION OF LONG-TERM ENVIRONMENTAL EFFECTS OF NONMETALLIC MATERIALS

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FOREWORD

This is a final report for the third phase of the program, Evaluation and Prediction of Long-Term Space Environmental Effects on Nonmetallic Materials, conducted by Martin Marietta for the National Aeronautics and Space Administration, Marshall Flight Center, under Contract NAS8-33578.

The program was conducted in the Mechanical Materials Engineering Section with Mohan Misra as Program Manager and Harold Papazian as Principal Investigator. Contributions to the program included W. J. Arbegast and C. E. Forsyth for material tests.

Don Wilkes of NASA-MSFC served as program monitor. Dr. Ray Gause and Ms. Ann Whitaker served as technical advisors.

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I. INTRODUCTION

Although nonmetallic materials are generally recognized as being susceptible to the changes caused by the environments associated with long-life spacecraft, data concerning the effects of irradiation and long-term thermal-vacuum exposure on the specific mechanical, electrical, and thermal properties of such materials have not been readily available. Because the performance and life of any structure, system or component directly depends on the integrity of the materials used in its construction, the ability of these materials in meeting service life requirements.

The degradation of any material or material system, even if slow at normal-use temperatures, can lead to failure over a long period. For example, in a polymer system used as a structural member, the accumulated changes may eventually lead to loss of integrity. Real-time tests of materials that may be used in a system can be clearly impractical in time and money. If short-time tests can be used to predict future behavior, these tests can considerably enhance mission success.

The emphasis of the first phase of this program was on the effects of long-duration thermal-vacuum exposure and had its foundation in the Viking materials qualification program of some years ago. The project established the requirements for materials suitable for the Viking spacecraft. Specimens of the same materials that had remained in a thermal-vacuum environment to the present time were tested to determine whether any changes in material properties had occurred over the long-term exposure. In general the largest changes occurred in such electrical properties as dielectric strength, dielectric constant and volume resistivity. The mechanical properties showed only small changes--some increasing and others decreasing in strength. The preceding phase thus established the important fact that thermal-vacuum exposure would not degrade the structural integrity of a spacecraft constructed with nonmetallic material systems.

The second phase of the program was devoted to the effects of charged particle irradiation on the mechanical properties of graphite/epoxy composites. There is a paucity of literature data[1] concerning the charged particle irradiation effects on such composites. In preparation for the future testing, expected radiation effects were discussed in considerable detail. Considerable effort was devoted to development of models and accelerated test methods useful for predicting material behavior. Zhurkov's approach to the strength of solids is a useful first step toward such predictions. This was discussed in considerable detail showing the underlying fundamentals of the approach as well as its application to decelerated testing of composites.

The present phase of the programs was to be devoted primarily to the effects of charged particle irradiation on the mechanical properties of composites; however, the thrust of the program was changed at the request of NASA-MSFC to further testing of thermal effects. Prior to the change, a model for the effects of electron irradiation on mechanical properties of polymers was developed and has been included as part of this report.

II. PROGRAM OBJECTIVE

The objective of this program is to continue the experimental evaluation of changes in these functional properties of a number of nonmetallic materials as a function of simulated space environments and to use such data to develop models for accelerated test methods useful for predicting such behavorial changes.

III. TECHNICAL APPROACH

A. TASKS

Task 1 required testing of graphite/epoxy composites exposed to thermal cycling.

Task 2 required in-vacuo testing of new-generation very high strength doubled-faced adhesive foam tapes exposed for varying times to a vacuum environment. The lap shear specimens were to be tested at one-, three-, and six-month intervals.

Task 3 was to involve testing of metal-matrix composites but this task was deferred at the request of NASA-MSFC.

Task 4 required predictive modeling to include strength and aging effects on composites, polymeric films and metals under space environmental conditions (including the atomic oxygen environment), extending the approach developed in the previous work.

Before deferring Task 3, five metal-matrix composites were tested for baseline data. A total of 60 lap-shear specimens of the high-strength adhesive foam tapes were tested. Thirty specimens of graphite/epoxy composites prepared by the Martin Marietta plastics lab were thermally cycled at MSFC and then returned and tested at Martin Marietta. For Task 4 a discussion is given on the effects of electron irradiation on mechanical properties of polymers as well as the effects of atomic oxygen on polymers and metallic films.

B. SPECIMEN DESCRIPTIONS

The very high-strength doubled-faced adhesives foam tapes were Korel 8031-00, Scotch Y-4445, and Arclad PE-6549. The Korel 8031-00 is a high-density closed-cell urethane with acrylic adhesive. The Scotch Y-4445 is a acrylic foam. The Arclad PE-6549 is a polythylene foam with acrylic adhesive. All specimens were made with adhesives areas of 1 square inch between aluminum adherends.

The graphite/epoxy specimens were prepared from Fiberite HYE 1034E(T-300) prepreg material. The longitudinal specimens were 8 plies of 0.5 x 7.6 inches and the transveres specimens were 20 plies of 1 x 7.6 inches, both having glass-epoxy tabs for testing.

The metal-matrix specimens were single-ply unidirectional. For the Pitch 100 graphite/epoxy composite, the precursor magnesium-matrix was AZ91C Mg with 8-mil AZ31B Mg face sheets. For the Pitch 100 graphite/6061 aluminum composite, the precursor aluminum matrix wire as well as the face sheet was 6061 aluminum 5 mils thick. The specimens prepared for testing were 0.5 x 6.0 inches and were tested as fabricated.

