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# TESTING OF ADHESIVES AND POLYCARBONATE LENSES IN A SIMULATED MINE ENVIRONMENT

PART 4

FINAL TECHNICAL REPORT

Contract H0387009  
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16. Abstract (Limit 200 words) A testing program was conducted to determine the suitability and reliability of adhesives and polycarbonate (PC) lenses for extended use in luminaires in mine environments. Polycarbonates were exposed, for periods up to 36 months, to four environments including ultraviolet light, humidity, intermittent water spray, and heat of either 180° F or 240° F in various combinations. Izod impact tests on the exposed lens material indicated that polycarbonate functions well under all 180° F environments and could be used with confidence for periods exceeding the test period, for as long as 10 years, with a suitable safety factor employed in design. The specimens exposed at 240° F showed decreased toughness after 24 months' exposure. Extrapolation of these data was deemed to be risky. A 462-day compatibility test between polycarbonate and six hydraulic fluids was run on stressed PC beams. One fluid caused beam breakage in less than 1 day, while three caused breakage at intermediate times. Two fluids exhibited essentially no effect on the PC when compared with a control. Epoxy and silicone adhesives were tested as lens adhesives and sealants. Three epoxy combinations tested showed low and erratic failure stresses. A room-temperature-cure silicone adhesive functioned extremely well for time periods up to 36 months and temperatures up to 240° F.				
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## FOREWORD

This report was prepared by Southwest Research Institute, Division of Engineering & Materials Sciences, San Antonio, Texas, under USBM Contract Number H0387009. The contract was initiated under the Health and Safety Technology Program. It was administered under the technical direction of the Pittsburgh Research Center with Mr. Lawrence W. Scott acting as Technical Project Officer. Mr. Joseph A. Gilchrist was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period September 1981 to February 1985. This report was submitted by the authors in November 1985.

The authors gratefully acknowledge the leadership and guidance given to the project by Mr. Lawrence W. Scott of the USBM.

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## EXECUTIVE SUMMARY

Explosion-proof luminaires require transparent windows or lenses capable of withstanding (1) dynamic pressures generated by methane gas explosions inside the enclosures, (2) high temperatures generated by electric lamps located inside the enclosures, and (3) ultraviolet radiation generated by fluorescent and discharge-type light sources. In addition, the windows must tolerate immersion in water and contact with hydraulic fluids without the initiation of cracking.

Glasses and borosilicate glasses, in particular, have been found to be excellent for construction of windows in explosion-proof enclosures, as the physical properties of glass meet all of the operational requirements. In addition, glass retains its original physical properties for time periods in excess of 20 years even though being subjected continuously to high temperature, moisture, ultraviolet radiation, and hydraulic fluids.

A different case presents itself when the windows are fabricated from plastics. Not only are the physical properties of plastics dependent upon temperature, but they can also be affected by the ambient atmosphere (i.e., water vapor, hydrocarbons). In addition, exposure to heat and UV radiation degrades plastics so that their structural performance may become unacceptable in a very short period of time. Since the rate of aging is a function of temperature, exposure to UV radiation, and composition of the ambient atmosphere, the useful life span for a window fabricated from a particular plastic may vary by a factor of 10, depending on the actual operational environment. Thus, with plastic windows, the accidental replacement of a burned out lamp with a lamp of higher power rating may be catastrophic, as the increase in ambient temperature will not only decrease the pressure rating of the window, but also its rated life span. These same comments are applicable to the adhesives which are used to bond or seal windows in enclosures; however, the adhesives are usually more protected from the environment (except for heat) than the plastic windows and may be less highly stressed.

It is clear from the foregoing discussion that the effect of environmental factors on plastic lenses and adhesives is very important from the standpoint of reliability in Schedule 2G enclosures with windows. The purpose of this task was to establish an accelerated aging test program by which one could determine the short- and long-term effects of the mine environment on plastic lenses and adhesives. The purpose of the tests was to qualify window and lens materials for use in the mine environment and to provide data so that an allowable service life can be established.

Under a previous contract, USBM Contract H0377052, a study was made of candidate plastics for luminaires. Polyarylates were believed to have the best combination of properties because of the relatively high service temperature and good UV resistance. Polycarbonates were the second choice, but because they were already in use in mines, it was believed to be of more importance to test them and defer polyarylate testing.

Accordingly, test equipment was fabricated and assembled under Contract H0377052. Testing was begun with the present contract.

Polycarbonate lenses, clamped in representative enclosures, were subjected to single and multiple exposure environments of elevated temperature, ultraviolet light and humidity. Temperatures of 180°F and 240°F were used. Some exposures were as long as 36 months, but most of them were at 24 months or less. Many mechanical failure criteria were tried to quantify the data. Izod impact testing was chosen because it measured material degradation in loading and failure modes similar to that of lenses in luminaires.

The results indicated that heat was the major factor in degradation of the lenses. At 180°F, the degradation was not great up to 36 months' exposure. It is recommended that lenses in 180°F environments have a service life of 48 months, while imposing a strength reduction for design purposes to 0.70 of the strength of virgin material. On the other hand, the deterioration of polycarbonate at 240°F was such that service life should be limited to 24 months with a design strength reduction to 0.49 of the virgin material value.

Exposure of polycarbonate to hydraulic fluids indicated rapid attack by certain fluids and no attack by others. Since the fluids were designated by code, no overall conclusion about suitable fluids can be made.

Epoxy adhesives were found not to be adequate for the installation of lenses. A silicone adhesive was found to be quite good as an adhesive and sealer.

## 1.0 INTRODUCTION

### 1.1 Problem Description

Explosion-proof luminaires require transparent windows or lenses capable of withstanding (1) dynamic pressures generated by methane gas explosions inside the enclosures, (2) high temperatures generated by electric lamps located inside the enclosures, and (3) ultraviolet radiation generated by fluorescent and discharge-type light sources. In addition, the windows must tolerate immersion in water and contact with hydraulic fluids without the initiation of cracking.

Glasses and borosilicate glasses, in particular, have been found to be excellent for construction of windows in explosion-proof enclosures, as the physical properties of glass meet all of the operational requirements. In addition, glass retains its original physical properties for time periods in excess of 20 years even though being subjected continuously to high temperature, moisture, ultraviolet radiation, and hydraulic fluids.

Thus, for all practical purposes, an explosion-proof enclosure equipped with glass windows needs to be checked for structural competence only once prior to being placed in service. Subsequently, the windows need to be only periodically inspected for cracks and fractures. Since the lamps fail at relatively short time intervals (one to two years), the inspection of the window can be performed during replacement of the lamp. If cracks cannot be detected by visual inspection, it can be safely assumed that the window is structurally competent to remain in service until next inspection.

Since glass can safely operate in ambient temperatures less than 500°F without significant decrease of physical properties, an accidental replacement of the burned out lamp with a lamp rated for larger power consumption may raise the temperature above the 300°F design temperature without compromising the pressure rating of the window.

A different case presents itself when the windows are fabricated from plastics. Not only are the physical properties of plastics dependent upon temperature, but they can also be affected by the ambient atmosphere (i.e., water vapor, hydrocarbons). In addition, exposure to heat and UV radiation degrades plastics so that their structural performance may become unacceptable in a very short period of time. Since the rate of aging is a function of temperature, exposure to UV radiation, and composition of the ambient atmosphere, the useful life span for a window fabricated from a particular plastic may vary by a factor of 10, depending on the actual operational environment. Thus, with plastic windows, the accidental replacement of a burned out lamp with a lamp of higher power rating may be catastrophic, as the increase in ambient temperature will not only decrease the pressure rating of the window, but also its rated life span. These same comments are applicable to the adhesives which are used to bond or seal windows in

enclosures; however, the adhesives are usually more protected from the environment (except for heat) than the plastic windows and may be less highly stressed.

It is clear from the foregoing discussion that the effect of environmental factors on plastic lenses and adhesives is very important from the standpoint of reliability in Schedule 2G enclosures with windows. The purpose of this task was to establish an accelerated aging test program by which one could determine the short- and long-term effects of the mine environment on plastic lenses and adhesives. The purpose of the tests was to qualify window and lens materials for use in the mine environment and to provide data so that an allowable service life can be established.

## 1.2 Previous Work

Under a previous contract, USBM Contract H0377052, a study was made of candidate plastics for luminaires. Table 1, taken from that report, shows the comparison between the candidate materials. Polyarylates were believed to have the best combination of properties because of the relatively high service temperature and good UV resistance. Polycarbonates were the second choice, but because they were already in use in mines, it was believed to be of more importance to test them and defer polyarylate testing.

Accordingly, test equipment was fabricated and assembled under Contract H0377052. Testing was begun with the present contract.

TABLE 1. - Transparent plastics for pressure resistant windows

Plastic	ASTM D 648 at 264 psi, °F	Resistance to UV	ASTM D 256 Izod Notch, ft-lb/in.	ASTM D 638 Tensile Strength, psi	ASTM D 638 Tensile Modulus, psi	ASTM D 638 Elongation at Break, %	ASTM D 785 Hardness	Resistance to Hydro- carbons
Acrylic (Plexiglass <sup>R</sup> G)	+ 200	Excellent	0.4	10,000	400,000	4-5	M-94	Fair
Nylon (AMIDEL <sup>R</sup> )	+ 250	Fair	1.1	10,500	280,000	9	M-89	Good
Polycarbonate (LEXAN <sup>R</sup> )	+ 276	Fair	16	9,500	340,000	110	M-70	Poor
Polyarylate (ARDEL <sup>R</sup> )	+ 340	Good	4.2	9,500	290,000	50	?	Poor
Polysulfone (UDEL <sup>R</sup> )	+ 340	Poor	1.2	10,200	360,000	50-100	M-69	Poor
Polephenylsulfone (RADEL <sup>R</sup> )	+ 400	Poor	12	10,400	310,000	60	M-83	Poor

## 2.0 PROGRAM DEFINITION

A program for the accelerated aging tests of polycarbonates and adhesives was given as Appendix K of the report on Contract H0377052. During the early stages of the test program, it became apparent that certain of the test procedures would have to be modified. The changes and the reasons for them are mentioned in the following sections, but the major emphasis is placed on the results of the program as conducted.

### 2.1 Polycarbonate Lenses

Lenses fabricated from Lexan 103 polycarbonate were placed in modified QUV weatherometers to test the effects of heat, humidity, water spray, and ultraviolet light on the polycarbonate. Different combinations of these variables were used with some exposures as long as 36 months.

The original test plan called for pressure tests of exposed lenses. Initial pressure tests showed that the polycarbonate lenses failed by bowing and extruding out of the fixture rather than by fracturing. It was evident that a more sensitive test was needed to give an accurate indication of material degradation.

Bending tests were considered, but it was decided instead to use high strain rate ( $\sim 1 \times 10^{-4} \text{S}^{-1}$ ) tensile tests. These tests again did not differentiate between exposed and unexposed lenses. Finally, a decision was made to utilize Izod impact testing for the polycarbonate lenses. The results reported here measure the deterioration of mechanical strength by the Izod toughness measurement.

The effect of hydraulic fluids on polycarbonates was measured in a simple test over a period of 16 months. Dramatic differences in the response to hydraulic fluids were recorded.

### 2.2 Adhesives

The objective of the adhesive test program was to evaluate candidate materials as adhesives and sealants in the 150°F to 300°F temperature range and 25 to 150 psi pressure range. Materials initially chosen for the test program included several epoxy resins and a silicone resin. Early tests with the epoxies indicated their unsuitability for this application, and the bulk of the testing was done on silicone adhesives. Exposure temperatures of 180°F, 240°F, and 300°F were used. The sealants were exposed to ultraviolet light and humidity. After exposure at times ranging from 1 to 36 months, the fixtures were pressurized to determine the failure pressure of the adhesives.

### 3.0 POLYCARBONATE LENS TESTING

#### 3.1 Literature Search on Environmental Effects

In early 1983, a literature search was made to locate recent publications which contained exposure data on polycarbonate materials. A total of 40B references were found, and abstracts from the references were scanned. After scanning the abstracts, 60 articles were obtained in full. Of the 60 articles, three were found to be pertinent to the exposure tests being conducted, and of the three articles, one was published just before this test program was initiated and two were published afterwards. A synopsis of these three articles follows:

##### 3.1.1 Effect of Elevated-Temperature Exposure

The terms "heat treatment" and "annealing" seem to be used interchangeably in the literature. In (5), PC (polycarbonate) sheets were heated in an oven at various temperatures at 20°C intervals between 40°C (104°F) and 160°C (320°F) for 48 hours, followed by slow cooling back to room temperature. Mechanical properties were then tested over a range of strain rates ranging from 0.29%/sec to  $2.3 \times 10^4\%$ /sec using the same type of tensile specimen. Differential scanning calorimetry (DSC) and gel permeation chromatography (GPC) were also performed.

It was determined that there was no significant change in PC modulus or yield stress in tensile impact testing. However, strain at break was affected markedly. Up to 100°C (212°F), failure was normal for PC. At treatment temperatures above 120°C (248°F), the character of failure changed and the value of breaking strains decreased steeply. This is shown in Figure 1, which is drawn from data given in (5).

Likewise, DSC showed changes indicating molecular rearrangement for treatment temperatures above 100°C (212°F). GPC also indicated substantial reduction in molecular weights for specimens treated above 100°C.

It was also shown that sheets annealed in air had appreciably lower breaking strains than sheets annealed in a vacuum. This indicates that oxygen and/or moisture enter into PC deterioration.

##### 3.1.2 Effect of Ultraviolet Light

In (4), the effects of UV light on molecular weight and tensile strength of UV-stabilized and unstabilized grades of PC were evaluated. Tensile specimens were exposed up to 2500 hours to a 2500-watt Xenon lamp in a weatherometer. Samples were exposed on one side and sprayed with distilled water 10 minutes per hour. The chamber temperature was 45°C (113°F). No statement of UV dosage at the surface was made, except that 2000 hours' exposure was equivalent to one year of outside exposure in Israel.

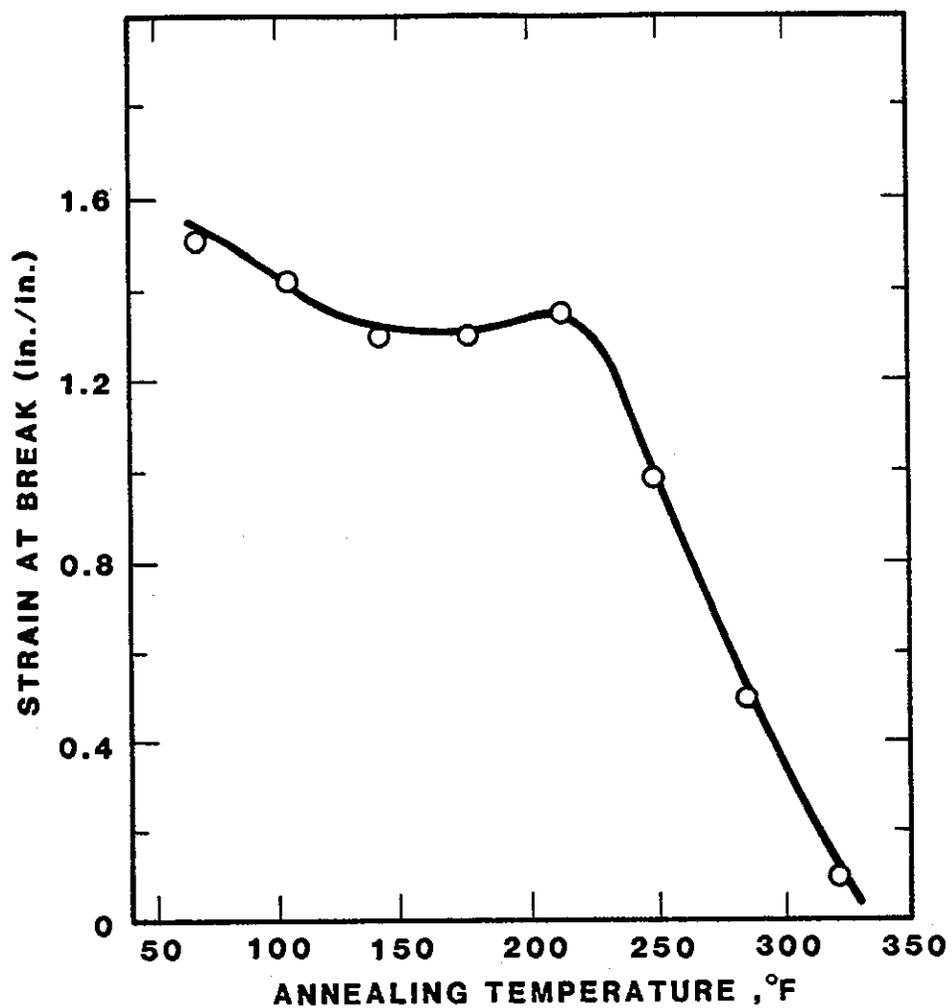


FIGURE 1. - Dependence of breaking strain of PC sheets on annealing temperature for 48 hr. Strain rate =  $226 \text{ sec}^{-1}$ . Data from (5).

