

Naval Surface Warfare Center Carderock Division

Bethesda, MD 20084-5000

NSWCCARDIV-TR-96/002 March 1996

Survivability, Structures, and Materials Directorate
Technical Report

Moisture Diffusion in Impact Damaged Face Sheets of Composite Sandwich Materials

by

Joseph M. Augl



19960510 007

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REPORT DOCUMENTATION PAGE

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OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 1996		3. REPORT TYPE AND DATES COVERED Interim; 1 January 1995 - 1 January 1996	
4. TITLE AND SUBTITLE Moisture Diffusion in Impact Damaged Face Sheets of Composite Sandwich Materials				5. FUNDING NUMBERS SC2B; RS34S56	
6. AUTHOR(S) Joseph M. Augl					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center Carderock Division White Oak Laboratory 10901 New Hampshire Ave. Silver Spring, MD 20903-5640				8. PERFORMING ORGANIZATION REPORT NUMBER NSWCCARDIV-TR-96/002	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Tower One 800 N Quincy St Arlington, VA 22217-5660				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Moisture permeation can weaken composite sandwich material structures. This report describes an investigation of the change in moisture diffusion coefficients in composite sandwich face sheet material which has sustained moderate damage. Sandwich panels were subjected to impacts of 50, 75 and 100 foot-pounds using a one-inch diameter instrumented impact head. After the panels were subjected to the impacts, the core and rear face material were removed, leaving only the impacted face sheet. In the analysis, a sufficient undamaged area of the composite was retained in order to prevent further damage to the impact area. Small squares of damaged and undamaged face sheet material were then dried in a vacuum oven and exposed to 80 percent RH at 22°C for a period of seven months. The diffusion coefficients were determined through the damaged area and compared with that of undamaged face sheets. The sorption curves of the damaged specimens were analyzed to estimate the moisture diffusion coefficients. It was determined that small damage, barely noticeable, increased the diffusion coefficients of the damaged area by about two orders of magnitude.					
14. SUBJECT TERMS moisture diffusion composite materials diffusion coefficient				15. NUMBER OF PAGES 33	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR		

FOREWORD

The work described herein was sponsored by the Office of Naval Research (James J. Kelly, Program Manager). It was administered by Mr. Ivan Caplan, Materials Block Manager at the the Naval Surface Warfare Center, Carderock Division (NSWCCD), Code 0115, under Ship Submarine Materials Program (SC2B), Composite Materials Project (RS34S56), and CDNSWC Work Unit 1-6440-613.

The purpose of this work was to provide a method for determining the change of the moisture diffusion coefficient caused by moderate impact damage on face sheets of composite sandwich structures. Knowledge of such changes are important for modeling the moisture take-up and distribution in damaged structures made of composite sandwich materials, especially for estimating whether or not repair work is necessary or how long one might tolerate the inflicted damage without repair.

This effort is a continuation of work documented in several previous reports. References 1 through 4 describe the experimental determination of constituent diffusion coefficients of materials for specific naval applications, provide a one-dimensional finite difference code for multilayer sandwich materials, and analyze several environmental scenarios for moisture sorption of test panels.

The author wishes to acknowledge Thomas Juska and Carol Williams of the NSWCCD Annapolis facility who performed the controlled impact experiments.

Approved by:



CARL E. MUELLER, Head
Weapons Materials Department

ABSTRACT

Moisture permeation can weaken composite sandwich material structures. This report describes an investigation of the change in moisture diffusion coefficients in composite sandwich face sheet material which has sustained moderate damage. Sandwich panels were subjected to impacts of 50, 75 and 100 foot-pounds using a one-inch diameter instrumented impact head. After the panels were subjected to the impacts, the core and rear face material were removed, leaving only the impacted face sheet. In the analysis, a sufficient undamaged area of the composite was retained in order to prevent further damage to the impact area. Small squares of damaged and undamaged face sheet material were then dried in a vacuum oven and exposed to 80 percent RH at 22°C for a period of seven months. The diffusion coefficients were determined through the damaged area and compared with that of undamaged face sheets. The sorption curves of the damaged specimens were analyzed to estimate the moisture diffusion coefficients. It was determined that small damage, barely noticeable, increased the diffusion coefficients of the damaged area by about two orders of magnitude.

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INTRODUCTION

Because of their light weight and high stiffness, composite sandwich structures have been used for many years on naval aircraft stabilizers and other structures. Recently, they have been introduced on ships for deckhouses, ducting, missile casings, raydomes, and other lightweight structures. Previous work investigating the diffusion characteristics of face sheet and core materials indicate that core candidate materials for naval application have diffusion coefficients three to four orders of magnitude higher than typical face sheet laminates. Therefore, the presence of an intact laminate serves to greatly slow the moisture permeation into the core.

Because significant permeation into the core structure can result in loss of mechanical properties, loss in electrical properties, and for balsa core structures, the potential for rot, and because 'thin-skinned' sandwich laminates may incur in-service impact damage, the effect of impact damage on the 'water-barrier' properties of the laminate was sought.

Such moisture permeation can be considerably accelerated when damage is done to the composite face sheets. In order to decide whether or not a repair is necessary or how long one may tolerate the damage without repair, one needs to be able to estimate the amount of moisture that will penetrate the structure and its internal moisture distribution as a function of time.

This report provides a method to determine the moisture diffusion coefficient for impact damaged areas in composites, especially for face sheets of sandwich structures.

Any modeling of moisture effects by analytical means requires knowledge of the moisture diffusion coefficient. In previous reports, we have discussed the measurement of moisture diffusion coefficients in composites and sandwich materials, as well as prediction of moisture uptake and distributions within these materials.¹⁻⁴ So far, our analyses were based on undamaged structures. In this report we extended our investigation to damaged structures, with the first objective, to provide an experimental procedure for measuring the change in the diffusion coefficient of composite face sheets that have been subjected to various levels of impact damage, excluding penetration.

EXPERIMENTAL

The panels selected for this analysis consisted of three layers, a core of balsa wood and front and back composite face sheets made from 24 oz. E-glass woven roving / 510A Dow Derakane vinyl ester fabricated using VARTM which we will call RTM3 for brevity reasons. Six one-foot square panels were used. They were nominally 1.2 inches thick, that is, 0.1 inch thickness for the face sheets (front and back) and 1.0 inch thickness for the balsa wood core.

Damage was inflicted on each panel using a one-inch diameter, instrumented impactor. Two panels were impacted at 50 ft-lb, two panels at 75 ft-lb and two panels at 100 ft-lb. The core and back face sheet material was removed from each specimen leaving only the impacted face sheet. The impacted areas showed partial delamination, which appeared to increase with greater impact force. The damage to the backside of the face sheet was very similar to the front side, indicating that the damage went through the thickness. We anticipated that cutting out the impacted area for direct measurements of the diffusion coefficients would result in further damage. Therefore, we decided to determine the diffusion coefficients indirectly by a combination of measurements.

One and one-half-inch squares which included the impacted area were cut from each of the six panels. The size of these squares included sufficient undamaged material to ensure that the damaged area would not be further aggravated. One additional, undamaged specimen of the same size was cut from each panel. This made a total of 12 specimens used to determine diffusion coefficients for damaged and undamaged material. Table 1 identifies each of the specimens and Figure 1 shows the six damaged specimens. The sorption curves of these samples, together with those of the undamaged specimens, permit one to derive the diffusion coefficients of the damaged areas.

Table 1. Specimen Identification.

Panel Number	Undamaged Specimens Designation	Damaged Specimens	
		Designation	Impact Force
1	1u	1d	50 ft-lb.
2	2u	2d	75 ft-lb.
3	3u	3d	100 ft-lb.
4	4u	4d	50 ft-lb.
5	5u	5d	75 ft-lb.
6	6u	6d	100 ft-lb.

After the specimens were cut and the face sheets separated from the core, they were dried for 96 hours in a vacuum oven at 100°C. They were placed flat on a metal plate for good heat transfer. The specimens were then exposed to 80 percent relative humidity (RH) at 22°C in a desiccator over a saturated solution of potassium chloride with excess, undissolved potassium chloride, to maintain 80 percent RH. The weight gain was measured over a period of seven months to assure moisture equilibrium in the specimens. Individual measurements are listed as a spreadsheet in the appendix. The analysis and data reduction are described in the DISCUSSION and RESULTS sections.

DISCUSSION

ESTIMATE OF THE MOISTURE DIFFUSION COEFFICIENT OF DAMAGED AREAS IN COMPOSITES

Estimate of the average diffusion coefficient from partially damaged specimens.

The uptake of moisture into a plate of infinite dimensions, when the partial pressure on both surfaces of the plate is the same and kept constant, may be described by

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{-D(2n+1)^2 \pi^2 t / 4l^2} \quad (1)$$

where M_t is the amount of moisture absorbed after time t , M_∞ is the maximum amount of moisture that can be absorbed for a given outside relative humidity (RH) after an infinite exposure time, D is the diffusion coefficient, and l is $1/2$ the plate thickness. On plotting M_t/M_∞ versus $(\text{time}/\text{thickness}^2)^{1/2}$, one obtains sorption curves shown by the solid lines in Figures 2 through 5. The initial slopes of these M_t/M_∞ -curves are straight lines up to a value of about 0.5 which can be used to determine the diffusion coefficients (see reference 5, p. 238). After simplifying and rearranging Equation (1), the average diffusion coefficients are obtained from the initial slopes of the sorption curves according to

$$D = (\pi/16) S^2 \quad (2)$$

where $S = d(M_t/M_\infty)/d(t/(2l)^2)^{1/2}$ is the initial slope of the curve.

