THE RESPONSE OF THE SPACE SHUTTLE ORBITER GRAPHITE/EPOXY SANDWICH PANELS TO EXPOSURE TO MOISTURE AND HEAT

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Abstract

The Shuttle Orbiter Payload Bay Door is covered with graphite/epoxy sandwich panels. Their interaction with ground environments causes a moisture absorption of ca. 1.0 % by weight at the time of launch. During the re-entry phase the temperature of the outer facesheets rises to 350 F (177 C) and their moisture content diminishes to 0.65 %. In this condition the facesheet strength deteriorates significantly. Also, desorption of moisture produces an internal pressure in the panels of ca. 50 psia (345 kPa). The paper discusses the prediction of expected moisture levels in the constituent parts of the sandwich panels. It describes further the test program necessary to assess the residual strength of the facesheets and the internal pressure capability of the sandwich panels.

I. Introduction

The unfavorable response of organic materials to a humid environment is a problem of long standing. Although the mechanism was not recognized, the gross effect of environmental aging of epoxy adhesives on their strength has been known for many years[1]. Environmental aging has also been shown to deleteriously affect epoxy potting compounds[2]. The fact that filamentary/epoxy composites are affected by the environment, therefore, came as no surprise to materials technologists[3,4,5].

Graphite/epoxy laminates tend to absorb moisture directly from the atmosphere, principally by diffusion through the epoxy matrix. The bonding of the water molecules to the hydroxyl groups of the epoxy polymers leads to swelling of the matrix and to changes in the state of stress of the laminates. The presence of moisture also lowers the glass transition temperature of the matrix, i.e., it softens the resin and degrades the matrix-dependent laminate properties at elevated temperatures. The severity of the degradation depends on the amount and the distribution of the moisture which are continually affected by changing temperature and humidity conditions. Drying of the moist laminates seems to restore the laminate properties fully unless thermal exposures beyond the moisture-reduced glass transition temperature has caused permanent damage to the matrix material. The design of graphite/epoxy structures destined for operation at high temperatures, therefore, mandates knowledge of the moisture state during critical service conditions in order to determine realistic margins of safety. The moisture issue is particularly sensitive in the case of lightweight graphite/epoxy sandwich panels with moisture absorbent cores. Here the structural safety is threatened not only by the degradation of the thin facesheets but by internal pressures generated by the desorption of water from the core as well.

The moisture problem became an important consideration in the design of the 60-foot long and 15-foot wide (18.29m x 4.57m) payload bay doors of the Space Shuttle Orbiter. The doors were constructed entirely of graphite/epoxy as cylindrical shells with semi-elliptical cross sections. Functional requirements led to the concept of two symmetrical door halves, hinged to the fuselage mid longeron and allowing opening and closing during orbital maneuvers. Figure 1 is an illustration of the Space Shuttle Orbiter with opened payload bay doors and deployed radiator panels. Figure 2 shows the payload bay doors in the final assembly stage.

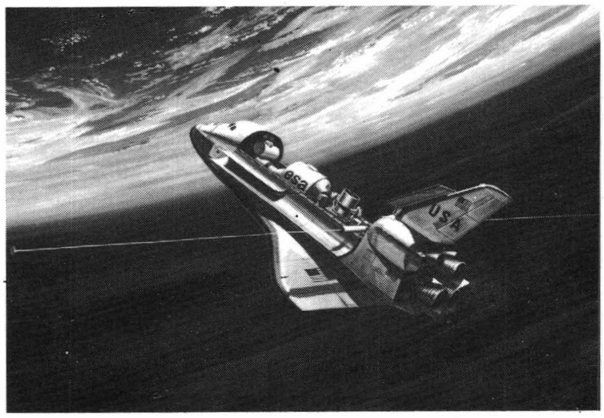

Figure 1. Space Shuttle Orbiter

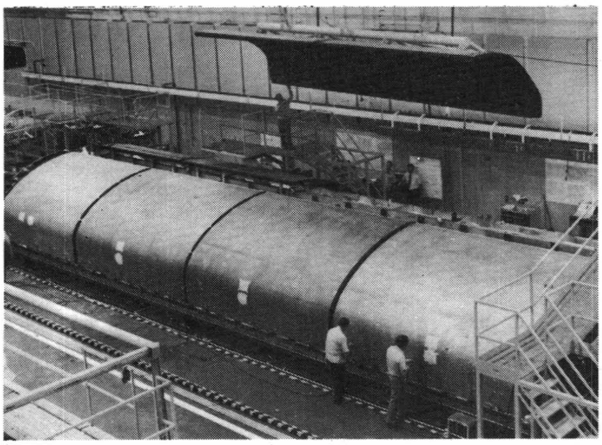

Figure 2. Assembly of Payload Bay Doors

Structurally, the door halves consist of a series of curved frames equally spaced and covered with sandwich-type skin panels. The sandwich panels are composed of thin graphite/epoxy facesheets bonded to a nylon/phenolic core with

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an epoxy adhesive. The exterior side of the panels is thermally insulated so that the temperature in the outside facesheets rises to a maximum of 350 F (177 C) during the reentry phase of the Orbiter, when the panels are also highly stressed by maneuver loads. Figure 3 depicts a typical section of a sandwich panel between adjacent frames under reentry conditions. The calculation of the moisture distribution in the panels and the experimental determination of their residual strength will be addressed in the following sections.

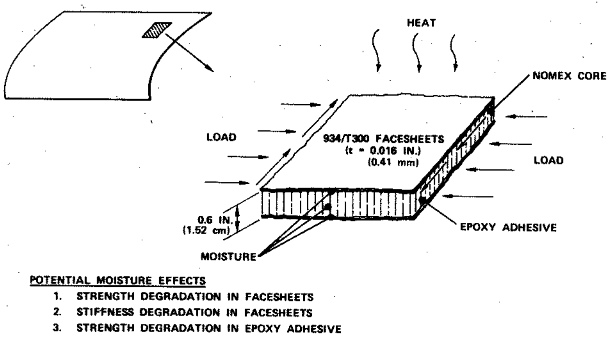


Figure 3. Problem Statement

II. Moisture Analysis

Theoretical Bases

The sandwich panels are highly stressed at their centerlines between adjacent frames. In these structurally critical regions, the moisture and temperature gradients in the planes of the facesheets tend to vanish because of the symmetry of the panel arrangement in one direction and the long extension in the other. The hypothesis of a one-dimensional flow of moisture through the thickness of the panel is, therefore, warranted and provides a major simplification. It is further assumed that the classical diffusion theory embodied in Fick's first and second laws is applicable to the diffusion process in graphite/epoxy laminates in the direction normal to the fibers.

