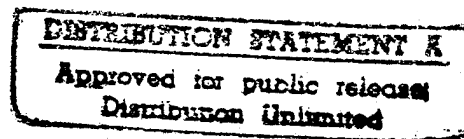


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NASA Contractor Report 187478

ENVIRONMENTAL EXPOSURE EFFECTS
ON COMPOSITE MATERIALS FOR
COMMERCIAL AIRCRAFT

Daniel J. Hoffman
William J. Bielawski



Boeing Commercial Airplane Group
Seattle, Washington

Contract NAS1-15148
April 1991

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Space Administration

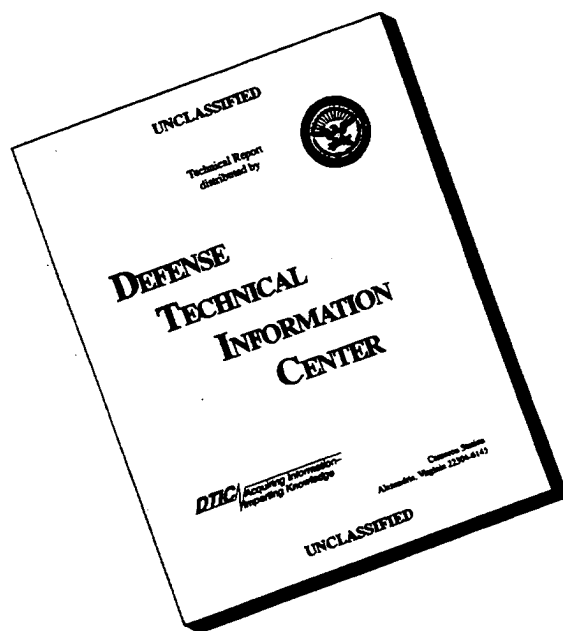
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April 1991



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Hampton, Virginia 23665-5225

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FOREWORD

This final report was prepared by Boeing Commercial Airplane Group representatives Daniel J. Hoffman and William J. Bielawski in Renton, Washington, under NASA contract NAS1-15148. It covers work performed between November 22, 1977, and December 31, 1990. The program was sponsored by the National Aeronautics and Space Administration, Langley Research Center (NASA-LRC). Mr. H. Benson Dexter was the NASA-LRC Technical Representative during the latter portion of the contract.

Key Boeing personnel associated with the program during the later stages include Program Manager Daniel P. Mooney and Technical Leader William J. Bielawski. Earlier contributors included Ronald K. Clark of NASA and the following Boeing personnel:

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The International System of Units (with parenthetic U.S. equivalents) is used for physical quantities throughout this report. Measurements and calculations were made in U.S. customary units.

1.0 SUMMARY

The expanded use of composite materials in primary aircraft structures requires an improved understanding of their durability. An experimental program was conducted from November 1977 to December 1990 to evaluate the influence of aircraft-associated environments on the performance of three composite materials systems that are available commercially. More than 7,000 specimens made from T300/5208, T300/5209, and T300/934 were exposed for as many as 10 years and then tested for residual strength.

Materials were purchased and processed according to existing specifications. Each material was evaluated for mechanical and chemical baseline properties before exposure. Large groups of specimens then were weighed, measured, assembled into fixtures, and deployed for exposure.

Sets of specimens were sent to three commercial airlines and deployed on Boeing model 737 aircraft flying in daily revenue service. The airlines, chosen for their willingness to support the required tasks and to provide a variety of flight environments, were Air New Zealand Ltd., Aloha Airlines, and Southwest Airlines.

Duplicate sets of specimens were sent to four separate ground exposure sites. Three locations were major operating bases of the three airlines involved in the program. The fourth site, NASA Dryden Flight Research Center, was selected because it provided a broad range of climatic features. Enough ground and aircraft specimen sets were deployed to permit returns and post-exposure evaluation after 1, 2, 3, 5, 7, and 10 years.

Specimen sets also were deployed to various controlled laboratory environments. The six laboratory exposures ranged from a simple exposure using only time as a parameter, to a complex exposure in a programmed temperature, pressure, and humidity chamber that simulated an aircraft ground-air-ground (GAG) cycle.

After 10 years of exposure, the tension and flexure specimens have shown little or no residual decrease in strength from baseline values; some specimens exhibited a residual-strength increase. The short-beam shear and compression specimens did decrease in strength, particularly after exposure to wet environments. Residual-strength tests conducted at elevated temperatures were best able to identify environmental effects.

Laboratory tests were able to reproduce qualitatively the effects observed on the long-term specimens. Ultraviolet radiation did not significantly affect the specimens as long as the protective paint coating remained intact. The freeze-thaw cycle normally encountered in the ground-air-ground cycle of commercial aircraft had no effect. Tests also showed that different materials displayed varying responses when they were exposed to similar environmental conditions.

2.0 INTRODUCTION

The past 18 years have brought dramatic changes in the application of advanced composite materials to commercial transport aircraft. In 1972, NASA sponsored the 737 graphite-composite flight spoiler service evaluation program. Five years later, Boeing began development work on a 727 elevator and a 737 horizontal stabilizer on the NASA-sponsored ACEE program (refs. 1 and 2). Other aircraft manufacturers built comparable flight demonstration articles (ref. 3). The knowledge derived from these early demonstration programs has contributed to more extensive and complex applications. For example, the Boeing baseline design for the 777 calls for a total composite empennage. The horizontal stabilizer on this aircraft will be larger than the entire 737 wing. Recent NASA-sponsored programs indicate that the future will bring even more applications (refs. 4 and 5).

Advances in the composite materials have also contributed to their increased use. The science of composite materials is relatively new and rapidly changing. The early 350°F cure epoxy systems are giving way to interlayer-toughened materials and newer manufacturing processes such as resin-transfer molding (RTM) that require matrix materials with specific flow characteristics. In order to take advantage of the advances in this maturing science, it will be advantageous to understand how to test for and predict long-term durability from short-term accelerated tests.

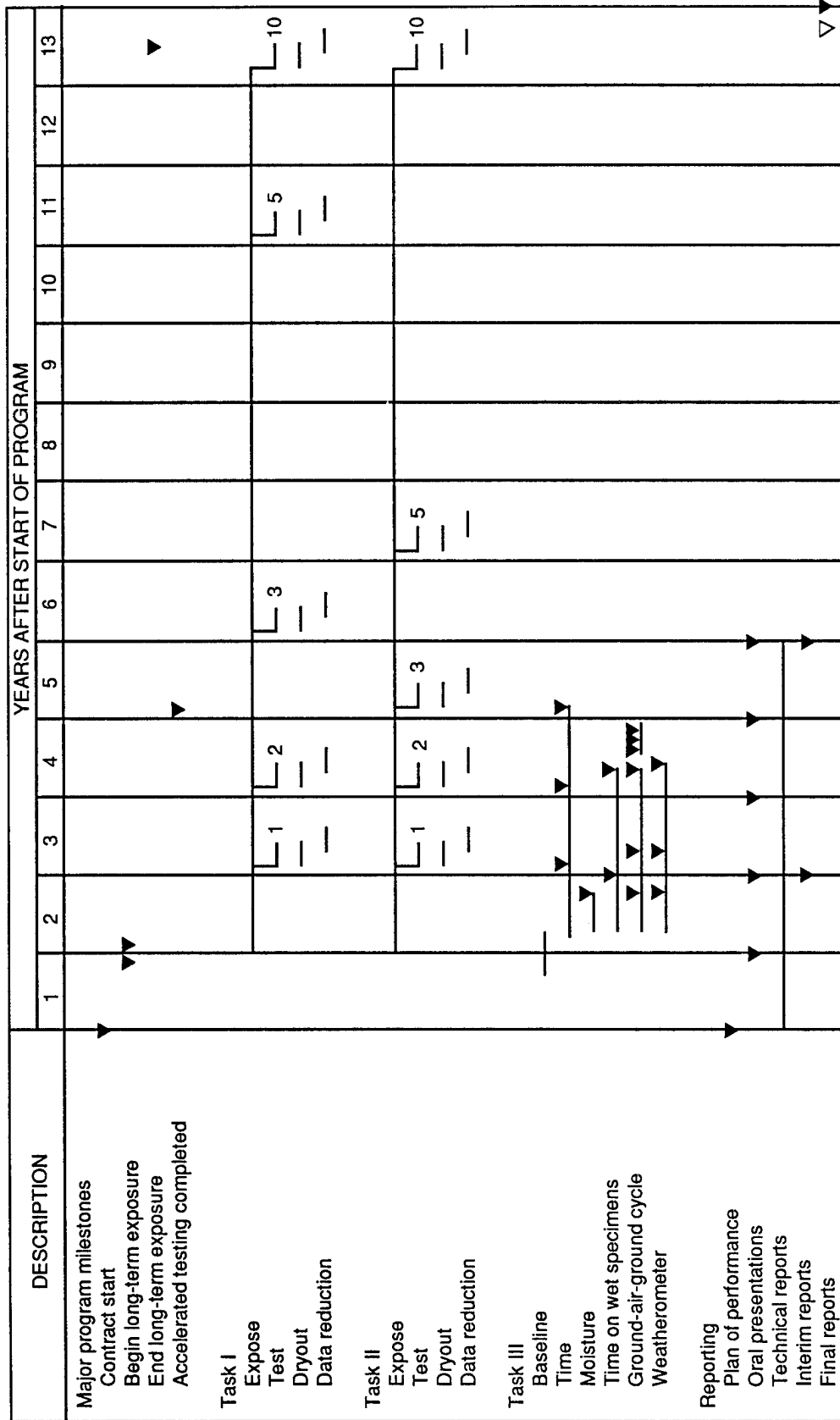
Under certain conditions, composite laminates absorb moisture. Absorbed moisture can degrade the mechanical properties of composite laminates, particularly at elevated temperatures. Aircraft components are frequently exposed to atmospheric moisture, rain, and accumulated (trapped) water. Quantitative data are required to show the amounts of fluids absorbed under various service conditions and the effect of this absorption on mechanical properties.

This program established and expanded a long-term environmental exposure database for three composite materials. Exposure included inflight and on-the-ground aircraft operational environments. The study also included accelerated laboratory exposure and a task to correlate the long- and short-term results.

The overall program had a duration of 13 years and involved three tasks:

- Task I, Flight Exposure, included--
 - Confidence through long-term exposure data.
 - Interior and exterior exposure on three different airlines for times up to 10 years.
 - Over 3,200 specimens.
- Task II, Ground Exposure, included--
 - Confidence through long-term exposure data.
 - Solar and nonsolar exposure at four different ground stations for times up to 10 years.
 - Over 3,200 specimens.
 - Baseline testing, including the effect of temperature.
- Task III, Accelerated Laboratory Exposure and Data Correlation, included--
 - Effect of time alone.
 - Accelerated tests to look at the combined effects of moisture, moisture and time, weatherometer, and simulated GAG cycling.
 - Over 1,200 specimens.
 - Correlation of long- and short-term results.
 - Recommended environmental test procedures.

A complete description of the program content was given in the first Quarterly Report (ref. 6). Other reports (refs. 7 through 21) have covered progress to date. The program schedule is shown in figure 1.



Note: Numbers on bar chart are numbers of years of exposure.

Figure 1. Program Schedule

3.0 SYMBOLS AND ABBREVIATIONS

C_v	coefficient of variation
D_{11}	bending stiffness
E	Young's modulus
GAG	ground-air-ground
MC	moisture content
NDI	nondestructive inspection
QI	quasi-isotropic
R&D	research and development
RH	relative humidity
RS	residual strength
RT	room temperature
RTM	resin transfer molding
σ	stress
t	specimen thickness
T_g	glass transition temperature
UV	ultraviolet
W	specimen width

4.0 MATERIALS AND PROCESSES

4.1 MATERIAL SELECTION AND PURCHASE

Materials selected for evaluation on this contract were chosen because of their prior or planned use on inservice demonstration components, and because they provided chemical makeup and cure temperature variables to the durability study. Because of the long-term nature of the planned program, no attempt was made to select the newest materials available. Components using all of these materials are in regularly scheduled commercial airline service as this report is being prepared.

The T300/5208 system was selected because of its widespread use on components in service at the beginning of this contract. The T300/934 system was selected because of its chemical and cure similarities to the 5208 system. Both systems were shown to possess similar environmental durability.

The T300/5209 system was selected because it is a 121°C (250°F) curing system. This system had been used successfully on the NASA-sponsored 737 graphite-epoxy spoiler evaluation. There were concerns, however, that the lower cure temperature would produce a less environmentally stable material.

Commercial products in this report are identified only to adequately describe them as test materials. Neither the identification of these commercial products nor the results of the investigation published herein constitutes official endorsement, expressed or implied, of any such product by either The Boeing Company or NASA.

Three materials were selected for evaluation:

- Narmco T300/5208 (material A).
- Narmco T300/5209 (material B).
- Fiberite T300/934 (material C).

Standard Boeing procedures were used to purchase the materials so that the resulting specimens would have characteristics representative of manufactured commercial aircraft structures.

4.2 MATERIAL PROCESSING

All specimen fabrication processes had two goals: to ensure production-quality specimens and to minimize batch-to-batch and process-variable effects.

Materials were purchased and controlled according to existing Boeing material specifications or modified versions of existing specifications. The T300/5208 system and the T300/934 system were purchased to comply with a Boeing material specification for epoxy preimpregnated graphite tapes cured at 177°C (350°F). The T300/5209 system was purchased to comply with a slightly modified version of the same specification. The primary changes for the 5209 system included a revised cure cycle and a reduced temperature for elevated-temperature property requirements.

Receiving inspection tests were conducted and their results made part of the baseline material characterization. Receiving inspection test results for all materials used on this contract can be found in references 7 and 8.

Once accepted, the material systems were processed according to existing process specifications or slightly modified versions of existing specifications. The modifications were essentially the same as those made at the time of purchase. No postcuring was used. The cure cycle for the 177°C (350°F) cure graphite systems is shown in figure 2. The cure cycle for T300/5209 is shown in figure 3.

To minimize material and process variables, all prepreg for a specific material system was procured from a single batch. Specimens also were cut from large, wide-area laminates. As an example, the 2,654 specimens required for the T300/5209 system were machined from only 10 laminates.

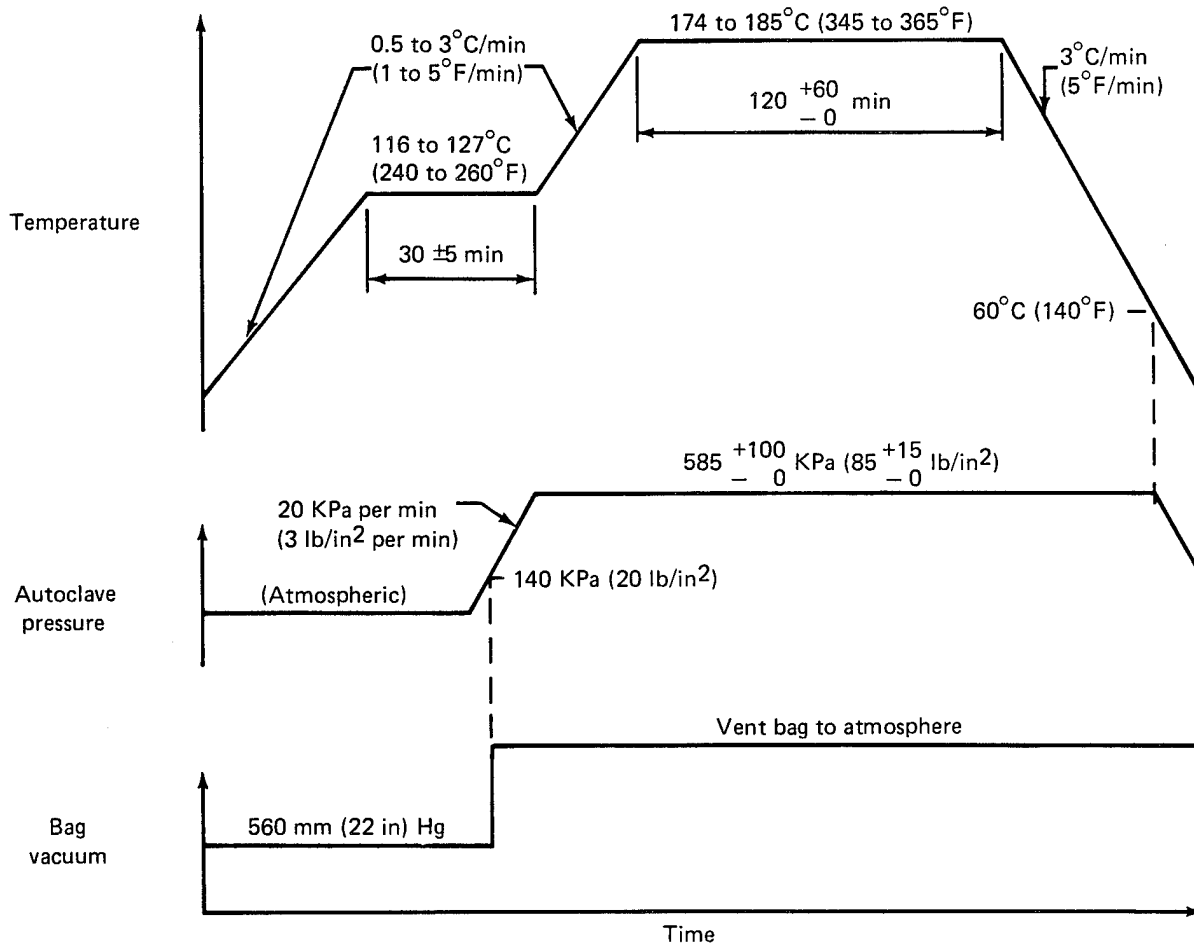


Figure 2. Cure Cycle for 177°C (350°F) Graphite-Epoxy Laminates

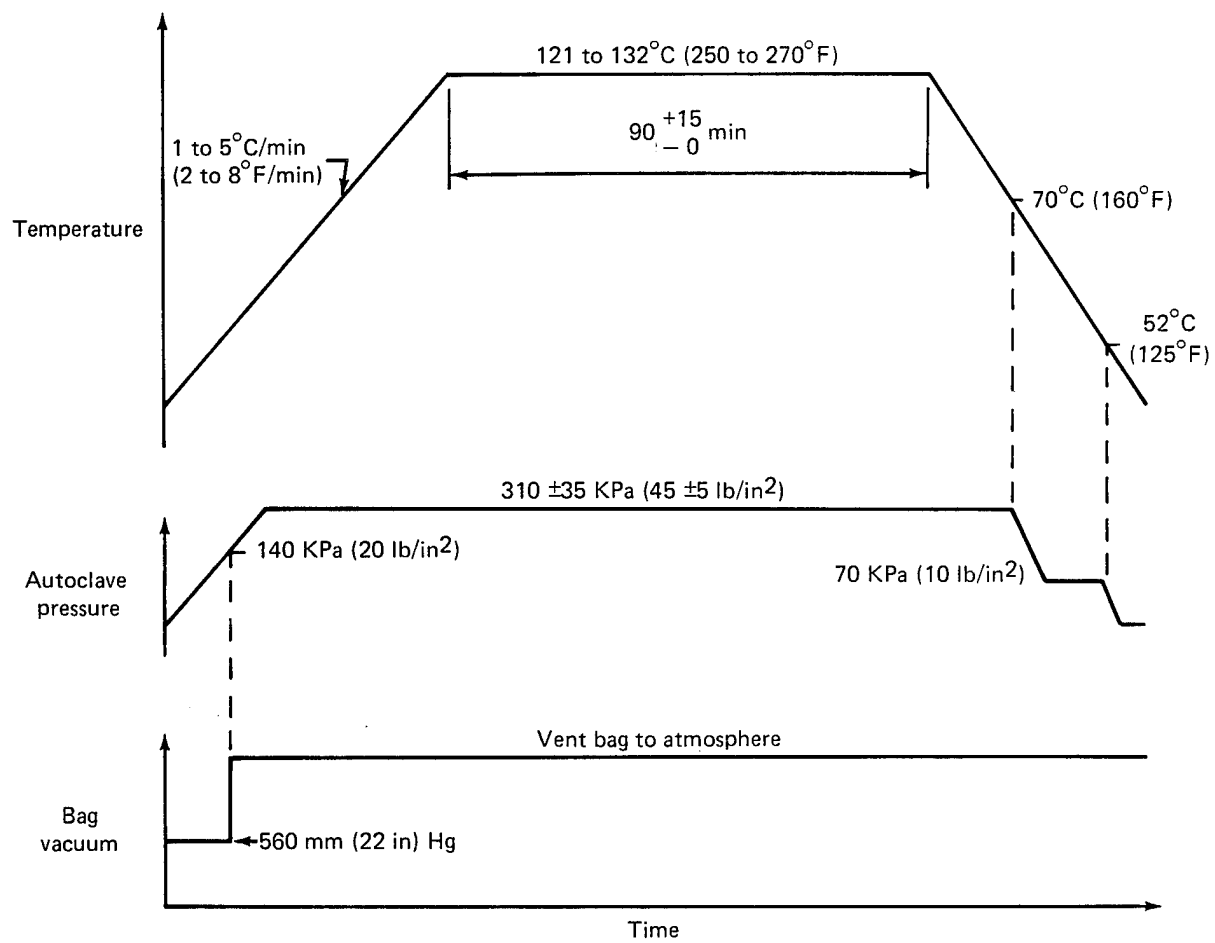


Figure 3. Cure Cycle for 121°C (250°F) Graphite-Epoxy Laminates

5.0 TEST SPECIMENS

Mechanical, physical, and chemical changes were monitored for all three advanced composite material systems. Most physical and chemical property measurements were made on mechanical property test specimens.

5.1 BASIC SPECIMENS

Four different mechanical test specimens were selected for evaluation and are found in all three tasks. They include tension, compression, short-beam interlaminar shear, and flexure. These specimens permitted a direct comparison between the long-term exposure data and the accelerated laboratory testing. The rationale for selecting each of these specimens was as follows:

- Unidirectional short-beam shear specimens provided an inexpensive test to determine relative change of matrix properties; this specimen provided an industry standard test, and was ideal for external flight exposure because of its small size.
- The crossplied flexure specimens could also be made small and were therefore well suited for external flight exposure. The 0-deg surface plies dominated the specimen strength, making the specimen fiber-dominated, but sensitive to surface degradation. This configuration allowed the plotting of a load-deflection curve during test, thereby providing some measure of stiffness change.
- The ± 45 -deg tension specimens produced matrix-critical data. The specimen had been used as an industry standard. This specimen also was stressed during exposure.
- The unidirectional compression specimens provided a surface-sensitive, matrix-critical specimen. Evidence suggested that this configuration would be the most discriminating of the four.

Engineering drawings of all specimen geometries appear in references 6 and 7. The four basic test specimens are shown in figure 4.

5.2 ADDITIONAL SPECIMENS FOR BASELINE CHARACTERIZATION

In addition to the four specimens, additional laminates of tension and compression specimens were added to the Task III accelerated laboratory test matrix. These specimens are--

<u>Specimen Configuration</u>	<u>Laminate Layup</u>
Compression	
Quasi-isotropic	$[\pm 45/0/90]_{3s}$
90 deg	$[90]_{20}$
Tension	
0 deg	$[0]_8$
Quasi-isotropic	$[\pm 45/0/90]_s$

The unidirectional laminate specimens were added to characterize more fully the material systems. The quasi-isotropic specimens were included to test the performance of the materials in a laminate that more closely resembled the actual structure.

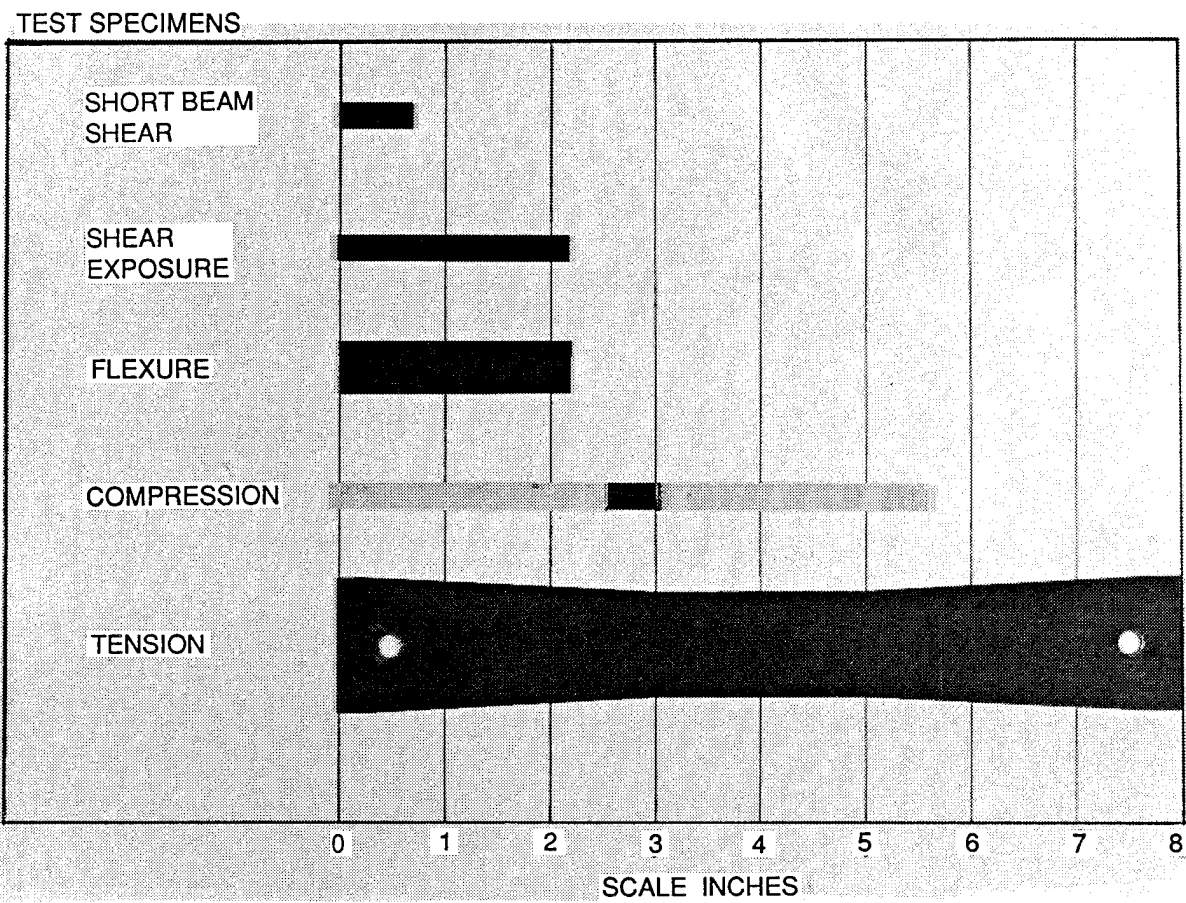


Figure 4. Basic Test Specimens

Specimens made from neat resin castings and specimens intended to evaluate the behavior of the paint film used in the long-term testing also were fabricated for Task III.

5.3 PROTECTIVE PAINT COATINGS

Composite structures in service require a coating to provide protection from ultraviolet (UV) radiation that degrades matrix material at the surface. All the long-term ground and flight specimens and half of the specimens in the weatherometer environmental exposure chamber were painted similarly to the NASA Aircraft Energy Efficient (ACEE) program structures. The complete coating consisted of one coat of primer and one coat of gloss enamel. The gloss enamel was a polyurethane exterior protective coating. The primer was corrosion-resistant and compatible with the gloss enamel. Most of the laboratory-exposed specimens were not painted because they received insignificant UV radiation.

Although the paint film afforded the required UV protection to the matrix, it also posed some problems. Among them were the following

- Absorption and desorption rates, as well as equilibrium moisture content levels, differed from those of the composite. (See section 5.5.)
- A method of specimen identification that would not interfere with test results had to be devised. (See section 5.4.1.)
- Irregularities in paint-film thickness because of edge buildup and runs meant that specimens sometimes were not perfectly aligned in their fixtures at the time of residual test. This could reduce the apparent residual strength and contribute to overall data scatter.

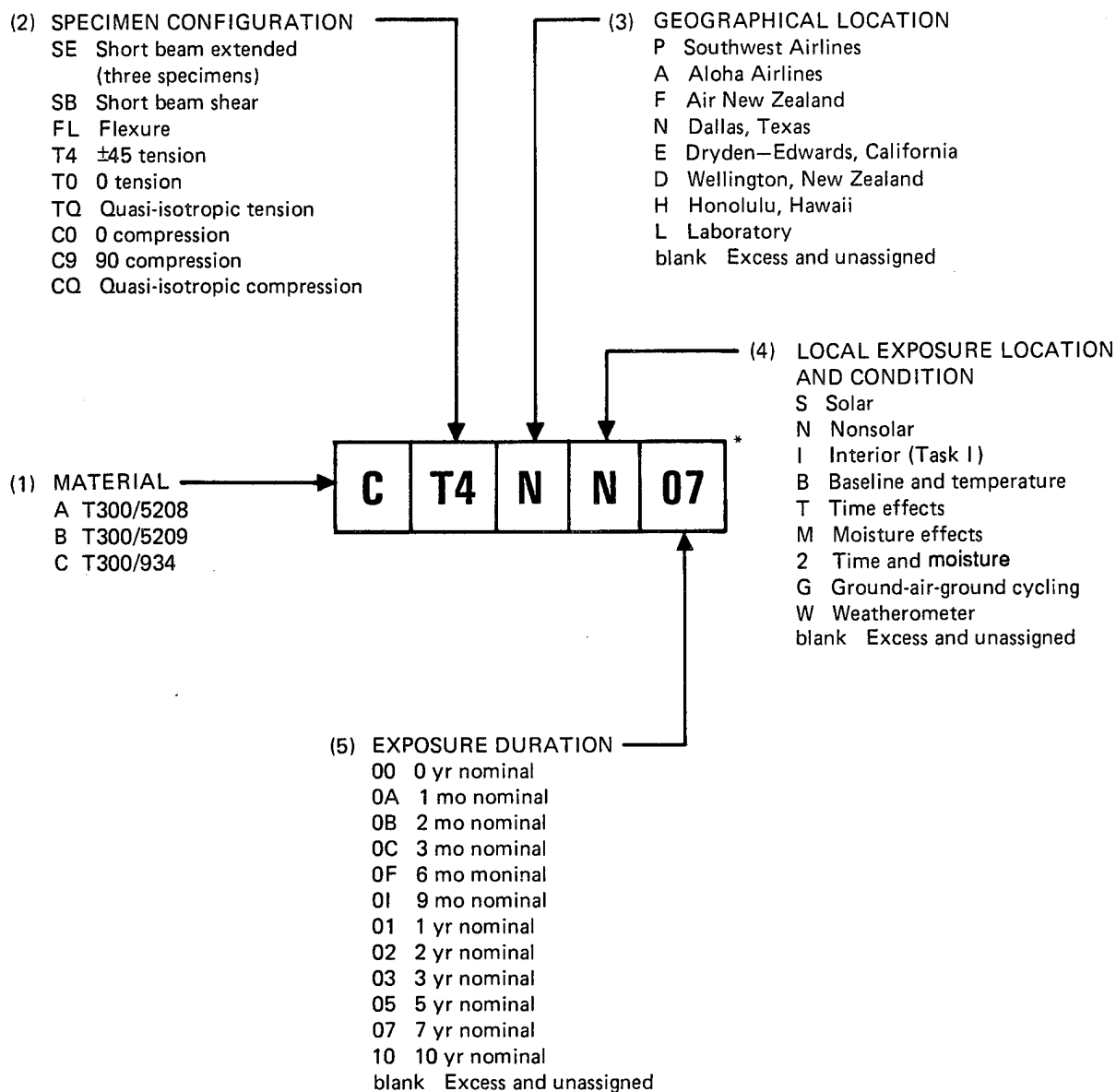
5.4 SPECIMEN IDENTIFICATION

5.4.1 SPECIMEN LABELING

Considerable time was required to identify and track specimens through weighing, measuring, painting, and reweighing. Because any method of identification capable of lasting through 10 years of exposure (e.g., vibro-etch) would have compromised the integrity of the test specimen or the paint film, a system involving stick-on labels was devised. A computer program generated the specimen numbers in a format that could be printed onto adhesive-backed paper and cut up into individual labels. These labels were initially applied to the specimens at the same time as the graphite-only weight and dimensions were recorded. Fixtures were built to hold the specimens during the painting operation. These fixtures provided a space adjacent to each individual specimen where the label could be placed during painting. Once the paint had dried, the labels were returned to the adjacent specimen.

5.4.2 SPECIMEN NUMBERING SYSTEM

A specimen numbering system was defined that identified the material system, specimen configuration, geographical exposure location, local exposure condition, and exposure duration. The seven-character alphanumeric identification scheme is summarized in figure 5.



*Material 934— ± 45 tension, Dallas (ground rack), nonsolar, exposed for 7 years

Figure 5. Specimen Numbering System

5.5 SPECIMEN WEIGHTS

The original test program plan called for recording specimen weights before and after exposure for the purpose of determining moisture content at testing time and to help determine items such as the time different specimen configurations take to reach equilibrium moisture level. Initially, weight measurements were planned for the following times.

- After storage in a drum under dry conditions at 25% to 30% relative humidity (RH), but before painting.
- After painting. (All of the long-term exposure specimens were painted, but most of the accelerated laboratory specimens were left unpainted.)
- After environmental exposure, but before mechanical testing or dryout.
- After dryout and before mechanical testing. (Most of the specimens were not dried before testing.)

These planned measurements were intended to provide comparisons of weight data collected before and after exposure; they also furnished the initial weight of the paint for painted specimens. In addition, many laboratory specimens were weighed throughout exposure to provide details of how exposure contributes to moisture gain and erosion. In general, the procedure of weighing specimens before and after exposure proved unacceptable for measuring or tracking absorbed moisture--especially when the exposure was to real-world conditions or complex environmental conditions in the laboratory.

Recording individual specimen weights was tedious and time-consuming. Because specimen configurations were intentionally small, weight changes because of moisture were very small. Much larger changes resulted from other factors, such as foreign substances (dirt, grease or hydraulic fluid) on the surface of the specimen, paint chipping, or paint degradation because of weathering. Outdoor specimens and those exposed in the laboratory weatherometer initially gained weight, but as time passed they actually lost considerably more weight than they had gained.

For some specific exposure conditions, such as tests limited to relative humidity effects, recording the weights for gross individual specimens may be an appropriate way of tracking moisture absorption. However, this method was not considered acceptable for most of the exposure conditions in this study. Individual specimen weights following exposure were not recorded after it became apparent that the data would serve no useful purpose. Unless specifically noted, weights and moisture contents published in this report are based on the specimen dryout procedure described in section 5.6.

5.6 TEST PROCEDURES

The following subsections briefly describe the testing procedures for all specimen configurations associated with this contract. Strengths for each exposure situation and material were averaged, and overall strength was reported as a percentage of baseline strength. Baseline values are considered to be 100%; therefore, strengths reported above 100% are stronger than baseline, and strengths reported below 100% are weaker than baseline. Baseline testing was performed at three temperatures: room temperature, 40°C (120°F), and 82°C (180°F). Environmentally exposed specimens were tested at room temperature and 82°C (180°F). Specimens were soaked at temperature for 5 min. Test results obtained for specimens exposed to the elevated temperature were compared with baseline tests for the elevated temperature.

5.6.1 SHORT-BEAM SHEAR

Short-beam shear testing is used to measure an apparent shear strength in composite materials. The shear strength is useful in comparative testing but should not be used for design. Testing was performed and strengths were calculated according to ASTM/ANSI standard D2344-76. The specimens were loaded in three-point bending. The support span dimension is a function of specimen thickness. For graphite-fiber-reinforced materials, the span/thickness ratio is 4. Spans for all specimens of each material were determined as a group using average laminate thicknesses. The resulting values were:

<u>Material</u>	<u>Span, mm (in)</u>
T300/5208	9.9 (0.39)
T300/5209	10.4 (0.42)
T300/934	11.2 (0.44)

Specimens were loaded to fracture in a universal mechanical testing machine at a crosshead deflection rate of 2.5 mm/min (0.1 in/min).

5.6.2 FLEXURE

The failure load of the crossplied flexure specimens used in this contract is dominated by the surface 0-deg plies; the specimens are therefore sensitive to surface effects. Testing was performed and strengths were calculated for extreme fiber stresses according to ANSI/ASTM standard D790-71. Specimens were loaded to fracture in three-point bending at a crosshead deflection rate of 2.5 mm/min (0.1 in/min).

5.6.3 TENSION

All tension testing was performed in either an Instron or a Tinius-Olson testing machine at a crosshead rate of 2.5 mm/min (0.1 in/min). The specimens were held in ordinary mechanical grips with serrated jaws. In addition to the 0-deg specimens, the stressed ± 45 -deg tensions were the only specimens with loading tabs; however, the jaw serrations did not adversely affect the testing quality of the untabbed specimens. Specimen response was monitored during each test with an extensometer, and a load-deflection curve was plotted up to specimen fracture. Fracture load was recorded for each test. Ultimate failure stress was calculated by dividing the failure load by the measured specimen cross-sectional area.

5.6.4 COMPRESSION

All compression testing was performed using Celanese-style compression specimens and fixtures. Tests showed that the load-deflection curves were more linear if a 13-mm (0.5-in) gage block was inserted between the Celanese fixture jaws and a load of 2,200N (500 lb) was applied. This preload was intended to align the jaws and set the jaw serrations into the specimen tab material without actually applying a load to the specimen.

Loading was performed at either a crosshead deflection speed of 2.5 mm/min (0.1 in/min) or a loading rate of 22 kN/min (5,000 lb/min).

5.6.5 SPECIMEN DRYOUT

One shear exposure specimen from each long-term exposure condition and for each material was reserved for a dryout procedure at the end of the deployment duration. Upon return to Boeing, the specimens were weighed and then placed in a 71°C (160°F) circulating-air oven. The specimen weights were tracked until the specimens stopped losing weight, a period usually lasting about 90 days. When dry, each specimen was divided into three short-beam shear specimens and tested in the usual manner.

The maximum weight loss incurred was found to be equal to the specimen moisture content at time of return. This value was found to represent the moisture content for all specimens of a particular material and exposure situation.

6.0 LONG-TERM FLIGHT AND GROUND EXPOSURE

6.1 EXPOSURE PLANS

The following sections describe flight exposure plans for Task I and Task II exposures.

6.1.1 TASK I--FLIGHT EXPOSURE PLAN

The plan for Task I exposure is shown in figure 6. The matrix covers--

- Participating airlines.
- Retrieval periods.
- Exterior and interior exposure.
- Material systems.
- Specimen configurations.
- Stress states.
- Replicate specimens.
- Residual test temperatures.

For the flight exposure plan, one basic interior or exterior specimen set for each composite material was deployed at each exposure site on the aircraft. (See section 6.4.1 for a detailed discussion of exposure sites.) Each airplane carried 98 specimens on the exterior and 81 specimens on the interior. Altogether, 3,222 specimens were deployed, with 1,074 specimens assigned to each of the three airlines over the course of the study. As each exposure period ended, a full specimen set was retrieved and returned to Boeing for testing and evaluation.

Initially, only the 1-, 2-, and 10-year flight exposure specimens were deployed. As specimens were retrieved, they were replaced with the 3-, 5-, and 7-year exposure specimens as follows.

- One-year specimens were replaced with 3-year specimens.
- Two-year specimens were replaced with 7-year specimens.
- Three-year specimens were replaced with 5-year specimens.

