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Environmental Effects on the Strength of A Glass Fiber-Reinforced-Plastic Rod Material

Nixon Halsey and Leonard Mordfin

Engineering Mechanics Section
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Edward O. Vetter, *Under Secretary*
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Acting Director*

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ENVIRONMENTAL EFFECTS ON THE STRENGTH OF A GLASS FIBER-REINFORCED-PLASTIC ROD MATERIAL

by

Nixon Halsey and Leonard Mordfin

ABSTRACT

Environmental stress-rupture test methods were developed for studying the weatherability of materials under stressed exposure to marine atmospheres and intense sunshine. These laboratory test methods were applied to a coated, pultruded, glass fiber-reinforced-plastic rod product, with the marine atmosphere simulated by a saltwater fog and intense sunshine simulated by ultraviolet radiation. Static tests of the material, conducted both before and after the environmental exposures, were used to characterize both the as-received mechanical properties of the product and the reductions in tensile strength attributable to the weathering actions. The experimental results essentially confirmed the rod manufacturer's contention that the effects of sunlight and weathering on the product range from none to slight. For applications as antenna guys, the results suggest that the strength limitations imposed on rods by conventional end fittings, and by the fact that rods are frequently bowed rather than straight, tend to overshadow any strength reductions attributable to environments of the types considered here.

A failure analysis of a tower guy, fabricated from material of the type tested in this investigation, is given in an appendix.

Key Words: Antenna-support materials; environmental degradation; guys, nonmetallic; marine atmospheres; plastics, fiber-reinforced; pultrusions; stress-rupture testing; sunlight; ultraviolet radiation; weatherability.

1. INTRODUCTION

A factor which has limited the use of plastics in outdoor applications is their susceptibility to degradation under weathering conditions. One of the principal objectives of polymer research, therefore, has been the development of plastics with superior resistance to thermal, hydrolytic and photolytic degradation. Evaluations of the anticipated weatherability of plastics are most commonly accomplished through the use of accelerated laboratory tests which expose the materials to elevated temperature, high humidity, simulated rain, ultraviolet radiation, salt spray, etc. While it is recognized that a direct correlation does not exist between these intensified environments and true weathering conditions, experienced researchers have nonetheless been able to make reasonable predictions from the test results, particularly for comparative purposes. This approach, together with data derived from real-time outdoor weathering tests, has been adequate, for the most part, for the design of acceptable plastic components for those outdoor applications for which plastics have traditionally been used. Examples of such applications include patio furniture, rainwear and footwear, glazing, certain items of playground equipment, tarpaulins and pond liners, etc. In none of these applications is the plastic a structural member and the mechanical stresses to which it is subjected are either low or infrequent.

The rapid development of continuous-fiber-reinforced plastics has changed this picture. Plastics, heavily reinforced with oriented glass fibers, exhibit mechanical properties which make them attractive for structural, load-bearing members. Pultrusions, in particular, offer strength/weight characteristics that make them directly competitive with aluminum and steel extrusions and rolled sections for applications requiring unidirectional strength. Guys and guy insulators for antenna masts and towers are noteworthy examples, where the dielectric properties of glass-reinforced plastic provide an additional advantage over steel.

Quite understandably, most laboratory test methods which have been developed over the years for studying the weatherability of plastics (see, for example, ASTM Designations D756, D1499, D1501 and D2565 [1]*) are inadequate for structural plastics because they make no provision for applying mechanical stresses to the specimens while they are exposed to the simulated environments. It is logical to expect that the weatherability of reinforced plastics would be strongly influenced by the presence of substantial stresses.

In response to this deficiency, the National Bureau of Standards adopted an environmental stress-rupture test method as a means for studying the accelerated weathering characteristics of reinforced plastic guys and guy insulators. In this test method the specimens are subjected to constant, predetermined tensile loads while they are simultaneously exposed to simulated, severe environments. Prior to the investigation described herein, the environments examined in this way included elevated temperature and elevated temperature plus high humidity. The objective of the present investigation was to examine the effects of a simulated marine atmosphere and simulated sunshine on the long-term durability of a reinforced plastic guy material.

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*Numerals in brackets refer to similarly numbered references listed in Section 8 of this report.

This investigation was carried out in the Engineering Mechanics Section of NBS under the sponsorship and with the financial assistance of the United States Information Agency. The authors gratefully acknowledge the assistance of Messrs. Raymond G. Russell and Oscar O. Owens in the conduct of the program. The authors also extend their thanks to the Nupla Corporation, and to Mr. Elbert Davis in particular, for furnishing two pairs of their proprietary high-strength end fittings for use in this work.

The U.S.A. is a signatory to the General Conference of Weights and Measures which gave official status to the metric SI system of units in 1960. It is recognized, however, that the American manufacturers and users of reinforced plastic guys use U.S. customary units almost exclusively at this time. For the convenience of this group, therefore, U.S. customary units have been used in this report followed, in each instance, by the SI equivalent in parentheses. Factors for converting between the two systems may be found in the ASTM Metric Practice Guide [2].

2. MATERIALS AND FITTINGS

2.1 Specimen Material

The reinforced plastic rod material selected for use in this investigation is a 1/2-in (13-mm) diameter pultruded rod product which is widely used in antenna guying applications. According to the manufacturer, the product has been in production for more than ten years, during which time its composition remained essentially unchanged.

The rod consists of unidirectional, continuous E-glass (electrical grade) roving impregnated with a resin binder. The rod is coated for resistance to ultraviolet radiation. The roving consists of fibers that are nominally 0.00052 in (0.013 mm) in diameter (Type K). According to tests performed for the manufacturer by an independent laboratory, the roving has an average tensile strength of 206 000 lbf/in^2 (1420 MPa).

The resin binder is believed to be an orthophthalic polyester, based on maleic anhydride and propylene glycol, and cross linked with styrene.

The coating, nominally 0.005 to 0.015 in (0.1 to 0.4 mm) thick, is an epoxy resin heavily loaded with titanium dioxide.

Some of the rated properties of the rod materials, and the 1/2-in (13-mm) size in particular, are given in Tables 1 and 2 respectively.

Table 1 - Rated Properties of Rod Material [a]

Tensile strength	>100,000 lbf/in^2	(>690 MPa)
Modulus of elasticity in tension	6.34×10^6 lbf/in^2	(43.7 GPa)
Specific gravity	1.85 to 2.05	
Coefficient of thermal expansion	2.67×10^{-6} in/in/°F	(1.48 μm/m/°C)
Maximum operating temperature (continuous)	250°F	(120°C)
Water absorption in 24 h	0.02 percent by weight (mass)	
Effect of sunlight and weathering	none to slight	

[a] According to the manufacturer

Table 2 - Rated Properties of 1/2-in (13-mm) Diameter Rods [(a)]

Diametral tolerance	+0.062, -0.000 in	(+1.6, -0.0 mm)
Unit weight (mass)	0.17 lb/ft	(0.25 kg/m)
Glass content	77±3 percent by weight (mass)	
Minimum breaking strength:		
with standard fittings	20,000 lbf	(89 kN)
with special fittings	28,000 lbf	(125 kN)
Maximum elongation at 6700 lbf (30 kN)	0.7 percent	

[(a)] According to the manufacturer

2.2 End Fittings

One of the most critical features affecting the tensile load-carrying capability of a reinforced-plastic rod is the type of end fitting which is affixed to it and through which the load is applied to it. Five different types of end fittings were used in various parts of this investigation.

