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CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM

Collector Subsystem Extended Life Test. Final Report

May 18, 1979

Work Performed Under Contract No. EY-76-C-03-1111

Boeing Engineering and Construction Company
Seattle, Washington

U.S. Department of Energy

Solar Energy

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FINAL REPORT

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Prepared for

United States
Department of Energy

under
Contract DE-AC03-76ET20424
(Formerly EY-76-C-03-1111-Modification No. 4)

by
Boeing Engineering and Construction Company
a Division of The Boeing Company
Seattle, Washington

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FOREWORD

This document is the final technical report to be issued under DOE Contract EY-76-C-03-1111 (Modification No. 4). The objective of this contract modification is to conduct a test program to evaluate the long term durability and stability of heliostat plastic materials. Work under this contract was initiated on March 31, 1977 and is scheduled for completion on May 31, 1979. This report, summarizing the effort from March 31, 1977, through December 31, 1978, complies with Contract Data Requirement No. 15.

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1.0 INTRODUCTION AND SUMMARY

To evaluate long term durability and stability of heliostat reflector and enclosure materials an extended life test program was performed on Research Experiment Heliostats by Boeing Engineering and Construction. The reflectors and enclosures were periodically evaluated and analyzed for the effects of dirt, sunlight, wind and thermal cycling on the mechanical and optical properties of Tedlar* and changes in the Mylar** reflector tension and reflectivity. During testing the heliostats were maintained and semi-annually evaluated for optical and mechanical stability. The heliostats tested were located at the Boeing Boardman, Oregon test facility. The following lists the dates of the more significant events related to the work described in this report.

EVENT	DATE
Installation of Heliostats H0, H1	August 27, 1976
Installation of Heliostat H2	October 28, 1976
Initial Data Sampling	December 15, 1976
Completion of Collector Subsystem Research Experiments Contract	June 24, 1977
Relocation of H2 at Sandia Livermore	September 16, 1977
First Semiannual Interval Data Collection	October 11, 1977
Final (Second Semiannual) Data Collection	April 12, 1978
Failure of H0 Enclosure	July 15, 1978
Failure of H1 Enclosure	November 3, 1978

The purpose of the program was to obtain data through measurements and observation to aid in heliostat design improvement. Certain weather and time related information, most reliably acquired by real time exposure testing, was sought through performance of mechanical and optical testing of the Boardman heliostats. The key areas of technical concern were:

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* DuPont polyvinyl fluoride, 400 SG (EXP) TR co-polished with Mylar.
** DuPont polyester, 200 X M648A

1) Enclosure and reflector optical property retention

2) Enclosure and reflector mechanical property retention

3) Reflector creep (or loss in membrane tension) using bonded joints

In-place optical measurements as well as laboratory optical measurements on coupons cut from a heliostat, mechanical measurements from heliostat coupons, reflector sag measurements, and observations of the air supply system pressure stability and filter condition were made during the initial and two semi-annual test samplings. Results are summarized here and discussed in greater detail in appropriate sections of the report.

SUMMARY

The in-place optical measurements of the heliostats showed a gradual decrease in overall reflectance (T^2R). This was expected, as the heliostats were not washed during the program. Some dust and dirt accumulation inside the heliostat was also observed. This was due to high air flow (from leakage in the base) and inadequate filtration. Near zero leakage and improved filtration, features of recent heliostat design, are expected to eliminate this problem.

Enclosure and reflector material coupons were cut from a heliostat and optically and mechanically evaluated in the laboratory before and after cleaning. Losses as high as 6% in enclosure specular transmittance and 16% in mirror specular reflectance were measured for the as-received (dirty) samples after 21 months of exposure. Permanent transmittance losses of 1 to 2% and reflectance loss of 12% were measured (after cleaning). Permanent reflectance loss is believed to be due to oxidation of the aluminum surface. Protective coating of the surface is recommended for future membranes.

Results of laboratory mechanical properties testing showed no losses in yield strength and moderate losses in ultimate strength and ultimate elongation for enclosure material. Substantial decreases in elongation were observed in the reflector Mylar, indicating ultra-violet damage and the need for using a stabilized film in the future. No creep (sag) in the reflector film or adhesive was measured over the 21 months, confirming the pretensioned/bonded membrane approach to reflector design.

The enclosure mechanical properties data were plotted against time along with data from other real-time and accelerated tests performed at other sites. Considerable data scatter exists, but the data suggests the useful life of Tedlar is much greater than the 6 year range of the plot.