C. TEST PROCEDURES

The lap-shear foam tape adhesive specimens were placed in a vacuum canister (approximately 10^{-5} torr) and never again exposed to the ambient environment. All specimens were transferred between the vacuum canister to the *in situ* test vacuum chamber via the airlock system of the latter. This was done periodically, removing the specimen to be tested at a particular time interval.

The graphite/epoxy specimens were thermally cycled between -100 and 300°F in the MSFC system. Specimens were periodically removed and sent to Martin Marietta for test.

All tests were done according to the appropriate ASTM test procedure.

IV. RESULTS

Figure 1 shows the results for the ultimate strength of the high-strength foam adhesives tapes as a function of time under vacuum, and Figure 2 shows the changes in percent elongation. Clearly the Korel 8031-00 appears to be the best candidate for space applications followed by the Arclad PE 6549. The Scotch T4945 tape should be avoided for such applications. Table 1 presents tabulated results of the tests, with a machine speed of 0.05 inch/minute.

Although not required under the task, witness samples of each adhesive were placed under vacuum for an estimate of weight loss. Korel 8031-00 was again the best candidate. At the end of 28 weeks it had a 0.12% weight loss whereas the Scotch Y4945 had at 0.23% weight loss. (The Arclad witness sample was lost during test.) Table 2 shows the activation energy for thermal decomposition as determined by thermogravimetric analysis (TGA).

Table 3 shows the ultimate strength changes in the graphite/epoxy specimens after thermal-vacuum cycling. The tests were carried out at a machine speed of 0.05 inch/minute. Beginning with the 50-cycle tests the white end tabs (glass/epoxy) where charred. The thermal-vacuum cycling system at MSFC was checked for an air leak but none was found. However almost certainly there was some source of oxygen in the system. Not only were the tabs charred but delamination was apparent in some of the specimens beginning with the 50-cycle specimens. Therefore, the results in Table 3 must be considered with caution.

Before Task 3 was defferred, metal-matrix composites were baseline-tested. Table 4 shows the results for Pitch 100 graphite/magnesium, and Table 5 shows the results for Pitch 100 graphite/6061 aluminum.

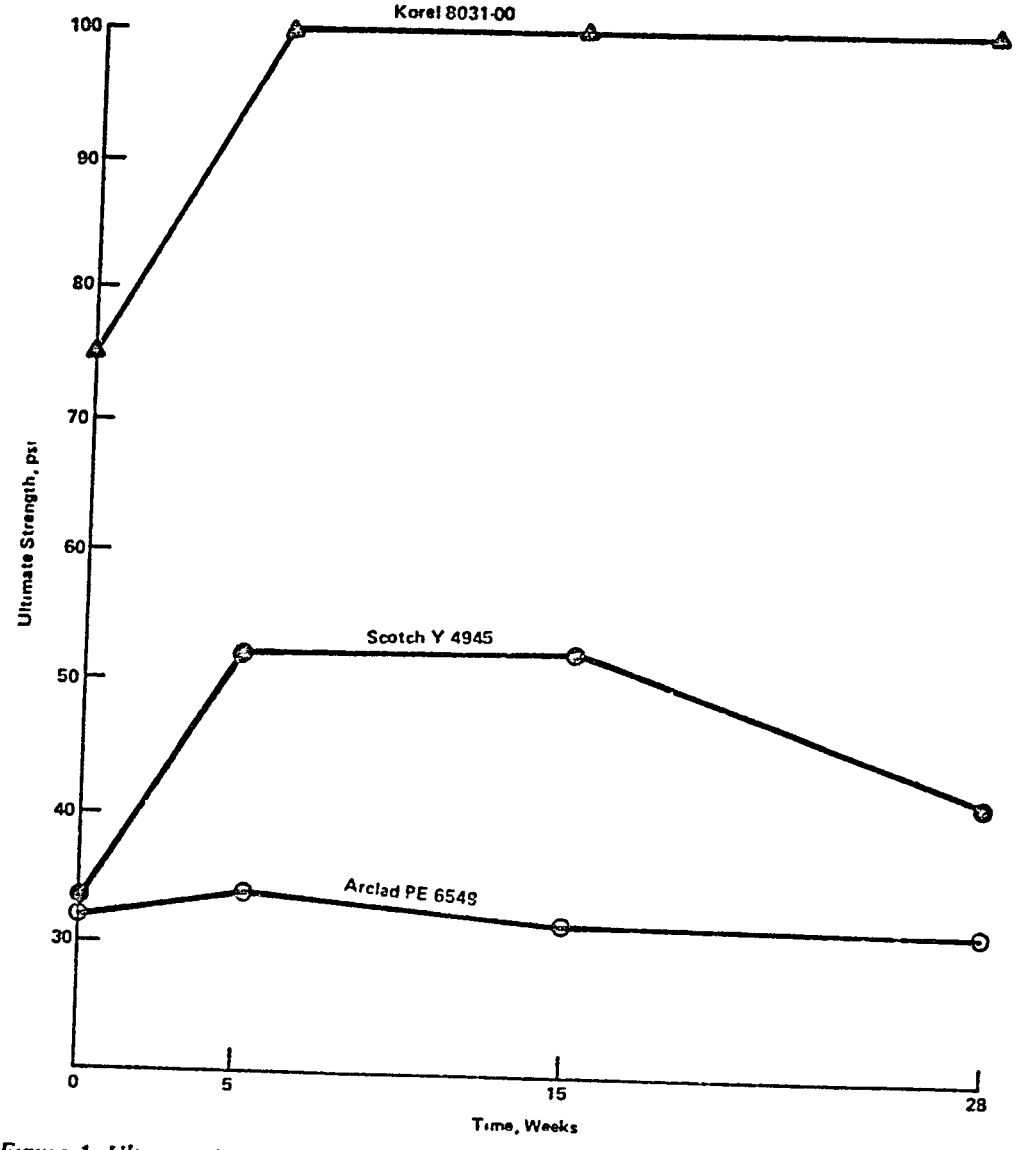

Figure 1 Ultimate Strength As a Function of Time in Vacuum of Adhesive Foam Tapes