The Type R/V end fitting (Fig. 1) is a basket-type mechanical end fitting for reinforced plastic rod materials. It grips the rod with a spring-loaded jaw system contained within the conical basket. The jaws are, essentially, wedges of a segmented cone. The basket is fitted with a yoke and bail for attachment to thimble-eye type hardware. The basket and the yoke are aluminum alloy, the jaws and the bail are stainless steel. The Type R/V end fitting is available commercially. Its principal advantage is the ease and rapidity with which it may be installed.

The Type R/P end fitting (Fig. 2) is a basket-type, potted, conical compression fitting which is intended primarily for synthetic ropes. The outward appearance of this fitting is quite similar to that of the Type R/V end fitting. The conical basket, or potting head, is fitted with a yoke and bail for attachment to thimble-eye type hardware. The potting head and the yoke are aluminum alloy, the bail is stainless steel. The Type R/P end fitting is available commercially.

The aluminum-block end fitting (Fig. 3) is a potted compression fitting that was developed at NBS [3]. This fitting is 2-5/8 x 3-1/4 x 6 in (67 x 83 x 150 mm) long and is machined from 2024-T4 aluminum-alloy stock. The block is split in half longitudinally and bolted together, and then a conical cavity is machined out. The cavity is 2-1/4 in (57 mm) in diameter at the large end, tapering to a short cylindrical section 5/8 in (16 mm) in diameter.

The H3M end fitting (Fig. 4) is a more or less streamlined version of the aluminum-block end fitting that was also developed at NBS [4,5] in order to reduce the costs of machining and to facilitate its use in a testing machine. It consists of a single piece of 2024-T4 aluminum-alloy round rod, 2-3/4 in (70 mm) in diameter and 6-1/2 in (165 mm) long. The conical cavity is 2 in (51 mm) in diameter at the large end, tapering to a 1/2-in (13-mm) long cylindrical section that is 3/4 in (19 mm) in diameter.

The Type S end fitting (Fig. 5) is a proprietary industrial development. Like the Type R/P, the aluminum-block, and the H3M, it is a potted compression end fitting. It is machined with an integral clevis for attachment with hardened steel pins.

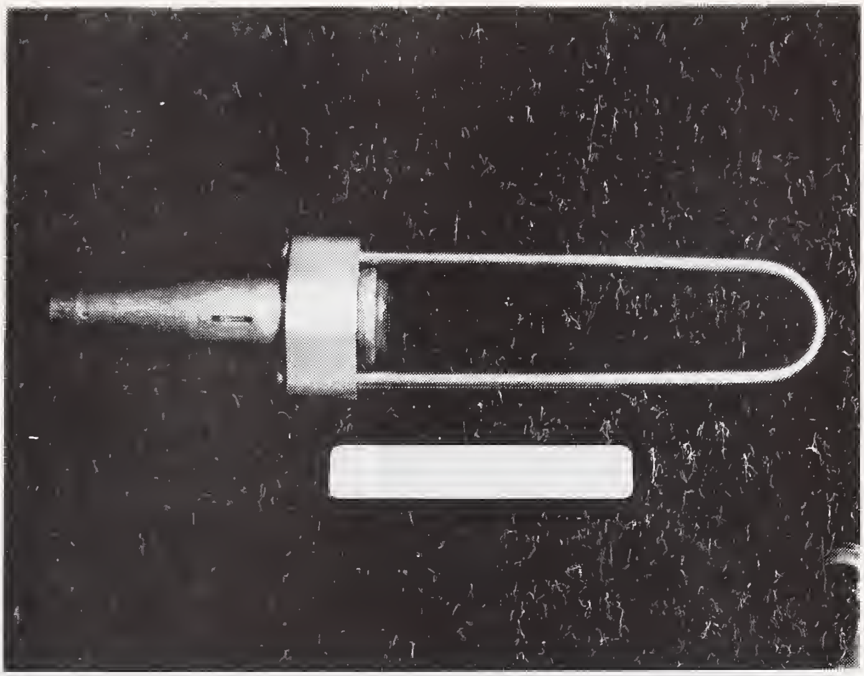

Figure 1. Commercially available, mechanical, compression type end fitting. (NBS designation: Type R/V.)

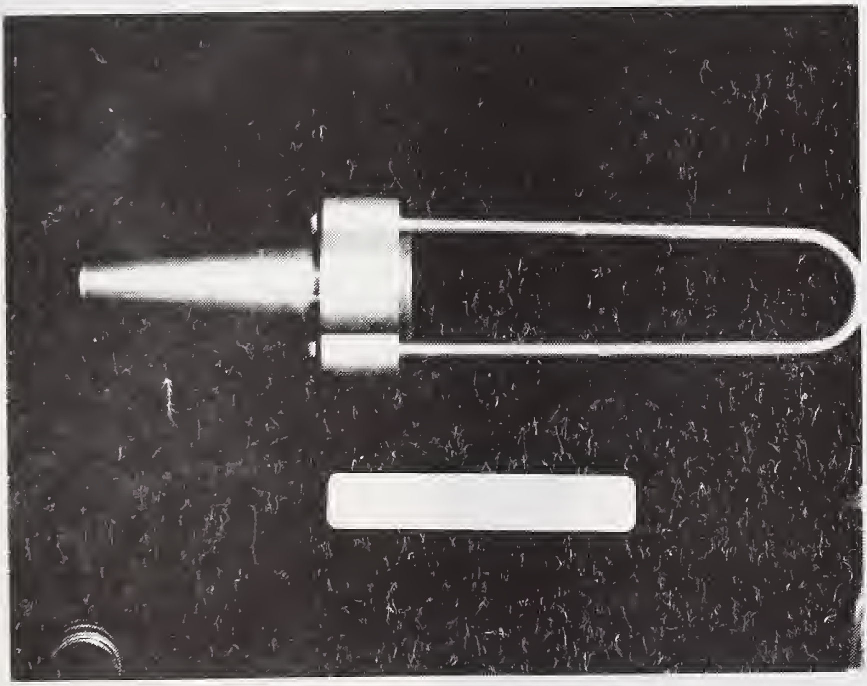

Figure 2. Commercially available, potted, compression-type end fitting. (NBS designation: Type R/P.)