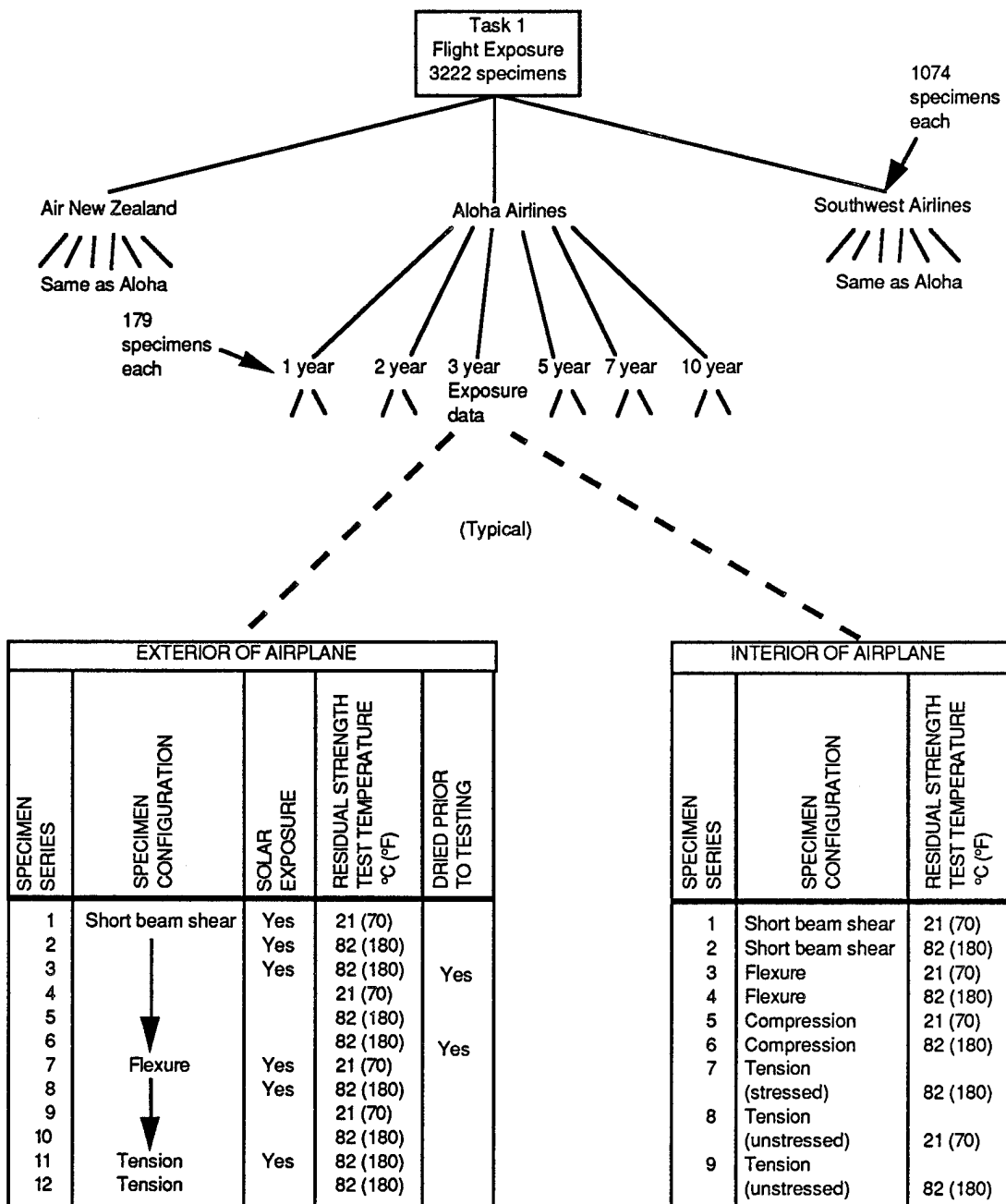
This deployment plan involved a minimum number of aircraft while keeping the total planned exposure duration within 10 years.

6.1.2 TASK II--GROUND EXPOSURE PLAN

The exposure plan for Task II testing is shown in figure 7. The matrix covers--

- Geographical exposure locations.
- Retrieval periods.
- Solar and nonsolar exposure.
- Material systems.
- Specimen configurations.
- Stress states.
- Replicate specimens.
- Residual test temperatures.

The plan called for 135 specimens to be retrieved and returned to Boeing at the end of each exposure period. Of these, 63 are from the solar exposure face and 72 are from the nonsolar face. All the ground-rack specimens for T300/5208, T300/5209, and T300/934 at each location were deployed on one rack.



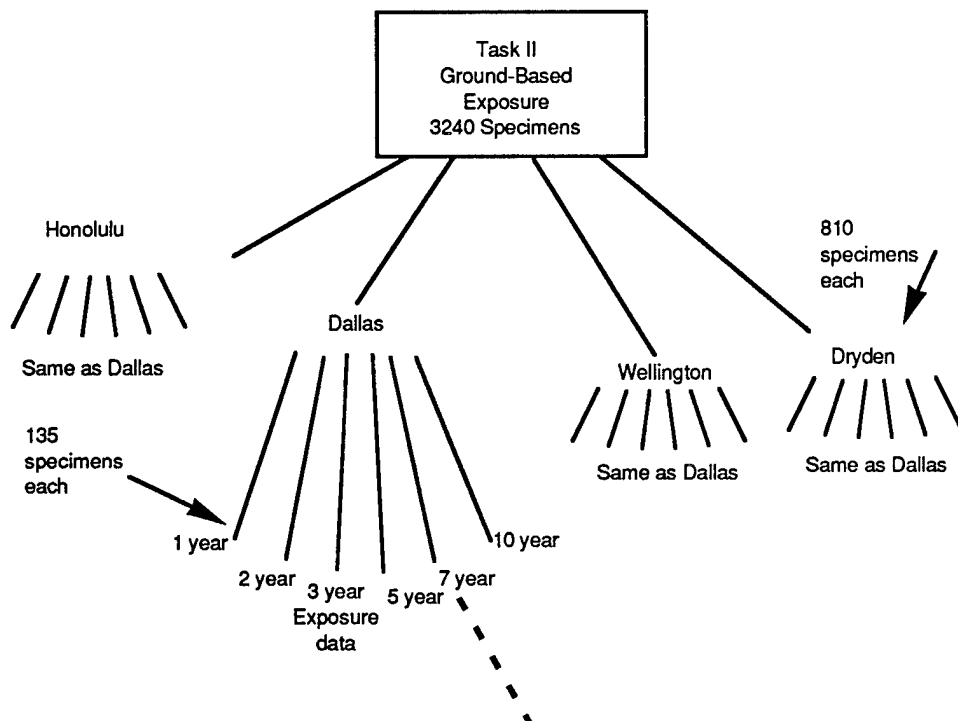
Note: (1) Matrix repeated for all three material systems, except that there are no tension specimens for T300/5209.

(2) Each specimen series contains three replicates except tension specimens which contain two replicates.

Note: (1) Matrix repeated for all three material systems.

(2) Each specimen series contains three replicates.

Figure 6. Flight Exposure Text Matrix



GROUND EXPOSURE DATA, Xth YEAR				
SPECIMEN SERIES	SPECIMEN CONFIGURATION	SOLAR EXPOSURE	RESIDUAL STRENGTH TEST TEMPERATURE °C(°F)	DRIED PRIOR TO TESTING
1	Short beam shear	Yes	21 (70)	Yes
2		Yes	82 (180)	
3		Yes	82 (180)	
4	↓		21 (70)	
5			82 (180)	
6			82 (180)	
7	Flexure	Yes	21 (70)	Yes
8		Yes	82 (180)	
9			21 (70)	
10	↓		82 (180)	
11			21 (70)	
12			82 (180)	
13	Compression		82 (180)	
14	Tension (stressed)		82 (180)	
15	Tension (unstressed)		82 (180)	
	Tension (unstressed)	Yes	21 (70)	
	Tension (unstressed)	Yes	81 (180)	

Note: (1) Matrix repeated for all three material systems.
(2) Each specimen series contains three replicates.

Figure 7. Ground Exposure Test Matrix

6.2 AIRLINE AND SITE SELECTION

Exposure locations for Task I flight exposure and Task II ground exposure were based on several factors. Three of the four ground sites were predesignated as major operating terminals of the selected Task I airlines, so that selection criteria were heavily biased toward the Task I requirements.

Individual factors that played a part in the selection process included--

- Airline route structure.
- Airline fleet size and willingness to support the program.
- General climatic factors within the area.
- Airline aircraft use.
- Political climate of the area.

No attempt was made to seek out arbitrary, worst-case environments. Instead, the selected sites represented typical environments expected for commercial transport structures.

A summary of the selected long-term exposure sites is shown in table 1. The selection criteria favored the use of regional airline carriers operating in a known climatic region. All three of the selected airlines had the required fleet size (six-airplane minimum) and expressed an interest in the program. Air New Zealand and Aloha Airlines had provided excellent support on similar programs in the past.

The general climatic factors within the airline route structure are summarized in figure 8. Honolulu's warm, moist conditions are typical of tropical climates, which provide a harsh environment for conventional aircraft structure and are considered a potentially severe condition for moisture absorption in composites. There is little variation in temperature or relative humidity throughout the year.

Wellington provides a cooler but more moist environment than Honolulu. Coupled with less solar heating, the Wellington specimens, on the average, were expected to contain more moisture than any of the other ground-rack specimens.

Historical climate data for Dallas show moderate and fairly constant relative humidity throughout the year, but an extreme range of temperatures.

Table 1. Flight and Ground Exposure—Locations and Participants

TASK I—FLIGHT EXPOSURE	TASK II—GROUND EXPOSURE	
AIRLINES	RACK LOCATION	COMMENT
Air New Zealand Ltd. Aloha Airlines Southwest Airlines	Wellington, New Zealand Honolulu, Hawaii Dallas, Texas NASA-Dryden Flight Research Center, California	Air New Zealand Headquarters Aloha Airlines Headquarters Southwest Airlines Headquarters

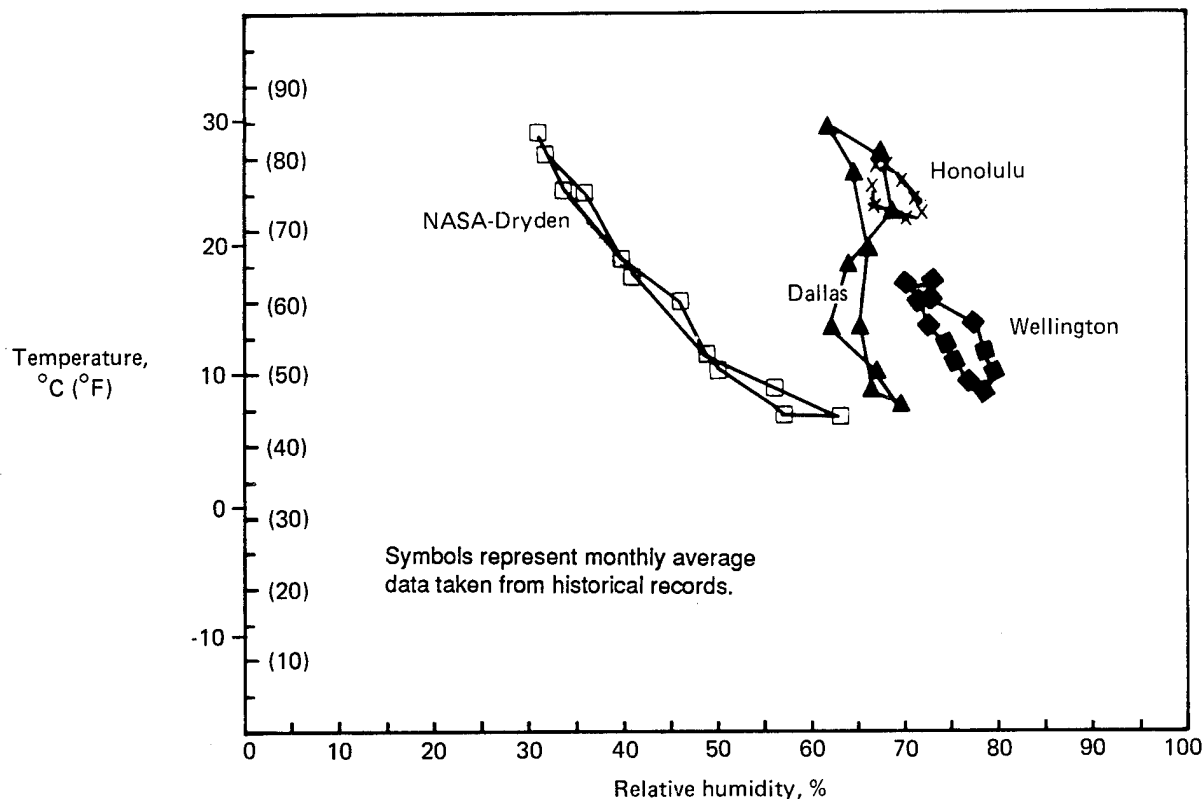


Figure 8. Ground Rack Climatic Data

The fourth ground exposure site was the NASA Dryden Flight Research Center at Edwards Air Force Base, California. This site represents arid to semiarid desert-like regions and shows a large, seasonal variation ranging from cool and moist to very hot and dry. Based on monthly averages, it never gets as wet as Honolulu. The Honolulu specimens were expected to absorb moisture to some equilibrium level and then change relatively little thereafter. The Dryden specimens, on the other hand, were expected to undergo an annual absorption-desorption cycle for their entire exposure duration. The residual strength tests were to assist in determining the relative severity of these two kinds of exposure.

The airline aircraft history of use also played a part in the selection process. Typical flight profiles for the three selected airlines are shown in figure 9.

Aloha Airlines, which provided a unique flight environment, represents one extreme of a flight-usage spectrum. Flights occur generally only during daylight hours and are flown in the area bounded by the Hawaiian Islands. Their hour-per-day usage rate is relatively low, but because of an extremely short flight length, they accumulate numerous flight cycles.

Air New Zealand operates 737s in a maritime environment, and all airfields either have overseas approaches and departures or are located close to the coast. Flights have a greater variation in range than Aloha Airlines, have longer average flight durations, and fly at higher average altitudes.

Southwest Airlines, on the other hand, operates in a more arid environment. Flight range and duration are between that of Air New Zealand and Aloha Airlines.

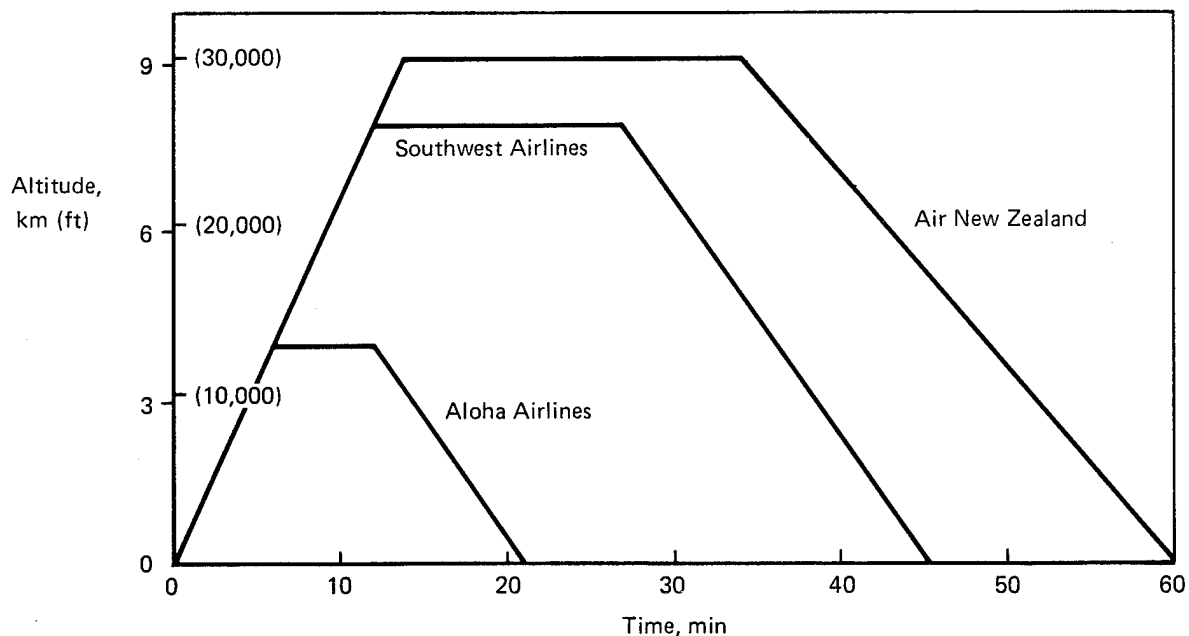


Figure 9. Typical Flight Profiles

6.3 TEST SPECIMEN HOLDING FIXTURES

Because of the numerous small specimens involved in the program, fixtures were designed to hold them in groups. This facilitated deployment and simplified identification and tracking. Short-beam shear and flexure specimens were housed in the fixture shown in figure 10. This fixture was designed to hold up to six flexure specimens and up to three shear exposure (nine short-beam shear) specimens. Compression specimens were housed as groups of six in a similar fixture, shown in figure 11. The production drawing for both fixtures is shown in appendix B of reference 7.

The holding fixture for stressed-tension specimens was designed to minimize size and weight while maintaining a sustained stress through a large variation in temperature. A cutaway of the completed fixture is shown in figure 12. It consists of a ventilated titanium tube, with its characteristically low coefficient of thermal expansion, and a custom aluminum clevis that compensated for the near-zero thermal expansion of the graphite test specimen. The length of the tube and the clevis were calculated so that the thermal expansion of the tube just equaled the thermal expansion of the specimen plus the aluminum clevis.

Load was applied with the aid of a Bellville spring washer located just outside the endcap. The production drawing for this fixture was presented in reference 7. The stressed tension specimens are loaded with a deadweight load procedure that accounts for springback in the test fixture. A target load of 1,100N (250 lb) was established to provide a reasonable stress level for determining differentiation with the unstressed specimens. This load produced a sustained stress of 22% to 24% of RT baseline tensile strength, depending on the material system. A complete development of the procedure used to achieve this constant load is given in reference 9.

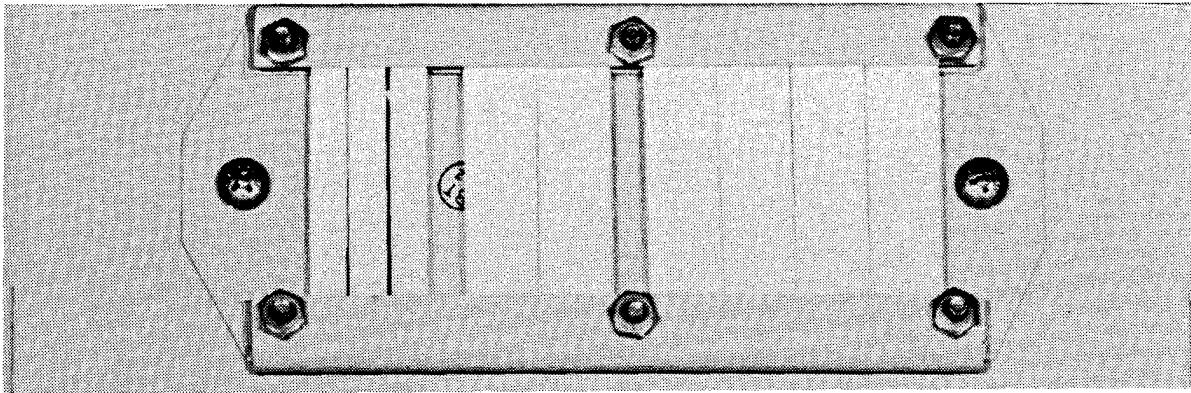


Figure 10. Short Beam Shear and Flexure Specimen Holding Fixture

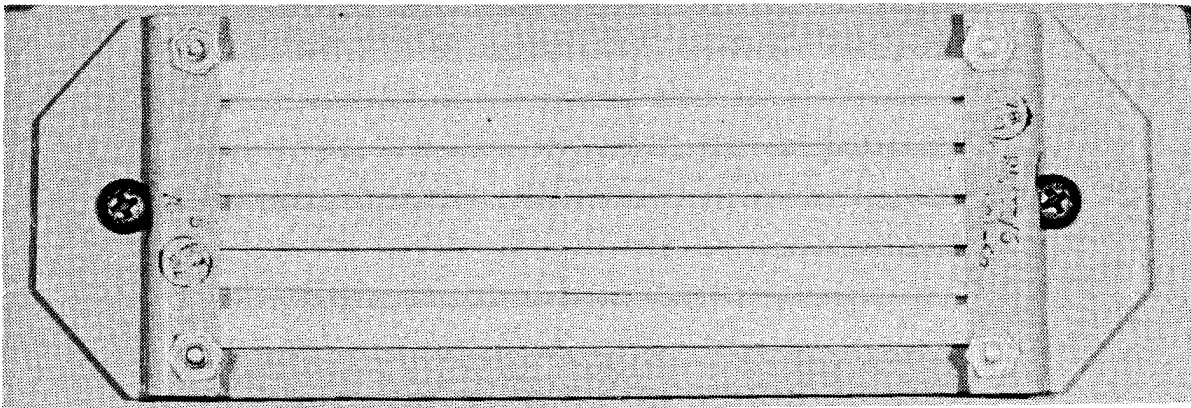


Figure 11. Compression Specimen Holding Fixture

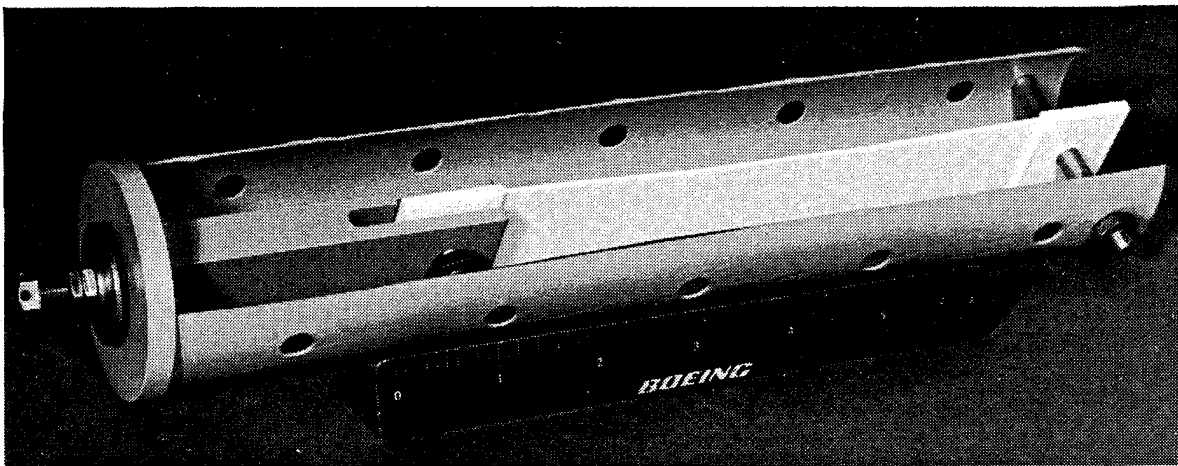


Figure 12. Cutaway of Stressed Tension Specimen Fixture

6.4 SPECIMEN DEPLOYMENT

6.4.1 AIRCRAFT SPECIMEN DEPLOYMENT

Two specimen deployment locations were selected on the Boeing model 737 aircraft. These included the flap-track fairing tailcone for exterior aircraft exposure and section 48 of the fuselage for interior aircraft exposure. These areas are shown in figure 13.

The tailcone of the flap-track fairing offered several advantages for generating actual flight service environmental data on the exterior of an aircraft. Because it is aft of the wing trailing edge, aerodynamic problems were minimized. The tailcone is held to the aircraft with 16 bolts, and no alterations were necessary in the existing aircraft structure. Once in place, the tailcone is readily accessible for inspection. Finally, mounting specimens on the upper and lower surfaces permitted examination of the effect of solar heating and UV radiation.

Two different modified flap-track fairing tailcones were designed. The first version carried three of the fixtures made to hold specimens for short-beam shear and flexure testing on the upper surface, and three additional fixtures on the lower surface. The fixtures were attached to the tailcone with bolts and floating nutplates. A second tailcone was designed to hold four tension specimens on the upper surface and four more on the lower surface. Because the tailcones are essentially conical, it was possible to position the specimens along radial lines and, with a slight amount of shimming, ensure that they lay flat (unstressed) during exposure. Bolts and floating nutplates were again used to attach the specimens to the tailcone.

The tailcones, specimens, and holding fixtures were assembled at Boeing and sent to the airlines, ready for installation. This reduced the downtime and installation time required of the airlines. Two modified tailcones are shown in figures 14 and 15.

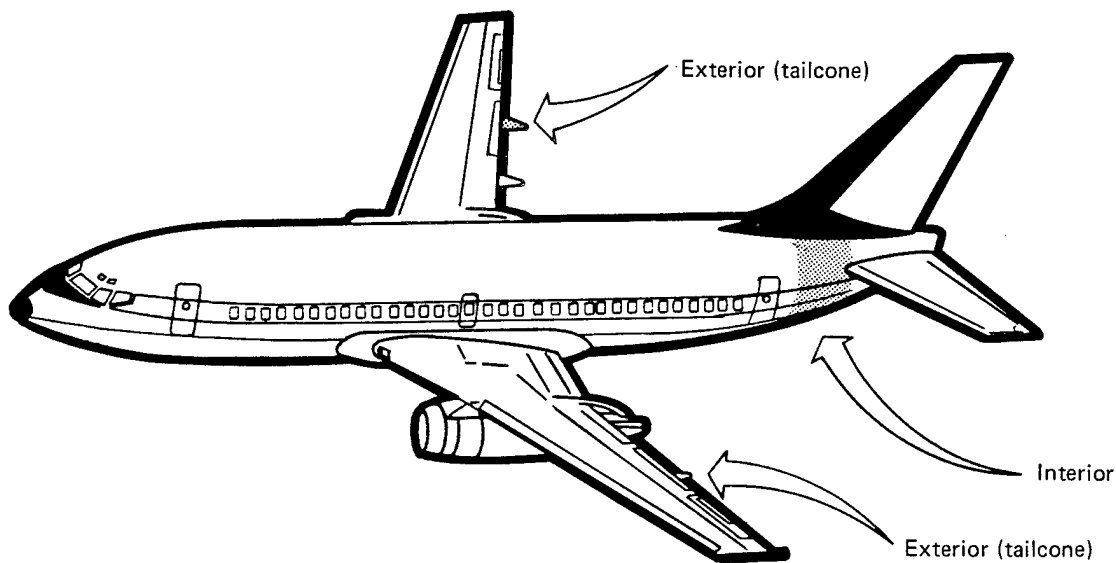


Figure 13. Flight Exposure Locations—Boeing 737

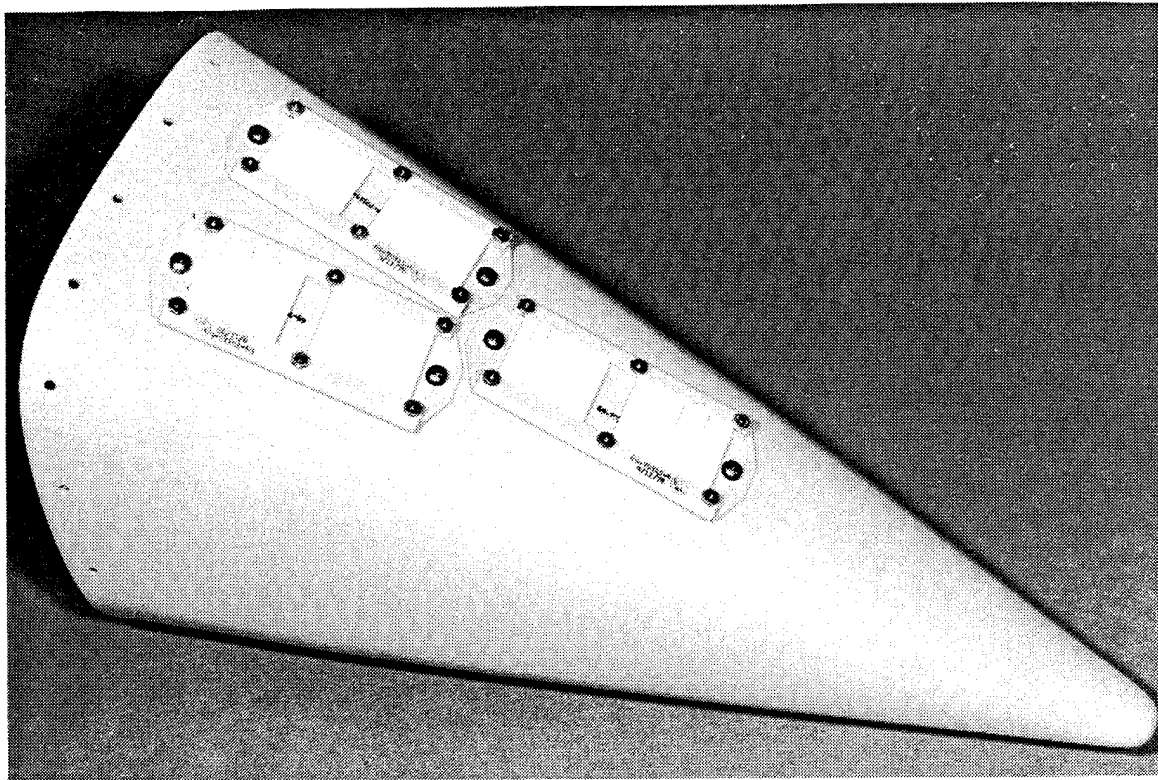


Figure 14. Tailcone With Shear and Flexure Specimen Fixtures Attached

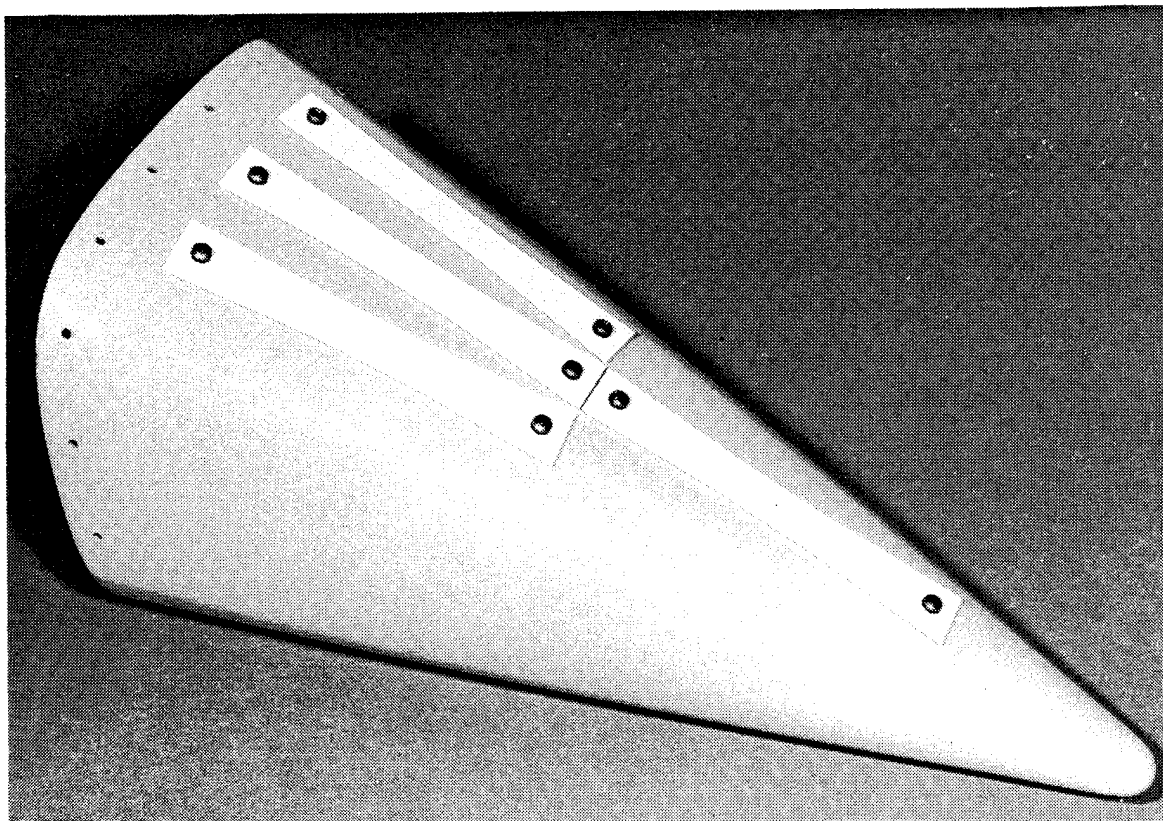


Figure 15. Tailcone With ± 45 -deg Tension Specimens Attached

The second area selected for specimen exposure was section 48 of the Boeing model 737 fuselage. The location is aft of the pressure bulkhead and ahead of the auxiliary power unit firewall. The specimens were exposed to the ambient temperature and relative humidity because of sizable openings through the side of body for the horizontal stabilizer. This region also provided the large geometry envelope necessary for stressed exposure testing.

Short-beam shear, flexure, and compression specimens were grouped in the specimen-holding fixtures described in section 6.4 and attached to the fuselage stringers. This was accomplished by adopting a nylon stringer clamp normally used in production to attach wiring bundles. Figures 16 and 17 show a mockup of the finished installation.

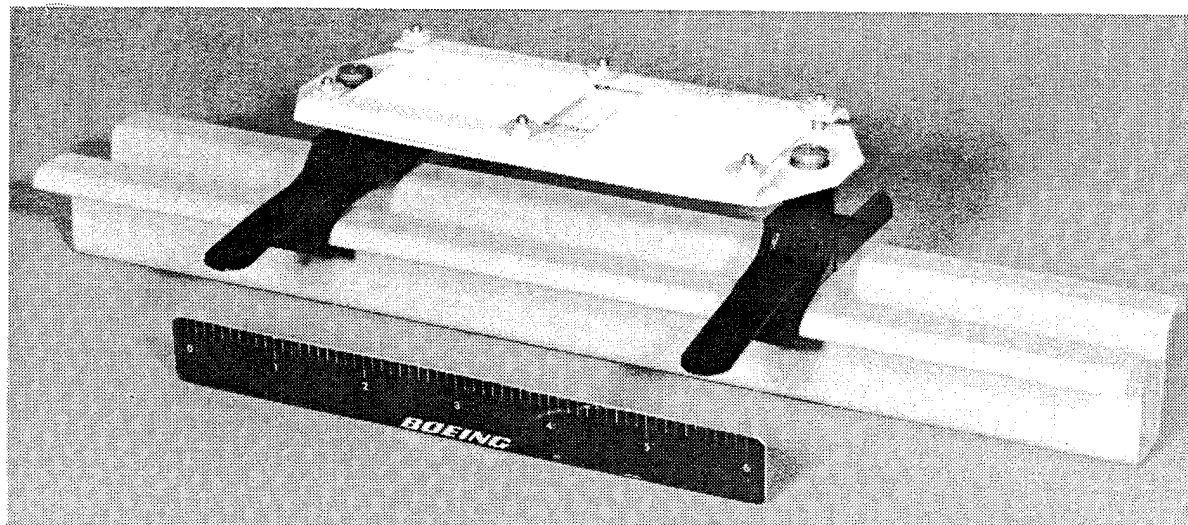


Figure 16. Interior Aircraft Shear and Flexure Specimen Fixture

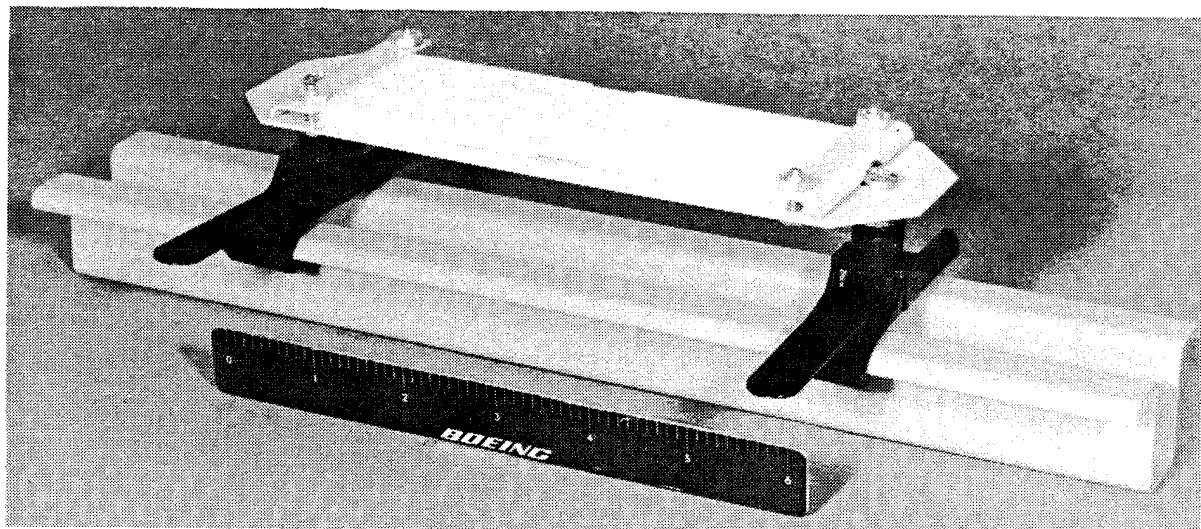


Figure 17. Interior Aircraft Compression Specimen Fixture

Figure 18 shows six tension specimens exposed on the interior of the aircraft. In this case, the nylon stringer clamps, along with standard fasteners and phenolic washers, were adequate, and no additional fixturing was required.

Stressed-tension fixtures also were attached to the fuselage stringers. The previously described nylon stringer clamp did not lend itself to this installation, so a phenolic saddle was designed that would attach to the stringer without the need to have holes drilled in the fixture tube or stringer. Figure 19 shows the complete installation in mockup form.

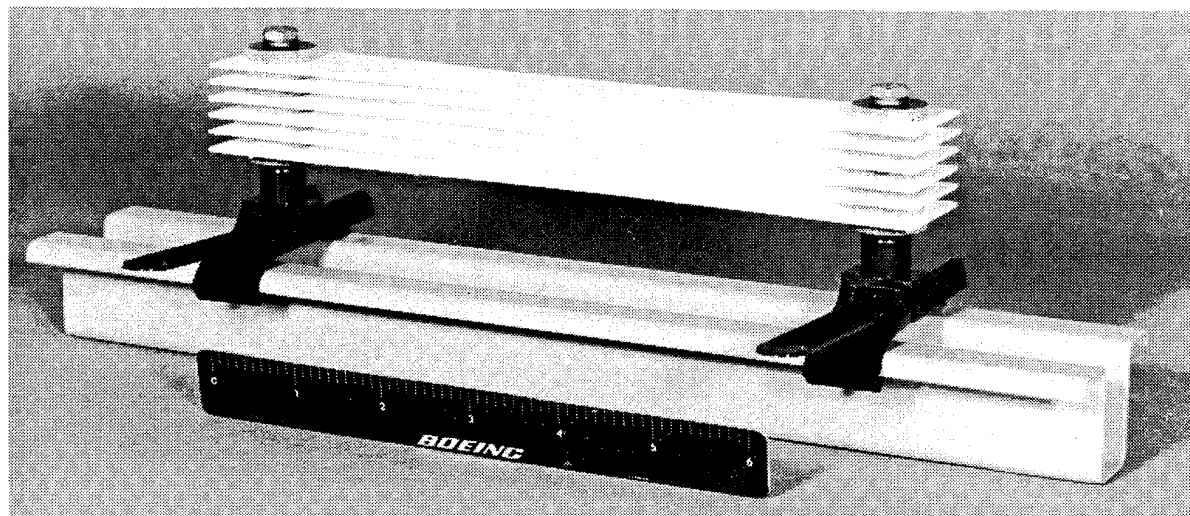


Figure 18. Interior Aircraft Tension Specimen Fixture

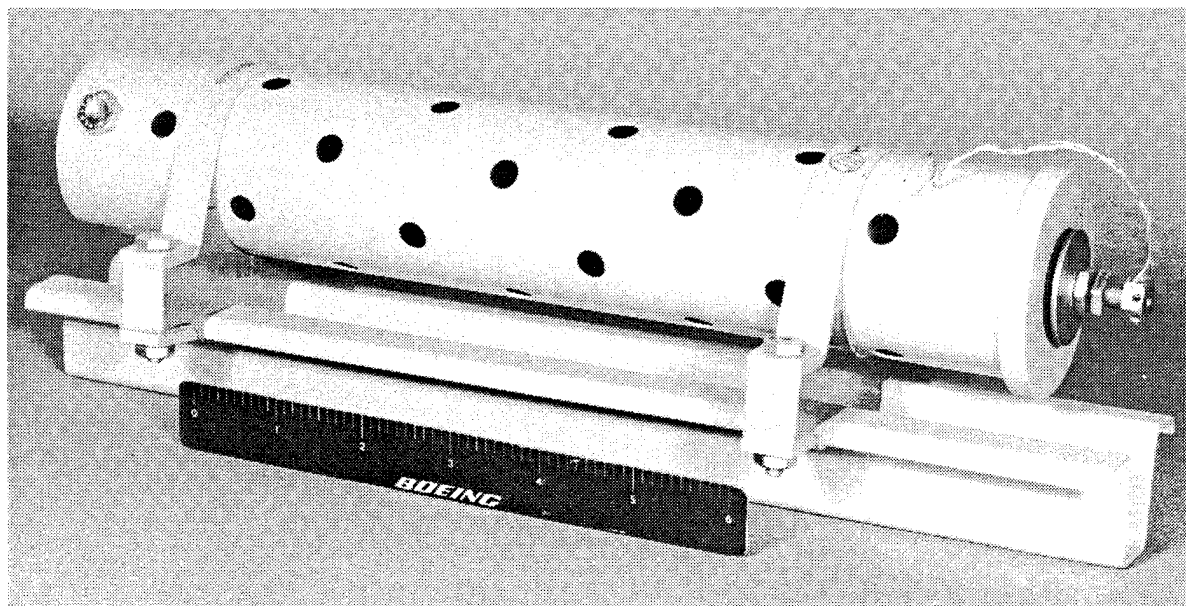


Figure 19. Interior Aircraft Stressed Tension Specimen Fixture

6.4.2 GROUND SPECIMEN DEPLOYMENT

A rack was designed to expose specimens to both solar conditions (all aspects of ambient environment, including direct sunlight) and nonsolar conditions (all aspects of ambient environment except direct sunlight). Consideration was given to--

- Exposure area requirements for each retrieval station.
- Maximum retrieval flexibility.
- Shielding nonsolar specimens.
- General simplicity for minimum cost.
- Rack transportation and setup.

