ENVIRONMENTAL EFFECTS ON COMPOSITES FOR AIRCRAFT

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INTRODUCTION

The influence of the operational environment on the behavior of composite materials and aircraft components fabricated with these composite materials is a subject of continuing concern both for the aircraft manufacturer and the airline operator. The structural weight savings and the potential for manufacturing cost savings have been well documented in a number of composite hardware development programs in recent years. These advantages have left the question of long-term environmental durability for composites as the major undetermined issue for widespread acceptance and application.

This paper reports on the interim results from a number of ongoing, long-term, environmental effects programs. The flight service experience to date of composite components is evaluated. In addition, the influence of a number of worldwide, ground-based outdoor exposures on the physical and mechanical properties of six composite materials is discussed. In particular, the current extent of the ultraviolet surface degradation and the moisture gained by diffusion is shown. Finally, several new environmental programs which have been started recently are reported to show the type of information that can be expected to be available in the next few years.

FLIGHT SERVICE OF COMPOSITE COMPONENTS

A number of composite structural components have been designed, manufactured, tested, and placed in operational service on a variety of aircraft. This operational flight service is monitored periodically to evaluate the long-term experience with composite durability. The types of aircraft and composite components are shown in figure 1. The L-1011 application is six fuselage fairing panels involving two types of Kevlar-49 epoxy composite on each of three airplanes (ref. 1). Three graphite-epoxy material systems are used for the spoilers on 27 Boeing 737 airplanes (ref. 2). A fourth graphite-epoxy material is used in the upper, aft rudder segment on ten DC-10 airplanes (ref. 3), and boron-aluminum composite skin is used in a panel on the aft pylon adjacent to the engine on three DC-10 airplanes (ref. 4). Boron-epoxy is used as a selective reinforcement in the aluminum aft fuselage, or tail cone, of an Army CH-54B helicopter (ref. 5) and in the aluminum center wing box of two Air Force C-130 transports (ref. 6).

The status of these composite structural components in the Langley flight service program, as of January 1, 1978, is given in table I. The boron-epoxy composite in the CH-54B helicopter tail cone has been in service for the longest calendar time, six years, but it has been flown very little compared to the other types of aircraft. The Kevlar-49 epoxy in the L-1011 fairing panels has

accumulated the greatest single component flight time, 13 138 flight hours in five years of service. The graphite-epoxy in the 108 spoilers on the 737 airplanes has accumulated the greatest total component flight hours, 921 600 in four and one-half years. The graphite-epoxy in one of the DC-10 upper aft rudders has been acquiring flight service time at the greatest rate of any of the components in the table, a rate of 400 hours per month or about 13 hours per day. Overall the 142 composite components have accumulated in excess of one million component flight hours in service around the world with 17 operators. Each of these composite components has been inspected at least annually by the manufacturer, under terms of the NASA contracts. There have been no significant incidents or damage detected in any of these flight components. Maintenance has been reported as less than that required on similar standard, production parts.

COMPOSITE SPOILERS

The large number (108) of replicate spoilers with graphite-epoxy skins allows a program of planned retrievals from flight service without seriously impairing the total exposure. Six spoilers are selected at random for removal annually, two of each of the three material systems. These spoilers are shipped to The Boeing Company where they are nondestructively inspected by ultrasonic C-scan. The C-scan record is compared with similar records made at the completion of manufacturing. To date, no significant differences have been observed. Three of the six spoilers are then selected for destructive testing and the remaining three are returned to flight service.

For destructive testing the spoilers are mounted in the same static test jig as was used for the initial airworthiness certification tests (ref. 2). A distributed load is applied to the outer surface of the spoiler, simulating aerodynamic loads, and the magnitude is increased until failure occurs. Results of these residual static strength tests on the graphite-epoxy spoilers are shown in figure 2. The residual strengths for each material system have been divided by the failure strength of the initial certification test for each material, and the results are presented nondimensionally as a function of the time in service. A scatter band for strength tests of 16 new replicate spoilers manufactured with the T300-5209 graphite-epoxy material has been superimposed on the individual tests of spoilers removed from service. In four years of service, the scatter in strength for the individual spoilers generally falls within the width of the new spoiler strength scatter band; an indication of essentially no degradation in strength.

After several years of unsuccessfully attempting to determine the moisture absorbed by the graphite-epoxy spoilers in service, a technique of cutting plugs from near the trailing edge was developed (fig. 3). The eight rectangular areas shown with an arrow in the center of each represent the whiffletree loading areas for static strength tests. Since failures always have initiated near the leading edge at one of the center hinges, it has been determined that three plugs of 6.4 cm (2.5 in.) diameter could be cut from the region behind the loading areas without influencing the failure load. These plugs, which consist of aluminum honeycomb core, two graphite-epoxy face sheets, two layers of epoxy film adhesive and two exterior coats of polyurethane paint, have about

90 percent of their weight in the composite faces, including the paint and adhesive. A good determination of the moisture level in the spoiler can be made by drying the plug and noting the weight change. After three years of service with Lufthansa Airlines in Germany, plugs taken from a T300-5209 graphite-epoxy spoiler indicated a moisture content of 0.64 percent, based on the composite weight. Somewhat greater significance may be attached to this value when corrections have been determined for relative differences in equilibrium moisture levels in the paint, the composite matrix, and the adhesive.

Subsequent to the introduction into flight service of the graphite-epoxy-skinned spoilers, a development program was undertaken for an all-composite spoiler which included glass-epoxy honeycomb core, molded graphite-epoxy hinge fittings and leading edge spar, and thermoplastic graphite-polysulfone skins (ref. 7). It was recognized that the polysulfone matrix had an environmental sensitivity to phosphate-ester-based hydraulic fluids, and the laboratory testing demonstrated this in elevated temperature, stressed immersions. However, based on the room temperature experience it was believed that the material could be successfully used in flight components with only minor, intermittent exposures to hydraulic fluid leakage from the spoiler actuators. Twelve of these spoilers were fabricated and placed in service on six of the aircraft that were flying graphite-epoxy spoilers. After six months of operational flight service the two spoilers installed on Aloha Airlines were reported to have developed significant delamination of the lower surface skin directly aft of the actuator attachment fitting (fig. 4). Within a month a third spoiler was reported as starting to experience delamination, so it was decided to remove all the remaining graphite-polysulfone spoilers. A closeup view of the delaminated area is shown in the photograph in figure 5. This experience demonstrated the difficulty of performing adequate laboratory accelerated environmental testing and provided a good example of the necessity for flight service evaluation.

There have been several instances in which the graphite-epoxy spoilers have received damage in service sufficient to require repairs. Examples of these are illustrated in figure 6. On this program, damaged spoilers are removed from the aircraft and returned to The Boeing Company for repair. Repairs are made by cutting out the damaged area, replacing honeycomb core as needed, and replacing graphite-epoxy plies on a one-for-one basis with each ply lapped over the underlying one by about 6 mm (0.25 in.). One piece of adhesive film is placed under the patch assembly and the built-up patch is cured and bonded in one cycle in an autoclave with the spoiler supported in its original assembly tooling (ref. 7). The repaired spoiler is ultrasonically inspected and returned to flight service with the airline which had previously used it.

WORLDWIDE GROUND-BASED OUTDOOR EXPOSURE

As a parallel part of the flight service exposures of composite components, a number of replicate mechanical property specimens have been manufactured from the same composite material systems used in the components. These specimens have been mounted in racks which are deployed on rooftops of airline buildings at a number of airports around the world so as to receive maximum exposure to the airport ground environment. The location of six of the exposure

sites is shown on the map of the world in figure 7. Each of these locations has an exposure rack with unstressed specimens as indicated in figure 8. Each of the five panels mounted in the rack contains triplicate specimens of four graphite-epoxies, one graphite-polysulfone, and two Kevlar-49 epoxies in short beam interlaminar shear, flexure and compression configurations. After one year and three years of exposure a panel is removed from each rack and shipped to Langley Research Center for specimen testing and evaluation.

