Analytical Prediction of Moisture Absorption in Composites

D. R. Tenney*
NASA Langley Research Center, Hampton, Va.
and
J. Unnam†
Virginia Polytechnic Institute and State University, Blacksburg, Va.

The moisture absorption/desorption behavior of resin matrix composites was mathematically modelled by classical diffusion theory using an effective diffusion coefficient. The appropriate diffusion equations were solved by a finite-difference technique allowing for time-dependent changes in the humidity and temperature of the environment. Calculations were made for conditions of periodically increasing or decreasing humidity at constant temperature. Good agreement was found between calculated moisture content and published data for T300/5208 graphite fiber-reinforced epoxy matrix composite. Weather Bureau data were used to calculate the amount of moisture a T300/5208 composite panel would contain if exposed outdoors. Calculations were made for different thickness specimens using weather information averaged on an hourly, monthly, and yearly basis. Solar radiation data, together with cloud and wind information, were included in the analysis to estimate an effective temperature of the composite panel during ground exposure. The results indicate that a composite panel exposed to solar heating will pick up approximately 30% less moisture than a panel exposed in the shade. Different flight scenarios were considered to determine the effect of flight service on the amount of moisture pickup expected for commercial aircraft applications.

I. Introduction

ADVANCED fiber-reinforced polymeric matrix composites have emerged as strong candidate materials for airframe applications. These materials are being used for secondary structures and are being considered for primary structures. However, structural integrity and life-cycle durability of these composites must be demonstrated for confident airframe design and widespread use.

Absorbed moisture degrades the matrix-dominated properties of fiber-reinforced epoxy composites,[1-10] particularly at elevated temperatures. This degradation in composite properties is attributed to the plasticizing effect of moisture on the resin system, which reduces the resin moduli over a wide temperature range, and lowers the glass transition temperature. The reductions in properties are functions of the amount of absorbed moisture,[10,11] and the original properties are recoverable upon drying.[10] The fact that the properties of the composite may be recovered upon removal of moisture is of little practical importance because of the difficulty of drying out large structures. On the other hand, the strength properties are expected to deteriorate only to specific values, depending on the equilibrium moisture content of the material.

Thus, the ability to predict the amount of moisture in a structure for a given service environment is important in determining allowable strength properties. The significant independent variables appear to be time, relative humidity, and temperature.[12] Although temperature is important in determining the kinetics of absorption/desorption, the average relative humidity encountered in actual service determines the equilibrium moisture content of the composite. For outdoor exposure, the ambient environment varies with geographical location and season of year. Also, solar heating of the composite panel will alter the surface temperature and therefore affect local relative humidity conditions at the surface. Aricraft utilization and flight conditions will further influence the equilibrium moisture level. Therefore, to predict the moisture content throughout the service life of a structure, all aspects of the service environment must be considered.

The primary objective of this study was to develop an analytical technique to predict the moisture content expected in resin matrix composites subjected to subsonic commercial aviation service. The moisture absorption/desorption behavior was mathematically modelled, using weather data to define ground exposure conditions and aircraft utilization data to define typical flight service environments. Solar radiation data, together with cloud and wind information, were included in the analysis to estimate an effective temperature of composite panels during ground exposure. The graphite fiber-reinforced epoxy composite material, T300/NARMCO 5208 was used for this study because it is the prime candidate material for several of NASA's current and planned flight service components, and because diffusion data as well as equilibrium moisture content versus humidity data were available.[12] Also, recent work[13] has shown that other epoxy resin composites (T300/Fiberite 934, T300/3M PR 313, Type AS/Hercules 3501-5, Type AS/Hercules 3502, Toray T300B/F&H Code 69, T300/Ferro CE9015, T300/Hexcel F178) have equilibrium moisture contents (at 98% RH) similar to that of T300/5208. Therefore, the predicted moisture contents in this study should be characteristic of several other graphite/epoxy systems.

II. Theory

Moisture absorption by resin matrix composites can take place by capillary action along the fiber/matrix interface, through cracks or voids in the resin, and by diffusion through the matrix. In large, well-bonded composite hardware, the primary mechanism is by surface absorption and diffusion through the matrix. Diffusion into the material in the direction normal (one-dimensional) to the surface can be mathematically described by

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial X^2} \tag{1}$$

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*Materials Engineer, Materials Research Branch.
†Research Associate, Materials Engineering Department.

where C is the moisture concentration of the composite at time t, X is distance from surface of panel, and D is the effective diffusion coefficient for the composite, treated as an isotropic material. If the panel absorbs moisture through both faces, the initial and boundary conditions to be satisfied are

$$C=C_0 \qquad 0\leq X\leq L/2 \qquad t=0 \tag{2}$$

$$C=C_s \qquad X=0 \qquad t>0 \tag{3}$$

$$\partial C/\partial X=0 \qquad X=L/2 \qquad t>0 \tag{4}$$

where C_0 is the initial moisture concentration, C_s is the time-dependent surface concentration, and $L/2$ is half the thickness of the laminate. The finite-difference expression (explicit-form second-order central difference) for Eq. (1) is given by

$$\frac{C_n^{j+1}-C_n^j}{\Delta t}=D\left(\frac{C_{n+1}^j-2C_n^j+C_{n-1}^j}{\Delta X^2}\right) \tag{5}$$