Heliostats H0 and H1 were damaged by high winds (29 m/s (65 mph)). The enclosures failed along the heat sealed seams. Seam strength, strain rate sensitivity and tear initiation resistance were measured and found to be more than adequate to withstand the wind loads encountered. Fatigue in the material adjacent to the heat sealed joint is the suspected failure mode. A research program to develop an understanding of the mechanism of failure is recommended.

2.0 OPTICAL PROPERTIES

2.1 Heliostat Transmittance/Reflectance

In-place optical measurements were taken for heliostat No. HO on December 15, 1976, October 11, 1977, and April 12, 1978. All data was taken with a TRW differential radiometer, model DR-2, equipped with a 5° collimating tube. Measurements were taken of single-pass transmittance (sun rays through single layer of dome material, taken along dome centerline normal to rays); double pass transmittance (sun rays through 2 layers of dome material, taken along line outside of dome in plane containing sun, dome horizontal diameter and radiometer); and overall heliostat reflectance (sun rays through 2 layers of dome material and reflected by mirror, taken along mirror centerline). Results are plotted in Figure 2-1. The mirror reflectance can be inferred by ratioing double pass transmittance (T^2) with the overall reflectance (T^2R). The heliostat was not washed prior to scanning.

The loss in transmittance observed in the first 12 months is believed to be due to dust and dirt accumulation on the outside of the enclosure, and to some extent on the inside. During the 6 months from October 11, 1977 and April 12, 1978, the blower filters required more frequent changing due to rodent damage and considerably greater dust ingestion was observed. Dust was visibly apparent on the reflector surface and gauze wipes revealed some dust had been settling on the inside surface of the enclosure. This loss of overall heliostat reflectance (T^2R) due to internal contamination emphasizes the need for reduced air flow and adequate dust filtration for future heliostat enclosure designs.

It should be emphasized that this heliostat enclosure had not been cleaned since April 3, 1977 and the reflector had never been cleaned since its installation on November 1, 1976. The degradation described above is attributed primarily to dust and dirt contamination. This is substantiated in Section 3.1 where coupons cut from the enclosure are optically evaluated in the laboratory before and after cleaning.