If we wish to determine the diffusion coefficient of a composite plate with finite size (for example 2"x 2"), we can use an analytical edge correction or seal the edges with a metal foil to account for the finite specimen dimensions. Depending on the length to plate-thickness ratio, this edge correction is usually not more than 1 or 2 percent difference in the average diffusion coefficient.

If we imagine the same composite plate being uniformly damaged, that is, it has many small cracks, then water transport into the specimen would be faster. One would get a similar curve with different values for $(\text{time}/\text{thickness}^2)^{1/2}$, that is, the initial slope of the curve would increase, and therefore, the average effective diffusion coefficient would be larger.

For practical experimental measurements, one rarely has the luxury of getting a uniformly damaged plate sample for measuring the diffusion coefficient of such damaged areas. Furthermore, the damage may be severe enough so that one is not able to cut the damaged area without doing further damage such as delamination. Therefore, it is desirable to cut the samples such that there is sufficient undamaged area around the damaged center, so that the sample holds together well. From the change in light transmission, one can usually estimate the damaged area in glass fiber composites. Direct measurement of the damaged area of graphite fiber composites is more difficult, although one could use X-ray or ultrasonic inspection for such estimates. As we will discuss in Method C, one does not need to measure the damaged area, it can be estimated directly from the sorption curves. One expects a distribution in the severity of the damage from the impact surface to the other side of the face sheet, and laterally, from the center of impact outward, perhaps in the shape of a Gaussian distribution. Therefore, the diffusion coefficient of the damaged area, obtained by the following analysis is, by definition, an average diffusion coefficient. For simplicity, we assume that the damaged area consists of a plug of uniformly damaged material through the thickness of the plate, surrounded by undamaged material.

Thus, we make the following suppositions:

- 1) The plate sample has a damaged area with a fraction (f_d) of the total area and is laterally surrounded by a fraction (f_u) of undamaged material. The average diffusion coefficients for these areas are D_d and D_u respectively.
- 2) There is enough undamaged material available, so that the sorption curve and therefore the diffusion coefficient of the undamaged material can be measured independently.
- 3) The maximum moisture saturation per gram of material (for a given RH value) is the same for both the undamaged and the damaged material. This assumption is true as long as the material loss caused by the damage does not change the resin to fiber mass ratio, and as long as one can neglect capillary condensation. If the sorption experiments were done by water submersion, then the maximum moisture sorption would be strongly affected by the void volume fraction, that is, the voids would be filled with liquid water and the maximum moisture sorption would be different from that of void free composites. Of course, this applies to all void containing composites, whether the composite is damaged or not. Although corrections could be made for such situations, we will not discuss them here.
- 4) The sorption curve M_t/M_∞ versus $(\text{time}/\text{thickness}^2)^{1/2}$ of the partially damaged specimen is a superposition of the moisture absorbed by the fraction of the damaged part and that absorbed by the fraction of the undamaged part. The respective initial slopes (S_d and S_u) for each fraction are straight lines, and so is the sum. Depending on the difference in the diffusion coefficients, D_u and D_d , and on the ratio of the damaged and undamaged parts, the sorption curve of the partly damaged specimen may show two straight line branches with actual slopes S_1 and S_2 , from which the respective diffusion coefficients can be derived as discussed below.

For a better visualization of the following arguments, we present four sample calculations which are graphically shown in Figures 2 through 5. From such graphical representations, one may gain a better understanding for the limitations that are inherent in this approach. The numerical values for these calculations have been chosen such that the ratio of the diffusion coefficients for the damaged to undamaged material are 10 to 1 (and 100 to 1), and the fractions of the damaged to undamaged areas are 0.25 to 0.75 (and 0.45 to 0.55) respectively. In each of the figures, we show five curves. The solid and the dotted curves are the only ones that are experimentally measured. They correspond to the sorption curves of the undamaged and of the partially damaged specimen respectively. For Figure 2, we have chosen the values: $D_u = 0.1$, $f_u = 0.75$, $D_d = 1.0$, $f_d = 0.25$; for Figure 3, the corresponding values are: $D_u = 0.1$, $f_u = 0.75$, $D_d = 10$, $f_d = 0.25$; for Figure 4, they are: $D_u = 0.1$, $f_u = 0.55$, $D_d = 1.0$, $f_d = 0.45$; and for Figure 5, they are: $D_u = 0.1$, $f_u = 0.55$, $D_d = 10$, $f_d = 0.45$. All curves were calculated using the first twenty terms of Equation (1).

Each graph has five curves. In the order they are listed in the legend box, they correspond to the following sorption curves (M_t/M_∞ versus $[\text{time}/\text{thickness}^2]^{1/2}$):

- (1) undamaged specimen with initial slope S_u and a diffusion coefficient of $D_u = 0.1$.
- (2) a curve one would get from a sample where the damage is uniform throughout the entire specimen (where $f_d = 1.0$). The initial slope is S_d and the diffusion coefficient of the damaged material is $D_d = 1.0$ (or $D = 10$).
- (3) and (4) are generated from curves (2) and (1) by multiplying them with their respective fractional values, f_d and f_u corresponding to their fractional damaged and undamaged areas.
- (5) this curve (dotted line) is the superposition of curves (3) and (4). Curve (1) and (5) are the sorption curves to be measured experimentally for this approach.

Method A. Estimate of D_d from the Slopes of Curves (1) and (5).

From the experimentally measured sorption curves (1) and (5), we expect that curve (1) has only one straight line (initial) slope, while curve (5) may have two straight line slopes (S_1 and S_2) in the sorption curve. If this is the case, one can readily obtain the fractions of the damaged and undamaged areas from a damaged sample corresponding to curve (5), and we can determine the diffusion coefficient (D_d) for the damaged material as follows:

From Figures 2 through 5, we observe that curve (1) of the undamaged specimen has a slope $S(1)$ which changes from an initial maximum slope (S_u) to a slope with value zero at its maximum moisture saturation level. Curve (5) (dotted line) has two fairly straight line portions in its slope $S(5)$ which we call S_1 , and S_2 . These are caused by superposing the fractional sorption curves (3) and (4) from the damaged and undamaged areas. Thus, from inspection of the graphs, one can easily see that the slope S_1 is generated by adding the initial slopes of curves (3) and (4),

and therefore, is a straight line. The slope S_2 will be a straight line only if the fractional part of the damaged area has essentially reached its maximum equilibrium concentration before M_t/M_∞ of the undamaged area has reached a value of 0.6. Above this value, S_2 is no longer a straight line and this graphical method no longer applies. The larger the difference between D_u and D_d , the easier it is to clearly separate the two branches S_1 and S_2 . Therefore, an estimate of the fractional values f_u and f_d is advisable. Even so, it is not necessary if the S_1 and S_2 parts are straight lines.

Thus we can write the expressions

$$S_1 = f_u S_u + (1 - f_u) S_d, \text{ and} \quad (3)$$

$$S_2 = f_u S_u \quad (4)$$

Substituting $f_u = S_2/S_u$ from Equation (4) into Equation (3) one obtains

$$S_d = (S_1 - S_2)/[1 - (S_2/S_u)] \quad (5)$$

which is used in calculating D_d from Equation (2). By changing the ratio of f_d and f_u , one may fine-tune the experimental accuracy.

Method B. Estimate of the average diffusion coefficient D_d by tracing the fraction of the damaged area.

This approach is useful for composites where the damaged fraction of the sample can be estimated directly (by tracing the damaged area via X-ray or ultrasonic scans, or for glass fiber composites, by direct inspection). Since $f_d + f_u = 1$, one obtains S_d directly from Equation (3), which rearranged gives

$$S_d = (S_1 - f_u S_u)/f_d \quad (6)$$

Again, we obtain D_d from Equation (2).

For the sample calculation where $D_u = 0.1$, $D_d = 1.0$, $f_u = 0.75$, and $f_d = 0.25$, we calculate the following slopes: $S_u = 0.71365$, $S_1 = 1.09943$, and $S_d = 2.25676$ with the reciprocal values 1.40125, 0.90956, and 0.44311 respectively. As one can see in Figure 6, one obtains the values 1.40, 0.91, and 0.44 by graphically extending the initial slopes of curves (1), (5), and (2).

Method C. Estimate of the average diffusion coefficient of the damaged fraction by using the intersection point of S_1 and S_2 .

The simplest method of obtaining the diffusion coefficient D_d of the damaged part is from the intersection of the slopes of S_1 and S_2 . This method does not require the knowledge of the fractional damaged and undamaged areas. However, their ratio may affect the accuracy of the desired diffusion coefficient (D_d) as is apparent when comparing the sample figures. To simplify the following equations, we will write x for $(\text{time/thickness}^2)^{1/2}$ and y for M_t/M_∞ . We assume now that the Slopes S_u , S_1 , and S_2 are available from the data. The initial slopes, S_u and S_1 , start at the origin. The slope, S_2 , intersects with the y -axis with value $b = f_u$, because the slope S_2 is parallel to the initial slope of curve 4 after curve 3 has leveled out. The intersection point of S_1 and S_2 is calculated from

$$y_i = S_1 x_i \quad (7)$$

$$y_i = S_2 x_i + b \quad (8)$$

where the x_i and y_i are the coordinates of the intersection of S_1 and S_2 . Solving for x_i and y_i from the known slopes S_1 and S_2 , and from the intersection b of S_2 with the y -axis, one obtains the intersection coordinates of S_1 with S_2 :

$$x_i = b/(S_1 - S_2) \quad \text{and} \quad y_i = S_1 x_i$$

and $1/x_i$ is therefore the initial slope of curve (2).

Using the same data set as in sample calculation of B above with $S_u = 0.71365$, $S_1 = 1.09943$, and $b = f_u = 0.75$, we obtain for x_i the same value as in the sample above (0.44311) with the reciprocal value $S_d = 2.25676$.