The resultant rack design consisted of an aluminum mainframe and 36 insert panels. Each insert panel or exposure station was designed to hold all of the specimens of one material system for one exposure time to either solar or nonsolar exposure. The area requirement for solar or nonsolar exposure for each material system at each withdrawal time is approximately 0.09m^2 (1 ft²).

The 36 exposure stations were housed on a triangular frame nominally 2.7m (9 ft) long by 0.6m (2 ft) high. The rack mainframe was primarily 6061 aluminum alloy with welded construction. This provided the required stiffness for the lattice to which each exposure station was attached.

The exposure stations or insert panels consisted of 2024-T3 aluminum sheets that were drilled to receive the appropriate specimens and then painted. They were attached to the mainframe with four quarter-turn quick-release fasteners. One insert panel design, shown in figure 20, was used for solar exposure, and the design shown in figure 21 was used for nonsolar exposure.

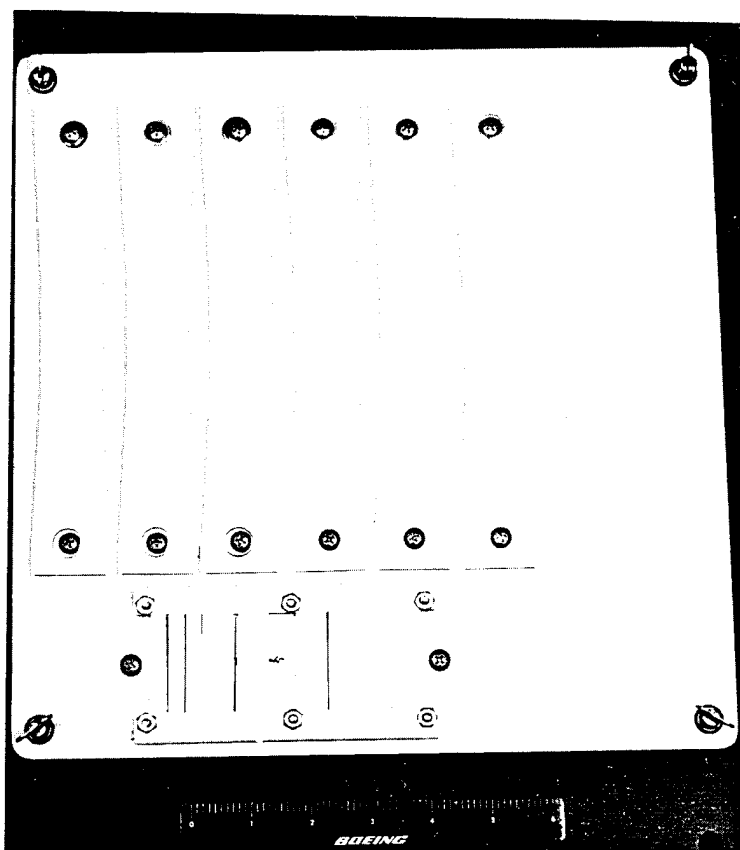


Figure 20. Solar Ground Exposure Insert Panel

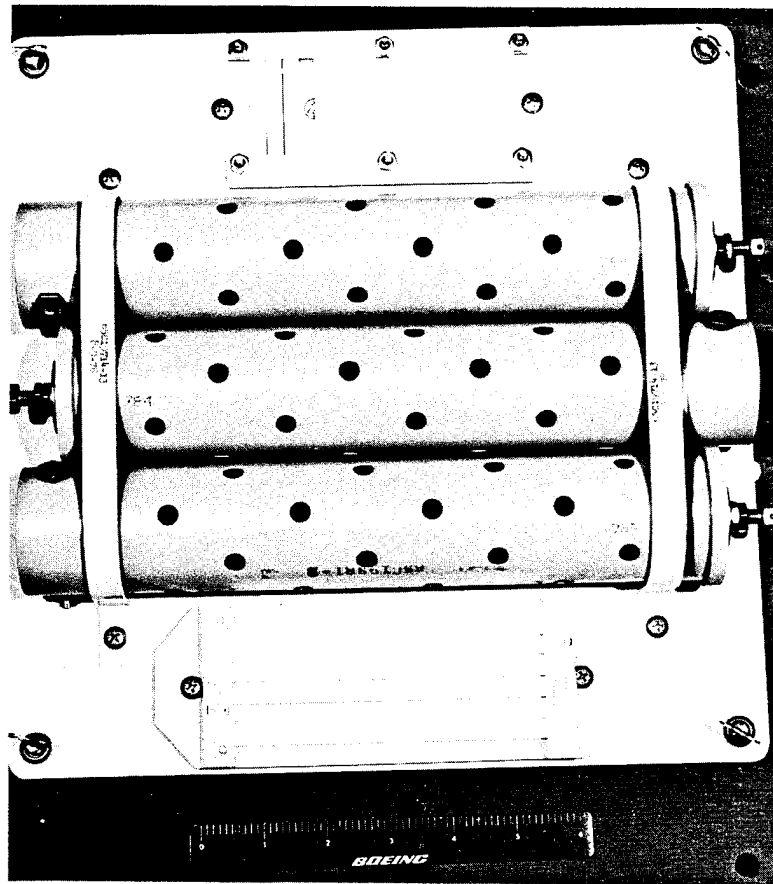


Figure 21. Nonsolar Ground Exposure Insert Panel

Nonsolar specimens were shielded from direct UV impingement with a slab of phenolic honeycomb core as shown in figure 22. This design provided adequate air circulation and allowed precipitation to drain down the individual cells and on the specimens.

A completed rack is shown in figure 23. The 18 solar exposure panels, complete with specimens, are shown on the front side. The honeycomb sunshield that protects the nonsolar specimens from direct exposure to the sun is visible on the back side.

6.5 LONG-TERM SPECIMEN TRACKING AND LOAD MAPS

Because it was impossible to maintain the identification tags on individual specimens, exposure history was tracked by the specimen-holding fixture. Each of the titanium fixtures and ground-rack insert panels described previously in this section contained a permanent steel, stamped identification number. A series of load maps was prepared that identified specific specimens for each holding fixture. An example is shown in figure 24. Once the test specimens were located in a fixture, the paper labels that had accompanied each specimen to that point were removed. When the fixture was returned following the desired exposure duration, individual specimens were reidentified before disassembling the fixture. This was done either with a new set of labels or with ink.

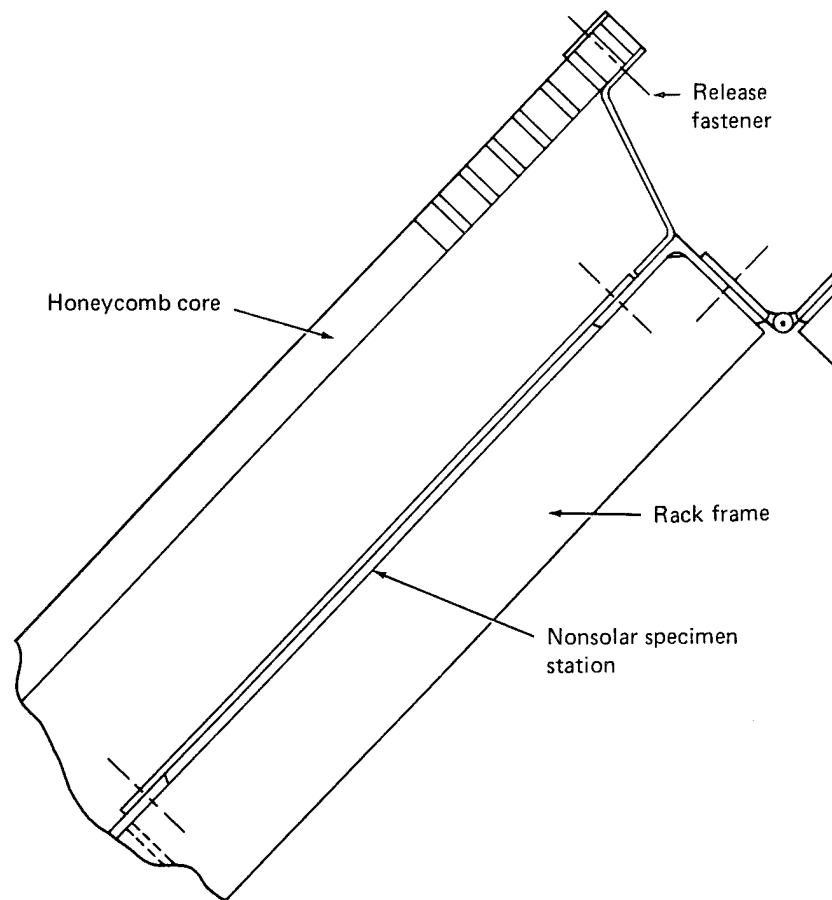


Figure 22. Honeycomb Sunshade Concept

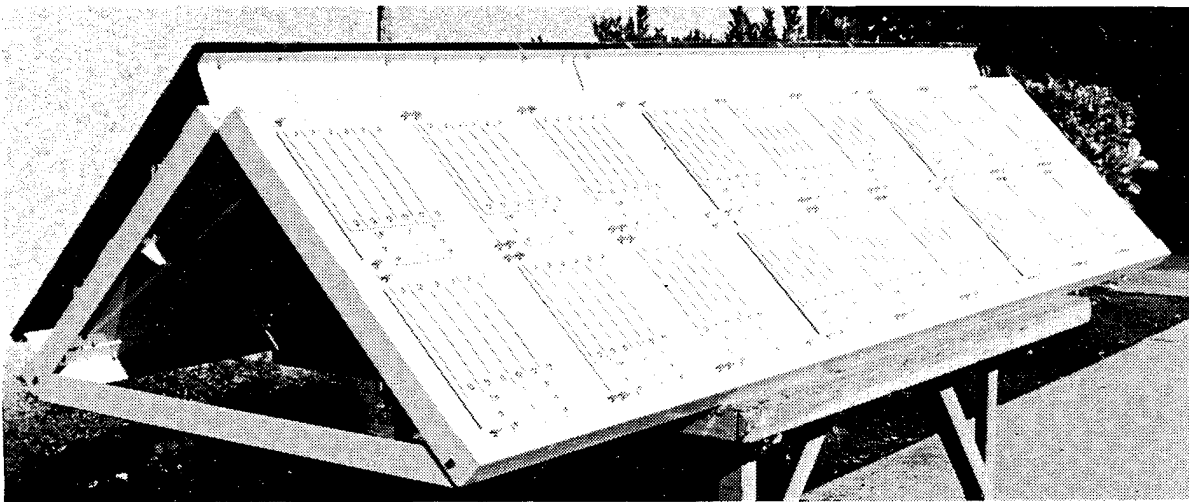


Figure 23. Ground Exposure Rack

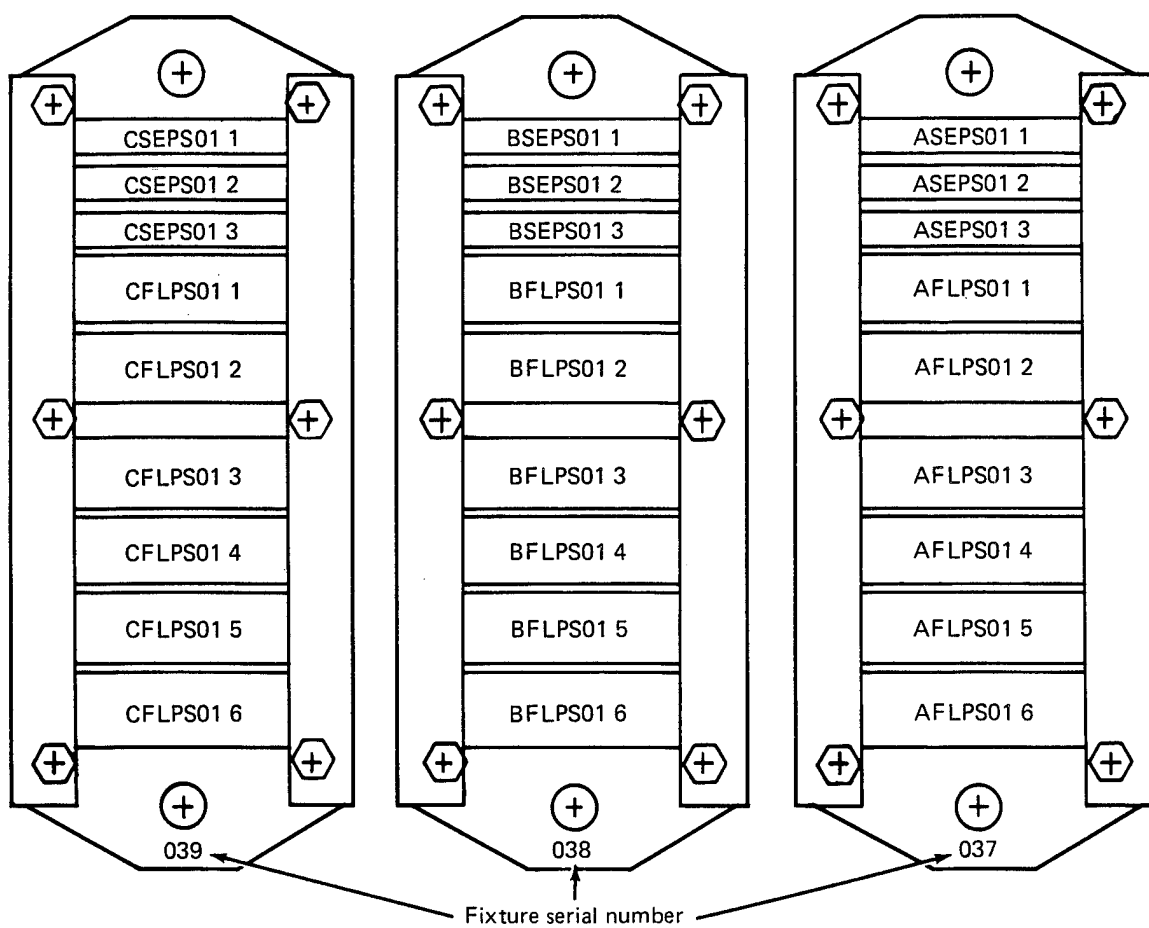


Figure 24. Sample Load Map

7.0 ACCELERATED LABORATORY EXPOSURE

7.1 BASELINE AND EFFECT OF TEMPERATURE ON DRY SPECIMENS

To establish basic specimen mechanical properties for the three contract materials, baseline and effect-of-temperature testing was performed. Specimens included short-beam shear, flexure, 0- and ± 45 -deg tension, quasi-isotropic tension, 0- and 90-deg compression, and quasi-isotropic compression. Normally, five replicate specimens of each configuration were tested at each of the three test temperatures. Table 2 gives a complete breakdown of specimens and testing used for baseline and effect of temperature. The specimens were tested at room temperature, 49°C (120°F), and 82°C (180°F). This testing provided a comparison of unexposed specimen strength values with all other testing and an indication of temperature effects on strength and modulus.

Before testing, all specimens were stored in a drum containing desiccant that provided a dry environment at room temperature. It was determined during The Effect of Moisture program described in sections 7.3 and 10.3 that the actual relative humidity in the storage drum stayed between 25% and 30%.

7.2 EFFECT OF TIME ALONE ON DRY SPECIMENS

A control group of specimens was carefully stored to evaluate the effects of time on the material systems. Postcure effects have been observed in both structural adhesives and resin matrix materials when exposed to mildly elevated temperatures for relatively short periods of time. It was not known if the contract materials would show this effect when exposed to room temperature for longer periods of time. Time-alone specimens were limited to short-beam shear and flexure configurations.

Table 2. Test Plan for Baseline Material Characterization and Effect of Test Temperature

MATERIAL	SPECIMEN CONFIGURATION AND PLY ORIENTATION				TEST TEMPERATURE AND REPLICATION			PROPERTIES			SUBTOTAL SPECIMENS
	SHORT BEAM SHEAR	FLEXURE	TENSION	COMPRESSION	ROOM	49°C (120°F)	82°C (180°F)	ULT	α/ε*	μ	
5208	[0] ₂₀	[0 ₂ /±45/90 ₂] _s	[0] ₈ [±45] _{2s} [±45/0/90] _s	[0] ₂₀ [±45/0/90] _{3 s} [90] ₂₀	5	5	5	-	-		15
					5	5	5	-	-		15
					5	5	5	-	-	-	15
					5	5	5	-	-	-	15
					5	5	5	-	-	-	15
					5	5	5	-	-	-	15
					5	5	5	-	-	-	15
					5	5	5	-	-	-	15
5209	Repeat 5208 matrix										120
934	Repeat 5208 matrix										120
* Head travel load deflection										Total	360

Before deployment, the specimens were stored in a desiccated 55-gal drum. For time-alone exposure, the specimens were sealed in small desiccated jars shown in figure 25 and stored at room temperature. Because the desiccant changed color when a certain level of moisture had been absorbed, it could be changed as needed. Exposure durations were 1, 2, and 3 years. Overall specimen weight change was measured immediately before testing. Half the specimens were tested for residual strength at room temperature and the other half at 82°C (180°F). Table 3 gives a breakdown of the specimens.

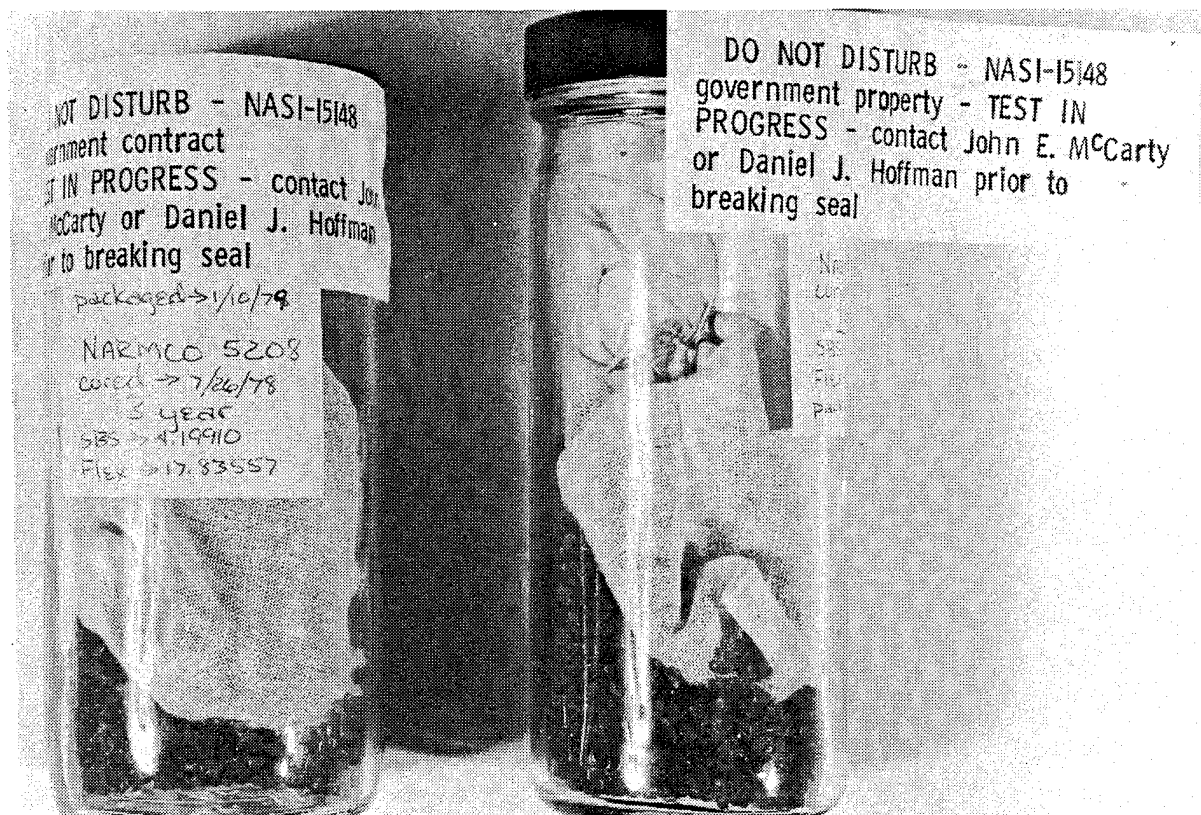


Figure 25. Time Alone Exposure Containers

Table 3. Test Plan for Effect of Time Alone

MATERIAL	EXPOSURE DURATION AT 21°C (70°F), <30% RELATIVE HUMIDITY. yr			SPECIMEN CONFIGURATION AND PLY ORIENTATION		RESIDUAL TEST TEMPERATURE AND REPLICATION		PROPERTIES		SUBTOTAL SPECIMENS	
	1	2	3	SHORT BEAM SHEAR	FLEXURE	ROOM	82°C (180°F)	ULT	σ/ε*		
5208	-	-	-	[0] ₂₀	[0 ₂ /±45/90 ₂] _s	5	5	-	-	30	
	-	-	-			5	5	-	-	30	
5209	Repeat 5208 matrix									60	
934	Repeat 5208 matrix									60	
* Head travel load deflection										Total	180

* Head travel load deflection

7.3 EFFECTS OF MOISTURE AND TIME ON WET SPECIMENS

The following sections describe the effects of moisture and time on wet specimens.

7.3.1 EFFECT OF MOISTURE

The Task III laboratory exposure program contained two test plans specifically oriented toward the effects of moisture. The initial plan, The Effect of Moisture, examined the short-term reversible effect of moisture absorption on graphite-epoxy laminates. Test specimens were exposed to 49°C (120°F) and four different relative humidity conditions: 40%, 60%, 75%, and 95%.

Table 4 gives a breakdown of the specimens and exposure conditions. The specimens were exposed until an equilibrium moisture level was achieved. They then were tested statically at both room temperature and the 82°C (180°F) elevated temperature. Instrumentation used on this program was similar to that used during testing of the baseline specimens. This program was designed to show how the various laminates reacted in the presence of absorbed moisture.

Dryout specimens for each material were included to determine whether the observed effects were reversible or irreversible.

7.3.2 EFFECT OF TIME ON WET SPECIMENS

The second moisture-related test plan was The Effect of Time on Wet Specimens. Specimens that had been conditioned to 49°C (120°F), 60% relative humidity and 49°C (120°F), 95% relative humidity were held at temperature for up to 2 years before residual test. A complete description of the test plan is given in table 5. Unlike the initial moisture program, this study was designed to determine whether or not moisture in a graphite-epoxy laminate can, given sufficient time, cause irreversible degradation. Short-beam shear and flexure specimens were tested.

Test specimens for both programs were preconditioned in desiccators containing a glycerin-water solution. Preparation of the solution was done in accordance with ASTM specification E104-52, method A. Its ability to provide a selected relative humidity was verified in the Boeing Scientific Research Center. Initially, two instruments were used for verification: a Panametrics model 2000 hydrometer that converts a dew-point measurement to relative humidity, and a Honeywell model 611 that measures the percentage of relative humidity (RH) directly.

Table 4. Test Plan for Effect of Moisture

MATERIAL	EXPOSURE ENVIRONMENT AT 49°C (120°F), RELATIVE HUMIDITY, % 				SPECIMEN CONFIGURATION AND PLY ORIENTATION		RESIDUAL TEST TEMPERATURE AND REPLICATION		PROPERTIES			SUBTOTAL SPECIMENS	
	40	60	75	95	SHORT BEAM SHEAR	FLEXURE	ROOM	82°C (180°F) 	ULT	σ/ε*	μ		
5208	-	-	-	-	$[0]_{20}$	$[0_2 \pm 45/90_2]_s$	5	5	-	-		40	
	-	-	-	-			5	5	-	-		40	
5209	Repeat 5208 matrix											80	
934	Repeat 5208 matrix											80	
NOTE:												Total	240

¹ Specimens remain until equilibrium moisture content is achieved.

² Control weight specimen will be used in test chamber to identify dryout during stabilization at elevated temperature.

³ As required.

Table 5. Test Plan for Effect of Time on Wet Specimens

MATERIAL	EXPOSURE ENVIRONMENT AT 49°C (120°F), RELATIVE HUMIDITY, %		EXPOSURE DURATION		SPECIMEN CONFIGURATION AND PLY ORIENTATION		RESIDUAL TEST TEMPERATURE AND REPLICATION		PROPERTIES	SUBTOTAL SPECIMENS
					SHORT BEAM SHEAR	FLEXURE	ROOM	82°C (180°F)	ULT	
	60	95	9 mo	2 yr						
5208	-	-	-	-	[0] ₂₀	[0 ₂ /±45/90 ₂] _s	5	5	-	40
	-	-	-	-			5	5	-	40
5209	Repeat 5208 matrix									80
934	Repeat 5208 matrix									80
Total										240

The humidity chambers consisted of two Pyrex desiccators with glycerin-water solutions formulated to achieve 59% RH and 74% RH at room temperature. These solutions convert to nominal 60% and 75% values when elevated to the 49°C (120°F) exposure temperature. The Panametrics instrument is highly accurate at low relative humidities but is less reliable at the high humidities involved with these desiccators. Results from the Honeywell instrument were used to verify the glycerin-water solutions. The desired humidities could be achieved with an accuracy of ±2%. A final check was made in the 49°C (120°F) environment using a Rustrak strip chart recorder. Figure 26 shows one of the desiccators undergoing checkout with the strip chart recorder.

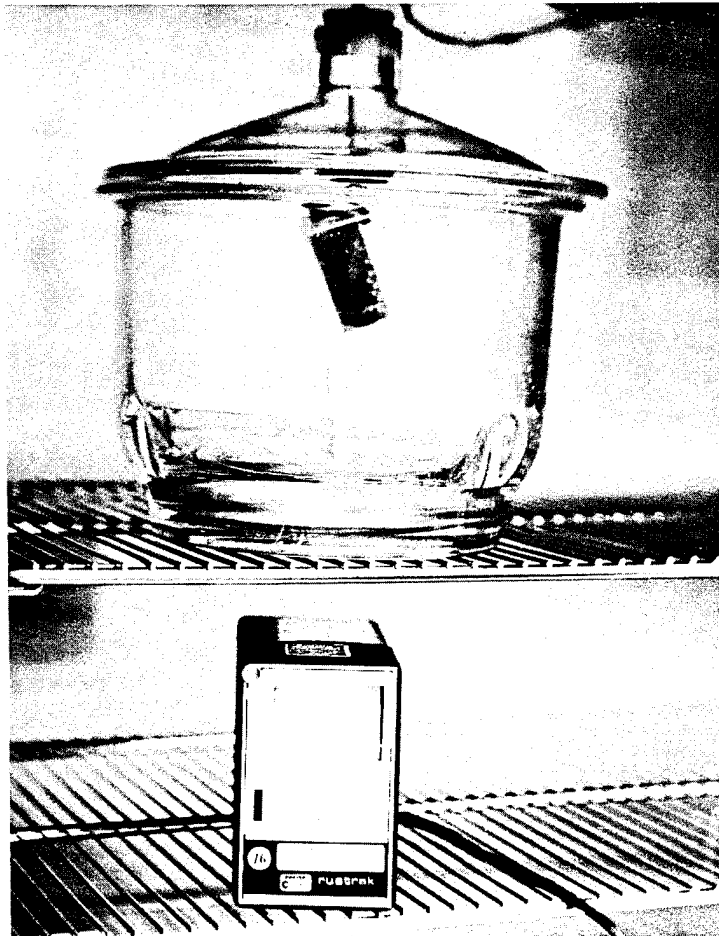


Figure 26. Rustrak Checkout of Humidity Environment

7.4 EFFECT OF WEATHEROMETER EXPOSURE

The weatherometer is an environmental exposure chamber consisting of continuous UV radiation and an intermittent water spray. Figure 27 shows the inside of the exposure chamber with the specimens held vertically around the perimeter. It is an effective simulation of the degrading effects of sunlight coupled with the erosive effects of surface water such as rain. In addition, there is the effect of the water washing away the UV degraded byproducts of the surface resin, thereby providing a fresh resin surface and continuing the degrading-eroding process. Only flexure specimens and paint evaluation specimens were involved. Table 6 gives a breakdown of specimens and test specifications.

Half of the flexure specimens were unpainted, and the other half were painted with the standard finish used on this contract and described in section 5.3. The paint evaluation specimens were 6.35- by 11.43-cm (2.5- by 4.5-in) coupons made of 0.51-mm (0.020-in) titanium that also was painted with the standard finish. The painted specimens were intended to determine the protective effectiveness of paint. Stainless steel fixtures, shown in figure 28, were designed to hold 20 flexure specimens and one paint evaluation specimen each. The fixtures provided for two-sided moisture access, but only one surface was exposed to UV radiation. Each 2-hr exposure cycle consisted of continuous carbon-arc lamp irradiation with an 18-min water spray.

Specimens of T300/5208 were divided between testing at room temperature and at 82°C (180°F). Specimens of T300/5209, and T300/934 were all tested at 82°C (180°F) only. Weight change, residual strength, and glass transition temperature data were collected.

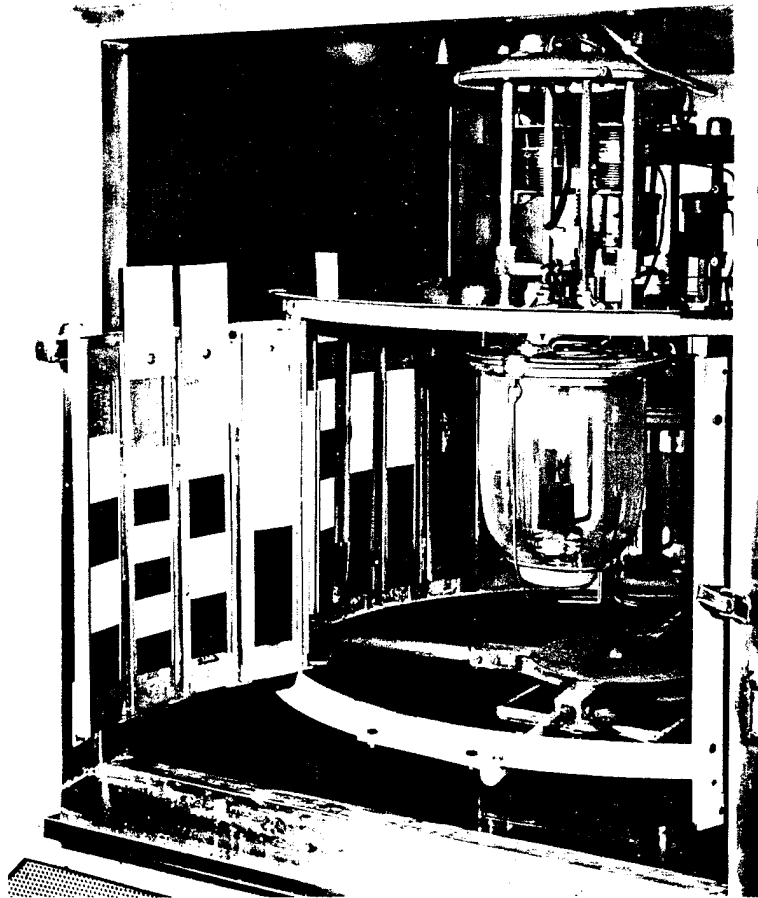


Figure 27. Interior of Weatherometer Exposure Chamber

Table 6. Test Plan to Evaluate Effect of Weatherometer Cycles

MATERIAL	EXPOSURE DURATION, mo			PAINTED	UNPAINTED	TEST SPECIMEN AND PLY ORIENTATION		RESIDUAL TEST TEMPERATURE AND REPLICATION	PROPERTIES	SUBTOTAL SPECIMENS
	6	12	24				FLEXURE	ROOM	82°C (180°F)	
5208	—	—	—	—	—	[0 2/±45/90 2]s	5	5	—	60
5209	—	—	—	—	—	[0 2/±45/90 2]s		5	—	30
934	Repeat 5209 matrix									30
Total										120

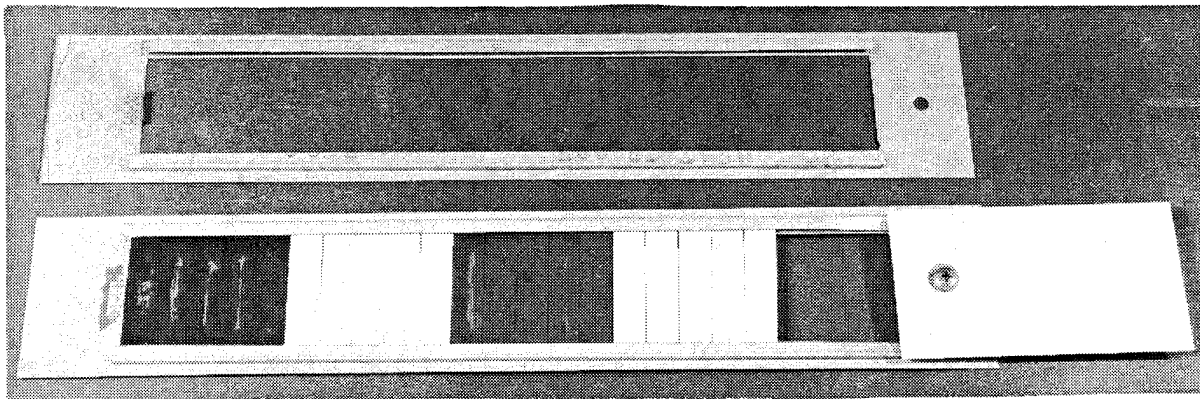


Figure 28. Weatherometer Specimen Holders

7.5 EFFECT OF SIMULATED GROUND-AIR-GROUND CYCLES

The Webber chamber is an environmental exposure device for simulating the conditions of a standard commercial aircraft ground-air-ground (GAG) flight cycle operating from a hot, moist, tropical climate. Figure 29 shows the Webber chamber with specimens in the exposure compartment. Specifically, cycles are 1 hr long and consist of four phases, as presented in figure 30. The first phase is 10 min long with constant conditions of 49°C (120°F), condensing relative humidity, and standard atmospheric pressure simulating a hot runway condition. The second phase is a 25-min steady transition from the first phase to the third phase and simulates aircraft takeoff and climb to cruise altitude. The third phase is a 10-min simulation of aircraft at cruise altitude with conditions of -54°C (-65°F)/0% relative humidity, and 12 000m (40 000-ft) altitude pressure. The fourth phase is a 15-min transition from phase 3 back to the conditions of phase 1, completing the cycle.

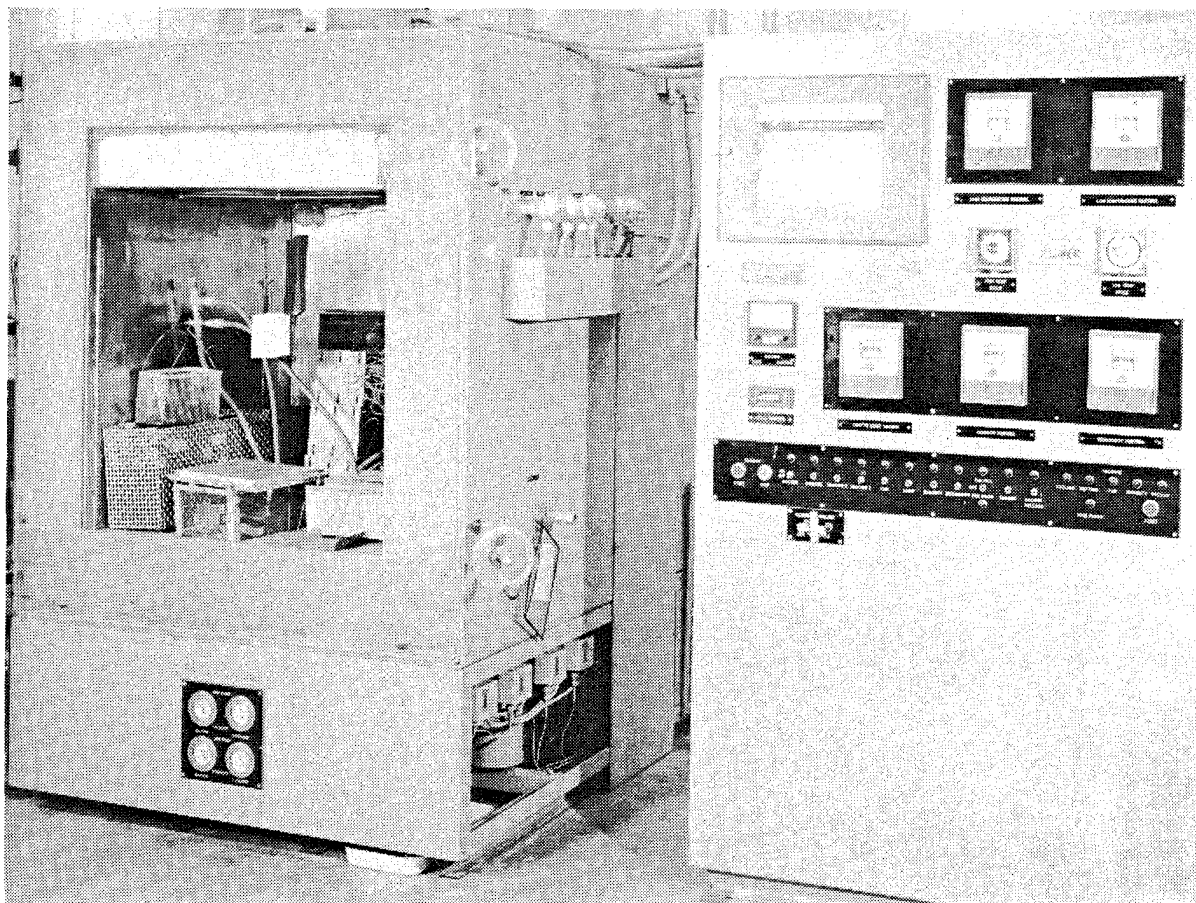


Figure 29. Webber Chamber for Ground-Air-Ground Exposure

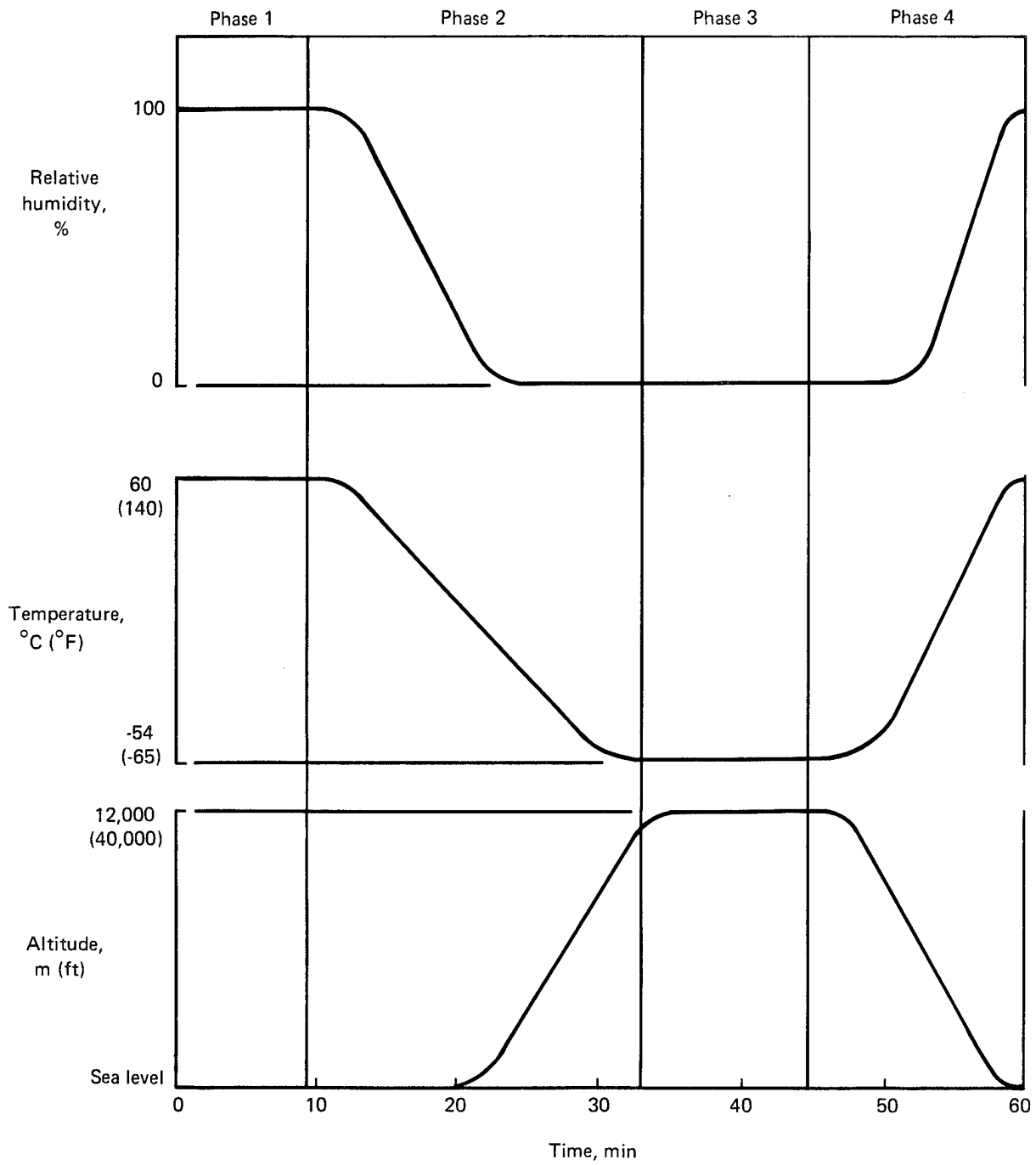


Figure 30. Webber Chamber Ground-Air-Ground Cycle Detail

Test specimens involved included short-beam shear and flexure. Painted titanium coupons were included to assess the ability of the paint film to withstand freeze-thaw cycles. Microcrack analysis was performed on selected specimens after exposure durations of 1, 2, and 3 months. Residual-strength measurements were made after an exposure duration of 6 months. Weight change measurements were performed on selected specimens at finer exposure intervals. Table 7 gives a complete description of the specimens involved, as well as the exposures.