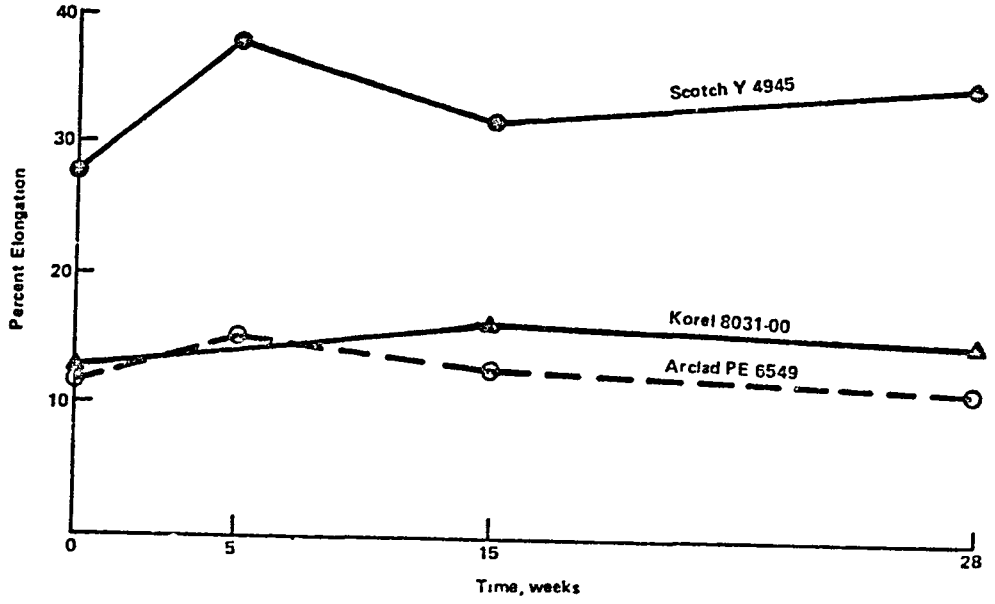

Figure 2 Percent Elongation As a Function of Time in Vacuum of Adhesive Foam Tapes

Table 1 Lap Shear Results for Form Tapes

Specimen	Time in Thermal Vacuum Weeks	Ultimate Strength, psi	% Elongation	Failure Mode
Scotch Y 4945	0 (Baseline)	25 2	16.0	Cohesive
		25 4	19 5	
		33 1	24.5	
		34 5	32 5	
		47 5	47 0	
		33 1 avg	27 9 avg	
	5	45 5	39 0	
		69 8	41 5	
		65 0	30 8	
		32 7	43 5	
		47 9	33 8	
		52 2 avg	37 7 avg	
	15	•	•	
		54 9	31.5	
		54 9	31.2	
		49 5	31.5	
		50 7	34 0	
		52 5 avg	32 0 avg	
	28	31.2		
		41 8	28 0	
		29 3	36 8	
		67 7	41 8	
		35 8		
		41 2 avg	35 5 avg	
Korel 8031-00	0	78 0	—	Adhesive
		82 1	14 5	
		79 9	—	
		69 3	12 0	
		65.0	11.5	
		74 9 avg	12 7 avg	
	5	—	—	
		110	13 5	
		110	13 0	
		100	16 0	
		89	15.0	
		102 avg	14 4 avg	
	15	108 7	17.2	
		106 6	14.8	
		115 8	19.5	
		95 2	18 5	
		93 7	12 0	
		104 avg	16 4 avg	
	28	93 0	—	
		99 1	16 0	
		121 4	15 0	
		99.5	14 0	
		103 4	14.5	
		104 3 avg	14 9 avg	
Arclad PE 6549	0	32 0	11 5	Adhesive
		31 2	11 8	
		31 8	11.0	
		31.8	11 2	
		33 3	13 0	
		32 0 avg	11 7 avg	
	5	37 8	—	
		31.1	—	
		38 1	15.8	
		35 6	14 5	
		26.5	—	
		33.8 avg	15.2 avg	
	15	30 8	16 0	
		31 6	13.0	
		32 0	12.0	
		32 9	12 5	
		30 7	11.0	
		31 6 avg	12 9 avg	
	28	27 6	11.8	
		31.7	16 5	
		25 6	10 0	
		35 3	11.8	
		33 7	11 5	
		30 8 avg	12 3 avg	

*Indicates some test problem (e g , grip slippage).