The superscripts j and $j+1$ designate time and the subscripts $n-1$, n, and $n+1$ designate grid point locations. The finite-difference expression for Eq. (1) at the center of the laminate ($X=L/2$) reduces to

$$\frac{C_N^{j+1}-C_N^j}{\Delta t}=2D\left(\frac{C_{N-1}^j-C_N^j}{\Delta X^2}\right) \tag{6}$$

where C_N is the concentration at the center of the laminate. The average moisture content of the panel was computed using,

$$\bar{C}=\int_0^{L/2} C\frac{\mathrm{d}X}{(L/2)} \tag{7}$$

To perform the finite-difference calculations, the grid spacing must be small enough to give convergent solutions of acceptable accuracy. Because an explicit formulation was used in the development of the the above equations, the time increment t was selected according to the stability requirement that

$$\Delta t\leq \Delta X^2/4D \tag{8}$$

Equations (2)-(8) were included in a general computer program written to perform the diffusion analysis.

An important input to the diffusion analysis is the relationship between equilibrium moisture content for the composite and humidity of the environment. For the T300/5208 graphite epoxy system with 30% resin content by weight, the equilibrium moisture content is equal to .01416 times the relative humidity expressed in percent (RH%).[12]

Whereas the equilibrium moisture content is determined by the relative humidity of the environment, the rate of absorption of moisture is controlled by the rate of diffusion in the composite. The effective diffusion coefficient depends on the diffusivity of the matrix, the diffusivity of the fibers, the volume fraction of the fibers, and the orientation of the fibers with respect to the exposed surface. Although analytical relationships among these parameters have been developed,[3] the simplest and perhaps most reliable method of obtaining the effective diffusion coefficient is to measure it experimentally for the composite laminates of interest. The effective diffusion coefficient is assumed to be of the form $D=D_0\ e^{-Q/RT}$ where D_0 and Q are determined experimentally. For absorption in T300/5208 system in the temperature range 297 K to 355 K, McKague and coworkers[12] determined that $D_0=1.415\times10^{-7}$ m²/s and $A=36{,}000$ J/mole. For desorption, they reported the same value for Q but different values for D_0, 1.415×10^{-7} at 297 K and 4.9×10^{-7} at 355 K. An average value of 3.158×10^{-7} m²/s was used for D_0 in the present study to determine the effective diffusion coefficient.

III. Results and Discussion

Static Laboratory Data Correlations

Figure 1 shows a comparison of calculated and experimental moisture contents for a sequentially increasing humidity environment. The thickness of the laminate was 8 plies and the exposure temperature was 297 K. The relative humidity of the environment was changed every nine days from a low of 15% to a high of 98%. The circles show the experimental data generated by McKague,[12] the dashed line gives the prediction of a model reported by McKague, and the solid line is the prediction of the analysis developed in this study. In general, the agreement between the two analytical predictions and experimental data is good. The mismatch between the predictions and the data in the 15% RH exposure may have been due to experimental difficulty in inserting specimens into the chamber without raising the chamber humidity.[12]

Figure 2 compares predicted and experimental moisture contents for sequentially decreasing humidities for an 8-ply T300/5208 laminate exposed at 297 K. The prediction of the present analysis is in good agreement with the experimental data. McKague's model does not accurately predict this case because the assumptions made in his solution are not valid for transient boundary conditions.

The results of these and other comparisons demonstrated that the finite-difference analysis accurately treated transient boundary conditions such as those expected for real-service environments.

Ground Exposure: No Solar Heating

To define ground exposure weather conditions, National Weather Bureau data tapes were secured for Norfolk, Va., and for Langley Air Force Base (LAFB) at Hampton, Va.,

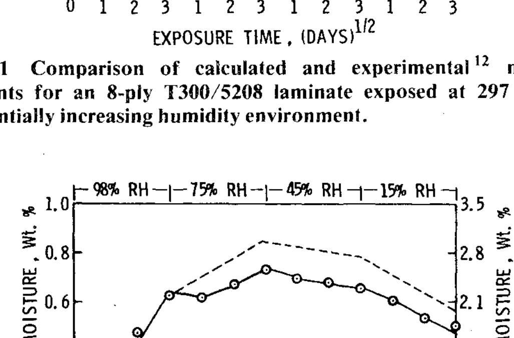

Fig. 1 Comparison of calculated and experimental[12] moisture contents for an 8-ply T300/5208 laminate exposed at 297 K to a sequentially increasing humidity environment.