Table 7. Test Plan for the Effect of Simulated Ground-Air-Ground Cycles

MATERIAL	SPECIMEN CONFIGURATION AND PLY ORIENTATION		RESIDUAL TEST AND TEMPERATURE REPLICATION		PROPERTIES	SUBTOTAL SPECIMENS	
	SHORT BEAM SHEAR	FLEXURE	ROOM	82°C (180°F)	ULT		
5208	[0] ₂₀	[0 ₂ /±45/90 ₂] _s	5	5	-	10	
			5	5	-	10	
5209	Repeat 5208 matrix					20	
934	Repeat 5208 matrix					20	
* All exposures for 6 months nominal.						60	

* All exposures for 6 months nominal.

8.0 BASELINE TEST RESULTS

8.1 SHORT-BEAM SHEAR

Baseline short-beam shear testing was completed on T300/5208, T300/5209, and T300/934 at three different test temperatures. Five replicate specimens were tested at room temperature, 49°C (120°F), and 82°C (180°F) for each material system. Testing was performed in a Tinius-Olson 12-kip mechanical testing machine. Load-deflection curves were recorded for the majority of the specimens using a D-2 Deflectometer. An American Instrument Company oven was used for all elevated temperature testing.

Summary short-beam shear strengths, as a function of test temperature, are shown in figure 31. Each point shows the average value for the group of five specimens. As expected, the Narmco T300/5208 and the Fiberite T300/934 systems show similar behavior while the Narmco T300/5209 [121°C (250°F)] cure system shows somewhat lower strengths at all temperatures.

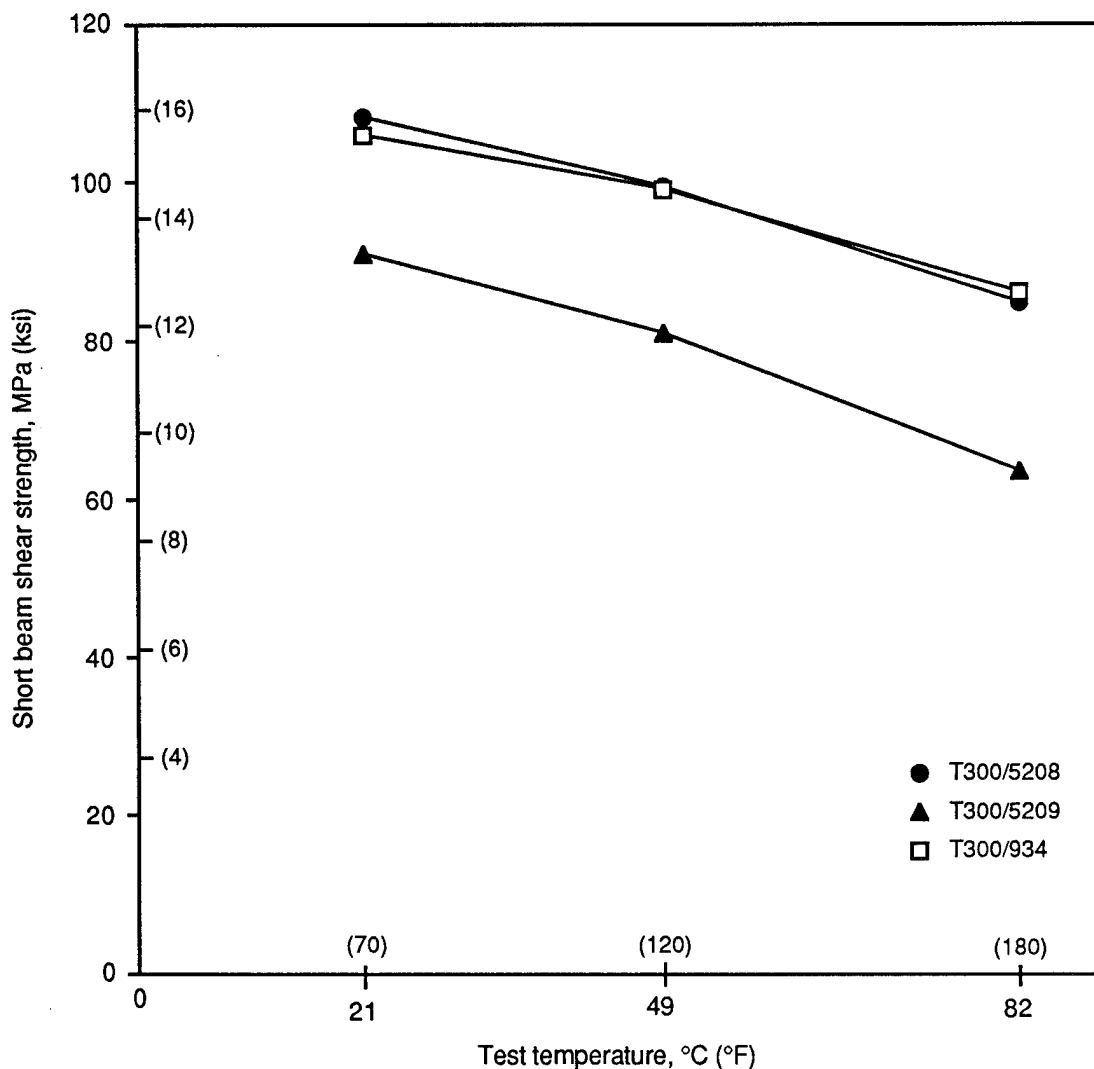


Figure 31. Baseline Short-Beam Shear Strength Results

8.2 FLEXURE

Baseline flexure testing was performed in the same equipment used for short-beam shear testing. Summary flexure strength data, as a function of test temperature, are shown in figure 32. In this case, strengths are reported as extreme fiber stresses. These are obtained using a laminated-plate bending theory.

For the layup considered, $[0_2/\pm 45/90_2]$, the bending stiffness, D_{11} , is:

$$D_{11} = \frac{2}{3} \left[E_{x0} \frac{1}{1-V_{xy0} V_{yx0}} \left\{ \left(\frac{t}{2}\right)^3 - \left(\frac{t}{3}\right)^3 \right\} + E_{x\pm 45} \frac{1}{1-V_{xy\pm 45} V_{yx\pm 45}} \left\{ \left(\frac{t}{3}\right)^3 - \left(\frac{t}{6}\right)^3 \right\} + E_{x90} \frac{1}{1-V_{xy90} V_{yx90}} \left(\frac{t}{6}\right)^3 \right]$$

where t is specimen thickness, E_x are extensional moduli for the 0-, ± 45 -, and 90-deg directions, and V_{xy} are Poisson's ratios for the 0-, ± 45 -, and 90-deg directions.

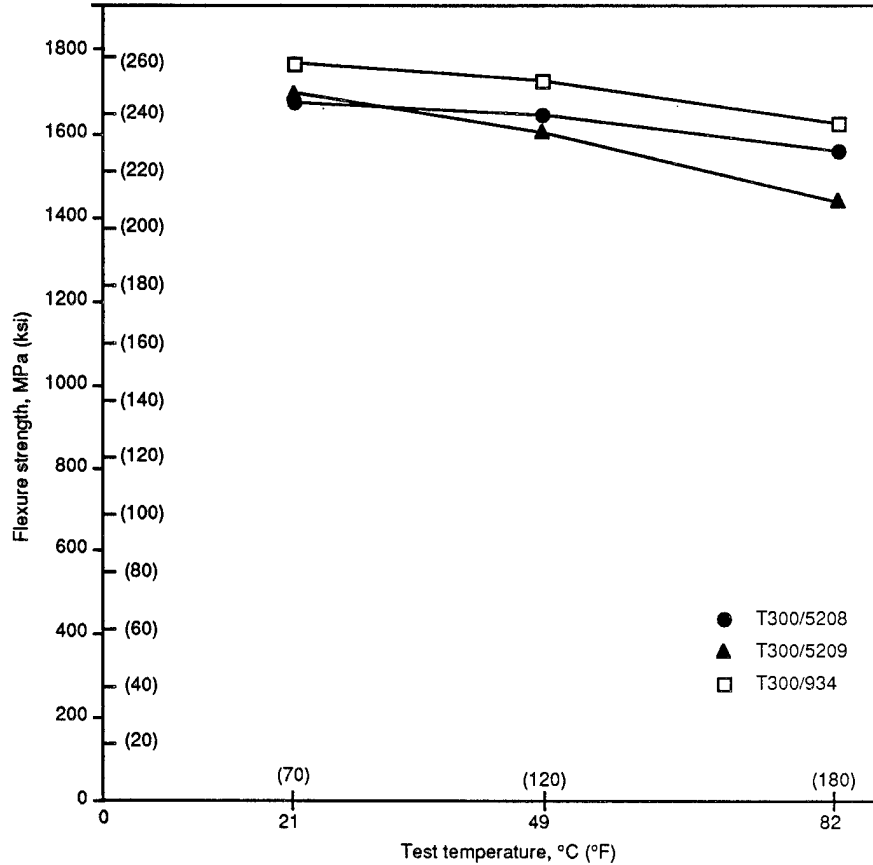


Figure 32. Baseline Flexure Strength Results

The maximum fiber stresses, σ_x , are computed assuming three-point bending with the formula

$$\sigma_x = \frac{Plt E_{x0}}{8 D_{11} w (1 - \nu_{xy0} \nu_{yx0})}$$

where P is the ultimate load, l is the span, and w is the specimen width.

These computations did not consider nonlinear, temperature-dependent properties at this time. Edge effects and stress concentrations in the vicinity of the load points were also neglected. The values for the moduli and Poisson's ratios are given in table 8.

8.3 TENSION

Baseline tension testing was performed in an Instron model TTD-2109 test machine. A summary of the strength results as a function of temperature is given in figure 33. The results represent three specimen test values at room temperature and at 82°C (180°F) and five specimen test values at 49°C (120°F). One unexpected aspect of the results revealed in figure 33 is that T300/5209 had substantially higher strength across the temperature range than has either T300/5208 or T300/934. If the T300/5209, elevated temperature baseline strengths are artificially high relative to the other materials, which could explain the apparently low residual strengths reported for tension specimens in section 9.5.

Table 8. Fundamental Properties Used for Flexure Fiber-Strength Computations

MATERIAL	LAYUP	E_x , MPa (lb/in ²) 	$1/1 - \nu_{xy}\nu_{yx}$ 
5208	0	1.31×10^5 (1.90×10^7)	1.005
	± 45	1.12×10^4 (1.63×10^6)	3.090
	90	1.17×10^4 (1.69×10^6)	1.005
5209	0	1.41×10^5 (2.05×10^7)	1.005
	± 45	1.12×10^4 (1.63×10^6)	3.090
	90	1.55×10^4 (2.25×10^6) 	1.005
934	0	1.29×10^5 (1.87×10^7)	1.005
	± 45	1.25×10^4 (1.81×10^6)	3.090
	90	1.68×10^4 (2.44×10^6)	1.005

Note:

 Values obtained from deflectometer room temperature data.

 Averages from design guide.

 Average of materials 5208 and 934.

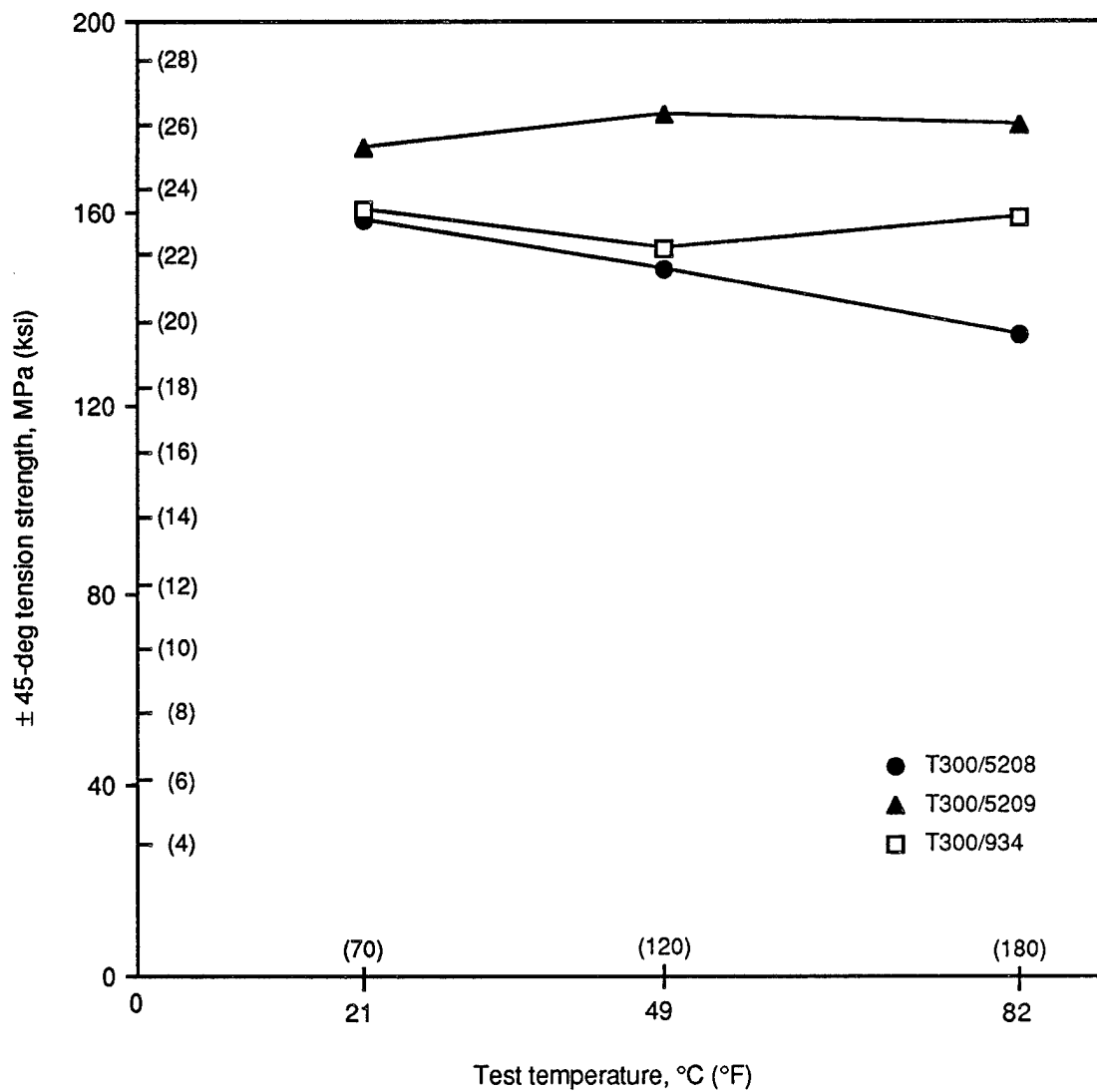


Figure 33. Baseline ± 45 -deg Tension Strength Results

8.4 COMPRESSION

Most of the baseline compression testing was performed in a Celanese compression fixture, although several room temperature tests were performed in an IITRI compression fixture during the comparison testing described in reference 15. Loading was performed in a Tinius-Olson 12-kip mechanical testing machine. Load and cross-head deflection curves were plotted for all tests.

A summary of the 0-deg compression strengths for all three materials is shown in figure 34. The only notable aspects of these results are the somewhat low-strength values measured for T300/5208 and T300/5209 tested at 82°C (180°F). Average values for all baseline strength and glass transition temperature measurements appear in tables 9, 10, and 11.

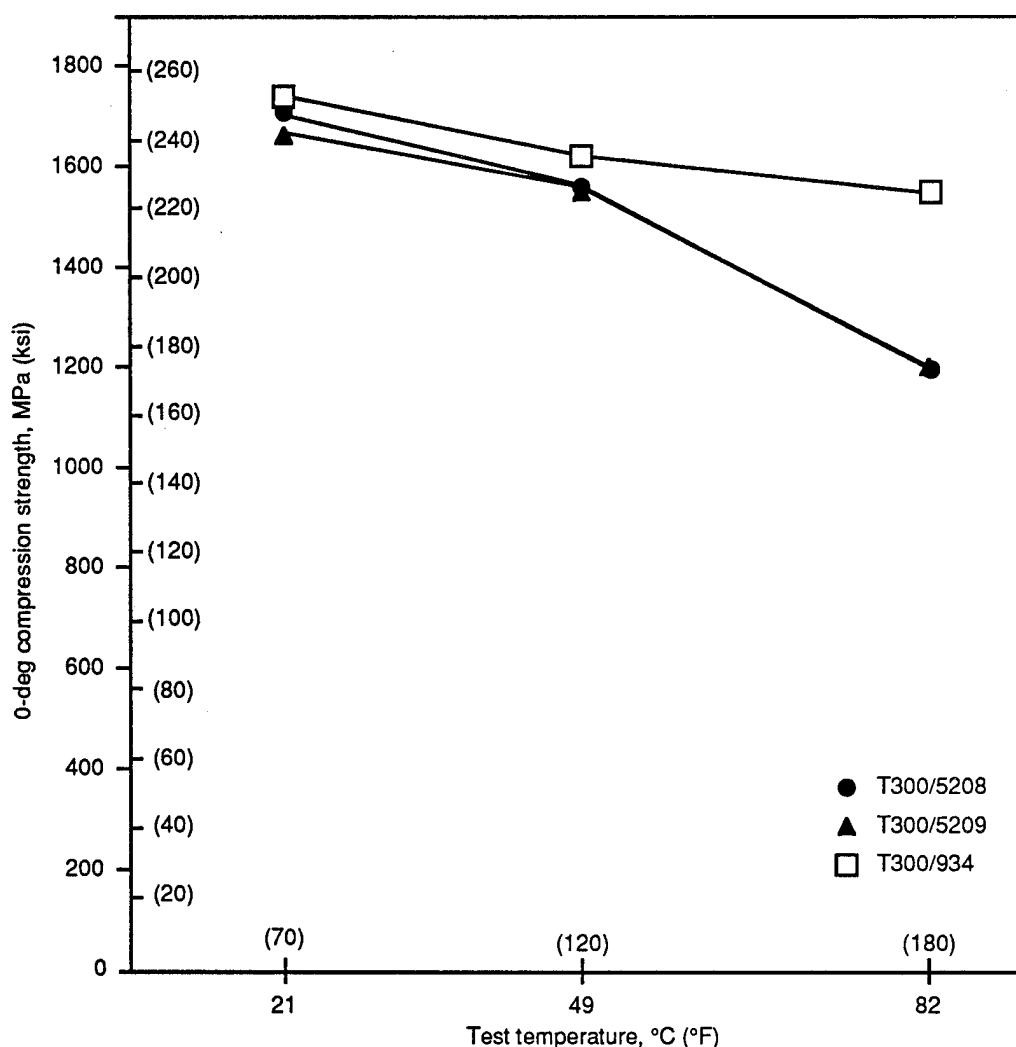


Figure 34. Baseline 0-deg Compression Strength Results

Table 9. T300/5208 Baseline and Effect of Temperature Results

SPECIMEN	STRENGTH, MPa (ksi)					
	ROOM TEMPERATURE		49°C (120°F)		82°C (180°F)	
0-deg short beam shear	108.2	(15.70)	99.5	(14.44)	85.0	(12.33)
Flexure	1679.0	(243.63)	1649.0	(239.17)	1559.0	(226.16)
+45-deg tension	158.4	(22.98)	147.7	(21.43)	134.2	(19.46)
0-deg compression	1706.0	(247.44)	1561.6	(226.49)	1199.7	(174.01)
0-deg tension	1448.0	(210.02)	1408.9	(204.46)	Tab failure	
Quasi-isotropic tension	335.6	(48.68)	324.6	(47.09)	340.4	(49.39)
90-deg compression	197.4	(28.63)	204.9	(29.73)	186.4	(27.04)
Quasi-isotropic compression	1048.9	(152.14)	919.5	(133.37)	867.6	(125.84)
Tg, °C (°F)	214 (417)					

Table 10. T300/5209 Baseline and Effect of Temperature Results

SPECIMEN	STRENGTH, MPa (ksi)					
	ROOM TEMPERATURE		49°C (120°F)		82°C (180°F)	
0-deg short beam shear	91.1	(13.22)	80.9	(11.74)	63.5	(9.22)
Flexure	1699.0	(246.48)	1606.0	(232.97)	1443.0	(209.30)
±45-deg tension	173.2	(25.10)	180.7	(26.21)	178.1	(25.83)
0-deg compression	1657.0	(240.35)	1551.8	(225.07)	1206.0	(174.94)
0-deg tension	1723.0	(249.94)	1562.2	(226.70)	Tab failure	
Quasi-isotropic tension	354.7	(51.45)	330.3	(47.91)	344.3	(49.93)
90-deg compression	209.6	(30.40)	179.6	(26.05)	158.5	(23.00)
Quasi-isotropic compression	573.5	(83.19)	538.8	(78.16)	475.5	(68.97)
Tg, °C (°F)	128 (262)					

Table 11. T300/934 Baseline and Effect of Temperature Results

SPECIMEN	STRENGTH, MPa (ksi)					
	ROOM TEMPERATURE		49°C (120°F)		82°C (180°F)	
0-deg short beam shear	106.1	(15.39)	99.1	(14.38)	86.2	(12.51)
Flexure	1770.0	(256.78)	1730.0	(250.94)	1626.0	(235.85)
±45-deg tension	160.2	(23.23)	152.3	(22.09)	158.9	(23.06)
0-deg compression	1738.0	(252.08)	1624.4	(235.60)	1554.0	(225.42)
0-deg tension	1523.2	(221.07)	1557.6	(226.03)	Tab failure	
Quasi-isotropic tension	386.8	(56.11)	371.3	(53.86)	324.9	(47.13)
90-deg compression	190.8	(27.68)	193.1	(28.01)	173.5	(25.17)
Quasi-isotropic compression	900.2	(130.56)	856.4	(124.22)	816.4	(118.41)
Tg, °C (°F)	205 (401)					

9.0 LONG-TERM TEST RESULTS

9.1 EXPOSURE HISTORY

Throughout this report, specimens are described by their nominal planned exposure duration. Tables 12 and 13 show the actual flight and ground exposure histories for long-term specimens. The dates are as reported by the personnel at the exposure sites. Aircraft hours and landings are as reported by personnel at the exposure sites or are close estimates based on Boeing fleet use statistics.

Because of budget constraints, specimens that had been scheduled for residual strength testing following 7 years of exposure were not removed at that time. They were removed in October 1990 and will be sent to NASA for disposition.

Table 12. Actual Aircraft Exposure History

Exposure site	Nominal exposure time (years)				
	1	2	3	5	10
Aloha	1.08 Y 1,942 H 5,760 L	2.04 Y 3,832 H 11,500 L	Lost during exposure	Not deployed	11.09 Y 21,476 H 54,894 L
Air New Zealand	1.41 Y 2,781 H 3,776 L	2.18 Y 4,491 H 6,125 L	Not deployed	5.03 Y 10,287 H 13,946 L	11.07 Y 46,988 H 61,627 L
Southwest Airlines	1.34 Y 4,769 H 6,320 L	2.41 Y 8,334 H 10,652 L	3.09 Y 10,790 H 14,155 L	6.34 Y 20,668 H 22,653 L	9.80 Y 32,637 H 38,304 L

Notes:

Y = Years

H = Flight hours

L = Landings

Table 13. Actual Ground Rack Exposure History

Exposure site	Nominal exposure time (years)				
	1	2	3	5	10
Honolulu	1.09	2.03	3.00	5.00	10.96
Wellington	1.39	2.15	3.19	4.96	11.37
Dallas	1.16	2.24	3.13	4.96	10.00
NASA Dryden	1.19	1.96	3.07	4.99	11.46

Several disruptions in the planned exposure took place over the 10-year exposure history. Most of these changes were insignificant. For example, early in 1984 the roof rack at NASA Dryden was stored in a nearby warehouse for just over 3 months. The only specimens remaining on the rack at that time were the 7- and 10-year sets. Because the proximity of the temporary storage site meant that the only elements missing from the exposure history for that time were direct sun and rain, test results should not have been affected. At one time or another, all of the ground racks were temporarily removed for roof repairs. In addition, aircraft sale and lease activity prompted several transfers of specimens from one airplane to another.

With few exceptions, all ground-rack specimens as well as all aircraft specimens from Air New Zealand and Southwest Airlines were retrieved following long-term exposure. Because some specimens originally deployed on Aloha aircraft were not recovered, middle exposure time data are unavailable for the Aloha aircraft. However, this absence is not significant. Early trends are available from the 1- and 2-year retrievals, and the 10-year data are available to show long-term effects. In addition, Honolulu ground-rack data are available for the times where flight data are missing. Section 9.7 shows that the ground-rack data parallel the flight data for both Air New Zealand and Southwest Airlines.

9.2 TREATMENT OF VARIABLES

The long-term portion of this contract involved numerous variables. In order to clarify the results for reporting purposes, individual variables are treated in a particular sequence. Also, results from 1-, 2-, and 3-year exposures are mentioned in terms of early trends but are not discussed in detail. The primary emphasis is on the long-term, 5- and 10-year data.

Most specimen sets contained only three replicates. This meant that data scatter for a single set of specimens could and sometimes did overshadow the particular environmental effect being studied. Figure 35 shows the residual flexure strength of 5,208 specimens that were exposed on the solar face of the Honolulu ground rack and then tested at room temperature. Each data point represents the average of three specimens. No clear trend is evident. Figure 36 shows the same data along with 11 other exposure sites. These include the nonsolar face of the Honolulu rack, both faces of ground racks at NASA Dryden and Dallas, and both exterior and interior specimens from Aloha and Southwest airlines. A total of 180 specimens are involved. The plot shows a modest but steady increase in strength over the exposure period. The figures shown in this report often combine results from individual specimen sets in order to display trends more clearly.

This report often presents typical results rather than supplying a graph for every possible combination of data. For example, room-temperature residual-flexure strengths for the T300/5209 and the T300/934 material systems showed the same results over time as those displayed in figure 36 for T300/5208. The responses of all three materials are considered typical.

The report also points out atypical results. The flexural strengths for both the T300/5208 and the T300/934 material systems did not change significantly when tested at 82°C (180°F). The elevated test temperature did not change the overall behavior pattern exhibited by the room-temperature tests. The T300/5209 system did behave differently. The elevated-temperature residual strengths for that material system following the same exposure, rather than showing a modest strength increase, showed a modest strength decrease. The reason for this is not known, but the 82°C (180°F) test temperature is a severe test for the 121°C (250°F) material system.

Individual data anomalies are noted. If known, the reason for the anomalous behavior is noted as well. One example of this would be long-term specimens that suffered paint loss and subsequent UV radiation degradation.

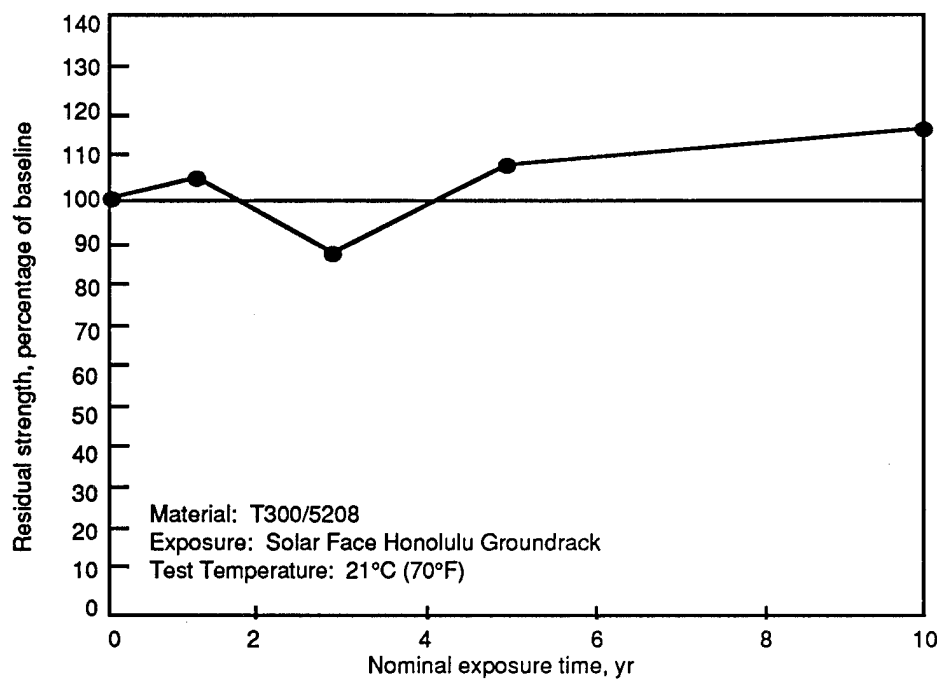


Figure 35. Room Temperature Residual Flexure Strength for T300/5208 Honolulu Solar Specimens

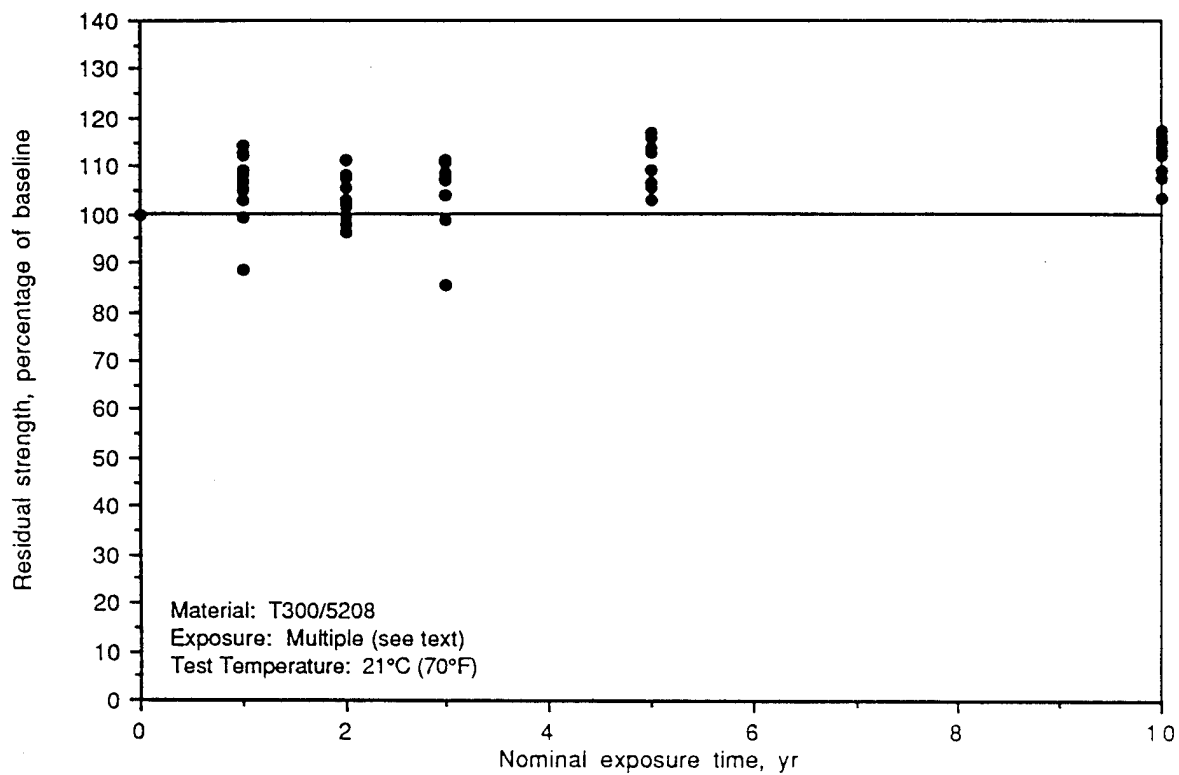


Figure 36. Room Temperature Residual Flexure Strength Summary for T300/5208

Mechanical property test results are reported as "Residual strength, percent of baseline." This means that results for specimens tested at elevated temperatures following exposure are compared with the baseline strength at that temperature. Changes in other properties such as stiffness are reported only when doing so would amplify the results.

9.3 MOISTURE CONTENT OBSERVATIONS

Measured or derived specimen moisture contents for the flight and ground exposure specimens are shown in table 14. In most cases, these moisture contents were obtained from the dryout procedure discussed in section 5.5. In some cases, no data were obtained. In a few cases, a moisture content was derived from individual specimen weights taken before and after exposure and then corrected for an estimated moisture content at the time of the initial weighing.

The data show the strong influence of exposure location (i.e., relative humidity). Based on normal historical weather patterns as shown in figure 8, NASA Dryden Flight Research Center located at Edwards Air Force Base was expected to be the driest location, and the data confirm this. Specimens exposed at this location achieved moderate equilibrium moisture levels ranging from 0.5% to 0.7% (depending on material) during the first year of exposure. The nominal 1-year specimens were removed in February, one of the wettest months of the year. The nominal 2- and 3-year specimens were removed in October, following the hot, dry, summer season. The lower moisture contents in these specimens reflect this. The 5-year specimens were removed in December and reflect the higher humidity again. Weather at the time of or immediately before specimen withdrawal significantly affected specimen moisture content.

The historical data show that Dallas maintains a reasonably constant relative humidity of approximately 65%. The average monthly temperature varies substantially, but the relative humidity changes very little. The Dallas specimens plateau at somewhat higher moisture contents than their Dryden counterparts. This is particularly true for the two 177°C (350°F) cure material systems. Moisture content levels for these two systems were fairly consistent in the 0.9% to 1.0% range for most of the 10-year exposure duration. The T300/5209 system absorbed less moisture and averaged about 0.62% for the 10 years.

The moisture content of specimens deployed on Southwest Airlines aircraft reached a plateau at slightly lower levels, but these specimens otherwise behaved very much like their ground-based counterparts in Dallas. This is predictable, considering the amount of time a commercial airplane spends on the ground. Flight records show that airplanes carrying 10-year specimens for Southwest Airlines were on the ground 62% of that time. This is a normal rate of use for a 737 aircraft.

Although Hawaii is generally thought to have a tropical or subtropical climate, the average relative humidity in Honolulu is just slightly higher than that of Dallas. In fact, some months in Honolulu are drier than some months in Dallas. Table 14 shows that the two 177°C (350°F) cure material systems do plateau at slightly higher moisture contents than the specimens exposed in Dallas. Moisture levels in the T300/5209 material rose from the previously stated 0.62% in Dallas to approximately 0.72% in Honolulu.

Unlike specimens carried by Southwest Airlines and their ground-based counterparts in Dallas, specimens exposed on Aloha aircraft generally showed moisture contents equal to--or, in some cases, higher than--those coming from the Honolulu ground rack. Differences were small, however.

Table 14. Specimen Moisture Contents

Material: T300/5208

Location	Nominal exposure in years				
	1	2	3	5	10
Aloha Airlines - Solar	.98	1.09	****	****	1.23
- Nonsolar	.98	.98	****	****	1.16
Honolulu Groundrack - Solar	.98	1.16	1.06	****	2.12
- Nonsolar	.86	1.20	.89	****	1.96
Air New Zealand - Solar	.83 †	.88	****	1.11	1.23 *
- Nonsolar	.53 †	.89	****	1.10	
Wellington Groundrack - Solar	1.00 †	1.06	1.17	1.23	****
- Nonsolar	.92 †	1.10	1.11	1.16	****
Southwest Airlines - Solar	.94	.82	.92	.71	.73
- Nonsolar	.86	.78	.86	.87	.97
Dallas Groundrack - Solar	.87	.96	.94	1.05	.72
- Nonsolar	.92	.90	1.17	1.07	.88
NASA Dryden Groundrack - Solar	.67	.38 †	.52	.62	****
- Nonsolar	.58	.44 †	.56	.71	****

Material: T300/5209

Location	1	2	3	5	10
Aloha Airlines - Solar	.84	.67	****	****	2.03
- Nonsolar	.70	.71	****	****	1.77
Honolulu Groundrack - Solar	.62	.98	.75	****	.60
- Nonsolar	.58	.93	.77	****	.60
Air New Zealand - Solar	.57 †	****	****	1.18	1.10 *
- Nonsolar	.60 †	.61	****	1.22	
Wellington Groundrack - Solar	.50 †	.61	.67	.80	****
- Nonsolar	.50 †	****	.62	.95	****
Southwest Airlines - Solar	.57	.53	.56	.55	.51
- Nonsolar	.53	.49	.56	.50	.46
Dallas Groundrack - Solar	.52	.65	.58	.68	.47
- Nonsolar	.55	.73	.57	.72	.46
NASA Dryden Groundrack - Solar	.68	.21 †	.28	.37	****
- Nonsolar	.55	.25 †	.35	.42	****

Material: T300/934

Location	1	2	3	5	10
Aloha Airlines - Solar	1.11	1.11	****	****	.98
- Nonsolar	1.10	1.17	****	****	.94
Honolulu Groundrack - Solar	.90	1.28	.88	****	.66
- Nonsolar	.97	1.34	.99	****	1.36
Air New Zealand - Solar	.70 †	.86	****	1.19	1.46 *
- Nonsolar	.94 †	.91	****	.87	
Wellington Groundrack - Solar	.87 †	1.03	1.36	1.23	****
- Nonsolar	.84 †	1.07	1.10	1.23	****
Southwest Airlines - Solar	.79	.90	.97	.74	.71
- Nonsolar	.85	.84	.91	.70	.72
Dallas Groundrack - Solar	.87	.97	1.00	1.17	.65
- Nonsolar	.81	1.02	.98	1.22	.75
NASA Dryden Groundrack - Solar	.69	.38 †	.56	.65	****
- Nonsolar	.72	.49 †	.54	.67	****

Notes:

* Estimate from individual aircraft interior specimen weights.

**** Not available

† Drying oven overheated to 177°C (350°F) for 2 days.

Wellington, New Zealand, offered the wettest average climate of the four ground rack sites. The monthly average relative humidity ranges from 70% to 80%. The data show that the two 177°C (350°F) cure material systems did absorb slightly more moisture in Wellington than they did in Honolulu. Moisture levels for the 5209 system were actually slightly lower than those observed in Hawaii.

Moisture contents in the specimens coming from Air New Zealand aircraft were slightly lower than those observed on the Wellington ground-rack specimens.

9.4 EFFECT OF TEST SPECIMEN CONFIGURATION

9.4.1 SHORT-BEAM SHEAR STRENGTH

Figure 37 shows the behavior of all three materials at all exposure sites when they were tested for residual short-beam shear strength at room temperature. The graph represents more than 750 specimens. These strengths were observed to drop for the first 2 years and then begin returning to 100% of baseline. After 5 years, the typical residual strength was just below 100% of baseline and, after 10 years of exposure, the typical residual was actually slightly higher than 100%.