Table 2 Activation Energies for Thermal Decomposition of Foam Tapes

Specimens	Activation Energy, kCal	Temperature for Beginning Decomposition, °C
Scotch Y-4945	16.3	About 200
Korel 8031	14 4	About 170
Arclad PE-6549	11.3	About 180

Table 3
Ultimate Strength of Graphite/Epoxy Composites after Thermal-Vacuum Cycling (-100 to 300° F)

	Baseline	50 Cycles	250 Cycles	400 Cycles
Longitudinal	245×10^3 psi 247 258	154×10^3 psi 158 136	228×10^3 psi 162 155	101×10^3 psi 106 126 93.5 101 102
Transverse	250×10^3 avg 9.8×10^3 psi 5 3 7 3 7.5×10^3	149×10^3 avg 10.1×10^3 psi * *	182×10^3 avg 3.2×10^3 psi 5 0 1 93 3.4×10^3 avg	105×10^3 avg All specimens broken during thermal cycling, one broken during test loading

*Specimen broken during cycling and/or placement into tensile test machine

Table 4 Baseline for Pitch 100 Gr/Mg Metal-Matrix Composite (Fiber Volume 26 5%)

	Ult Strength, psi	Modulus	% Elongation
Longitudinal	83.2×10^3	32.4×10^6	0 42
Transverse	$14\ 6 \times 10^3$	4.8×10^6	0.89

Table 5 Baseline for Pitch 100 Gr/6061 Al Metal-Matrix Composite

Ultimate Strength, psi	Yield Strength at 0.2%	Modulus x 10^6	Poisson's Ratio
97,333	None Observed	42 1	0 31
102,933	None Observed	35 6	
100,266	None Observed	37.2	
100,177 avg		$38\ 3 \times 10^6$	

V. ANALYSIS

A. IRRADIATION MODELING

Prior to the change of Task 1 from irradiation tests to thermal-vacuum cycling, modeling of irradiation effects, within the Zhurkov framework, was conducted and is embodied in this section. It shows for the first time a potentially viable method for predicting mechanical properties under ionizing radiation.[2]

The most important effects of irradiation in polymers are crosslinking and degradation. If crosslinking predominates, the ultimate effect of irradiation will be to producer a network polymer in which all molecules are joined to each other. If degradation predominates, the molecules become smaller and smaller as irradiation proceeds and the material losers its polymeric properties.

The degree of unsaturation of a polymer can also change on irradiation. Polymers that are initially highly saturated tend to become less so on irradiation, wile with initially saturated polymers the amount of unsaturation increases with dose. The formation of an unsaturated double bond will tend to labilize the bonds (free to move) in the allyl position, leading to a conjugated double bond system. Such an effect accounts for the cloration of some polymers on irradiation. Another important change is the formation of gas during irradiation. The amount of gas produced depends on the polymer, dose, temperature, type of irradiation, etc.

The free radicals (highly labile molecular fragments) formed during irradiation must play an important part in chemical changes. These free radicals can be both short-lived and long-lived depending on the polymer. The response of polymers to irradiation is markedly affected by the presence of other substances, most probably from reaction with the free radicals produced. Oxygen produces a marked effect, usually a decrease in the tendency to crosslink, i.e, oxygen reaction with the

broken bonds (of long-lived radicals) rather than crosslinking. Thus any irradiation study that allows sample to be exposed to the ambient environment after irradiation must be suspect. The amount of oxygen initially present in the material causes only a small effect. LArge effectors can occur if the sample is thin enough and the dose rate is low enough for oxygen to diffuse during the irradiation.

The behavior of materials under ionizing radiation is of continuing concern because of its practical importance. With the increased use of advanced materials such as graphite/epoxy composites, especially in spacecraft, predicting the lifetime of any mechanical property is of prime importance.

In approaching this problem in the laboratory, generally an irradiated polymer is removed from the radiation source and tested in some other place. As a consequence, there is a considerable lapse in time as well as the potential for contamination, for example with oxygen. Also it is well known that irradiation of a polymer results in the formation of free radicals. Modeling such a procedure requires the kinetics of radical reaction as well as the chemistry. In the solid state the complexities of such reactions are compounded, making the predictive task almost hopeless. The purpose of this chapter is to show that under the appropriate conditions, i.e., testing while under irradiation, which in a practical case is similar to a spacecraft maneuver under space irradiating conditions, it may be possible to predict mechanical properties.

kecently a detailed discussion[3] of the Zhurkov approach to the strength of solids was presented, and thermodynamic considerations[4] developed the method from a more rigorous basis. Zhurkov's method determines the time to failure under constant stress (here defined as creep rupture). It has been shown[5] that the Zhurkov method can also be applied to a variety of mechanical properties.

The purpose of the present communication is to give another example of the versatility of the Zhurkov approach. A literature search uncovered only one study in which irradiation and property testing were conducted concurrently.[6] Data from this study will be discussed here in the Zhurkov framework.

Zhurkov developed his creep rupture method by successfully applying his relationships to a variety if materials. The relationships of Zhurkov are

[1] $\tau = Ae^{-\alpha\sigma}$ (at constant temperature)

[2] $\tau = \tau_o e^{U^*/kT}$ (at constant stress),

which may be combined into the well known form

[3] $\tau = \tau_c e^{(U_o - \gamma\sigma)/kT}$

where

τ = time to rupture,
α = constant,
A = constant,
σ = applied uniaxial stress,
τ_c = constant,
$U^* = U_0 - \gamma\sigma$, energy,
U_0 = an activation energy,
γ = constant,
k = Boltzmann's constant,
T = absolute temperature..

According to Zhurkov, when a material behaves according to Equations [1] and [2], τ_c is considered to be the period of natural oscillation in the solid (10^{-12} s) and γ is a constant that depends on the structure of the material. Equations [(1)] and [(2)] are related through $A = \tau_c \exp(U_0/kT)$ and $\alpha = \gamma/kT$.