The one-dimensional form of Fick's first law

$$\phi = -D \frac{dc}{dx} \tag{1}$$

states that the moisture flux is proportional to the concentration gradient, the constant of proportionality being the diffusion coefficient. Fick's second law treats the transient condition and for the one-dimensional case assumes the form

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D(C,T)\frac{\partial c}{\partial x}\right] \tag{2}$$

Strictly speaking, the diffusion coefficient is a function of both the concentration and the temperature. However, sufficient evidence exists to show that the dependence on the concentration is generally slight and may be ignored for graphite/epoxy materials[6]. With respect to temperature, it may be stipulated that it changes with time but that no temperature gradient exists in the thickness direction of the material. The stipulation is justified since, for the materials under discussion, the rate of heat transfer is faster than that of moisture diffusion by several orders of magnitude. Accordingly, Equation (2) can be simplified to

$$\frac{\partial c}{\partial t} = D(T)\frac{\partial^2 c}{\partial x^2} \tag{3}$$

It may be found convenient to work in terms of weight percentage of moisture, M, relative to the dry weight of a laminate, rather than of concentration, c. The corresponding form of Fick's first law is

$$\phi = -\frac{D\rho}{100}\frac{dM}{dx} \tag{4}$$

and that of Fick's second law

$$\frac{\partial M}{\partial t} = D(T)\frac{\partial^2 M}{\partial x^2} \tag{5}$$

Analysis of Single-Layered Slabs

Equation (3) or the equivalent Equation (5) but with a constant value for D can be solved in closed form only for a single layer of material. The solution further requires the restrictions that the initial concentration gradient be zero, and that the temperature and the moisture concentration be the same and constant on both sides of the layer[6]. However, Chandler[7] has shown that if the boundary conditions are piecewise constant and the intervals between changes in boundary conditions are sufficiently great, then Equation (5) can still be solved in closed form. Weitsman[8] has shown that, given constant boundary conditions, Equation (5) can be solved in closed form for the case D = D(T). All restrictions can be removed except for a constant diffusion constant on the interval, Δt, by a transformation of the differential Equation (5) into a finite difference form

$$\frac{M(i,j)-M(i,j-1)}{\Delta t} = D\,\frac{M(i+1,j)-2M(i,j)+M(i-1,j)}{\Delta x^2} \tag{6}$$

and a subsequent numerical solution of the matrix equation

$$[A]\{C\}_{t_1} = \{B\}_{t_0} \tag{7}$$

The equation relates the unknown moisture at the interfaces of the slab subdivisions at time, $t_1 = t_0 + \Delta t$, in state vector C, to the known initial concentrations at time, t_0, in state vector B, via a square matrix A containing elements which are functions of the diffusion coefficient and the stepsize. The matrix A is tridiagonal and does not change with time if the temperature (and therefore the diffusion coefficient) is constant. The solution for state vector, C, provides new known conditions at time, t_1, from which those at t_2 can be obtained, etc. It is apparent that the closed-form solution can be used as a convenient check for the accuracy of the finite-difference solution.

Analysis of Multilayered Slabs

The analysis of moisture diffusion becomes somewhat more complicated if several dissimilar materials are joined in a multilayered slab[9]. While the same principles apply for the treatment of the individual layers, two additional conditions must be satisfied at each of the internal interfaces between adjacent layers.

The first of these conditions merely demands that the flux of moisture leaving material I be equal to the flux entering material I + 1, i.e.,

$$(D\rho)_{I+1}\left(\frac{dM}{dx}\right)_{I+1} = (D\rho)_{I}\left(\frac{dM}{dx}\right)_{I} \tag{8}$$

The second condition requires compatibility of the moisture levels in the two materials at the interface. The instantaneous moisture level, M, in any material is characterized by the equation

$$M = M_u H^b \tag{9}$$

where M_u is the maximum solubility of water in percent of the dry weight of the material, H is the relative humidity of the environment, and b is an appropriate exponent. At the interface, the term, H^b, in the equations for materials I and I + 1 can be eliminated if the value of the exponent is the same for both materials so that the interface condition becomes

$$M_I \, M_{u,I+1} = M_{I+1} \, M_{u,I} \tag{10}$$

At the interface between the I^{th} and the $(I+1)^{th}$ materials, let the surface of the I^{th} material be numbered KI. The surface of the $(I+1)^{th}$ material in contact with the I^{th} material will be numbered KI+1. Then in finite difference notation Equation (8) takes the form

$$(D\rho)_{I+1}\left[\frac{M(KI+2,j) - M(KI+1,j)}{\Delta X_{I+1}}\right] = (D\rho)_{I}\left[\frac{M(KI,j) - M(KI-1,j)}{\Delta X_{I}}\right] \tag{11}$$

In the same notation, the finite difference form of Equation (10) is

$$M(KI,j)\ Mu_{I+1} = M(KI+1,j)\ Mu_{I} \tag{12}$$

For the case of a multilayered slab consisting of N_L layers of different materials, each of the layers is subdivided into an arbitrary number of laminae, N_i. Equations of the form of Equation (6) are written for N_i-1) laminae in each of the layers. Counting the interface Equations (8) and (10) for the (N_L-1) interfaces, a total of N_L-2 + ΣN_i linear algebraic equations are then assembled into the matrix equation

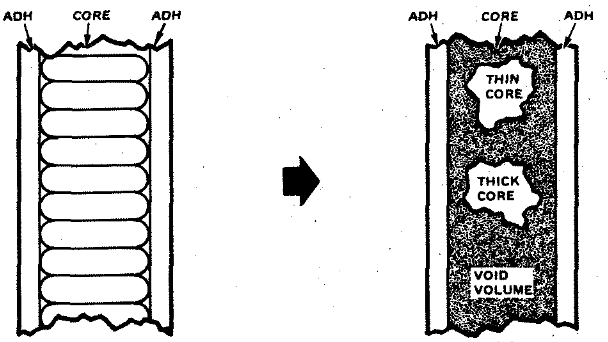
$$[E]\{F\}_{t_1} = \{G\}_{t_o} \tag{13}$$

which is similar to Equation (7) except that E incorporates the interface conditions. The matrix E is populated only on the five center diagonals. Solution of Equation (13) provides the unknown moisture distribution at time, t_1, as input for the next time interval.

Analysis of Sandwich Panels

In a gross sense, sandwich panels can be analyzed as multilayered slabs if the core material can be regarded as a homogeneous layer with uniformly distributed densities and diffusion characteristics. In the case of honeycomb cores, this idealization is inadequate because the predominant portion of the moisture transfer occurs normal to the surfaces of the core ribbons through the entrapped air in the cells. A more realistic treatment of the problem is the coupling of the adhesive layers to both sides of the core by means of an internal moisture balance which more accurately reflects the core properties. A welcome by-product of this approach is the calculability of the amount of moisture in the entrapped air space, and the corresponding vapor pressure.

Figure 4 (detail A) shows a cross section through a honeycomb-type core with layers of adhesive on both sides. The core ribbons are connected so that the cell walls alternately have single and double thicknesses. The mathematical model in Figure 4 (detail B) contains the void volume and two moisture absorbers simulating the two cell wall thicknesses. The void volume is defined as the product of core depth and unit area of the panel less the volume of the core cell material. The control volume includes the adhesive layers.