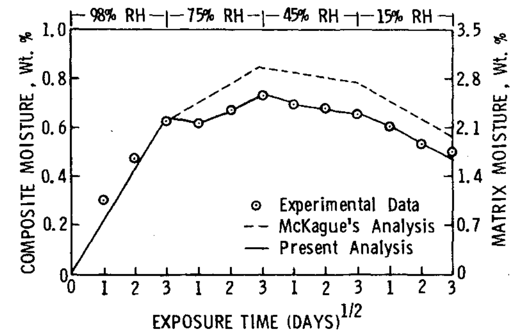

Fig. 2 Comparison of calculated and experimental[12] moisture contents for an 8-ply T300/5208 laminate exposed at 297 K to a sequentially decreasing humidity environment.

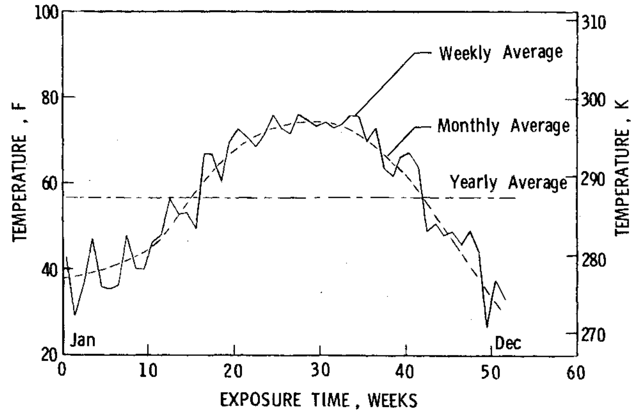

Fig. 3 Average temperature at LAFB for the year 1962.

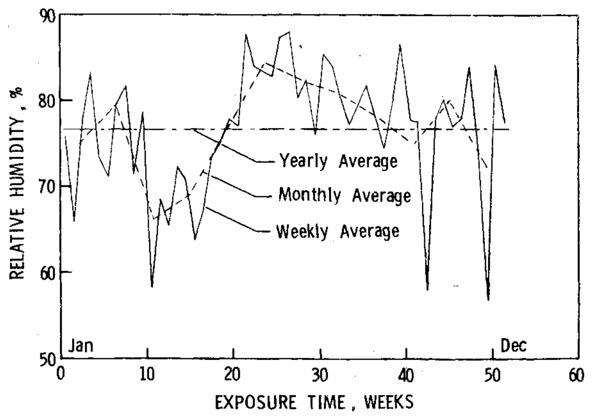

Fig. 4 Average relative humidity at LAFB for the year 1962.

The Langley weather tape contained hourly data for years 1954 to 1964, whereas the Norfolk tape contained data taken every three hours for the period 1969 to 1975. The data recorded on these tapes include: dry-bulb temperature, wet-bulb temperature, dew point, relative humidity, wind velocity, and type and amount of cloud cover. Figure 3 shows the temperature variation at LAFB for the year 1962 from January through December averaged on a weekly, monthly, and yearly basis. The daily or hourly fluctuations were larger than the averages shown. The yearly average temperature was approximately 287 K.

The variations in relative humidity over the same period similarly averaged on a weekly, monthly, and yearly basis are shown in Fig. 4. The yearly average relative humidity was 77%. The spring was the driest part of the year and the summer was the most humid.

Moisture contents calculated for 4-, 12-, and 24-ply panels of T300/5208 exposed for one year to 1962 LAFB weather conditions are shown in Fig. 5. Hourly temperature and relative humidity data were used for the calculations. The composite panels were assumed to have the same temperature as the ambient air (exposure in shade) and the air in contact with the panels was assumed to have the relative humidity determined from the data tape. The boundary conditions in the finite difference analysis were updated every hour and were assumed to remain constant over that hour. Further assumptions were made that the panels absorbed moisture through both faces and that the panels were large enough so that moisture absorption was essentially one-dimensional.

The thin laminate gained weight very rapidly and reached an equilibrium level that corresponded to the moisture content expected for the yearly average humidity condition. The moisture contents of the panels fluctuated due to fluctuations in the relative humidity of the environment. The thicker the laminate, the longer the time required to reach equilibrium

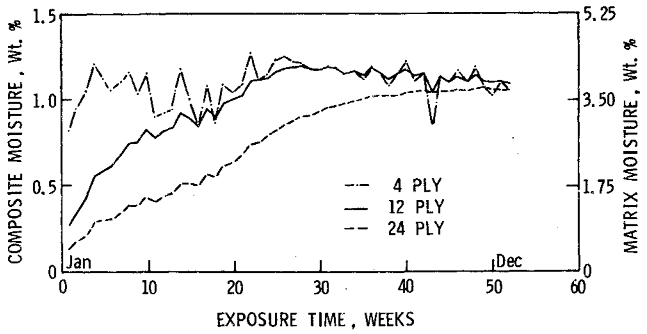

Fig. 5 Calculated moisture contents for 4-, 12-, and 24-ply T300/5208 laminates using hourly temperature and relative humidity conditions at LAFB for the year 1962.