In addition to the unstressed exposures, three racks containing stressed tensile specimens (fig. 9) are also deployed, one each at San Francisco, Seattle, and Langley. Individual specimens are mounted in fixtures which apply a constant load through a compressed helical spring. Unstressed tensile specimens are also placed in these same racks for comparison.

When specimens are removed and shipped to Langley periodically, they are weighed to determine weight changes associated with moisture absorption and weathering. An example of the specimen weight changes with exposure time is shown in figure 10 for a thin graphite-epoxy specimen in the unstressed rack at Langley. The solid curve in the center of the figure drawn through the circular test points is the record of the repeated weighings. The specimen initially gained weight and then began to gradually lose weight as a result of the combined effects of moisture and solar ultraviolet exposure. The exposure of this specimen was terminated after 140 days and the specimen was then dried to a fully dry condition. The weight change associated with this drying indicated the actual measured moisture level in the specimen at 140 days. Comparing the fully dry weight to the initial fully dry weight showed the measured ultraviolet effect of a weight loss after 140 days. Since the ultraviolet effect is a loss from the exposed specimen surface, it is assumed to be linear with exposure time. Corrections can then be calculated for the measured weights at intermediate times, and an interpolated moisture curve can then be plotted as shown by the upper dashed line in figure 10. This curve appears to have reached an equilibrium level of moisture absorption between 0.6 and 0.7 percent. The small fluctuations correspond to changes in the daily levels of relative humidity.

The results of fully drying the flexure specimens from five exposure sites after three years of exposure provided a pattern of weight losses due to ultraviolet exposure as shown in figure 11. For any given material, the weight losses are greater for exposure sites closest to the equator. Variations in the epoxy matrices for the different material systems seem to provide a greater variation in weight loss than changes in exposure site latitude. In all cases the specimens were exposed in an as-laminated condition without any protective coating. The weight losses in three years time correspond to less than 25 percent of one ply thickness.

Scanning electron micrographs of two areas on one of the T300-5209 graphite-epoxy specimens exposed at the Honolulu site are shown in figure 12. The left-hand area was shielded from the solar ultraviolet by the specimen mounting clamp on the exposure rack. The magnified view is essentially the original as-laminated surface, which is entirely epoxy. The right-hand area was typical of the unshielded portion of the same specimen. In this area the epoxy matrix has been removed by the ultraviolet weathering process, exposing

a layer of individual graphite fibers. Although the effect looks bad, it really is quite superficial in three years time and it can be prevented by painting the exposed specimen surface.

The amount of moisture absorbed by the various composite material systems is shown in figure 13. These results represent the determinations made on flexure specimens after their worldwide outdoor exposures for times up to three years. The weight gains shown have been corrected for the ultraviolet weight losses as described previously for figures 10 and 11. The scatter bands indicated for the three-year exposures contain all the data for triplicate specimens and five exposure sites. In general there is no separation of individual sites by the magnitude of absorbed moisture. The largest variable appears to be the type of epoxy matrix used in the composites. Even the Kevlar-epoxy values are in the same range as one of the graphite-epoxies. Data for T300-5208 graphite-epoxy is only shown for a 1.7-year exposure because the specimens which were made as a part of the graphite-epoxy rudder flight service program were not available to be deployed in the exposure rack panels until 1.3 years after the other specimens were deployed. However, the absorbed moisture for the T300-5208 is essentially the same as for the T300-5209 material, and both appear to be at an equilibrium level of about 0.5 percent of the laminate weight.

A comparison of the measured moisture contents for both T300-5208 and T300-5209 materials with predicted moisture contents for a 12-ply laminate of T300-5208 graphite-epoxy is shown in figure 14. The predicted moisture contents are based on calculations using the Fickian diffusion equations with varying inputs for relative humidity and temperature (ref. 8). These varying inputs are taken directly from tape recordings of the weather at Langley Research Center. The predicted curve marked "No Solar" was calculated assuming that the temperature of the specimen was the same as that of the ambient air. This is a reasonable assumption for specimens exposed in shade; however, if the specimens are exposed to the Sun, they will be heated to temperatures well above the ambient air temperature on clear, sunny days. This will increase the rate of moisture diffusion and, more importantly, decrease the local relative humidity at the surface of the specimens. Inclusion of these effects in the calculations results in the lower predicted curve marked "Solar". The weather data for the year 1962 were used repetitively in the calculations, starting at the first of October to correspond with the initial deployment of the exposure racks and specimens. The experimental data points at 1, 1.7, and 3 years are taken from the overall worldwide exposure data previously discussed in figure 13 for T300-5208 and T300-5209 graphite-epoxies. The correlation between prediction and experiment is good.

The observed loss of material from ultraviolet exposure and pickup of moisture from the relative humidity leads to a concern for the effect on residual mechanical properties. Figure 15 shows the results of flexure strength tests performed after various exposure times at all of the worldwide exposure sites for six composite materials. The data are shown in nondimensional form obtained by dividing residual strengths by the initial as-laminated strengths. The width of the scatter band for strength is largely a function of the scatter in triplicate tests from various exposure sites. However, it is not sufficiently greater than the scatter in the initial replicate tests to justify any

conclusions. It is evident that for three years of outdoor ground-based unstressed exposure there has been no indication of degradation in flexure strength. Similar conclusions can be drawn from results of the short beam interlaminar shear and the compression tests also, after three years of unstressed outdoor exposure.

To consider the possible influence of constant stress during the outdoor exposure, three sets of tensile specimens have been included in the program. The first set consists of T300-5209 graphite-epoxy material laminated at $\pm45^{\circ}$ ply orientation and stressed during exposure at 25 percent of the initial ultimate strength. Exposure and residual strength testing have been conducted in the Seattle, Washington area by The Boeing Company under NASA contract. Results shown in figure 16 indicate essentially no difference between stressed and unstressed exposure and no degradation in tensile strength for up to three years of exposure. The second and third sets of tensile specimens are T300-5208 graphite-epoxy material laminated in a $[0^{\circ},\pm45^{\circ},90^{\circ}]$ quasi-isotropic ply orientation and stressed during exposure at 40 percent of the initial ultimate strength. Exposure sites for these are located at the San Francisco airport and at Langley. Specimens have been retrieved and tested at Langley after one and three years exposure. The results shown in figure 17 indicate about the same amount of scatter as shown previously for the flexure strengths and indicate essentially no difference between stressed and unstressed exposures and no degradation in tensile strength.

Another type of environmental exposure includes the interaction of composite materials with extended exposure to aircraft fuels and hydraulic fluids. Under NASA contract The Boeing Company has conducted a series of exposures of several composite materials in JP-4 jet fuel, a commercial aviation phosphate-ester hydraulic fluid, a fuel-and-water mixture, and a fuel-and-air cyclic environment. All exposures are outdoors in an unheated shed in the Seattle area. Short beam interlaminar shear and tensile specimens are being exposed. Typical results are shown in figure 18 for T300-5209 graphite-epoxy material laminated at a $\pm45^{\circ}$ ply orientation. The data indicate no degradation in tensile strength for up to three years exposure in any of the above environments.

NEW ENVIRONMENTAL PROGRAMS

All of the previously described environmental activities have been under way for extended times and are planned to continue for some time in the future. As data have developed from these and other composite materials technology programs, the need for additional environmental exposure data has become apparent. Several new programs have been started recently which will be producing significant data in the future and these are described in the following paragraphs to provide a more complete view of the Langley program.

Figure 19 shows two views of an outdoor environmental exposure site at Langley in which the Structural Integrity Branch is conducting flight-by-flight spectrum loading on chains of composite materials specimens. The two views provide graphic evidence that the specimens see the full extremes of summer and winter weather. Specimens with and without open-hole stress concentrations

are being exposed. Similar chains of specimens are being subjected to the same loads inside a controlled-environment laboratory for comparison.