(A)
PHYSICAL MODEL

(B)
MATHEMATICAL MODEL

Figure 4. Core Representation

The moisture balance within the control volume is

$$\overline{WMT}_2 = \overline{WMT}_1 + (\phi_1-\phi_2)\Delta t \tag{14}$$

where the fluxes ϕ_1 and ϕ_2 are governed by Fick's first law. The moisture in the control volume exists as moisture absorbed by the core or as vapor in the void volume. The amount absorbed by the core and adhesive is

$$\overline{WMA}_2 = \Sigma \overline{M}_i W_i \tag{15}$$

The difference between $\overline{WMT}_2$ and $\overline{WMA}_2$ is the weight of the vapor at the end of the time step

$$\overline{WMV}_2 = \overline{WMT}_2 - \overline{WMA}_2 \tag{16}$$

At the low pressures encountered, the pressure generated by this amount of vapor can be adequately computed from the ideal gas law

$$P = \frac{\overline{WMV2}}{\overline{MW}}\,\frac{RT}{V} \tag{17}$$

where $\overline{MW}$ is the molecular weight of water. The relative humidity in the cavity is then

$$H_I = \frac{P}{P_S} \tag{18}$$

where P_S is the vapor pressure of water under saturated conditions. H_I in turn sets the boundary conditions at the interface between the internal vapor and the surface of core ribbon or adhesive via Equation (6).

Application to Payload Bay Doors

For the moisture analysis of the payload bay door components, computer programs were developed for laminates composed of one, two, and nine layers. In all cases a backward difference formulation was used for the time steps and a backward difference formulation, substituted into a forward difference formulation, for the distance steps.

The need for a nine-layered slab arose from the composition of the payload bay door sandwich panels which are shown, typically, in Figure 5.

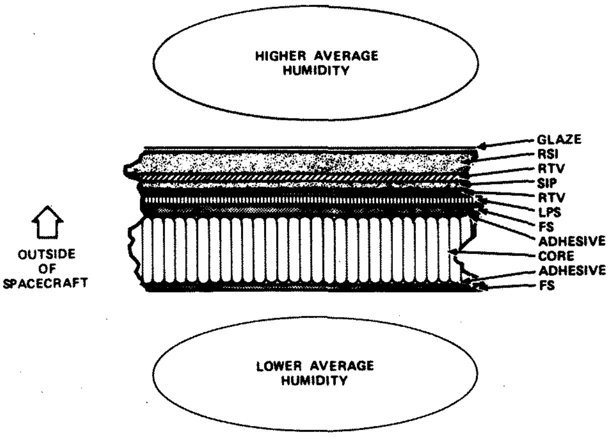


Figure 5. Payload Bay Door Sandwich Panel

Directly attached to the outside facesheet (FS) is a calendered aluminum wire mesh embedded in a layer of epoxy adhesive as lightning protection (LPS). The thermal protection system consists of a reusable ceramic surface insulation (RSI) glazed on one side and separated from the surface of the panel by a pad of felt acting as a strain isolator (SIP). An RTV silicone rubber compound is used for the attachment of the RSI to the SIP, and the SIP to the LPS, respectively. The nine-layered program was used for the material combination GLAZE/RSI/RTV/SIP/RTV/LPS/FS/ADH on the exterior side of the core. The redundant layer in the nine-layered program was lumped into the LPS layer. The two layers, ADH/FS, on the interior side of the core were analyzed with the two-layer program. The coupling of the two programs and the incorporation of the core properties occurred in accordance with the previous section.

The goal of the analysis was the prediction of the moisture content in each of the layers of the sandwich panel together with the internal pressure during the reentry mode of the Space Shuttle Orbiter. The ingredients for such an analysis are depicted in Figure 6. Obviously, the accuracy of the computed values depends directly on the proper description of the initial conditions, the environmental conditions inside and outside the payload bay as functions of time, and on the reliable definition of the material properties affecting diffusion.

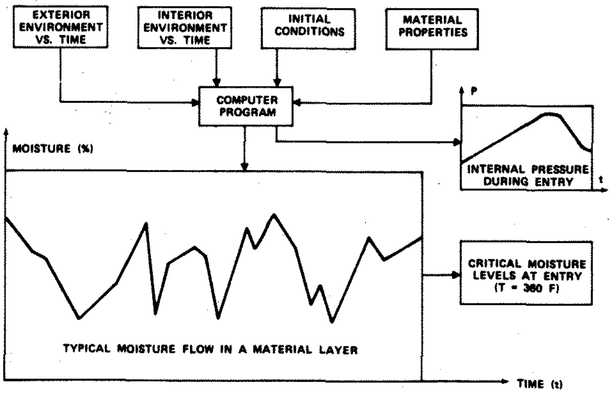


Figure 6. Analysis Process

Initial and Environmental Conditions. The mission environmental time-lines in terms of temperature and relative humidity for Orbiter 101 were readily available and served as input for the payload bay door analysis. Subsequent to the scheduled delivery, the doors will remain at Palmdale, California, for approximately 15 months. Regarding the initial conditions, it may be assumed that after 15 months the moisture level in all components of the sandwich panel will be in equilibrium with the rather constant relative humidity of 30% at that location. The already established mission timelines provided by NASA prescribe in sufficient detail the environmental conditions after departure from Palmdale for the first 10 missions with respect to temperature and relative humidity. The response of the sandwich panel to the changing environment must be determined in time-step intervals varying, typically, between 1 minute to 12 hours in duration.

Material Properties. For each material, the properties affecting diffusion are comprised of: (a) the diffusion coefficient, D, as a function of temperature; (b) the maximum absorptivity, M_u, at 100% relative humidity; (c) the value of the exponent "b" in Equation (9) defining moisture equilibrium at relative humidities $\leq$100%; and (d) the density.

Experience has shown that a valid determination of these properties may be subject to controversy, particularly with regard to diffusion coefficients at 350 F (177 C), and the value of the exponent "b". Table I contains a tabulation of the material properties established for the components of the payload bay door sandwich panels. These properties reflect the consensus of Rockwell International, McDonnell Douglas, and NASA as of January 1977[10].

Material	Diffusion Constants (cm^2/sec x 10^{-10})				M Max (100% RH)	Density (lbs/ft^3) (Kg/m^3)
	RT 75 F (24 C)	140 F (60 C)	250 F (121 C)	350 F (177 C)		
Graphite/Epoxy (32% resin by wt) (52% fiber by vol)	3.1	17	320	6,500	2.0	0.055
Narmco 329-7 Film Adhesive (0.06 psf)	1.36	183	518	4,880	3.5	0.069
Screen Plus 329-7 Adhesive	3.1	17	320	6,500	2.0	0.075
Nomex Core	3.1	17	320	6,500	9.0 Flex 9.5 Hex	3.0 pcf to 5.5 pcf
RTV560	4400			276,000	0.83	0.051

Table I. Material Properties Affecting Diffusion

Summary of Results. With the initial conditions, the environmental conditions, and the material properties as input data, the computer program allows the tracking of the moisture distribution and the internal pressure in the sandwich panels during all phases of the Orbiter missions. Figure 7 depicts the calculated moisture content over a period comprising the first five missions. Upon the departure from Palmdale, 15 months after delivery, a moisture content of 0.6% of the facesheet dry weight represents equilibrium with the environment at Palmdale. During the ferry flight to Cape Kennedy, storage at the cape, and prior to launch, the moisture content rises to about 1.0%. Despite the existing vacuum on orbit, only insignificant drying occurs because of the very low temperatures. The heavy bars (see Figure 7) indicate the moisture change due to drying between departure from orbit and the end of cooldown shortly after landing. The circles indicate the moisture content in the outside facesheets at the critical instant of maneuver, load application, and at a temperature of then 328 F (164 C). Accordingly, a maximum moisture content of 0.68% must be expected under such conditions.