UV effects were limited to the top 0.2 to 0.3 mm (0.01 in.). This material had major reductions in molecular weight which produced brittle behavior. This brittle surface permitted crack formation which changed the ductile behavior to brittle and reduced breaking strains in the tensile test. The effect on UV-stabilized material was much less than on unstabilized material. However, Figure 2, from data in (4), shows significant reduction in breaking strain, even for the stabilized material. Yield stresses were affected very little in either material.

### 3.1.3 Effects of Humidity

While heat alone has an effect on PC, the effects of humidity are greatly accelerated by heat, so that humidity cannot be discussed alone. The work reported in (2) was conducted at high humidity levels (75%, 100%) and at temperatures between 65 to 93°C (149°F to 199°F). Exposure times were up to 80 weeks.

It was shown that the water rapidly hydrolyzes the PC, reducing the molecular weight substantially. At a critical molecular weight, there is a transition from ductile to brittle failure. Ductile-to-brittle was defined by the appearance of the fracture surface of ASTM D 638 tensile specimens tested at a low rate (0.2 in./min). Failure strains at the transition were about 5-6%.

### 3.1.4 Discussion

Each of the three references discussed above related environmental changes to molecular weight changes. Thus, molecular weight may be the most sensitive and valid way to relate material damage to environmental effects; however, molecular weight changes do not correlate well with material strength changes. Most of the environmental effects seem to reduce strain at break, so that those effects would be reflected in toughness measurements.

## 3.2 Test Program

### 3.2.1 Deviations from Original Plan

The original test plan called for test specimens to be circular windows fabricated from a single sheet of UV-stabilized polycarbonate plastic sheet. The thickness was to be 1/2 in. and five diameters were chosen which would produce stresses ranging from 5000 psi to 630 psi when the test fixture was pressurized to 150 psi. Initial testing indicated that the plastic flow behavior of the lenses was so great that the "failures" consisted of extrusion in the fixture. There were no fractures or total extrusions at test pressures up to 360 psi and 180°F. One fixture was pressurized to 900 psi before the lens blew out. The lens did not break.

Subsequently, it was decided to use 3/16-in.-thick specimens and only two diameters--3.29 in. and 4.62 in. Some exploratory tensile testing of samples cut from these lenses was done. Because of the small

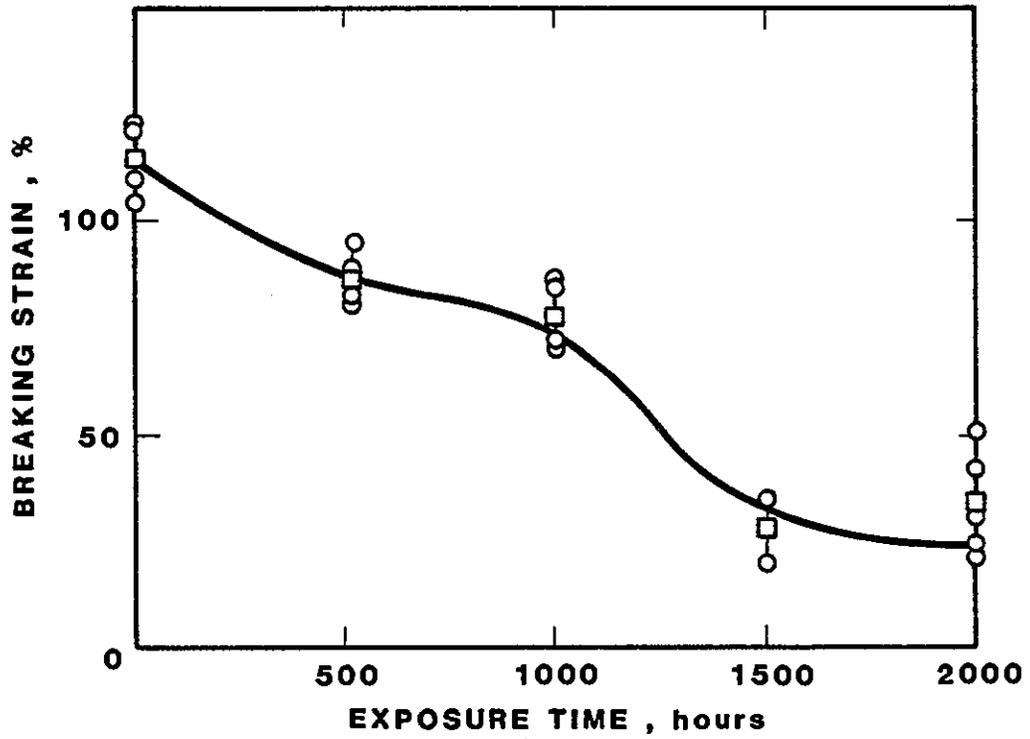


FIGURE 2. - Strain at failure as a function of exposure to UV for injection-molded bars of PC. Data from (4).

size of the lens, only one tensile sample could be made of each, and it was of a very small size. It was not clear from the limited testing that this tensile test could detect changes in behavior caused by environmental exposure.

During this period, environmental exposure of lenses continued. At the completion of a lens' exposure period, the lens was stored. In April 1983, a decision was made to use the Izod impact test as a measure of the ability of the material to maintain its integrity under explosion conditions in the luminaire. This type of testing is discussed in more detail in Section 3.3.

### 3.2.2 Environmental Exposure Equipment

The primary equipment used in the environmental exposure consisted of two QUV Weathering Testers.<sup>1</sup> As manufactured, these machines can subject test specimens to UV from eight 40-watt mercury vapor fluorescent bulbs of Type UVB-313. These bulbs emit most of their light in the 280 to 315 nanometer range which is responsible for most polymer damage. The machines also have provisions for providing a 100% relative humidity environment.

For the present program, the chambers were modified by cutting access holes in the door for special holding and pressurization fixtures for the polycarbonate and glass lenses. The special fixtures are shown in Figures 3 and 4. The fixtures served to act as a pressure test vessel (when removed from the QUV unit), a realistic lens holding fixture, and an attachment for special heaters to maintain the lens at specific temperatures. A picture of the modified QUV units is shown in Figure 5. The unit in the foreground has 14 of 15 test fixtures in place on the near side. Thermocouple and heating wires are shown coming out of the closure flanges. The unit in the background has several of its fixtures removed. A cross section of the QUV unit is shown in Figure 6.

Resistance heaters were placed inside each fixture and connected to a rheostat for varying the current. The temperature was monitored with a thermocouple placed on the surface of the lens facing the interior of the fixture. There were a number of failures of this arrangement, causing overheating of the lenses and loss of those test samples. Subsequently, a reset switch was purchased and used for the rest of the program. After installation of the reset switch, there was one other instance of overheating when a relay stuck in the closed position.

To simulate the exposure of PC lenses to water found underground, fine jets, located in front of each window, sprayed water intermittently on the hot exterior of the windows. A typical arrangement is shown in Figure 7. Water is collected in the bottom of the chamber. Heaters in

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<sup>1</sup>Manufactured by the Q-Panel Company, 26200 First Street, Cleveland, OH 44145.

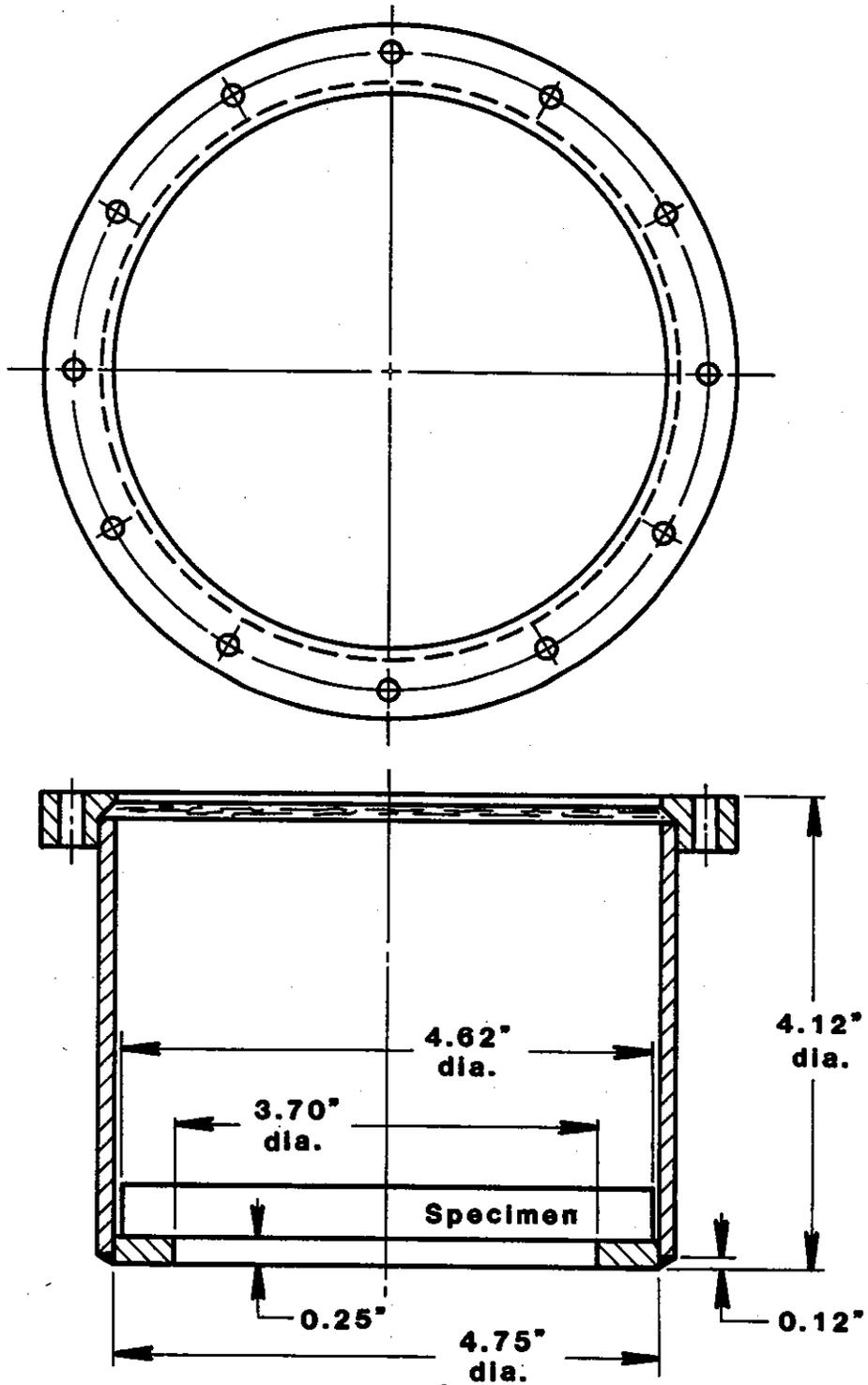


FIGURE 3. - Type A fixture for polycarbonate lens specimens. Closure flange not shown.

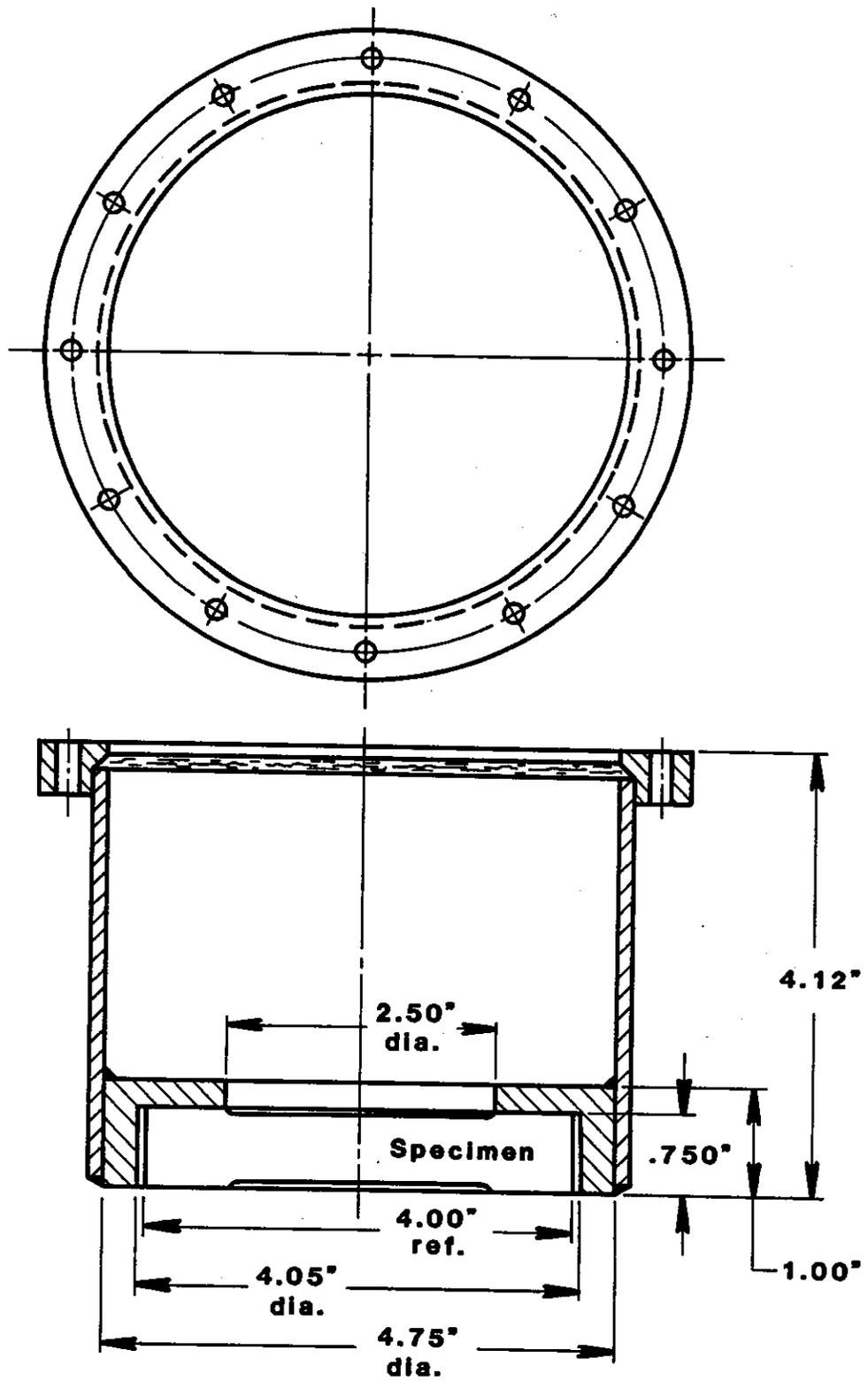


FIGURE 4. - Type B fixture for glass lens adhesive specimen. Closure flange not shown.

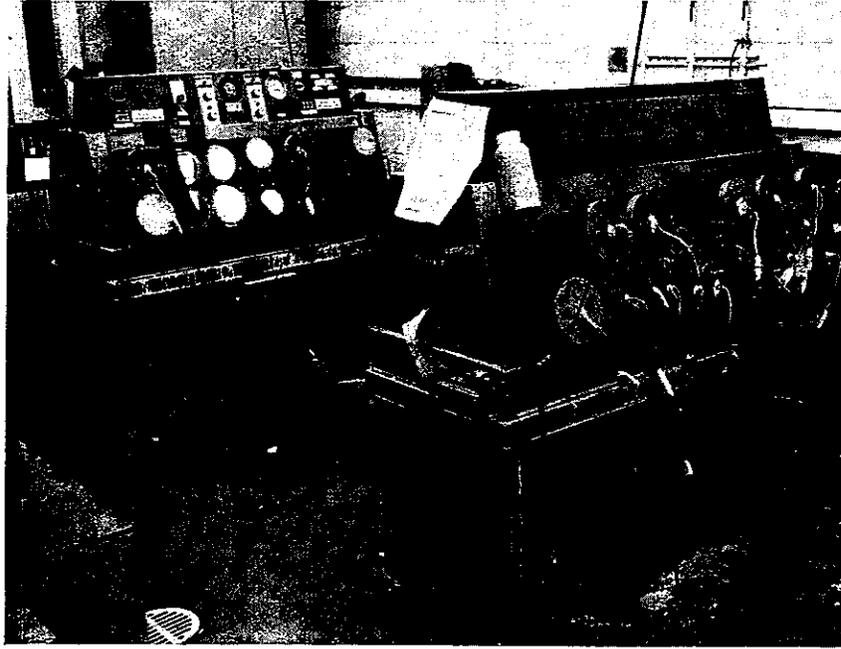


FIGURE 5. - Modified QUV testers.