Technology for designing primary structural discontinuities such as bolted joint wing splices in composite materials is being developed in programs like the one discussed in reference 9. Test specimens with multiple, repeating patterns of bolted fasteners (fig. 20) have been fabricated with laminate thicknesses of 1.37 cm (0.54 in.) and static strength tested successfully. With the validation of the static design, replicate specimens have been fabricated and are under long-term stressed exposure outdoors at Langley as shown in figure 21. The sustained stress level has been set at 25 percent of the static ultimate.

In order to obtain some information on the rate of moisture diffusion into composite materials in actual flight service, as well as to determine directly the equilibrium levels achieved, two programs have been initiated to fly specimens of three graphite-epoxy material systems on three 737 and three DC-10 transport airplanes which are already involved in the flight service evaluation of graphite-epoxy spoilers and rudders. Moisture pickup in flight on the exterior surface of the 737 airplane will be determined from specimens mounted on both the upper and lower surfaces of the flap track fairing tail cone as shown in figure 22. Specimens are mounted in titanium holding fixtures which are attached to the fiberglass tail cone. Periodically one upper and one lower surface fixture are removed and sent to The Boeing Company where they will be weighed and fully dried. Moisture pickup in flight on interior surfaces of parts which are vented to the atmosphere on DC-10 airplanes will be determined from specimens mounted in a holding fixture attached inside the wing leading edge as shown in figure 23. Periodically these specimens will be removed, weighed, and reinstalled by Douglas Aircraft Company personnel during normal aircraft stopovers at Los Angeles or San Francisco.

CONCLUSIONS

Interim results from a number of programs relating to the long-term environmental durability of composite materials in the commercial airline operational environment have been presented and the following conclusions can be drawn:

1. More than five years and 1 000 000 component flight hours of successful flight service evaluation have been achieved for 142 composite components.

2. Residual strength tests of graphite-epoxy spoilers removed from service annually have shown no significant effects in four years.

3. Ground-based outdoor exposures of composite material coupons after 3 years of exposure have reached equilibrium levels of moisture pickup ranging from 0.5 to 2.1 percent of the composite laminate weight, and have produced a solar ultraviolet-induced material loss for unprotected epoxy matrix specimens which is less than 25 percent of one ply. Specific levels of moisture pickup are predictable and are dependent on the particular material system.

4. No significant degradation has been observed in residual strength tests of 3-year outdoor exposures worldwide for interlaminar shear, flexure and compression specimens; for stressed and unstressed tensile specimens; and for exposures to aviation fuels and fluids.

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TABLE I
LANGLEY COMPOSITES FLIGHT SERVICE PROGRAM

AIRCRAFT, COMPONENT	TOTAL COMPONENTS	START OF FLIGHT SERVICE	CUMULATIVE FLIGHT HOURS	
			HIGH TIME AIRCRAFT	TOTAL COMPONENT
CH-54B TAIL CONE	1	MARCH 1972	924	924
L-1011 FAIRING PANELS	18	JANUARY 1973	13 138	186 600
737 SPOILER	108	JULY 1973	11, 315	921, 600
C-130 CENTER WING BOX	2	OCTOBER 1974	2 394	4 800
DC-10 AFT PYLON SKIN	3	AUGUST 1975	6, 516	19 400
DC-10 UPPER AFT RUDDER	10	APRIL 1976	6 600	27 800
GRAND TOTAL	142			1, 161, 100

L-1011 FAIRING

B-737 SPOILER

CH-54 B FUSELAGE

DC-10 RUDDER AND AFT PYLON

C-130 CENTER WING BOX
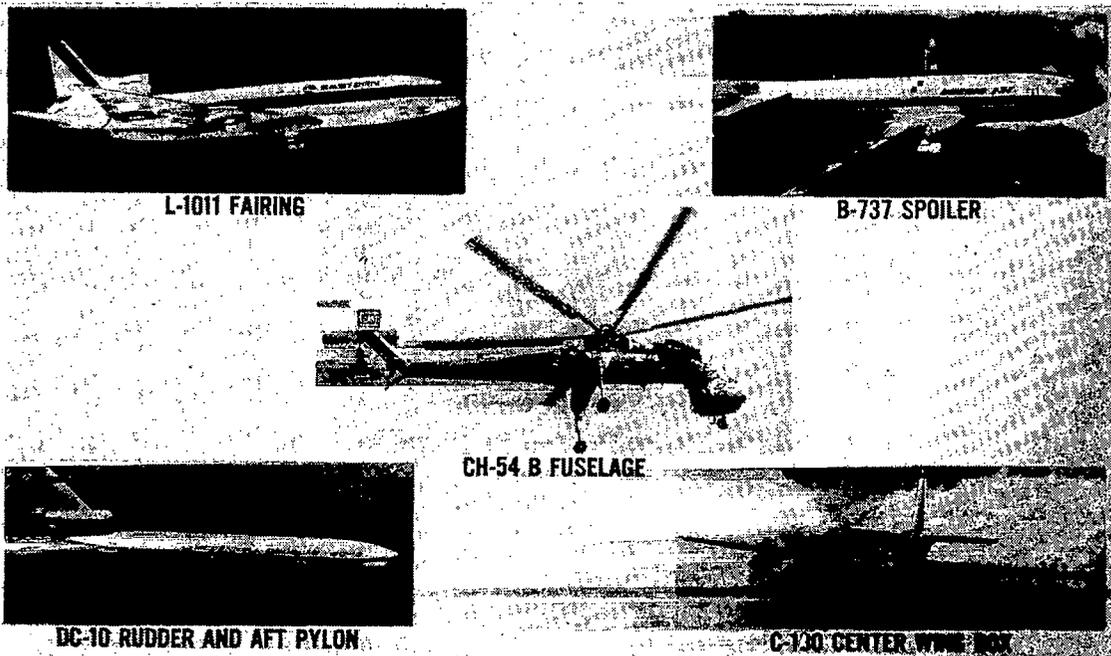
Figure 1.- Flight service evaluation of composite structural components.

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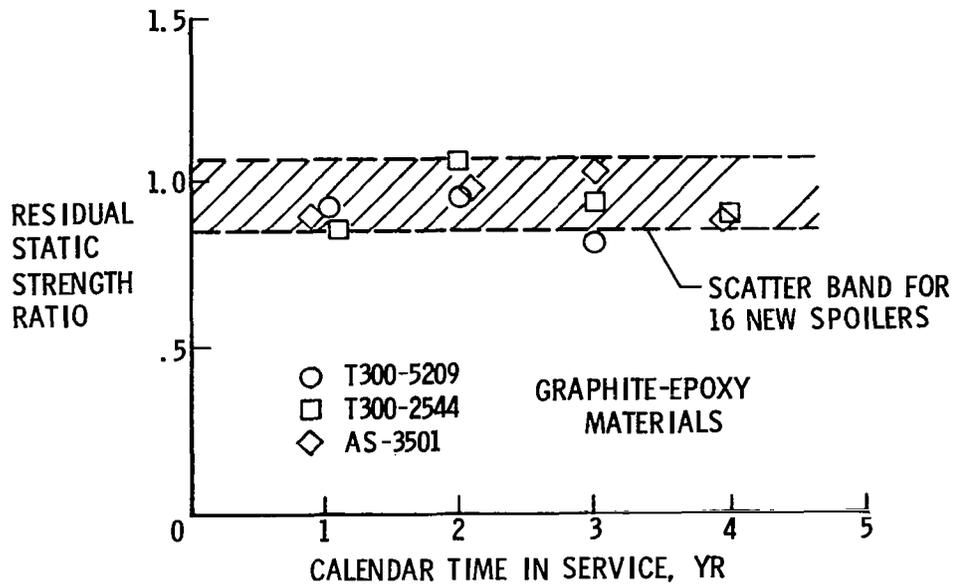
Figure 2.- Residual static strength of graphite-epoxy spoilers.