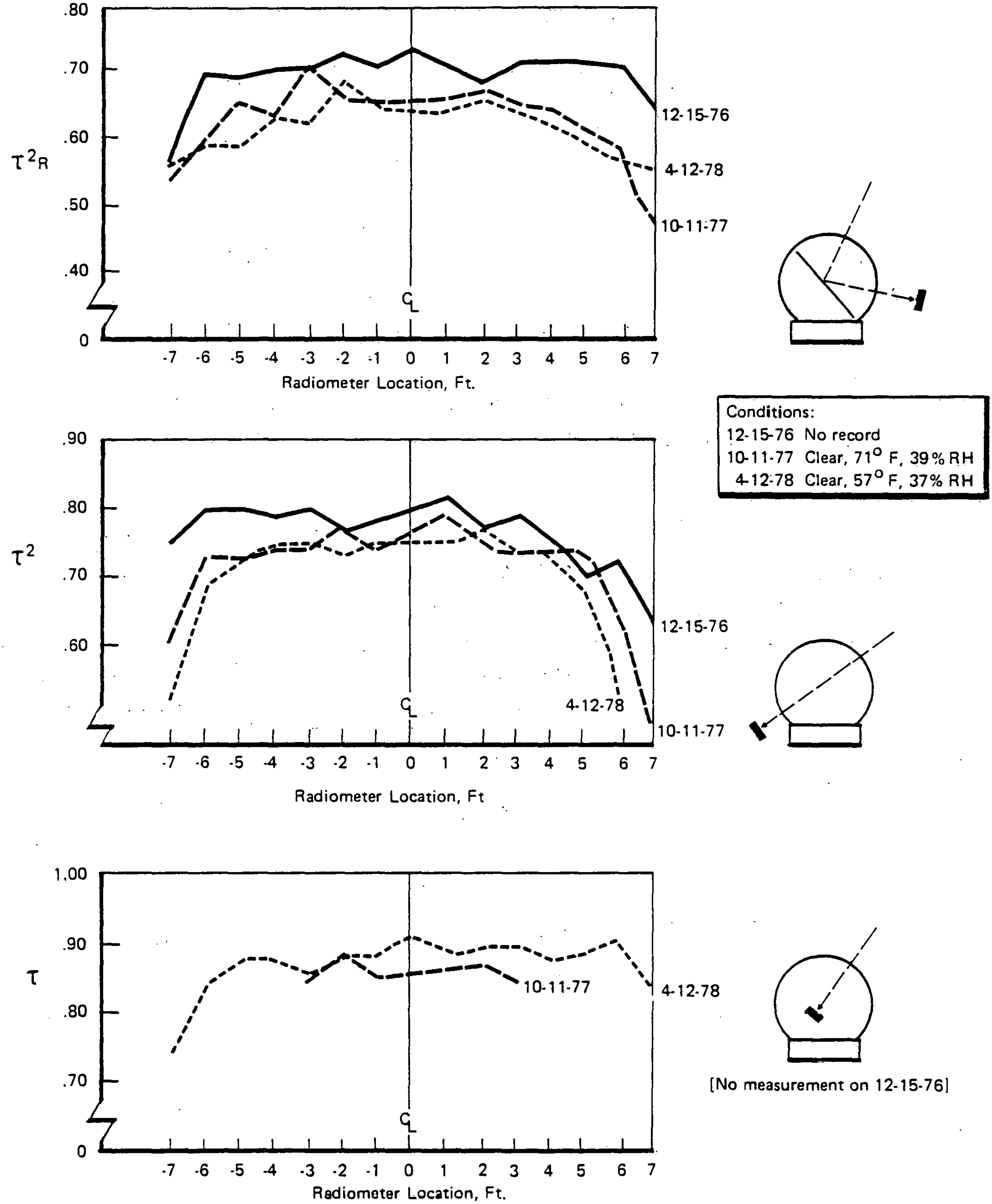

Figure 2-1 Transmittance/Reflectance Tests

2.2 Enclosure Transmittance

Mechanical (micro-tensile) and optical (specular transmittance) coupons were cut from a south facing enclosure gore on October 11, 1977 and April 12, 1978. (BEC owned heliostat erected in July, 1976.) Coupons were taken at 6 feet and 12 feet up from the heliostat ground plane. In addition, a mechanical test coupon was cut to include a gore seam. Removal of the coupons was accomplished with a scalpel. The holes were patched with pressure sensitive Tedlar tape with acrylic adhesive. No tear propagation from these holes was ever observed during the program. The coupons were taken to Boeing laboratories and tested for specular transmittance before and after cleaning, yield strength, ultimate strength and ultimate elongation. The results of the transmittance tests, along with control specimen data are provided in Table 2-1.

The optical data reveals that as received degradation (dust, dirt, etc.) occurred to the extent of approximately 4 to 6% at 6 feet above the base plane, while a 0 to 2% loss was observed at the 12 foot level. Upon cleaning, (water/detergent/soft brush and distilled water rinse) the transmittance values were restored to within 0 to 2-1/2% of the control sample value. It should be noted that 3 of the 4 post-cleaning transmittance values are grouped within 1.2% band (89.5 ± .6%) with their average about 0.5% below the control value (90.3). (The instrument accuracy is estimated to be ± .5%). The 4th value (87.4) is about 2-1/2% below the control and represents the worst case degradation observed.

Table 2-1.

Optical Data for Enclosure

SPECIMEN IDENTIFICATION		OPTICAL SPECULAR TRANSMITTANCE % (1)	
		PRIOR TO CLEANING	POST CLEANING
South-Southwest Gore Location - 6 feet up from base	10/11/77	84.6	88.8
	4/12/78	83.5	89.6
South-Southwest Gore Location - 12 feet from base	10/11/77	87.1	87.4
	4/12/78	87.6	90.0
Seam Sample - SSW Gore - 5.5 feet up from base	10/11/77	-	-
	4/12/78	-	-
Control		89.8	90.3

(1) 0.5°Cone Angle
Normal Incidence
Angle

The transmittance-versus-exposure-time data taken from the Boardman enclosure coupons, along with real time data from other Tedlar coupon exposure testing, is plotted in Figure 2-2. Included on the same plot is data from accelerated testing of Tedlar material. Real time test data is shown for Boardman, Albuquerque and the Desert Sunshine Test Facility (DSET) in Phoenix. Accelerated exposure data are from tests on samples from DSET and the Boeing X-200 Xenon arc-solar simulator.