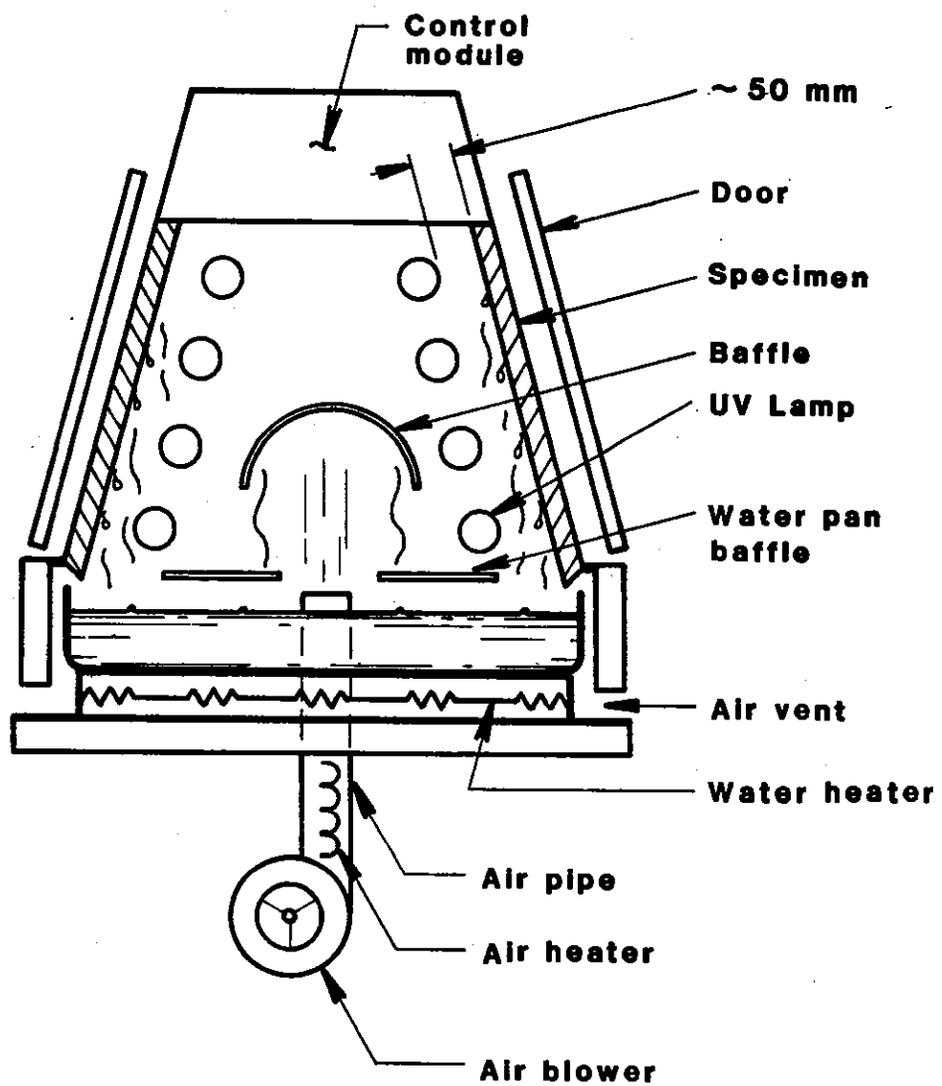


FIGURE 6. - Cross section of QUV tester.

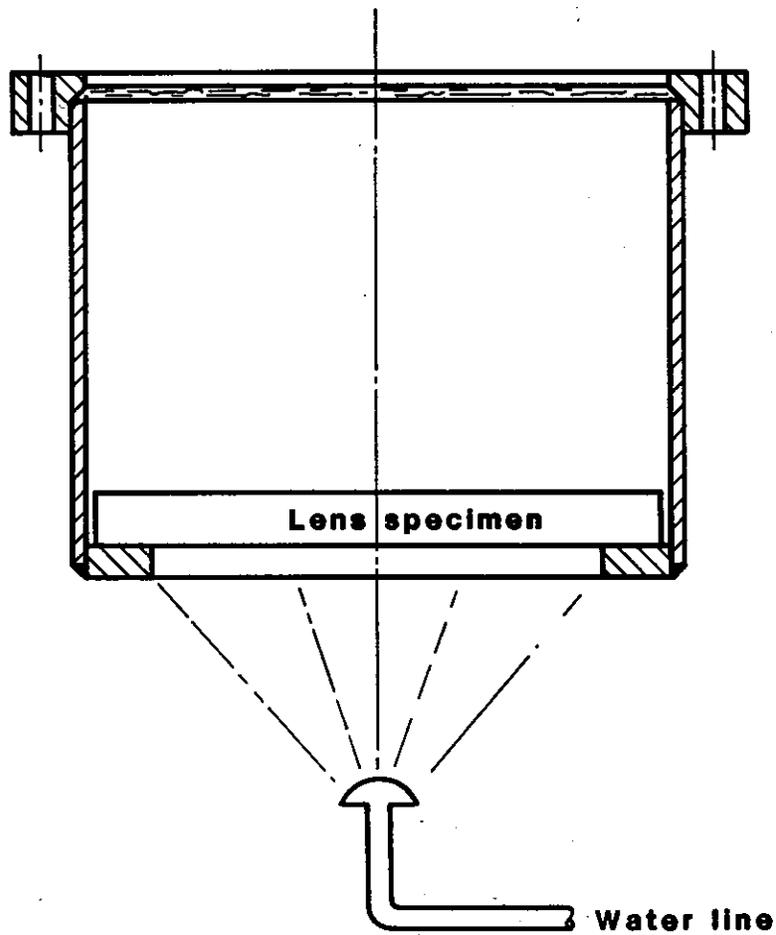


FIGURE 7. - Typical water spray nozzle.

the water reservoir maintained the interior of the chambers at 100% relative humidity. Temperatures measured in the QUV chamber varied between 90° to 115°F, depending on location. Thus, the lenses were subjected to a thermal gradient caused by either 180°F or 240°F applied on one side and the ambient convective condition of approximately 100°F and 100% humidity applied on the other side. The cooler side was also subjected to intermittent water spray (which simulated mine water) and to UV. Ideally, the UV exposure would have been on the opposite (hot) surface, but the pressurization fixtures prevented that.

### 3.2.3 Assembly Procedure

Prior to mounting a PC lens in a fixture, a thermocouple was bonded with RTV silicone rubber to the window's interior surface at the center. After a 48-hour cure time for the adhesive, the lens was mounted in the fixture. The mounting process consists of (1) lightly coating the face of the seat with RTV silicone rubber, (2) centering the lens on its seat, and (3) pressing the lens with a 1-lb force for 48 hours. Care was taken to avoid entrapment of air, which might rupture the seal by expansion at high temperatures. The freshly-potted windows were cured by letting them stand at least 100 hours at room temperature to allow for vulcanization of the silicone seal.

After vulcanization was complete, the test fixture was inserted into the QUV unit and bolted in place with a rubber gasket for sealing. An end closure plate with heater attached was then bolted in place.

A similar procedure is followed for attaching glass lenses in the Type B fixtures using either epoxy or silicone seals.

### 3.2.4 Exposure Procedure

The objective of exposure testing was to simulate the environment which a PC lens would experience in service in a luminaire. The fixturing permitted the lens to be heated to a fixed temperature on one side, to be exposed to high humidity and water spray, and to be exposed to UV light. One deviation was that the exposures to UV and heat were on opposite faces of the lens, while in practice they are on the same sides of the lens.

The daily exposure procedure consisted of:

- (1) Continuous operation of the UV lamp for 12 hours, followed by 12 hours of darkness,
- (2) Recording of the temperatures,
- (3) Continuous humidity, and
- (4) Water spray on the lenses for 15 minutes once every 12 hours.

Upon completion of the scheduled exposure time, a lens was removed from the fixture and stored until mechanical testing could be performed.

### 3.3 Mechanical Tests

#### 3.3.1 Impact Tests

When low-speed tensile and bending tests failed as definitive measures of deterioration of the polycarbonate samples, it was decided to use an impact test. Reference 5 had used an impact tensile test to evaluate the effects of heat. However, in this program, test specimens have to be cut from lenses and there exists a real limitation on the size of specimen. Both the Izod and Charpy impact tests are easy to run. Since either four or six Izod specimens could be made from each lens, it was decided to utilize this method for subsequent testing.

The choice of test method is not at all straightforward. The impact properties of polymers are directly related to the toughness of the material. It was demonstrated in (5) that the effects of environmental exposure affects toughness, as measured in a tensile impact test. Toughness is the ability of a material to absorb applied energy. The higher the impact resistance, the higher the toughness. Impact resistance is the ability of a material to resist breaking under a shock loading or the ability to resist the fracture under stress applied at a high speed.

Because of the high-speed loading characteristics inherent in an explosion in a luminaire, a high-speed test such as impact is appropriate.

Many factors affect the impact strength of polymers. The rate of loading, the method of loading, the shape of notches, temperature, molecular orientation, processing conditions, degree of crystallinity, and molecular weight are important. The effects of loading, notches, and temperature have been taken into account by standardizing the tests. See, for instance, ASTM D 256-78 (1), which specifies both the Charpy and Izod tests.

#### 3.3.2 Izod Impact Test

The objective of the Izod impact test is to measure the relative susceptibility of a standard test specimen to the pendulum-type impact load. The results are expressed in terms of kinetic energy needed to break the specimen. The energy required to break a standard specimen is actually the sum of energies needed to deform it, to initiate its fracture, and to propagate the fracture across it, and the energy needed to throw the broken ends of the specimen. The energy lost through the friction and vibration of the apparatus is minimal for all practical purposes and usually neglected.

The specimen is usually notched. The reason for notching the specimen is to provide a stress concentration area that promotes a brittle

rather than a ductile failure. The impact values are seriously affected because of the notch sensitivity of certain types of plastic materials.

The Izod test requires a specimen to be clamped vertically as a cantilever beam. The specimen is struck by a swing of a pendulum released from a fixed distance from the specimen clamp.

The testing machine consists of a heavy base with a vise for clamping the specimen in place during the test. A pendulum-type hammer with an antifriction bearing is used. Additional weights may be attached to the hammer for breaking tougher specimens. The pendulum is connected to a pointer and a dial mechanism that indicates the excess energy remaining in a pendulum after breaking the specimen. The dial is calibrated to read the impact values directly in in.-lb or ft-lb. A hardened steel striking nose is attached to the pendulum. Figure 8 shows the Izod impact testing machine used in this program. The test specimens can be prepared either by molding or cutting them from a sheet. Izod test specimens are 2-1/2 in. x 1/2 in. x thickness. The most common specimen thickness is 1/8 in., but 1/4 in. is preferred since they are less susceptible to bending and crushing. A notch is cut into a specimen very carefully by a milling machine or a lathe. The recommended notch depth is 0.100 in.

The test specimen is clamped into position so that the notched end of the specimen is facing the striking edge of the pendulum. The pendulum hammer is released, allowed to strike the specimen, and swing through. The impact values are read directly in in.-lb or ft-lb from the scale. The impact strength is calculated by dividing the impact values obtained from the scale by the thickness of the specimen. For example, if a reading of 2 ft-lb is obtained using a 1/8-in.-thick specimen, the impact value would be 16 ft-lb/in. of notch. The impact values are always calculated on the basis of 1-in.-thick specimens even though much thinner specimens are usually used.

#### 3.3.2.1 Critical Thickness

Polycarbonate, more than any other material, seems to show sensitivity to variations in the specimen width and notch root radius in the Izod test. In this testing program, Lexan® 103, a high-viscosity, UV-stabilized grade was used. General Electric Company lists a range of notched Izod values of 12 to 16 ft-lb/in. for this material for a 1/8-in.-thick notched specimen and the standard 0.010-in. root radius notch. This value compares favorably with other plastics such as polymethylmethacrylate (Plexiglas®) with a notched Izod value of about 0.4 ft-lb/in.

However, as will be shown in more detail, the Izod values obtained for polycarbonate in testing yielded values for virgin material in the range of 2 to 3 ft-lb/in. The explanation for this difference from published values lies in the critical thickness phenomenon.

In (3), R. J. Kohl of Mobay Chemical Company, another polycarbonate manufacturer, says that samples of small width have a high impact strength with a ductile fracture with necking in the notched area.

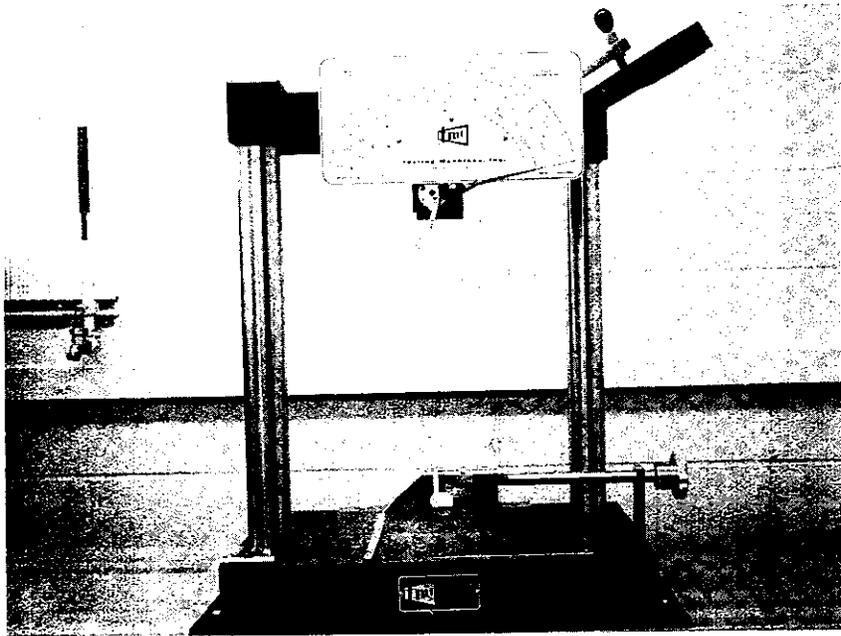


FIGURE 8. - Cantilever beam (Izod-type) impact machine.

As the sample width increases, the fracture energy drops to only a fraction of the initial value at a specific width, and the fracture changes discontinuously into a brittle failure with no necking in the notched area. This is illustrated by the dashed line in Figure 9 which is plotted from Kohl's work. He further states that the critical thickness of polycarbonate at room temperature is approximately 0.145 in. to 0.220 in. The value depends on the molecular weight and additives such as stabilizers (UV). Annealing causes the critical thickness to drop.

Also shown in Figure 9 are data measured at SwRI on four thicknesses of PC--0.125, 0.172, 0.250, and 0.500 in. These samples were tested in the as-received condition. These data would seem to indicate a critical thickness for the UV-stabilized Lexan 103 used in this program of about 1/8 in., which is somewhat lower than the 0.145 in. lower range value stated by Kohl. The reasons for this deviation are not known, but there are several possibilities. In addition to UV stabilizers and molecular weight, which can vary from batch to batch, the quality of surface finish in the machined notch is important. This point is discussed in more detail in Section 3.3.2.2.

Although the SwRI data are low, they seem to be consistent. Note also that when one is testing material at the "critical thickness", Izod values varying from 2 to 18 can be expected! This point should be remembered when considering the scatter of test results.

This notch behavior in PC is caused by its ductility which permits adjacent material to flow and relieve stresses in the vicinity of a notch. In thin notched specimens, material can flow from two directions in the notch root. For thick (or wide) specimens, flow is partially restrained in the thickness direction, so the specimen does not show the ductility demonstrated by the thin specimen.

It should be noted that although the Izod values for polycarbonate being measured in the program are close to "non-high impact" plastics such as PMMA, there should be no inference that the impact toughness of the polycarbonate has been compromised. The high impact toughness of polycarbonate has been proven in practice for many years. Rather, the question we should ask is "How appropriate is this impact test to the design of luminaire lenses?". Classically, impact tests can be only very tenuously connected with real design and service parameters. The use of the impact test in this program was chosen only after tensile testing and blowout tests had failed to demonstrate lens degradation. Further, because impact loading is a design requirement for enclosure lenses, we believe that the use of an impact test to measure material degradation is appropriate.

#### 3.3.2.2 Preparation of Izod Specimens

Because of its ductile flow characteristics, polycarbonate is difficult to machine. Attempts to machine a notch in Izod specimens using standard tooling for metals was unsuccessful. Characteristically, poorly-machined notches had material torn, rather than sliced, away.