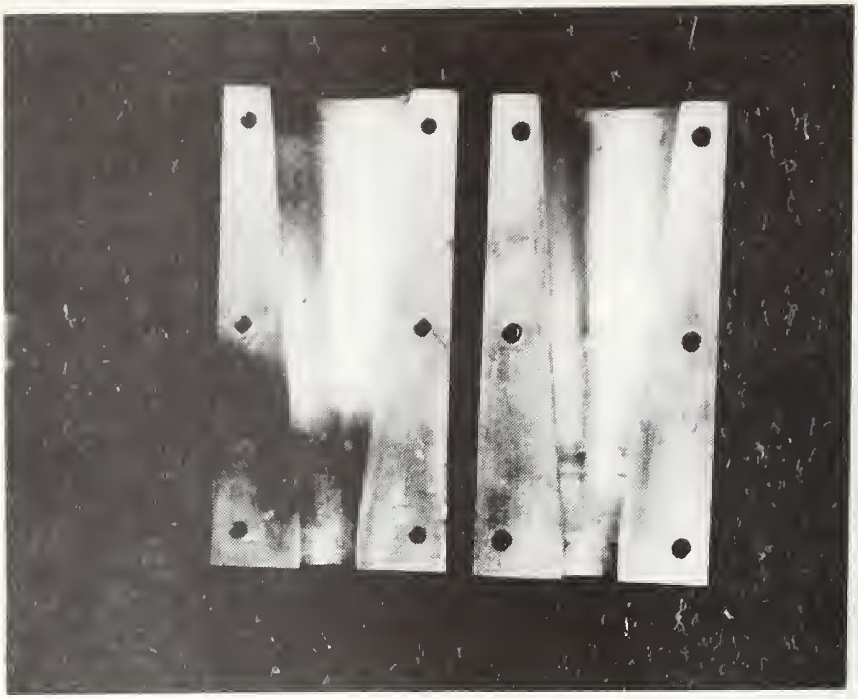

Figure 3. NBS aluminum-block end fitting.

Figure 4. NBS Type H3M end fitting.

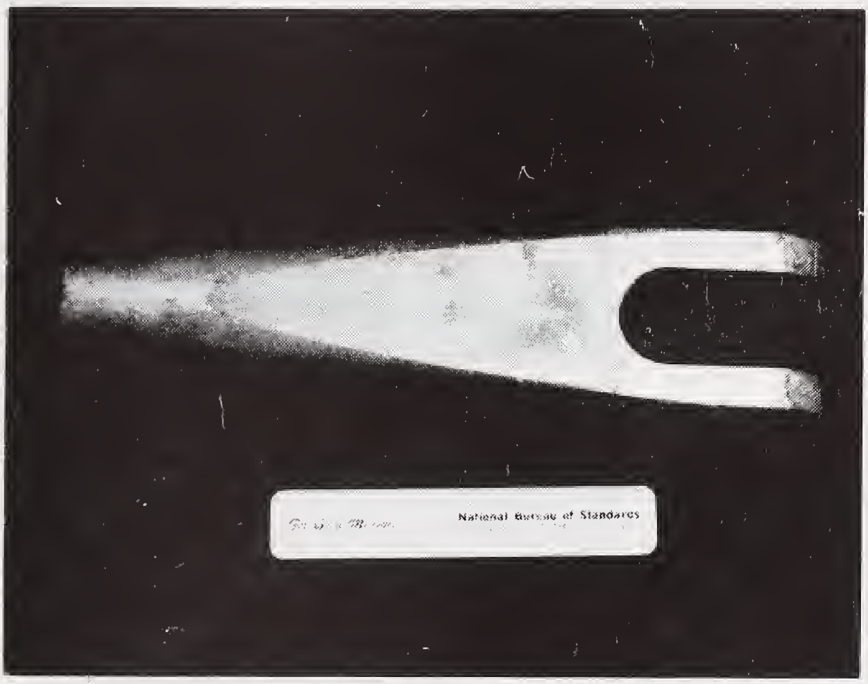

Figure 5. Proprietary, potted, compression-type end fitting. (NBS designation: Type S.)

2.3 Test Specimens

The test specimens were cut from long lengths of the rod material that had been procured in three different batches. A few exploratory tests were performed on specimens from a quantity of the rod material (Batch 0) that had been available in the laboratory as surplus from a previous investigation. Subsequently, a 300-ft (91-m) length of the rod material (Batch 1) was procured from the manufacturer in a continuous 7.7-ft (2.3-m) diameter coil. Finally, 324 ft (99 m) of the rod material (Batch 2) were procured from the manufacturer in 18-ft (5.5-m) lengths.

Specimens for use in tensile or stress-rupture tests consisted of lengths of the rod material with end fittings on the ends. The procedure for mounting any of the four different kinds of potted compression end fittings was essentially the same. The surface of the potting cavity in the end fitting was first treated with an epoxy-release agent. The fitting was slipped over the end of the rod and a fluted, cruciform wedge (Fig. 6) was driven into the end of the rod, axially and concentrically. This divided the rod end into four quarters. The circumference of the rod, where it emerged from the end fitting, was built up with tape to provide a seal with the fitting. The rod was then alined concentrically and parallel with the fitting, in a vertical orientation, and the potting cavity was filled with a high-strength, flexible potting compound developed previously [4] to meet the needs of this specific application. The compound consists of two parts of a fully reactive epoxy resin adhesive and three parts of an activator. The mixture was cured in place, with infrared lamps, for approximately 2 h at 165 °F (74 °C).

The lengths of the tensile specimens were approximately 4 ft (1.2 m) between end fittings. The lengths of the stress-rupture specimens were approximately 9 ft (2.3 m) overall.

3. PRELIMINARY TESTS AND MEASUREMENTS

Several series of tests and measurements were performed on specimens of the rod material from Batches 1 and 2 in order to characterize the material.

3.1 Dimensional Measurements

The diameters, densities and unit weights (masses) were determined on samples of Batches 1 and 2. The results of these measurements are summarized here.

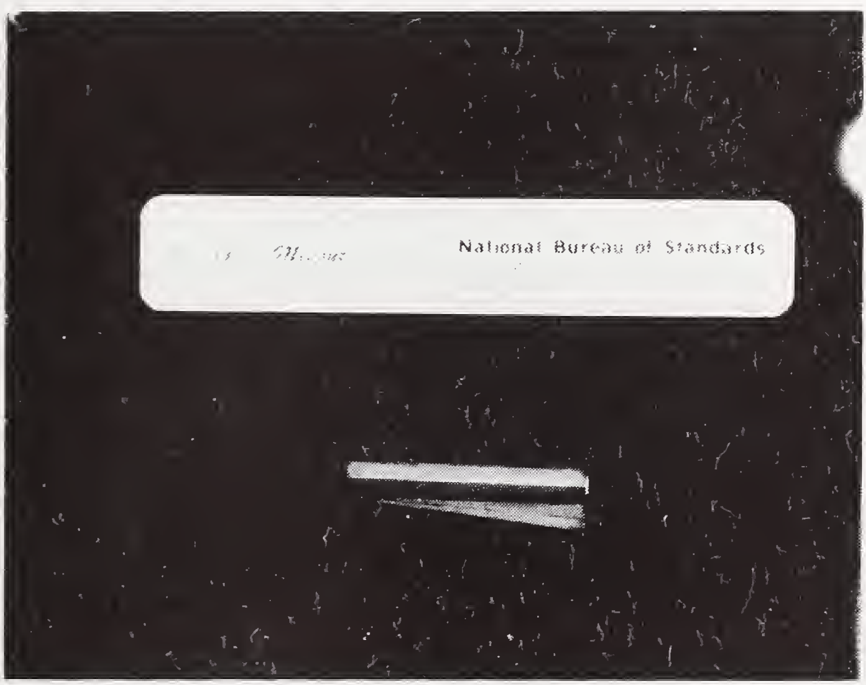

Figure 6. Commercially available cruciform wedge for potted, compression-type end fittings.