T300-5209 GRAPHITE-EPOXY AFTER
THREE YEARS SERVICE WITH LUFTHANSA
RESIDUAL MOISTURE
0.63 PERCENT
0.66   } AV = 0.64 PERCENT
0.62
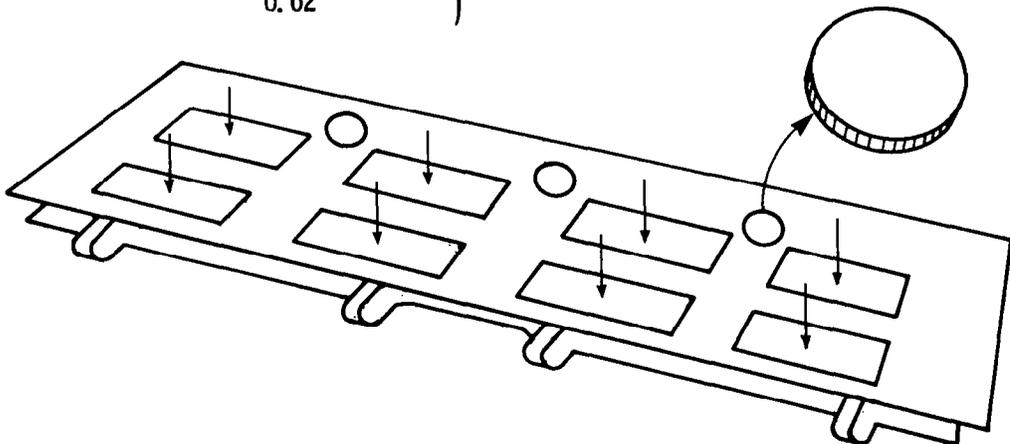
Figure 3.- Spoiler moisture levels determined from plugs.
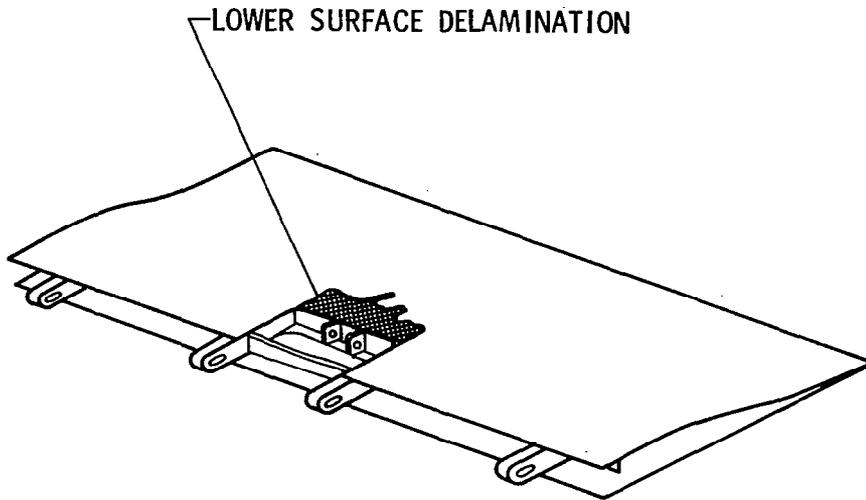
Figure 4.- General area of spoiler delamination.
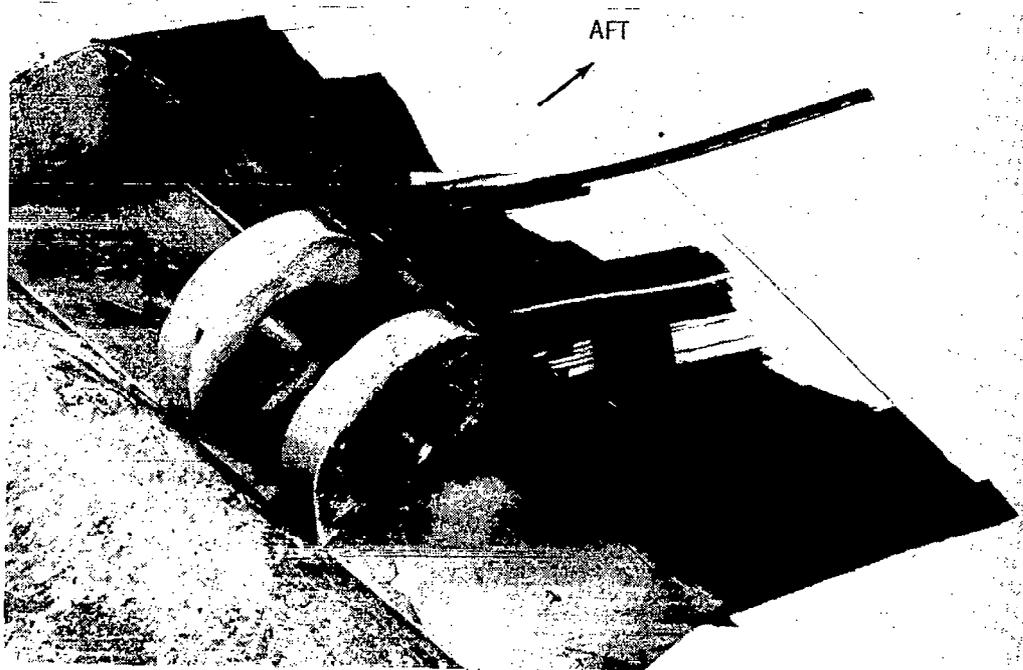
Figure 5.- Delamination of spoiler cover due to hydraulic fluid attack.

DAMAGED
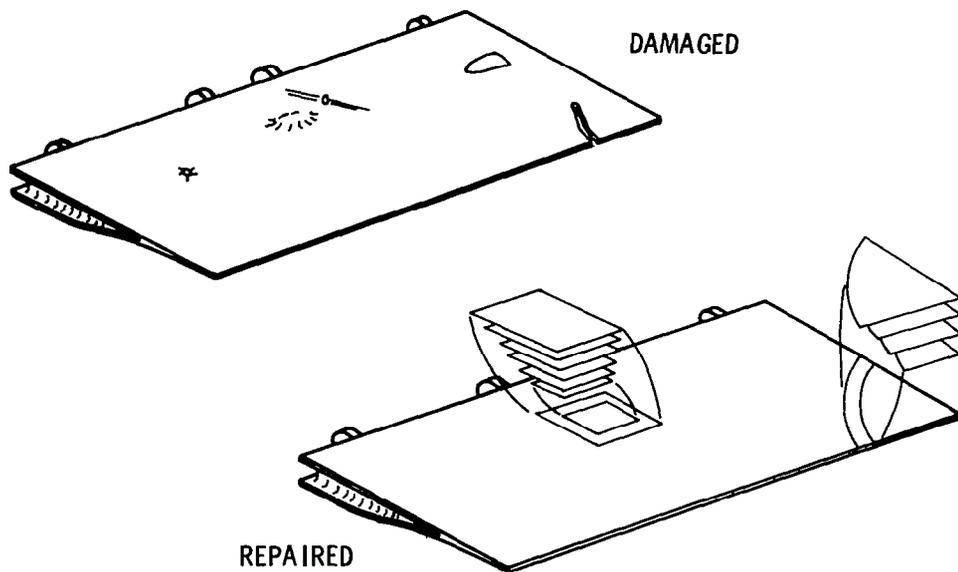
REPAIRED

Figure 6.- Graphite-epoxy spoiler repair techniques.