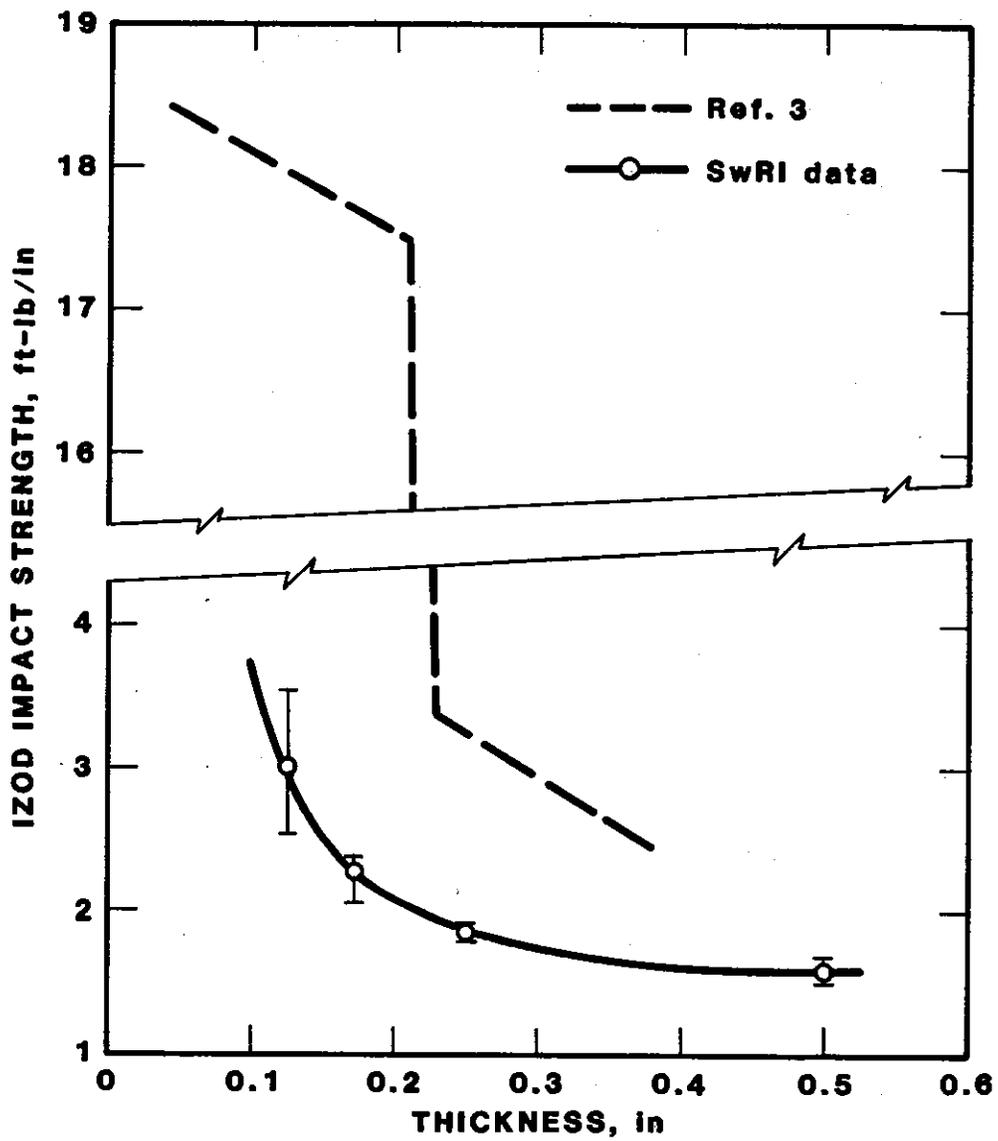


FIGURE 9. - Critical thickness for PC in Izod tests at room temperature.

This would leave the surface rough, often with deep grooves, and with a heat-affected zone extending about 10 mils deep from all faces of the V-notch. The nature of the heat effects was not known, but the affected area could be observed under a microscope because of a change in the index of refraction of polycarbonate in the heat-affected zone.

Inquiries to the General Electric Lexan Products Division produced no helpful advice. Subsequently, a special cutter coated with diamond frit was fabricated, but it gave similarly poor results. Finally, a clever machinist developed a cutting surface on a carbide tool which gave satisfactory results.

Figure 10 shows a close-up of the machined notch surface on the two halves of a broken specimen. Although some machining marks are evident along the width of the notch, there is no tearing of surface and no heat-affected zone. This surface is typical of the specimens tested in this program.

### 3.4 Mechanical Test Results

An environmental exposure program and subsequent evaluation by Izod testing were completed on a total of 48 polycarbonate disks. The disks were 3/16 in. thick and either 3.29 or 4.62 in. in diameter. The Izod specimens are nominally 1/2 in. x 3/16 in. x 2.5 in., as shown in Figure 11. The smallest dimension, the lens thickness in this case, is sometimes called the thickness and sometimes called the width. Care should be taken when evaluating literature to distinguish which dimension is being referred to. Environmental exposures were made under the following conditions:

- o Ultraviolet light and humidity
- o 180°F heat and humidity
- o 180°F heat, humidity, and UV
- o 180°F heat, humidity, UV, and water spray
- o 240°F heat and humidity
- o 240°F heat, humidity, and UV
- o 240°F heat, humidity, UV, and water spray

Izod specimens were cut from the lenses in the manner illustrated in Figure 12. Generally, four specimens could be cut from a small lens and six specimens could be cut from a large lens. An occasional specimen would be lost during machining.

As shown in Figure 13, one end of the notch was on the surface exposed to heat, and the other end of the notch was on the surface exposed to UV, humidity, and water spray. The Izod test would certainly show more sensitivity to the environmental degradation if a premachined notch was exposed. However, the present method assures that the edges of the notch are composed of degraded material, and the specimen will be notch-sensitive to even surface degradation effects.

The results of the exposure testing are shown in Tables 2 through 8. For each lens, the number of Izod specimens is noted, and the range of

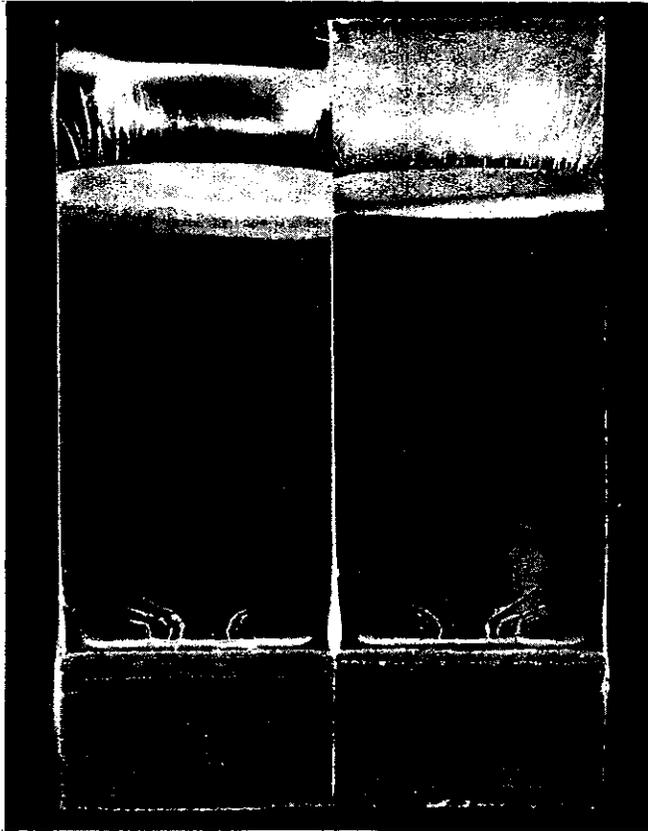


FIGURE 10. - Detail of Izod notch and fracture surface in broken specimen.

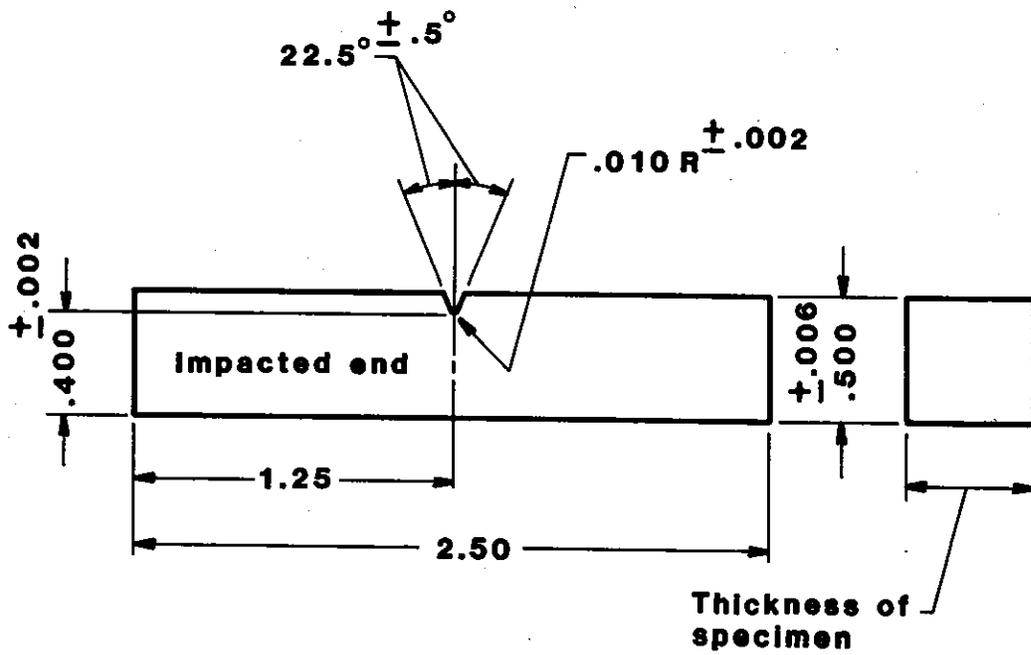


FIGURE 11. - Dimensions of Izod specimen.

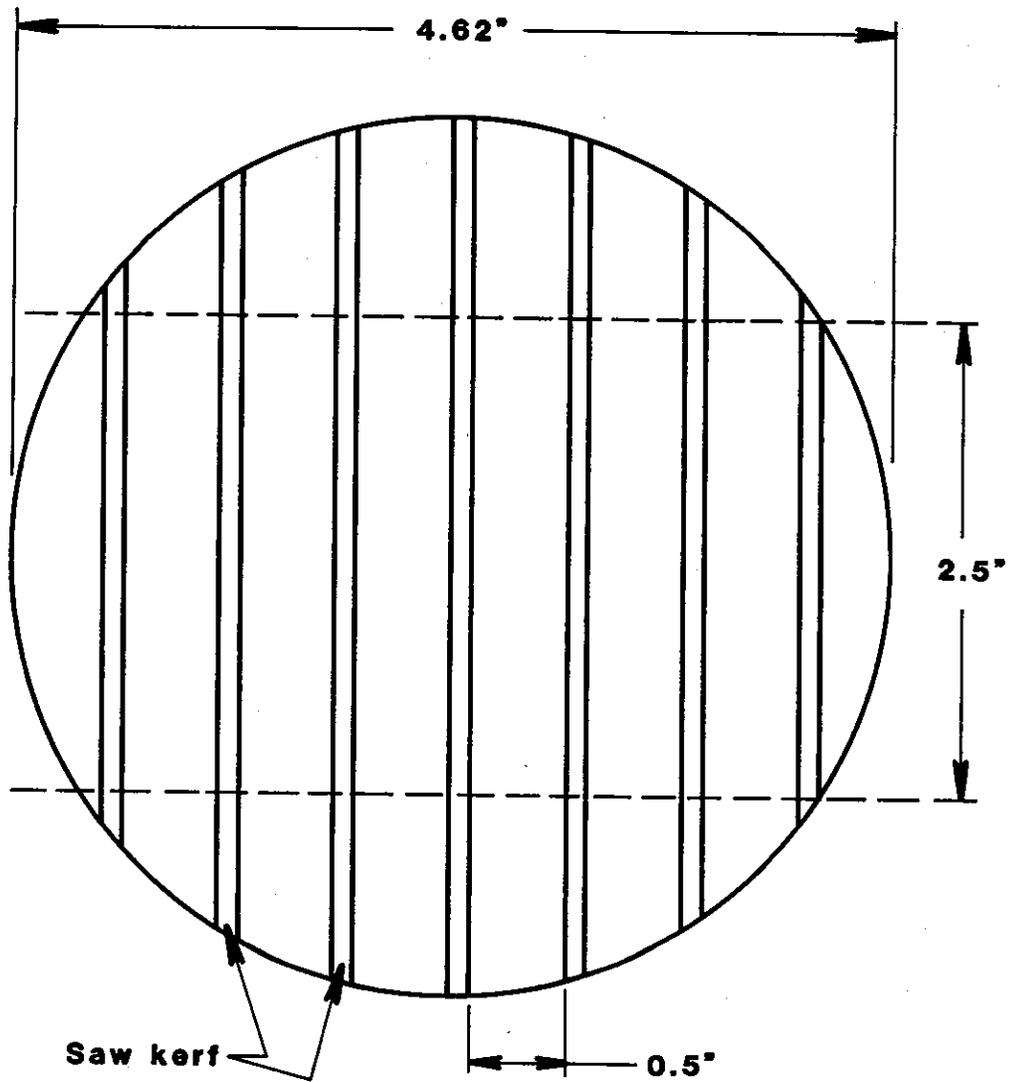


FIGURE 12. - Method of cutting 0.5 in. x 2.5 in. x thickness Izod blanks for 4.62 lens.

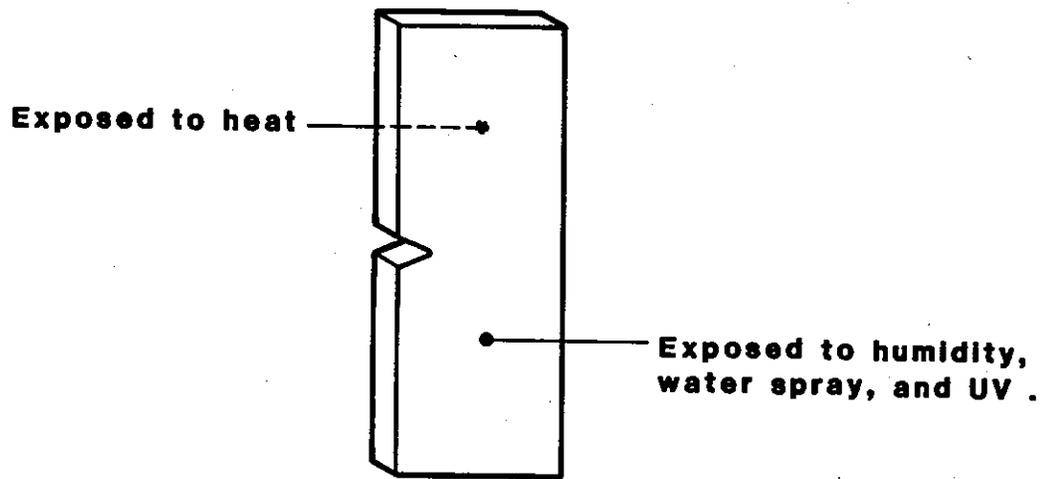


FIGURE 13. - Position of notch relative to exposed face of lens.

TABLE 2. - PC lens exposure data. Environment: UV and humidity.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
1	L	10/81	12/82	2	5	2.36-2.56	2.44
3	S	3/82	5/82	2	3	2.55-2.72	2.57
8	S	8/84	10/84	2	4	2.39-2.55	2.45
4	S	3/82	7/82	4	3	2.31-2.32	2.31
2	L	10/81	2/82	4	5	2.31-2.52	2.38
9	S	8/84	12/84	4	4	2.12-2.37	2.27
10	L	8/84	1/85	6	6	2.22-2.27	2.25
5	L	3/82	10/83	18	5	2.59-2.78	2.65
7	L	5/83	1/85	18	6	2.16-2.26	2.22
6	L	3/82	3/84	24	6	2.42-2.77	2.56

TABLE 3. - PC lens exposure data. Environment: Heat (180°F) and humidity.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
21-2	L	9/82	3/83	6	6	2.18-2.50	2.29
23-3*	L	8/84	1/85	6	6	1.85-2.39	2.22
16-2	L	9/82	9/84	24	6	1.79-1.94	1.88

\* Overheated

TABLE 4. - PC lens exposure data. Environment: Heat (180°F), humidity, and UV.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
19-2	L	9/82	12/82	3	5	2.13-2.28	2.25
16-3	L	10/84	1/85	3	4	1.74-1.84	1.80
20-2	S	9/82	3/83	6	3	1.95-2.11	2.01
19-3*	L	8/84	1/85	6	6	1.88-2.09	2.01
14-2	L	9/82	9/83	12	5	1.54-2.12	1.79
22-2	L	9/82	11/84	24	6	1.90-2.18	2.04

\* Overheated

TABLE 5. - PC lens exposure data. Environment: Heat (180°F), humidity, UV, and water spray.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
1-1	L	4/81	5/81	1	Pressurized at 360 psi 0.50 in. DEFL		
2-1	S	4/81	6/81	2	3	1.89-2.06	1.99
3-1	S	4/81	6/81	2	3	2.08-2.14	2.11
7-1	S	4/81	7/81	3	3	2.14-2.19	2.17
8-1	L	4/81	7/81	3	5	2.05-2.27	2.21
9-1	S	4/81	7/81	3	3	2.01-2.08	2.05
4-4	L	8/84	11/84	3	6	1.77-1.94	1.86
15-1	S	4/81	8/81	4	3	1.62-1.70	1.66
17-1	S	4/81	8/81	4	3	1.95-2.00	1.98
7-4	L	8/84	1/85	6	6	1.69-1.97	1.82
1-2	L	8/81	8/82	12	5	1.97-2.01	1.99
10-3	L	9/82	9/83	12	5	1.83-2.13	1.99
2-2	L	8/81	2/83	18	5	1.86-2.08	1.98
12-3	S	9/82	10/84	24	4	1.89-2.08	1.99
3-2	S	8/81	8/83	24	3	1.77-1.85	1.80
8-2	L	8/81	10/84	36	6	1.94-2.08	2.01

TABLE 6. - PC lens exposure data. Environment: Heat (240°F) and humidity.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
4-1	L	4/81	5/81	1	Pressurized to 360 psi 0.85 in. DEFL		
5-1	L	4/81	6/81	2	Pressurized to 360 psi 0.70 in. DEFL		
9-3	L	10/84	1/85	3	6	2.21-2.41	2.31
20-3	L	8/84	1/85	6	6	1.76-2.01	1.88
17-2	S	9/82	1/84	15	6	.831-1.57	1.132
18-2	L	9/82	11/84	24	6	1.80-2.20	1.96

TABLE 7. - PC lens exposure data. Environment: Heat (240°F), humidity, and UV.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
23-2	S	9/82	12/82	3	3	1.83-2.20	1.96
21-3	L	10/84	1/85	3	6	1.74-1.81	1.77
15-2	L	9/82	3/83	6	5	1.75-1.92	1.87

TABLE 8. - PC lens exposure data. Environment: Heat (240°F), humidity, UV, and water spray.