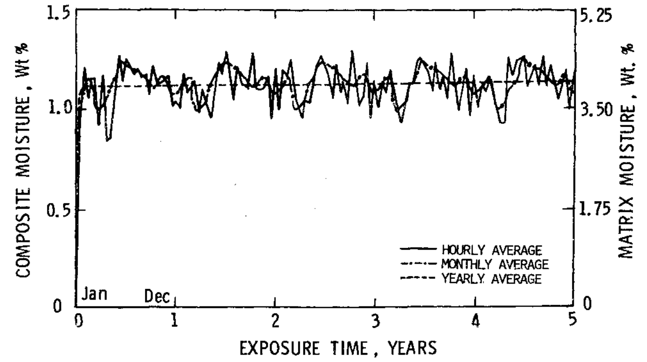

Fig. 6 Moisture contents for a 4-ply T300/5208 laminate calculated for a 5-yr period using hourly, monthly, and yearly weather data for LAFB.

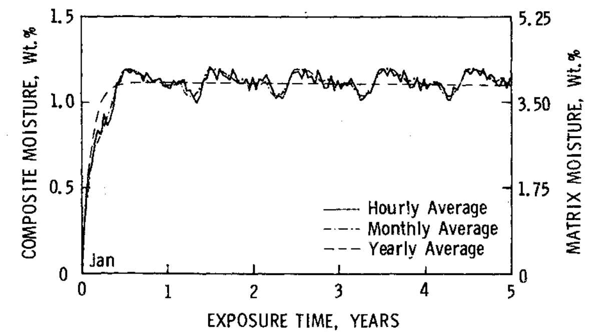

Fig. 7 Moisture contents for a 12-ply T300/5208 laminate calculated for a 5-yr period using hourly, monthly, and yearly weather data for LAFB.

and the smaller the fluctuations in the moisture content curve. However, at the end of the year, all the laminates contained essentially the same weight percent moisture. For a given type of composite, this level is determined by the solubility characteristics of the epoxy, volume fraction of fibers, and average relative humidity of the environment.

Because detailed weather data tapes cannot be obtained for every location, a study was conducted to determine whether monthly average weather data, readily available in National Weather Bureau publications, would be sufficient to adequately define the local weather conditions. Composite moisture contents for 4- and 12-ply laminates calculated using hourly, monthly, and yearly average data for LAFB are shown in Figs. 6 and 7. For both laminates, the moisture contents predicted with monthly averages agreed very favorably with the ones predicted with hourly averages.

Therefore, monthly average weather data were obtained from National Weather Bureau publications[14,15] for several locations in the continental United States and the world.

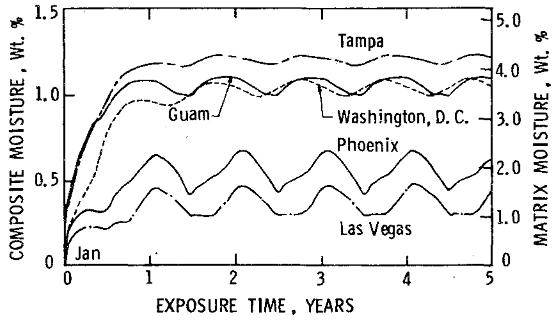

Fig. 8 Calculated moisture contents for 12-ply T300/5208 laminates using monthly average weather data for five different cities.

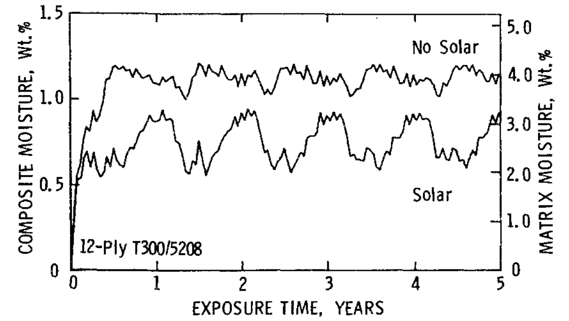

Fig. 9 Effect of solar radiation on the moisture content of a horizontal panel exposed at LAFB.

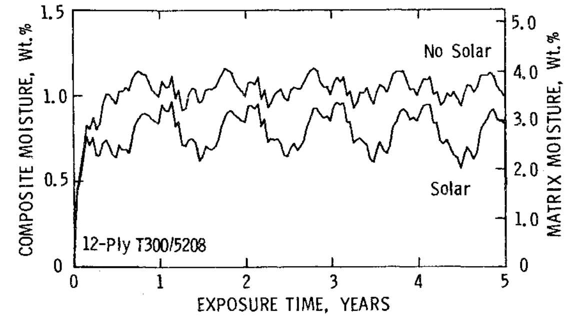

Fig. 10 Effect of solar radiation on the moisture content of a horizontal panel exposed at Norfolk, Va.