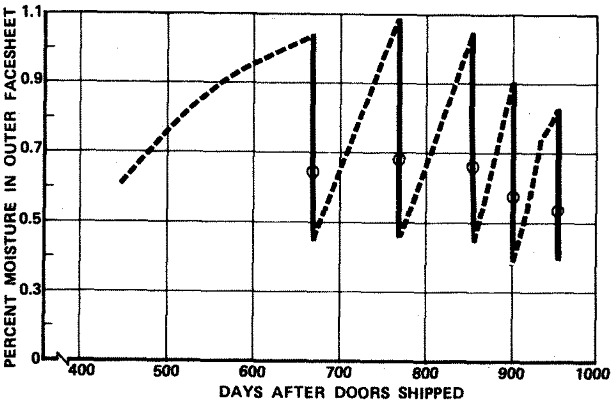


Figure 7. Facesheet Moisture Contents During Reentry

Figure 8 shows the concurrent rise of the internal pressure in the panel during reentry. The maximum pressure of approximately 45 psia (310 kPa) is the aggregate of the partial pressures of the water vapor and of the trapped air. It is partially offset by atmospheric pressure at the time of maximum load.

The analysis of the moisture distribution in the sandwich panels is a necessary prerequisite for the proof of structural sufficiency. It remains to be shown with what margins of safety the outside facesheets, in their moist and hot state, can sustain the maneuver loads and whether the magnitude of the internal pressure threatens the strength of the bond lines.

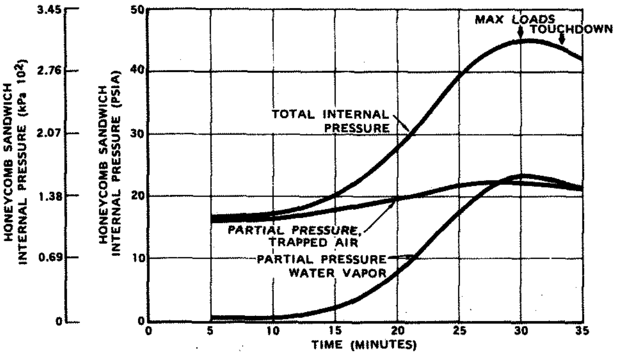


Figure 8. Internal Panel Pressure During Reentry

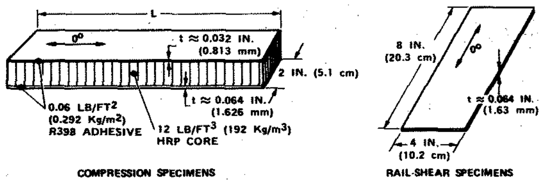
III. Degradation of Laminate Strength and Stiffness Properties

During the early design phases of the payload bay doors for the Space Shuttle Orbiter, a reduction of the matrix-dependent laminate strength properties of 934/T-300 graphite/epoxy under moist and hot conditions was anticipated and assumed not to exceed 30% of the dry and hot strengths. A corresponding deterioration of the stiffness properties was not expected. For the final design of the doors a refinement of these assumptions and their substantiation was an obvious requirement. Since the complexity of the problem precludes an analytical derivation of the moisture effect on the properties of graphite/epoxy, a determination by test was the only alternative. The scope of the test program was limited to the response of the sandwich panel facesheets considering that all other components of the payload bay doors are less critical either because of lower temperatures, or lower moisture content, or both. In order to keep the test effort within manageable bounds, it was decided to develop reduction factors for the existing 350 F (177 C) A-Basis design allowables for dry laminates rather than to determine bona fide design allowables for moist laminates[3]. Specifically, the test objectives were: (1) the definition of reduction factors for the compression and shear properties in facesheet-type laminates containing various amounts of moisture at room temperature and at 350 F (177 C), and (2) the resolution of the question whether the compression and shear properties of moist laminates are affected further by repeated exposures of moist laminates to 350 F (177 C), simulating the reentry condition of the Space Shuttle Orbiter.

Test Program and Test Specimen Description

Testing was limited to the facesheet properties most susceptible to moisture degradation, i.e., compression in the two principal directions of the (0,±45,0)-laminates, and in-plane shear. Specimens containing approximately 0.0%, 0.6%, 0.8%, and 1.0% moisture were tested under static loads at room temperature and at 350 F (177 C). Additional specimens were moisturized to 0.6%, 0.8%, and 1.0% and subjected to short-duration exposures to 350 F (177 C). After each thermal cycle the original moisture con-

MOISTURE CONTENT	SPECIMENS NOT THERMALLY SPIKED						SPECIMENS THERMALLY SPIKED					
	COMPRESSION				SHEAR		COMPRESSION				SHEAR	
	0-DEGREE DIRECTION		90-DEGREE DIRECTION		0-DEGREE DIRECTION		0-DEGREE DIRECTION		90-DEGREE DIRECTION		0-DEGREE DIRECTION	
	RT (24 C)	350 F (177 C)	RT (24 C)	350 F (177 C)	RT (24 C)	350 F (177 C)	RT (24 C)	350 F (177 C)	RT (24 C)	350 F (177 C)	RT (24 C)	350 F (177 C)
0.0%	3	3	2	2	3	3	—	—	—	—	—	—
0.6%	3	3	2	2	3	3	3	3	2	2	3	3
0.8%	—	—	—	—	—	—	3	3	2	2	—	—
1.0%	3	3	2	2	3	3	3	3	2	2	3	3



SPECIMEN TYPE	L	TOP FACESHEET	BOTTOM FACESHEET
0° DIRECTION	19 IN. 483 mm	[0, ±45, 0]$_S$	[0, ±45, 0]$_{2S}$
90° DIRECTION	13 IN. 33 mm	[90, ±45, 90]$_S$	[90, ±45, 90]$_{2S}$

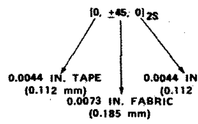


Figure 9. Test Matrix and Test Specimen Configuration

tent was restored and the residual strength of the moist specimens determined after up to 100 thermal cycles. A summary of the test program is contained in Figure 9. For reasons of compatibility, the test specimens were configured identically to those of the previous design allowables tests except that the thicknesses and the ply arrangements shown in Figure 9 were chosen as multiples of the facesheet thickness to obtain pure compression and shear failure modes. All of the laminates had a nominal resin content of 32% and were cured for 2 hours at 350 F (177 C) under 85 psi (586 kPa) autoclave pressure, followed by a postcure of 4 hours at 400 F (204 C). Subsequent to the bonding of the sandwich-type compression specimens the exposed core edges were sealed with aluminum foil. In addition to the test specimens, shorter control specimens of otherwise identical configuration were prepared for the monitoring of the moisture content in the facesheets. The rail shear specimens were partially coated with adhesive to enhance the friction in the attachment areas. Figure 10 depicts typical test and control specimens after sealing and coating. The instrumental consisted of strain gages and thermocouples at the locations of expected failure.