Specimen No.	Lens Size	Start Date	Stop Date	Duration, Months	IZOD		
					No. of Tests	Range, ft-lb/in.	Average, ft-lb/in.
6-1	S	4/81	6/81	2	3	1.67-1.85	1.76
10-1	S	4/81	7/81	3	2	1.79-1.79	1.79
10-4	S	8/84	11/84	3	4	1.89-1.99	1.95
11-1	L	4/81	7/81	3	5	1.66-1.78	1.71
12-1	S	4/81	7/81	3	3	1.64-1.81	1.71
18-1	L	4/81	8/81	4	5	1.58-1.64	1.60
19-1	L	4/81	8/81	4	3	1.59-1.69	1.63
20-1	S	4/81	8/81	4	2	2.01-2.07	2.04
2-3*	L	8/84	1/85	6	6	1.99-2.14	2.03
4-3	L	9/82	9/83	12	5	1.88-1.97	1.92
7-3	S	9/82	3/84	18	3	1.59-1.64	1.61
11-3	L	9/82	3/84	18	5	1.60-1.74	1.66
6-3	S	9/82	11/84	24	4	1.82-2.07	1.91
13-2	S	9/82	11/84	24	3	1.04-1.39	1.24

\* Overheated

values and average values are shown. The average value for each lens is plotted in the series of graphs, Figures 14 through 22, which show how the Izod impact toughness changes with time for given exposure conditions. The solid points shown in Figure 14 through 22 indicate an overheating condition which is discussed in Section 3.4.8.

#### 3.4.1 UV and Humidity Exposure

References 2 and 4 give data on humidity effects and UV, respectively. According to the data in (2), a five-year exposure to 100% relative humidity at 100°F would be necessary for hydrolysis to markedly affect the failure of PC. However, although the chamber condition is 100°F and 100% relative humidity, the lens temperature is indeterminate on the humid side and the moisture profile in the PC is not known.

The results noted in (4) indicate that UV exposure equivalent to one year in Israel gives up to 75% reduction in elongation at failure. The results of our tests do not show a corresponding affect. In fact, if anything, the data shown in Figure 14 indicate that the Izod strength increases with exposure time. However, this conclusion must be interpreted carefully. First, the UV-affected depth of PC is only a few mils, so that the fraction of the failure surface which is (presumably) embrittled is small, on the order of 3%. Therefore, the energy change measured by the Izod test reflects principally the energy change in crack initiation, not energy absorbed in crack propagation.

Also, the evaluations of elongation made in (4) utilized low-speed tensile tests which indicated substantially similar behavior between exposed and unexposed samples up to yield. The presence of a brittle surface permitted cracks to initiate at a relatively low strain level which would then propagate rapidly. As noted in (3), the PC is notch-size sensitive, e.g., if the notch root radius is very small (a crack), then the ductility of the PC does not manifest itself.

The third point is that UV damage to lenses is on the inside of a luminaire which would be loaded in compression in case of an internal explosion. This face would not be subject to cracking from tensile stresses.

Exposure to UV alone or with other environments affected the clarity of the lenses. Figure 23 shows a remnant of a lens which had heat and UV exposure for three months. The outer 1/2 in. or so was shielded from the light by a metal flange. The interior shows the amber color imparted by UV-induced deterioration. The depth of the UV-induced color change can be seen in the section shown in Figure 24. The affected depth is on the order of 10 mils.

The amber color darkens with more exposure. It may be possible to monitor UV damage with a strictly subjective evaluation of color change, e.g., if the lens darkens, replace it.

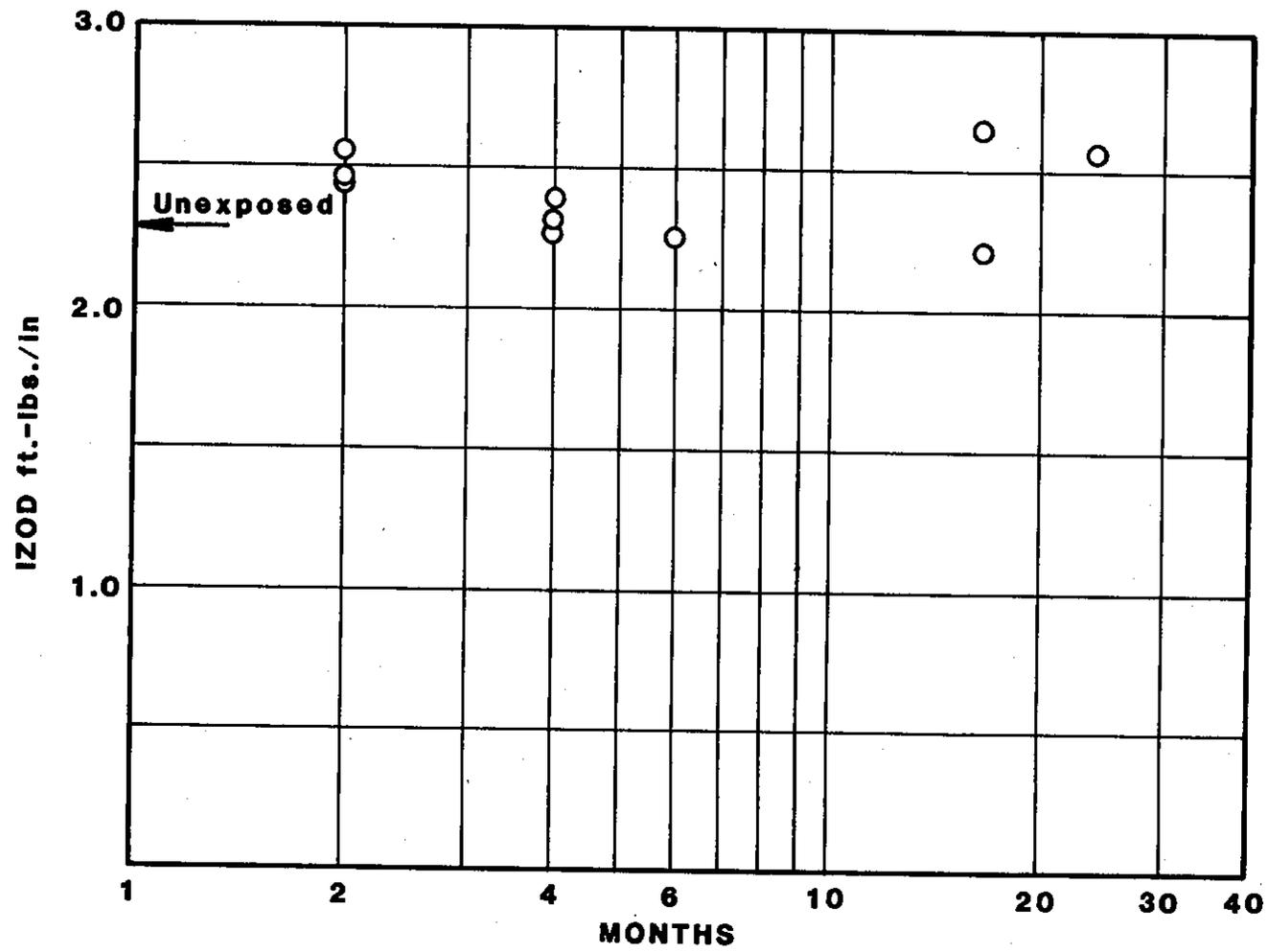


FIGURE 14. - Izod data for PC. Environment: UV and humidity exposure.

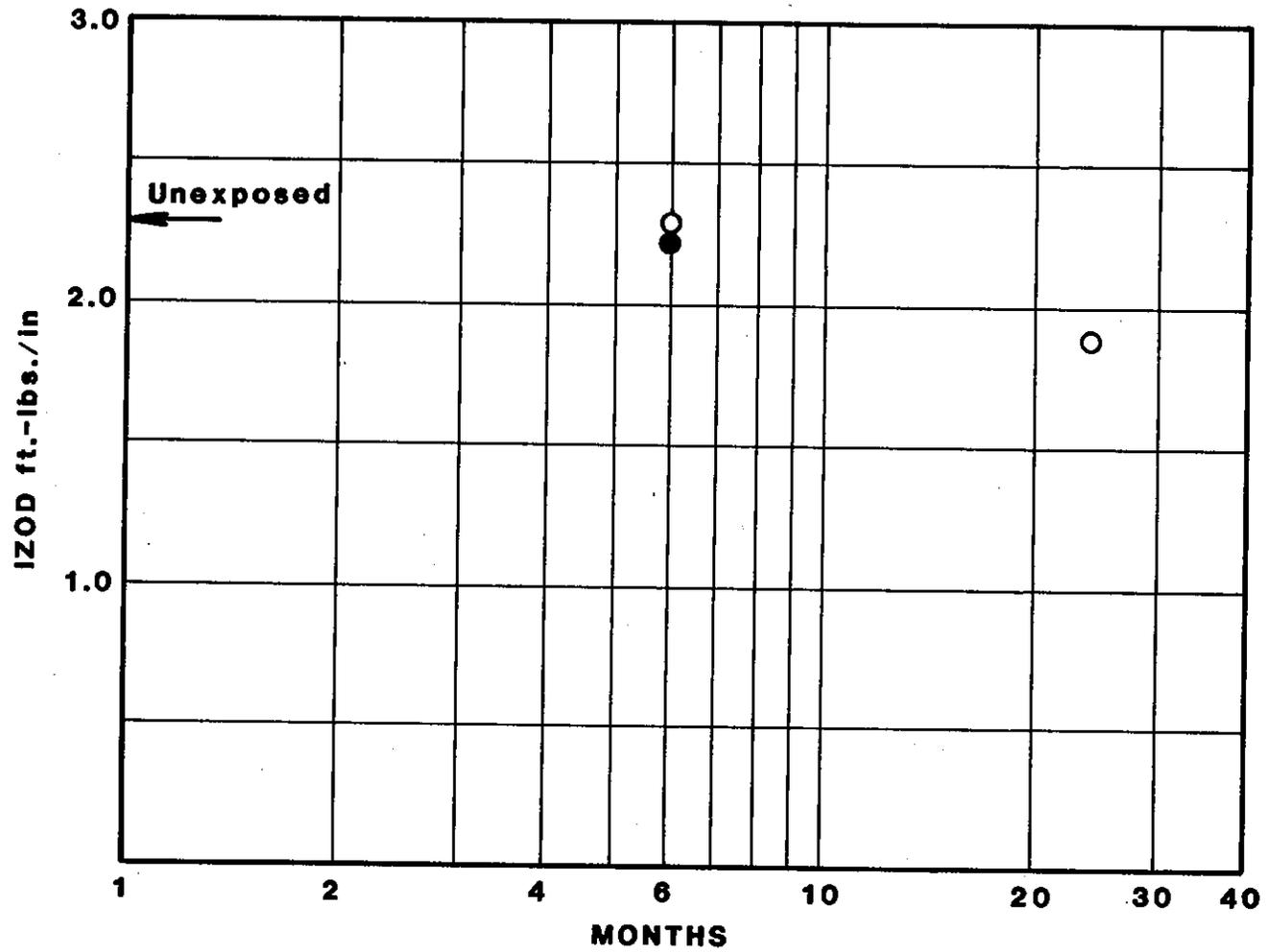


FIGURE 15. - Izod data for PC. Environment: Heat (180°F) and humidity exposure.

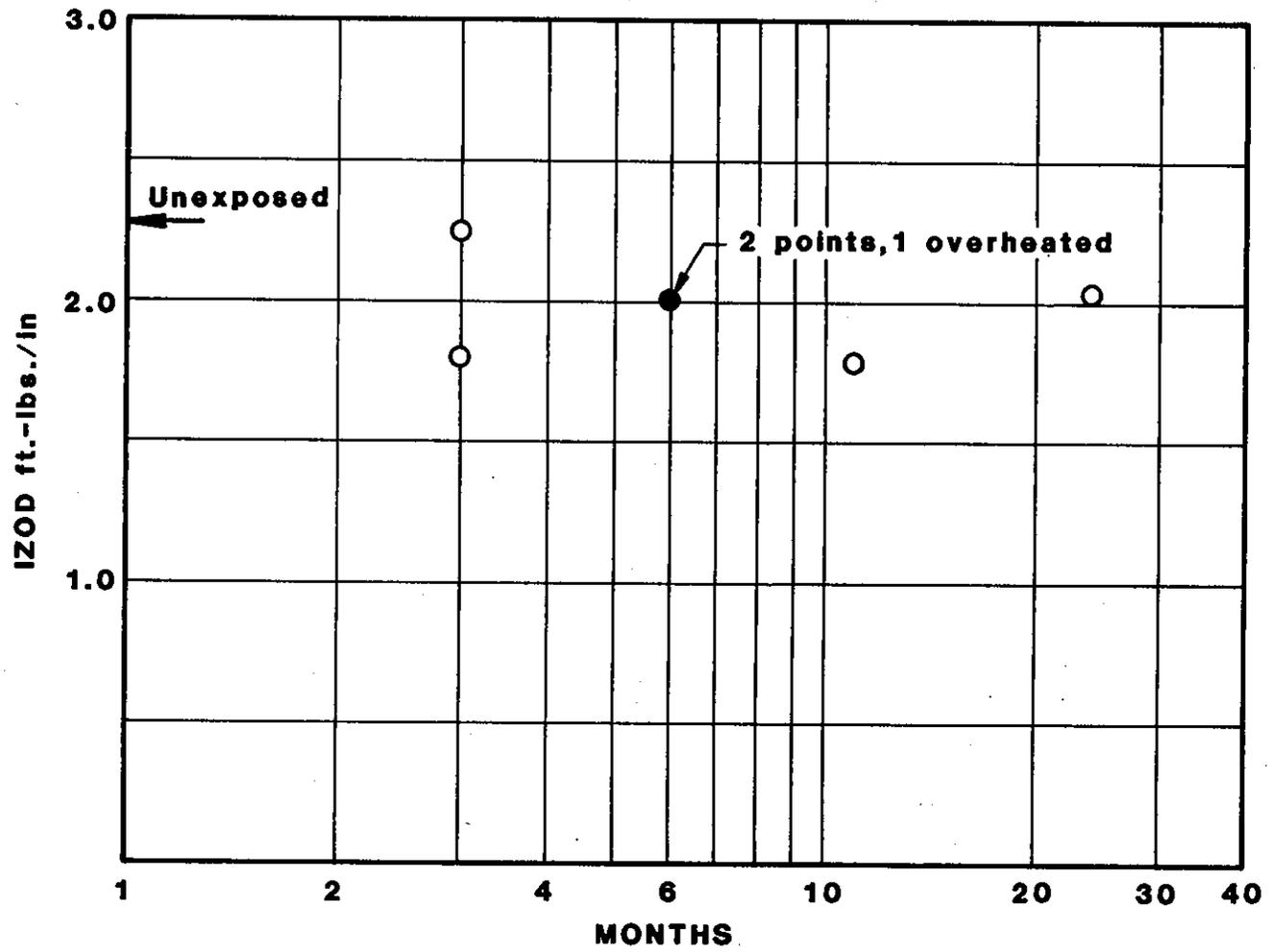


FIGURE 16. - Izod data for PC. Environment: Heat (180°F), humidity, and UV exposure.