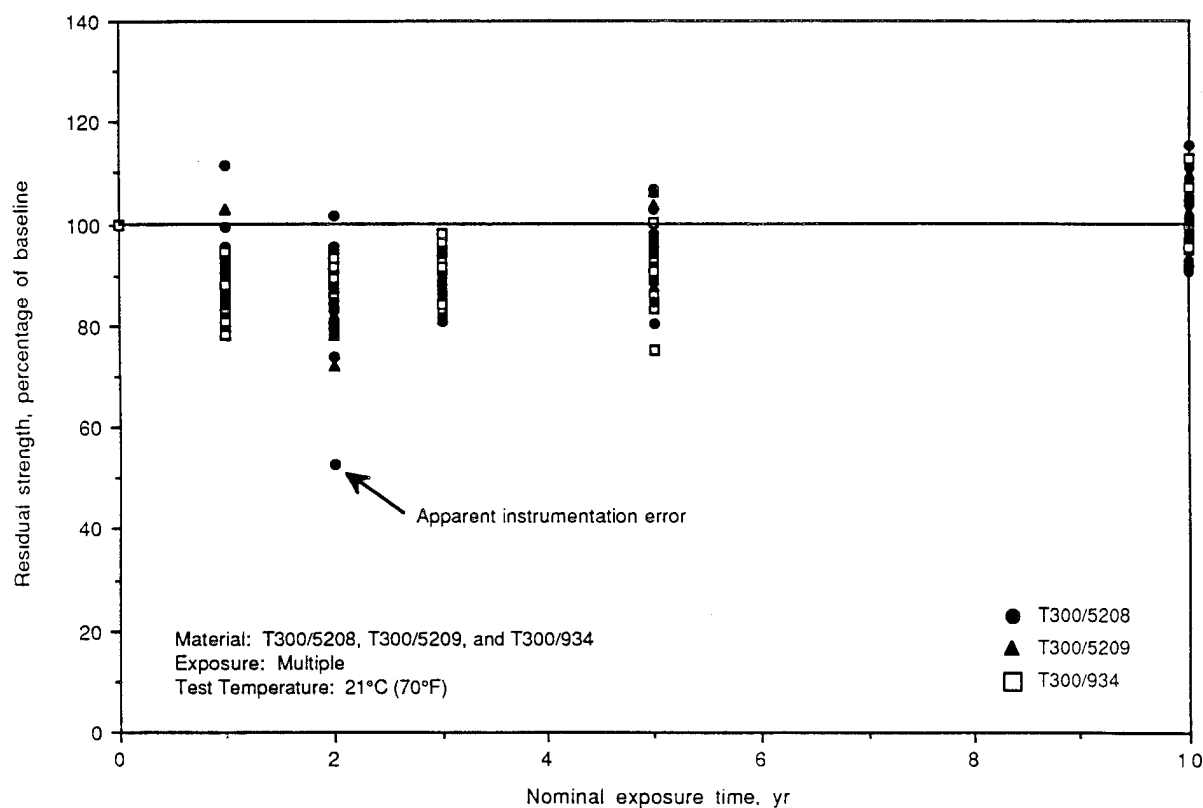


Figure 37. Room Temperature Residual Short Beam Shear Strength for T300/5208, T300/5209, and T300/934

The one obviously low point represents specimens taken from the solar face of the Honolulu ground rack. The reason is unknown, but some type of test procedure error is suspected. Specimens removed from the nonsolar face contained about the same amount of moisture and tested at 85.7% of baseline, or about average for the group. A review of the data broken out by material did not show any effect of material system.

The strength of more than 30 specimens involved in the 10-year withdrawals all ranged from 90% to 115% of baseline. These percentages are within the range of normal baseline scatter.

9.4.2 FLEXURE STRENGTH

Figures 35 and 36 showed room-temperature residual-flexure strength for the T300/5208 material system gathered from one and from several exposure sites. These results were considered either typical or atypical, as noted in the text. Strength increased modestly over the entire exposure duration. Data for the other two material systems show similar results.

9.4.3 TENSION

Figure 38 shows room temperature residuals for 45-deg tension specimens. All three materials are included for exposures to the solar side of the ground racks at Dallas, Honolulu, and NASA Dryden as well as aircraft specimens from Southwest and Aloha airlines. Like the flexure specimens tested at room temperature, these specimens were observed to gain strength after 1 year of exposure and largely retain that strength increase for the remainder of the exposure duration. The figure represents more than 200 individual test specimens.

Some individual specimens showed strength losses after 5 and 10 years, but the epoxy matrix of these specimens had been exposed to direct UV radiation because of substantial paint loss. The low values may be attributable to UV degradation.

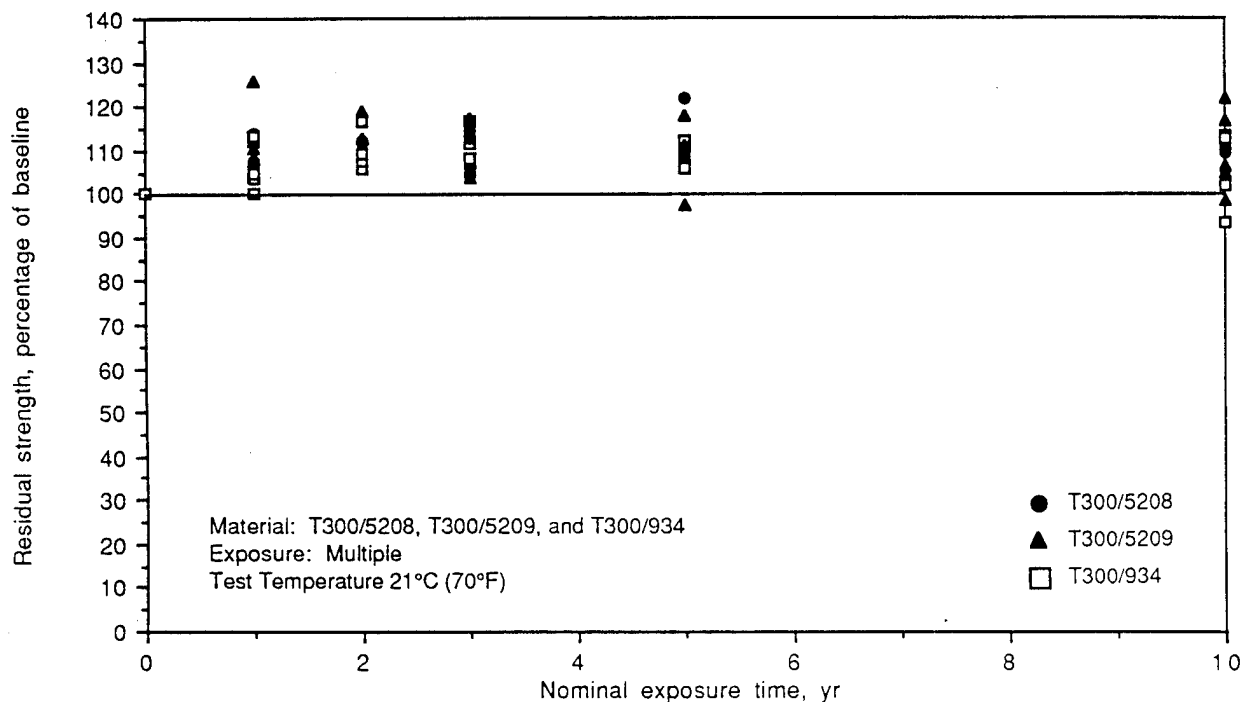


Figure 38. Room Temperature Residual Tensile Strength for All Materials

9.4.4 COMPRESSION

Figure 39 shows room-temperature residual-compression strengths for the T300/5209 material exposed to the interiors of Aloha and Southwest aircraft, as well as the ground environments at Honolulu, Dallas, and NASA Dryden. Given the amount of data scatter inherent in the compression tests, it could be said that the specimens showed no change in strength for the first 5 years but then dropped significantly between 5 and 10 years. The T300/934 material showed very similar behavior but with less data scatter. The T300/5208 material differed slightly in that it exhibited strength losses after 1 year and, with the exception of the Southwest aircraft, showed some strength loss for the entire 10 years. After 10 years, the observed losses were almost identical to those exhibited by the T300/5209 material.

These data should be treated with some caution. Throughout the program, there were recurring incidents of grip-tab failure with these specimens. Obvious tab failures are not included in the data shown in figure 39. However, it is possible that some graphite failures were precipitated by slipping grip tabs.

9.5 EFFECT OF TEST TEMPERATURE

The results discussed in section 9.4 were all based on room-temperature residual-strength testing. All datasets contained residual-strength tests at 82°C (180°F) as well. Elevated-temperature tests were initially assumed to be more discriminating for some environmental effects. This proved to be so in some but certainly not all cases.

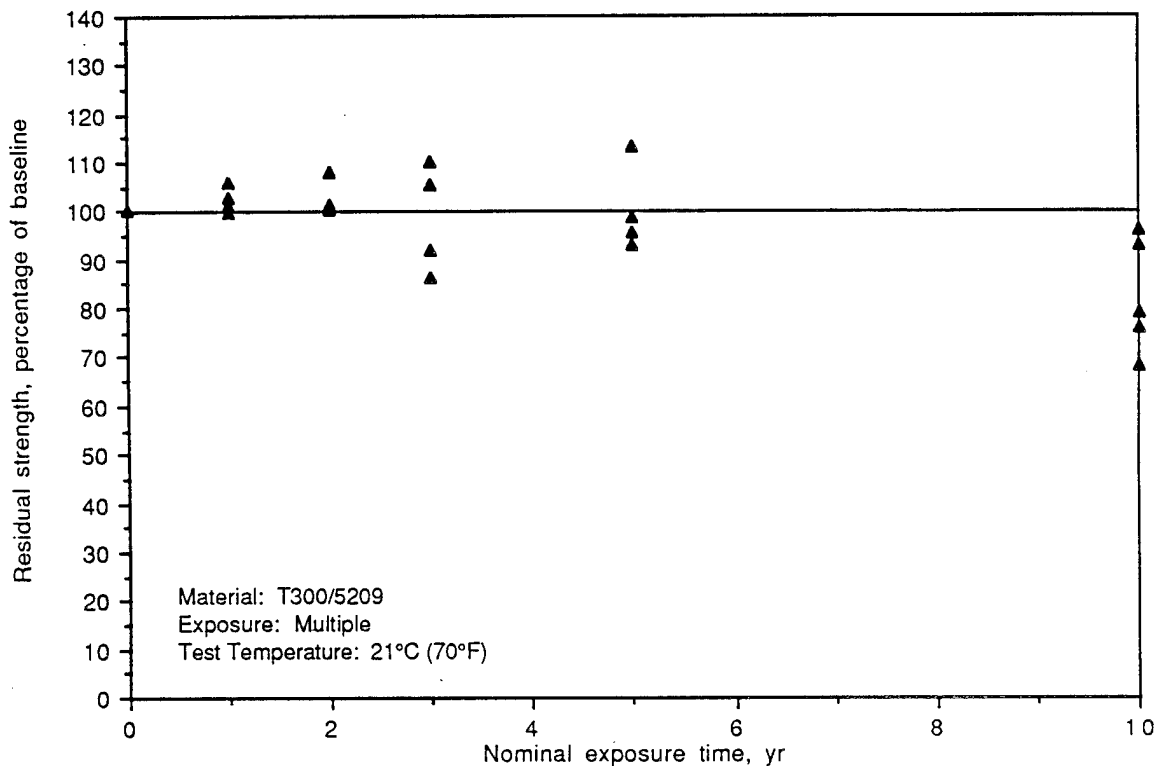


Figure 39. Room Temperature Residual Compression Strength Summary for T300/5209

9.5.1 SHORT-BEAM SHEAR

Short-beam shear tests did show a slight effect of test temperature. In general, specimens tested at elevated temperature retained slightly less of their baseline temperature than did those tested at room temperature. The overall shape of the curve covering a given exposure and material for the 10-year timeframe did not change, however. Figure 40 shows a typical comparison for the T300/5208 material incorporating the data from 12 exposure sites.

9.5.2 FLEXURE

Elevated temperature testing did appear to influence residual flexure strength although each of the three material systems displayed a different pattern of behavior. The T300/5208 material system seemed least affected by the elevated-temperature testing. Specimens exposed on Aloha aircraft and the Honolulu ground rack showed greater strength loss early but came out about equal to their room-temperature counterparts after 10 years. Specimens exposed on Southwest aircraft and the Dallas ground rack showed no effect and specimens exposed at NASA Dryden actually tested slightly higher at the elevated temperature.

Flexure results for the T300/5209 material system were completely different. Specimens at all five of the sites mentioned above displayed earlier strength loss (after 1 year), and strengths remained lower for the entire exposure duration. The differences were most pronounced in Hawaii and relatively small at NASA Dryden.

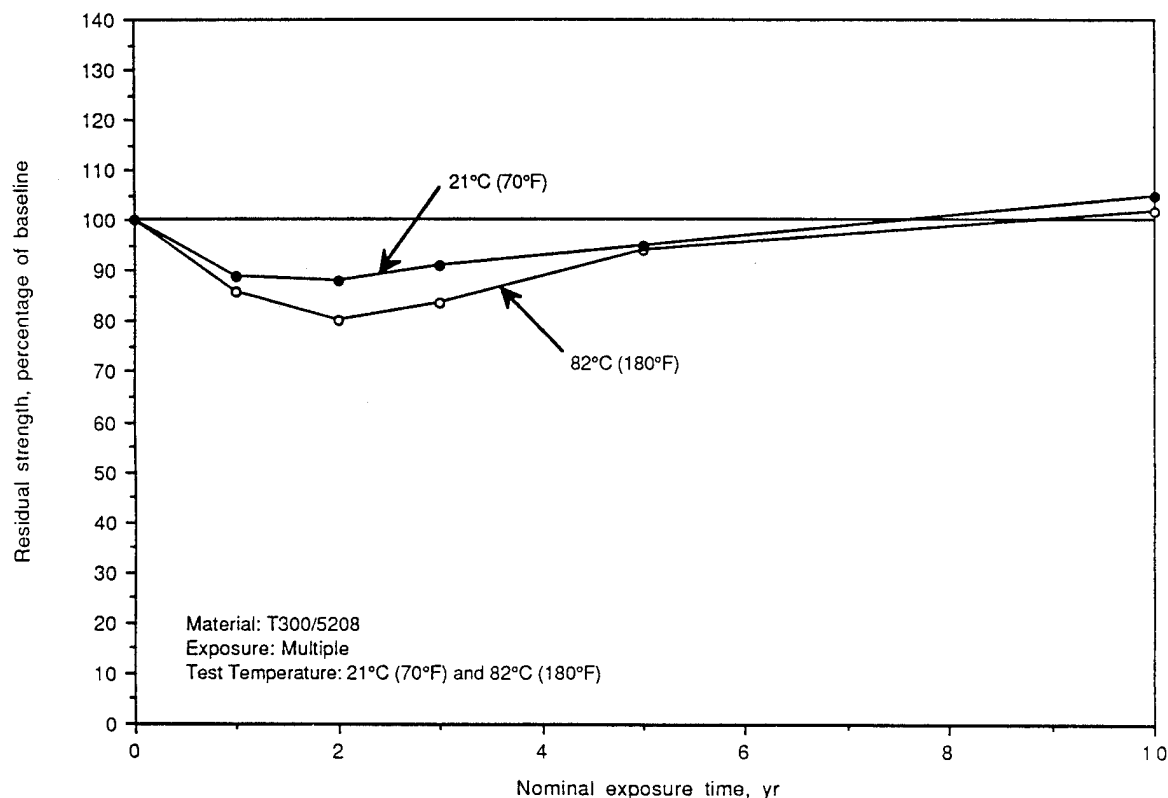


Figure 40. Room and Elevated Temperature Residual Short Beam Shear Strength for T300/5208

The T300/934 material system had some characteristics of both of the other materials. Like T300/5209, this system showed lower elevated temperature residual strengths after 1 and 2 years of flight and ground exposure in Hawaii and Texas. In addition, the elevated temperature residuals remained lower for the entire 10 years. Differences were slight, however.

The T300/934 system behaved like T300/5208 at the NASA Dryden site. Elevated-temperature residuals were actually higher than their room-temperature counterparts following 1, 2, 3, and 5 years of exposure but fell below room temperature values after 10 years. Again, differences were slight.

9.5.3 TENSION

Elevated-temperature residual-strength testing of the 45-deg tension specimens produced trends somewhat parallel to those found by testing flexure specimens. The results varied, primarily by material.

Figure 41 shows specific data for the T300/5209 material exposed on ground racks at NASA Dryden, Dallas, and Honolulu.

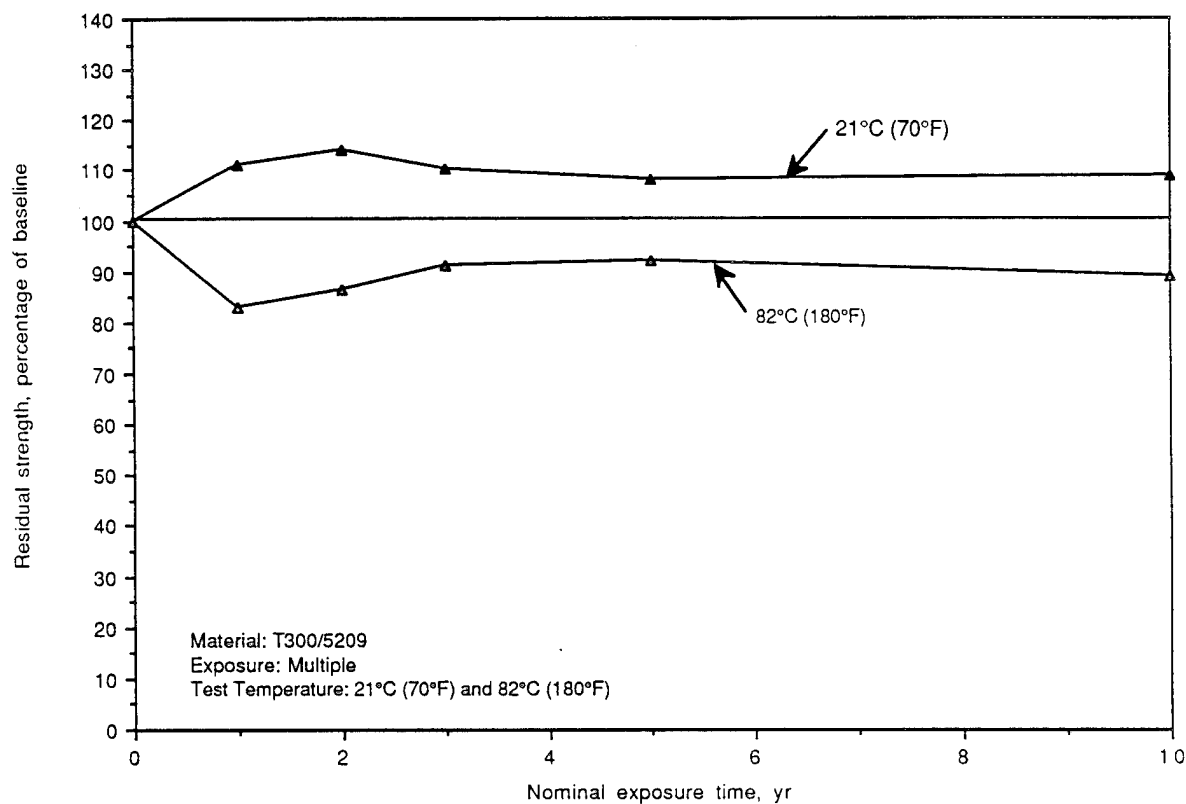


Figure 41. Room and Elevated Temperature Residual Tensile Strength for T300/5209

9.5.4 COMPRESSION

Because of repeated grip-tab failures, relatively little data were obtained from elevated-temperature compression testing. Data published in appendix A and appendix B should be treated with caution.

9.6 EFFECT OF SUSTAINED STRESS DURING EXPOSURE

Industry testing had shown that some polymeric materials (i.e., structural adhesives) showed accelerated environmental degradation when exposed to adverse environments and stress. In order to study this phenomenon, some tension specimens were exposed to a sustained load equal to 20% of their baseline failure load. Stressed-tension specimens were deployed in Section 48 of the aircraft for each of the participating airlines and on the nonsolar side of each of the four ground racks. All residual-strength testing of stressed-tension specimens was conducted at the elevated temperature.

Figures 42 and 43 show the results of unstressed- and stressed-tension specimens respectively for the T300/5209 material system. These results are typical. The presence of the sustained load neither altered nor accelerated environmental effects for any of the materials or any of the exposure locations. Results of stressed versus unstressed specimens were well within normal data scatter.

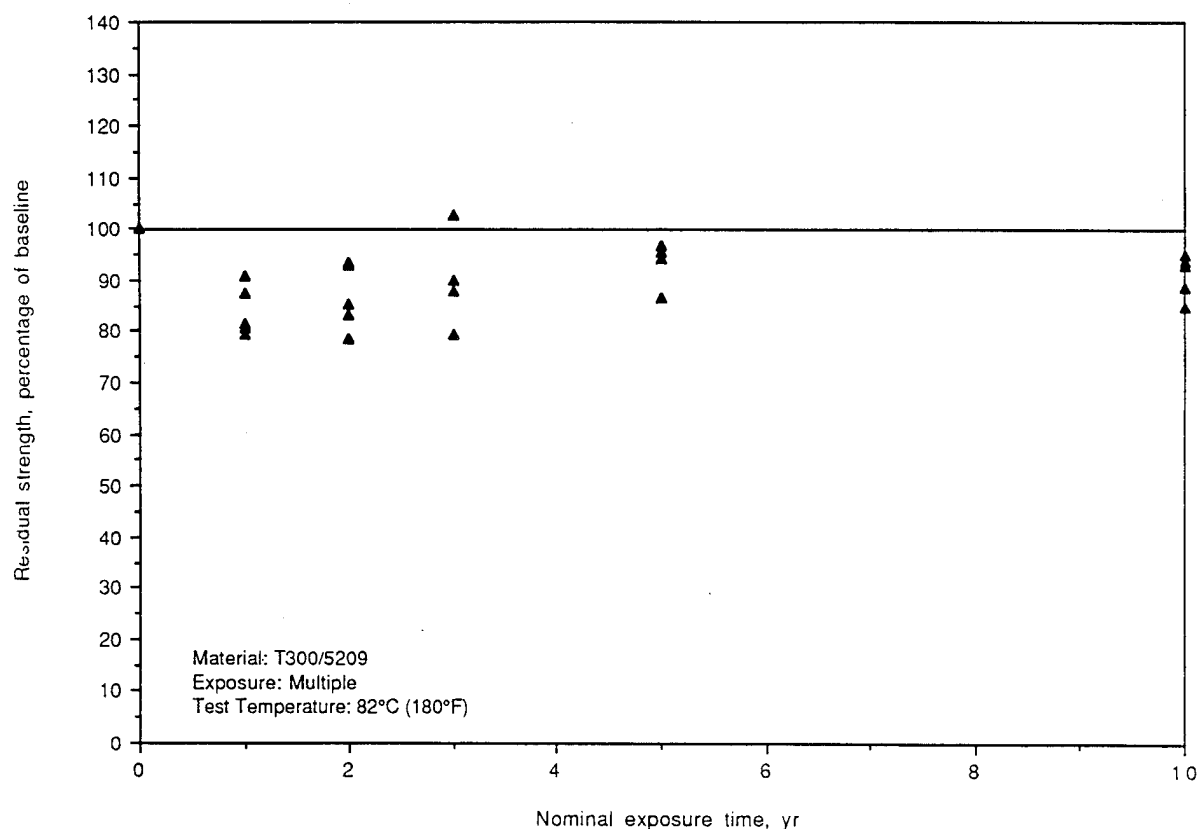


Figure 42. Elevated Temperature Residual Tension Strength for T300/5209

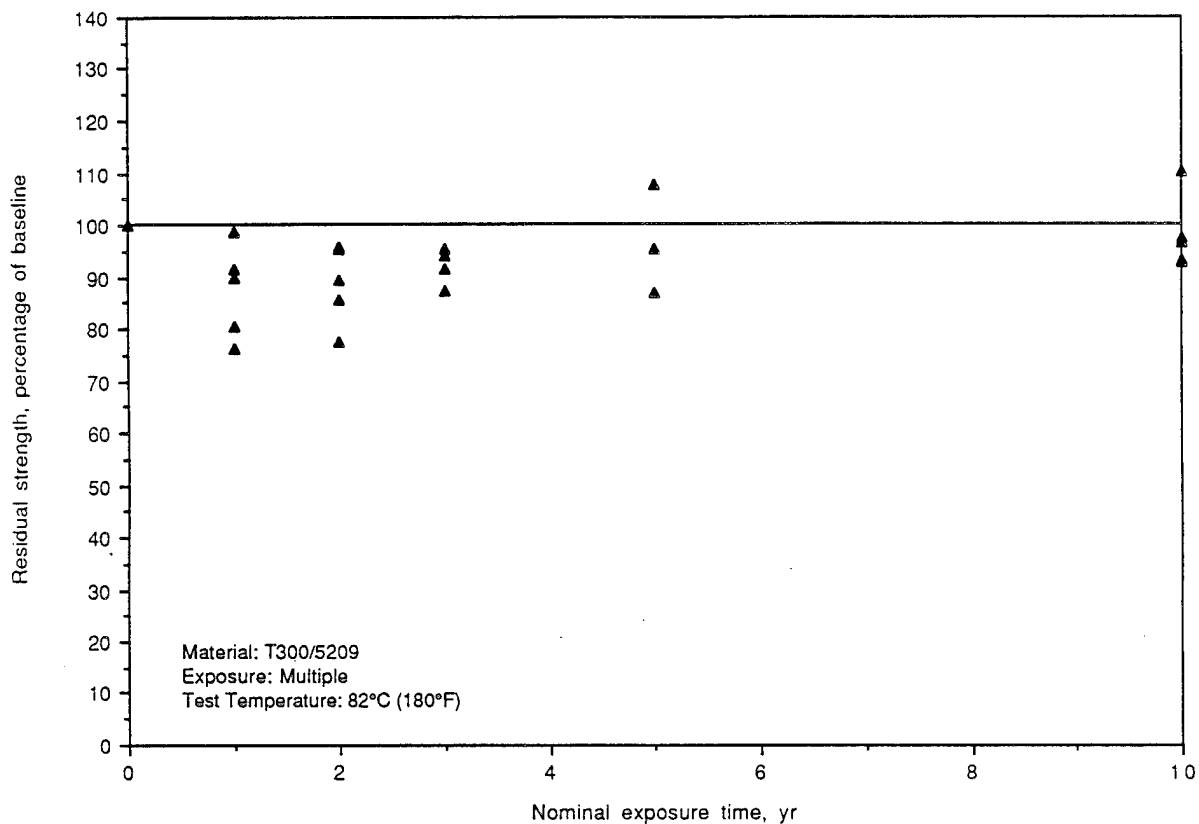


Figure 43. Elevated Temperature Residual Stressed Tension Strength for T300/5209

9.7 EFFECT OF FLIGHT VERSUS GROUND EXPOSURE

The relative degrading effects of ground exposure versus actual flight exposure were investigated using elevated-temperature short-beam shear specimens exposed on the nonsolar side of the ground racks and in the aircraft interior. These specimen sets were selected to eliminate any possibility of introducing extraneous effects because of UV degradation and also to minimize the chance of error because of specimen contamination. The elevated-temperature short-beam shear data were selected because they offered the best opportunity to examine what was expected to be a relatively minor effect if it existed at all.

Comparisons were made for Aloha-Honolulu and Southwest-Dallas. There were no discernable effects because of flight versus ground specimens. Generally, the data were almost identical. Differences, when they did exist, did not consistently identify either flight or ground exposure as being more severe.

9.8 EFFECT OF SOLAR VERSUS NONSOLAR EXPOSURE

An analysis of the relative degrading effects of solar versus nonsolar exposure showed that there was no effect as long as the specimens were protected by paint. Two sets of data were reviewed regarding this effect. Again, the comparisons involved elevated-temperature short-beam shear tests. The first comparison involved specimens on the solar and nonsolar faces of individual ground racks. The second comparison for solar radiation effects involved specimens taken from the top and bottom of the flap-track fairing tailcones.

Like the flight-ground comparison, the solar versus nonsolar ground-rack comparison revealed very small differences and did not consistently favor one face over the other.

The solar versus nonsolar flight comparison yielded similar results; however, comparisons were more difficult because of the conditions of the specimens. Long-term solar tailcone specimens often suffered some loss of paint. This loss is probably due more to the air currents around the specimens and their holding fixtures than to any of the planned program variables.

Figure 44 shows the results of one comparison. The data are for the T300/5208 material exposed on Southwest Airlines. Data for the corresponding aircraft interior specimens are also shown on the figure. These results are typical.

9.9 EFFECT OF INTERIOR VERSUS EXTERIOR AIRCRAFT EXPOSURE

Comparisons were made between elevated-temperature short-beam shear specimens exposed on the interior and the nonsolar tailcone surface of Southwest Airlines aircraft. The results shown in figure 44 for the T300/5208 material are typical of the other materials and the other airlines.

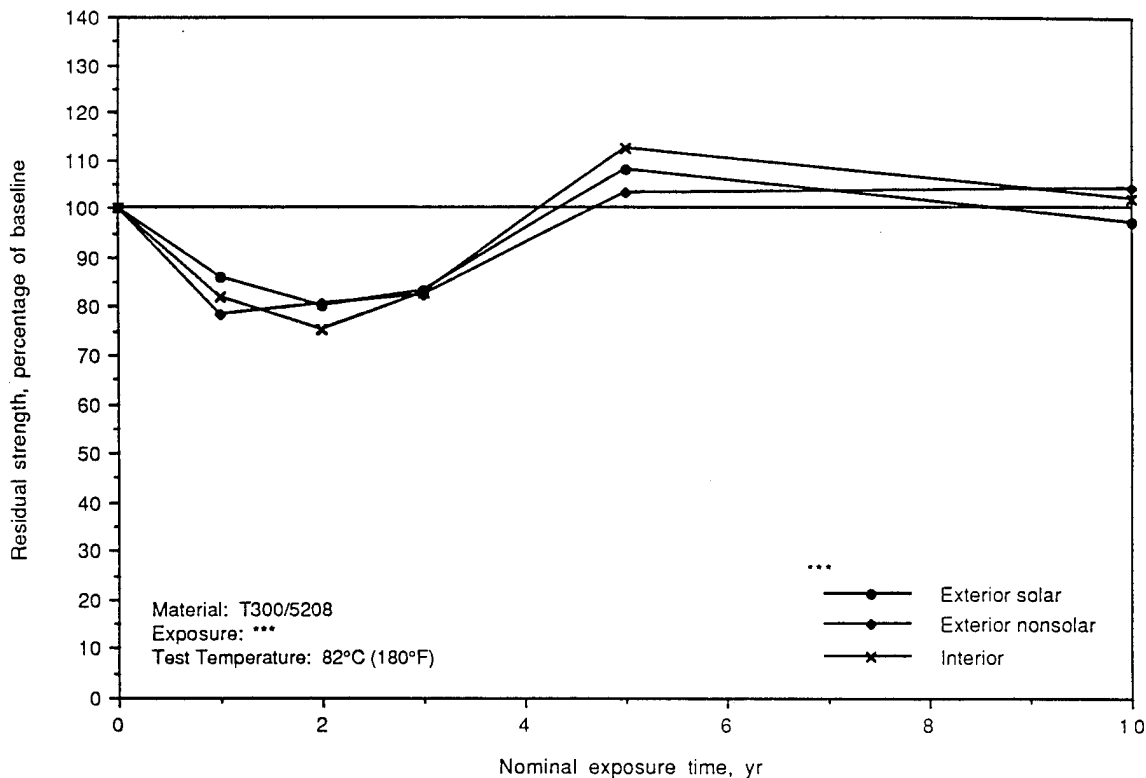


Figure 44. High Temperature Residual Short Beam Shear Strength for T300/5208 Exposed on Southwest Airlines

9.10 EFFECT OF EXPOSURE LOCATION (GEOGRAPHY)

Geography affected residual strength results because it affected moisture content in the specimens. Moisture content is discussed in section 9.3. Beyond moisture content, there were no obvious effects because of geography. The annual thermal swings experienced at NASA Dryden and Dallas had no effect, nor did the intense solar radiation experienced at Dryden.

9.11 EFFECT OF SPECIMEN DRYOUT BEFORE TEST

Drying specimens before test did have a significant effect on residual strength. Figure 45 shows undried and dried elevated-temperature short-beam shear strengths for the T300/5208 material exposed on Aloha and Southwest Airlines as well as the Honolulu, Dallas, and NASA Dryden ground racks. The dried specimens are consistently higher than the undried specimens and do not vary significantly from 100% of baseline for the entire 10 years.

9.12 EFFECT OF MATERIAL

Similarities and behavioral differences between material systems are noted throughout this report. In general, the two 177°C (350°F) curing systems (T300/5208 and T300/934) behaved somewhat differently than the one 121°C (250°F) system (T300/5209).

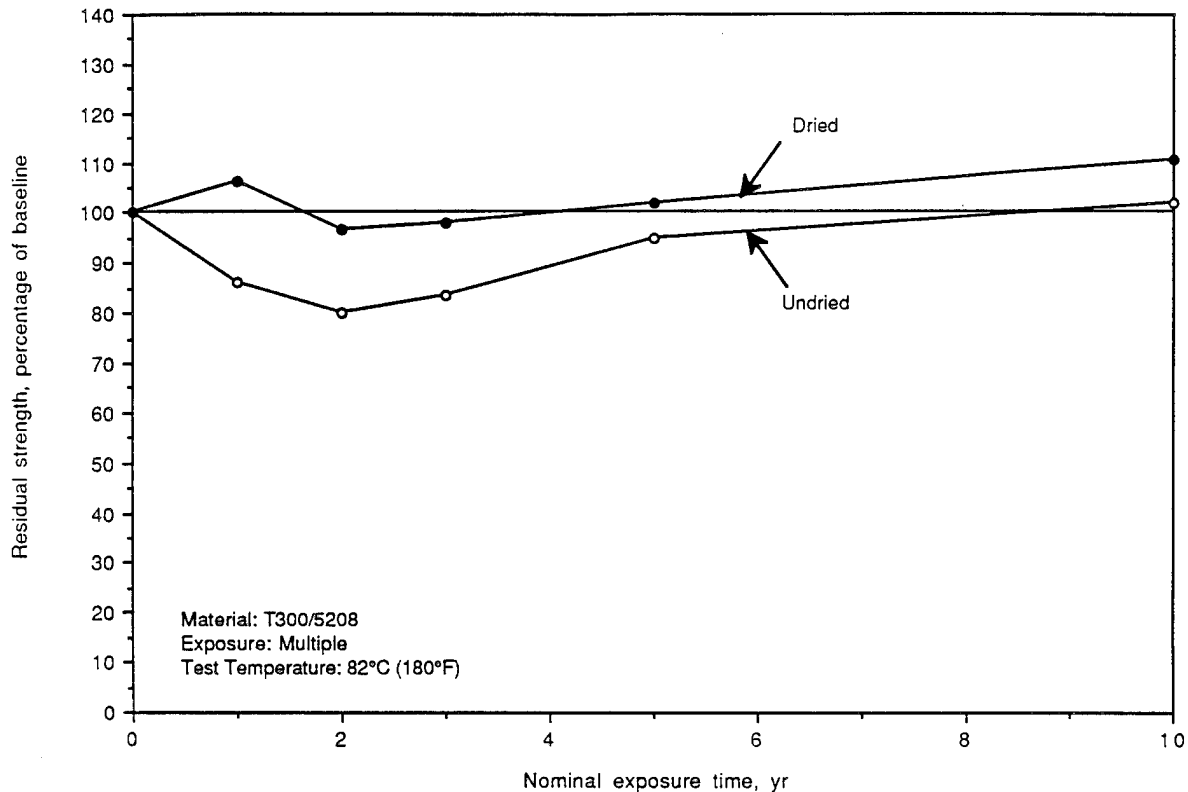


Figure 45. High Temperature Residual Short Beam Shear and Dryout Strength for T300/5208

In the drier locations, the T300/5209 system generally absorbed less moisture and performed as well as the other two systems. This was particularly true for room temperature residuals. Elevated-temperature residuals for T300/5209 were generally somewhat below the other two systems but still at a reasonable level. This pattern changes when the specimens are taken from the wetter exposure sites.

Moisture contents for the T300/5209 specimens retrieved from the wetter locations were usually, but not always, below those found on the other two systems. Nevertheless, a significant difference shows on elevated-temperature residual strengths. The T300/5209 system showed a definite susceptibility to moisture content when tested at elevated temperature. Table 15 shows a comparison of elevated-temperature short-beam shear strength results along with observed moisture contents for eight relatively wet exposures in Honolulu and on Aloha aircraft. On average, both of the 177°C (350°F) curing systems absorb more moisture yet retain a higher percentage of their baseline strength than does the T300/5209. When compared with the T300/5208 material, T300/5209 loses almost 17% more strength.

The reason that the T300/5209 material absorbed less moisture than the other two material systems is unknown, particularly since it absorbed slightly more moisture than the other systems during controlled laboratory exposures. The strength sensitivity, particularly at elevated temperatures, was expected. The lower-temperature cure produces less crosslinking in the 5209 matrix. In addition, the 82°C (180°F) test temperature is probably near the wet glass transition temperature for this material.

In general, the T300/5208 material system was the most moisture-resistant, the T300/934 system is slightly less resistant, and the T300/5209 system significantly less resistant. (Section 10.3 shows that the T300/5209 system is actually more resistant to UV degradation than the other two materials.)

Table 15. Influence of Material on the Moisture Content and Residual Strength of Selected Specimens*

Exposure Site/Duration	5208		5209		934	
	MC	RS	MC	RS	MC	RS
Aloha Airlines - Solar 2 yrs	1.09	75.9	.77	59.4	1.11	64.4
Aloha Airlines - Solar 10 yrs	1.23	94.1	2.03	74.5	.98	86.9
Aloha Airlines - Nonsolar 10 yrs	1.16	92.3	1.77	75.2	.94	84.8
Honolulu - Solar 2 yrs	1.16	81.7	.98	65.6	1.28	70.1
Honolulu - Nonsolar 2 yrs	1.20	80.9	.93	64.3	1.34	63.7
Honolulu - Solar 3 yrs	1.06	78.8	.75	68.0	.88	73.2
Honolulu - Solar 10 yrs	2.12	96.6	.60	78.8	.66	88.0
Honolulu - Nonsolar 10 yrs	1.96	93.7	.60	76.5	1.36	85.1
AVERAGE	1.37	86.8	1.04	70.2	1.06	77.0

MC = Moisture Content

RS = Residual Strength, percentage of baseline

* Residual Strengths are for Short-Beam Shear Specimens tested at 82°C (180°F)

10.0 LABORATORY TEST RESULTS

10.1 EFFECT OF TIME ALONE

Test specimens representing the effects of "time alone" were tested after 1, 2, and 3 years of exposure to room temperature and approximately 25% RH. Both short-beam shear and flexure specimens were involved. Summary results for 1, 2, and 3 years of exposure are shown in tables C-1, C-2, and C-3, respectively.

These tests were influenced unintentionally by specimen moisture content. All specimen groups lost weight during the first 2 years of exposure. This loss was because of the moisture that had been absorbed between the time that the specimens were cured and the time they were weighed and placed in their desiccated storage containers.

Specimens were observed to regain some of the weight loss during the third year of exposure; however, this was attributed to the desiccant aging, thereby raising the relative humidity in the jars slightly.

The influence of time (and some moisture absorption) on the residual room-temperature short-beam shear strengths of all three materials is shown in figure 46. Comparable results for elevated-temperature residuals are shown in figure 47. Flexure data are shown in figures 48 and 49.