	Batch 1	Batch 2
Diameter, in	0.514 ± 0.002	0.540 ± 0.004
(mm)	(13.05 ± 0.05)	(13.71 ± 0.10)
Density, lb/in^3	0.074 ± 0.0005	0.0733 ± 0.0005
(Mg/m^3)	(2.05 ± 0.02)	(2.03 ± 0.02)
Unit weight, lb/ft	0.184 ± 0.001	0.200 ± 0.003
(Unit mass, kg/m)	(0.275 ± 0.001)	(0.298 ± 0.004)

Several conclusions may be drawn from these measurements. The material was quite uniform within each batch but there were significant differences between the batches. The diameters and the densities were within the ranges specified by the manufacturer (Tables 1 and 2)*, but the unit weights (masses) exceeded the rated value. (This finding is consistent with earlier measurements made on another batch of this material [6].) The diameter of Batch 2 was greater than that of Batch 1, but the density was less. This suggested that the quantity of glass reinforcement may have been the same in both and that the additional weight (mass) of Batch 2 consisted of resin binder. On this basis the tensile breaking loads of the two batches (which depend primarily on the quantities of glass reinforcement present) were expected to be essentially the same.

3.2 Tensile Tests

Tensile tests were performed to evaluate the static breaking loads of the rod from Batches 1 and 2. These tests were carried out in a horizontal, universal testing machine having a capacity of 100 000 lbf (450 kN) [7]. A crosshead speed of 0.75 in/min (0.32 mm/s) was used.

The results of these tests are given in Table 3. The results of the first two tests listed in the table are of questionable value since it was noted that the potting compound in the end fittings, for some unknown reason, had not cured properly. These tests, as well as all of the others on rod from Batch 1, all culminated in failures which initiated in an end fitting. Thus, it is probable that the full strength of the rod was not attained. The occurrence of this type of failure is attributed to the fact that the specimens were bowed. Batch 1, as noted earlier, was procured in a single 7.7-ft (2.3-m) diameter coil. Upon unraveling the coil it was found that the rod tended to remain in a coiled condition, exhibiting a residual radius of curvature of approximately 14 ft (4.3 m). It is virtually impossible to introduce a tensile force into a bowed rod uniformly and, under the action of the applied tensile loads, the rod specimens

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*Note that the density, in Mg/m^3, is numerically equal to the specific gravity.

Table 3 - Tensile Tests of Rod Specimens

Batch No.	Specimen No.	End fitting	Breaking load lbf	(kN)
1	TN1	H3M	21100	(93.9)
1	TN2	H3M	22150	(98.5)
1	TN3	H3M	24550	(109.2)
1	TN4	H3M	23450	(104.3)
1	TN5	Al-block	25400	(113.0)
1	TN6	Al-block	25100	(111.6)
2	NR1Pc1T1	H3M	20300	(90.3)
2	NR2Pc1T2	H3M	22600	(100.5)
2	NR2PcXT3	H3M	24850	(110.5)
2	NR2PcXT4	H3M	24450	(108.8)
2	NR2Pc7T5	H3M	25250	(112.3)
2	NR2Pc8T8[(a)]	S	23300	(103.6)

(a) This specimen had a free length of 6 ft (1.8m) rather than 4 ft (1.2m).

tended to straighten. This created longitudinal shearing stresses in the specimens, which caused them to split longitudinally, starting from a point inside one of the end fittings.

Because of this deficiency in the rod from Batch 1, which also caused difficulties in the stress-rupture tests (to be discussed later), the second batch of rod (Batch 2) was procured, this time in uncoiled lengths. Unfortunately, this material was also bowed, although not as severely as the material in Batch 1. Nevertheless, the degree of bowing was sufficient to cause all of the tensile tests of this material (Table 3) to also culminate in failures which initiated in the end fittings.

Table 3 shows that all of the rod specimens exhibited tensile breaking loads exceeding 20 000 lbf (89 kN), which is the manufacturer's rated value with standard end fittings. None of the specimens attained 28 000 lbf (125 kN), which is the manufacturer's rated value with special fittings. While this value possibly could have been reached with straight specimens that failed in their free lengths, it is also true that the highest breaking load ever achieved in this laboratory on 1/2-in (13-mm) diameter rod from this manufacturer is 26050 lbf (116 kN) [4]. This load was attained with a straight specimen of the rod material which was tested with aluminum-block end fittings and which failed in its free length. (It should be pointed out that the potting compound used in the end fittings for these tests was different from that which the rod manufacturer uses.)

3.3 Diametral Compression Tests

The dielectric strength of dry samples of rod, of the type studied in the present investigation, has already been shown [3] to be quite high in comparison with that of other glass-reinforced-plastic rod materials [8].

In an earlier study [9] it was shown that an approximate relationship exists between the dielectric strengths of wet samples of glass-reinforced-plastic rod materials and the transverse tensile strengths of the (dry) materials. The basis for this relationship appears to stem from the fact that the wet dielectric strength and the transverse tensile strength are both influenced by the quality of the fiber/matrix bond in the material. Since electrical properties as well as mechanical properties are important in antenna guying applications, measurements of transverse tensile strength were performed in the present investigation in order to obtain some indication of the wet dielectric strength of the rod product being studied.

An indirect measurement of the transverse tensile strength of glass-reinforced-plastic rod products can be obtained by means of diametral compression tests. In this well-known test method for brittle materials [10] a cylindrical disk-shaped specimen is compressed diametrically between two flat platens. Under the proper conditions [11] the test culminates in a tensile fracture along the loaded diameter, and the transverse tensile strength σ_t of the rod is calculated from the relation

$$\sigma_t = \frac{2P}{\pi D t}$$

where P is the compressive load at fracture, D is the diameter of the disk and t is its thickness.

Disk specimens, approximately 1/4 in (6 mm) thick, were sliced from the rods using a water-cooled, diamond cutoff saw. Care was taken during this cutting process to prevent fraying of the edges. The coolant was carefully blotted from the disks which were then allowed to dry, under ambient laboratory conditions, for at least 24 h prior to testing. The diameter and thickness of each specimen were measured, and the specimen was mounted, on edge, in a compression subpress [12] and loaded to fracture in a universal testing machine.

The results of these tests are given in Table 4. Although the variability of the test results was greater for Batch 2 than for Batch 1, the average transverse tensile strengths of the two batches were not excessively inconsistent, i.e., 1740 lbf/in^2 (12.0 MPa) for Batch 1 versus 1600 lbf/in^2 (11.0 MPa) for Batch 2*. The difference between these two values is not particularly significant in view of the test-to-test variabilities observed. On the basis of the relationship discussed above, these values suggest that the rods had wet dielectric strengths within the range observed for other glass-reinforced-plastic rod materials.

3.4 Hardness Measurements

Hardness measurements were made on samples of the rod product using Procedure A of ASTM Designation D785 [1]. The measurements showed a hardness of 75 $\pm$ 4 for Batch 1 and 71 $\pm$ 5 for Batch 2, on the Rockwell E scale. Ordinarily, hardness measurements of this kind can be used to give some indication of the degree of cure in plastics products. However, since the rod product was coated, the measurements in this case reflected the hardness of the coating and gave no meaningful indication of the degree of cure of the resin binder in the rod.