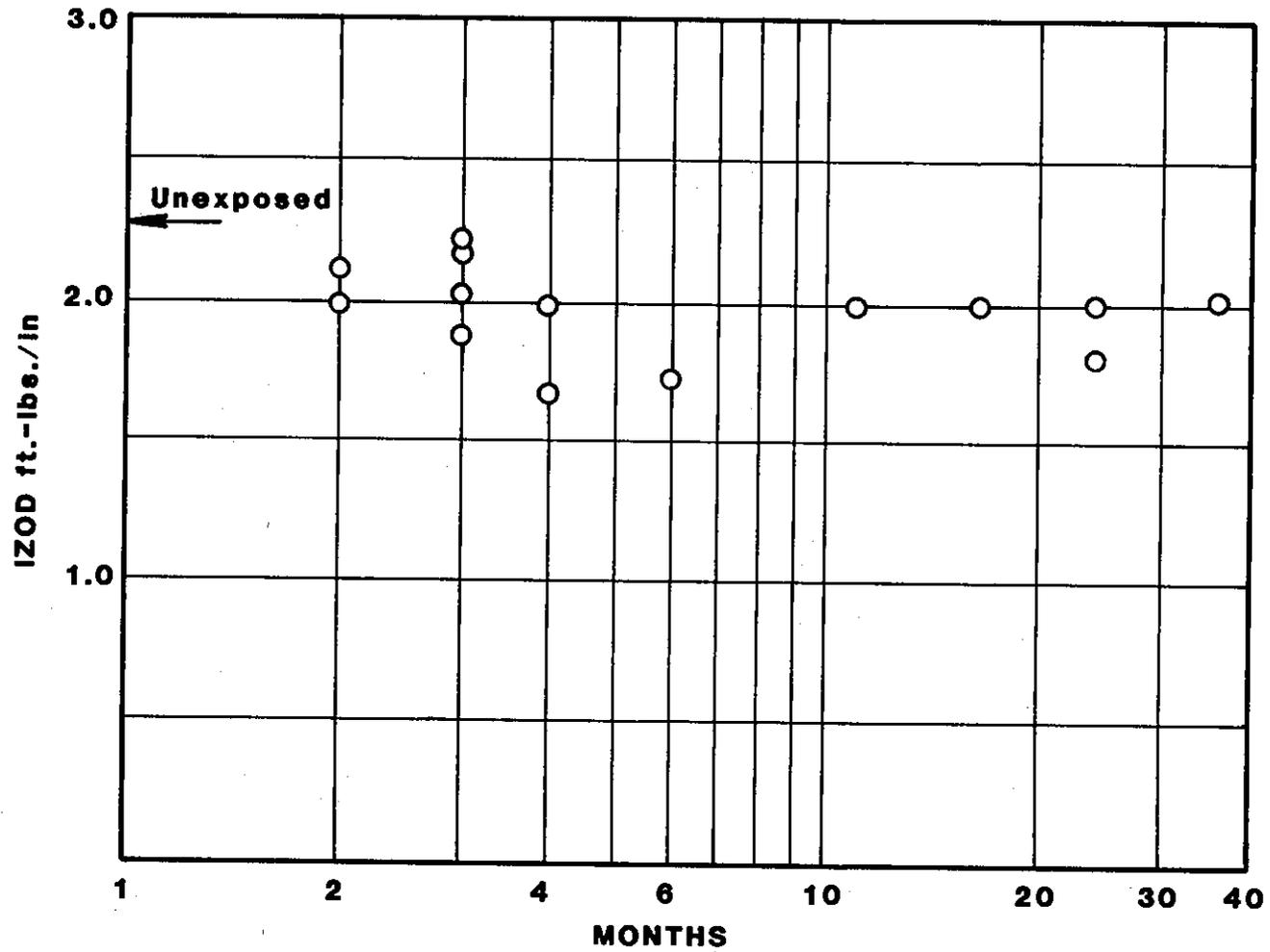


FIGURE 17. - Izod data for PC. Environment: Heat (180°F), humidity, UV, and water spray exposure.

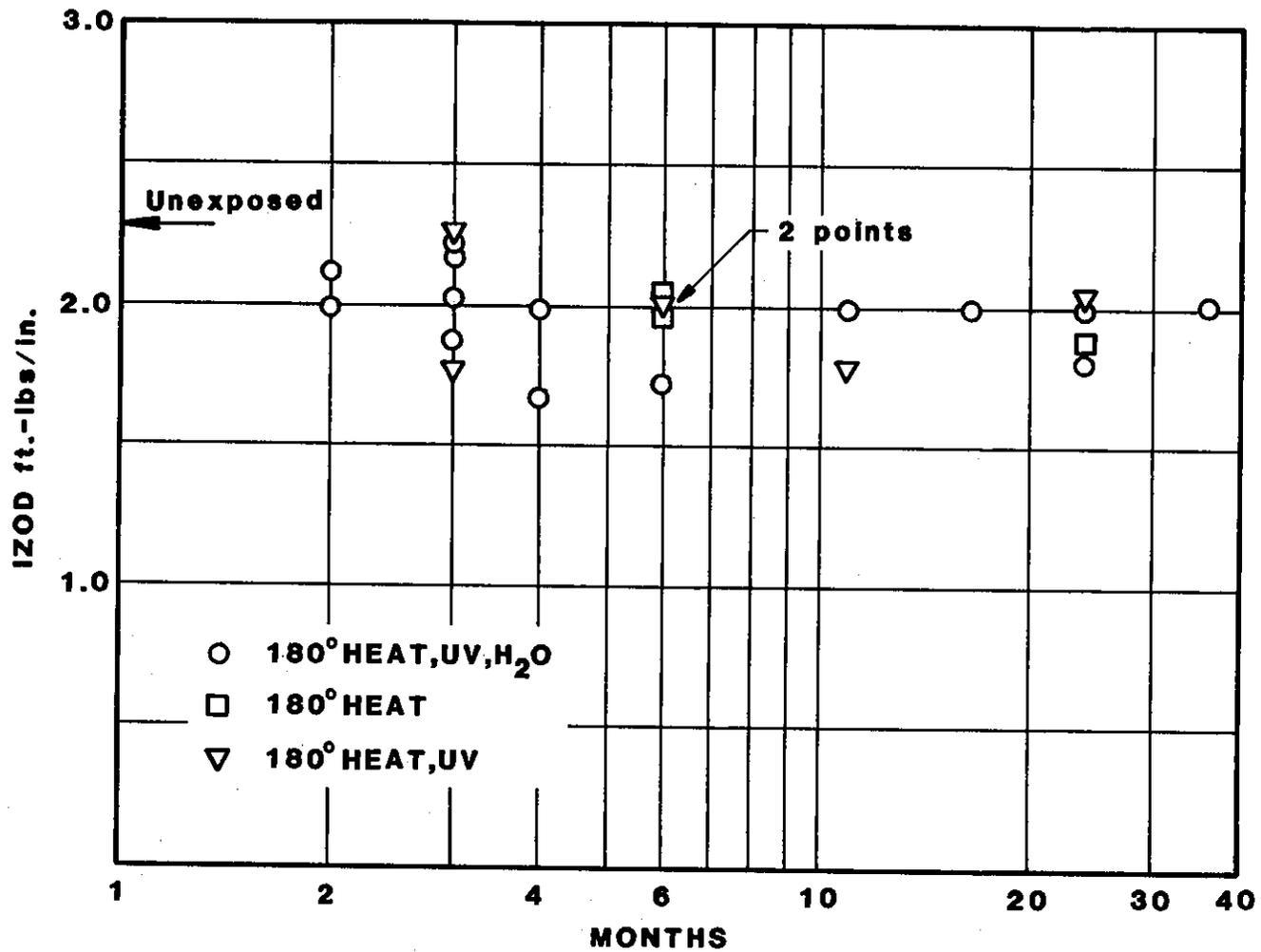


FIGURE 18. - Izod data for PC. Environment: Heat (240°F) and humidity exposure.

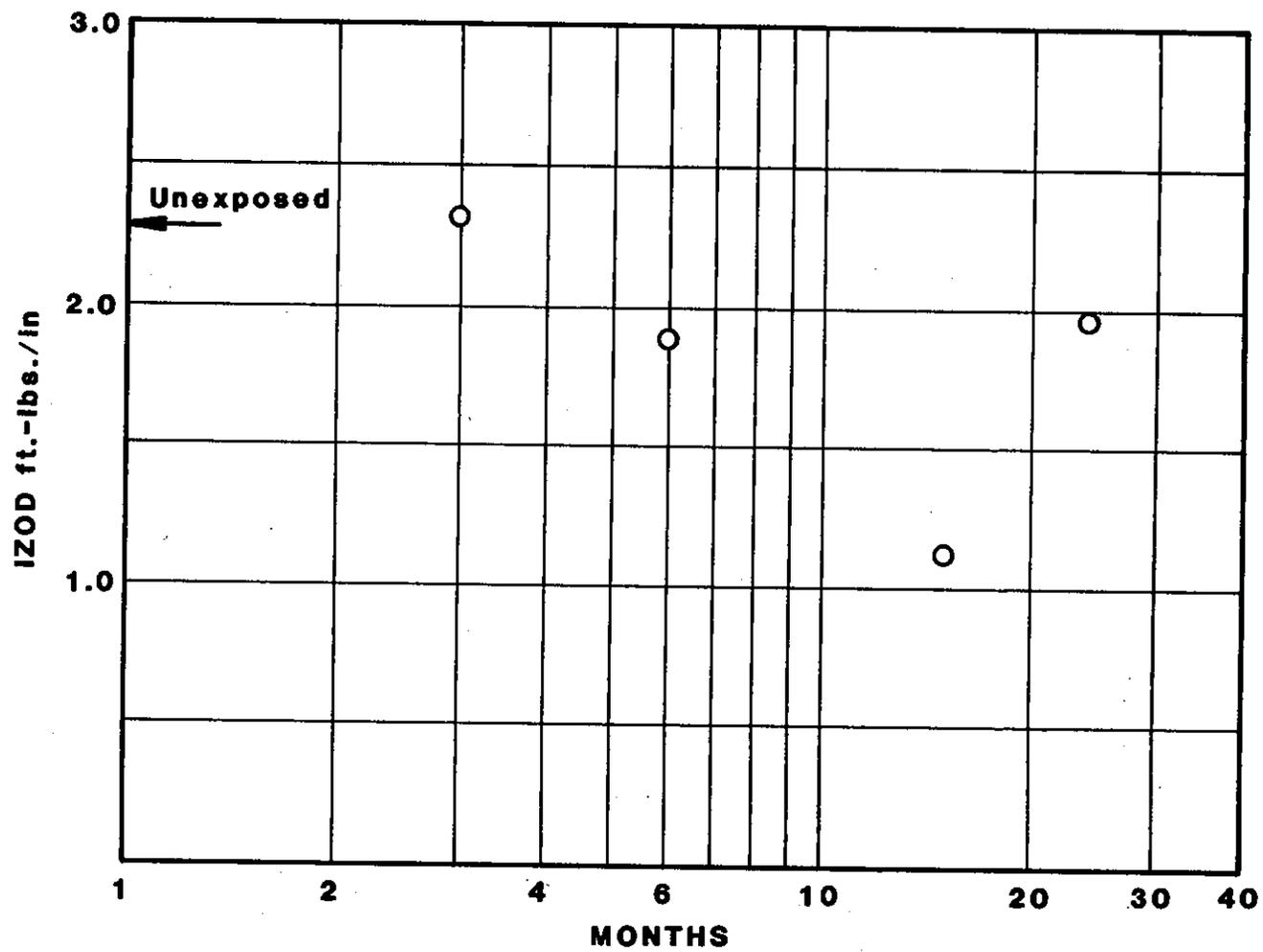


FIGURE 19. - Izod data for PC. Environment: Heat (240°F), humidity, and UV exposure.

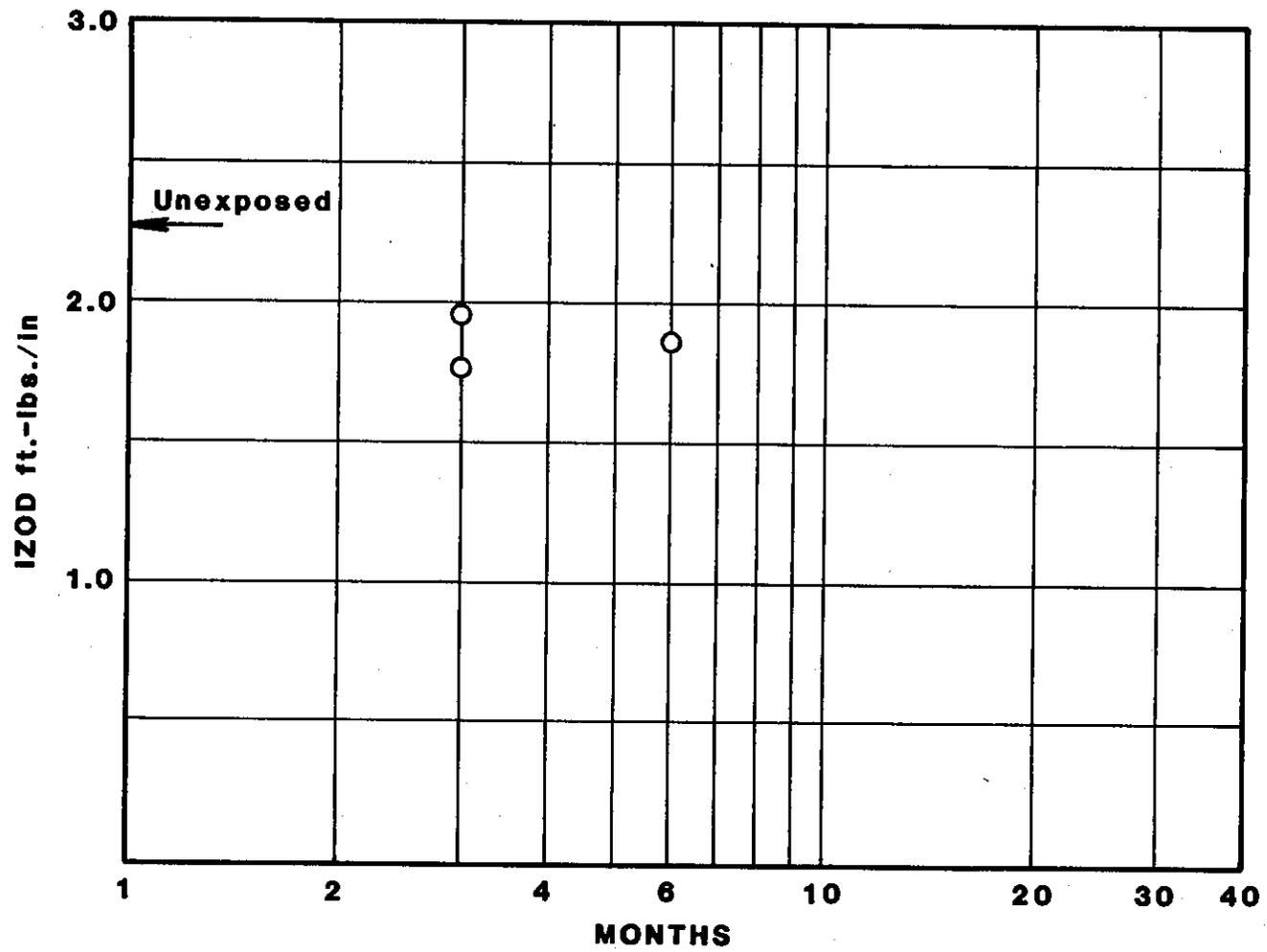


FIGURE 20. - Izod data for PC. Environment: Heat (240°F), humidity, UV, and water spray exposure.