SEATTLE

SAN FRANCISCO

SAN DIEGO

HONOLULU

LANGLEY

FRANKFURT

SÃO PAULO

WELLINGTON
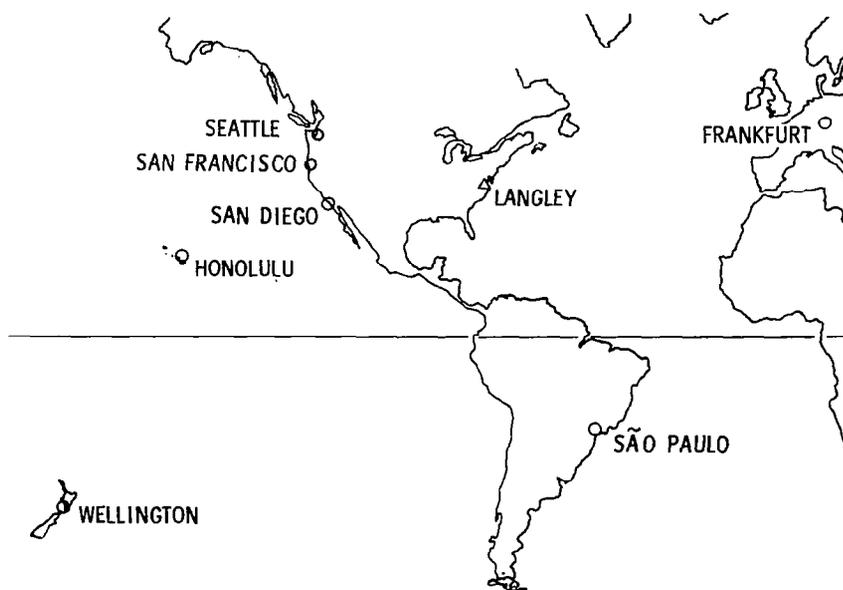
Figure 7.- Distribution of environmental exposure racks.
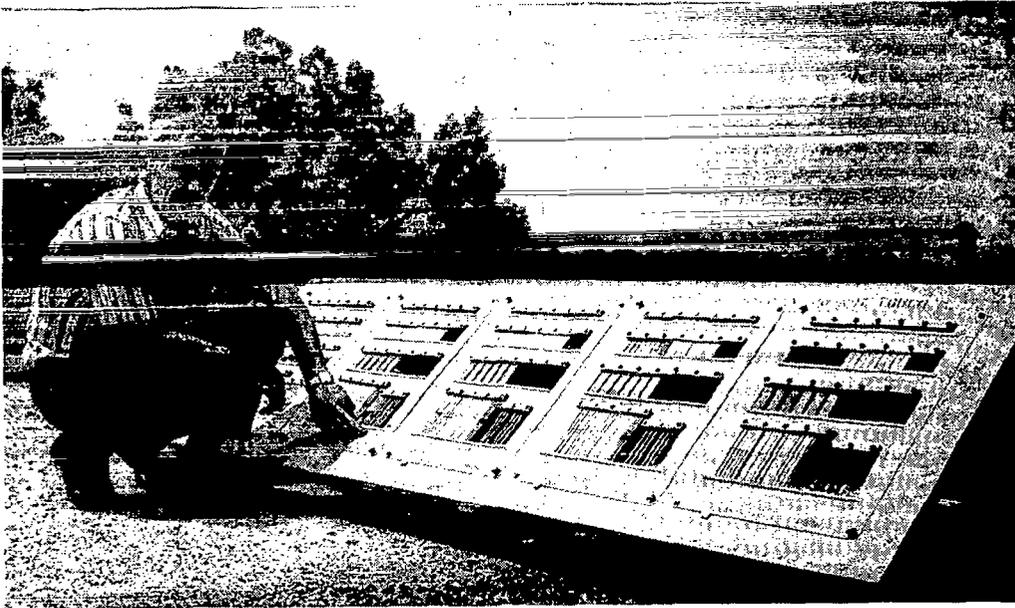
Figure 8.- Unstressed exposure rack.
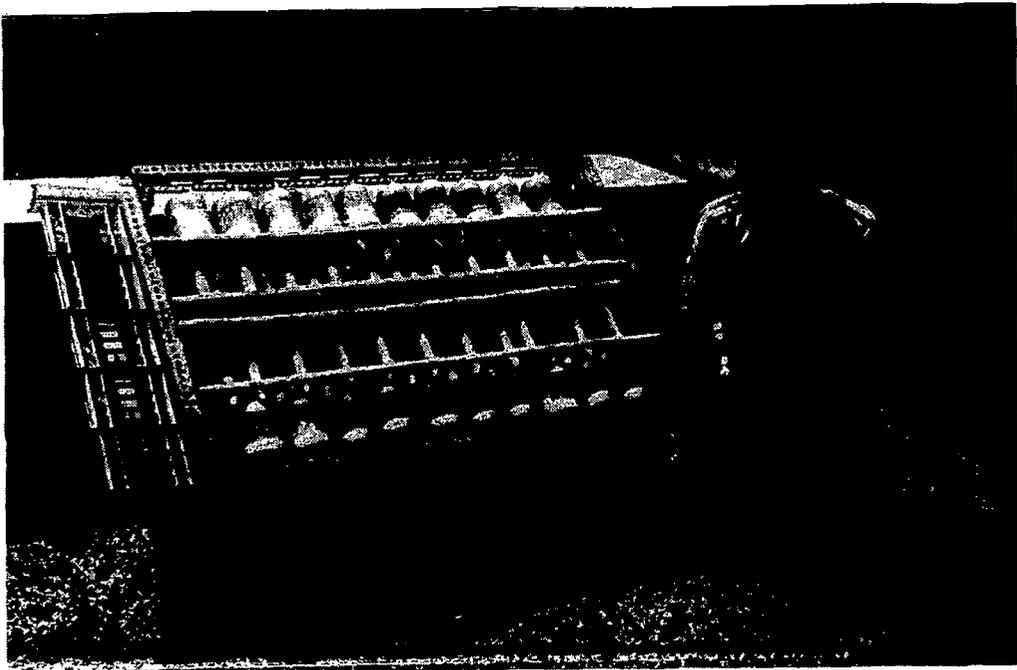
Figure 9.- Stressed exposure rack.

4-PLY LAMINATE, T300-5209
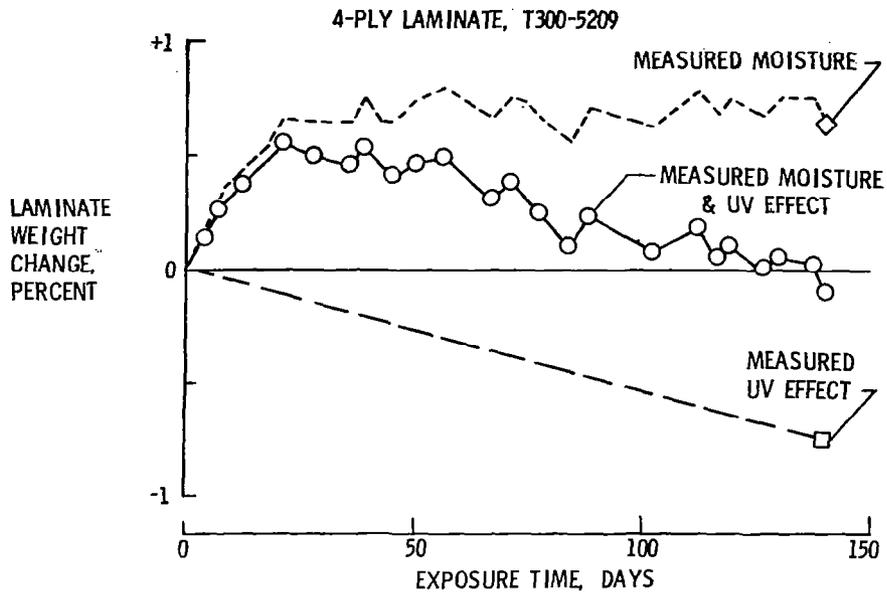
Figure 10.- Weight change in outdoor exposure; 4-ply laminate, T300-5209.
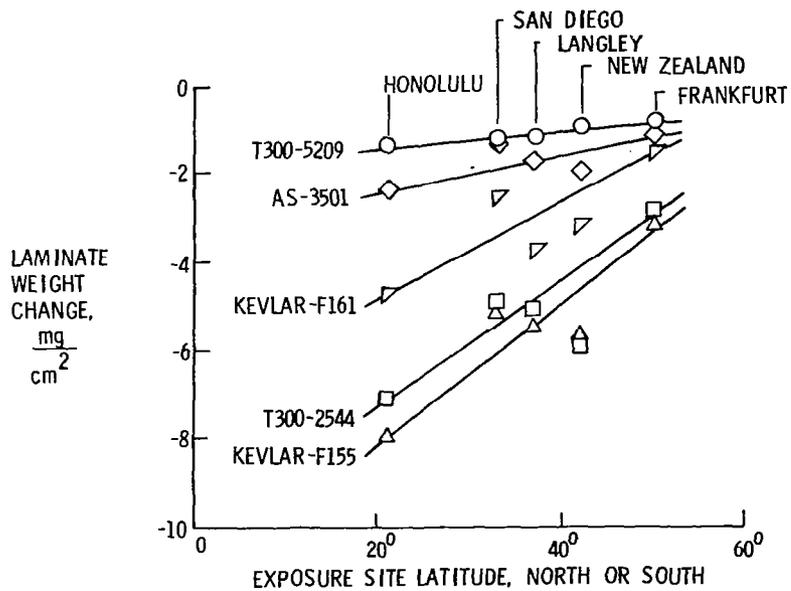
Figure 11.- Weight loss from three years outdoor ultraviolet exposure.