4. ENVIRONMENTAL STRESS-RUPTURE TESTS

4.1 Testing Equipment

As pointed out in the Introduction, environmental stress-rupture tests were selected as the means to be used to assess the weatherability of the

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*The anomalously low value measured in Test No. 4 of Batch 2 (Table 4) was not included in the calculation of the average.

Table 4 - Diametral Compression Tests of Rod Specimens

Batch No.	Test No.	Transverse tensile strength	
		lbf/in^2	(MPa)
1	1	1590	(11.0)
1	2	1740	(12.0)
1	3	1720	(11.9)
1	4	1770	(12.2)
1	5	1570	(10.8)
1	6	1940	(13.4)
1	7	1830	(12.6)
2	1	1810	(12.5)
2	2	1540	(10.6)
2	3	1610	(11.1)
2	4	1030	(7.1)
2	5	1340	(9.2)
2	6	1660	(11.4)
2	7	1620	(11.2)
2	8	1900	(13.1)
2	9	1340	(9.2)

rod product. These tests were performed in a series of creep-testing machines (Fig. 7) that had been designed and assembled earlier for environmental stress-rupture testing [4]. Each of these machines has a tensile load capacity of 30 000 lbf (130 kN), which is applied by dead weights (masses) acting through a 100:1 compound lever system. Specimens up to 9 ft (2.7 m) long, including the end fittings, can be accommodated. The overall height and length of each machine are approximately 7 ft (2 m) and 12 ft (4 m), respectively.

Each machine may be equipped with any of a variety of test chambers for providing the required environment to the test specimen while it is under tensile load. The housing for each of the test chambers used in this investigation consisted of a 10-in (0.25-m) diameter asbestos-cement pipe, 4 ft (1.2 m) long. The specimen passes concentrically through the chamber with its ends, including the end fittings and the pull rods, remaining outside the chamber. Three types of chambers were employed; one for providing elevated temperature, one for providing a simulated marine atmosphere, and one for simulating the damaging effects of sunshine.

The elevated temperature chamber contains a brass tube, mounted concentrically, which extends nearly the full length of the chamber. The ends of the chamber are fitted with transparent plastic windows. The purpose of the brass tube and the end closures is to provide more uniform temperature distributions on specimens. Heat was supplied by twelve tubular infrared lamps affixed to the inside of the asbestos-cement pipe, outside of the brass tube. Each lamp had a capacity of 500 W at 120 V. The temperature distribution in the chamber was kept uniform within 2 °F (1 °C) by regulating the power to the lamps. The test temperature was maintained constant within 5 °F (3 °C) with a temperature controller.

A marine atmosphere was simulated by means of a saturated-humidity salt-fog environment. The test chamber for this purpose was identical to the elevated-temperature chamber except that an atomizing nozzle was passed through a small hole in one of the plastic windows. The nozzle was powered by a pneumatic mist generator and delivered a soft, finely divided spray of saltwater to the interior of the chamber. The nozzle was directed so that the spray did not impinge directly on the specimen. The saltwater supply for the mist generator was a standard solution [13, 14], prepared by dissolving 5 parts by weight (mass) of sodium chloride in 95 parts of distilled water. The rate of consumption of the solution was adjusted by regulating the air flow rate to maintain a light film of condensate on the windows of the chamber. The chamber was operated at an elevated temperature of 125 °F (52 °C) for reasons which will be explained later.

It has been established, from both theoretical considerations [15] and experimental measurements [16], that the degrading effect of sunshine on plastics is due, almost entirely, to that portion of the solar spectrum that lies in the near ultraviolet range. For this reason sunshine was

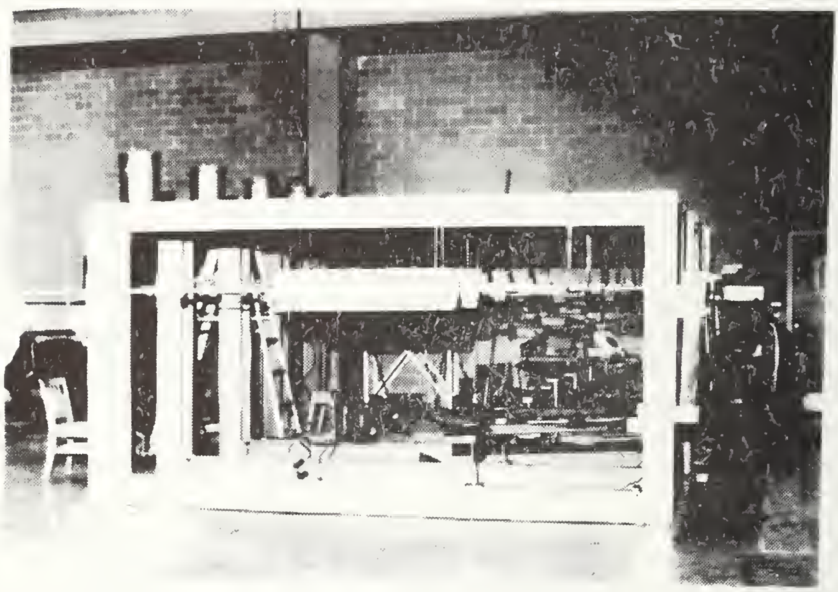

Figure 7. NBS high-capacity creep-testing machines equipped for environmental stress-rupture testing.

simulated, in this study, by ultraviolet radiation. The test chamber consisted of twelve 48-in (1.2-m) tubular fluorescent lamps uniformly spaced around, and affixed to, the inner surface of the asbestos cement pipe. Six of the fluorescent lamps were sunlamps, and were mounted alternately with six blacklight lamps. The peak spectral emission of the sunlamps is at a wavelength of approximately 310 nm* and that of the blacklights is at 350 nm [17]. By combining the two kinds of lamps a total spectral distribution is obtained that closely approximates the solar spectrum in the ultraviolet region below 360 nm [18], where the peak activation spectra of most polymers, including polyesters (325 nm), lie [19].

The ultraviolet energy impinging upon the test specimen was monitored with a commercial ultraviolet intensity meter that is sensitive to wavelengths from 300 to 400 nm. It was found that the energy distribution was quite uniform over the surface of the specimen within the chamber. At the start of a test the intensity averaged about 10.3 mW/in^2 (16 W/m^2). This value diminished to about 9.7 mW/in^2 (15 W/m^2) after 2000 h due to normal deterioration of the lamps. New lamps were installed at the start of each test.

Since fluorescent lamps emit a small amount of infrared energy, no windows were used on the ends of the test chamber in order to minimize heating effects. In this way the temperature of the specimen was observed to remain at about 150 $\pm$ 5 °F (66 $\pm$ 3 °C) throughout each test.

4.2 Tests and Results

In an earlier study of the stress-rupture properties of the rod product, which was limited to tests of relatively short duration, it was concluded that humidity did not have a seriously damaging effect on the durability of the material [6]. Later work on other rod products, using tests of longer duration, tended to refute this conclusion, however, [9]. It is now believed that humidity does, indeed, have a degrading effect but that the effect becomes significant only after a period of time sufficient to allow a substantial amount of moisture to diffuse into the interior of the product where it can attack the fiber/matrix interfaces. For this reason the environmental stress-rupture tests in the present program were allowed to run for 2000 h before termination unless, of course, failure occurred sooner.