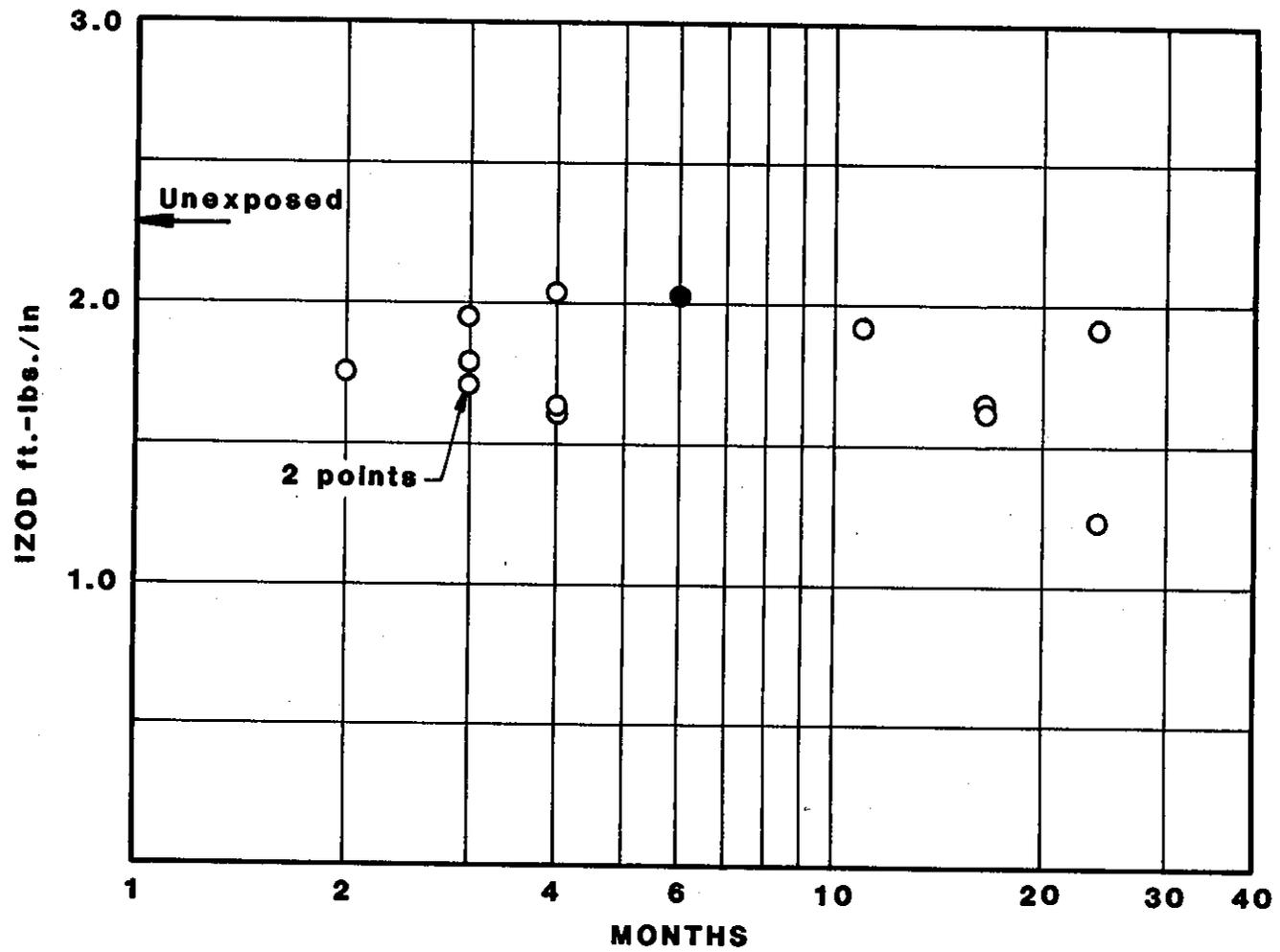


FIGURE 21. - Izod data for PC. Environment: Heat (180°F), all environments.

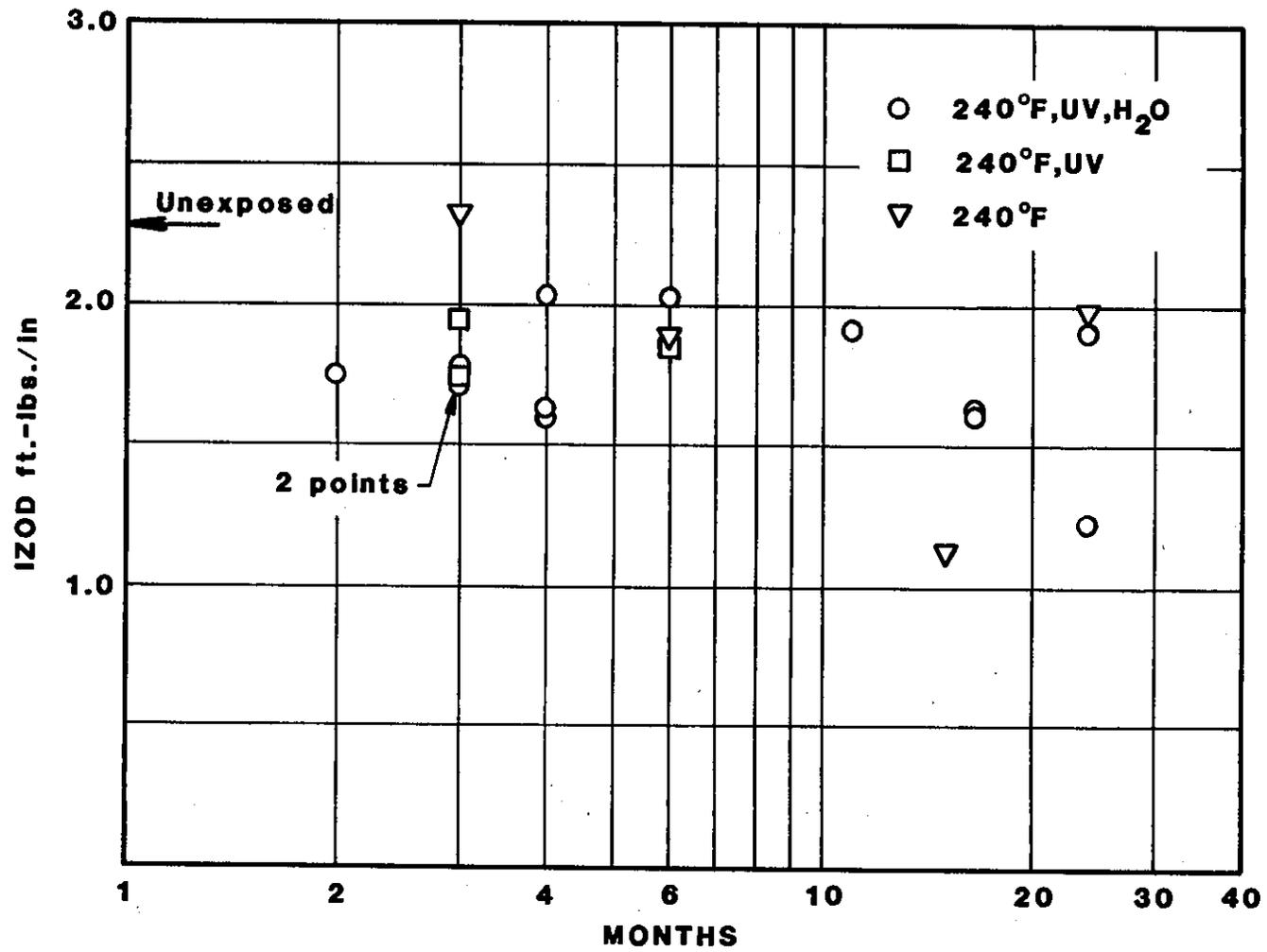


FIGURE 22. - Izod data for PC. Environment: Heat (240°F), all environments.



FIGURE 23. - Darkening of PC lens caused by UV exposure.

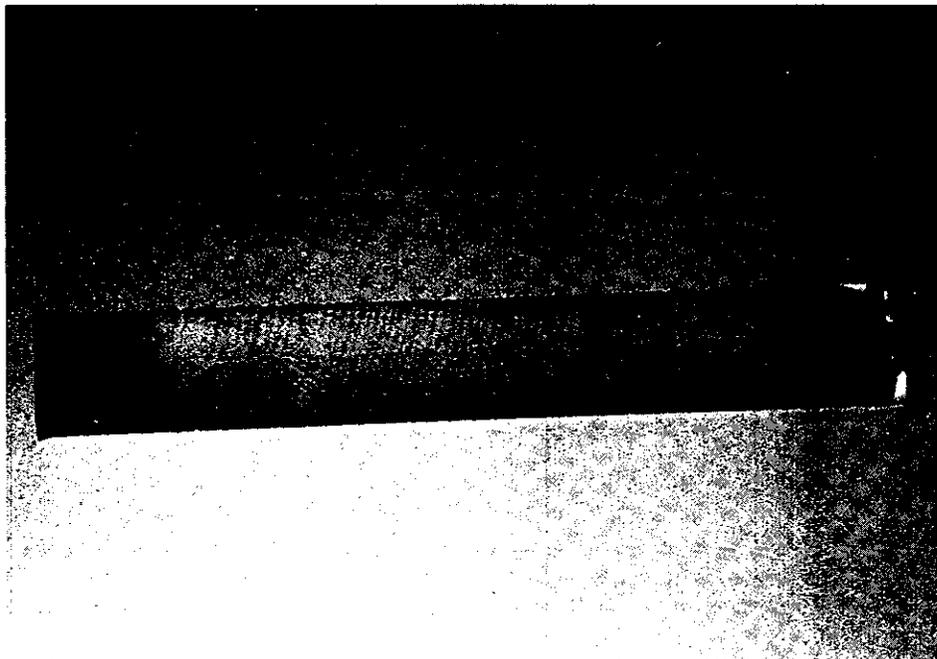


FIGURE 24. - Depth of discoloration caused by UV exposure.

In summary, the results of the present testing are consistent with (2) regarding humidity effects and not at odds with (4) on UV effects when the nature of the tests are considered. Humidity and UV exposures used in this test do not degrade the material toughness. Also, because of the limited extent of the UV-affected area and the fact that this area would be in compression during a luminaire explosion would indicate that UV exposure alone is not a significant factor for PC lenses for luminaires.

#### 3.4.2 Heat (180°F) and Humidity Exposure

Reference 5 indicates that heat affects do not occur below 100°C (212°F). The limited data obtained in this program (three lenses), shown in Figure 15, would indicate no diminution of properties at six months and 17% diminution after 24 months exposure.

#### 3.4.3 Heat (180°F) Humidity and UV Exposure

The data for six lenses exposed to 180°F heat, humidity, and UV up to 24 months do not conflict with the data for each environment alone. A maximum reduction of 22% in the Izod toughness, shown in Figure 16, would seem to indicate little effect of UV and no synergism between UV, heat, and humidity.

#### 3.4.4 Heat (180°F), Humidity, UV, and Water Spray Exposure

The most complete data for 180°F exposure was obtained with 14 lenses subjected to humidity, UV, and water spray. These data are shown in Figure 17. In fact, the population of Izod values is indistinguishable between heat and humidity, heat, humidity, and UV; and heat, humidity, UV, and H<sub>2</sub>O. The three groups are shown plotted together in Figure 18.

The major effects of water hydrolyzing PC which are noted in (2) are based on 100% relative humidity. According to data in (2), samples exposed to 100% relative humidity and 180°F for 30 days will have their molecular weights diminished by hydrolysis sufficiently to change from ductile to brittle failure behavior in a tensile test. AT 240°F exposure, the transition time is only 10 days.

No such drastic effect was exhibited in our data for two reasons. Because of the "critical thickness" effect, all of the PC specimens in our program failed in a brittle<sup>1</sup> manner. Therefore, there was no ductile behavior from which to transition. Secondly, the lenses were heated to 180°F on one side with one face exposed to 100% relative humidity at a somewhat lower temperature. This is a realistic use-condition, but there is no accurate indication of how much water actually enters the specimen under these conditions.

<sup>1</sup>Brittle in this sense is intended to refer to failure characteristics of thermoplastics, and not relative to glass. A brittle thermoplastic will show many times the ductility of a glass.

In summary, any effects of humidity and water vapor were not evident in this test. If lenses are designed to the relatively ductile "brittle" failure behavior of PC, it would appear that water exposure would have little or no effect on the life.

#### 3.4.5 Heat (240°F) and Humidity Exposure

The 240°F data shown in Figure 19, while sparse and showing considerable scatter, give indications of substantial effects after 12 months exposure. This is in agreement with (5) which indicates that heat degradation occurs at temperatures above 212°F.

#### 3.4.6 Heat (240°F), Humidity, and UV Exposure

The three short time data points for this exposure, which are shown in Figure 20, show the same general trend as 240°F heat and humidity in the previous section.

#### 3.4.7 Heat (240°F), Humidity, UV, and Water Spray

There is substantially more data available at this condition than for the other 240°F conditions. See Figure 21. Again, as with the 180°F data, the three exposure populations cannot be distinguished. They are shown plotted together in Figure 22. It would appear that the major effect comes from the 240°F heat and that there is little effect of UV and H<sub>2</sub>O spray. At 24 months' exposure time, the toughness of the PC appears to be one half that of virgin material.

#### 3.4.8 Effects of Overheating

As was mentioned earlier, a number of overheats caused specimens to be discarded. Several specimens overheated to an undetermined extent during the last month of the test. They had deformed under their own weight so that the temperature had at least reached the heat deflection temperature of 280°F. The exact temperature is not known, and the exposure time was less than six hours. Three of these specimens were only slightly warped and were cut into Izod specimens and tested. The specimens are noted in Tables 3, 4, and 8, and are plotted as solid symbols in Figures 15, 16, and 21.

Again, these data are indistinguishable from the total population at the specified test temperature. It would appear that drastic, but short term, overheats do not have a deleterious effect on PC.

#### 3.4.9 Pressurization Tests

Tables 5 and 6 list data from three specimens which were pressurized in their test fixtures early in the program (May and June of 1981). They were expected to break at 150 psi but only deflected when taken to a maximum pressure of 360 psi.

### 3.4.10 Fracture Surface

Figure 25 shows the fracture surface of an Izod specimen cut from a lens exposed to humidity and UV only for 18 months. It is clear from the break pattern that that failure began in the corner of the notch which was exposed to UV. Compare this failure surface with that of Figure 8 which shows the failure surface of a virgin specimen. This illustrates that the fractures are affected by the test conditions and helps to establish the validity of the test method.

## 3.5 Effect of Hydraulic Fluids on Polycarbonate

### 3.5.1 Procedure

To evaluate the effect of hydraulic fluids on the mechanical properties of polycarbonate, a specialized creep test was devised. The test is shown schematically in Figure 26. A cantilever beam, 1 in. wide, 3/16 in. thick, and 3-1/2 in. long, is notched at the base. The notch was selected so that the stress at the root of the notch would be about one half of the yield strength of the material. The edges of the notch were dammed with a silicone adhesive elastomer so that the notch would retain fluids. The beam is loaded with a 1-lb weight, as shown in Figure 26.

The fluids used in test were identified to SwRI only by a code number and type. The manufacturer was identified only by a code letter. Mr. Kenneth Klouse of the U.S. Department of Labor supplied 28 five-gallon cans of hydraulic fluid from 14 companies. These are summarized in Table 9. Six of the fluids, covering three major types, were chosen for evaluation. These are also shown in Table 9.

The precise nature of the attack of the hydraulic fluids on the polycarbonate was not investigated. The mechanical creep response of the cantilever test specimens was recorded for times up to 482 days. A total of 19 specimens were exposed--1 control and 3 for each of 6 fluids.

### 3.5.2 Results

In Figure 27, the deflection of the cantilevers as a function of log time is plotted. For clarity only, one specimen for each fluid is plotted. This gives an excellent picture of how the attack of the hydraulic fluids on the polycarbonate occurs.

The glycol fluid No. 20 caused specimen failure in four to six hours, which appears on the semilogarithmic chart of Figure 27 as one day. The dark symbols indicate the failure point. The remainder of the oils have a much less severe effect on the PC. Generally, the mechanical response was a rapid creep over two or three days followed by weeks of very little creep. Then a particular sample begins a faster creep which is markedly different from the other specimens, and which results in fracture.



FIGURE 25. - Fracture surface of UV-exposed specimen.

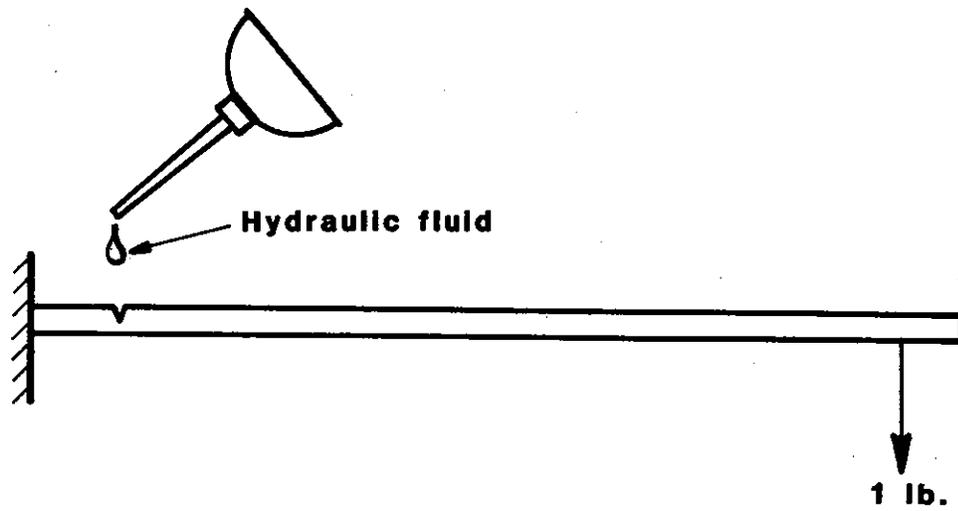


FIGURE 26. - Test schematic and effect of hydraulic fluids on polycarbonate.