Again, from Figure 6, one can see how to use a simple graphical approach for determining S_d . The x -coordinate of the intersection of slopes S_1 and S_2 is shifted up to the line $M_t/M_\infty = 1.0$. This point is then connected with a straight line to the origing which gives the initial slope (S_d) of the sorption curve (2) from which one can calculate D_d .

In conclusion, methods A, B, and C are equivalent. For Method A, one requires the slopes for S_1 , S_2 , and S_u ; for method B, one requires an estimate of the fractional damage of the sorption specimens, together with S_1 and S_u ; and for method C, one requires an estimate of the x -coordinate for the intersections of S_2 with S_1 . Method C seems to be the easiest and simplest to use.

RESULTS

In the last section, we analyzed how to determine the moisture diffusion coefficient in areas of damaged composites caused by impact experiments on sandwich panels. In this section we will show the results of the actual measurements, and the change in diffusion coefficient as a function of various impact levels using a one-inch steel ball impact head.

The individual weight changes due to moisture sorption, their maximum moisture solubilities at 80 percent RH, their calculated values of M_t/M_∞ versus $[\text{time}/\text{thickness}^2]^{1/2}$ are listed in the appendix together with the calculated diffusion coefficients determined by method C of the previous section.

Figure 7 shows the curves of M_t/M_∞ versus $(\text{time}/\text{thickness}^2)^{1/2}$ for the first three damaged panels, 1d through 3d. Figure 8 shows the same curves for the second set of damaged panels, 4d through 6d. The individual data points are listed in the appendix.

We will demonstrate with one example how the experimental data were used to determine the diffusion coefficient of the damaged specimens (using method C described in the last section). Figure 9 shows the sorption curves of the damaged and undamaged specimens from panel No. 3d which has been impacted with 100 foot-pounds. For a better estimate, we have expanded the time axis (of Figure 9) giving Figure 10. Using the nomenclature of the last section, we find that the intersection of S_1 and S_2 (indicated by dashed lines) is projected parallel to the M_t/M_∞ -axis up to the value 1.0, giving a value of 520 on the $(\text{time}/\text{thickness}^2)^{1/2}$ -axis. The straight line from the origin to that point is the slope S_d (with a value of 0.001923) from which the diffusion coefficient of the damaged area is calculated [using Equation (2)] resulting in a value of $7.34\text{E-}07 \text{ cm}^2/\text{sec}$. The other sorption curves of the impacted specimens were evaluated the same way. The respective diffusion coefficients of the undamaged face sheet specimens were calculated in the usual way from the slope S_u of the sorption curves.

Table 2 lists the measured maximum equilibrium solubilities and diffusion coefficients of undamaged specimens. Table 3 lists the same properties of the samples which included the damaged center.

Although the samples impacted with 50 foot-pounds (see Figure 1) appear to have only a small damage, the resulting diffusion coefficient of the damaged area, however, is almost hundred times larger than the diffusion coefficient measured on samples without the damaged area. The average diffusion coefficient measured from all undamaged specimens is $4.10\text{E-}9 \text{ cm}^2/\text{sec}$, while that of the 50 foot-pounds impacted samples is $3.27\text{E-}7 \text{ cm}^2/\text{sec}$. The average maximum equilibrium moisture solubility of all undamaged samples is 0.1716 g/100g. The average of all

Table 2. Maximum Moisture Solubilities and Diffusion Coefficients in Undamaged Face Sheet Areas of Balsa Wood Sandwich Panels which had been Impacted with 50, 75, and 100 Foot-Pounds.

Specimen ID	Specimen Origin	Equilibrium Solubility	Diff. Coeff. (cm ² /sec)
1u	50 ft-lbs	0.1666	3.82E-9
2u	75 ft-lbs	0.1764	4.44E-9
3u	100 ft-lbs	0.1532	3.30E-9
4u	50 ft-lbs	0.1993	5.47E-9
5u	75 ft-lbs	0.1616	3.93E-9
6u	100 ft-lbs	0.1727	3.62E-9
Average		0.1716	4.10E-9
Standard Deviation		0.0158	7.71E-10
Coeff. Var. (%)		9.21	18.81

Table 3. Maximum Moisture Solubilities and Diffusion Coefficients in Face Sheet Specimens with the Impact Damage in the Center. (Machined from the Same Panels as in Table 1.)

Specimen ID	Impact level (ft-lbs)	Equilibrium Solubility	Diff. Coeff. (cm ² /sec)
1d	50	0.1687	3.43E-7
4d	50	0.1741	3.10E-7
2d	75	0.1981	7.20E-7
5d	75	0.1657	4.35E-7
3d	100	0.1638	7.34E-7
6d	100	0.1503	6.56E-7

damaged samples is also of the same order, 0.1701. Any difference in sample solubilities between damaged and undamaged samples, would be within experimental error.

Figure 11 shows the change in moisture diffusion coefficient of the damaged area in a 0.1-inch thick RTM3 vinyl/E-glass face sheet of 1.0 inch thick balsa wood sandwich panels after they had been impacted.

CONCLUSIONS

The most suitable method for measuring diffusion coefficients in composite materials is the well known sorption technique using plate samples. Although a lot of work has been done to characterize the sorption and diffusion behavior in composites and sandwich materials, little is known of how to estimate the moisture effects of relatively small damages caused by objects impacting sandwich structures. This work dealt with the first step of such an analysis, namely the estimation of the change in diffusion coefficient caused by minor impacts on composite structures.

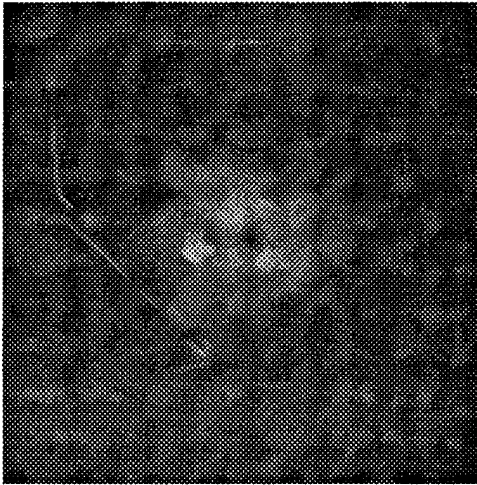
An analysis of how to extend the measurements of diffusion coefficients of small damaged areas, using the same technique as for undamaged composites, was carried out. The analysis showed that this can indeed be done by a choice of three different methods.

The experimental approach was to measure the change of the moisture diffusion coefficient in the face sheet of sandwich test panels to be used for Navy shipboard structures. We demonstrated that sorption measurements can be used to characterize moisture diffusion in damaged composite materials.

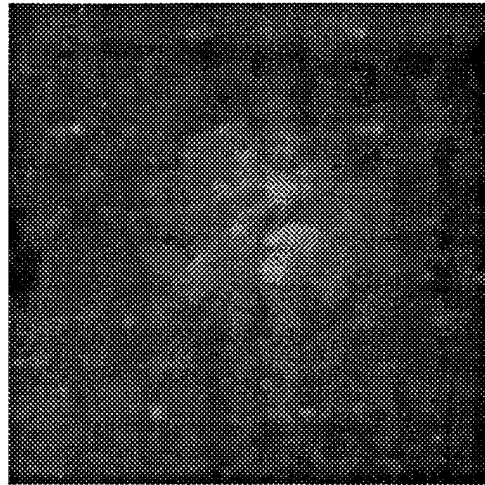
We found that a significant increase in the diffusion coefficient of impacted areas where the damage is hardly noticeable. A low level impact (50 foot-pounds) caused only a small spot of discoloration (caused by micro-cracks) in the green colored vinyl/E-glass composite face sheet. However, the resulting change in diffusion coefficient between the damaged and undamaged area was about 100 to 1.

RECOMMENDATIONS

Additional investigation is proposed in two areas. First, a typical composite material, consisting of a balsa wood core covered by RTM3 vinyl/E-glass face sheets was used for this investigation. We recommend calculating finite difference analysis or finite element analysis to estimate how much faster the moisture uptake and internal distribution will be in materials presently used or proposed for ship structures. In addition, studies performed to date have investigated diffusion of gaseous moisture. This represents a realistic environment of high relative humidity which would be encountered at sea. Further study should consider the proximity of shipboard composite material structures to sea water and rain. This work would involve permeation of liquid water through damaged face sheets.