The original test plan called for tests to be performed in the ambient laboratory atmosphere, as well as in a simulated marine atmosphere and simulated sunshine, to provide baseline data for evaluating the degradation

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*1 nanometer (nm) = 10 angstroms

attributable to the latter two environments. The test conditions and results are given in Table 5 and are discussed below.

Tests Series No. 1. Three exploratory tests, in air, were performed on specimens from Batch 0 while awaiting delivery of the material procured specifically for this investigation. The first two of these tests were carried out in the ambient laboratory atmosphere. Following this it was learned that the laboratory heating and air conditioning system would be shut down during evenings and weekends as part of the Bureau-wide energy conservation program. Recognizing that this could introduce some serious temperature fluctuations in the laboratory environment, it was decided to conduct all subsequent "ambient" tests at a temperature of 80 °F (27 °C), which is about the lowest elevated temperature which can be maintained uniformly with the elevated-temperature environmental chamber.

The first two tests in this series, conducted at 16 000 lbf (71 kN) using Type R/P end fittings, culminated in failures which initiated in the fittings. Since failures of this kind do not necessarily provide an indication of the durability of the specimen material itself, the third test was performed with H3M end fittings. This test was terminated after 2000 h without any evidence of damage in the specimen and, although it was conducted at a lower load level (15000 lbf, 67 kN), it suggested that the H3M fittings would be preferable, in this application, to the Type R/P fittings.

At this point the Batch 1 material arrived and further testing of Batch 0 material was discontinued.

Test Series No. 2. Tests were performed on Batch 1 specimens in air, at 15 000 and 14 000 lbf (67 and 62 kN), using H3M end fittings. The test at 15 000 lbf (67 kN) culminated in a failure in one of the end fittings which appeared to have been induced by the bow in the rod. This confirmed the observations in the tensile tests (Section 3.2) and led to the procurement of Batch 2 and the abandonment of further testing on Batch 1.

Test Series No. 3. As pointed out earlier, the rod material in Batch 2 was also bowed and, as it turned out, this precluded the attainment of failures within the free lengths of these specimens in the stress-rupture tests. Five tests were performed in this series using three different types of end fittings but failure in each case initiated in an end fitting.

Test Series No. 4. In a further attempt to obtain meaningful stress-rupture data for the material in an air environment four more tests were performed, this time using an environmental temperature of 125 °F (52 °C). Since the end fittings in these tests remain outside of the environmental chamber it was felt that this change might enable failures to be obtained in the free lengths of the specimens. Such was not the case but some

Table 5 - Environmental Stress-Rupture Tests of Rod Specimens

Batch No.	Specimen No.	End fittings	Environment	Specimen temperature	Tensile load	Test duration	Notes
				°F (°C)	lbf (kN)	h	
			Test Series No. 1				
0	0-1	R/P	air	ambient	16000 (71)	0.1	a
0	0-2	R/P	air	ambient	16000 (71)	1.4	a
0	0-3	H3M	air	80 (27)	15000 (67)	2039.	b
			Test Series No. 2				
1	SRN2	H3M	air	80 (27)	15000 (67)	634.7	a
1	SRN1	H3M	air	80 (27)	14000 (62)	2021.	b
			Test Series No. 3				
2	NR2Pc2SR1	H3M	air	80 (27)	15000 (67)	23.3	a
2	NR2Pc3SR3	R/P	air	80 (27)	15000 (67)	33.0	a
2	NR2Pc2SR2	R/P	air	80 (27)	14000 (62)	166.7	a
2	NR2Pc3SR4	R/P	air	80 (27)	14000 (62)	<24.	a,c
2	NR2Pc5SR5	R/V	air	80 (27)	14000 (62)	0.2	a
			Test Series No. 4				
2	NR2Pc4SR6	R/P	air	125 (52)	12000 (53)	1054.	a
2	NR2Pc4SR7	R/P	air	125 (52)	13000 (58)	2087.	b
2	NR2Pc9SR10	S	air	125 (52)	14000 (62)	2234.	b
2	NR2Pc9SR11	S	air	125 (52)	15000 (67)	2160.	b
			Test Series No. 5				
2	NR2Pc7SR8	R/P	salt fog	125 (52)	13000 (58)	2214.	b
2	NR2Pc12SR13	H3M	salt fog	125 (52)	15000 (67)	2036.	b

(continued)

Table 5 (continued)

Batch No.	Specimen No.	End fittings	Environment	Specimen temperature °F (°C)	Tensile load lbf (kN)	Test duration h	Notes
			Test Series No. 6				
2	NR2Pc6SR9	R/P	ultraviolet	150 (66)	13000 (58)	2266.	b
2	NR2Pc12SR12	S	ultraviolet	150 (66)	15000 (67)	108.9	a
2	NR2Pc11SR14	S	ultraviolet	150 (66)	15000 (67)	1249.	a

a. Failure initiated in an end fitting.
b. Test discontinued without failure.
c. Timer malfunctioned.

degree of success was nevertheless achieved. It was found, by using the Type S end fittings, that the rod material was capable of sustaining a tensile load of 15 000 lbf (67 kN) at 125 °F (52 °C) for 2000 h without any visible evidence of damage or deterioration. This is consistent with earlier findings [6] which indicated long-term stress-rupture strengths of 16000 lbf (71 kN) at room temperature and 14000 lbf (62 kN) between 150 and 200 °F (66 and 93 °C) for this product.

Test Series No. 5. In order to facilitate comparisons with the stress-rupture tests in air, the stress-rupture tests in a salt-fog environment were also performed at 125 °F (52 °C). Two tests were performed, one at 13000 lbf (58 kN) with Type R/P end fittings and one at 15000 lbf (67 kN) with H3M end fittings. Both tests were terminated after 2000 h without failure. Upon removal of the test specimens from their environmental chambers it was observed that the specimen which had been tested at the lower load level exhibited evidence of damage. In two locations near the midlength of this specimen the coating had begun to split away, longitudinally, taking some glass fibers with it. Strangely, the specimen which had been tested at the higher load exhibited no signs of damage. On the basis of the evidence available it is not clear whither the damage in the specimen tested at 13000 lbf (58 kN) was due to the simulated marine atmosphere or, simply, to the bow in the specimen. However, since none of the specimens which had been tested in air had exhibited damage of this kind although they too were bowed it is surmised that the simulated marine atmosphere had contributed, at least, to the observed damage.

Test Series No. 6. Three tests were performed with simulated sunshine at a specimen temperature of 150 °F (66 °C). This temperature is not at all unrealistic for a material exposed to direct sunlight in many parts of the world [20]. At a tensile load of 13000 lbf (58 kN) the specimen survived the entire 2000-h exposure. Upon removal of this specimen from the environmental chamber it was observed to have experienced no visible mechanical damage but the coating on the rod material, which had originally been white and glossy, had become dull and pale yellow. Two tests performed at 15000 lbf (67 kN) culminated in fractures which appeared to have initiated in the end fittings due to the bow in the specimens. There was no evidence that these failures had been accelerated by the simulated sunshine environment.