TABLE 9. - Summary of hydraulic fluids

Oil Type	Company Designation	Fluid Specimen Numbers	Fluid Specimens Tested	Number of Test Specimens
Inverts	A	16/17*	16	3
	B	1,25,26/27*		
	D	22/23*		
	F	2,4,5	2,5	6
	G	7,9	7	3
	H	14/18*		
	Undesignated	12		
Glycols	C	19,20,28	20	3
	Undesignated	21		
Synthetics	E	6,8,10,13	24	3
	Undesignated	3,11,15,24		

Total Specimens Tested 18

\* 16/17, etc. indicates two samples of the same oil were received.

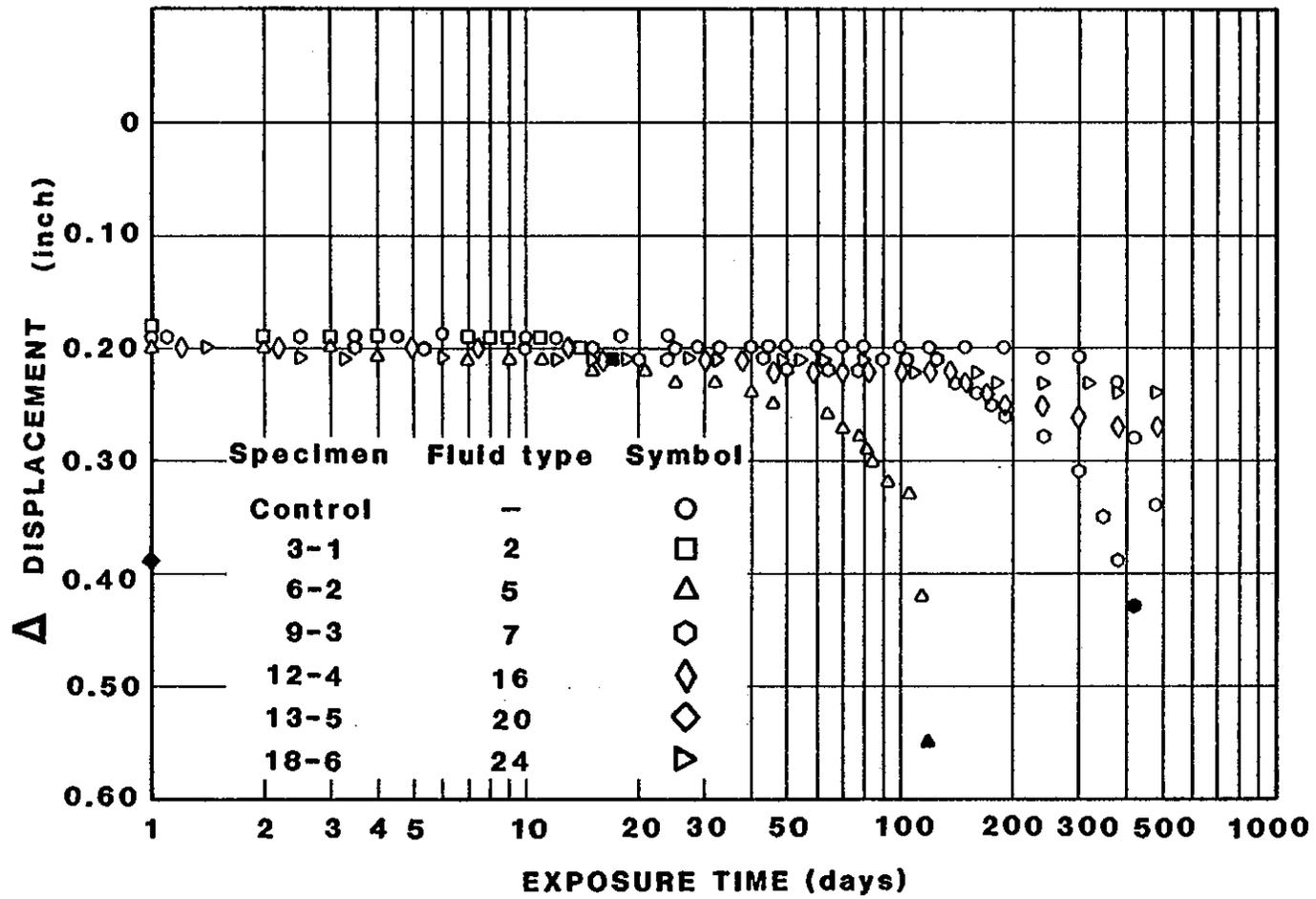


FIGURE 27. - Creep deflection of cantilever beam specimens.

Figure 27 shows only the deformation pattern of one specimen of each type. The actual failure time of all specimens is given in Table 10, and log time comparison of all failure times is given in Figure 28. Although some types differ in fail time by 253 days, the groupings on a log time basis are fairly consistent.

### 3.5.3 Conclusions

Inspection of Figures 27 and 28 and Table 10 leads to the following conclusions. Fluid Nos. 24 and 16 have no apparent effect on the polycarbonate. In fact, for the last 100 days of the test, the single control exhibited more creep than the specimens with Fluid No. 24. To say that this fluid improved the performance, which may be true, cannot be substantiated on the basis of these tests alone.

A ranking of these fluids with qualitative comments is given in Table 11.

Obviously, the glycol type No. 20 is completely unsatisfactory because of its rapid attack on the polycarbonate. The three invert fluids, Nos. 7, 5, and 2, attack the polycarbonate but in a less severe manner than No. 20. It would appear that the invert No. 16 and the synthetic No. 24 are perfectly satisfactory for use with polycarbonate.

Note that of the four invert fluids tested, three manufacturers were represented. The fluid of Manufacturer A caused no failures, while the two fluids of Manufacturer F both caused all specimens to fail during the test.

TABLE 10. - Results of oil exposure tests 482-day duration

Oil Type	Specimen Number	Days to Break
2	1-1	37
2	2-1	18
2	3-1	64
5	4-2	119
5	5-2	372
5	6-2	119
7	7-3	301
7	8-3	No break
7	9-3	430
16	10-4	No break
16	11-4	No break
16	12-4	No break
20	13-5	< 1
20	14-5	< 1
20	15-5	< 1
24	16-6	No break
24	17-6	No break
24	18-6	No break
Control	19	No break

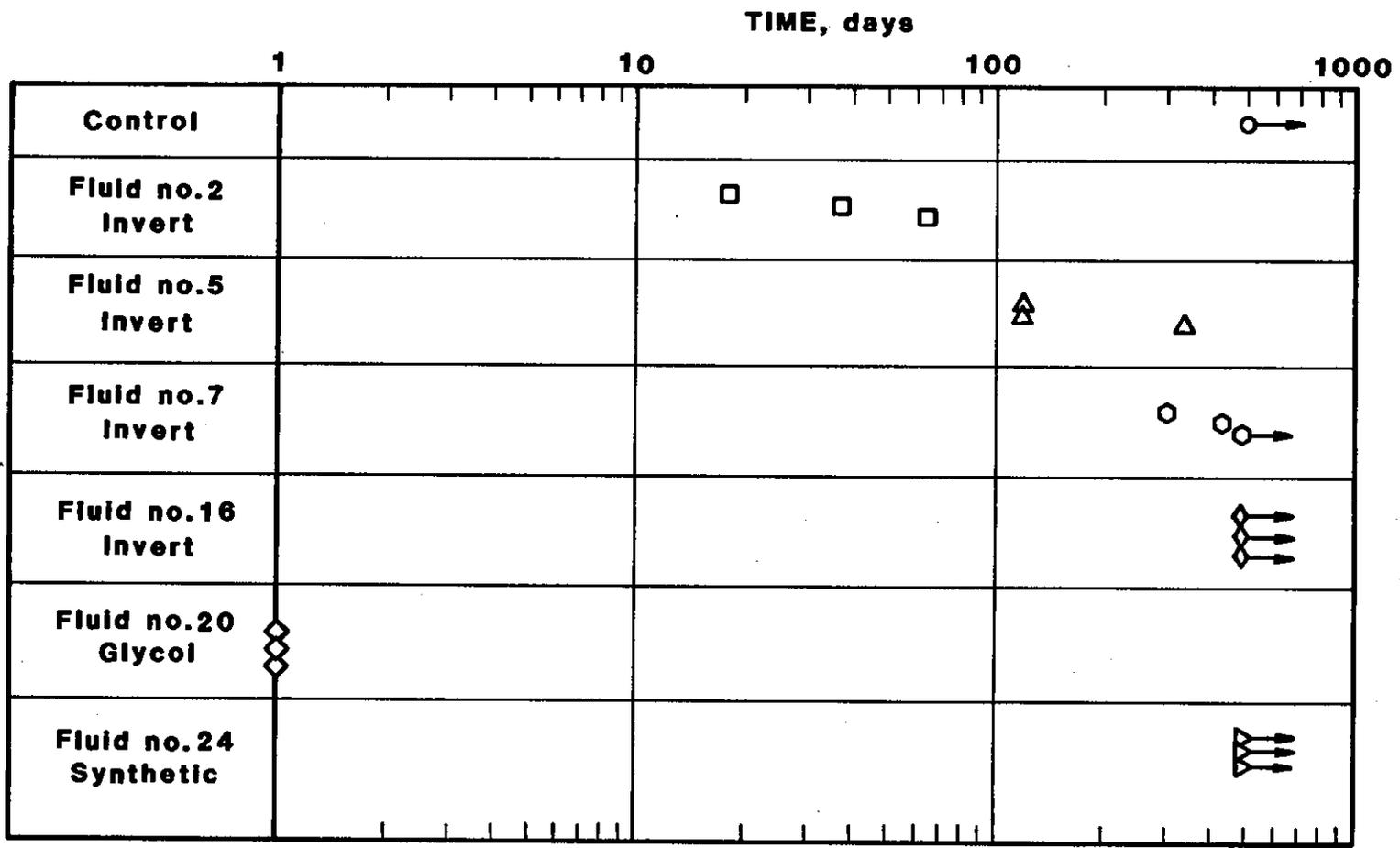


FIGURE 28. - Failure time of beam specimens.

TABLE 11. - Ranking of hydraulic fluids

Fluid Number	Company Designation	Oil Type	Qualitative Rating
24	E	Synthetic	Best
16	A	Invert	Good
7	G	Invert	Fair
5	F	Invert	Marginal
2	F	Invert	Not satisfactory
20	C	Glycol	Unuseable

## 4.0 ADHESIVE TESTS

The adhesives tested were Armstrong<sup>1</sup> 2000 (epoxy), Hysol<sup>2</sup> 934 (epoxy), and General Electric<sup>3</sup> RTV 108 (silicone). They were used to bond glass lenses into the Type B fixture shown in Figure 4. The glass lenses were 0.75-in.-thick x 2.5-in.-diameter, circular, Pyrex, annular edge, sight glass with 150 psi x 400°F service rating. This particular window was chosen because it is a commercially-available, off-the-shelf item and it is rated to a pressure and temperature compatible with the test conditions.

### 4.1 Test Procedure

The Type B fixture is similar to the Type A fixture in design and usage except that it is designed to place the adhesive in tension when the fixture is pressurized. This does not correspond to the use condition but is a definitive test for adhesive degradation. The adhesive/sealants were lightly coated onto the face of the seat. The lens was centered in the seat and pressed in place with a 1-lb force. Thermocouples were bonded to the lenses with RTV silicone. The specimens were cured and mounted in chamber in a similar manner as the Type A fixtures with PC lenses.

After exposure to heat and humidity for the correct length of time, the adhesives were subjected to tensile forces by pressurizing the fixture. Pressurization was done at the test temperature.

### 4.2 Adhesive Test Results

Table 12 shows the results of tests on epoxy resins, and Table 13 shows the results for the GE RTV 108 silicone adhesive. The epoxy adhesives failed at extremely low pressure. Only one, Hysol 934, reached 300 psi, but a similar Hysol specimen failed at 5 psi.

The RTV 108, however, showed good results with exposures up to 24 months at 300°F and 36 months at 240°F. The lowest result was 100 psi for Specimen 31-3.

### 4.3 Conclusions

Because of their brittle nature, epoxy adhesives are not suited for this application. Their failures were erratic. The RTV silicone, however, retains its flexibility and provides adequate bonds and seals at high temperatures and long times.

<sup>1</sup>Armstrong Products Company, 407 Argonne Road, Box 647, Warsaw, IN 46580.

<sup>2</sup>The Dexter Corporation, Hysol Division, Olean, NY 14760.

<sup>3</sup>Silicone Product Department, General Electric Company, Waterford, NY 12188.

TABLE 12. - Exposure tests for epoxy adhesives

Specimen No.	Adhesive Adhesive	Start Date	Stop Date	Duration	Temperature, °F	Failure Pressure, psi
29-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	20
32-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	15
35-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	0
37-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	0
27-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	5
34-1	Armstrong T-900	2/10/81	2/11/81	1 day	300	25
27-2	Armstrong T-900	5/81	6/81	1 month	300	26
28-2	Armstrong T-900	5/81	6/81	1 month	300	20
27-3	Hysol 934	6/81	10/81	4 months	180	140
27-4	Hysol 934	12/81	2/82	2 months	240	5
28-5	Hysol 934	12/81	2/82	2 months	240	300

TABLE 13. - Exposure tests for GE RTV 108 silicone adhesives

Specimen No.	Start Date	Stop Date	Duration	Temperature, °F	Failure Pressure, psi
30-1	2/10/81	2/11/81	1 day	300	150*
31-1	2/10/81	2/11/81	1 day	300	150*
36-1	2/10/81	2/11/81	1 day	300	125*
38-1	2/10/81	2/11/81	1 day	300	125*
28-1	2/10/81	2/11/81	1 day	300	100*
33-1	2/10/81	2/11/81	1 day	300	100*
31-2	5/81	7/81	2 months	240	272
35-1	5/81	7/81	2 months	180	280
36-1	5/81	7/81	2 months	180	268
35-2	9/81	11/81	2 months	300	290
36-2	9/81	11/81	2 months	300	300
31-3	9/81	1/82	4 months	180	100
32-3	9/81	1/82	4 months	180	300
35-4	1/82	5/82	4 months	240	210
36-4	1/82	5/82	4 months	240	280
31-5	8/84	1/85	6 months	240	320
32-5	8/84	1/85	6 months	180	360
31-4	2/83	10/83	12 months	300	290
32-4	2/83	10/83	12 months	300	285
27-5	2/83	12/84	22 months	180	305
28-2	2/83	12/84	22 months	180	310
29-2	2/83	12/84	22 months	240	300
30-2	2/83	12/84	22 months	240	285
35-5	2/83	12/84	24 months	300	310
36-5	2/83	12/84	24 months	300	200
37-2	9/81	11/84	36 months	180	320
38-2	9/81	11/84	36 months	180	330
33-2	9/81	11/84	36 months	240	340
34-2	9/81	11/84	36 months	240	350

\* No failure

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

### 5.1 Polycarbonate Lenses

Polycarbonate lenses were tested under conditions which realistically represent conditions in mine luminaires. The conditions include exposure to 180°F and 240°F heat, humidity, water spray, and ultraviolet light. The major effective environment in causing degradation is heat. Exposures at 180°F up to 36 months showed a slight reduction in toughness. Appropriate design safety factors can be utilized to extrapolate these data for use for periods of four years or more.

Similar testing at 240°F indicated definite degradation after two years exposure. Extrapolation of these results would be risky because of the nonlinear nature of some of these degradation processes. Additional testing at extended times at 240°F is recommended.

For design purposes, the material strength should be modified to reflect the degradation caused (principally) by elevated temperature exposure. A strength reduction factor is proposed which is based on a ratio of the Izod values. One value is based on the average of all tests at a given temperature. The other is the Izod value for unexposed lens material. In addition, a limitation of service life at a given temperature should be imposed.

The strength reduction factor (SRF) is defined by

$$\text{SRF} = \frac{\text{Lowest Average Izod for Exposed Lenses.}}{\text{Izod for Unexposed Lenses}}$$

Based on this formula, the SRF for 180°F service is 0.70 and for 240°F service is 0.49.

Because of the small amount of degradation in the lenses exposed at 180°F, there is little risk in extrapolating the data past the 36 months maximum exposure. Therefore, a service life of 48 months is recommended for 180°F exposure. Conversely for 240°F exposure, the degradation is such that a service life limitation of 24 months is recommended.

The service life limitation and strength reduction factors should be used in addition to normal design safety factors. For instance, the short-term design stress can be taken as one-half the yield strength at the in-service operating temperature, and the SRF applied to this value.

Exposure of polycarbonate to hydraulic fluids indicated rapid attack of certain fluids and no attack by others. Since the fluids were designated by code, no overall conclusion about suitable fluids can be made.

### 5.2 Adhesives

Epoxy adhesives are not adequate for the installation of lenses. GE RTV 108 silicone adhesive is quite good as an adhesive and sealer.

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