These locations included: Norfolk, Va.; Washington, D. C.; Pittsburgh, Pa.; Miami, Fla.; Tampa, Fla.; Atlanta, Ga.; Buffalo, N.Y.; Nantucket, Mass.; Phoenix, Ariz.; Las Vegas, Nev.; Oakland, Calif.; Anchorage, Al.; Fairbanks, Al.; Guam, Pacific; San Juan, P.R.; Rangoon, Burma; and Cristobal, Panama. The moisture absorption expected for outdoor exposure of T300/5208 at each of these cities was calculated using these data. Typical results are shown in Fig. 8 where curves for Tampa, Washington, D. C., Phoenix, Las Vegas, and Guam are shown. Phoenix and Las Vegas are typical of desert areas. The curves for all the other cities considered were close to the curves for Washington, D.C. and Guam, where the yearly average relative humidities were approximately 75%. These results suggest that, except for desert areas, a T300/5208 aircraft panel would pick up about the same amount of moisture for a given flight service, regardless of the specific cities included in the ground exposure portions of flight service.

Ground Exposure: Solar Heating

The foregoing results were calculated assuming that the temperature of the panel was the same as that of the ambient air. This is a reasonable assumption for a panel exposed in shade. However, if the panel is exposed to the sun, it will be heated well above the ambient air temperature on clear sunny days. This will increase the rate of diffusion of moisture in the panel and more importantly decrease the local relative humidity at the surface of the panel. Depending on the moisture content of the panel, moisture may be desorbed to the heated air next to the panel surface and transported away by convection resulting in a drying of the panel. To include solar heating in the analysis, a heat balance calculation was performed to determine the temperature of the panel as a function of time of day and year. Inputs for this calculation included: absorptivity of the panel, the latitude of the exposure location, the orientation of the panel surface, and the local weather conditions including ambient air temperature, wind velocity, and cloud cover. The details of the heat balance calculations and the analytical relationship used to compute the relative humidity of the air in the boundary layer at the panel surface are given in the Appendix.

The effect of solar heating on moisture absorption was determined for a 12-ply T300/5208 laminate exposed horizontally at LAFB and is shown in Fig. 9. The weather data for the year 1962 were used repetitively to calculate these curves. The panel exposed to solar heating absorbed 30-40% less moisture. Also the seasonal variations in moisture content are greater when solar heating is included because solar radiation is significantly more intense during summer than during winter.

Similar calculations were performed for Norfolk, Va., using weather data for 1975. The results are shown in Fig. 10. The moisture content curves are nearly identical to those for Langley shown in Fig. 9. On the other hand, calculation for a geographic location which has the same relative humidity as Langley or Norfolk, but has a significantly larger number of overcast days would predict a higher moisture content than observed for Langley or Norfolk.

Flight Service Predictions

To determine the effect of flight service on moisture absorption by resin matrix composites, the first task was to define a typical flight service environment. Although flight environments will vary with type of aircraft, an attempt was made to pick average conditions. Civil Aeronautics Board records[16] indicate that on the average, most commercial aircraft fly from 7-9 hours a day. Based on this, three 9-hour flight scenarios were considered. These were: "long-haul" day flights (8-12 A.M. and 1-6 P.M.); "short-haul" day flights (8-10 A.M., 11 A.M.-1 P.M., 2-4 P.M., and 5-8 P.M.); and "long-haul" night flights (8-12 P.M. and 1-6 A.M.). Average temperature and humidity variations with altitude for several locations about the U.S. were obtained from the literature.[14] Monthly average data shows that the temperature and relative humidity of the air at a typical flight altitude (6000 m) is not appreciably different regardless of where and when one flies. The absolute amount of moisture is small at 6000 m. However, because the temperature is very low, 231 K, the relative humidity is approximately 36%.

The effect of type of flight service on the moisture content of a 12-ply T300/5208 laminate over a five-year period is shown in Fig. 11. Curves are shown for long-haul service during the day and during the night, and short-haul service during the day. When the planes were not flying, they were assumed to be exposed to ambient air conditions at LAFB. Further assumptions were made that during flight, the temperature of the panel was 231 K, the relative humidity of the surrounding air was 36%, and the panel could lose or gain moisture through both faces. No solar radiation effects were included for the ground exposure.

The three curves are very close to each other, with the night flight resulting in the lowest moisture content. The primary reason for this is the fact that the night flight scenario avoided the relatively more humid conditions on the ground at night. Similarly, the short-haul day flight curve is slightly lower than the long-haul day flight curve because the flight

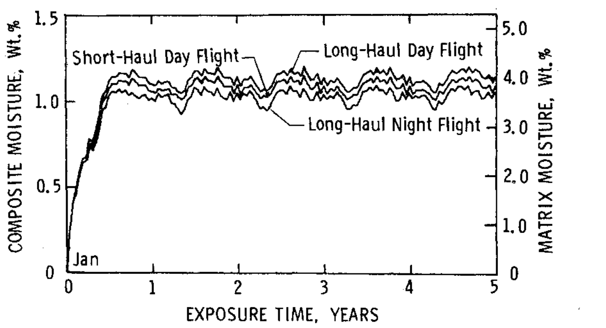

Fig. 11 Comparison of calculated moisture contents for three types of flight service.