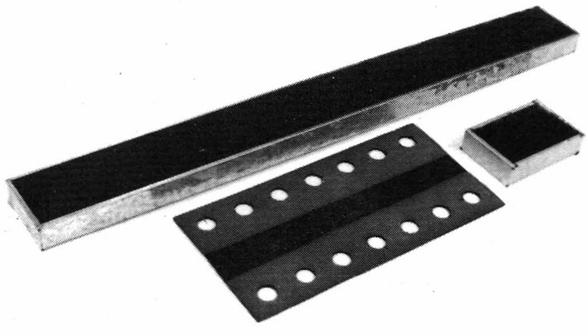


Figure 10. Test and Moisture Control Specimens

Moisture Control

All specimens were initially placed in a 250 F (121 C) oven and considered dry when periodic weighings showed no further weight changes. Specimens to be moisturized were then transferred to a humidity chamber maintained at 140 F (60 C) and 95% relative humidity with the intent of producing a moisture content of approximately 0.6%, 0.8%, and 1.0% in the facesheets at the time of testing. A precise realization of those percentages was not necessary since, for the purpose of generating plots of specimen strength and stiffness versus moistire content, it sufficed to obtain moisture percentages in the desired range.

With respect to the target moisture content in the facesheets of the compression specimens was deduced by comparison with the measured moisture content in the control specimens. A total of 18 control specimens, initially dry, had been exposed to humidity conditions identical to those of the test specimens. At intervals of two days, two specimens were removed from the chamber. The moisture content of their facesheets was determined by separating the facesheet from the core, and by weighing the facesheet coupons prior to and after drying. The relationship between exposure time and moisture content is shown in Figure 11. As in the case of the rail shear specimens, the initially non-uniform moisture distribution through the facesheet thickness tended to improve during exposure to the test temperature. The actual moisture content at the time of failure was again determined by the weighing of facesheet coupons prior to and after drying.

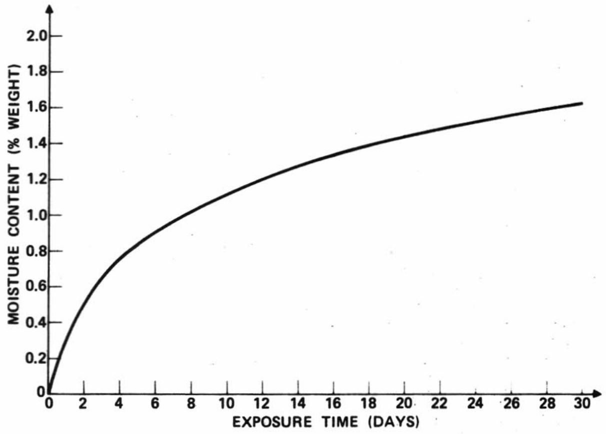


Figure 11. Moisture Absorption of Control Specimens

Thermal Spiking

Thermally spiked specimens were included in the test program to ascertain the effect of repeated exposures of moist specimens at 350 F (177 C) on the strength and stiffness of graphite/epoxy laminates. Initially, dry compression and shear specimens were subjected to a constant humidity environment long enough to absorb approximately 0.6%, 0.8%, and 1.0% moisture in the facesheet. The determination of the laminate moisture levels was guided by analysis and by the absorption rates previously collected and presented in Figure 11. After recording their total weight, the moist specimens were placed into a preheated 350 F (177 C) oven and, upon attaining a temperature of 345 F (174 C), allowed to dwell for 5 minutes. Following the dwell, the test specimens were cooled under ambient conditions, and then returned to the humidity chamber to restore the loss of moisture during the thermal spike. This process was repeated 106 times and 97 times for specimens with 0.6% and 1.0% moisture, respectively, and 36 times for specimens with 0.8% moisture. Subsequently, the specimens were tested in their moist condition, at room temperature and at 350 F (177 C), similar to the nonspiked specimens. The thermal spiking process is defined in Figure 12.

Test Procedure and Test Results

The compression tests were performed under four-point loading with constant crosshead speeds of 0.2

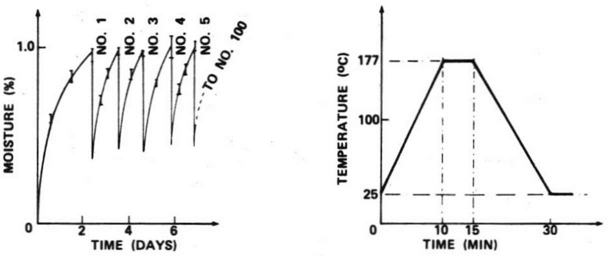


Figure 12. Thermal Spiking of Test Specimens

in./min (5.08 mm/min) for the 0°-direction specimens and 0.1 in./min (2.54 mm/min) for the 90°-direction specimens. The high temperature test specimens were inserted into a preheated 350 F (177 C) oven. Upon attaining 345 F (174 C) in approximately 10 minutes, the application of loads led to specimen failure at 350 F (177 C) after an additional thermal exposure of 2 to 4 minutes.

The test procedure for the rail shear specimens was similar except that tensile loads were applied with a crosshead speed of 0.5 in./min (12.7 mm/min). The heating to 345 F (174 C) required up to 20 minutes because of the heat sink effect of the test fixture. Specimen failure occurred at 350 F (177 C) after an additional thermal exposure of 2 to 5 minutes.

The test results for the strength and stiffness response of the compression specimens are summarized in Figures 13 through 16. The solid lines link test data for unspiked specimens at room temperature and at 350 F (177 C). The test data for thermally spiked specimens are represented by solid circles. In each case the lowest, highest, and average test values are depicted. The scatter of the 0°-direction specimens is pronounced but, compared to the imilar scatter of dry specimens in the previous design allowables test, apparently more a characteristic of the test method than of the moisture content. Figures 17 and 18 contain similarly treated test results for the rail-shear specimens.