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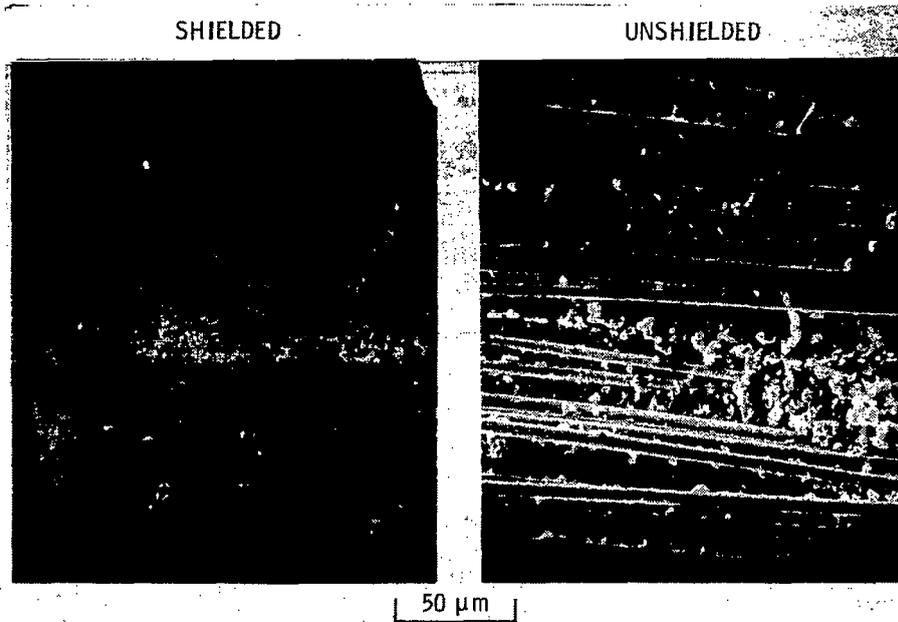
Figure 12.- Graphite-epoxy surface degradation; 3-year outdoor exposure.
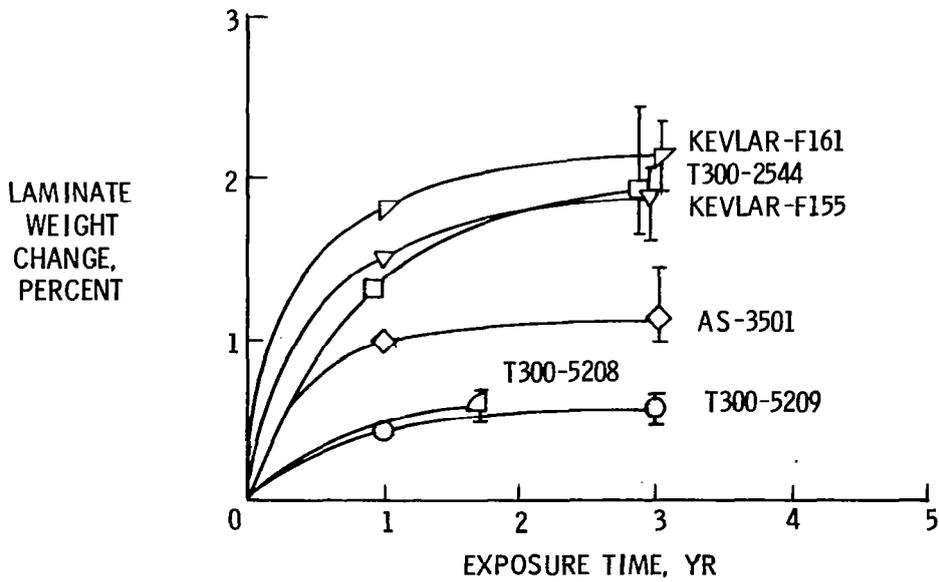
Figure 13.- Moisture pickup after worldwide exposures.