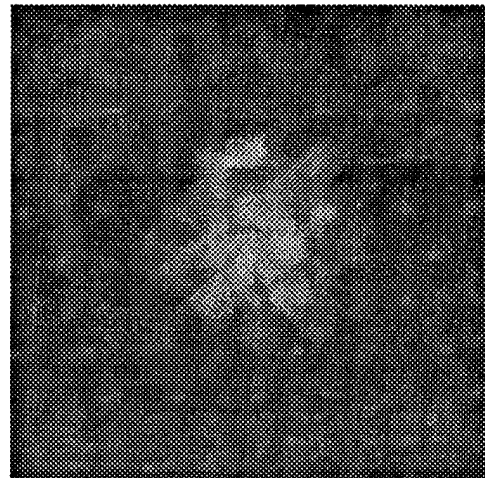
(a) Sample 1d, 50 ft lb



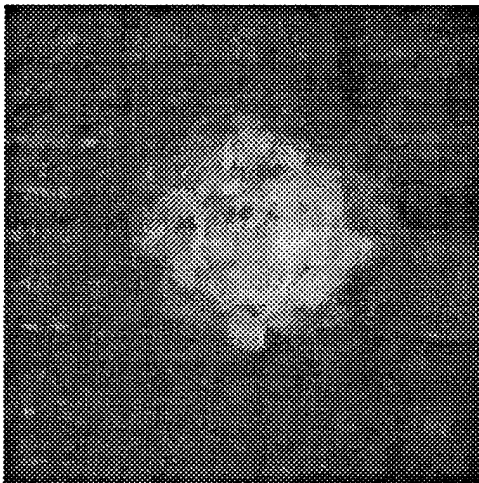
(b) Sample 4d, 50 ft lb



(c) Sample 2d, 75 ft lb



(d) Sample 5d, 75 ft lb



(e) Sample 3d, 100 ft lb



(f) Sample 6d, 100 ft lb

Figure 1. Impacted Specimens, Front Side

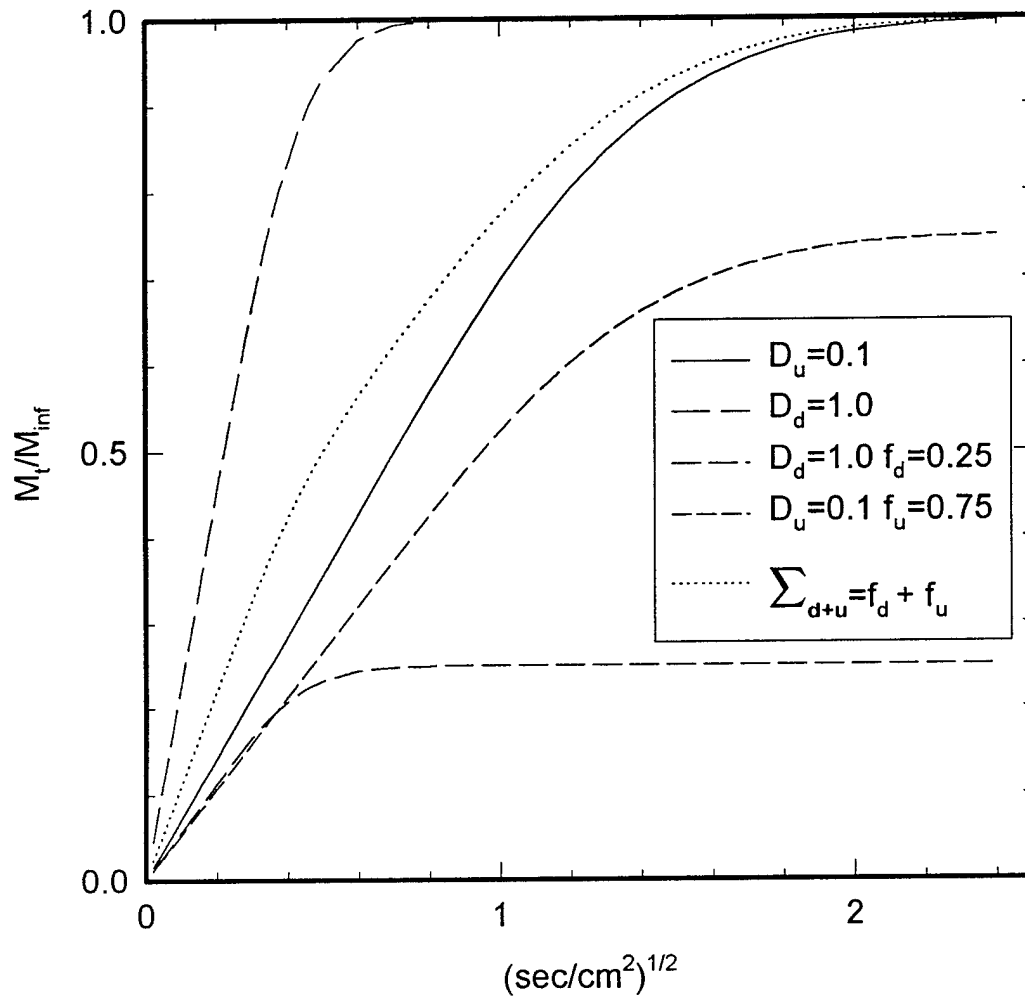


Figure 2. Sorption Behavior of Plate Samples with and without a 25 Percent Damaged Area, where the Ratio of the Diffusion Coefficients of the Damaged/Undamaged Area is 10/1.

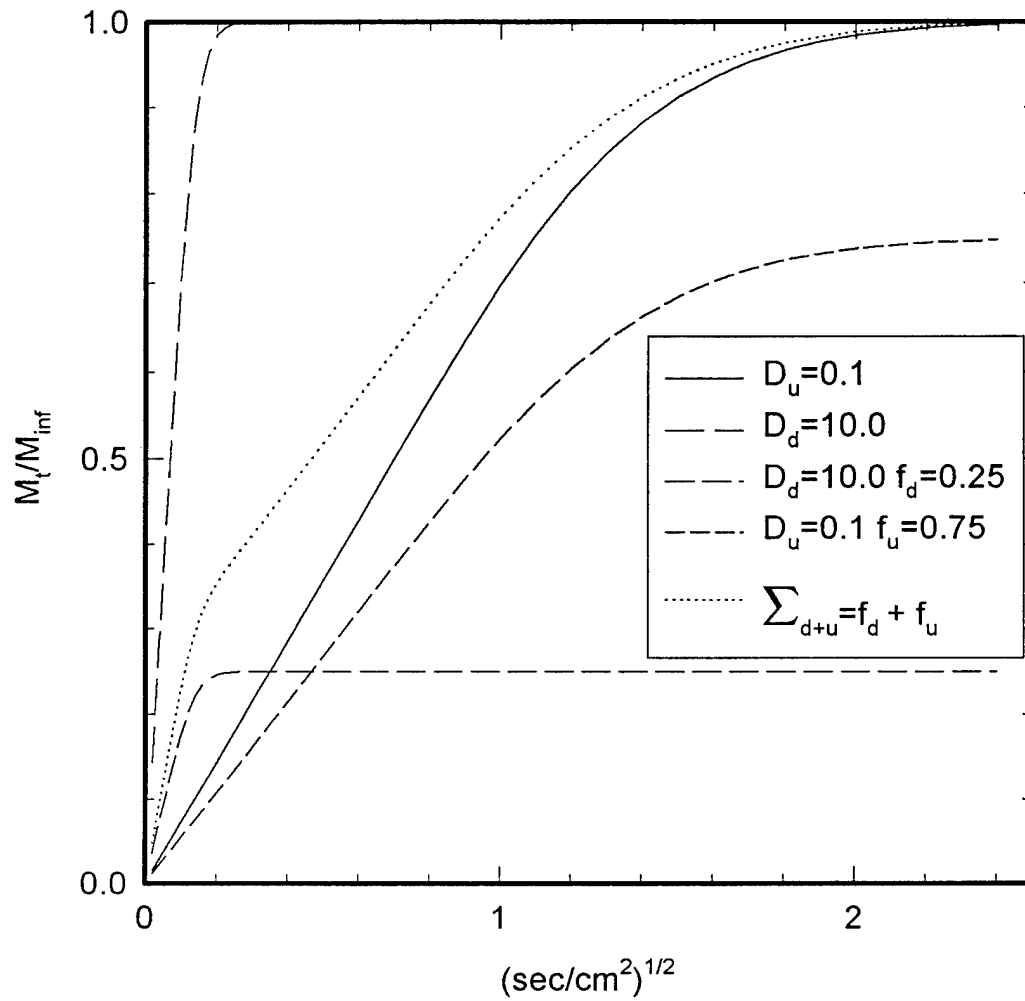


Figure 3. Sorption Behavior of Plate Samples with and without a 25 Percent Damaged Area, where the Ratio of the Diffusion Coefficients of the Damaged/Undamaged Area is 100/1.