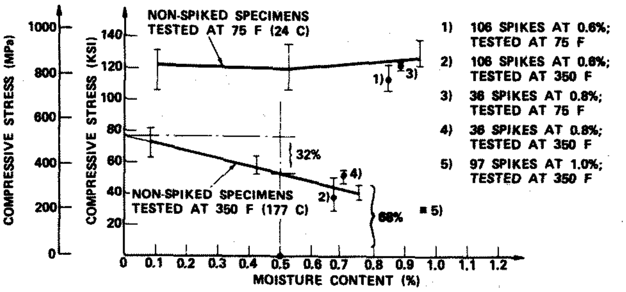


Figure 13. Compressive Strength of 0-Degree Direction Specimens

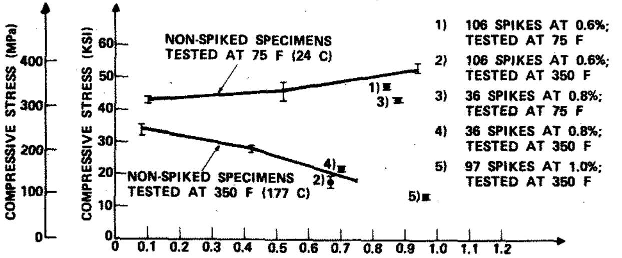


Figure 14. Compressive Strength of 90-Degree Direction Specimens

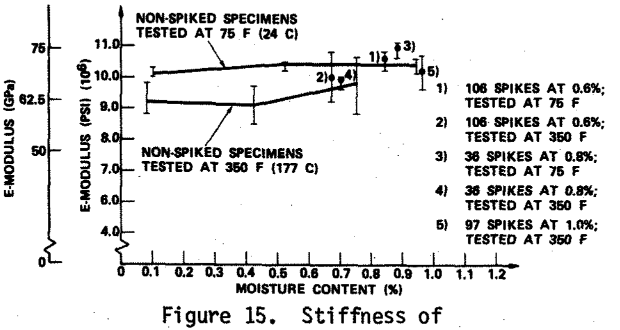


Figure 15. Stiffness of 0-Degree Direction Specimens

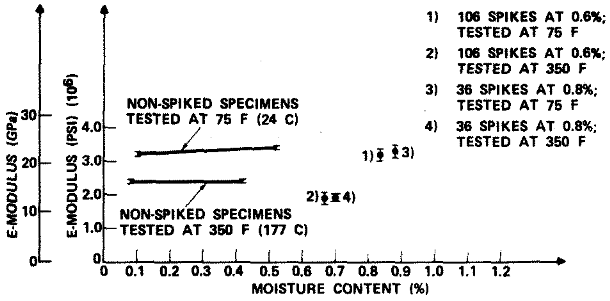


Figure 16. Stiffness of 90-Degree Direction Specimens

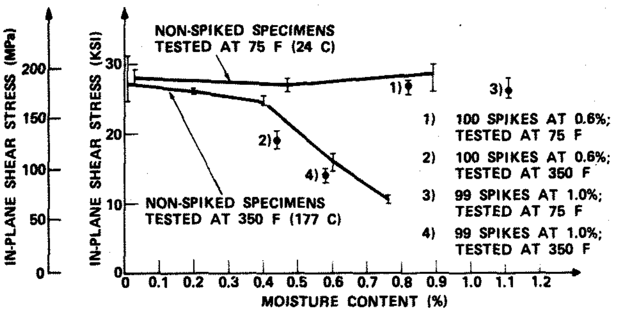


Figure 17. Strength of Rail Shear Specimens

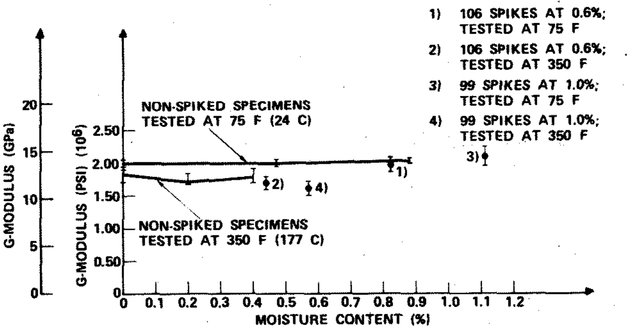


Figure 18. Stiffness of Rail Shear Specimens

Conclusions

The test results show that: (1) at ambient temperature the compression and in-plane shear strengths are not adversely affected by moisture, (2) the compressive and in-plane shear strengths at 350 F (177 C) are reduced substantially and in proportion to the moisture content, (3) the exposure to thermal spikes of the described severity and at constant moisture levels has no significant deterioration effect, and (4) the stiffness properties of the 934/T300 laminates at room temperature and at 350 F (177 C) are not degraded by presence of moisture.

IV. Degradation of the Bond Strength of Sandwich Panels

The sandwich panels consist of thin graphite/epoxy facesheets bonded to a non-vented phenolic core with an epoxy-based adhesive. At elevated temperature and in partial vacuum the vaporization of the moisture absorbed by all components of the panel, and the presence of the entrapped air in the core cells, produce an internal pressure which tends to separate the facesheets from the core. In accordance with Figure 8, the maximum pressure 30 minutes after departure from orbit, at 350 F (177 C), is approximately 45 psi (310 kPa), comprised of a partial vapor pressure of 23 psi (159 kPa) and a partial absolute gas pressure of 22 psi (152 kPa). Considering the moisture/heat weakened condition of the epoxy adhesive, the ability of the panels to sustain such pressure loads cannot be taken for granted. However, only a few square feet of door panel area will be exposed to the 350 F (177 C) maximum temperature.

Short-Beam Shear Strength of Sandwich-Type Panels

The compression test specimens described in one of the preceding chapters failed at their center sections in such a manner that the remaining halves, away from the actual break, showed no evidence of damage. Preparatory testing indicated that three-point loading of 5-inch (127-mm) long specimens, with the heavy facesheet on the compression side, invariably led to adhesive shear failures in the bond lines. It was recognized that the failure modes of sandwich specimens subjected to internal pressure and transverse shear loads, respectively, are different and that short-beam shear tests, therefore, could not provide conclusive results. However, the ready availability of thermally spiked and non-spiked specimens, and the hope of gaining additional insight into the behavior of moist adhesives, justified the test effort.

The characteristics of the test specimens and the test matrix are shown in Figure 19. As indicated, a total of 18 non-spiked and 11 spiked specimens were prepared for tests at room temperature and at 350 F (177 C). The designations dry, 1/2 moist, and moist relate to specimens which were dried in a 250 F (121 C) oven, or saturated in humidity chambers containing 50% and 95% relative humidity, respectively. Since the specimen edges were not sealed, saturation was accomplished in approximately 90 days.

CONDITION	TEMP	NO. OF SPECIMENS
NON-SPIKED		
DRY	RT	3
1/2 MOIST	RT	3
MOIST	RT	3
DRY	350 F (177 C)	3
1/2 MOIST	350 F (177 C)	3
MOIST	350 F (177 C)	3
SPIKED (1/2 MOIST)		
0.6%	350 F (177 C)	4
0.8%	350 F (177 C)	4
1.0%	350 F (177 C)	3

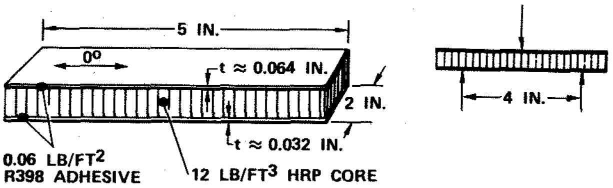


Figure 19. Test Matrix and Test Specimen Configuration

The test results are summarized in Figure 20. Evidently, the presence of moisture has a degrading effect on the adhesive shear strength both at room temperature and at 350 F (177 C). In comparison to the non-spiked specimens, the performance of the thermally spiked specimens was somewhat poorer but the differences are not severe enough to rule out the possibility of data scatter. Figure 21 contains more detailed test data of the 11 spiked specimens.