T300-5208, 12-PLY LAMINATE
GROUND EXPOSURE
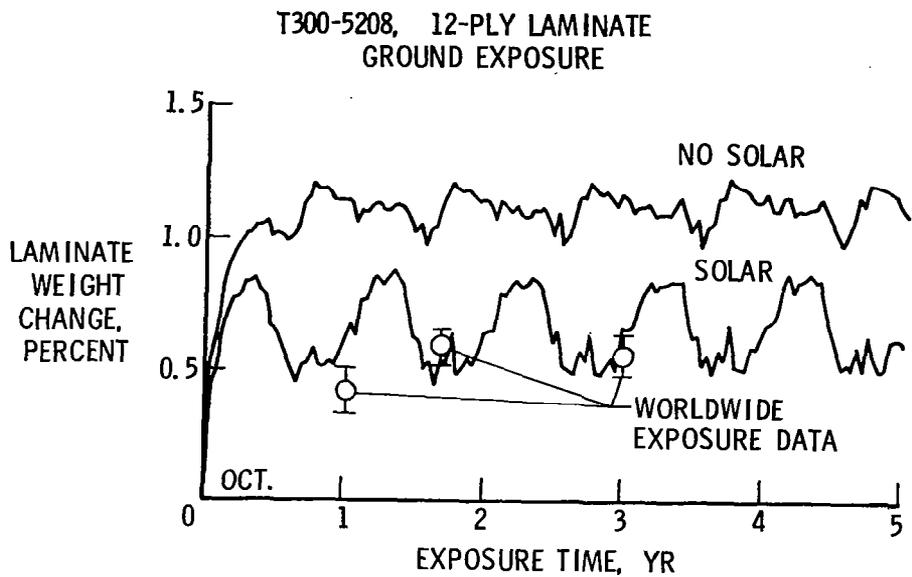
Figure 14.– Comparison of predicted and measured moisture contents; T300-5208, 12-ply laminate; ground exposure.
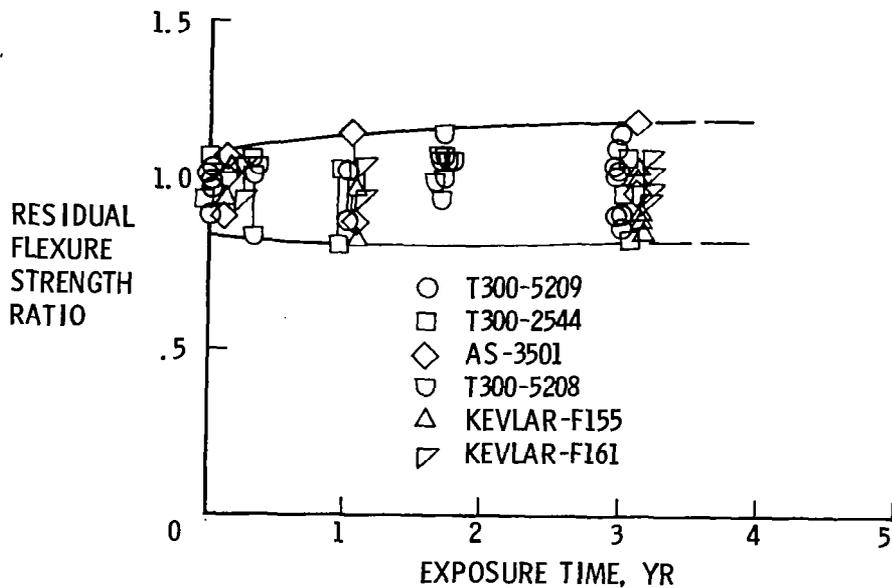
Figure 15.– Residual flexure strength after worldwide exposure.
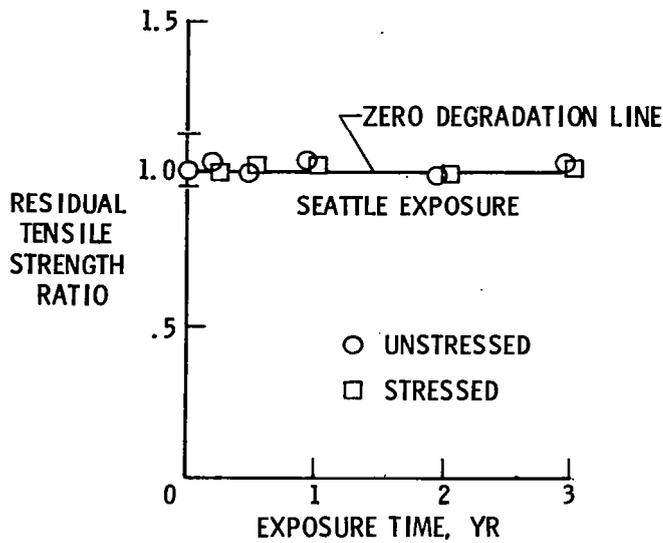
Figure 16.- Residual tensile strength after sustained stress outdoor exposures; T300-5209, ±45° laminate stressed at 25 percent ultimate.
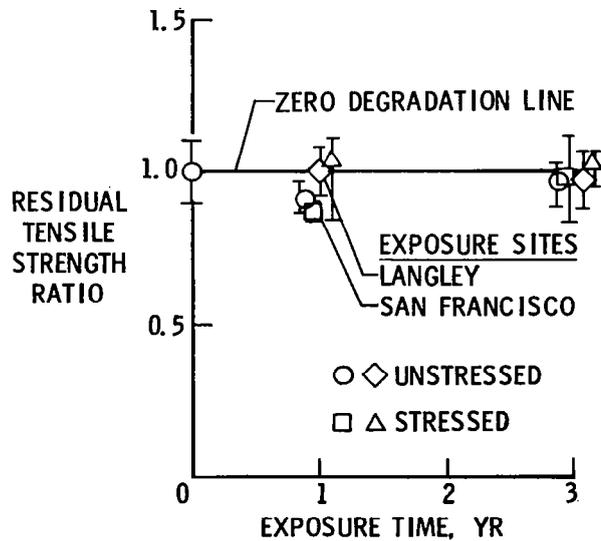
Figure 17.- Residual tensile strength after sustained stress outdoor exposures; T300-5208, [0°, ±45°, 90°] laminate stressed at 40 percent ultimate.
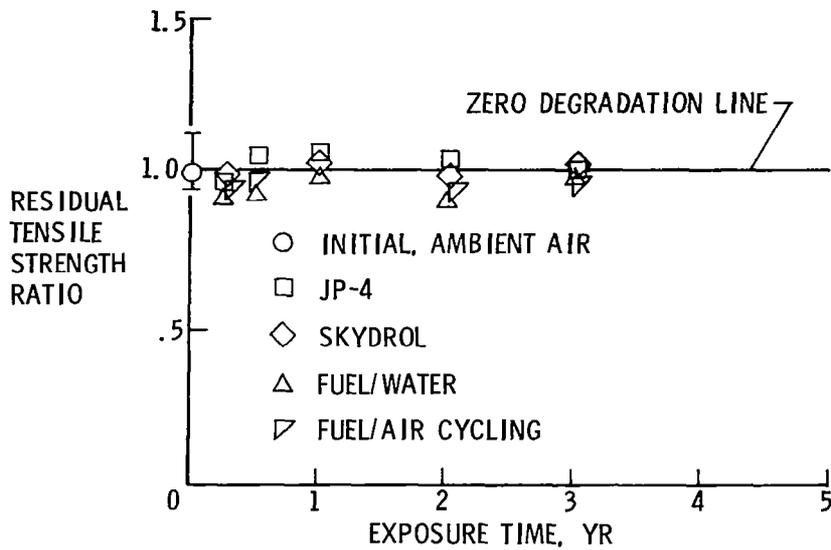
Figure 18.- Effect of fuels and fluids on strength; T300-5209, ±45° tensile specimens.
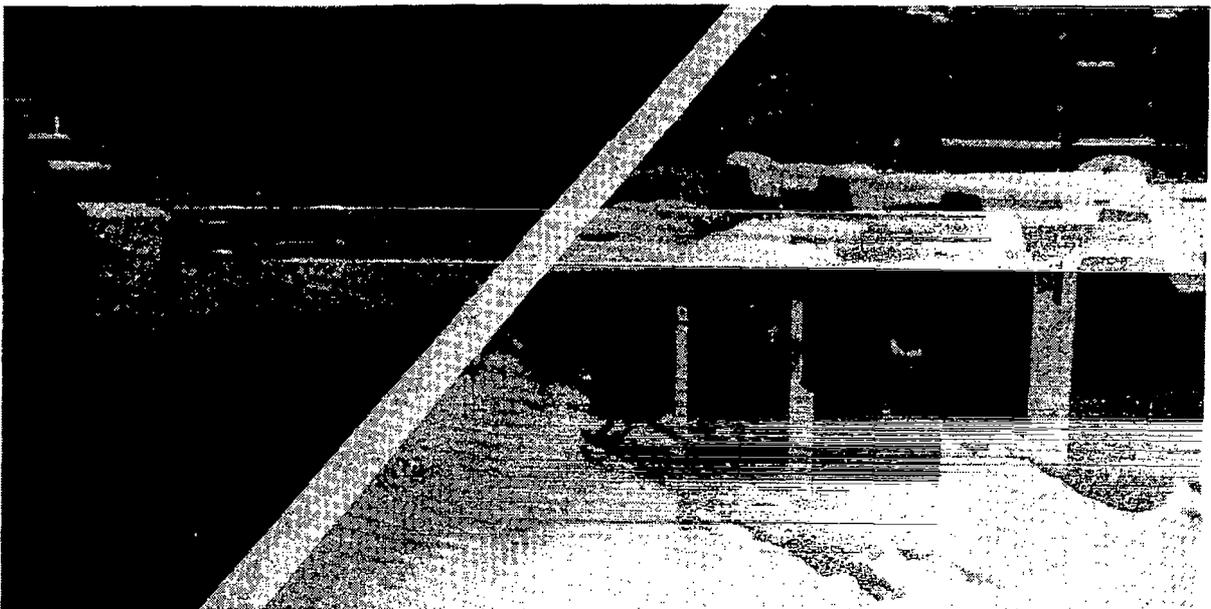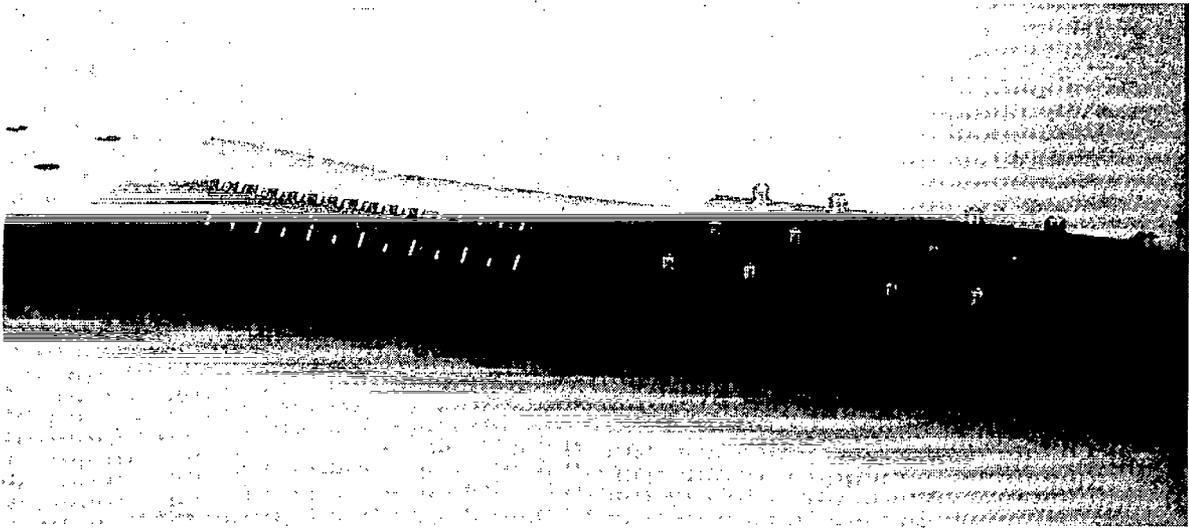