5. RESIDUAL STRENGTH TESTS

Each specimen which survived the 2000-h environmental stress-rupture tests was subjected to a tensile test to measure its residual strength. These tests were performed at the same crosshead speed and in the same testing machine as had been used for the tensile tests on virgin specimens. In this case, however, the specimens were 9 ft (2.3 m) long and were tested with the end fittings that had been affixed for the environmental stress-rupture tests. The results of these tests are given in Table 6.

Table 6. Residual Strength Tests of Rod Specimens.

Batch No.	Test Series No.[a]	Specimen No.	Breaking load lbf	(kN)
0	1	0-3	24500	(109.0)
1	2	SRN1	24350	(108.3)
2	4	NR2Pc4SR7	24250	(107.9)
2	4	NR2Pc9SR10	23700	(105.4)
2	4	NR2Pc9SR11	22400	(99.6)
2	5	NR2Pc7SR8	23100	(102.8)
2	5	NR2Pc12SR13	25750	(114.5)
2	6	NR2Pc6SR9	21750	(96.7)

(a) Refers to environmental stress-rupture test series in Table 4.

Failure, in every test but one, initiated in an end fitting and appeared to have been induced by the bow in the specimens. In the test of Specimen No. NR2Pc7SR8, which had sustained some surface damage during its salt-fog exposure, failure initiated at this damage site. In every case but one the residual tensile strength was found to lie within the range of strength values measured on virgin specimens (Table 3). The exception, Specimen No. NR2Pc12SR13, exhibited a residual tensile strength in excess of the values measured on virgin specimens. It must be concluded, therefore, that the degradation of the specimens, due to their stressed environmental exposures, was not great, at least in terms of its effects on tensile strength.

6. DISCUSSION

It is widely recognized that a direct correlation does not generally exist between the results of accelerated laboratory tests in simulated environments and real-time performance in outdoor weathering situations. Within this limitation, however, some general observations can be made regarding the implications of the test results on the durability of antenna-support systems in field installations.

A very minimal amount of evidence was obtained which suggests that the laboratory salt-fog environment may have caused some degradation of the product in 2214 hours while under a tensile load of 13 000 lbf (53 kN). This salt-fog environment was probably more severe than any marine atmosphere which might be encountered in service. The humidity was maintained at saturation level and the temperature was held at 125 °F (52 °C). These conditions produced a more extensive deposition of salt on the rod and greater diffusion of saltwater into the rod than would be the case in the field. Thus, it is logical to expect that whatever degradation was experienced in the laboratory would be attained in service only after an exposure time substantially greater than 2214 hours (0.25 years) while carrying the same tensile load.

The simulated sunshine tests revealed no evidence of strength degradation in the rod even after 2266 hours while carrying a tensile load of 13000 lbf (58 kN). In fact, there was some evidence that this exposure actually raised the tensile strength of the product, presumably by post curing the resin binder in the rod. Calculations in Appendix A show that, in terms of total incident ultraviolet radiation, this exposure was equivlent to that which would be experienced by an antenna guy in 2.5 years in Puerto Rico or in 5.6 years in Alaska.

Of even more significance, perhaps, than the severity of the simulated environments was the magnitude of the tensile loads which the specimens were able to carry for more than 2000 hours in these environments. These tensile loads (13000 lbf, 58 kN) were substantially higher than those which would ordinarily be used in field installations on a continuous basis. The rod manufacturer recommends a working load of only 6700 lbf (30 kN); there is evidence that even lower loads are actually used (see Appendix B). Stress-rupture behavior is extremely sensitive to load; small reductions in load characteristically produce large increases in time to rupture. It is not at all unreasonable to expect, therefore, that whatever damage was incurred in 2000 hours at 13 000 lbf (58 kN) would not be incurred at half this load level until an exposure many times longer had been sustained.

In planning the test program described herein it had been hoped to acquire definitive data on the effects of certain severe environments on the strength of a pultruded rod product. Unfortunately, this was not to be the case. The inability to accurately measure the strength of the product, in tensile as well as in stress-rupture tests, precluded the attainment of the original objective. In every case but one, failure in the test specimens resulted from the bow in the rod and/or from the inability of the end fittings to allow the full strength of the product to be attained. In retrospect, however, this observation may, in fact, be of greater importance than the considerations discussed above.

In effect, the minor amounts of environmental degradation which the rod specimens experienced in this test program were rendered inconsequential by the strength limitations already introduced by the end fittings and by the bow in the rods. Two out of the three batches of material which were examined in this investigation were bowed and this suggests a reasonable likelihood that batches of the material procured for use in structural systems will also be bowed. Similarly, the types of end fittings which will be used on the rod material in structural systems, particularly in antenna-support systems, are not likely to be superior to those used in this investigation, in terms of their capability to allow the rods to resist high tensile loads. It appears, therefore, that in the design of such systems, the environmental degradation of the rod material due to a marine atmosphere or to intense sunshine need not be addressed explicitly so long as the effects of bow and the limitations of the end fittings are properly accounted for. One way of doing this is, simply, to base the design on the manufacturer's rated breaking strength value for rod with standard end fittings (Table 2) rather than on the true strength of the rod, whatever that might be. The breaking loads which were measured in twenty tensile tests in this investigation (Tables 3 and 6) on both virgin and environmentally exposed specimens using four different kinds of end fittings were, in every case, greater than this rated value (20 000 lbf, 89 kN). This is not to say that the working load should be set equal to the rated load--certainly, the long-term strength of the rod is less than its static tensile strength--but, rather, that the factor which has been used to establish the working load from the rated load need not be modified to compensate for degradation due to environments such as those examined here.

7. CONCLUSIONS

Environmental stress-rupture test methods were developed for studying the weatherability of materials under stressed exposure to a simulated marine atmosphere and simulated intense sunshine. These test methods were used to examine the environmental degradation of a coated, pultruded, glass fiber-reinforced-plastic rod product. The experimental results essentially confirmed the rod manufacturer's contention (Table 1) that the effects of sunlight and weathering on the rod product are "none to slight". These results suggest that for antenna guying applications, the strength limitations imposed on the rod by the use of conventional end fittings, and by the fact that the rod is frequently bowed rather than straight, tend to overshadow any strength reductions attributable to environments of the types considered here.

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APPENDIX A

Ultraviolet Radiation Calculations

Let q_1 be the ultraviolet radiation intensity which was incident upon the rod specimen in the simulated sunshine environmental chamber. Then the total ultraviolet energy which struck a length L of the specimen during a time interval t_1 was

$$U_1 = \pi D L q_1 t_1 \tag{A.1}$$

where D is the rod diameter. Using D = 0.5 in (12.7 mm) and q_1 = 10.0 mW/in^2 (15.5 W/m^2), and converting to consistent units, it is found that the total ultraviolet energy which impinged upon the specimen in 2266 h was 417 W.h per foot of rod length (4.93 MJ per meter of rod length).