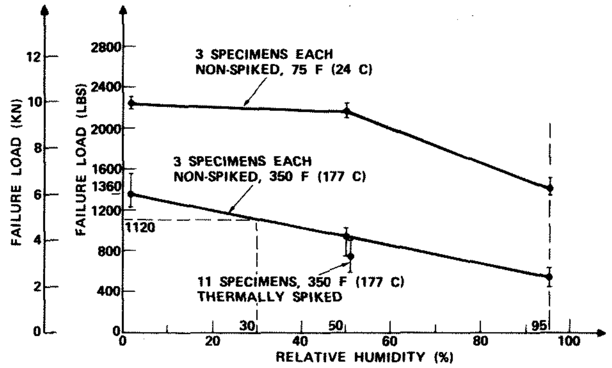


Figure 20. Shear Strength of Short Beam Specimens

A 0.6% moisture level in the facesheets corresponds to saturation at 30% relative humidity. Assuming that under service conditions the moisture level in the outer facesheet and the adjacent adhesive layer are identical, a shear strength loss of approximately 25% might be anticipated in the payload bay door sandwich panels during the reentry phase.

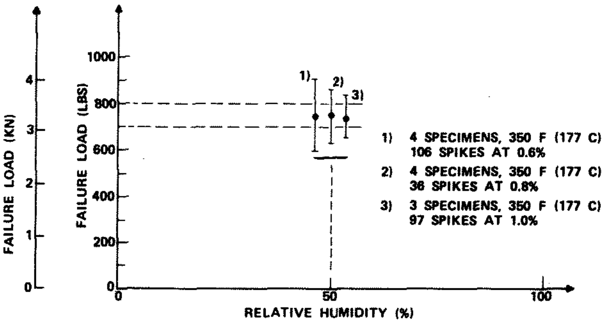


Figure 21. Shear Strength of Thermally Spiked Specimens

Internal Pressure Capability of Sandwich Panels

A quantitative evaluation of the internal pressure capability of the payload bay door skin panel is difficult in several respects. Since the thin facesheets tend to bulge between supporting cell walls, stress concentrations occur in the fillets of the adhesive which promote a failure in the adhesive layer rather than a tensile failure of the core. The expected failure mode precludes a strength investigation by flatwise tension tests since the standard test apparatus constrains the critical deformations of the facesheets. A direct measurement of the pressure rise in a single cell of the non-perforated core must also be ruled out because any one cell may not be descriptive of the panel behavior, not to mention the difficulty of accurate pressure measurements in very small volumes.

Test Specimens and Test Procedure. These considerations led to the choice of 12-inch x 14-inch (0.3048m x 0.3556m) sandwich panels as test specimens. The center portion of the panels were of flight configuration except that each cell of the core was vented, either by perforating or by slitting of the cell walls, to allow uniform pressurization of the entire panel interior. The relatively fragile phenolic core was surrounded by a narrow strip of dense and perforated aluminum core for the stabilization of the panel periphery. Several of the panels contained a deliberately induced adhesive void of 0.50 inch (12.7 mm) of 0.75 inch (19.05 mm) diameter between one of the facesheets and the core in order to assess the significance of such disbonds. Disbonds as small as 0.25 inch (6.35 mm) diameter can be detected by non-destructive testing methods.

The test objective was the determination of the maximum internal pressure the panels were capable of sustaining in dry and moist states at temperatures in the 350 F (177 C) and 280 F (138 C) range. The latter temperature was included to provide information beyond the scope of the payload bay door problems. Panels to be tested in the dry state were allowed to contain up to a total of 1.5g moisture. The panels to be tested moist were exposed to a humidity chamber maintained at 95% RH and 140 F (60 C), after sealing the panel edges with aluminized tape to preclude the entrance of moisture through the vented core walls. The panels were weighed periodically until an analytically prescribed moisture gain was achieved which, at elevated temperature, produced the expected vapor pressure during the reentry phase of the Shuttle Orbiter.

The test specimens were mounted in a picture-frame type aluminum fixture capable of sealing the panel edges by means of silicone rubber inlays. Figure 22 shows details of the sealing arrangement. An external N_2 supply was tapped into the fixture for augmentation of the vapor pressure. The resulting panel pressures were measured by two pressure transducers located at opposite panel edges; a third transducer was attached to the N_2 line. Thermocouples were used to monitor the test specimen facesheet and frame fixture temperatures.

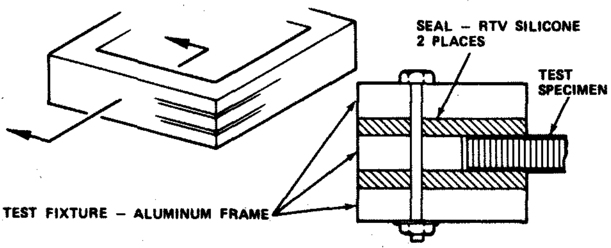


Figure 22. Sealing of Test Panels

The mounted test specimens were placed in an oven. The oven temperature was then raised from ambient to the desired test level of 350 F (177 C) or 280 F (138 C). The resulting pressure due to the entrapped air in core cells and the vaporizing moisture was then increased through the N_2 source until panel failure occurred. The heat-up time of the panel to 350 F (177 C) was approximately 40 minutes. Analysis showed that almost mo moisture would be lost from the interior portion of the panel (adhesive layers and core) during the 40-minute heat-up time. The N_2 pressurization phase required between 5 and 10 minutes.

Test Results. A total of 24 test panels were prepared. In the early phases of the test program sealing problems were encountered with panels A and B, rendering their test results useless. Table II lists the 14 panels tested in the moist condition and identifies their moisture response. Of the remaining eight, five panels (J, L, Q, R, and S) were tested dry at 350 F (177 C) and 280 F (138 C); two panels (T and U) were used for creep tests prior to failing them in the dry state at 350 F (177 C); and one panel was held in abeyance.

Panel Specimen	Dry Weight* (grams)	Days in Chamber	Weight Gain (grams)
D	354.676	15	5.602
E	314.620	15	5.864
F	332.928	18	5.785
G	304.993	20	6.535
H	305.597	18	5.171
K	417.716	70	10.080
N	383.933	29	6.047
O	379.646	28	5.738
P	377.669	26	5.969
W	369.285	37	7.213
X	382.912	40	7.192
Y	375.185	52	7.982
Z	378.710	51	7.805
A-A	390.355	22	5.129

*Panel weight as fabricated contains approximately 1.6 grams of moisture. These specimens were placed under vacuum at 250 F (121 C) for 24 hours for drying.

Table II. Moisture Gain of Test Panels

Of the panels tested in the dry condition at 350 F (177 C) and 280 F (138 C), panels J, L, Q, R, T, and U sustained in excess of 190 psig (1310 kPa) before failing or, as indicated by the upward directed arrow in Figure 23, before leakage of the seals forced the termination of the test. Panel S, at 280 F (138 C) failed unexpectedly low at 172 psi (1186 kPa). The presentation of the test results in Figure 23 of the moist panels versus moisture in the core at launch is self explanatory. Table III is a numerical representation of the test data including supplementary comments.