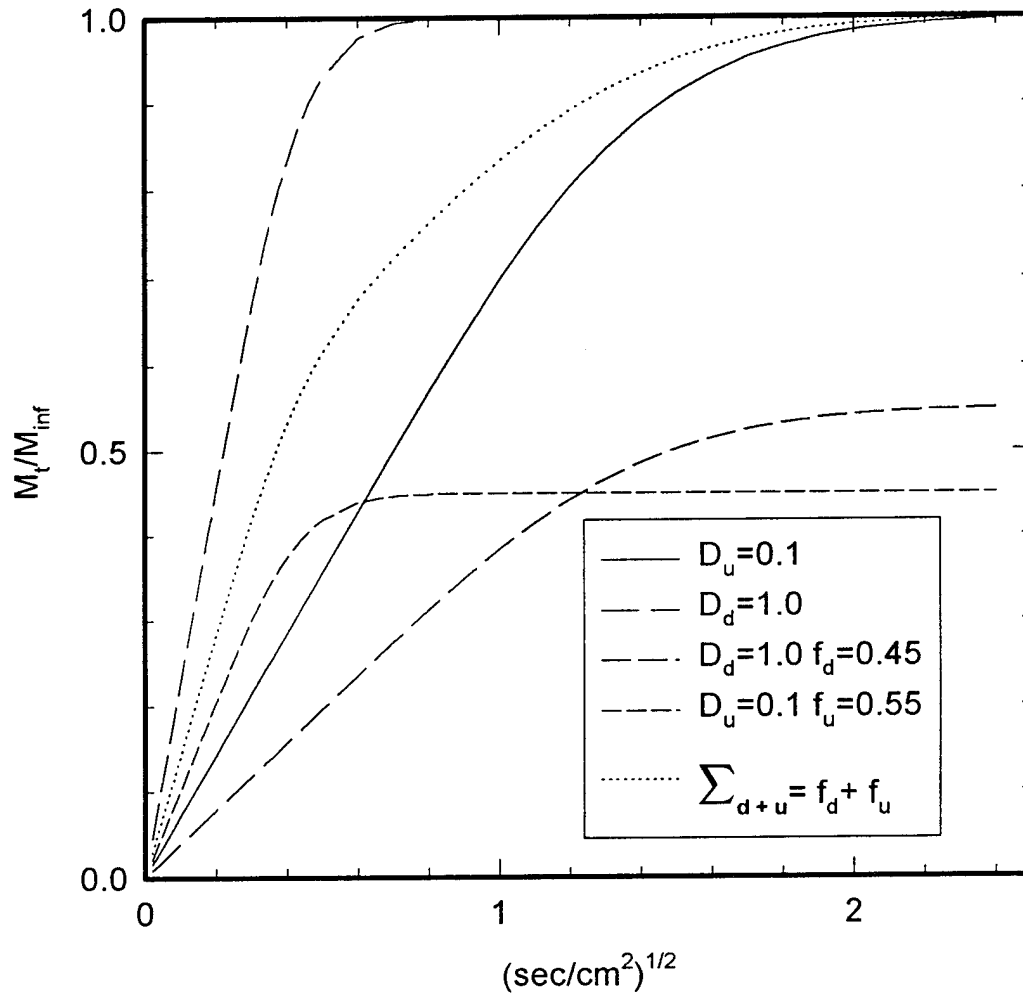


Figure 4. Sorption Behavior of Plate Samples with and without a 45 Percent Damaged Area, where the Ratio of the Diffusion Coefficients of the Damaged/Undamaged Area is 10/1.

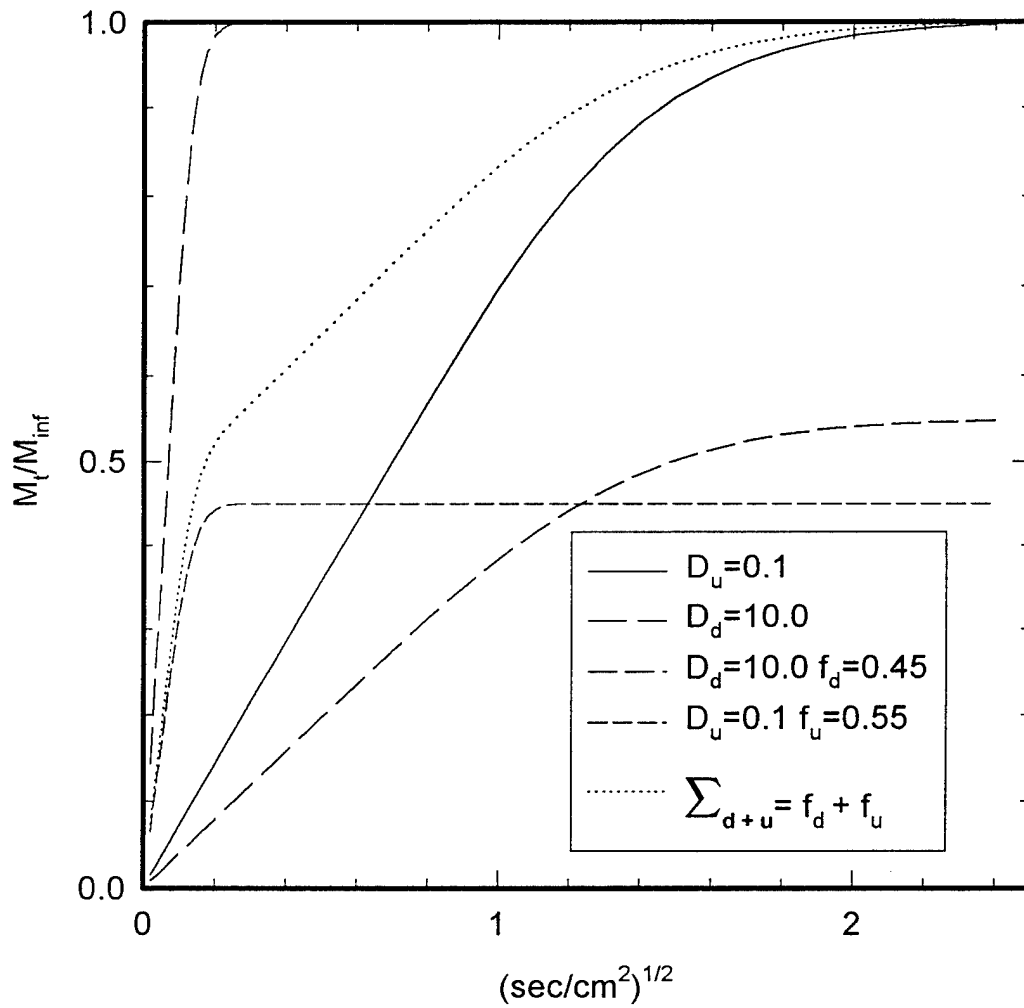


Figure 5. Sorption Behavior of Plate Samples with and without a 45 Percent Damaged Area, where the Ratio of the Diffusion Coefficients of the Damaged/Undamaged Area is 100/1.

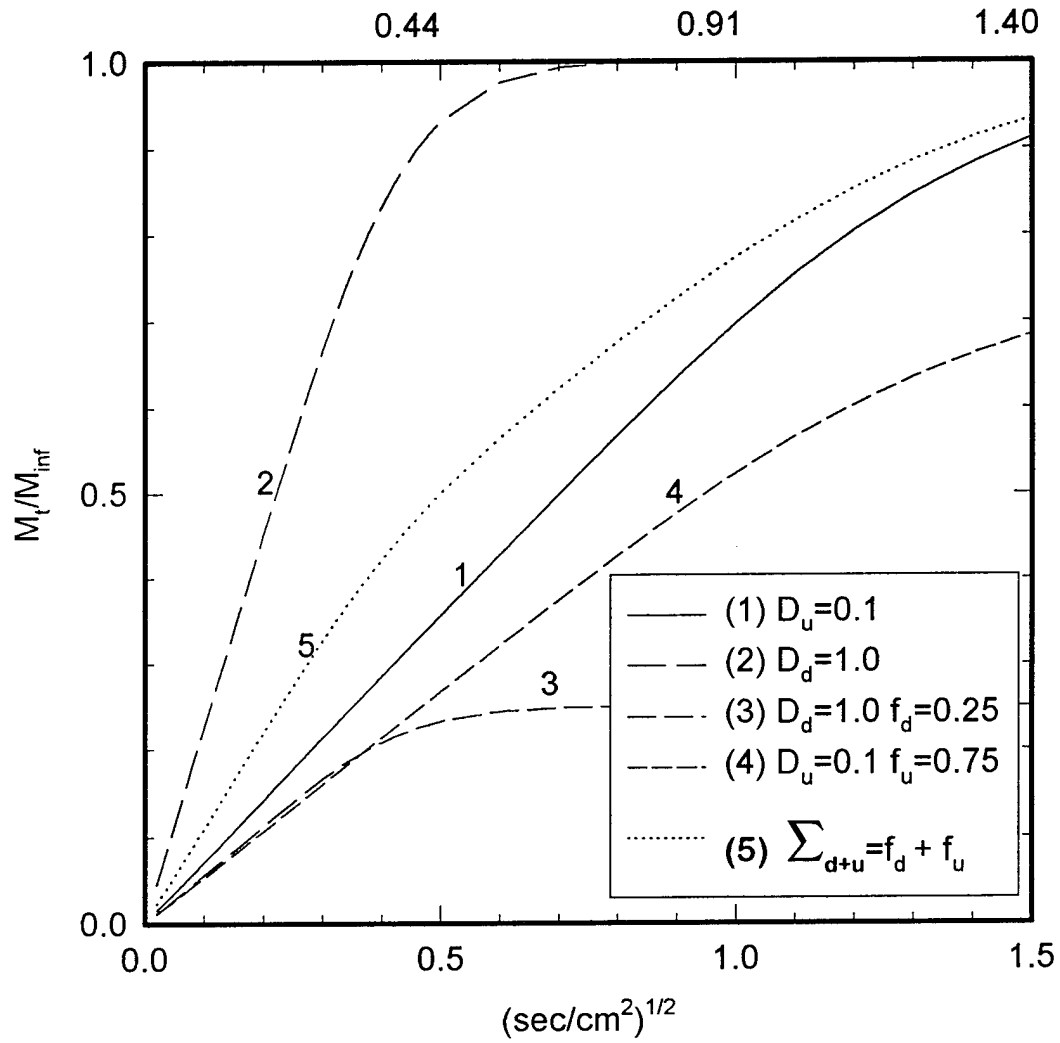


Figure 6. Enlarged Figure 2: Extrapolation of the Initial Slopes of Curves (1), (2), and (5) to Give the Abscissa Points at the Ordinate = 1.0.