The Boardman data was plotted directly (no adjustments). Albuquerque data was adjusted by increasing the months of exposure by the ratio of the Albuquerque average insolation to that in Richland, Washington (site nearest Boardman with available insolation data) DSET real time data was adjusted similarly, multiplying the months of exposure by the ratio of Phoenix average insolation to Richland average insolation. The DSET and Boeing X-200 accelerated test data equivalent exposure duration was determined by dividing the total insolation (in Langleys) on the specimen by the annual average insolation at Richland.

The plot of Figure 2-2 suggests that the transmittance would remain at 96% of its original value for up to 5 years. (Under the real time/acceleration ratio assumptions discussed in the previous paragraph).

2.3 Mirror Reflectance

Reflectance and micro-tensile coupons were cut from a reflector membrane and returned to the laboratory for testing. Table 2- 2 provides specular reflectance test results for the same two time intervals as for enclosure.

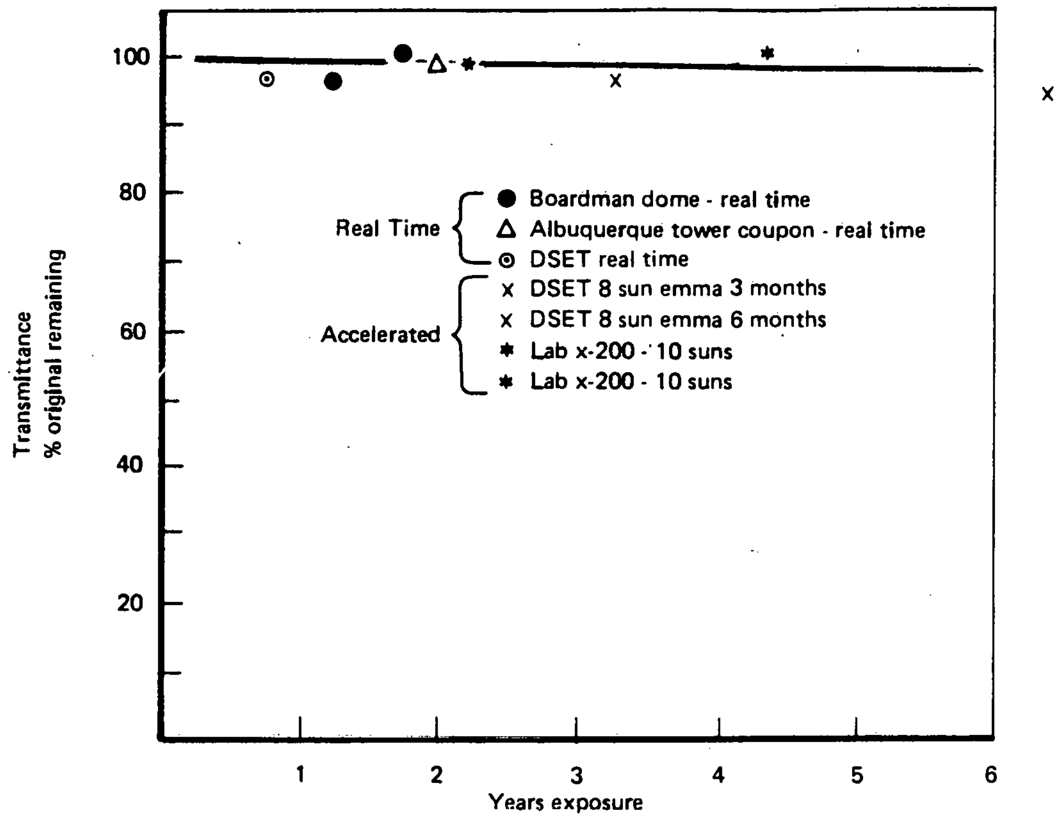

Figure 2-2 Residual Transmittance vs. Exposure

TABLE 2-2: OPTICAL TEST RESULTS

SAMPLE IDENTIFICATION	REFLECTANCE ▷1 Prior to Cleaning	Post Cleaning
CONTROL	.86	.86
REFLECTOR SAMPLE 10/11/77 (15 months)	.78	.82
REFLECTOR SAMPLE 4/12/78	.70	.74

▷1 .14° Cone Angle
633 Nanometer Source
12° Incidence Angle

Table 2-2 reveals reflectance loss. The degradation rate is greater than that observed on other coupons tested on racks at Albuquerque during the Research Experiments (SAN 1111-76-7 Collector Subsystems Final Report). It is believed that the Albuquerque samples degraded less because of a lower humidity environment. These data strongly suggest the need for a protective coating on the aluminum surface.