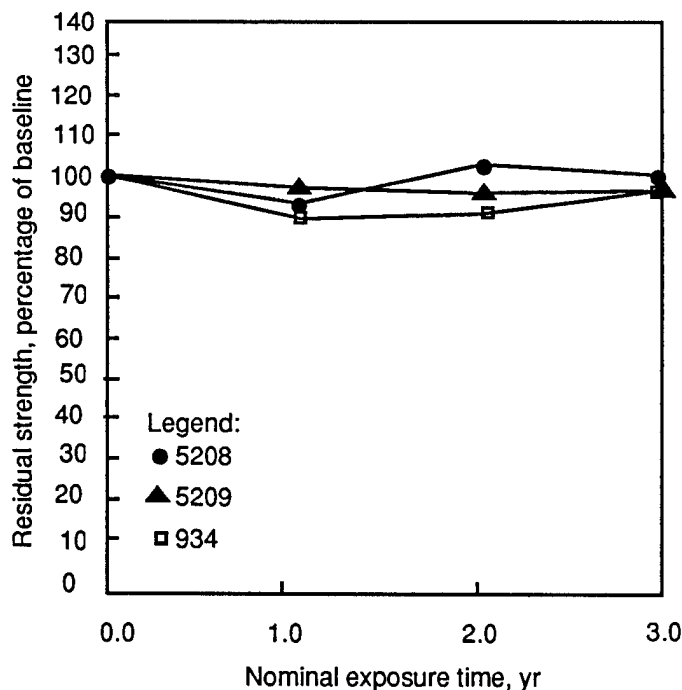


Figure 46. Room Temperature Short-Beam Shear Strength Following Time Alone Exposure

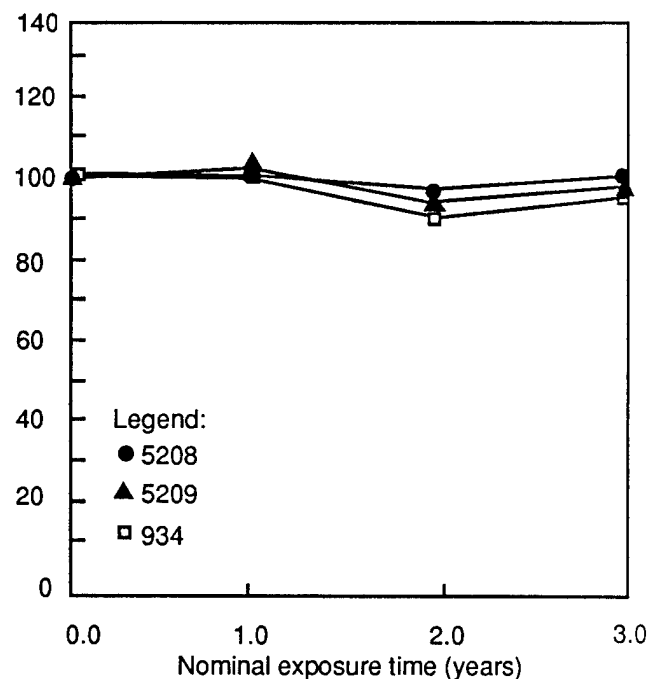


Figure 47. Elevated Temperature Short-Beam Shear Strength Following Time Alone Exposure

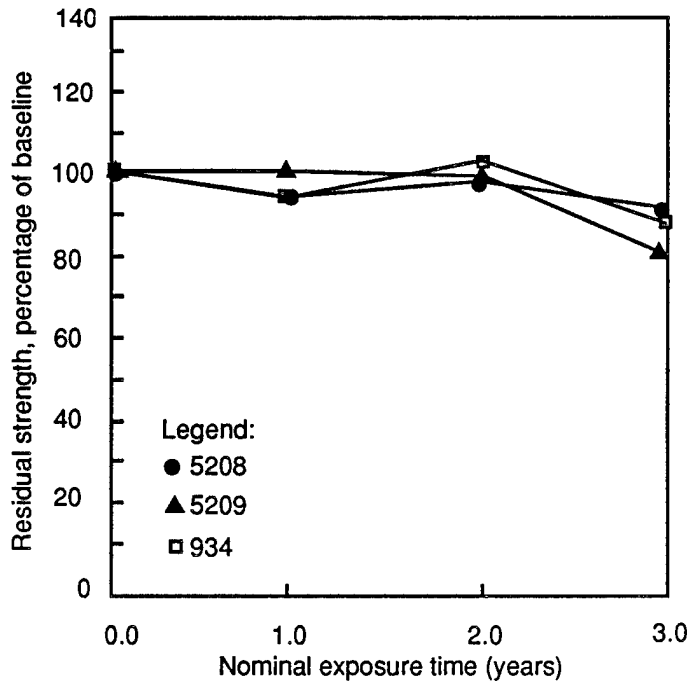


Figure 48. Room Temperature Flexure Strength Following Time Alone Exposure

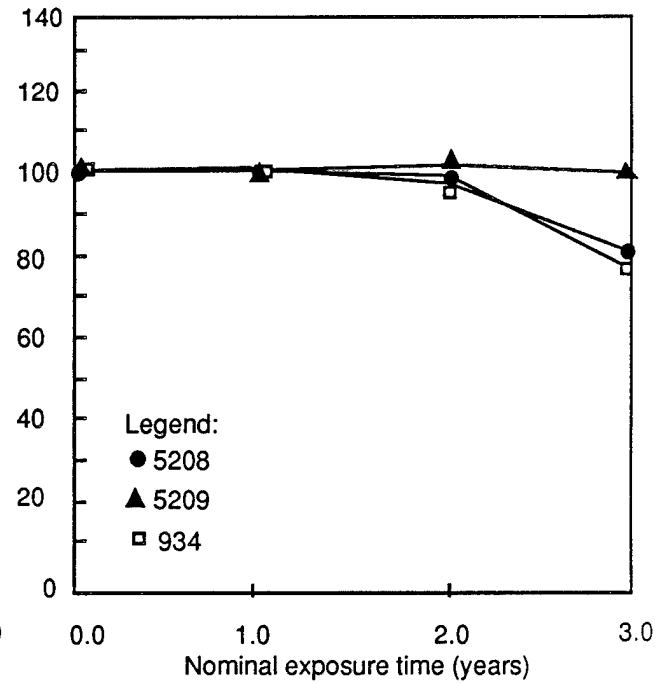


Figure 49. Elevated Temperature Flexure Strength Following Time Alone Exposure

The levels of short-beam shear strength at both room and elevated temperatures remained steady for the entire 3 years. Flexure strengths remained close to their baseline values for the first 2 years and then declined at the end of the third year. Strength declines were approximately the same on a percentage basis for both room- and elevated-temperature tests. The observed losses are believed to reflect the data scatter inherent in testing small groups of specimens rather than any environmental effect. Based on a comparison of head-travel load-deflection curves, no change in stiffness was observed with any of these specimens. Neither the failure mode nor the appearance of the specimens following testing changed from those tested in previous years.

Glass transition temperature (T_g) measurements were made only after 1 year of time-alone exposure. Changes from baseline values were within 2% at this time, so no additional tests were conducted for the other exposure durations.

10.2 EFFECTS OF MOISTURE AND TIME ON WET SPECIMENS

Moisture-gain data were tracked for at least 130 days of exposure using individual specimen weighings. Figure 50 shows the normalized weight-change data for specimens exposed to 95% RH and 49°C (120°F). The data represent three individual flexure specimens from each of the three material systems. Generally, the data follow predictable moisture diffusion trends. The T300/5209 specimens behaved differently from both of the 177°C (350°F) curing systems. Initially, the T300/5209 specimens absorbed moisture at a lower rate. After 121 days of exposure, however, they had absorbed more moisture than the other two systems and were still gaining. The T300/5208 and T300/934 specimens were still picking up moisture but at a much lower rate.

Normalized weight changes for specimens exposed to 75% relative humidity are shown in figure 51. Although there are no individual specimen anomalies, the entire set of data showed a dramatic desorption during the middle of the exposure period. An investigation indicated that either the lid on the 75% RH desiccator was not resealed properly following the weighing on the 55th day of exposure, or it was bumped during other activities around the desiccator. The air-circulating oven used to maintain the 49°C (120°F) exposure temperature then rapidly altered the makeup of the glycerin-water solution. As the water evaporated, the resultant solution became more biased towards the glycerin, thus producing a lower RH condition even after the lid was correctly sealed. Therefore, the old solution was discarded and replaced. As a precaution, the solutions for the other exposures also were replaced to maintain the assigned moisture levels.

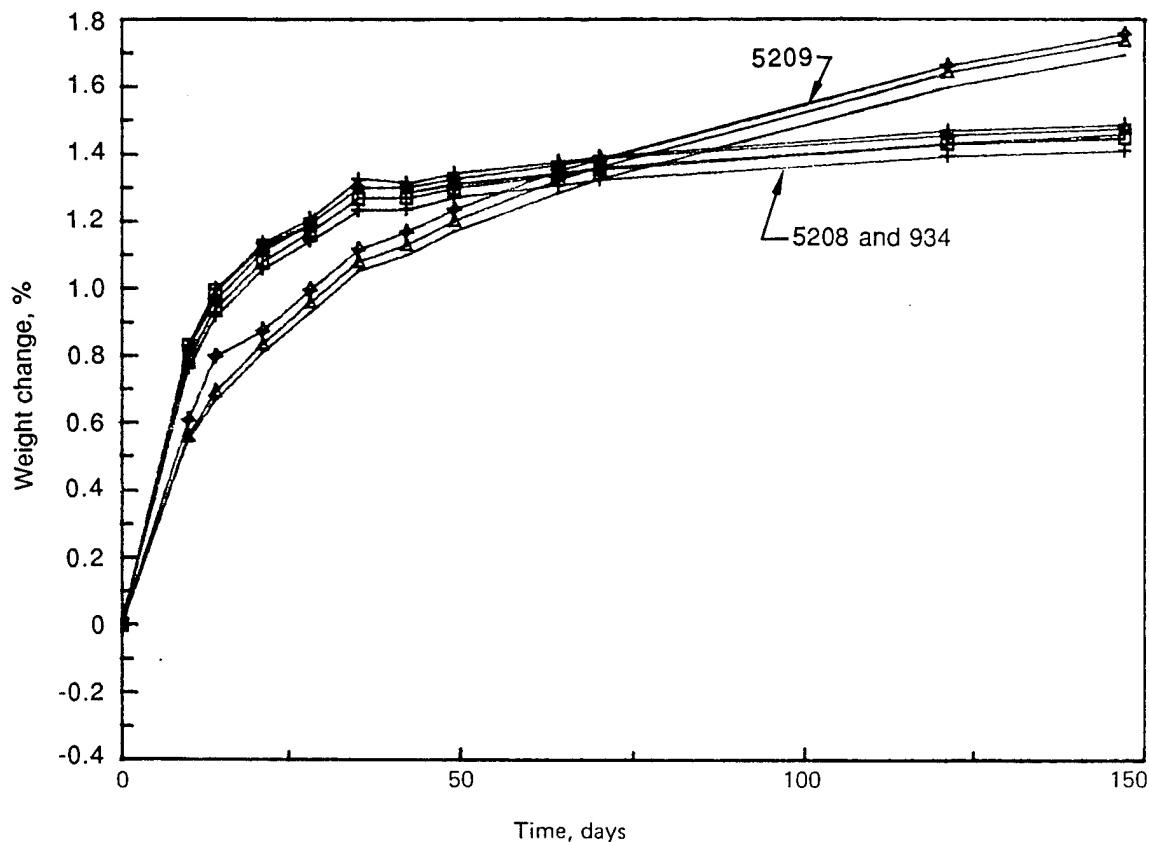


Figure 50. Percentage of Weight Change for 95% Relative Humidity Exposure

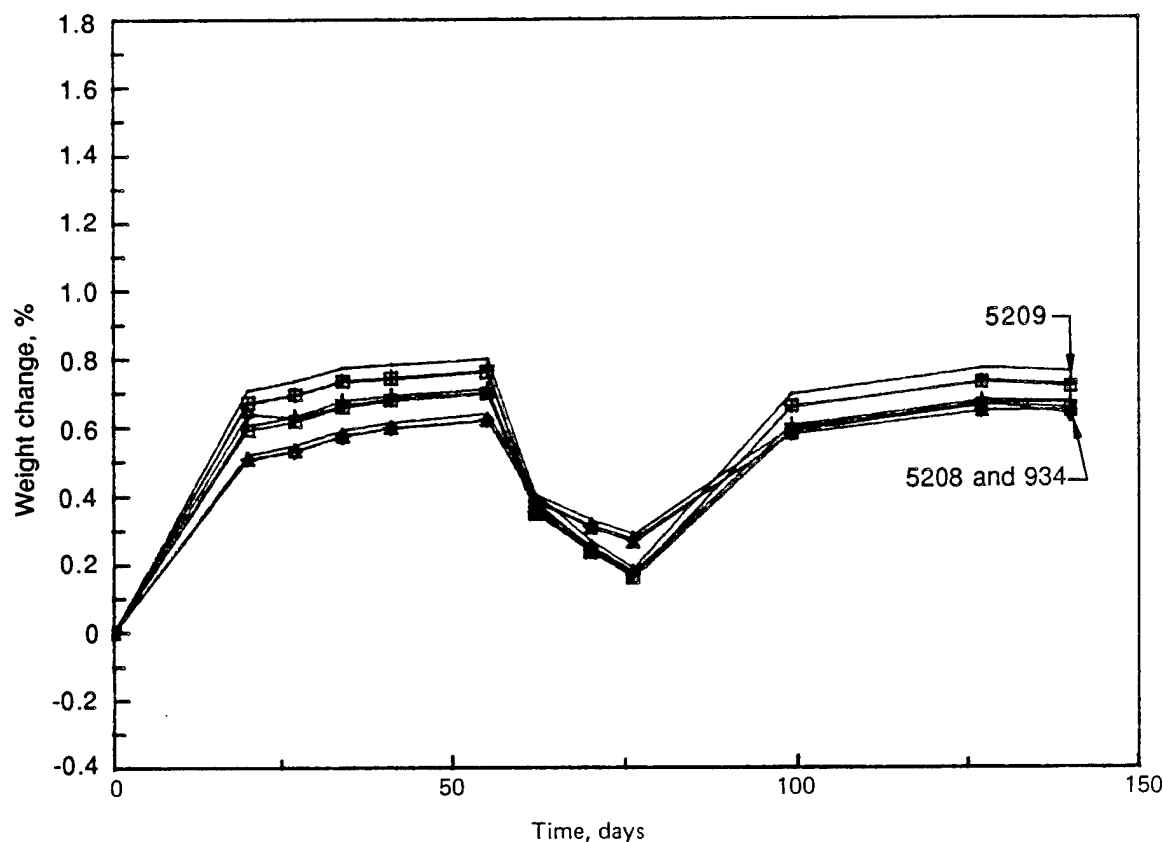


Figure 51. Percentage of Weight Change for 75% Relative Humidity Exposure

Weight change measurements for 60% RH and 40% RH are shown in figures 52 and 53, respectively. Both of these sets of specimens reached equilibrium moisture content, and neither showed any significant anomalies. The 40% RH measurements show a slight decline after peaking at about 55 days of exposure. This may be because of a lesser degree of the same problem experienced with the 75% specimens.

Table 16 shows the observed moisture content in the specimens at the time of mechanical testing. Figure 54 portrays the same data. All three material systems are shown and, with one exception, the data are relatively consistent at humidities below 75%. The figure also illustrated a 0% moisture content for specimens at approximately 25% RH, indicating that this was representative of the original (dry-drum storage) environment. Finally, the moisture content at 95% (i.e., condensing humidity) are higher than a linear extrapolation of the lower values would indicate.

The test plans called for one set of specimens to be tested when an equilibrium weight gain was achieved. Two other sets were planned for testing following various times at equilibrium. Unlike tests conducted on the time alone specimens, these tests showed significant strength changes. Residual strength results, as a percentage of baseline strengths, are presented in table C-4.

Summary results of the specimens exposed to constant relative humidity levels of 60% and 95% at 49°C (120°F) for 2 years nominal (28 months actual) are given in table C-5. Table 17 shows the observed moisture content in these specimens at the time of mechanical test. Figures 55 through 62 show the strength retention data for these specimens along with the data for specimens exposed 150 days.

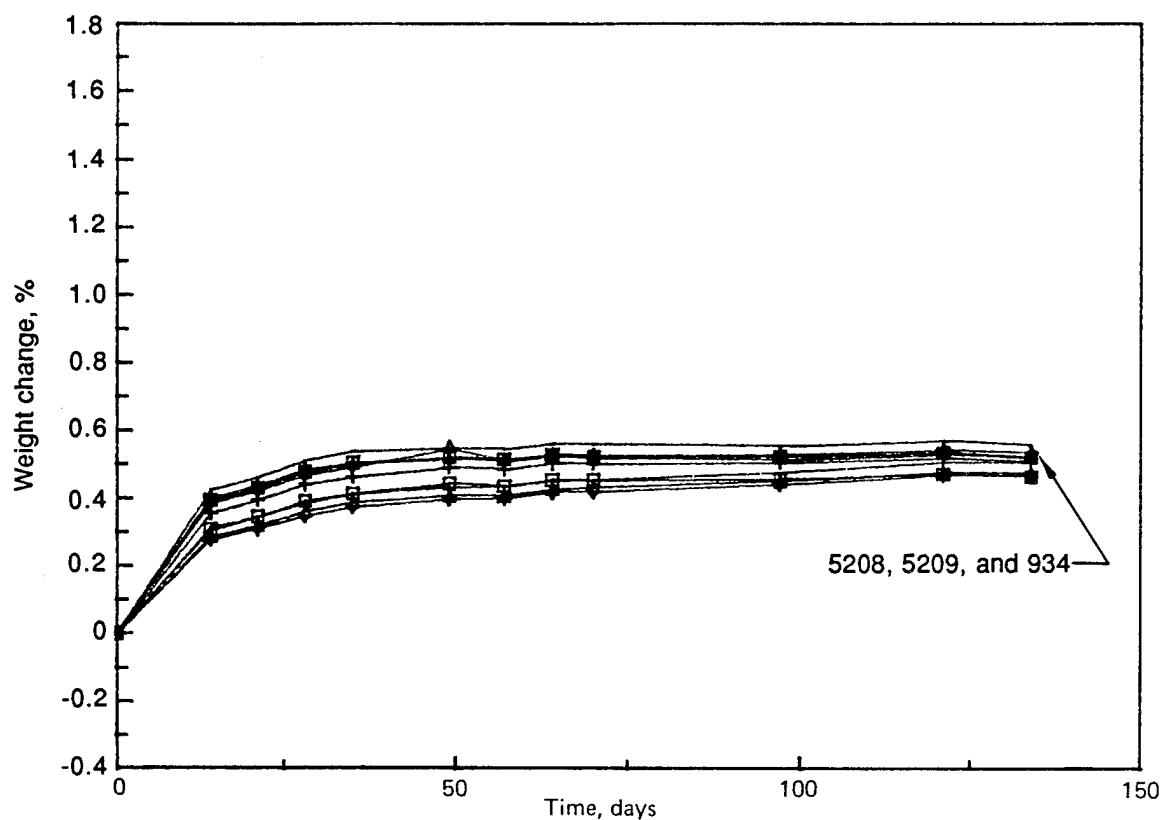


Figure 52. Percentage of Weight Change for 60% Relative Humidity Exposure

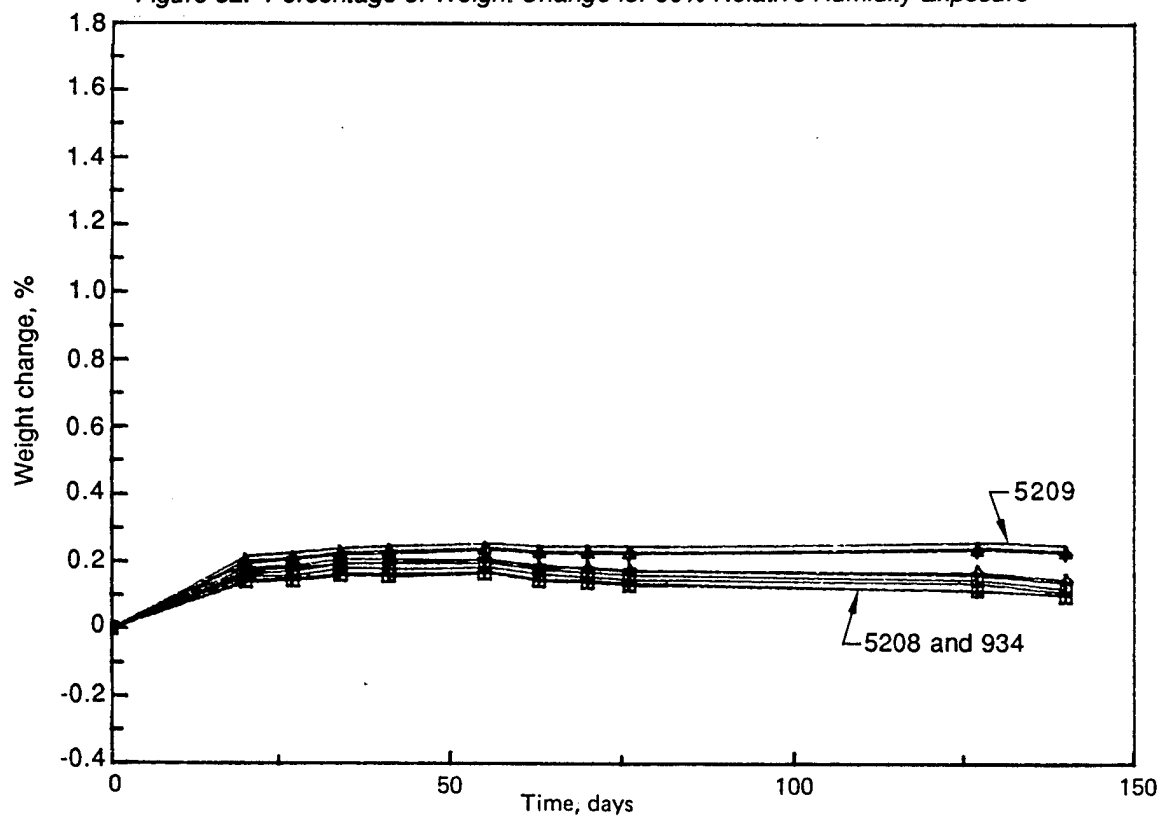


Figure 53. Percentage of Weight Change for 40% Relative Humidity Exposure

Table 16. Observed Percentage of Moisture Content
After Humidity Conditioning 

TYPE OF SPECIMEN	RELATIVE HUMIDITY			
	40%	60%	75%	95%
Short beam shear	0.24	1.10 	0.74	1.34
	0.28	0.57	0.81	1.32
Flexure	<u>0.21</u>	<u>0.58</u>	<u>0.82</u>	<u>1.44</u>
5208 AVG	0.24	0.57	0.79	1.37
Short beam shear	0.30	0.50	0.78	— 
	0.33	0.63	0.92	— 
Flexure	<u>0.34</u>	<u>0.57</u>	<u>0.84</u>	<u>1.84</u>
5209 AVG	0.32	0.57	0.85	1.84
Short beam shear	0.25	0.56	0.85	1.59
	0.33	0.65	0.95	1.71
Flexure	<u>0.22</u>	<u>0.53</u>	<u>0.80</u>	<u>1.45</u>
934 AVG	0.27	0.58	0.87	1.58

Note:



Apparently erroneous value was not used in average calculation.



Never weighed.



95% Relative humidity specimens exposed for 145 days.

75% Relative humidity specimens exposed for 140 days.

60% Relative humidity specimens exposed for 130 days.

40% Relative humidity specimens exposed for 140 days.

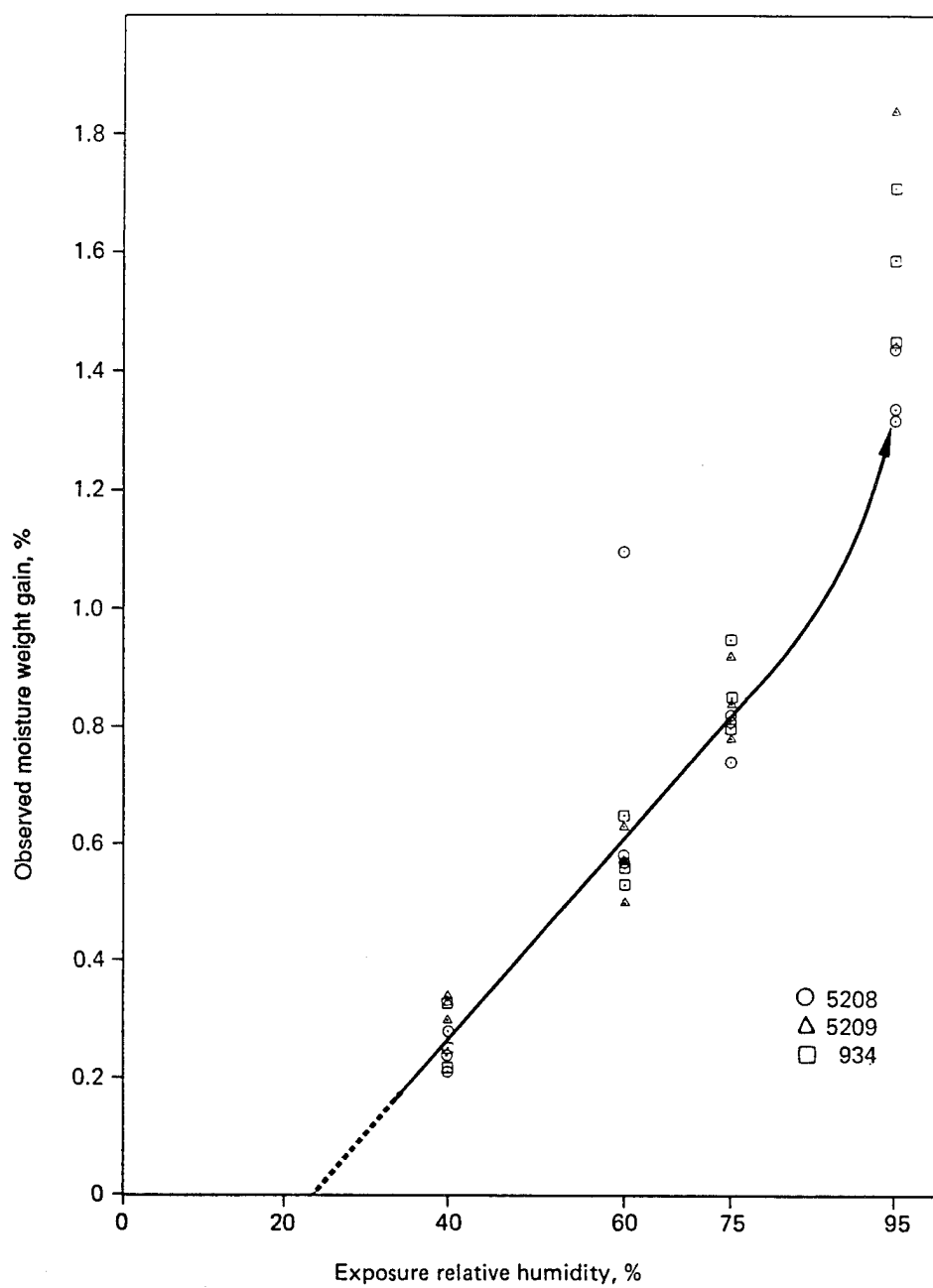


Figure 54. Moisture Content as a Function of Humidity

Table 17. Observed Percentage of Moisture Content Following 28-month Exposure

Type of Specimen	Relative Humidity	
	60%	95%
Short beam shear	1.29	1.84
Flexure	<u>.91</u>	<u>1.65</u>
5208 AVG	1.10	1.75
Short beam shear	1.55	2.35
Flexure	<u>1.06</u>	<u>2.04</u>
5209 AVG	1.31	2.20
Short beam shear	1.22	2.17
Flexure	<u>.91</u>	<u>1.65</u>
934 AVG	1.07	1.91

All three material systems show a general decrease in short-beam shear strength with increasing humidity exposure. As expected, the strength reductions are more pronounced at 82°C (180°F) than they are at room temperature. Again, the two 177°C (350°F) curing systems behaved similarly, while the 121°C (250°F) curing system reacted differently.

Flexure strengths also changed because of humidity exposure but, as expected, the strength reductions were less severe with the more fiber-dominated specimen. At room temperature, some strengths actually increased.

One notable characteristic of these plots is that the primary strength loss occurred within the initial 150 days of exposure. Additional time in a wet state did not cause significant additional deterioration. However, a comparison of tables 16 and 17 reveals that the additional time did cause some additional weight gain.

Figures 57 and 58 show additional data points for short-beam shear dryout specimen residual strengths tested at the elevated temperature. Note that these strengths return to approximately 100% of baseline, suggesting that the observed strength and commensurate stiffness losses observed on wet specimens are the result of a simple, reversible, plasticization phenomenon and do not involve a chemical change to the matrix material.

One could infer from tables 16 and 17 that any or all of the material systems shown could develop a severe moisture problem; however, a 95% exposure at 40°C (120°F) is considerably more severe than real-world conditions. Although the test may be useful as an indicator, the absolute number achieved may not be realistic. A 75% humidity condition at 40°C (120°F) is considered to be the upper end of real-world environment. Most airplane structures are better represented by the flexure specimen than by the matrix-dominated short-beam shear specimen. Finally, note that Boeing model 737 spoilers using the T300/5209 system have been performing well in actual service for over 10 years (ref. 22). The T300/5209 moisture weight-gain data show a definite behavior change in the 95% exposure condition when compared with the other three humidity levels. For some humidities, the T300/5209 absorbs the same or possibly even less moisture than the 177°C (350°F) curing systems.

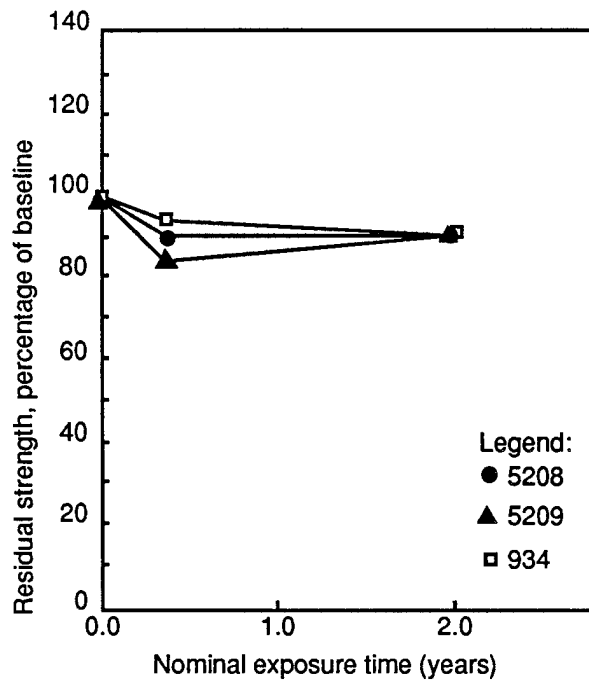


Figure 55. Short Beam Shear, 60% RH Exposure, Tested at Room Temperature

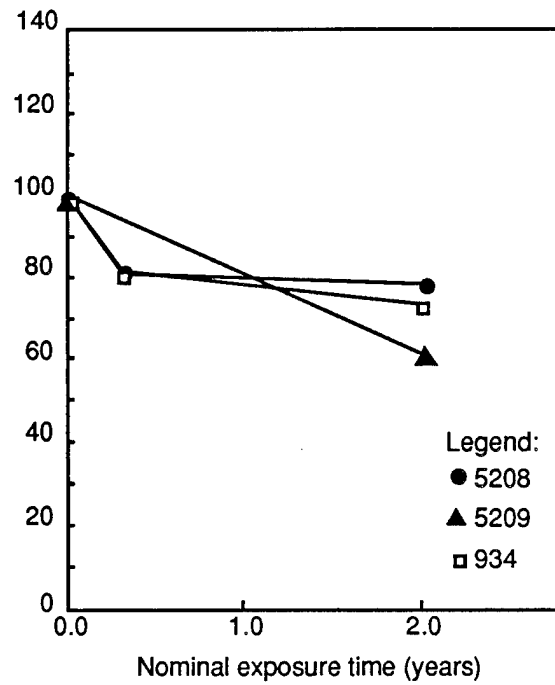


Figure 56. Short Beam Shear, 95% RH Exposure, Tested at Room Temperature

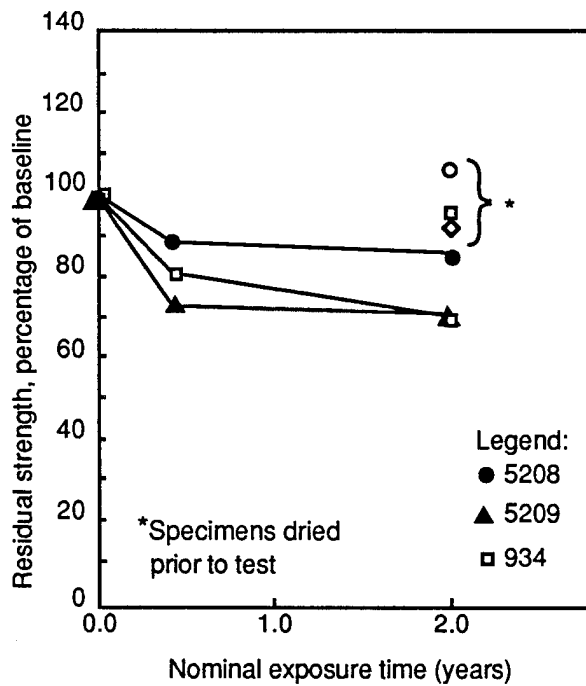


Figure 57. Short Beam Shear, 60% RH Exposure, Tested at 180°F

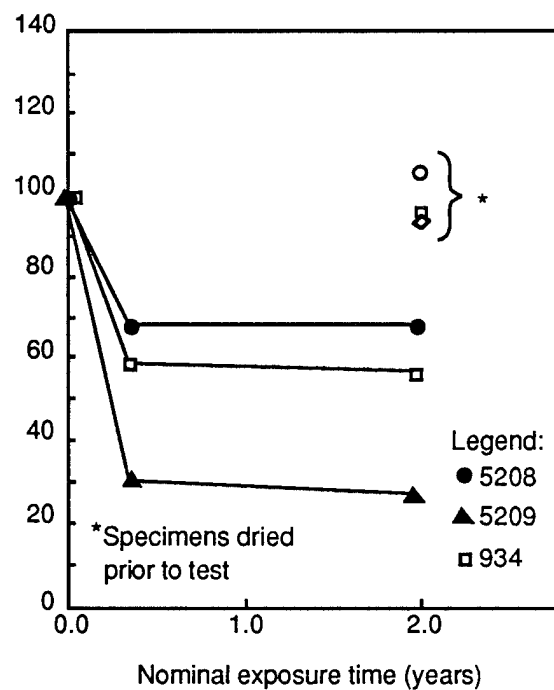


Figure 58. Short Beam Shear, 95% RH Exposure, Tested at 180°F

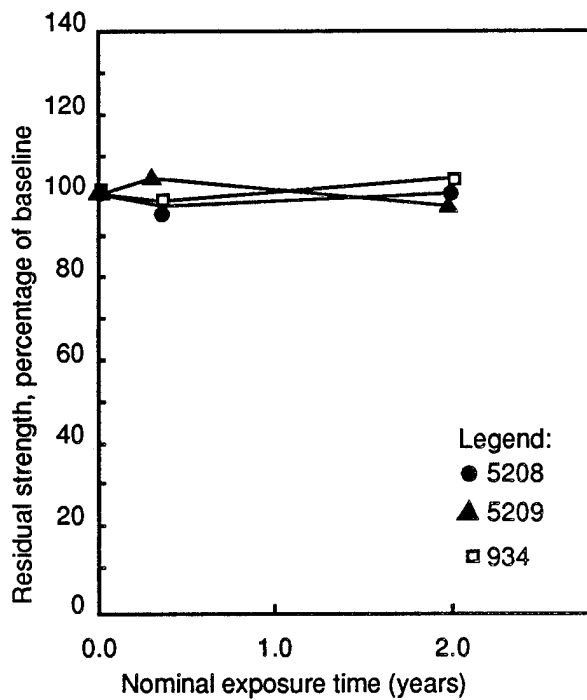


Figure 59. Flexure, 60% RH Exposure, Tested at Room Temperature

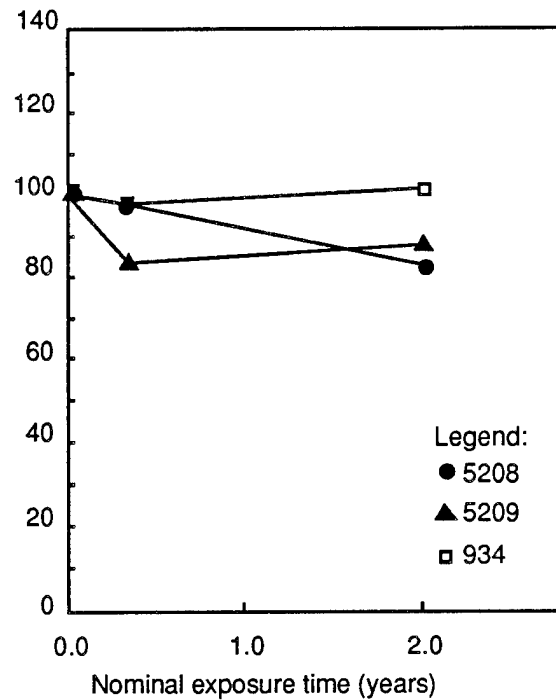


Figure 60. Flexure, 95% RH Exposure, Tested at Room Temperature

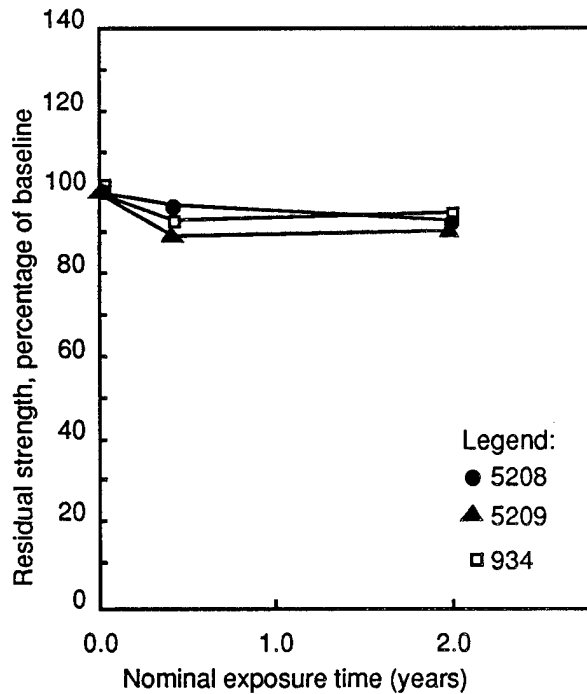


Figure 61. Flexure, 60% RH Exposure, Tested at 180°F

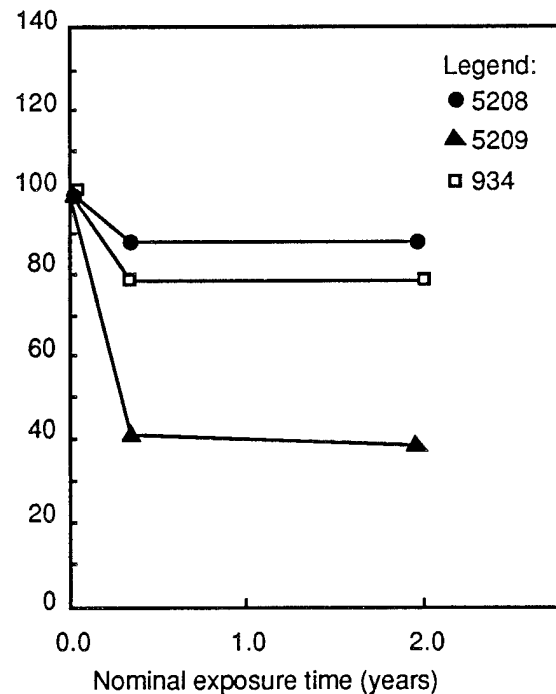


Figure 62. Flexure, 95% RH Exposure, Tested at 180°F

10.3 EFFECT OF WEATHEROMETER EXPOSURE

Flexure specimens were subjected to weatherometer exposure for times up to 2 years. All three material systems were tested at 82°C (180°F) following nominal exposure durations of 6 months, 1 year, and 2 years. In addition, the test matrix included room-temperature residual-strength testing for the T300/5208 material. In all cases, both painted and unpainted specimens were included.

During exposure, one group of specimens was tracked for weight changes through approximately 1 year or almost 7,000 cycles. Figure 63 shows the average results for unpainted specimens, and figure 64 shows comparable data for the painted specimens. In the case of the unpainted specimens, the two 177°C (350°F) cure materials, T300/5208 and T300/934, behaved similarly, losing weight from the outset of exposure. The 121°C (250°F) cure T300/5209 system increased slightly in weight before losing weight. Although the patterns for all three materials are similar, the T300/5209 system loses less weight throughout the tracking period. The exact reason for this difference is unknown; however, both of the 177°C (350°F) cure materials use MY 720 as their base resin. This material has been shown to be particularly susceptible to UV degradation. The T300/5209 system does not use MY 720 as a base.