Equation [1] can be used to predict failure times at low loads where the failure times are long. With high load tests at two, or at most three, temperatures, the constants of Equation [2] can be evaluated. Failure times can then be predicted at other temperatures and loads.

Reference 6 studied the creep rate of polystyrene during irradiation with high-energy electrons. Because it was earlier shown[7] that the time to a given strain could be given by the Zhurkov model, creep rate data were extracted from Figures 5 and 9 of Reference 6 and reciprocals presented below as $\dot{\gamma}$ (τ = time) to be consistent with earlier discussions and to clearly show the Zhurkov framework.

Figure 3 shows the relationship of τ with the electron beam current. Stress data at constant beam current may be extracted from this figure. Figure 4 shows the dependence of τ on stress, which is of the form of Equation [1], and clearly under irradiation polystyrene behaves in accordance with the first Zhurkov relationship.

Figure 5 shows the dependence of τ on temperature. The nonirradiated results behave as expected and follow Zhurkov's second relationship. The irradiated specimens behave similarity with no apparent change in activation energy.

Thus both of Zhurkov's equations can be applied to results under irradiation.

Even though creep is enhanced under electron irradiation, the response to stress may be formulated within the Zhurkov approach to the strength of solids not under ionizing radiation. The results indicate that under these conditions it may be possible to model, and therefore predict, mechanical property behavior.