Consider, now, an antenna guy rod in a real field application. Let q be the average intensity of solar radiation at this location on the earth's surface, and let f represent that fraction of this intensity which is concentrated in the ultraviolet range. Then the total ultraviolet energy which strikes a length L of the rod during a time interval t is

$$U = DLfqt\sin\theta \tag{A.2}$$

where θ is the angle between the sun's rays and the axis of the rod. Note that this relationship differs from Eq. (A.1) because in this case the energy incident on the rod is determined by the projected area of the rod normal to the sun's rays whereas in the environmental chamber the ultraviolet lamps radiate to the entire surface of the rod.

The fraction f has been variously estimated at 1 to 7 percent [21], 2 percent [16], 3 percent [22] and 5 percent [23]. The angle θ depends upon the orientation of the guy and the instantaneous location of the sun. When the rod is normal to the sun's rays sin θ is unity and when it points directly at the sun sin θ is zero. For long-term averages it is probably adequate, for present purposes, to take f as 0.04 and sin θ as 1/2. With these values and Eq (A.2) the total ultraviolet radiation which impinges on a unit length of guy rod over a one-year exposure in various locations may be calculated using available tabulations of q [23]. The results are as follows:

Location	Average intensity of solar radiation, q		Annual uv energy on unit length of guy, U	
	mW/in^2	(W/m^2)	W·h/ft	(MJ/m)
San Juan, P. R.	160	(248)	168	(1.99)
Las Vegas, Nev.	157	(244)	165	(1.95)
Washington, D. C.	109	(170)	115	(1.36)
Seattle, Wash.	94	(146)	99	(1.17)
Fairbanks, Alas.	71	(110)	75	(0.88)

APPENDIX B

Failure Analysis of a Tower Guy

During the course of the investigation, the sponsor submitted to this laboratory a segment of a tower guy that had failed in service [24]. The diameter (1/2 in, 13 mm) and the manufacture of the guy were nominally identical to those of the rods tested in this investigation.

The tower is located in the hot, moist climate of Thailand but, being situated about 60 miles (97 km) from the coast, it is not exposed to a marine atmosphere. It is supported by numerous guys in parallel pairs. The particular guy in question was 448 ft (137 m) long and was oriented at approximately 45 degrees to the horizontal. It was designed to carry a tensile load of 2000 lbf (8.9 kN) under static conditions and a peak dynamic load of 5575 lbf (24.8 kN) under full wind conditions.

During a routine inspection of the facility about six years after installation the guy was observed to have suffered a transverse crack, approximately 30 ft (9 m) from its upper end, which penetrated almost halfway through the rod cross section. The opposing surfaces of the crack were quite jagged and uneven, not at all resembling the hairline cracks that occasionally afflict materials of this kind. Clean longitudinal splits extended almost 3 ft (1 m) in both directions from the base of the crack. See Figure 8.

Since this particular guy, alone out of many, sustained damage it is considered unlikely that weathering was a significant causative factor. The absence of any evidence of burning in the vicinity of the crack tends to rule out the possibility that it was caused by a lightning strike.

On the basis of these observations, plus the fact that the longitudinal splits did not extend into the upper end fitting, it is considered likely that the transverse crack was the result of local damage inadvertently introduced prior to, or during, installation, or by impact with a stone or other missile after installation. However, being in a relatively inaccessible location, the crack was probably difficult to detect by routine inspections until the fatiguing action of wind-induced vibrations, coupled with the low longitudinal shear strength of the material, produced the longitudinal splits which enabled the crack to widen. Worn areas at the edges of the crack suggest that it had been subjected to rubbing, due to wind-induced vibrations, for a considerable length of time.

Largely as a matter of curiosity, hardness and diametral compression tests were conducted on samples cut from the guy rod. These tests showed an average hardness of 75 on the Rockwell E Scale and an average transverse tensile strength of 2400 lbf/in^2 (16.5 MPa). The hardness measurement, as pointed out earlier, is relatively meaningless since it was determined

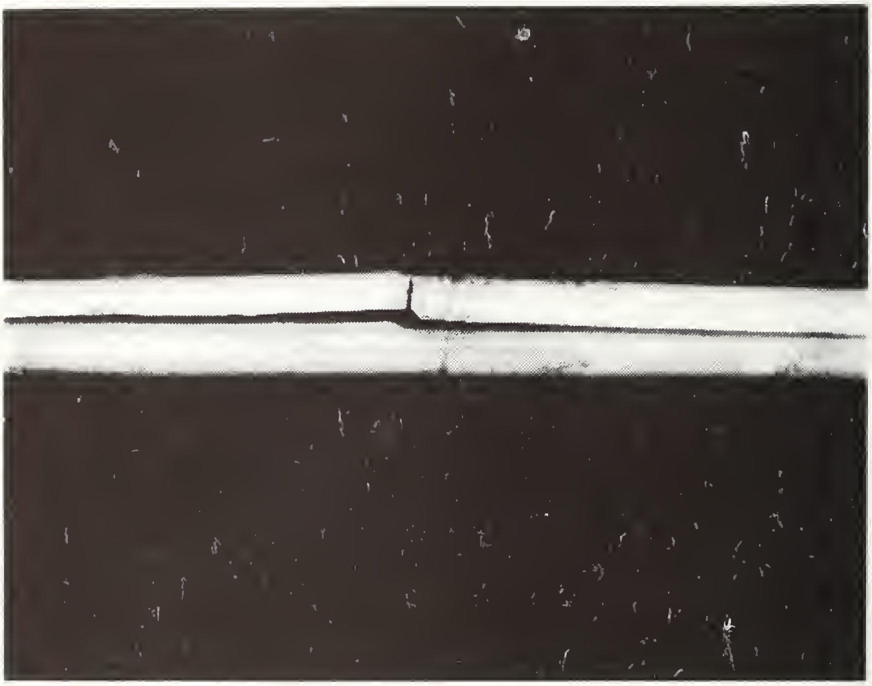

Figure 8. Failed section of glass fiber-reinforced-plastic tower guy.

on the rod's coating material rather than on the resin matrix. The transverse tensile strength value, on the other hand, is interesting because it is about 24 percent higher than the highest value measured on virgin material (Table 4). This is consistent with observations made on other guys which have been removed from service and suggests the existence of a natural curing process in the polyester matrix which apparently goes on for months or years after fabrication.

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Environmental stress-rupture test methods were developed for studying the weatherability of materials under stressed exposure to marine atmospheres and intense sunshine. These laboratory test methods were applied to a coated, pultruded, glass fiber-reinforce plastic rod product, with the marine atmosphere simulated by a saltwater fog and intense sunshine simulated by ultraviolet radiation. Static tests of the material, conducted both before and after the environmental exposures, were used to characterize both the as-received mechanical properties of the product and the reductions in tensile strength attributable to the weathering actions. The experimental results essentially confirmed the rod manufacturer's contention that the effects of sunlight and weathering on the product range from none to slight. For applications as antenna guys, the results suggest that the strength limitations imposed on rods by conventional end fittings, and by the fact that rods are frequently bowed rather than straight, tend to overshadow any strength reductions attributable to environments of the types considered here.

A failure analysis of a tower guy, fabricated from material of the type tested in this investigation, is given in an appendix.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Antenna-support materials; environmental degradation; guys, nonmetallic; marine atmospheres; plastics, fiber-reinforced; pultrusions; stress-rupture testing; sunlight; ultraviolet radiation; weatherability.

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