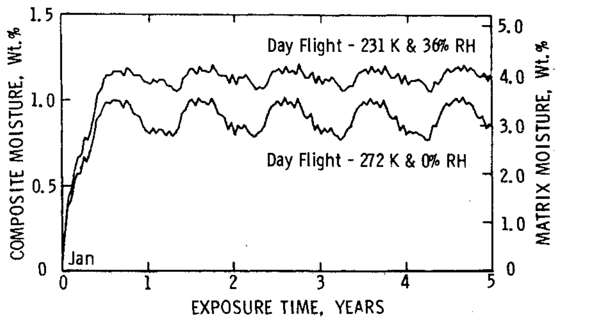

Fig. 12 Effect on the moisture content of skin temperature and boundary-layer humidity during flight.

hours included the evening hours (5-8 P.M.), which are generally more humid than the early afternoon periods.

Because the temperature is so low during flight, essentially no change occurs during flight. However, the skin temperature of a commercial aircraft is unlikely to be as cold as was assumed. Therefore, an additional calculation was made assuming that the skin temperature was 272 K instead of 231 K and that the effective relative humidity of the air in the boundary layer was 0% instead of 36%. A comparison of the moisture contents calculated for these two flight environments is shown in Fig. 12. The aircraft was considered to fly 9 hours per day (8-12 A.M. and 1-6 P.M.) and to remain in shade at LAFB for the balance of the day. The calculated moisture content is about 20% less for the 272 K skin temperature than for the 231 K case. If the skin stays relatively warm during flight, significant drying can occur. Data on actual skin temperatures during flight are not available in the literature for composite skins and verification of assumptions awaits more definitive data.

The combined effects of long-haul day flight (272 K and 0% RH) and solar heating while the plane is on the ground are shown in Fig. 13. These curves were calculated using ground exposure and solar heating data for LAFB for that period when the plane was on the ground. Inclusion of solar heating in the calculations results in a decrease in the equilibrium moisture content to approximately .75 composite weight percent.

Because the aircraft is flying during the time of day that solar heating is important, the moisture contents calculated with and without solar heating are not appreciably different. If the plane were to fly at night and stay on the ground during the day, solar heating would be much more important.

IV. Summary and Conclusions

The absorption of moisture by resin matrix composites subjected to subsonic commercial aviation service conditions has been analytically treated by using weather data to define ground exposure conditions and diffusion theory to describe the kinetics of moisture absorption. Aircraft utilization data were used to define typical flight scenarios. Solar radiation data and cloud and wind information were included in the analysis to estimate an effective temperature of the composite panel during ground exposure. The T300/5208 graphite/epoxy system was selected as the model system for this study. Because several epoxy resins have equilibrium moisture contents similar to that of NARMCO 5208, the moisture contents calculated in this study should be typical of those calculated for several other graphite/epoxy systems. Based on the results obtained, the following conclusions can be drawn:

1) Good agreement was found between calculated and experimental moisture contents for varying humidity conditions at constant temperature. This agreement demonstrated that the finite-difference analysis employed in this study is capable of accurately treating transient boundary conditions, a necessary requirement for treating real-service environments.

2) Moisture content calculations with hourly, monthly, and yearly averaged weather data show that the equilibrium moisture content fluctuates about the yearly value, with amplitude and frequency dependent on the laminate thickness and magnitude of temperature and relative humidity changes in the weather.

3) Composite moisture contents calculated with monthly averaged weather data were not significantly different from those calculated with hourly data.

4) Calculations made for several locations around the world showed that, except for desert type areas, approximately the same moisture level was found in a 12-ply laminate after a 1-year exposure period. These results suggested that, excluding desert areas, a T300/5208 aircraft panel would pick up about the same amount of moisture for a given flight service, regardless of the specific cities in the ground exposure period of flight service.

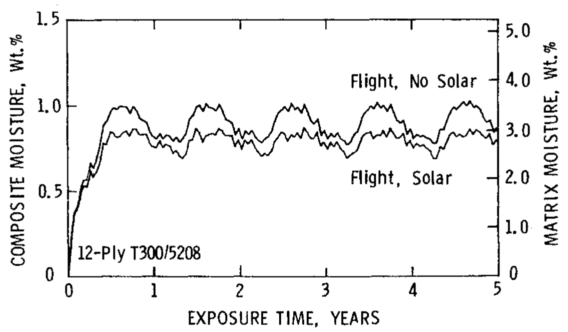

Fig. 13 Comparison of moisture contents for flight service with and without a correction for solar heating during periods of ground exposure.

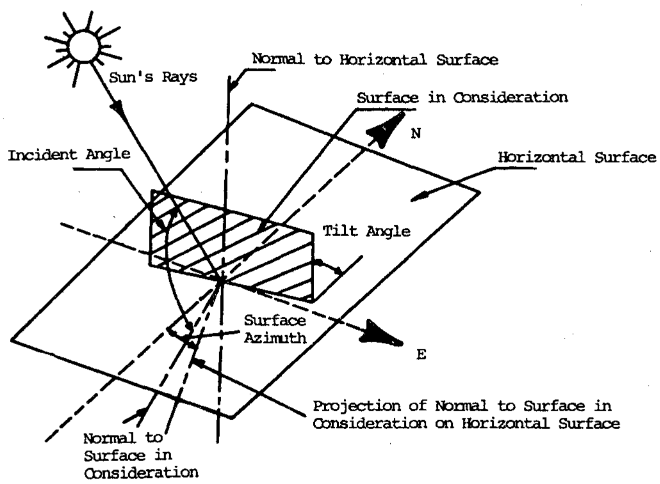

Fig. 14 Schematic of panel orientation parameters.