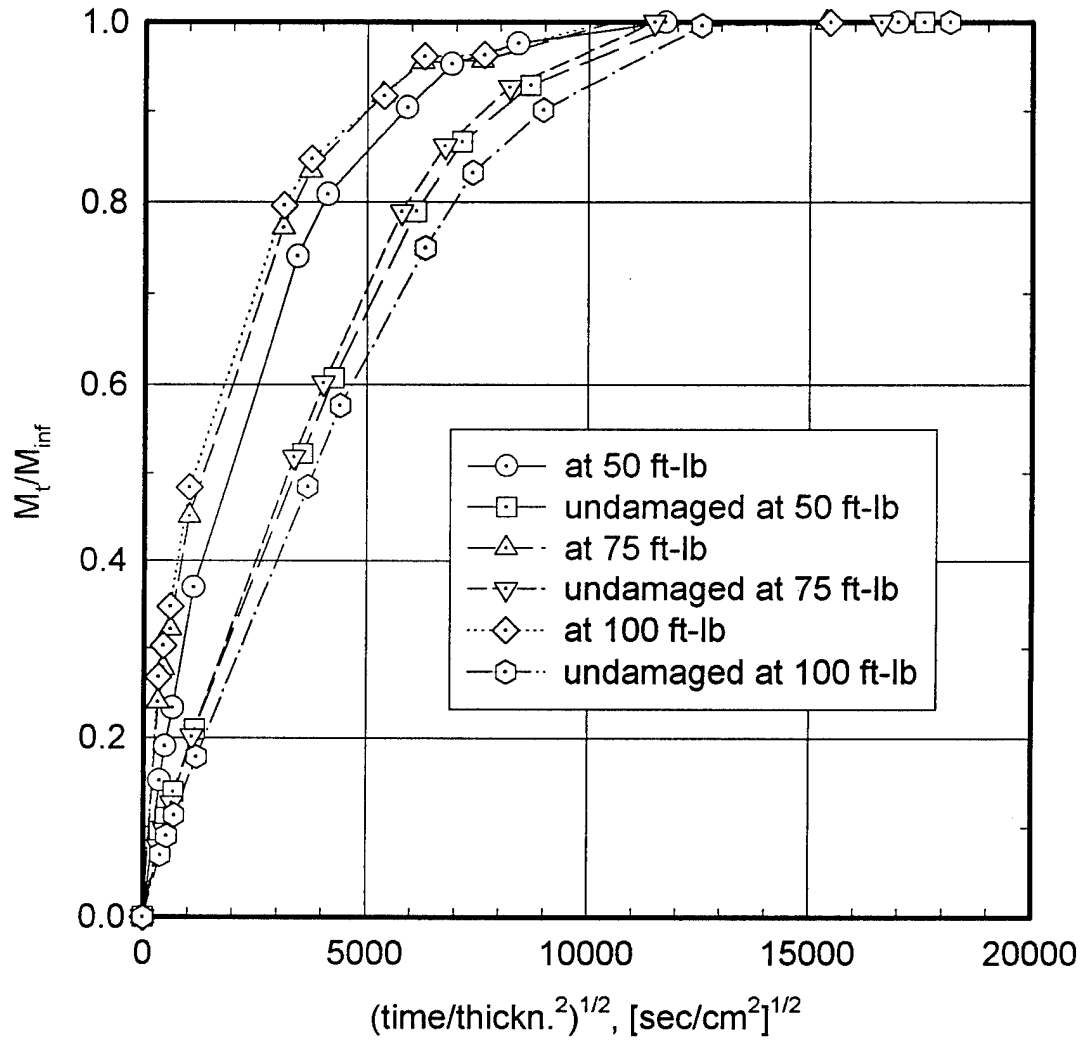


Figure 7. Sorption Isotherm of RTM3 Sandwich Panel Face Sheets
(No. 1d through 3d) with Damaged and Undamaged Specimens.

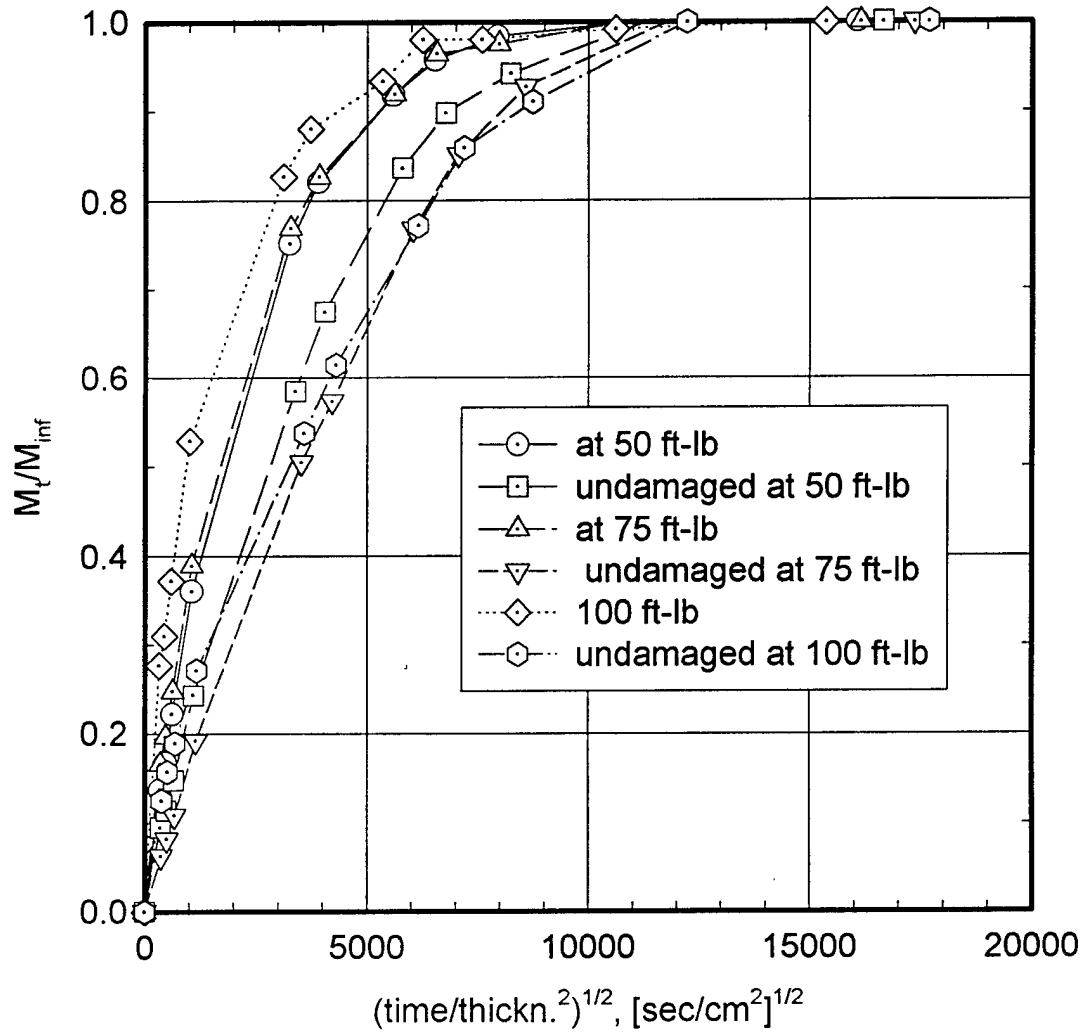


Figure 8. Sorption Isotherm of RTM3 Sandwich Panel Face Sheets (No. 4d through 6d) with Damaged and Undamaged Specimens.

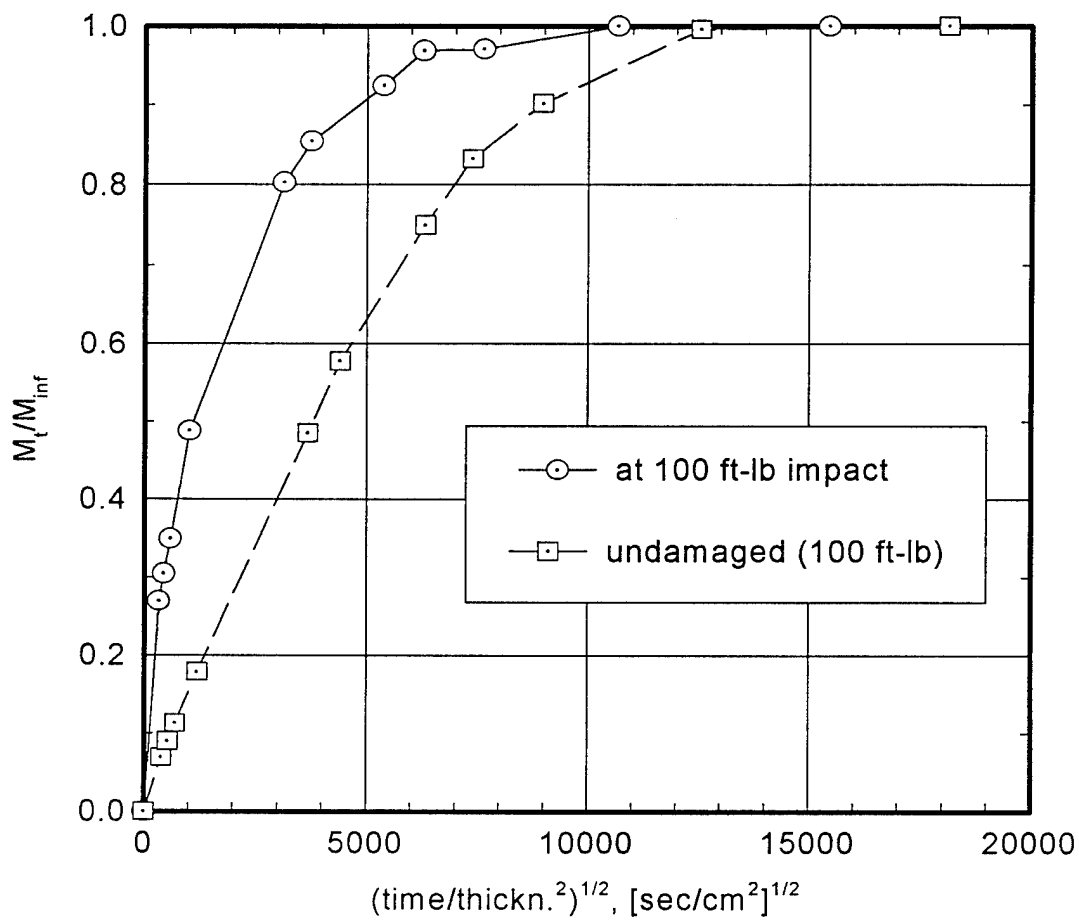


Figure 9. Sorption Isotherm of RTM3 Sandwich Panel Face Sheets (No. 3d) Impacted with 100 ft-lb, Damaged and Undamaged Specimen.