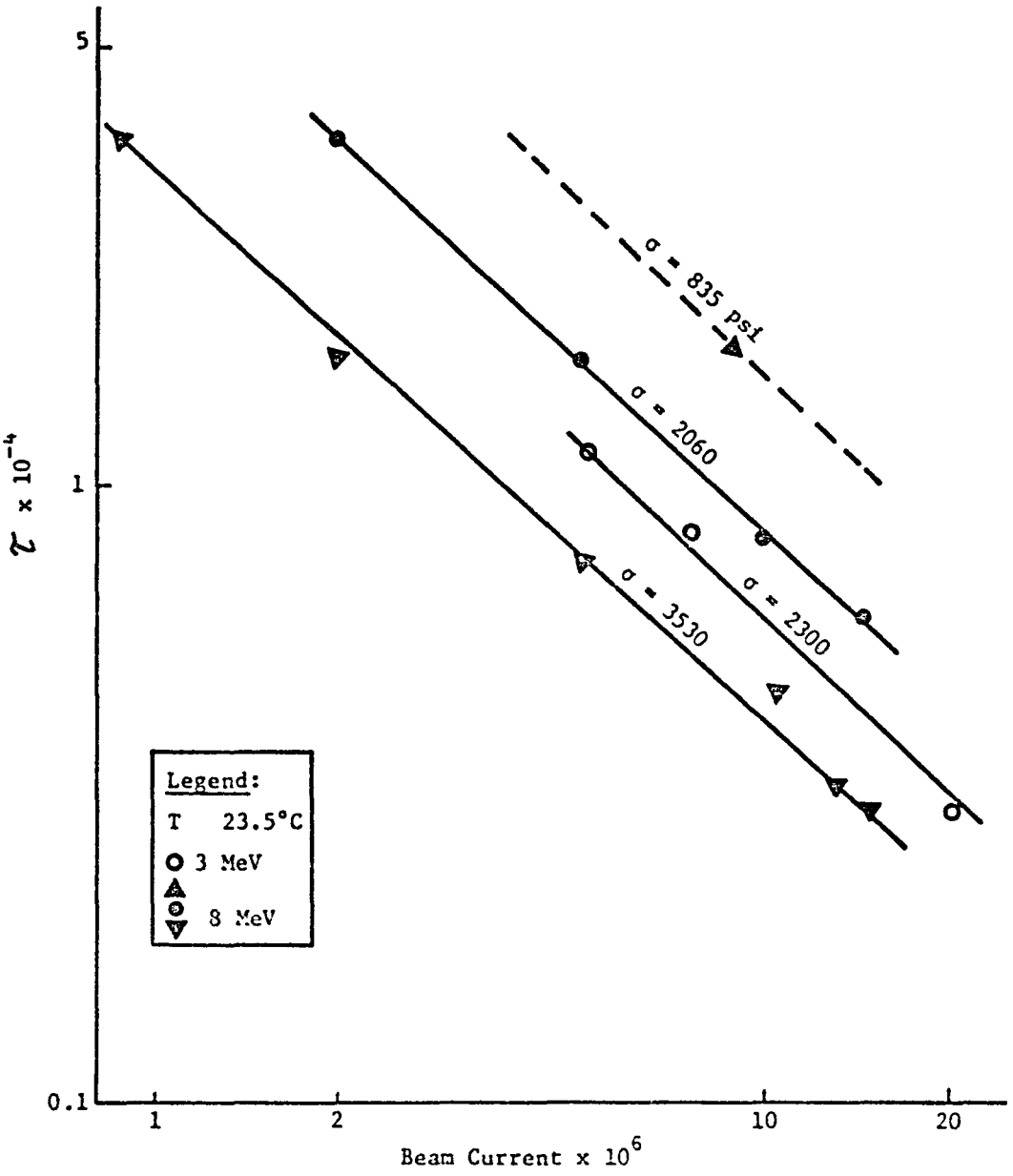

Figure 3 Dependence of τ on Beam Current at Constant Stress

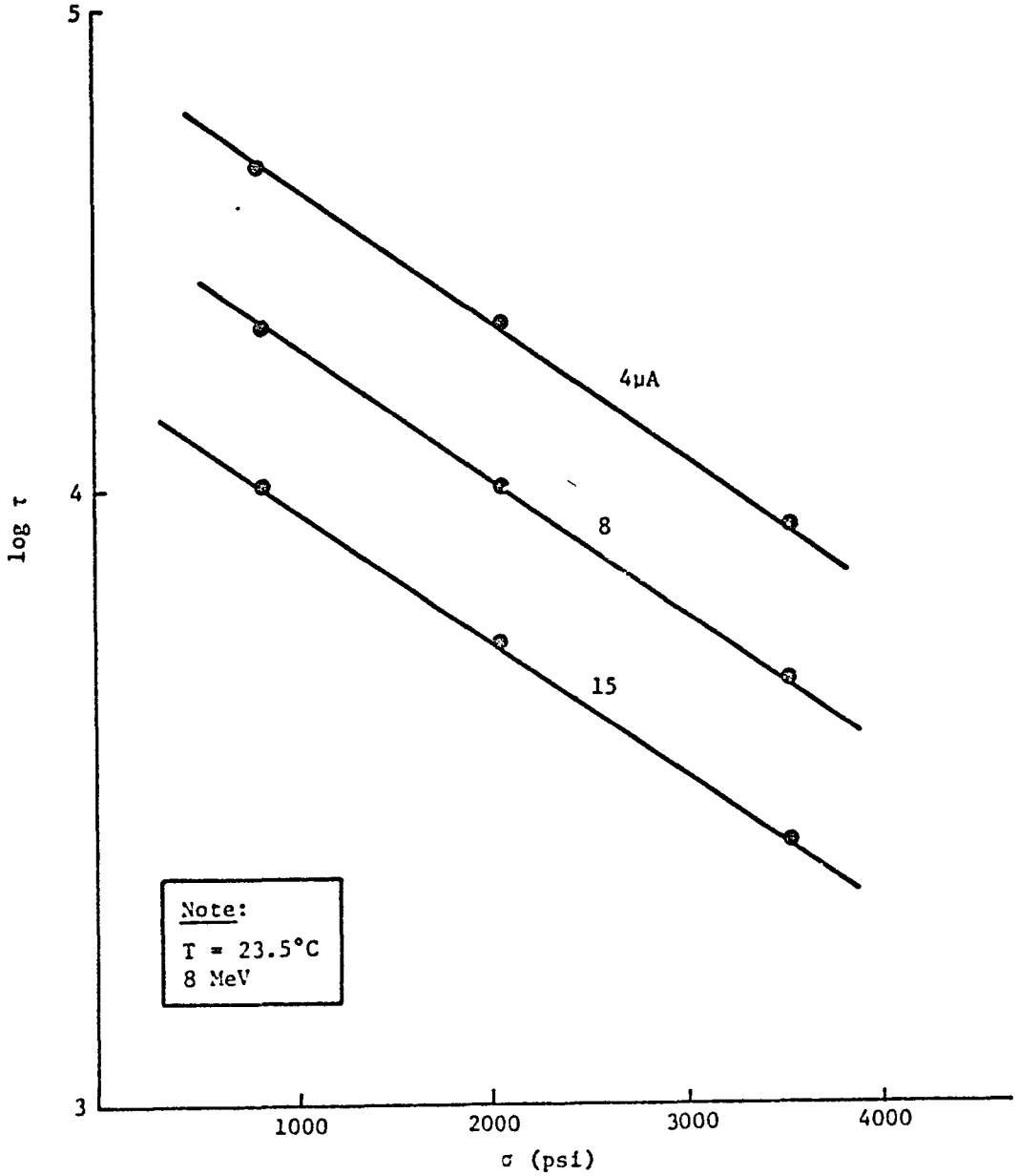

Figure 4 Dependence of τ on Stress at Constant Beam Current

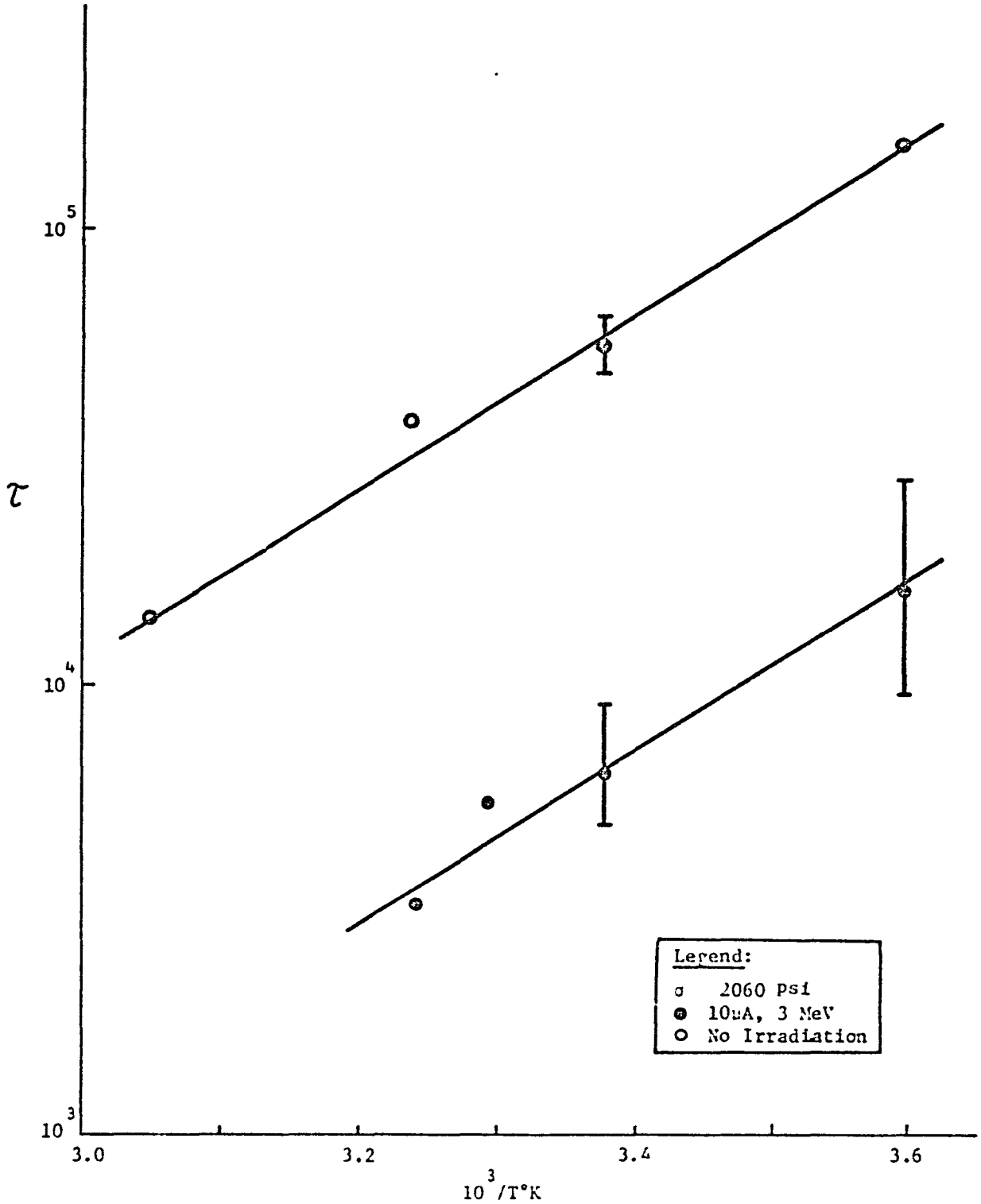

Figure 5 Temperature Dependence of τ

The beam current, I, appears to be related to a temperature. Note that the results of Figure 4 are of the form of Zhurkov's first equation except that beam current rather than temperature is held constant. From Figure 3, $\tau \propto 1/I$, and from Figure 5, $\tau \propto U^*/kT$ from which may be implied that $I \propto e^{U^*/kT}$. However because current is an electron rate that in turn leads to a rate of damage that is temperature dependent through an Arrhenius-type rate constant, the implied relationship of current with temperature is superficial and merely reflects a damage/temperature relationship. This relationship, which leads to the enhanced creep observed for specimens under irradiation, can be considered as an enhanced temperature at the damage site even though the macroscopic temperature is, presumably, held constant. These comments indicate why, under irradiation, polymers may be expected to behave according to the Zhurkov model for unirradiated specimens.

As suggested in the Introduction, when time lapses between irradiation and test, generally a nonrealistic situation, modeling may be an impossible task because unknown rates of damage healing can take place. More work similar to that carried out in Reference 6 is required to firmly establish the Zhurkov approach under ionizing conditions. An important part of this would be to study the effect of temperature for more than one stress level (Fig. 5). The present results for, however, show that under appropriate, more realistic conditions (i.e., behavior during irradiation). property predictions within the Zhurkov framework are possible.