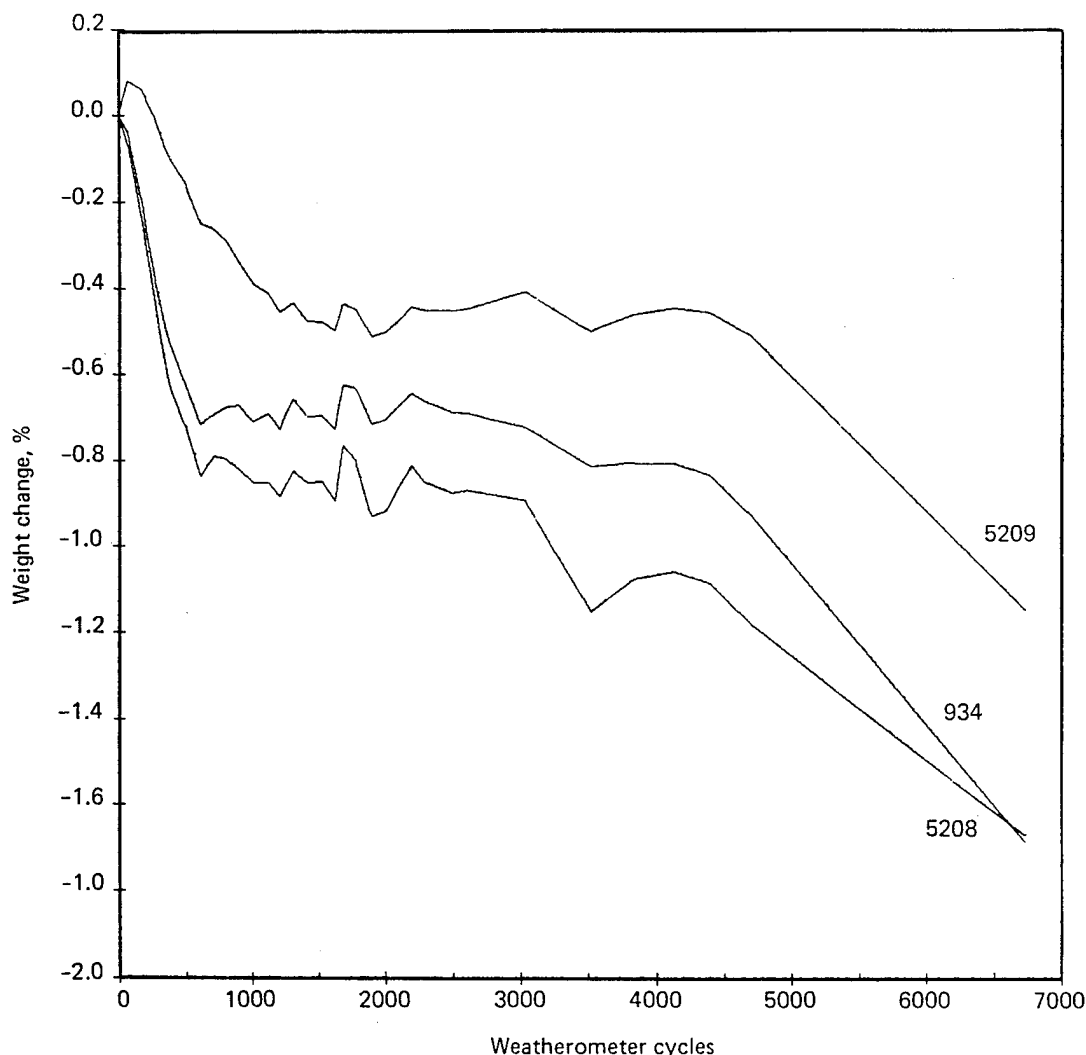


Figure 63. Weights of Unpainted Weatherometer Specimens

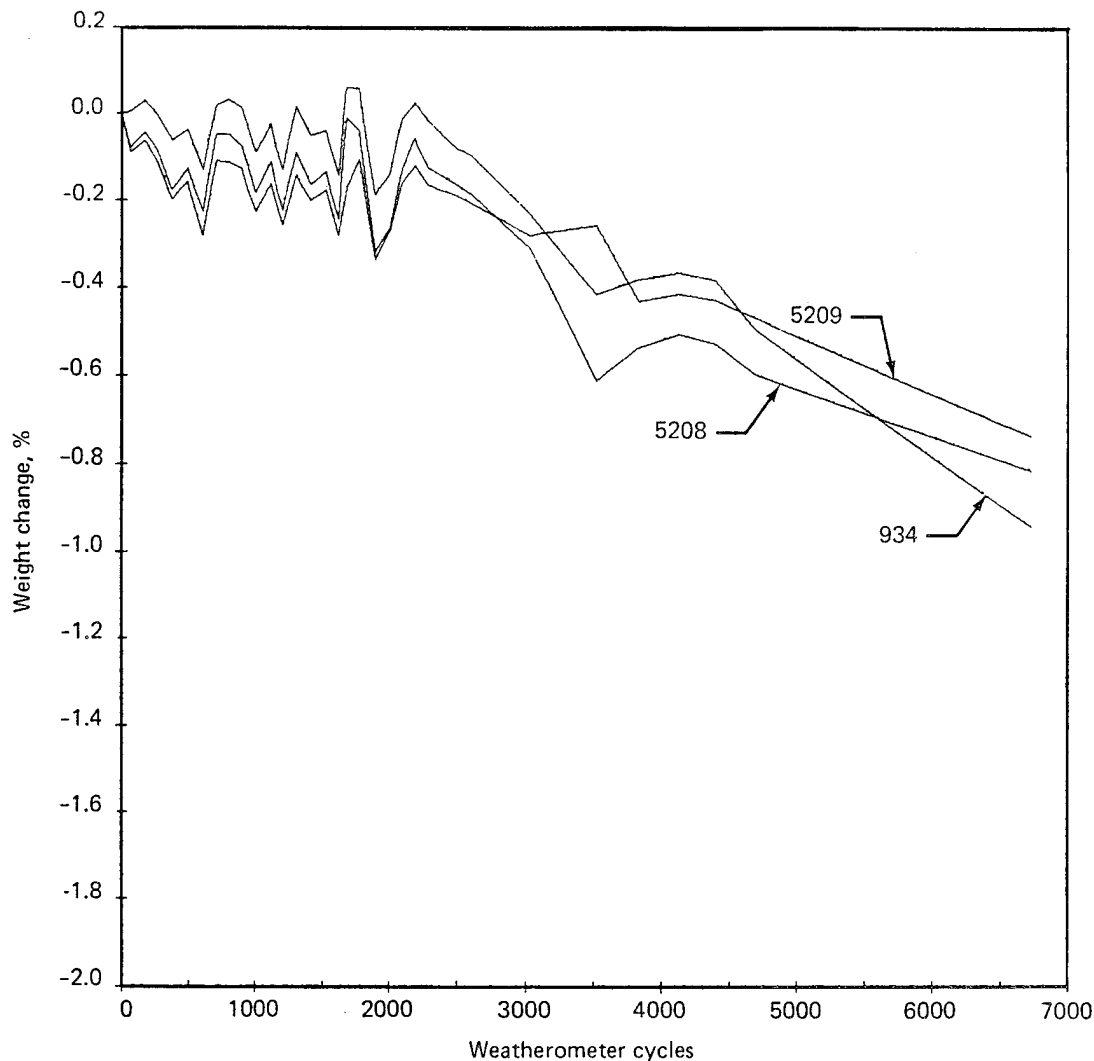
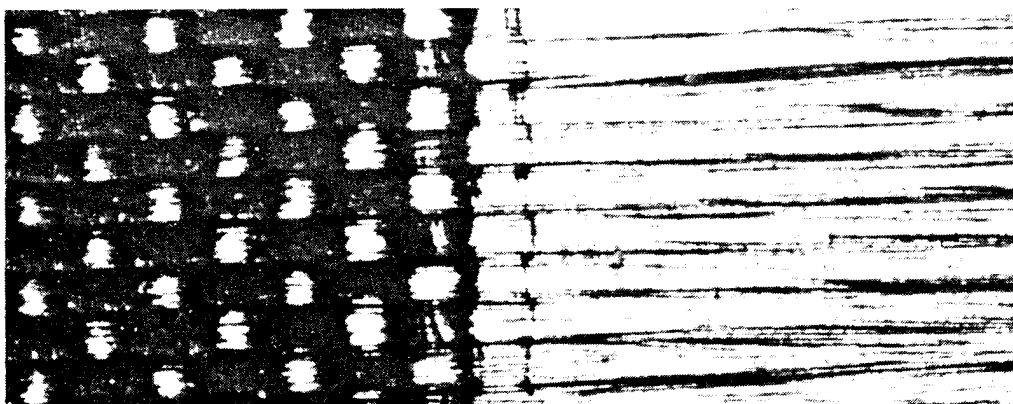


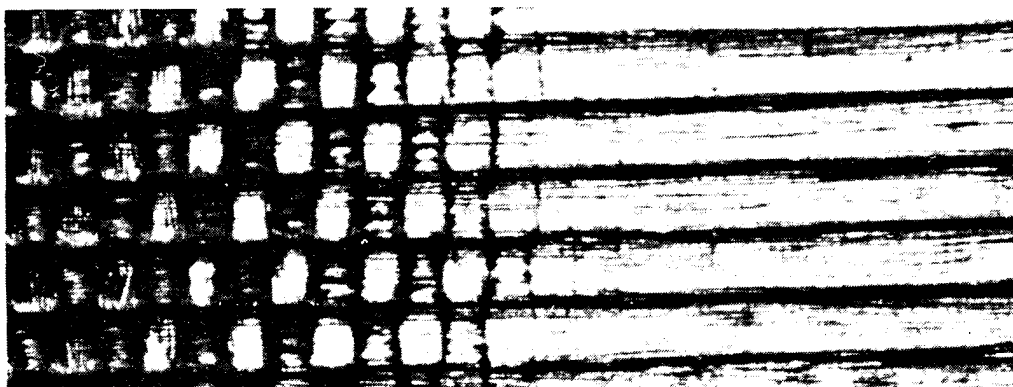
Figure 64. Weights of Painted Weatherometer Specimens

The large weight losses ultimately displayed by the unpainted weatherometer specimens are caused by surface-matrix erosion, as shown in figure 65. The magnified view of the surfaces exposed to UV radiation shows the exposed graphite fibers on the right and the integrated peel-ply texture on the left. The integrated portion was protected from direct UV radiation by the specimen-holding fixture.

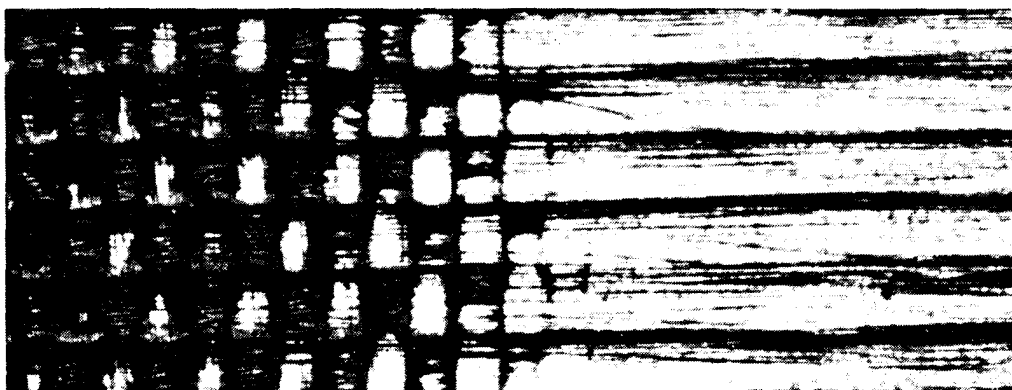
A comparison of figures 63 and 64 demonstrates the ability of the paint scheme to protect the graphite-epoxy laminate from UV degradation and erosion. Large weight decreases did not occur for the painted specimens until 2,000 weatherometer cycles had been completed. At this point, the paint system itself began to break down. Even after 2,000 cycles, the weight-loss rate was slower than that of the unpainted specimens. Although the paint began cracking and blistering, it still afforded some protection to the laminate.



5208



5209



934

Figure 65. Surfaces of Nominal 6-mo Weatherometer-Exposed Specimen

As expected, the painted specimen weight-loss rates had no appreciable differences with respect to material type. The amount of weight lost by the painted specimens can be attributed to the chalking and erosion of the paint. Differences that do exist probably reflect different levels of moisture absorption in the three material systems.

Residual strength and Tg test results for these flexure specimens are summarized in tables C-6, C-7, and C-8. Figures 66 and 67 depict these results for unpainted and painted specimens respectively. The results largely parallel the weight-loss curves. Relatively little loss of strength was observed during the first year for any of the specimen sets. All sets showed strength losses between 1 and 2 years. At the end of 2 years, the T300/5209 material system shows no loss of strength for the unpainted or the painted specimens. Both of the other materials that use the MY 720 resin as a base show that strength declines regardless of paint.

The Tg results were not conclusive. All three systems showed a loss of Tg between 6 months and 1 year, but all three also showed increases between 1 and 2 years.

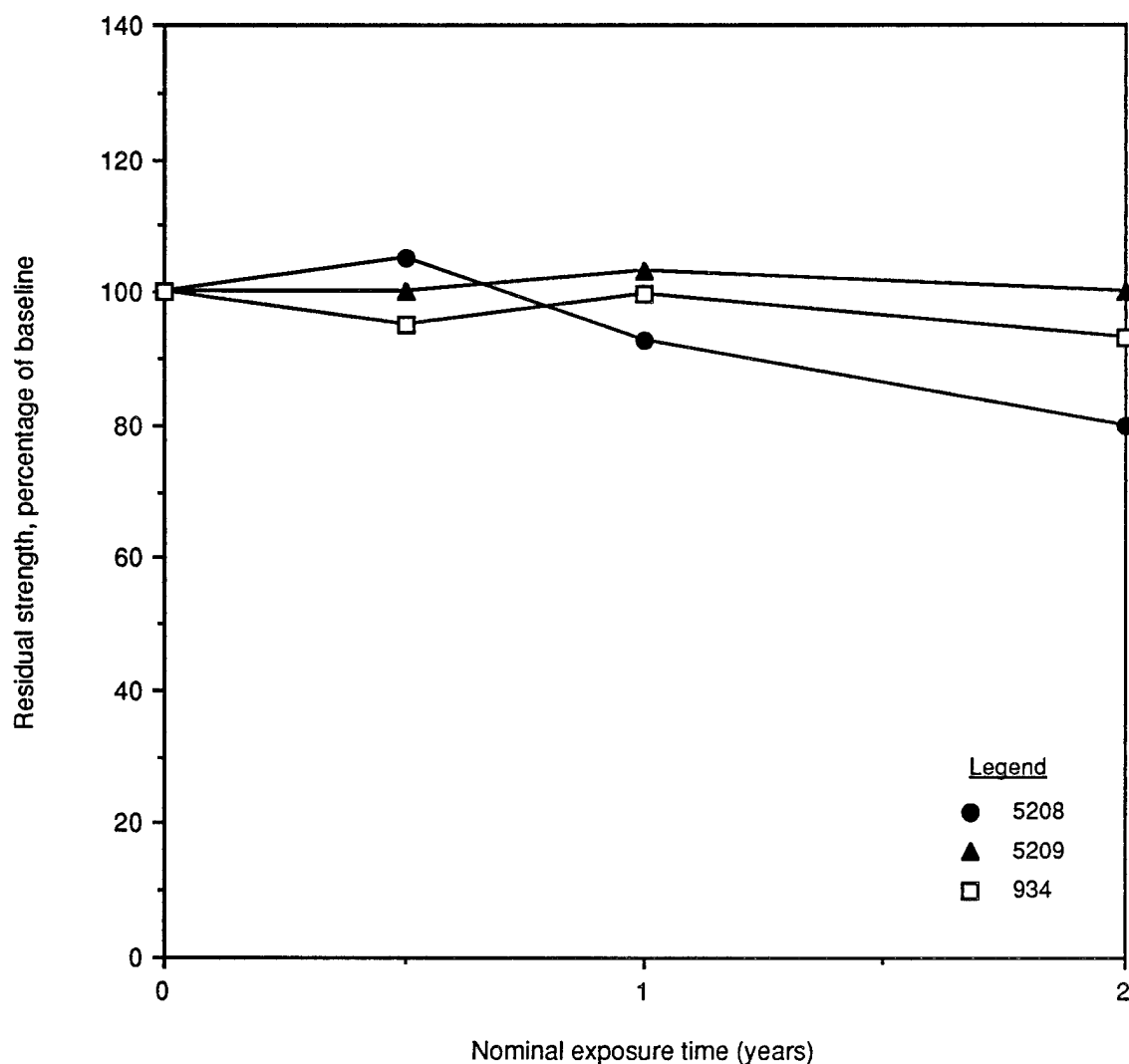


Figure 66. Elevated Temperature Residual Flexure Strength of Unpainted Weatherometer Specimens

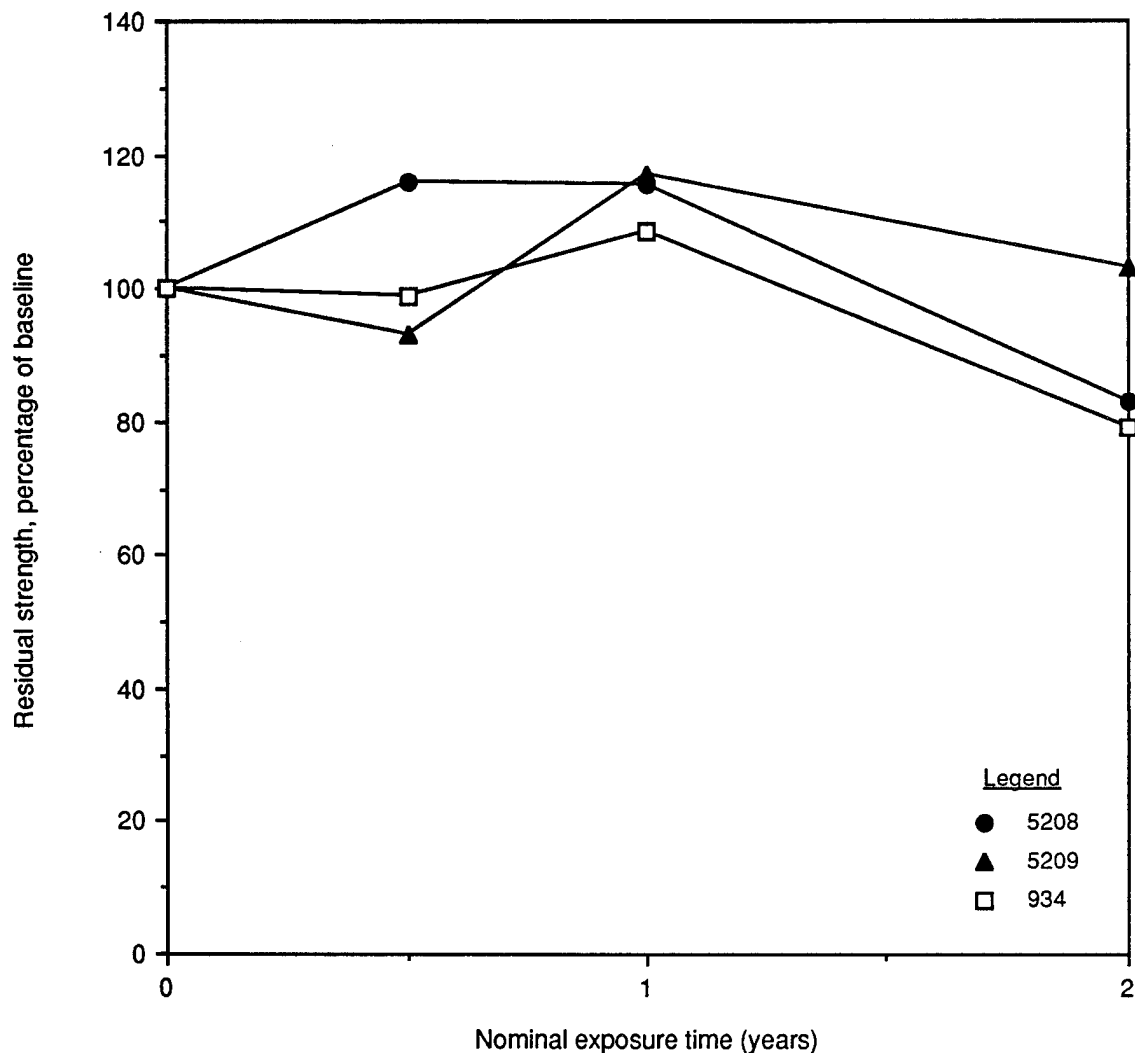


Figure 67. Elevated Temperature Residual Flexure Strength of Painted Weatherometer Specimens

10.4 EFFECT OF SIMULATED GROUND-AIR-GROUND CYCLES

Short-beam shear, flexure, and painted titanium specimens were subjected to 3,200 GAG cycles in a Webber environmental chamber. All three material systems showed definite weight gains as illustrated in figures 68, 69, and 70. As with several other exposures, the T300/5208 system absorbed the most moisture and the T300/5209 system absorbed the least.

All three material systems gained weight, reached a plateau, then resumed the weight-gain process. This led to some concern that a freeze-thaw damage mechanism was gradually cracking the specimens. Several photomicrographs were taken of these specimens to look for possible cracks, but no macrocracking or microcracking was visible.

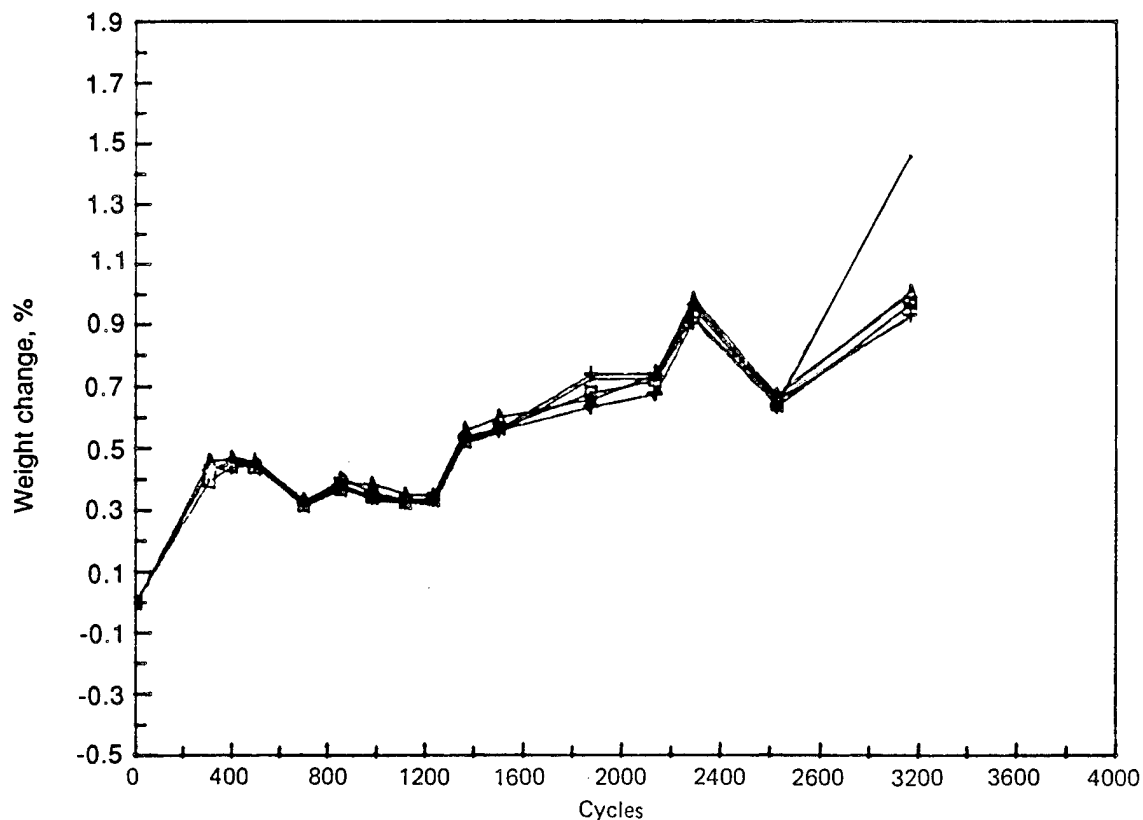


Figure 68. Weight Change of Unpainted 5208 as a Function of Ground-Air-Ground Cycles

Residual-strength tests were conducted after the 3,200 GAG cycles. Summary results are shown in table C-9. Testing at 82°C (180°F) generally produced a greater strength loss than testing at room temperature, with one exception: the flexure strength of T300/5208. The measured moisture contents of these specimens ranged from 0.7% to 1.0%. Most of the observed strength losses can be attributed to the presence of this amount of moisture.

Paint film specimens showed little weight change and did not display any cracking because of the GAG cycles. Although the specimens involved in this test plan were unpainted, the ability of the paint film to protect the laminates after freeze-thaw cycles (such as those experienced by the long-term flight specimens) was verified.

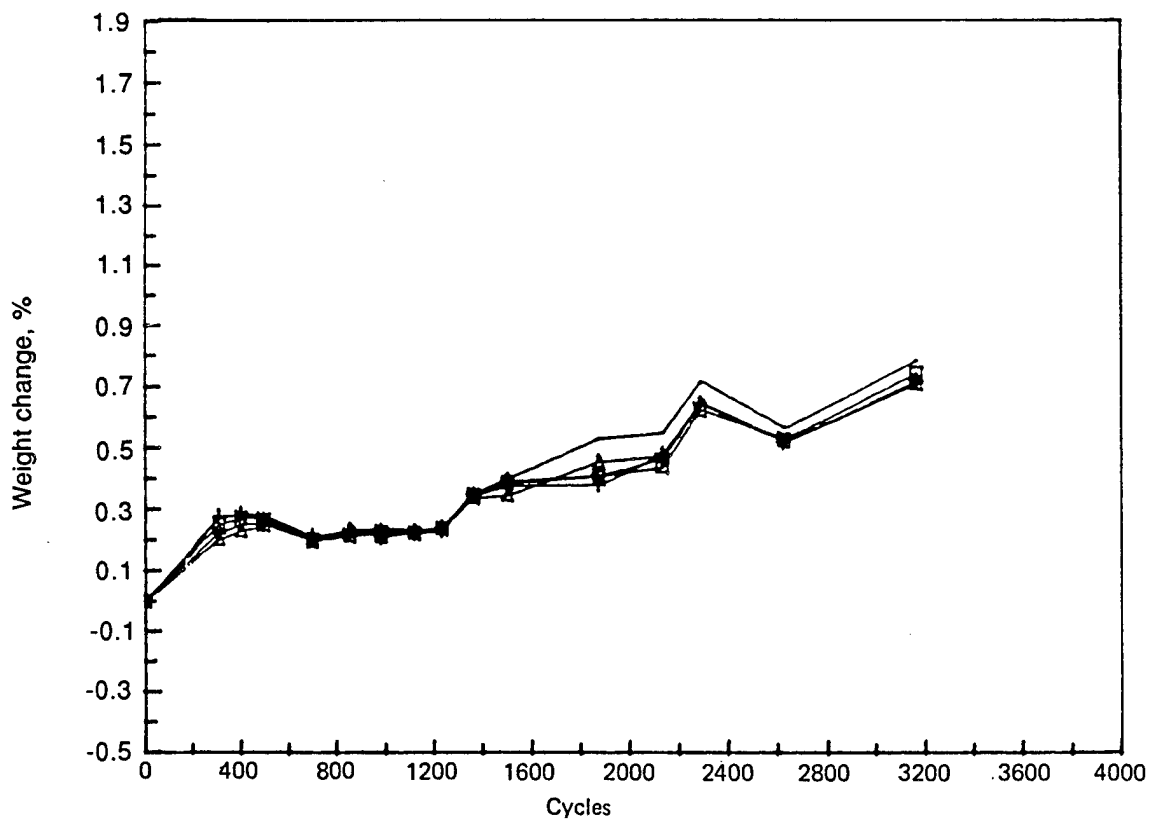


Figure 69. Weight Change of Unpainted 5209 as a Function of Ground-Air-Ground Cycles

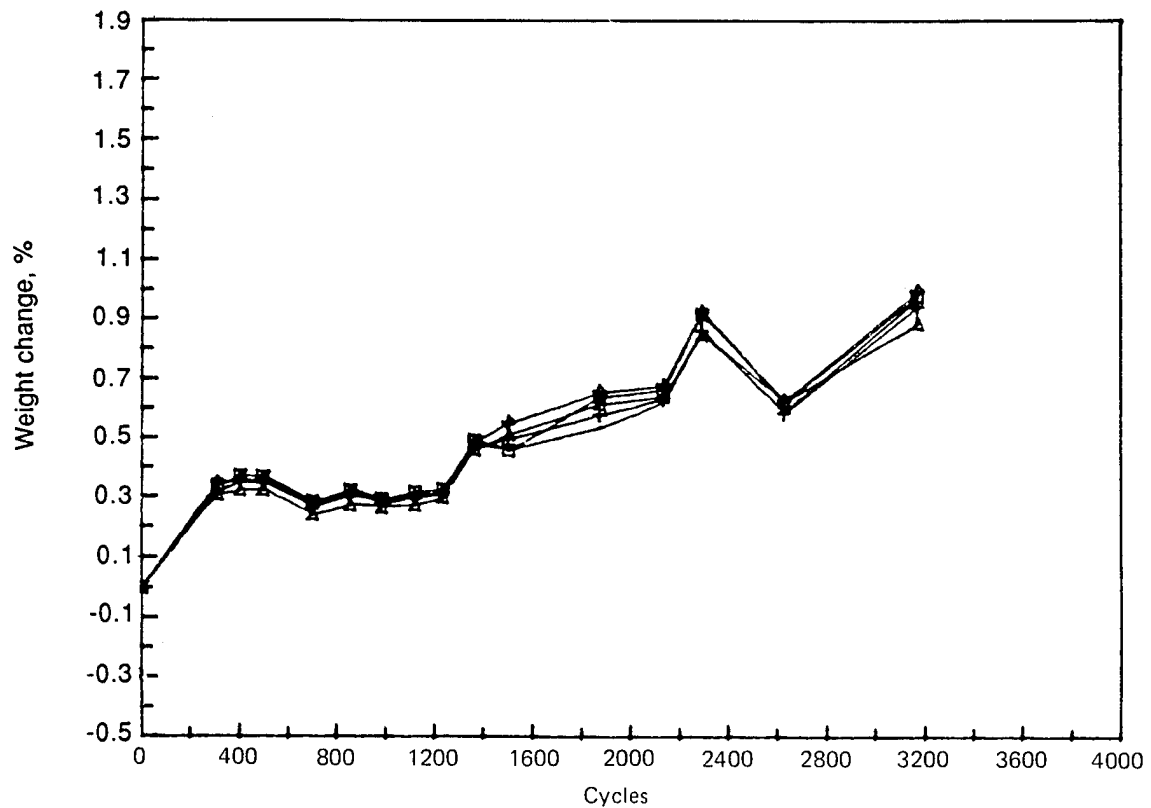


Figure 70. Weight Change of Unpainted 934 as a Function of Ground-Air-Ground Cycles

11.0 CORRELATION OF LONG-TERM AND LABORATORY RESULTS

In general, it was possible to correlate, at least qualitatively, the results obtained from the laboratory tests with the results obtained from the long-term real world exposures. In some cases, this meant that no effect was seen in either location. Specifically--

- Controlled laboratory exposure to 60% relative humidity reasonably predicted real-world exposure specimen strengths for room- and elevated-temperature flexure residuals. This was true for all three materials except T300/5208. When T300/5208 was tested for flexure strength at the elevated temperature, the controlled lab exposure predicted a small strength decline while the long-term data showed a small strength increase. Six months of the controlled laboratory exposure was usually sufficient to make the prediction.
- Long-term short-beam shear specimens displayed a curious residual-strength pattern: they lost strength for the first 3 years of exposure, then showed less degradation after 5 years, and were normally at or near their baseline levels after 10 years. The same 60% relative humidity laboratory exposure described above would have predicted the strength drops that were exhibited by the long-term specimens early in their exposure history. It is not known whether they would have predicted the recovery had the lab exposure duration gone beyond 2 years.
- Neither natural nor laboratory-induced ultraviolet radiation produced degradation when specimens were protected by paint.
- Laboratory simulation of the freeze-thaw cycle experienced by aircraft during normal operation indicated that this exposure would not be a problem. Long-term tests confirmed this.
- Test specimen configurations or conditions that were critical following long-term exposure were also critical following accelerated laboratory exposure.

12.0 CONCLUSIONS

This program yielded two general areas of conclusions. The first area concerns the relative response of the three advanced composite material systems involved in this contract and their ability to function successfully in the commercial aircraft operating environment. The second area concerns how and where to test for environmental durability as well as the ability to predict long-term durability from short-term accelerated tests.

While a large amount of data are involved in this contract, a considerable amount of data scatter is present as well. The scatter was more evident during residual-strength tests conducted at the elevated temperature. The data scatter experienced on this program was partially the result of too few replicate specimens for each test condition and partially inherent in the process of testing specimens after uncontrolled and widely varying environmental exposure. Combining data from several specimen sets revealed behavior patterns more clearly.

The two 177°C (350°F) material systems (T300/5208 and T300/934) were more environmentally stable than the one 121°C (250°F) material system (T300/5209). The differences were most noticeable with elevated-temperature residual-strength tests.

The data showed that composite materials can be designed for successful applications to commercial aircraft structures. Crossplied tension and flexure strengths actually increased following real-time ground and flight exposure. Short-beam shear and compression properties were reduced following exposure, but it is industry practice to account for these reductions.

Room-temperature flexure and crossplied tension strengths for all three materials showed some increase after 1 year and then remained above 100% of baseline strength for the duration of the 10-year exposure. At elevated temperature, these results were mixed. T300/5209 flexure and crossplied tension strengths were down slightly, as was the T300/934 flexure strength. Both of these properties remained over their baseline strengths for the T300/5208 system. The T300/934 tension strength was up as well. In all cases, these differences, up or down, were relatively small.

Room-temperature compression strengths were normally down, but the amounts and timing varied by material. At the end of 10 years, all three materials were down approximately 30%. Elevated temperature residual compression strength tests were plagued by repeated grip-tab failures. Remaining data showed strength dropoff patterns similar to those obtained with the room-temperature tests, although the long-term strength dropoffs were more severe. There was some indication that the strength losses were caused more by test methodology than by material deterioration.

The short-beam shear specimens displayed a peculiar pattern of residual-strength behavior for both room-temperature and elevated-temperature tests on all three material systems. Invariably, strengths showed a definite drop during years 1, 2, and 3, and then began showing less degradation until they were at or near their baseline levels after 10 years. The reason for this pattern is unknown.

Short-term laboratory exposures can be useful in predicting the relative durability of composite materials. However, until behavior patterns such as the one displayed by the short-beam shear specimens are better understood, real-time, real-world exposure on ground racks is recommended in addition to any controlled laboratory testing. Also, test plans for controlled laboratory exposures should include test specimens for extended exposure durations.

Ground-rack exposure appears to be the most economical and convenient way to obtain long-term exposure data. Testing on commercial aircraft is considerably more expensive and much more limiting in terms of the space envelope available for specimens. These factors, in turn, constrain the choice of test specimen geometry and sample size. Ground racks have none of these limitations. Most important, the results of this program showed that nothing was learned from exposing specimens on the aircraft that could not be learned from ground-rack exposure.

Several factors should influence exposure site selection. For moisture exposure, a site with high and relatively constant relative humidity such as Honolulu or Wellington is most desirable. For long-term testing, ambient temperature at the site does not appear to be an issue. Sites such as NASA Dryden that experience a wide range of relative humidity are less preferable for humidity studies but would definitely be of value to verify resistance to UV radiation. Site selection should also involve consideration of the ability to monitor and retrieve specimens.

The results of this program indicated little or no difference in strength between specimens exposed on the solar and nonsolar faces of the rack as long as the protective paint coating remained on the specimen. This would eliminate the duplicate testing performed on this contract. Based on testing of the three materials involved in this program, stressing specimens during exposure is not beneficial.

The exposure of test panels, rather than test specimens, on the racks would greatly simplify deployment and permit more test flexibility following exposure.

Test plans should include sufficient material to permit a minimum of 10 replicate baseline specimens and five replicate postexposure residual-strength specimens.

Another recommendation is to carry specimens or panels in the matrix whose sole function is to measure the weight gain or loss used to determine moisture content. These coupons could be sized to provide a more accurate and simplified means of obtaining these data.

Finally, the Celanese compression specimen and fixture are not recommended because of repeated grip-tab failures. Some work should be done to develop a compression specimen that can be painted and yet provide reliable residual-strength data.

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APPENDIX A LONG-TERM FLIGHT EXPOSURE SUMMARY RESULTS

Table A-1. Summary of Results—Aloha Airlines, Nominal 1-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	87.4	84.6	85.2
		106.6	110.3	105.3
Elevated temperature residual strength data (percentage of baseline) **	SBS	87.9	72.7	77.4
	Flexure	110.7	87.5	101.8
	± 45 degree tension	125.5	****	106.2
	SBS dryout	104.4	97.4	93.1
Weight change data Percentage gain + Percentage loss —	SBS	.39	.28	.50
	Flexure	.41	.10	.40
	± 45 degree tension	.48	****	.01
Weight loss during dryout	SBS dryout	.98	.84	1.11

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	90.4	80.9	83.3
		114.5	100.8	103.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	84.1	74.0	73.9
	Flexure	110.1	84.6	99.6
	± 45 degree tension	106.9	****	114.4
	SBS dryout	100.5	94.9	93.1
Weight change data Percentage gain + Percentage loss —	SBS	.43	.23	-.23
	Flexure	.29	.14	.32
	± 45 degree tension	.09	****	.16
Weight loss during dryout	SBS dryout	.94	.70	1.10

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	84.3	81.4	83.5
	Flexure	107.0	112.4	104.5
	± 45 degree tension	112.3	107.6	100.4
	Compression	75.9	102.6	98.6
Elevated temperature residual strength data (percentage of baseline) **	SBS	90.0	76.4	80.0
	Flexure	114.3	102.8	103.6
	± 45 degree tension	115.6	87.6	103.0
	Stressed tension	110.4	89.7	109.0
	Compression	81.9	80.4	76.6
Weight change data Percentage gain + Percentage loss —	SBS	.16	.07	.24
	Flexure	.09	.17	.06
	± 45 degree tension	.04	.23	.20

Notes:

- * These specimens exposed for 394 days, 1,942 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available

Table A-2. Summary of Results—Aloha Airlines, Nominal 2-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	73.7	82.3	92.1
	Flexure	101.3	103.4	93.2
Elevated temperature residual strength data (percentage of baseline) **	SBS	75.9	59.4	64.4
	Flexure	96.0	70.9	89.7
	± 45 degree tension	128.2	****	112.0
	SBS dryout	93.1	97.0	94.4
Weight change data Percentage gain + Percentage loss —	SBS	.48	.23	.51
	Flexure	.98	.04	.29
	± 45 degree tension	-.06	****	.45
Weight loss during dryout	SBS dryout	1.18	.77	1.14

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	83.0	80.4	88.5
	Flexure	97.9	107.3	94.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	74.6	58.6	65.6
	Flexure	81.5	82.7	87.0
	± 45 degree tension	96.8	****	112.5
	SBS dryout	96.9	95.8	91.4
Weight change data Percentage gain + Percentage loss —	SBS	.48	.33	.68
	Flexure	-.09	.22	.37
	± 45 degree tension	.36	****	.47
Weight loss during dryout	SBS dryout	1.04	.76	1.20

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	88.4	84.9	86.1
	Flexure	99.3	101.5	91.9
	± 45 degree tension	****	110.9	107.7
	Compression	86.4	100.3	96.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	63.5	65.0	70.7
	Flexure	58.2	75.1	84.3
	± 45 degree tension	126.4	85.1	105.3
	Stressed tension	119.8	95.5	108.1
	Compression	90.5	87.5	79.2
Weight change data Percentage gain + Percentage loss —	SBS	.29	.12	.37
	Flexure	.17	-.02	.13
	± 45 degree tension	.07	-.13	-.14

Notes:

- * These specimens exposed for 744 days, 3,832 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.

Table A-3. Summary of Results—Aloha Airlines, Nominal 10-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	91.6	101.6	98.7
		113.1	101.3	100.1
Elevated temperature residual strength data (percentage of baseline) **	SBS	94.1	74.5	86.9
	Flexure	113.5	80.7	97.6
	± 45 degree tension	****	****	****
	SBS dryout	108.8	110.3	103.9
Weight change data Percentage gain + Percentage loss —	SBS			
	Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	1.23	2.03	.98

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	93.0	102.4	92.0
		115.3	100.9	104.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	92.3	75.2	84.8
	Flexure	109.5	80.1	99.0
	± 45 degree tension	****	****	****
	SBS dryout	112.2	107.1	105.9
Weight change data Percentage gain + Percentage loss —	SBS			
	Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	1.16	1.77	.94

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	111.0	101.8	104.5
	Flexure	117.6	114.5	114.9
	± 45 degree tension	109.9	104.6	101.6
	Compression	83.7	75.7	79.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	92.9	82.3	90.6
	Flexure	119.2	92.7	96.7
	± 45 degree tension	126.5	84.7	103.3
	Stressed tension	126.7	92.8	101.7
	Compression	23.8 †	56.5	37.7 †
Weight change data Percentage gain + Percentage loss —	SBS			
	Flexure ± 45 degree tension	****	****	****

Notes:

- * These specimens exposed for 4,051 days, 21,476 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

Table A-4. Summary of Results—Air New Zealand, Nominal 1-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	92.6	87.4	90.6
	Flexure	104.2	102.2	101.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	93.2	73.1	77.7
	Flexure	96.8	80.4	93.9
	± 45 degree tension	124.8	****	117.3
	SBS dryout	103.4	99.7	96.6
Weight change data Percentage gain + Percentage loss —	SBS	.58	.54	.58
	Flexure	.65	.36	.52
	± 45 degree tension	.15	****	.49
Weight loss during dryout	SBS dryout †	.83	.57	.70

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	90.3	85.6	88.2
	Flexure	105.7	104.7	98.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	89.0	73.8	75.9
	Flexure	103.4	99.7	94.9
	± 45 degree tension	114.2	****	112.6
	SBS dryout	78.4	100.9	98.2
Weight change data Percentage gain + Percentage loss —	SBS	.60	.36	.55
	Flexure	.66	.28	.49
	± 45 degree tension	.64	****	.57
Weight loss during dryout	SBS dryout †	.53	.60	.94

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	95.5	102.8	94.7
	Flexure	107.4	106.7	101.5
	± 45 degree tension	118.9	120.5	123.4
	Compression	89.4	101.5	96.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	76.1	71.7	77.9
	Flexure	99.1	96.4	90.5
	± 45 degree tension	102.6	83.3	113.7
	Stressed tension	110.1	87.4	105.9
	Compression	79.2 ††	89.6	78.1
Weight change data Percentage gain + Percentage loss —	SBS	.43	.35	.49
	Flexure	.50	.25	.49
	± 45 degree tension	.41	.37	.50

Notes:

- * These specimens exposed for 516 days, 2,681 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Dryout oven overheat to 177°C (350°F). 2 days.
- †† Grip tab slippage.