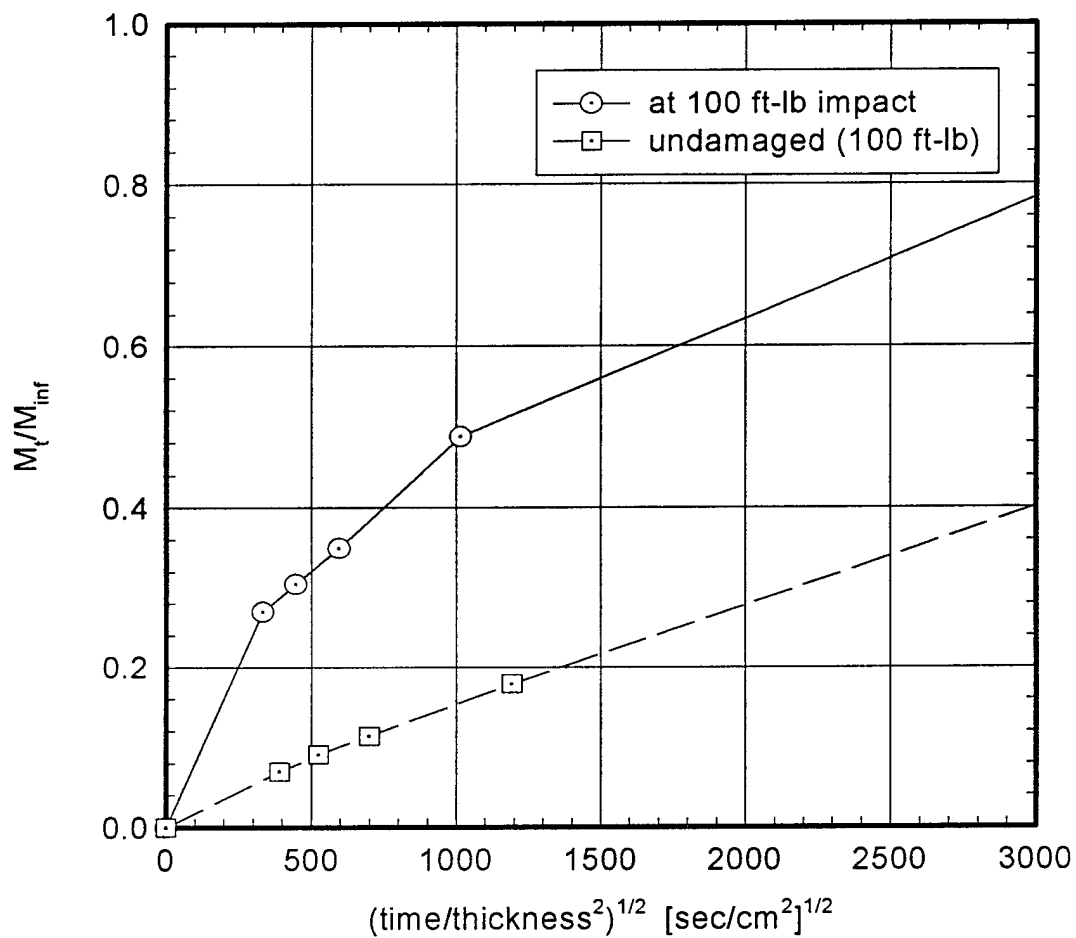


Figure 10. Magnified Initial Moisture Sorption (in Damaged and Undamaged RTM3 Face Sheet of Panel No. 3d) for a Graphical Determination of the Diffusion Coeff. for the Damaged Area.

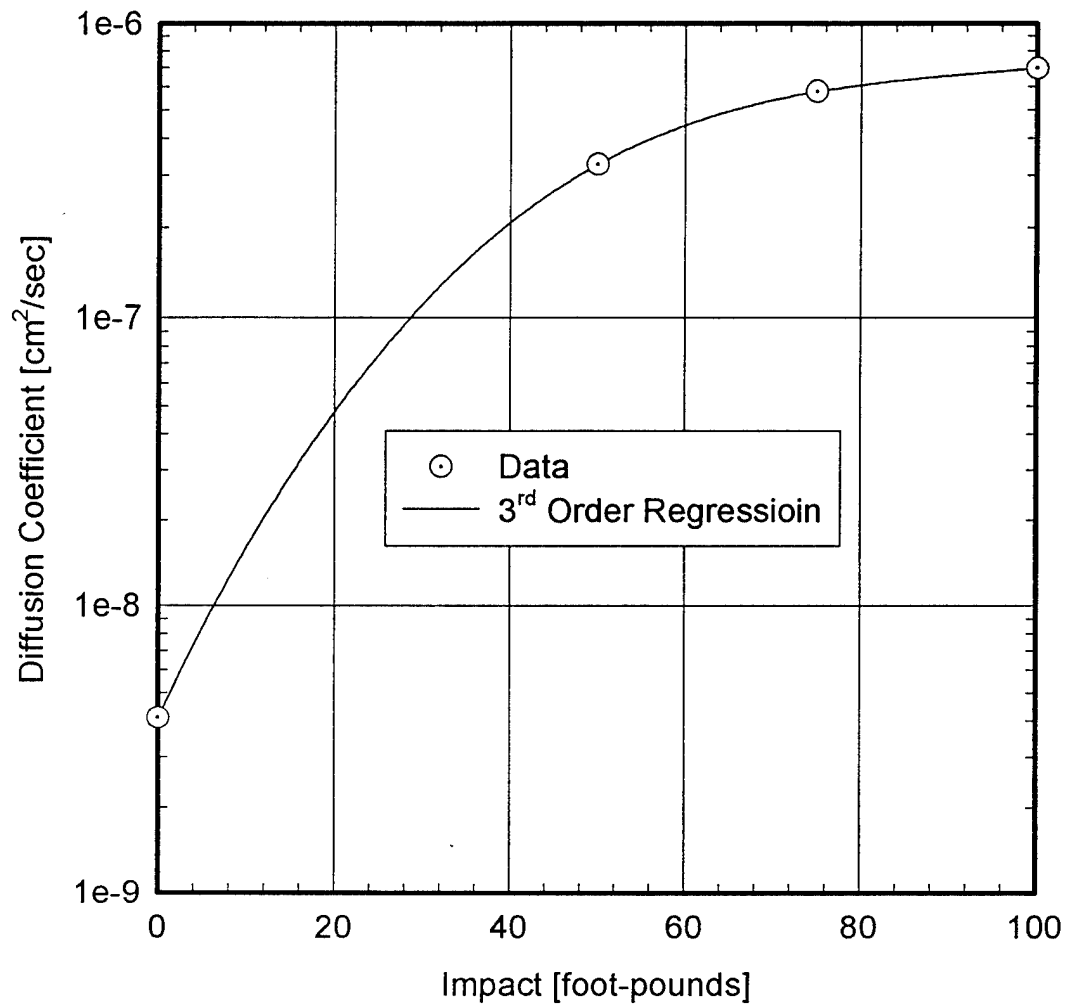


Figure 11. Change of the Moisture Diffusion Coefficient in a Vinyl RTM3/E-Glass Composite Face Sheet as a Function of Impact Level.

REFERENCES

1. Augl, J. M., *Moisture Diffusion Analysis in Multilayer Composite Materials by Finite Difference Analysis*, NSWCCARDIV-TR-95/013 (in print).
2. Augl, J. M., *Use of Finite Element Analysis for Transient Moisture Diffusion Studies in Multilayer Composite AEM/S System Sandwich Materials*, CARDIVNSWC/TR-94/019, November 1994.
3. Augl, J. M., *Sorption and Diffusion of Moisture in Multilayer Composite AEM/S System Sandwich Material*, CDNSWC/TR-94/018, October 1994.
4. Augl, J. M. and Berger, A. E., *The Effect of Moisture on Carbon Fiber Reinforced Epoxy Composites. III Prediction of Moisture Sorption in a real Outdoor Environment*, NSWC/WOL/TR 77-13, June 1977.
5. Crank, J., *The Mathematics of Diffusion*, (Second Edition), Clarendon Press, p. 48 1976.

APPENDIX

EXPERIMENTAL DATA

The individual experimental data collected from the sorption experiments are listed in a spreadsheet printout in pages A-3 and A-4, columns A through M. The impact levels, sample ID-numbers, and specimen dimensions are listed in lines 2 through 6. The specimen weights at the start and end of the sorption experiments are listed in lines 8 and 9. The intermittent times of the measurements and the sample weights are listed in lines 11 through 32. In lines 38 and 39 are the diffusion coefficients of the specimens with and without edge correction for finite sample size. The listed diffusion coefficients for the impacted specimens (xd) are those belonging to the centrally damaged areas, while the diffusion coefficients of the undamaged specimens (xu) belong to the entire area of the specimens. The maximum moisture sorption equilibria at 80 percent RH are listed in line 41.