5) Calculated equilibrium moisture content for a panel continuously exposed in a horizontal position at LAFB was about 30% less when solar heating was included in the analysis than when shade conditions were assumed. Seasonal fluctuations in composite moisture content are greater when solar heating is included due to the difference between the intensity of solar radiation from summer to winter.

6) Based on flight utilization data for commercial aircraft service, three flight scenarios were considered. The flight conditions were assumed to be 231 K and 36% relative humidity, typical of ambient conditions at 6000-m altitude. The results indicate that the equilibrium moisture level depends primarily on the ground relative humidity during nonflight hours, and the flight service does not have a large effect on equilibrium level. Calculations were also made with 272 K and 0% relative humidity, perhaps more indicative of the actual flight conditions. The equilibrium moisture level was about 20% less for this condition than for the 231 K and 36% RH condition. Inclusion of solar heating in these calculations results in a decrease in the equilibrium moisture content to approximately .75 composite weight percent.

Appendix: Solar Heating Calculations

Algorithms published in a report[17,18] entitled, "NECAP-NASA's Energy-Cost Analysis Program," were employed in this investigation to calculate the amount of direct and diffuse solar radiation incident on a flat surface as a function of geographical location, time of day, and year. NECAP is a comprehensive computer program developed to perform heat balance calculations on buildings to determine optimum heating and air-conditioning systems. The subroutines used in NECAP to perform solar heating calculations were added to the moisture analysis program of this investigation. A detailed discussion of the solar radiation calculations can be found in Refs. 17-19, and therefore will not be repeated in this paper. However, the essential features of the calculations are given below.

To perform a solar radiation calculation, the latitude and longitude of the exposure location, the clearness number for the atmosphere,[19] and the orientation of the panel must be specified. The pertinent panel orientation information is illustrated in Fig. 14. If the panel is not horizontal, it is necessary to specify the surface tilt angle from horizontal, and surface azimuth angle with respect to south.

For each day of the year, the time of sunrise and sunset (when solar altitude is zero), apparent solar constant, atmospheric extinction coefficient, and sky diffuse factor were computed. This information was used to calculate, on an hourly basis, the direction cosines of sun's rays, the intensity of direct normal solar radiation and diffuse radiation (brightness of sky). For this calculation, the atmosphere was assumed to be clear (no clouds). To account for cloud cover, the total intensity was multiplied by a cloud cover modifier which varied between 0.3 and 1.0.[18] The cloud cover modifier was calculated on an hourly basis as a function of solar altitude angle, cloud type, and total cloud amount. The cloud type and total cloud amount were determined from the Weather Bureau data tape for the location of interest.

To perform a heat balance calculation for the panel exposed to solar radiation, the following expression was used:

$$Q = q_1 + q_2 - q_3 \tag{A1}$$

where q_1 is the absorbed solar radiation (direct, diffuse, and ground reflected), q_2 is the heat transfer due to convection and long-wave radiation, and q_3 is the heat loss by reradiation. These quantities are given by the following expressions:[18]

$$q_1 = \alpha\beta I_s \tag{A2}$$

$$q_2 = h_0 (T_{db} - T_p) \tag{A3}$$

$$q_3 = a \cos\phi (10 - \gamma) \tag{A4}$$

where

α = absorptivity of panel surface to radiation in solar spectrum
β = cloud cover modifier
I_s = total solar radiation intensity (direct, diffuse and ground reflected), $J/s/m^2$
h_0 = overall film coefficient for the surface (includes convection and long-wave radiation) $J/s/m^2/K$
T_{db} = dry-bulb temperature of ambient air, K
T_p = surface temperature of panel, K
a = 6.305, $J/s/m^2$
ϕ = angle between zenith and outward normal of panel
γ = cloud amount index (varies from 0-10)

The overall film coefficient h_0 was calculated as a function of wind velocity obtained from the weather tape. Reference 18 gives equations for h_0 as a function of wind velocity and type of surface. Coefficients are tabulated for a number of surfaces including brick, concrete, rough plaster, smooth plaster, glass, stucco, etc. The values reported for smooth plaster were selected as being closest to that expected for a graphite/epoxy surface.