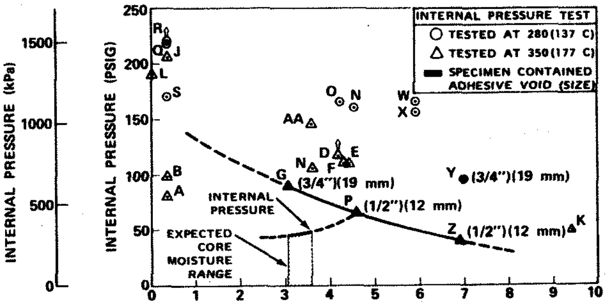


Figure 23. Internal Pressure Test Results

Panels T and U were used for a study of potential creep damage in the hot and moist adhesive. Contrary to the other moist panels, panels T and U were placed in a humidity chamber operated at 50% relative humidity and 180 F (82 C) with the intent of complete saturation at that humidity level. The moisture gain, after approximately 90 days exposure, was measured as 6.2g and 5.6g, respectively, i.e.,

Panel Configuration		Specimen T01T31118-	Test Condition		Failure (psi/cycles)	Remarks
			Temp (F)	Moisture		
Standard Panel	Slit Core	T	348	Dry	190 psi	Developed seal leak at 190 psi
Standard Panel	Slit Core	U	350	Dry	226 psi	Developed seal leak at 226 psi
Standard Panel	Slit Core	J	347	Dry	205 psi	Initial test developed seal leak at 165 psi and 175 psi
Standard Panel	Perf Core	D	357	5.60 gm H_2O	110 psi Seal Failure	Initial test developed seal leak at 96 psi (water added) and 74 psi (humidified)
Standard Panel	Perf Core	E	353	5.86 gm H_2O	108 psi	Initial test developed seal leak at 87 psi. Facesheets contain skin splice
Standard Panel	Perf Core	H	345	5.17 gm H_2O	104 psi	Corners potted with 934 RT adhesive
Standard Panel	Slit Core	K	339	10.08 gm H_2O	50 psi	Panel sustained 200 cycles at 45 psi and 350 F (dry), then leak checked at 60 and 30 psi RT and dry. Panel blew at 50 psi during heat up to 350 F
Standard Panel	Slit Core	L	350	Dry	193 psi Seal Failure	Initial test developed seal leak at 165 psi
Panel with 1/4 Adhesive Void	Perf Core	F	353	5.79 gm H_2O	109 psi	Initial test developed seal leak at 84 and approximately 100 psi. Corners potted with 934 RT adhesive
Panel with 1/2 Adhesive Void	Slit Core	P	367	5.97 gm H_2O	67 psi	
Panel with 3/4 Adhesive Void	Perf Core	G	349	4.61 gm H_2O	93 psi	Panel lost 2.0 grams weight during 24 hour test delay. Corners potted with 934
Standard Panel	Slit Core	Q	282	Dry	218 psi	
Standard Panel	Slit Core	R	285	Dry	220 psi Seal Failure	
Standard Panel	Slit Core	S	283	Dry	172 psi	
Standard Panel	Slit Core	N	280	6.05 gm H_2O	151 psi	
Standard Panel	Slit Core	O	286	5.74 gm H_2O	154 psi	
Standard Panel	Slit Core	W	280	7.21 gm H_2O	156 psi	
Panel with 1/4 Adhesive Void	Slit Core	X	278	7.19 gm H_2O	147 psi	
Panel with 1/4 Adhesive Void	Slit Core	Z	348	7.81 gm H_2O	41 psi	Panel blew during heatup to 350 F
Panel with 3/4 Adhesive Void	Slit Core	Y	279	7.98 gm H_2O	91 psi	
Standard Panel	Slit Core	A-A	350	5.13 gm H_2O	138 psi	

Table III. Internal Panel Pressure Tests in the range of the other moist panels but apparently with a somewhat different moisture distribution. The creep tests commenced with the application of a test temperature of 350 F (177 C) in the facesheets at which combined vapor and trapped air pressures of 39 psig in panel T, and of 33 psig (228 kPa) in panel U, were measured. Subsequently, the internal pressure was increased to 50 psig (345 kPa) and maintained at that level for 25 hours at 350 F (177 C). The loss of internal pressure due to the drying of the panel was continually balanced by the addition of N_2 gas. During the test no abnormal effects were observed. After 25 hours the panels were found completely dry and were then pressurized after reaching 196 psi (1351 kPa) and 220 psi (1517 kPa) in panels T and U, respectively. In both cases, however, the tests were discontinued because of seal leakage.

Conclusions

Figure 23 showed that, at the level of moisture expected to be in the adhesive/core substructure at entry, the capability of the panel is more than twice the expected panel internal pressure. It must be emphasized that most of the panel area will be exposed to temperatures considerably lower than 350 F (177 C). It is, therefore, apparent that from an internal pressure standpoint the design of the graphite/epoxy payload bay door is adequate.

V. SUMMARY

Computational methods have been developed for predicting the level of absorbed environmental moisture in the Space Shuttle Orbiter graphite/epoxy panels. Based on analytical results, the requirements for a test program were defined to obtain "knock-down" factors for A-basis allowables previously determined for dry graphite/epoxy laminates at 75 F (24 C) and 350 F (177 C). Drying data and sandwich panel internal pressure data gathered from the test program have been used in turn to validate the analytical methodology.

Application of the "knock-down" factors to the sandwich panels of the Space Shuttle Orbiter showed positive design margins in all areas. Results of the internal pressure portion of the test program proved that the small area of the payload bay door subjected to 350 F (177 C) can withstand the maximum internal pressure expected.

The combined analytical/test program has demonstrated the integrity of the Space Shuttle Orbiter graphite/epoxy payload door design.

Nomenclature

A	Matrix of constants, single-layered slab
B	State vector containing initial and boundary conditions ($t = t_o$)
b	Exponent in the moisture equilibrium equation
C	State vector at $t = t_o + \Delta t = t_1$
c	Concentration
D	Diffusion coefficient
E	Matrix of constants including those resulting from interfaces in the multi-layered slab
F	State vector at $t = t_o + \Delta t = t_1$ for multi-layered slab
G	State vector containing initial and boundary conditions ($t = t_o$) for the multi-layered slab case
H	Relative humidity
H_I	Relative humidity in the honeycomb void volume
I	Signifies the I^{th} material in a multi-layered slab
i	Subscript for the i^{th} lamina in a single- or multi-layered slab
j	Subscript for time in subscripted variables
M	Percent moisture by weight
M_u	Equilibrium percent moisture by weight at 100% relative humidity
$\overline{MW}$	Molecular weight of water, 18.016/mole
p	Pressure
p_s	Saturated vapor pressure at temperature, T
R	gas constant
RH	Relative humidity
T	Absolute temperature
t	Time
V	volume
W_i	Dry weight of the i^{th} layer in a multi-layer slab
$\overline{WMA}$	Weight of absorbed moisture in solid components of the adhesive/core/adhesive substructure
$\overline{WMT}$	Total weight of moisture in the adhesive/core/adhesive substructure
$\overline{WMV}$	Weight of water vapor in the core void volume
X	Thickness
Δ	Change in
ϕ	Moisture flux
ρ	Density

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