B. ATOMIC OXYGEN EFFECTS ON POLYMERIC FILMS AND METALS

With the first shuttle flight it became obvious that materials exposed to the environment had undergone changes. Qualitative observations of STS-1 and STS-2 showed a loss of surface gloss of polymers (in particular Kapton) and an apparent "aging" of painted surfaces. With STS-3, Leger developed a quantitative factor, the reaction efficiency (RE), to account for the interaction of the flight environment with materials. The RE is derived by normalizing the thickness loss by the

oxygen atom fluence[8] to yield units of cubic centimeters/atom. Table 6 shows the results obtained on various shuttle flights. This method for RE is internal by self-consistent for comparing the resistance of materials to oxidation.

An insight into the RE and its pctential shortcomings can be determined by considering the loss of carbon or osmium films from the temperature-controlled quartz crystal microbalance (TCQM) on various shuttle flights. On STS-4 a film of carbon of 300 Å thickness was completely removed. The RE for carbon on this flight was 300 Å/ 7×10^{19} cm^{-2} = 0.43×10^{-25} cm^3/atom. From the density of carbon and its atomic weight, the volume of a carbon atom can be calculated to be 8.8×10^{-24} cm^3/atom (r = 1.28 Å), a probability of reaction, P, may be defined as RE/atomic volume and, for this instance, $P = 5 \times 10^{-3}$ or 200 oxygen atoms are required to remove the carbon atom. The same calculation for STS-8 yields 100 oxygen atoms for carbon atom and a probability calculated for STS-5 was 0.1 or 10 oxygen atoms to remove one carbon atom. Similar calculations for osmium in STS-4 yielded a $P = 1.5 \times 10^{-3}$ or 666 oxygen atoms to remove an osmium atom, and for STS-8 the P calculated as 6×10^{-5} or 1.67×10^{4} oxygen atoms to remove an osmium atom.