Table A-5. Summary of Results—Air New Zealand, Nominal 2-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	87.2	80.2	93.4
	Flexure	106.1	103.5	101.3
Elevated temperature residual strength data (percentage of baseline) **	SBS	81.1	73.2	77.4
	Flexure	108.9	83.1	95.6
	± 45 degree tension	120.8	****	112.5
	SBS dryout	103.8	96.4	92.9
Weight change data Percentage gain + Percentage loss —	SBS	.54	.38	.57
	Flexure	.61	.30	.55
	± 45 degree tension	.27	****	.61
Weight loss during dryout	SBS dryout	.88	.16	.86

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	88.7	84.9	89.5
	Flexure	109.0	110.1	106.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	83.2	72.1	75.5
	Flexure	98.9	87.7	94.2
	± 45 degree tension	135.3	****	111.0
	SBS dryout	106.5	99.8	93.7
Weight change data Percentage gain + Percentage loss —	SBS	.57	.42	.63
	Flexure	.68	.29	.61
	± 45 degree tension	.33	****	.69
Weight loss during dryout	SBS dryout	.89	.61	.91

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	84.4	83.8	91.4
	Flexure	107.5	112.6	99.1
	± 45 degree tension	115.1	111.6	118.0
	Compression	101.1	105.5	94.2
Elevated temperature residual strength data (percentage of baseline) **	SBS	84.9	73.6	75.6
	Flexure	108.9	103.7	94.5
	± 45 degree tension	121.8	95.0	120.3
	Stressed tension	115.9	89.9	115.6
	Compression	67.5 †	80.3	75.6
Weight change data Percentage gain + Percentage loss —	SBS	.48	.43	.58
	Flexure	.59	.25	.56
	± 45 degree tension	.48	.42	.52

Notes:

- * These specimens exposed for 797 days, 4,439 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

Table A-6. Summary of Results—Air New Zealand, Nominal 5-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	80.5 ****	88.8 ****	89.0 ****
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure	88.6 ****	79.2 ****	87.1 ****
	± 45 degree tension SBS dryout	102.4 ****	****	115.8 ****
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	1.11	1.18	1.19

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	84.7 ****	89.1 ****	75.1 ****
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure	89.6 ****	80.9 ****	60.7 ****
	± 45 degree tension SBS dryout	106.0 ****	****	115.9 ****
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	1.10	1.22	.87

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	80.5	94.4	90.7
	Flexure	****	****	****
	± 45 degree tension	103.1	99.7	105.4
Elevated temperature residual strength data (percentage of baseline) **	Compression	77.2	87.2 †	61.9 ††
	SBS	88.0	87.4	84.8
	Flexure	****	****	****
	± 45 degree tension	112.1	84.4	110.8
Weight change data Percentage gain + Percentage loss —	Stressed tension	115.6	83.6	103.3
	Compression	74.9 †	82.8	60.7
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****

Notes:

- * These specimens exposed for 1,837 days, 10,287 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Single specimen.
- †† Average of two specimens.

Table A-7. Summary of Results—Southwest Airlines, Nominal 1-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	88.7	87.5	83.3
		112.7	99.8	107.3
Elevated temperature residual strength data (percentage of baseline) **	SBS	86.0	71.1	72.4
	Flexure	111.0	78.7	88.2
	± 45 degree tension	93.5	****	108.7
	SBS dryout	98.3	97.9	91.4
Weight change data Percentage gain + Percentage loss —	SBS	.55	.46	.48
	Flexure	.42	.32	.33
	± 45 degree tension	.49	****	.62
Weight loss during dryout	SBS dryout	.94	.57	.79

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	84.1	89.7	86.6
		105.2	107.3	103.2
Elevated temperature residual strength data (percentage of baseline) **	SBS	78.6	78.3	73.6
	Flexure	114.4	95.6	93.0
	± 45 degree tension	103.1	****	108.1
	SBS dryout	104.6	99.4	88.1
Weight change data Percentage gain + Percentage loss —	SBS	.36	.35	.51
	Flexure	.40	.21	.31
	± 45 degree tension	.47	****	.49
Weight loss during dryout	SBS dryout	.86	.53	.85

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	86.7	88.3	78.2
	Flexure	88.7	99.4	104.8
	± 45 degree tension	113.7	125.5	113.0
	Compression	93.8	99.8	99.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	81.8	75.7	69.9
	Flexure	108.9	92.1	93.9
	± 45 degree tension	98.1	76.0	110.1
	Stressed tension	120.2	81.5	118.0
	Compression	86.7	91.0	86.6
Weight change data Percentage gain + Percentage loss —	SBS	.50	.35	.53
	Flexure	.31	.19	.56
	± 45 degree tension	.40	.35	.39

Notes:

- * These specimens exposed for 488 days, 4,652 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.

Table A-8. Summary of Results—Southwest Airlines, Nominal 2-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	95.4	88.4	92.9
		108.0	102.6	103.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	80.3	69.5	76.3
	Flexure	111.2	91.4	100.0
	± 45 degree tension	106.7	****	115.0
	SBS dryout	100.1	90.9	94.0
Weight change data Percentage gain + Percentage loss —	SBS	.59	.44	1.03
	Flexure	.69	.36	.71
	± 45 degree tension	.33	****	.41
Weight loss during dryout	SBS dryout	.82	1.53	.90

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	95.5	72.1	87.4
		102.7	108.9	92.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	80.7	72.1	77.6
	Flexure	113.3	94.5	97.8
	± 45 degree tension	103.4	****	111.4
	SBS dryout	100.9	91.2	90.6
Weight change data Percentage gain + Percentage loss —	SBS	.62	.40	.20
	Flexure	.66	1.13	.51
	± 45 degree tension	.25	****	.37
Weight loss during dryout	SBS dryout	.78	.49	.84

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	88.5	90.8	84.0
	Flexure	105.7	99.0	107.5
	± 45 degree tension	112.0	119.0	109.1
	Compression	98.1	101.5	98.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	75.1	71.8	79.0
	Flexure	112.0	93.0	105.1
	± 45 degree tension	103.9	95.9	117.2
	Stressed tension	114.0	92.8	109.3
	Compression	44.4 †	90.7	81.3
Weight change data Percentage gain + Percentage loss —	SBS	.42	.20	.52
	Flexure	.40	-.63	.36
	± 45 degree tension	-.51	.26	.27

Notes:

- * These specimens exposed for 884 days, 8,334 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

Table A-9. Summary of Results—Southwest Airlines, Nominal 3-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	95.0	87.0	98.0
		110.7	105.9	103.2
Elevated temperature residual strength data (percentage of baseline) **	SBS	83.2	69.1	77.4
	Flexure	115.8	91.0	95.3
	± 45 degree tension	108.9	****	119.3
	SBS dryout	99.9	103.7	90.9
Weight change data Percentage gain + Percentage loss —	SBS	.34	.45	-.03
	Flexure	.35	.21	-.19
	± 45 degree tension	.56	****	.55
Weight loss during dryout	SBS dryout	.92	.56	.97

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	92.2	89.3	93.4
		107.3	101.9	105.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	82.4	70.7	78.1
	Flexure	112.4	82.7	90.9
	± 45 degree tension	106.6	****	117.8
	SBS dryout	108.6	102.5	90.8
Weight change data Percentage gain + Percentage loss —	SBS	-.38	.44	-.22
	Flexure	.87	.45	-.12
	± 45 degree tension	.24	****	.30
Weight loss during dryout	SBS dryout	.86	.56	.91

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	86.9	90.3	98.2
	Flexure	107.7	110.2	99.2
	± 45 degree tension	112.0	115.5	111.3
	Compression	102.2	110.2	102.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	83.0	70.4	67.6
	Flexure	111.8	94.6	103.1
	± 45 degree tension	105.3	90.1	113.6
	Stressed tension	114.9	87.3	111.6
	Compression	73.9	85.9	96.3
Weight change data Percentage gain + Percentage loss —	SBS	.49	.47	.63
	Flexure	.34	.22	.35
	± 45 degree tension	.35	.34	.37

Notes:

- * These specimens exposed for 1,128 days, 10,790 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.

Table A-10. Summary of Results—Southwest Airlines, Nominal 5-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	93.8	93.0	100.1
		112.9	111.3	103.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	107.9	109.0	103.5
	Flexure	103.7	95.9	96.3
	± 45 degree tension	137.3	****	100.7
	SBS dryout	116.4	108.8	107.5
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure ± 45 degree tension			
Weight loss during dryout	SBS dryout	.71	.55	.74

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	103.0	103.9	94.1
		109.2	106.9	116.0
Elevated temperature residual strength data (percentage of baseline) **	SBS	103.1	106.4	94.6
	Flexure	116.5	95.8	97.6
	± 45 degree tension	142.2	****	103.2
	SBS dryout	88.6	103.3	94.6
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure ± 45 degree tension			
Weight loss during dryout	SBS dryout	.87	.50	.70

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	106.6	106.1	****
	Flexure	115.7	102.4	****
	± 45 degree tension	121.9	110.7	109.0
	Compression	104.5	95.8	90.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	112.4	108.9	****
	Flexure	128.1	92.7	****
	± 45 degree tension	140.3	94.2	105.8
	Stressed tension	123.9	95.2	116.2
	Compression	28.9 †	65.9	58.3 †
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure ± 45 degree tension			

Notes:

- * These specimens exposed for 2,316 days, 20,668 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

Table A-11. Summary of Results—Southwest Airlines, Nominal 10-year Specimens *

Exterior Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	98.1	92.1	98.1
		114.7	104.7	97.1
Elevated temperature residual strength data (percentage of baseline) **	SBS	96.9	109.7	95.3
	Flexure	106.5	98.9	90.3
	± 45 degree tension	103.2	****	107.0
	SBS dryout	110.8	108.7	107.1
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	.73	.51	.71

Exterior Nonsolar

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure	97.3	98.5	95.1
		114.8	102.3	93.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	104.0	105.5	100.4
	Flexure	107.9	84.2	86.0
	± 45 degree tension	106.1	****	114.7
	SBS dryout	109.9	105.0	104.0
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	.97	.46	.72

Interior

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	103.7	100.7	95.3
	Flexure	112.4	111.8	108.6
	± 45 degree tension	109.6	121.7	112.5
	Compression	95.5	96.3	45.9 †
Elevated temperature residual strength data (percentage of baseline) **	SBS	102.0	105.6	102.0
	Flexure	110.0	93.3	94.2
	± 45 degree tension	123.6	95.0	119.2
	Stressed tension	126.4	93.0	116.5
	Compression	37.2 †	70.0	55.7 †
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****

Notes:

- * These specimens exposed for 3,579 days, 32,637 flight-hours.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

APPENDIX B LONG-TERM GROUND EXPOSURE SUMMARY RESULTS

Table B-1. Summary of Results—Honolulu, Nominal 1-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	89.4	82.4	87.0
	Flexure	102.7	101.7	105.6
	± 45 degree tension	107.5	104.9	103.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	87.5	74.6	73.4
	Flexure	111.1	89.4	103.2
	± 45 degree tension	98.2	80.8	94.0
	SBS dryout ***	95.5	117.0	100.5
Weight change data Percentage gain + Percentage loss —	SBS	.27	-.03	.29
	Flexure	.06	-.08	.18
	± 45 degree tension	.04	.07	.16
Weight loss during dryout	SBS dryout	.98	.62	.90

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	95.0	83.7	80.4
	Flexure	108.2	107.7	106.6
	Compression	83.5	105.8	97.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	85.1	73.4	72.9
	Flexure	111.0	95.8	102.1
	Compression	77.4 ††	79.0	80.2
	Stressed tension	112.5	80.4 †	106.1
	SBS dryout ***	84.1	111.0	102.3
Weight change data Percentage gain + Percentage loss —	SBS	.30	.07	.31
	Flexure	-.01	-.01	.22
	Stressed tension	.31	.09	.32
Weight loss during dryout	SBS dryout	.86	.58	.97

Notes:

- * These specimens exposed for 398 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- *** SBS dryout specimens incorrectly tested at RT.
- † Average of two measurements.
- †† Grip tab slippage.

Table B-2. Summary of Results—Honolulu, Nominal 2 -year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	52.5	78.9	79.9
	Flexure	96.4	99.3	103.4
	± 45 degree tension	109.2	112.7	106.0
Elevated temperature residual strength data (percentage of baseline) **	SBS	81.7	65.6	70.1
	Flexure	96.6	82.9	93.7
	± 45 degree tension	112.6	78.5	106.9
	SBS dryout	82.7	95.2	87.3
Weight change data Percentage gain + Percentage loss —	SBS	.32	-.03	.35
	Flexure	.24	-.15	.17
	± 45 degree tension	-.10	-.19	.03
Weight loss during dryout	SBS dryout	1.16	.98	1.28

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	85.7	78.0	80.3
	Flexure	105.7	108.3	96.7
	Compression	****	****	****
Elevated temperature residual strength data (percentage of baseline) **	SBS	80.9	64.3	63.7
	Flexure	100.8	84.2	98.6
	Compression	****	****	****
	Stressed tension	126.3	77.3	118.3
	SBS dryout	109.1	91.8	87.2
Weight change data Percentage gain + Percentage loss —	SBS	.42	.23	.53
	Flexure	.33	.08	.39
	Stressed tension	.20	.09	.21
Weight loss during dryout	SBS dryout	1.20	.93	1.34

Notes:

- * These specimens exposed for 740 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.

Table B-3. Summary of Results—Honolulu, Nominal 3-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	91.0	82.2	83.3
	Flexure	85.6	88.4	80.0
	± 45 degree tension	104.1	103.4	106.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	78.8	68.0	73.2
	Flexure	88.0	72.5	89.2
	± 45 degree tension	128.4	79.5	110.6
	SBS dryout	87.9	94.6	95.1
Weight change data Percentage gain + Percentage loss —	SBS	.50	.29	.50
	Flexure	.22	.03	.24
	± 45 degree tension	-.26	-.35	-.22
Weight loss during dryout	SBS dryout	1.06	.75	.88

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	90.1	85.9	81.3
	Flexure	98.8	79.2	86.7
	Compression	74.8	92.2	88.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	84.6	67.0	71.9
	Flexure	100.5	86.0	91.5
	Compression	22.9 †	59.5	62.4
	Stressed tension	121.5	95.3	119.2
	SBS dryout	101.3	93.7	93.2
Weight change data Percentage gain + Percentage loss —	SBS	.55	.41	.63
	Flexure	.39	.21	.39
	Stressed tension	.62	.32	.59
Weight loss during dryout	SBS dryout	.89	.77	.99

Notes:

- * These specimens exposed for 1,096 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- † Grip tab slippage.

Table B-4. Summary of Results—Honolulu, Nominal 5-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	91.3	90.3	96.7
	Flexure	105.3	104.8	113.5
	± 45 degree tension	107.5	97.6	105.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	83.5	61.3	71.6
	Flexure	98.8	88.1	96.8
	± 45 degree tension	121.8	96.6	108.9
	SBS dryout	****	****	****
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure	****	****	****
	± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	****	****	****

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	98.3	87.5	85.2
	Flexure	109.0	109.9	103.7
	Compression	88.3	98.9	99.3
Elevated temperature residual strength data (percentage of baseline) **	SBS	82.2	61.9	69.9
	Flexure	99.4	94.0	90.0
	Compression	45.3 †	59.6 †	63.8
	Stressed tension	125.6	86.8	119.5
	SBS dryout	****	****	****
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure	****	****	****
	Stressed tension	****	****	****
Weight loss during dryout	SBS dryout	****	****	****

Notes:

- * These specimens exposed for 1,826 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Grip tab slippage.

Table B-5. Summary of Results—Honolulu, Nominal 10-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension	104.8	98.5	97.8
		113.5	107.0	120.0
		105.3	98.6	93.2
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension SBS dryout	96.6	78.8	88.0
		121.1	86.5	98.2
		122.3	93.9	93.9
		107.5	108.1	100.7
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
		****	****	****
		****	****	****
Weight loss during dryout	SBS dryout	2.17	.61	.66

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure Compression	90.8	97.8	100.5
		115.0	106.5	113.1
		78.7	78.8	74.1
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure Compression Stressed tension SBS dryout	93.7	76.5	85.1
		115.1	88.1	92.7
		24.8 †	61.7	38.8 †
		104.4	110.1	89.5
		99.0	111.0	99.8
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	****	****	****
		****	****	****
		****	****	****
Weight loss during dryout	SBS dryout	2.00	.60	1.36

Notes:

* These specimens exposed for 4,002 days.

** Residual strength data based on baseline tests at the respective temperatures.

**** Not available.

† Grip tab slippage.

Table B-6. Summary of Results—Wellington, New Zealand, Nominal 1-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension	94.2 102.8 112.2	87.9 100.7 118.5	90.8 104.7 118.4
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension SBS dryout	81.8 101.6 118.7 98.8	67.0 78.2 88.1 100.9	74.6 91.1 109.5 99.3
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	.65 .68 .64	.39 .38 .39	.51 .56 .49
Weight loss during dryout	SBS dryout ***	1.00	.50	.87

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure Compression	86.6 106.2 94.6	87.0 98.9 99.1	87.8 93.8 100.4
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure Compression Stressed tension SBS dryout	88.1 96.8 73.0 † 125.4 104.2	69.9 78.9 87.1 87.0 97.6	73.4 92.5 85.6 105.7 97.3
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	.60 .61 .57	.43 .40 .42	.67 .56 .61
Weight loss during dryout	SBS dryout ***	.92	.50	.84

Notes:

- * These specimens exposed for 508 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- *** Dryout oven overheat to 177°C (350°F), 2 days.
- † Grip tab slippage.

Table B-7. Summary of Results—Wellington, New Zealand, Nominal 2-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension	82.6	94.1	86.7
		102.2	100.4	108.1
		116.5	125.9	122.8
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension SBS dryout	85.0	70.9	72.4
		100.9	83.5	87.7
		129.0	86.4	111.0
		101.0	98.3	89.4
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	.80	.49	.85
		.75	.43	.64
		.66	.50	.56
Weight loss during dryout	SBS dryout	1.06	.61	1.03

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure Compression	88.5	88.8	86.3
		107.0	107.5	105.9
		92.2	106.8	97.8
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure Compression Stressed tension SBS dryout	100.3	76.2	73.0
		94.8	82.6	89.9
		40.5 †	79.3	74.4
		121.1	89.5	120.8
		105.5	96.7	89.9
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	.83	.53	.86
		.76	.50	.71
		.60	.56	.60
Weight loss during dryout	SBS dryout	1.10	.16	1.07

Notes:

* These specimens exposed for 786 days.

** Residual strength data based on baseline tests at the respective temperatures.

† Grip tab failure.

Table B-8. Summary of Results—Wellington, New Zealand, Nominal 3-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	86.3	88.1	93.3
	Flexure	105.0	99.8	106.5
	± 45 degree tension	109.3	121.8	115.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	80.4	67.7	73.7
	Flexure	103.1	89.6	95.0
	± 45 degree tension	106.0 [†]	86.4 ^{††}	115.3
	SBS dryout	92.3	94.8	89.0
Weight change data Percentage gain + Percentage loss —	SBS	****	.49	.74
	Flexure	.70	.40	.61
	± 45 degree tension	.39	.42	.29
Weight loss during dryout	SBS dryout	.89	.77	.99

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	94.0	87.1	91.8
	Flexure	105.4	104.7	107.6
	Compression	86.5	100.2	93.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	82.4	69.2	73.6
	Flexure	96.1	80.5	91.6
	Compression	73.0 ^{†††}	76.6	69.6 ^{†††}
	Stressed tension	129.4	81.4	118.8
	SBS dryout	93.9	93.9	96.2
Weight change data Percentage gain + Percentage loss —	SBS	****	.49	.74
	Flexure	.70	.40	.61
	Stressed tension	.39	.42	.29
Weight loss during dryout	SBS dryout	1.11	.62	1.10

Notes:

- * These specimens exposed for 1,163 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.
- † Average of two test values.
- †† Tested at room temperature.
- ††† Grip tab slippage.

Table B-9. Summary of Results—Wellington, New Zealand, Nominal 5-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	86.7	88.8	86.1
	Flexure	105.5	103.7	103.8
	± 45 degree tension	106.8	118.4	77.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	91.7	70.9	72.9
	Flexure	110.4	90.1	102.8
	± 45 degree tension	106.2	92.5	110.6
	SBS dryout	100.2	102.7	59.4
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure ± 45 degree tension			
Weight loss during dryout	SBS dryout	1.23	.80	1.23

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	96.9	****	****
	Flexure	106.3	103.6	103.5
	Compression	102.9	107.2	108.6
Elevated temperature residual strength data (percentage of baseline) **	SBS	81.9	****	****
	Flexure	105.5	85.0	87.1
	Compression	70.6	82.7	87.9
	Stressed tension	114.1	104.8	109.9
	SBS dryout	****	****	****
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure Stressed tension			
Weight loss during dryout	SBS dryout	1.16	.95	1.23

Notes:

- * These specimens exposed for 1,812 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- **** Not available.

Table B-10. Summary of Results—Dallas, Nominal 1-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	80.7	85.6	80.8
	Flexure	109.3	110.2	103.8
	± 45 degree tension	113.6	111.9	113.5
Elevated temperature residual strength data (percentage of baseline) **	SBS	73.8	71.8	72.3
	Flexure	112.2	85.9	94.3
	± 45 degree tension	120.0	79.4	119.3
	SBS dryout	94.2	95.9	86.3
Weight change data Percentage gain + Percentage loss —	SBS	.49	.36	.51
	Flexure	.41	.05	.41
	± 45 degree tension	.33	.28	.34
Weight loss during dryout	SBS dryout	.87	.52	.87

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	88.1	86.9	83.1
	Flexure	112.2	101.9	108.0
	Compression	86.1	101.2	97.6
Elevated temperature residual strength data (percentage of baseline) **	SBS	79.8	72.1	69.2
	Flexure	111.5	88.8	85.8
	Compression	70.5	89.4	82.0
	Stressed tension	122.3	98.9	115.5
	SBS dryout	101.4	96.4	89.5
Weight change data Percentage gain + Percentage loss —	SBS	.50	.32	.46
	Flexure	.40	.15	.33
	Stressed tension	.37	.38	.37
Weight loss during dryout	SBS dryout	.92	.55	.81

Notes:

* These specimens exposed for 424 days.

** Residual strength data based on baseline tests at the respective temperatures.

Table B-11. Summary of Results—Dallas, Nominal 2-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	91.5	90.0	91.3
	Flexure	111.0	108.4	103.1
	± 45 degree tension	110.0	110.9	116.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	85.8	72.9	80.2
	Flexure	109.6	83.8	100.4
	± 45 degree tension	125.5	83.1	116.3
	SBS dryout	99.8	92.4	93.4
Weight change data Percentage gain + Percentage loss —	SBS	.49	.45	.53
	Flexure	.35	.03	.36
	± 45 degree tension	.30	.22	.28
Weight loss during dryout	SBS dryout	.96	.65	.97

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	94.1	90.1	88.8
	Flexure	107.8	101.7	99.0
	Compression	90.0	108.2	95.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	82.7	68.6	75.0
	Flexure	103.0	78.5	92.7
	Compression	34.8 †	76.0	79.4
	Stressed tension	130.7	85.5	120.2
	SBS dryout	97.8	94.8	89.8
Weight change data Percentage gain + Percentage loss —	SBS	.58	.58	.61
	Flexure	.47	.30	.48
	Stressed tension	.23	.18	.48
Weight loss during dryout	SBS dryout	.90	.73	1.02

Notes:

- * These specimens exposed for 816 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- † Grip tab slippage.

Table B-12. Summary of Results—Dallas, Nominal 3-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	95.7	91.5	88.1
	Flexure	107.2	101.7	101.7
	± 45 degree tension	113.1	106.1	116.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	84.3	68.8	74.6
	Flexure	113.8	87.0	91.1
	± 45 degree tension	123.2	88.0	118.1
	SBS dryout	99.9	94.6	95.3
Weight change data Percentage gain + Percentage loss —	SBS	.28	.22	.36
	Flexure	.34	.23	.13
	± 45 degree tension	.19	.13	.16
Weight loss during dryout	SBS dryout	.94	.58	1.00

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	93.8	92.0	84.1
	Flexure	108.7	102.0	108.5
	Compression	97.6	105.5	98.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	77.6	67.2	74.0
	Flexure	109.9	87.7	92.7
	Compression	51.2 †	70.0	69.0
	Stressed tension	118.8	91.6	114.4
	SBS dryout	105.1	95.7	75.0
Weight change data Percentage gain + Percentage loss —	SBS	.45	.32	.54
	Flexure	.31	.05	.22
	Stressed tension	.20	.18	.19
Weight loss during dryout	SBS dryout	1.17	.57	.98

Notes:

- * These specimens exposed for 1,144 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- † Grip tab slippage.

Table B-13. Summary of Results—Dallas, Nominal 5-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension	91.1 116.8 111.0	87.9 109.4 108.8	83.6 116.0 112.0
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension SBS dryout ***	88.7 101.8 119.3 107.6	73.6 91.4 86.7 104.0	79.2 94.9 119.2 99.0
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	1.05	.68	1.17

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure Compression	95.4 113.8 85.3	86.7 106.1 112.9	90.7 114.2 102.8
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure Compression Stressed tension *** SBS dryout ***	91.2 90.2 81.8 110.3 98.4	67.1 90.8 94.0 107.7 103.9	79.2 95.6 83.1 115.8 100.1
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	****	****	****
Weight loss during dryout	SBS dryout	1.07	.72	1.22

Notes:

- * These specimens exposed for 1,812 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- *** Tested at room temperature.

Table B-14. Summary of Results—Dallas, Nominal 10-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	109.0	98.9	100.4
	Flexure	109.4	99.5	116.6
	± 45 degree tension	110.6	106.2	113.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	106.7	109.8	94.2
	Flexure	118.0	92.3	98.6
	± 45 degree tension	136.3	88.5	121.4
	SBS dryout	101.3	99.6	100.7
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	.72	.47	.65

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	105.5	96.4	99.6
	Flexure	116.1	104.9	114.2
	Compression	94.2	93.1	86.4
Elevated temperature residual strength data (percentage of baseline) **	SBS	103.4	104.1	96.6
	Flexure	108.9	80.6	90.8
	Compression	52.1 †	56.0	45.7 †
	Stressed tension	109.4	97.4	118.4
	SBS dryout	107.0	104.5	105.0
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	****	****	****
Weight loss during dryout	SBS dryout	.88	.46	.75

Notes:

* These specimens exposed for 3,653 days.

** Residual strength data based on baseline tests at the respective temperatures.

**** Not available.

† Grip tab slippage.

Table B-15. Summary of Results—NASA Dryden, Nominal 1-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	111.5	84.1	93.2
	Flexure	99.3	104.6	104.5
	± 45 degree tension	104.6	110.4	104.8
Elevated temperature residual strength data (percentage of baseline) **	SBS	98.5	79.1	79.8
	Flexure	106.1	98.8	102.5
	± 45 degree tension	95.8	90.6	95.9
	SBS dryout	115.2	92.7	90.8
Weight change data Percentage gain + Percentage loss —	SBS	.05	.02	.11
	Flexure	-.17	-.24	-.10
	± 45 degree tension	-.08	-.11	-.05
Weight loss during dryout	SBS dryout	.67	.68	.47

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	99.2	89.5	92.0
	Flexure	105.4	106.5	99.8
	Compression	96.9	105.9	97.0
Elevated temperature residual strength data (percentage of baseline) **	SBS	101.4	82.2	77.8
	Flexure	112.8	107.0 †	107.5
	Compression	78.2 ††	117.5	60.7
	Stressed tension	105.5	91.7	101.6
	SBS dryout	104.2	86.2	88.9
Weight change data Percentage gain + Percentage loss —	SBS	.10	.06	.07
	Flexure	-.02	-.13	-.05
	Stressed tension	.12	.15	.05
Weight loss during dryout	SBS dryout	.58	.55	.72

Notes:

- * These specimens exposed for 433 days.
- ** Residual strength data based on baseline tests at the respective temperatures.
- † Average of two specimens.
- †† Grip tab slippage.

Table B-16. Summary of Results—NASA Dryden, Nominal 2-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	101.4	94.4	93.4
	Flexure	107.8	111.1	100.2
	± 45 degree tension	111.9 ††	112.7	109.1
Elevated temperature residual strength data (percentage of baseline) **	SBS	104.6	87.2	86.0
	Flexure	108.4	92.6	102.7
	± 45 degree tension	97.0	93.5	97.0
	SBS dryout	109.7	98.0	100.8
Weight change data Percentage gain + Percentage loss —	SBS	.01	.01	.07
	Flexure	-.33	.25	-.25
	± 45 degree tension	-.32	.23	-.22
Weight loss during dryout	SBS dryout †	.38	.21	.38

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	91.7	95.2	94.6
	Flexure	102.3	106.9	102.0
	Compression	91.7	100.5	102.7
Elevated temperature residual strength data (percentage of baseline) **	SBS	99.4	86.3	86.0
	Flexure	112.3	103.5	106.4
	Compression	88.3	82.6	85.1
	Stressed tension	106.8	89.5	108.3
	SBS dryout	107.9	100.8	98.6
Weight change data Percentage gain + Percentage loss —	SBS	.11	-.01	.11
	Flexure	-.47	-.26	-.18
	Stressed tension	-.01	-.23	-.05
Weight loss during dryout	SBS dryout †	.44	.25	.49

Notes:

* These specimens exposed for 715 days.

** Residual strength data based on baseline tests at the respective temperatures.

† Dryout oven overheat to 177°C (350°F), 2 days.

†† Average of two measurements.

Table B-17. Summary of Results—NASA Dryden, Nominal 3-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	88.2	94.4	94.9
	Flexure	111.1	104.3	107.3
	± 45 degree tension	112.4	117.2	108.2
Elevated temperature residual strength data (percentage of baseline) **	SBS	95.5	88.3	87.3
	Flexure	112.1	108.0	117.5
	± 45 degree tension	103.9	102.7	101.4
	SBS dryout	95.2	89.6	85.8
Weight change data Percentage gain + Percentage loss —	SBS	.04	.01	.05
	Flexure	-.18	-.28	-.21
	± 45 degree tension	-.26	-.18	-.18
Weight loss during dryout	SBS dryout	.52	.28	.56

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	80.9	93.1	96.5
	Flexure	103.9	112.0	107.5
	Compression	88.8	86.1	99.3
Elevated temperature residual strength data (percentage of baseline) **	SBS	95.0	86.8	88.4
	Flexure	113.7	107.1	122.6
	Compression	75.5 †	91.7	85.2
	Stressed tension	107.4	94.2	113.0
	SBS dryout	90.2	86.5	91.5
Weight change data Percentage gain + Percentage loss —	SBS	.07	-.22	.12
	Flexure	-.10	-.26	-.18
	Stressed tension	.04	-.08	-.01
Weight loss during dryout	SBS dryout	.56	.35	.54

Notes:

* These specimens exposed for 1,121 days.

** Residual strength data based on baseline tests at the respective temperatures.

† Grip tab failure.

Table B-18. Summary of Results—NASA Dryden, Nominal 5-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension	98.2	86.2	85.5
		103.1	105.2	105.2
		110.0	117.9	105.7
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure ± 45 degree tension SBS dryout	98.2	78.1	82.9
		108.0	103.3	107.9
		102.2	95.4	97.3
		106.7	92.9	90.6
Weight change data Percentage gain + Percentage loss —	SBS Flexure ± 45 degree tension	.08	.05	.17
		-.19	.10	.26
		-.32	-.23	-.21
Weight loss during dryout	SBS dryout	.62	.37	.65

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS Flexure Compression	98.3	89.9	93.2
		106.5	104.0	105.2
		87.0	93.1	97.2
Elevated temperature residual strength data (percentage of baseline) **	SBS Flexure Compression Stressed tension SBS dryout	96.3	80.5	81.3
		113.3	95.4	113.1
		82.3	86.4	82.3
		106.9	95.4	109.8
		105.9	97.0	91.4
Weight change data Percentage gain + Percentage loss —	SBS Flexure Stressed tension	.18	.04	.23
		-.04	-.12	-.72
		.06	.06	-1.19
Weight loss during dryout	SBS dryout	.71	.42	.67

Notes:

* These specimens exposed for 1,822 days.

** Residual strength data based on baseline tests at the respective temperatures.

Table B-19. Summary of Results—NASA Dryden, Nominal 10-year Specimens *

Solar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	107.2	109.8	112.9
	Flexure	103.5	107.3	114.5
	± 45 degree tension	109.2	116.4	112.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	99.9	108.3	113.0
	Flexure	109.5	87.2	101.0
	± 45 degree tension	104.4	93.0	123.8
	SBS dryout	118.0	118.3	112.6
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure	****	****	****
	± 45 degree tension	****	****	****
Weight loss during dryout	SBS dryout	****	****	****

Nonsolar Face

Property	Specimen configuration	Material system		
		5208	5209	934
Room temperature residual strength data (percentage of baseline) **	SBS	115.2	101.2	107.1
	Flexure	107.5	95.6	113.1
	Compression †	69.0	68.0	79.9
Elevated temperature residual strength data (percentage of baseline) **	SBS	112.3	111.6	106.8
	Flexure	104.4	87.4	97.7
	Compression †	132.8	111.7	85.7
	Stressed tension	95.0	96.7	111.7
	SBS dryout	121.0	118.5	112.0
Weight change data Percentage gain + Percentage loss —	SBS	****	****	****
	Flexure	****	****	****
	Stressed tension	****	****	****
Weight loss during dryout	SBS dryout	****	****	****

Notes:

* These specimens exposed for 4,186 days.

** Residual strength data based on baseline tests at the respective temperatures.

**** Not available.

† Tested in IITRI style fixture.

APPENDIX C LABORATORY EXPOSURE SUMMARY RESULTS

Table C-1. One-Year Time Alone Residual Strength* and Weight Change Results

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)	SBS	93.0	92.0	96.7
	Flexure	93.3	99.6	93.3
Elevated temperature residual strength data (percent of baseline)	SBS	99.6	100.7	99.5
	Flexure	100.3	100.4	96.7
Weight change data Percent gain + Percent loss -	SBS	-.10	-.05	-.09
	Flexure	-.18	-.08	-.16
Glass transition temperature (percentage of baseline)		102	98	100

* Residual strength data reported as a percentage of baseline strength at the respective temperature. Each data point represents five specimen tests.

Table C-2. Two-Year Time Alone Residual Strength* and Weight Change Results

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percent of baseline)	SBS	99.6	93.6	96.6
	Flexure	96.5	97.7	103.0
Elevated temperature residual strength data (percent of baseline)	SBS	96.2	94.9	87.3
	Flexure	97.7	102.2	98.6
Weight change data Percent gain + Percent loss -	SBS	-.10	-.03	-.25
	Flexure	-.14	-.09	-.22
Glass transition temperature (percentage of baseline)		Not	recorded	

* Residual strength data reported as a percentage of baseline strength at the respective temperature. Each data point represents five specimen tests.

Table C-3. Three-Year Time Alone Residual Strength* and Weight Change Results

Property	Specimen Configuration	Material System		
		5208	5209	934
Room temperature residual strength data (percentage of baseline)	SBS	99.4	95.8	95.0
	Flexure	82.0	75.2	80.4
Elevated temperature residual strength data (percentage of baseline)	SBS	100.2	96.2	93.8
	Flexure	82.1	98.1	78.5
Weight change data Percentage gain + Percentage loss -	SBS	-.04	+.07	-.07
	Flexure	-.11	+.02	-.13
Glass transition temperature (percentage of baseline)		Not	recorded	

* Residual strength data reported as a percentage of baseline strength at the respective temperature. Each data point represents five specimen tests.

Table C-4. Summary of Residual Strength After Humidity Exposure

PROPERTY	EXPOSURE HUMIDITY, %	PERCENTAGE OF BASELINE STRENGTHS					
		5208		5209		934	
		ROOM TEMPERATURE	82°C (180°F)	ROOM TEMPERATURE	82°C (180°F)	ROOM TEMPERATURE	82°C (180°F)
Short beam shear strength	40	94	95	93	86	96	90
	60	88	85	83	72	91	80
	75	88	81	84	68	88	75
	95	80	66	*	30	80	57
Flexure strength	40	98	96	102	96	101	97
	60	99	92	105	88	100	91
	75	97	91	101	77	101	86
	95	94	84	86	41	94	76

*Due to a testing error these specimens tested at 82°C (180°F)

Note:

Each data point represents five specimen tests.

82°C (180°F) values measured against 82°C (180°F) dry baseline.

*Table C-5. Summary of Residual Strength After
2-year Exposure on Wet Specimen*

PROPERTY	EXPOSURE HUMIDITY, %	PERCENTAGE OF BASELINE STRENGTHS					
		5208		5209		934	
		ROOM TEMPERATURE	82°C (180°F)	ROOM TEMPERATURE	82°C (180°F)	ROOM TEMPERATURE	82°C (180°F)
Short beam shear strength	60	88.6	81.9	88.6	64.9	88.0	65.5
	95	75.3	64.9	60.0	25.5	70.5	50.6
Flexure strength	60	102.5	91.9	100.4	89.6	104.8	92.8
	95	78.8	81.2	84.0	35.3	99.1	74.9

Note:

Each data point represents five specimen tests.

82°C (180°F) values measured against 82°C (180°F) dry baseline.

Table C-6. Weatherometer 6-month Nominal Exposure

MATERIAL	RESIDUAL FLEXURE STRENGTHS*, %		GLASS TRANSITION TEMPERATURE
	ROOM TEMPERATURE	82° C (180°F)	PERCENTAGE OF BASELINE
5208 Painted	112	116	— —
Unpainted	111	105	97
5209 Painted	—	93	— —
Unpainted	—	100	102
934 Painted	—	99	— —
Unpainted	—	95	94

* Residual strength data reported as a percentage of baseline strength at the respective temperatures. Each data point represents five specimen tests.

Table C-7. Weatherometer 1-year Nominal Exposure

MATERIAL	RESIDUAL FLEXURE STRENGTHS*, %		GLASS TRANSITION TEMPERATURE
	ROOM TEMPERATURE	82° C (180°F)	PERCENTAGE OF BASELINE
5208 Painted	89.9	115.5	95
Unpainted	94.4	92.6	97
5209 Painted	—	117.3	92
Unpainted	—	103.0	95
934 Painted	—	108.7	96
Unpainted	—	99.6	96

* Residual strength data reported as a percentage of baseline strength at the respective temperatures. Each data point represents five specimen tests.

Table C-8. Weatherometer 24-month Nominal Exposure

MATERIAL	RESIDUAL FLEXURE STRENGTHS* %		GLASS TRANSITION TEMPERATURE
	ROOM TEMPERATURE	82° C (180°F)	PERCENTAGE OF BASELINE
5208 Painted	87	83	107
Unpainted	73	80	107
5209 Painted	—	103	103
Unpainted	—	100	102
934 Painted	—	79	105
Unpainted	—	93	105

* Residual strength data reported as a percentage of baseline strength at the respective temperatures. Each data point represents five specimen tests.

Table C-9. Ground-Air-Ground Residual Strength* Results

SPECIMEN	TEST TEMPERATURE	
	ROOM TEMPERATURE	82°C (180°F)
Short beam shear		
5208	88.4	79.3
5209	79.9	61.7
934	86.1	67.3
Flexure		
5208	80.4	83.4
5209	83.1	72.6
934	87.9	79.9

* Residual strength data reported as a percentage of baseline strength at the respective temperatures. Each data point represents five specimen tests.

Note: All specimens exposed to 3200 simulated ground-air-ground cycles are described in section 7.5 and figure 30.

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16. Abstract A study was conducted to determine the effects of long-term flight and ground exposure on three commercially available graphite-epoxy material systems: T300/5208, T300/5209, and T300/934. Sets of specimens were exposed on commercial aircraft and ground racks for 1, 2, 3, 5, and 10 years. In-flight specimen sites included both the interior and exterior of aircraft based in Hawaii, Texas, and New Zealand. Ground racks were located at NASA Dryden Flight Research Center and airports in Dallas, Honolulu, and Wellington, New Zealand. Similar specimens were exposed to controlled lab conditions for up to 2 years. After each exposure period, specimens were evaluated for residual strength and a dryout procedure was used to measure moisture content. Both room and elevated temperature residual strengths were determined and expressed as a percentage of the unexposed strength. Lab exposures included the effects of time alone, moisture, time on moist specimens, weatherometer, and simulated ground-air-ground cycling. Residual strengths of the long-term specimens were compared with residual strengths of the lab specimens. Strength retention depended on the exposure condition and the material system. Results showed that composite materials can be successfully used on commercial aircraft if environmental effects are accounted for in the design.					
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