The calculated values for M_t/M_∞ are given in lines 60 through 71, and those for the values of $(\text{time}/\text{thickness}^2)^{1/2}$ are listed in lines 73 through 84.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Moisture Absorption in impacted RTM3 at 22 Deg.C and 80 Percent RH												
2	Impactd ft-lb, 1in ball	50	0	75	0	100	0	50	0	75	0	100	0
3	Sample #	1d	1u	2d	2u	3d	3u	4d	4u	5d	5u	6d	6u
4	Thickness (cm)	0.2594	0.2507	0.2865	0.2652	0.2849	0.2426	0.2739	0.2642	0.2725	0.2536	0.2864	0.2489
5	Length (cm)	3.5	3.65	3.47	3.65	3.57	3.65	3.62	3.63	3.6	3.61	3.7	3.65
6	Width (cm)	3.6	3.75	3.6	3.75	3.7	3.75	3.48	3.75	3.7	3.71	3.56	3.75
7	Start:0715, 3-7-95												
8	Dry Weight a,t t=0	6.19355	6.62755	6.44351	6.83553	6.44586	6.50049	6.42221	6.62081	6.63357	6.58621	6.35912	6.63415
9	Wt at t=inf	6.204	6.63859	6.45628	6.84759	6.45642	6.51045	6.43339	6.63401	6.64456	6.59685	6.36868	6.64561
10													
11	Min	150	150	150	150	150	150	150	150	150	150	150	150
12	Weight (Grams)	6.19514	6.62859	6.44658	6.83647	6.44871	6.50118	6.42374	6.62208	6.63539	6.58688	6.36177	6.63558
13	Min	270	270	270	270	270	270	270	270	270	270	270	270
14	Weight	6.19554	6.62876	6.44706	6.83669	6.44908	6.50139	6.42408	6.62231	6.63573	6.58708	6.36208	6.63595
15	Min	480	480	480	480	480	480	480	480	480	480	480	480
16	Weight	6.19599	6.62909	6.44762	6.83706	6.44955	6.50162	6.42469	6.62275	6.63629	6.58736	6.36268	6.63632
17	Min	1395	1395	1395	1395	1395	1395	1395	1395	1395	1395	1395	1395
18	Weight	6.19741	6.62986	6.44928	6.83796	6.45101	6.50227	6.42624	6.62402	6.63785	6.58825	6.36417	6.63726
19	Min	13260	13260	13260	13260	13260	13260	13260	13260	13260	13260	13260	13260
20	Weight	6.20129	6.63332	6.45339	6.84178	6.45434	6.50532	6.43062	6.62852	6.64203	6.59158	6.36703	6.64031
21	Min	19035	19035	19035	19035	19035	19035	19035	19035	19035	19035	19035	19035
22	Weight	6.202	6.63426	6.45419	6.84279	6.45488	6.50624	6.43139	6.62971	6.64266	6.59231	6.36754	6.64119
23	Min	39120	39120	39120	39120	39120	39120	39120	39120	39120	39120	39120	39120
24	Weight	6.203	6.63627	6.45526	6.84505	6.45562	6.50796	6.43248	6.63185	6.64368	6.59439	6.36805	6.643
25	Min	53445	53445	53445	53445	53445	53445	53445	53445	53445	53445	53445	53445
26	Weight	6.20351	6.63711	6.45573	6.84592	6.45609	6.50878	6.43292	6.63266	6.64417	6.59528	6.36849	6.644
27	Min	79200	79000	79000	79000	79000	79000	79000	79000	79000	79000	79000	79000
28	Weight	6.20375	6.63781	6.45575	6.84671	6.45611	6.50947	6.43321	6.63324	6.64429	6.59608	6.36849	6.64459
29	Min	154380	154380	154380	154380	154380	154380	154380	154380	154380	154380	154380	154380
30	Weight	6.204	6.6386	6.45628	6.84759	6.45642	6.51041	6.43334	6.634	6.64459	6.5969	6.3686	6.64564
31	Min	322860	322860	322860	322860	322860	322860	322860	322860	322860	322860	322860	322860
32	Weight	6.204	6.63859	6.45628	6.84759	6.45642	6.51045	6.43339	6.63401	6.64456	6.59685	6.36868	6.64561
33													
34	Regression Analysis:												
35	b (intersection)		0.03223		0.02208		0.01727		0.030954		0.011392		0.068455
36	a (x-coeff)	0.001316	0.000139	0.001905	0.00015	0.001923	0.000129	0.00125	0.000166	0.001481	0.000141	0.001818	0.000135
37													
38	D=x^2*Pi/16	3.4E-07	3.79E-09	7.12E-07	4.4E-09	7.26E-07	3.27E-09	3.07E-07	5.41E-09	4.31E-07	3.9E-09	6.49E-07	3.59E-09
39	D(corr. R&M)	3.43E-07	3.82E-09	7.2E-07	4.44E-09	7.34E-07	3.3E-09	3.1E-07	5.46E-09	4.35E-07	3.93E-09	6.56E-07	3.62E-09
40													
41	22C, 80RH Sorb.	0.168724	0.166577	0.198184	0.176431	0.163826	0.153219	0.174083	0.199371	0.165672	0.16155	0.150335	0.172743
42													
43													
44	Moisture Sorption of impacted and non-impacted samples cont'd												
45													
46													
47	Impact	50 ft-lb	75 ft-lb	100 ft-lb		0 ft-lb		Impact lb	50 ft-lb	75 ft-lb	100 ft-lb		0 ft-lb
48	D(corr)	3.43E-07	7.20E-07	7.34E-07		3.82E-09		Sorb.	0.1687	0.1981	0.1638		0.1666
49		3.10E-07	4.35E-07	6.56E-07		4.44E-09			0.1741	0.1657	0.1503		0.1764
50	Av.D(corr)	3.27E-07	5.78E-07	6.95E-07		3.30E-09		Av.Sorb.	0.1714	0.1819	0.15705		0.1532
51						5.47E-09							0.1992
52						3.93E-09		Av.Sorb.	0.1701	same as 0 ftlb impact			0.1616
53						3.62E-09							0.1727
54					Av.D(corr)	4.1E-09						Av.Sorb.	0.1716
55													

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	A	B	C	D	E	F	G	H	I	J	K	L	M
56													
57	Moisture Absorption in Impacted RTM3 at 22 Deg.C and 80 Percent RH (continued)												
58													
59	Sample #	1d	1u	2d	2u	3d	3u	4d	4u	5d	5u	6d	6u
60	MU/M(inf)	0	0	0	0	0	0	0	0	0	0	0	0
61	From: Line 12	0.152153	0.094203	0.240407	0.077944	0.269886	0.069277	0.136852	0.094697	0.165605	0.06297	0.277197	0.124782
62	Line 14	0.190431	0.109601	0.277995	0.096186	0.304924	0.090361	0.167263	0.113636	0.196542	0.081767	0.309623	0.157068
63	Line 16	0.233493	0.139493	0.321848	0.126866	0.349432	0.113454	0.221825	0.14697	0.247498	0.108083	0.372385	0.189354
64	Line 18	0.369378	0.209239	0.45184	0.201493	0.487689	0.178715	0.360465	0.243182	0.389445	0.191729	0.528243	0.271379
65	Line 20	0.74067	0.522645	0.773688	0.518242	0.80303	0.48494	0.752236	0.584091	0.769791	0.504699	0.827406	0.537522
66	Line 22	0.808612	0.60779	0.836335	0.60199	0.854167	0.577309	0.821109	0.674242	0.827116	0.573308	0.880753	0.614311
67	Line 24	0.904306	0.789855	0.920125	0.789386	0.924242	0.75	0.918605	0.836364	0.919927	0.768797	0.9341	0.772251
68	Line 26	0.95311	0.865942	0.95693	0.861526	0.96875	0.832329	0.957961	0.897727	0.964513	0.852444	0.980126	0.859511
69	Line 28	0.976077	0.929348	0.958496	0.927032	0.970644	0.901606	0.9839	0.941667	0.975432	0.927632	0.980126	0.910995
70	Line 30	1	1.000906	1	1	1	0.995984	0.995528	0.999242	1.00273	1.004699	0.991632	1.002618
71	Line 32	1	1	1	1	1	1	1	1	1	1	1	1
72													
73	(time/th^2)^.5 (sec)	0	0	0	0	0	0	0	0	0	0	0	0
74	From: Line 11	365.7222	378.4138	331.1286	357.7237	332.9882	391.0484	346.3612	359.0777	348.1407	374.0865	331.2442	381.1504
75	Line 13	490.6678	507.6953	444.2556	479.9367	446.7505	524.6464	464.6923	481.7533	467.0797	501.8897	444.4107	511.3669
76	Line 15	654.2237	676.9271	592.3408	639.9156	595.6673	699.5286	619.5897	642.3377	622.7729	669.1862	592.5476	681.8225
77	Line 17	1115.303	1154.007	1009.806	1090.911	1015.477	1192.537	1056.26	1095.04	1061.686	1140.81	1010.159	1162.352
78	Line 19	3438.566	3557.894	3113.313	3363.364	3130.797	3676.686	3256.532	3376.094	3273.263	3517.209	3114.4	3583.624
79	Line 21	4119.857	4262.827	3730.16	4029.754	3751.108	4405.156	3901.755	4045.007	3921.801	4214.08	3731.462	4293.655
80	Line 23	5906.158	6111.119	5347.495	5776.989	5377.527	6315.158	5593.492	5798.855	5622.229	6041.236	5349.363	6155.313
81	Line 25	6903.339	7142.904	6250.353	6752.361	6285.455	7381.394	6537.883	6777.919	6571.472	7061.223	6252.535	7194.561
82	Line 27	8403.656	8684.3	7599.142	8209.48	7641.819	8974.254	7948.719	8240.553	7989.556	8584.993	7601.795	8747.104
83	Line 29	11732.79	12139.95	10622.98	11476.19	10682.64	12545.28	11111.66	11519.62	11168.75	12001.12	10626.69	12227.74
84	Line 31	16967.3	17556.11	15362.37	16596.22	15448.64	18142.28	16069.07	16659.04	16151.63	17355.35	15367.73	17683.08
85													
86													

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