No temperature dependence for RE was found in the range from 25 to 125°C on STS-5 and on STS-8 the range was narrowed to 65 to 125°C. This is not unexpected because the oxygen atoms impinge with kinetic energies on the order of 5eV.

A quantitative assessment for carbon or osmium removal per oxygen atom can be made from the ST8-8 TCQM results. For carbon 2500 Å were completely lost in 15.8 hours or at a rate of 0.044 Å/second. A monolayer of carbon is equal to 2.56 Å (2 times the radius = 1.28 Å). Therefore, 58 seconds are required to remove a monolayer. The number

of carbon atoms in a monolayer is just the area of TCOM deposit (5.06 cm^2) divided by the area of a carbon atom (5.14×10^{-16} cm^2) or 0.98×20^{16} carbon atoms. The number of oxygen atoms per second impinging on the specimen is calculated as (fluence/time in the "ram" direction)(sample area) = $(3.5 \times 10^{20}$ $cm^{-2}/1.48 \times 10^5$ s)(5.06 cm^2) = $1.2 \times 10^{-16} s^{-1}$. Then 0.98×10^{-16} carbon atoms/(1.2×10^{-16} s^{-1})(58 s) = 0.0144 carbon atoms per oxygen atom or 70 oxygen atoms to remove one carbon atom.

From the density and atomic weight of osmium, the radius of an osmium atom can be calculated as 1.495 Å. For the 300 Å film on STS-8, a similar calculation shows 0.0054 Å/second to be removed or 564 seconds to remove a monolayer. Thus the number of carbon atoms per oxygen atom is 0.00133 or 752 oxygen atoms are required to remove an osmium atom.

If it is assumed that OsO_4 is the species evaporating from the osmium surface and CO is that evaporating from the carbon film, the efficiency of osmium compared to carbon removal is (70)(752/4) = 0.37. Using the RE method, this ratio is $100/1.67 \times 10^4$ = 0.006, some 62 times less. The calculations show the caution that must be exercised if RE is used quantitatively.

Table 6 Atomic Oxygen Reaction Efficiencies

Shuttle Flight	Thin Film Material	Thickness, μm (a)	Thickness, Loss, μm	Fluence, 10^{20} Atoms/cm^2	Reaction Efficiency, 10^{-24} cm^3/Atom (b)
STS-3	Kapton TV Blanket	12 7	4.4	2.16	2.0
	Kapton, OSS-1 Blanket	25 4	5.5		2.5
STS-4	Kapton MLI Blanket				
Witness	Kapton	7 6	1.8	0 65	2 8
Samples	Kapton	12.7	1 6		2 7
	Kapton	25 4	1 7		2.6
	Mylar	12 7	1.8		2.8
	Teflon FEP & TFE	12 7	0.07		0.1
	AL/Teflon FEP				
STS-5	Kapton	12 7	1.50	1.0	1.5
Witness	Kapton	25 4	2 18		2.2
Samples	Kapton	50.8	2.79		2.8
	Kapton, Black	25 4	1.35		1.4
	Mylar	12 7	2 16		2.2
	Mylar	25 4	1.83		1.8
	Mylar	50.8	1.50		1.5
	Tedlar, Clear	12.7	1 30		1.3
	Tedlar, White	25 4	0 41		0.4
	Teflon FEP & TFE	12 7	<0.2		<0.2
	Kapton (Coated)				
	DCI 2755	12 7 (Kapton)	<0.2		<0.2
	T-650	12 7 (Kapton)	<0.2		<0 2
	Kevlar 29				
STS-8	Kapton				
Witness	Kapton	12.7	10 6	2.5	3.0
Samples	Kapton	25 4	9.9		2.8
	Kapton	50.5	11 0		3 1
	Mylar A	12 7	13.0		3 7
	Mylar A	40 6	12 0		3 4
	Mylar D	50 8	10 4		3.0
	Tedlar, Clear	12 7	11 2		3.2
	Polyethylene	20 3	11.5		3.3
	Teflon TFE	12 7	<0 1		<0.03
	Kapton F (FEP-Coated)	30.5	<0 1		<0.03
	AL/Kapton				
	Kevlar 29 Bare				
	Kevlar 29 Coated with DC1 2577				

[a]Note Film thicknesses of 12 7, 25 4, and 50 8 μm correspond to 0.5, 1 0, and 2 0 mils, respectively
[b]Most probable error is +30 to 40%

VI. CONCLUSIONS AND RECOMMENDATIONS

Clearly the Korel 8031-00 high-strength adhesive foam tape is superior to the other two tested. It would be of great value to test this tape for longer periods of time to establish its usefulness with a greater degree of confidence for space use. It would also be of value to carry it through the NASA-JSC outgassing criteria for qualification for spacecraft use. This is a valuable, yet inexpensive, test.

Because the graphite/epoxy composites that were thermal-vacuum cycled showed charring of the white glass/epoxy end tabs, and it was determined that there was no air leak in the MSFC thermal-vacuum system, it would be of value to determine the amount of air that may be trapped in such specimens during fabrication. Perhaps all such composites for space use should be fabricated under vacuum conditions.

Modeling for irradiation effects is an almost impossible task when tests for such effects are done by irradiating at one time and place and testing at some later time and place. Testing for predictive modeling should be done as discussed in Chapter V.A, and we strongly urge that such studies be done.

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