Figure 19.- Environmental fatigue tests on composites.

Figure 20.- Bolted joint for graphite-epoxy wing splice.
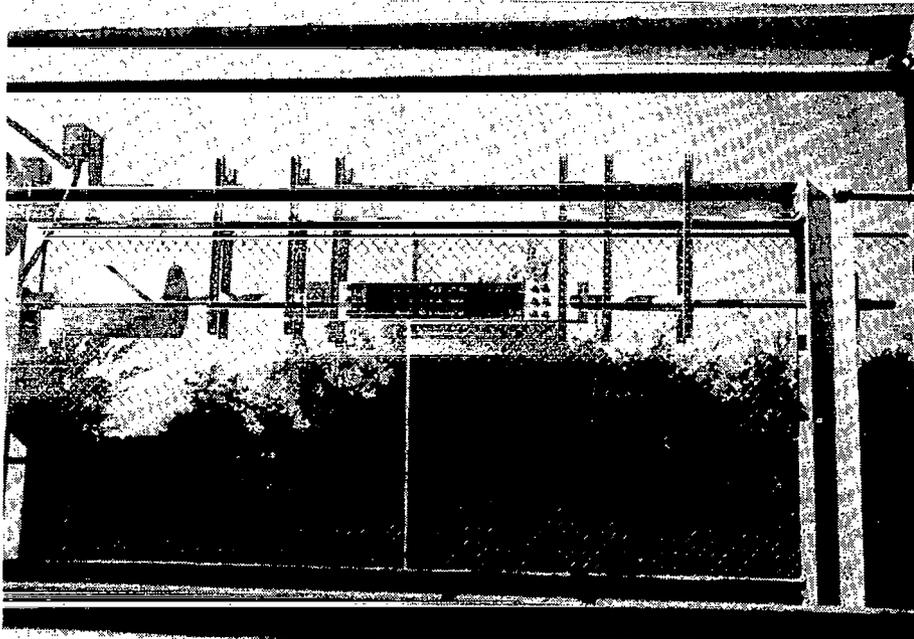

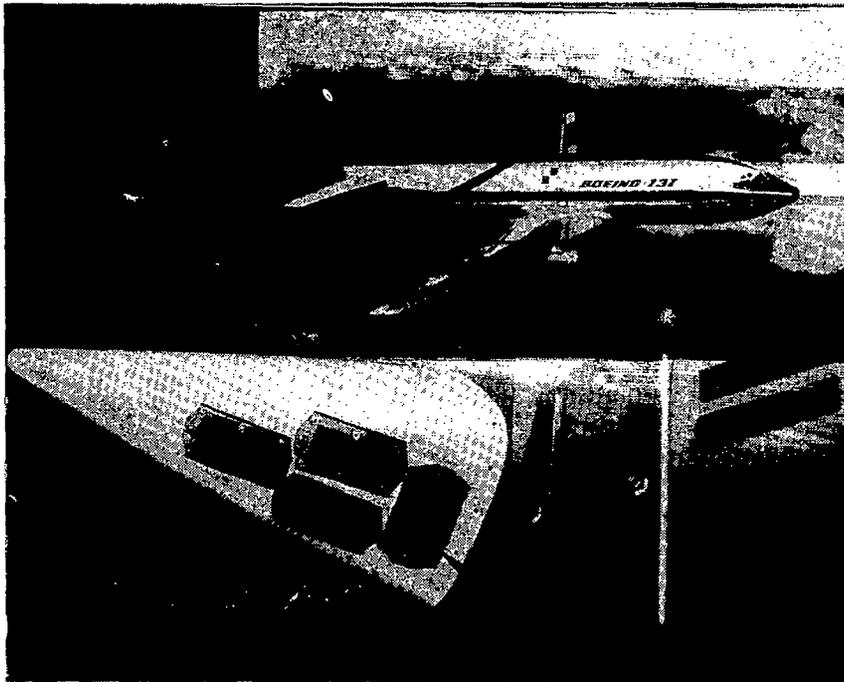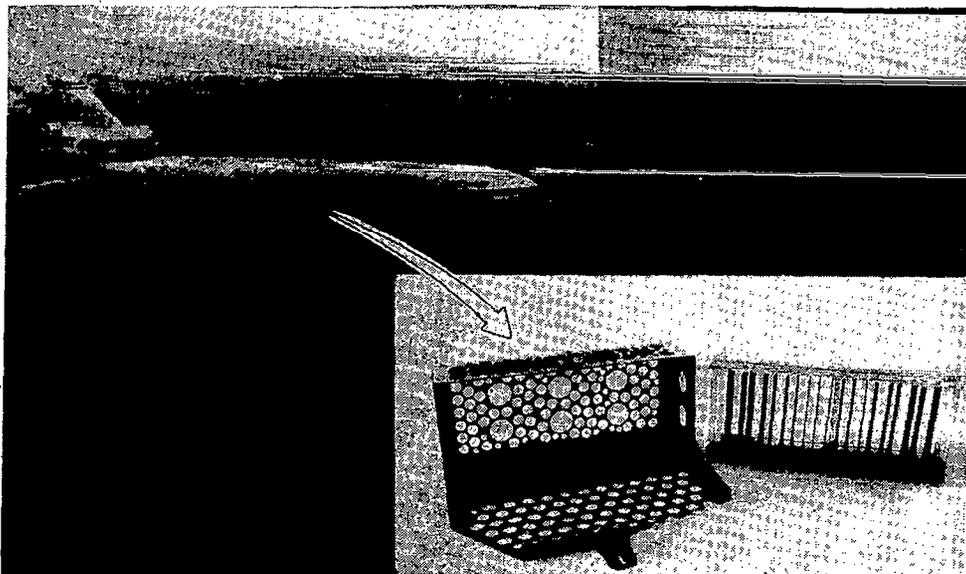Figure 21.- Wing splice environmental exposure.

Figure 22.- Exterior moisture pickup in flight.

Figure 23.- Interior moisture pickup in flight.