3.0 MECHANICAL PROPERTIES

3.1 Enclosure Material

Table 3-1 presents the results of the mechanical properties tests. No loss of yield strength was observed in any of the microtensile coupon tests performed. Results for ultimate strength and percent elongation varied, however. Ultimate strength showed changes from -30% to + 2% and elongation varied from -43% to + 12%. A single sample (3 microtensile coupons) taken at the 6 foot plane on April 12, 1978 accounts for the -30% ultimate and -43% elongation values. Excluding it results in variations in ultimate strength of -5% to + 2% and -9% to +12% for elongation. Reasons for the low values for this sample are unknown and do not agree with other Boardman, Albuquerque and Phoenix sample data.

Figures 3-1, -2, and -3 are plots of the Boardman data along with other real time data from Albuquerque and Phoenix tests. Also shown are data from accelerated testing at Phoenix (DSET) and a Boeing Laboratory (X-200;10suns). The treatment of the data prior to plotting was described in Section 2.2.

SPECIMEN IDENTIFICATION	YIELD STRESS MN/m² (PSI)	ULTIMATE STRESS MN/m² (PSI)	ULTIMATE ELONGATION %
South-Southwest Gore Location - 6 feet up from base 10/11/77	38.8 (5627)	73.9 (10721)	289
4/12/78	36.4 (5280)	50.8 (7370)	147
South-Southwest Gore Location - 12 feet from base 10/11/77	39.3 (5692)	68.4 (9920)	289
4/12/78	38.6 (5602)	73.9 (10,720)	236
Seam Sample - SSW Gore - 5.5 feet up from base 10/11/77	38.8 (5630)	49.3 (7149)	104
4/12/78	37.6 (5450)	47.2 (6840)	85.5
Control	38.0 (5503)	72.4 (10494)	258