If steady-state conditions are established at the specimen surface, then $Q = 0$ and we have

$$\alpha\beta I_s + h_0 (T_{db} - T_p) = a \cos\phi (10 - \gamma) \tag{A5}$$

Solving for T_p gives

$$T_p = T_{db} + [\alpha\beta I_s - a \cos\phi (10 - \gamma)]/h_0 \tag{A6}$$

For a horizontal surface, $\cos\phi = 1$ and Eq. (A6) reduces to

$$T_p = T_{db} + [\alpha\beta I_s - a(10 - \gamma)]/h_0 \tag{A7}$$

In the present analysis, the entire panel was assumed to be at temperature T_p. Also the temperature of the air in contact with panel surface, T_e, was assumed equal to T_p. This temperature, T_e, along with the dew point, T_{dp}, of the ambient air was used in an approximation formula reported by Bosen[20] to calculate the relative humidity of the air in the boundary layer. Bosen's expression for relative humidity is

$$\mathrm{RH} = \left(\frac{1.80T_{dp} - .18T_{db} - 240.46}{1.62T_{db} - 240.46}\right)^8 \tag{A8}$$

This expression was evaluated by setting $T_{db} = T_e$ and obtaining T_{dp} from the weather data tape.

References

[1] Powell, J. H. and Zigrang, D. J., "The Moisture Absorption and Desorption Characteristics of Three Epoxy-Graphite Systems," *National SAMPE Technical Conference Series*, Vol. 8, Oct. 1976, pp. 224-243.

[2] Bergmann, H. W. and Dill, C. W., "Effect of Absorbed Moisture on Strength and Stiffness of Graphite-Epoxy Composites," *National SAMPE Technical Conference Series*, Vol. 8, Oct. 1976, pp. 244-256.

[3] Augl, J. M. and Berger, A. E., "Moisture Effect on Carbon Fiber Epoxy Composites," *National SAMPE Technical Conference Series*, Vol. 8, Oct. 1976, pp. 383-427.

[4] Maske, E. B., Waddoups, M. E., Howeth, M. S., Fant, J. A., and Lasalle, R. M., "Final Report on Wing/Inlet Composite Advanced Development," General Dynamics Corp., Fort Worth, Texas, AF-FDL-TR-76-88, Sept. 1976.

[5] Ishai, O., "Environmental Effects on Deformation, Strength, and Degradation of Unidirectional Glass Fiber Reinforced Plastics," *Polymer Engineering and Science*, Vol. 15, July 1975, pp. 486-499.

[6] Hofer, K. E., Larsen, D., and Humphreys, V. E., "Development of Engineering Data on the Mechanical and Physical Properties of Advanced Composite Materials," AFML-TR-74-226, Feb. 1975.

[7]Verette, R. M., "Temperature/Humidity Effects on the Strength of Graphite/Epoxy Laminates," AIAA Paper 75-1011, Los Angeles, Calif., Aug. 1975.

[8]Sumsion, H. T., "Environmental Effects on the Torsional and Flexure Fatigue Properties of Graphite Epoxy," AIAA Paper 75-771, Denver, Col., May 1975.

[9]Browning, C. E. and Hartness, J. T., "Effects of Moisture on the Properties of High-Performance Structural Resins and Composites," *Proceedings of the Third Conference on Composite Materials Testing and Design*, American Society for Testing and Materials, 1974, pp. 284-302.

[10]Shirrell, C. D., Halpin, J. D., and Browning, C. E., "Moisture – An Assessment of Its Impact on the Design of Resin Based Advanced Composites," *Third Conference on Fibrous Composites in Fight Vehicle Design*, NASA TM X-3377, April 1976, pp. 405-425.

[11]Kelley, F. N. and Bueche, F., "Viscosity and Glass Temperature Relations for Polymer/Diluent Systems," *Journal of Polymer Science*, Vol. 50, April 1961, pp. 549-556.

[12]McKague, E. L., Reynolds, J. L., and Halkias, J. E., "Life Assurance of Composite Structures," Vol. 1, AFML-TR-75-51, May 1975.

[13]Kaminski, B. E., "Impact of Water Absorption on Composite Material Selection," General Dynamics Corp., Fort Worth, Texas, ERR-FW-1751, Dec. 1976.

[14]Ratner, B., "Upper-Air Climatology of the United States, Part 1 – Averages for Isobaric Surfaces," U.S. Weather Bureau, Washington, D. C., Tech. Paper 32, 1957.

[15]Conway, H. M. Jr. (ed.), *The Weather Handbook*, Conway Publications Inc., Atlanta, Ga., 1963.

[16]"Aircraft Operating Cost and Performance Report for Calendar Years 1973 and 1974," Bureau of Accounts and Statistics, Civil Aeronautics Board, Washington, D. C.

[17]Henninger, R. H., "NASA's Energy-Cost Analysis Program, Part I – User's Manual," NASA CR2590, Sept. 1975.

[18]Henninger, R. H., "NASA's Energy-Cost Analysis Program, Part II – Engineering Manual," NASA CR2590, Sept. 1975.

[19]Threlkeld, J. L., *Thermal Environmental Engineering*, Prentice-Hall Inc., Englewood Cliffs, N. J., 1962, pp. 309-339.

[20]Bosen, J. F., "An Approximation Formula to Compute Relative Humidity from Dry Bulb and Dew Point Temperatures," *Monthly Weather Review*, Vol. 86, Dec. 1958, p. 486.