Table 3-1

Mechanical Data for Enclosure

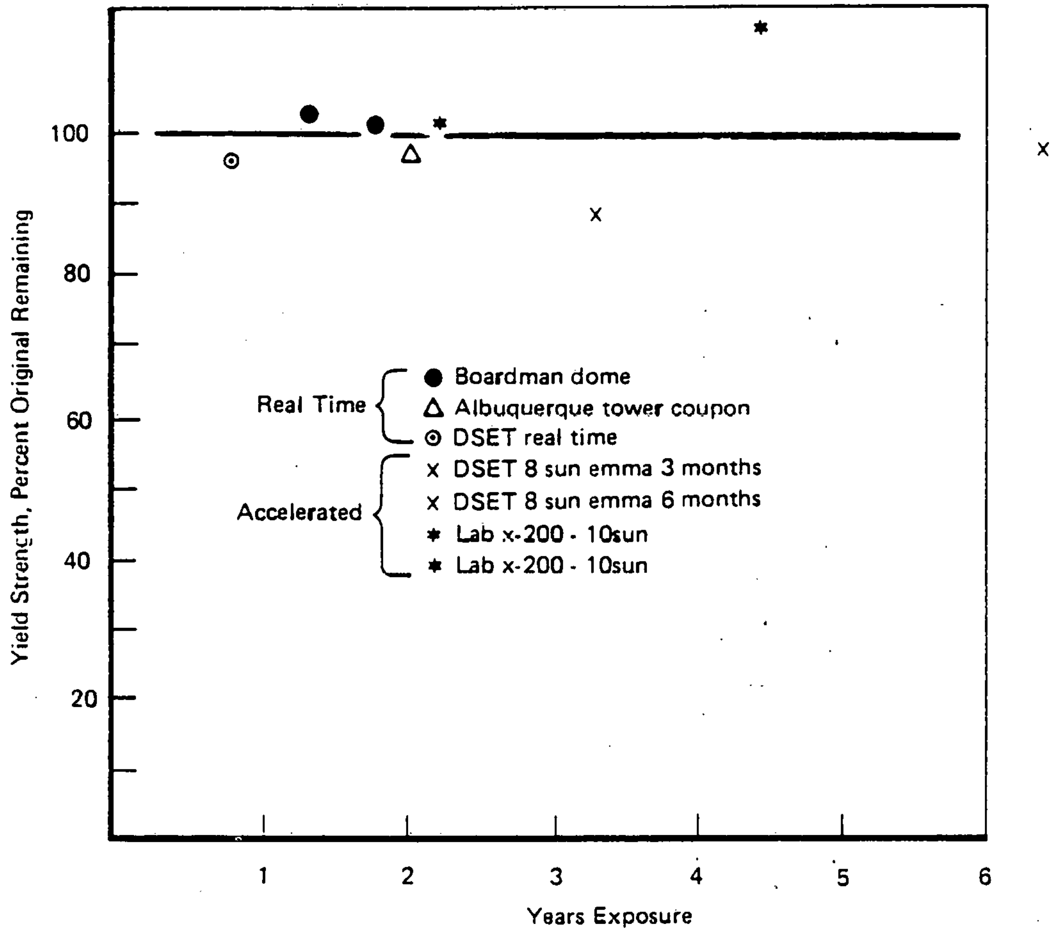

Figure 3-1 Residual Yield Strength vs. Exposure

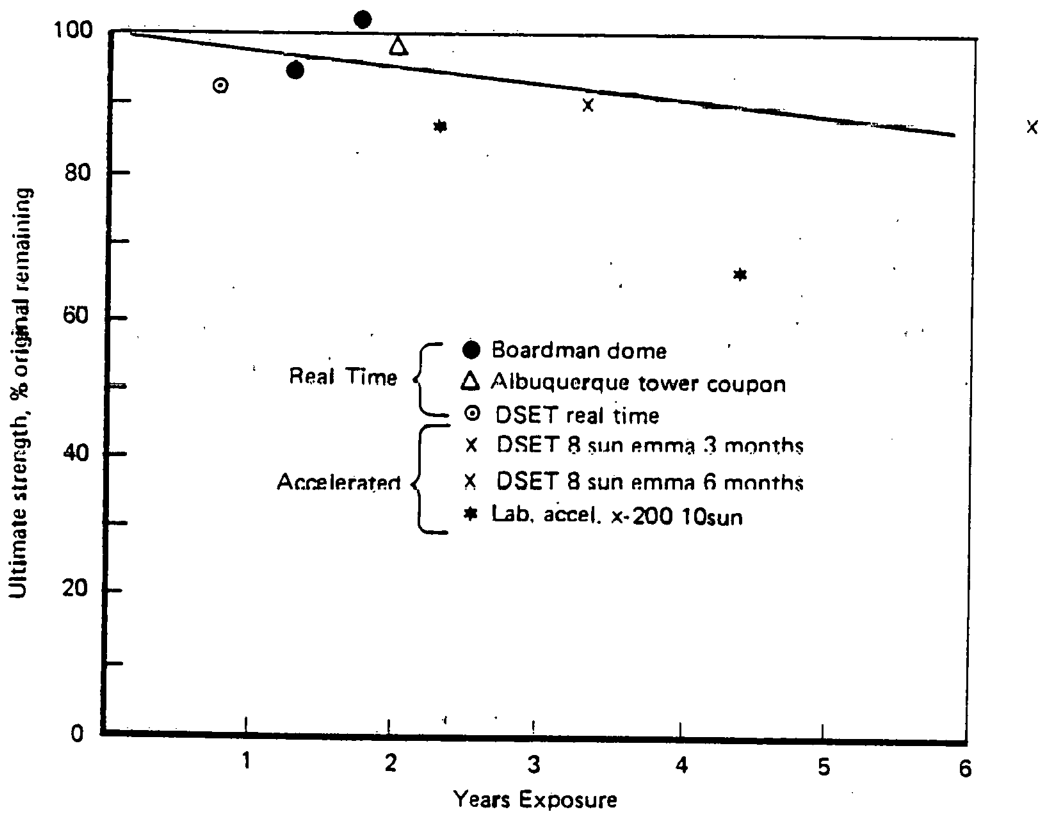

Figure 3-2 Residual Ultimate Strength vs. Exposure

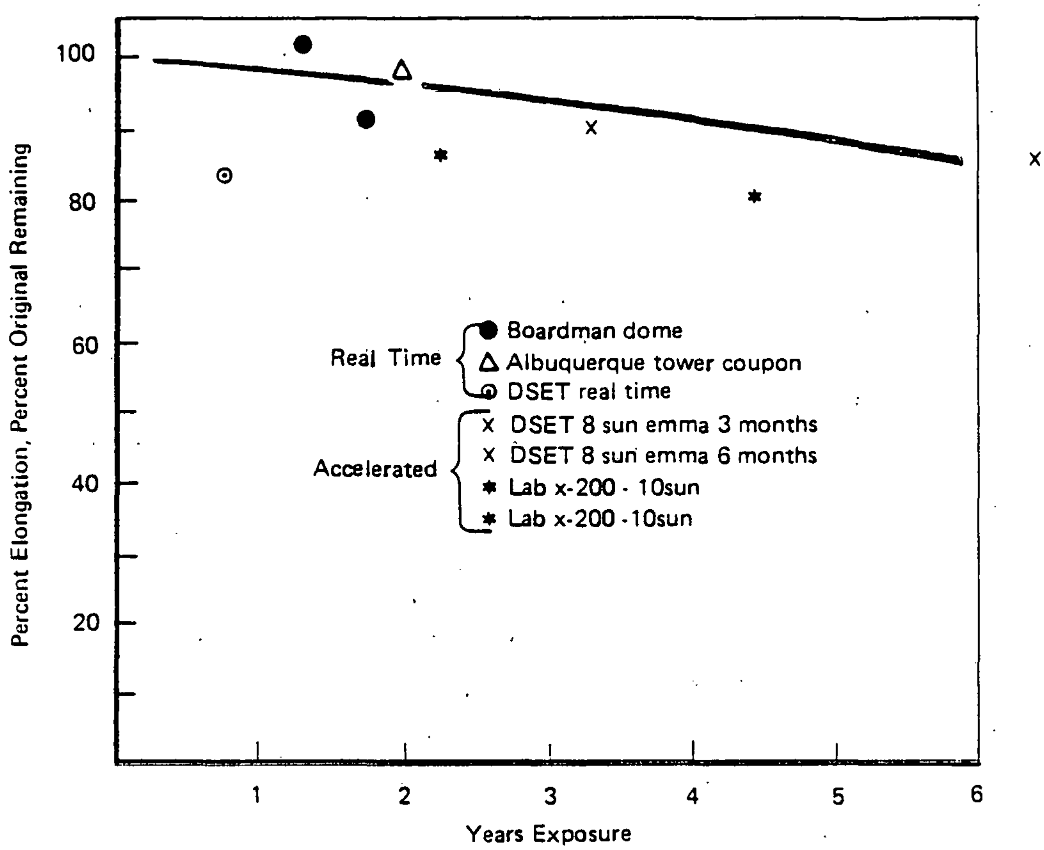

Figure 3-3. Residual Elongation vs. Exposure

Figure 3-1 suggests that the yield strength was not detrimentally affected by exposure, and would remain at a high level for at least 6 years. (Assuming the 1:1 acceleration/real time correlation used here; i.e., XLangleys for 1 day-= 1 Langley for X days.) Ultimate strength and % elongation (Figure 3-2 and 3-3) appear to roll off with time, but would likely retain sufficient values well in excess of 6 years, particularly in view of film stress margins used in the enclosure design.

The two test enclosures at the Boardman site (H0, H1) were damaged beyond repair by separate wind storms. H0 failed on July 15, 1978 under 29.5 m/sec (66 MPH) gust conditions and H1 failed on November 3, 1978 under 29 m/sec (65 MPH) peak winds. In both cases tearing along the seams appeared to be the failure mode.

Representative material was cut from H0 enclosure at Boardman and returned to the laboratory for mechanical testing. Tensile tests were performed on material specimens and joint specimens removed from vertical gore seams near the top and bottom of the enclosure and from the horizontal seam near the steel base. In addition, tensile tests were conducted on unexposed material and material with joints for control purposes. Figure 3-4 presents the test results graphically.

While small losses in ultimate and yield strengths of the material were observed, the yield strength was greater than the allowable stress by 1.5:1. The ultimate strength was approximately 3 times the allowable stress. These data strongly suggest that the material strength was adequate at the time of enclosure failure. Attention to joint data reveals a similar situation. Only slight loss in yield margin occurred and the ultimate failure margin was equal to at least 2:1 in all cases. The most obvious change was the nearly 2:1 loss in ultimate elongation observed in the horizontal seam joint. However, over 100% elongation still remained at the weakest joint; certainly not indicative of a brittle material.

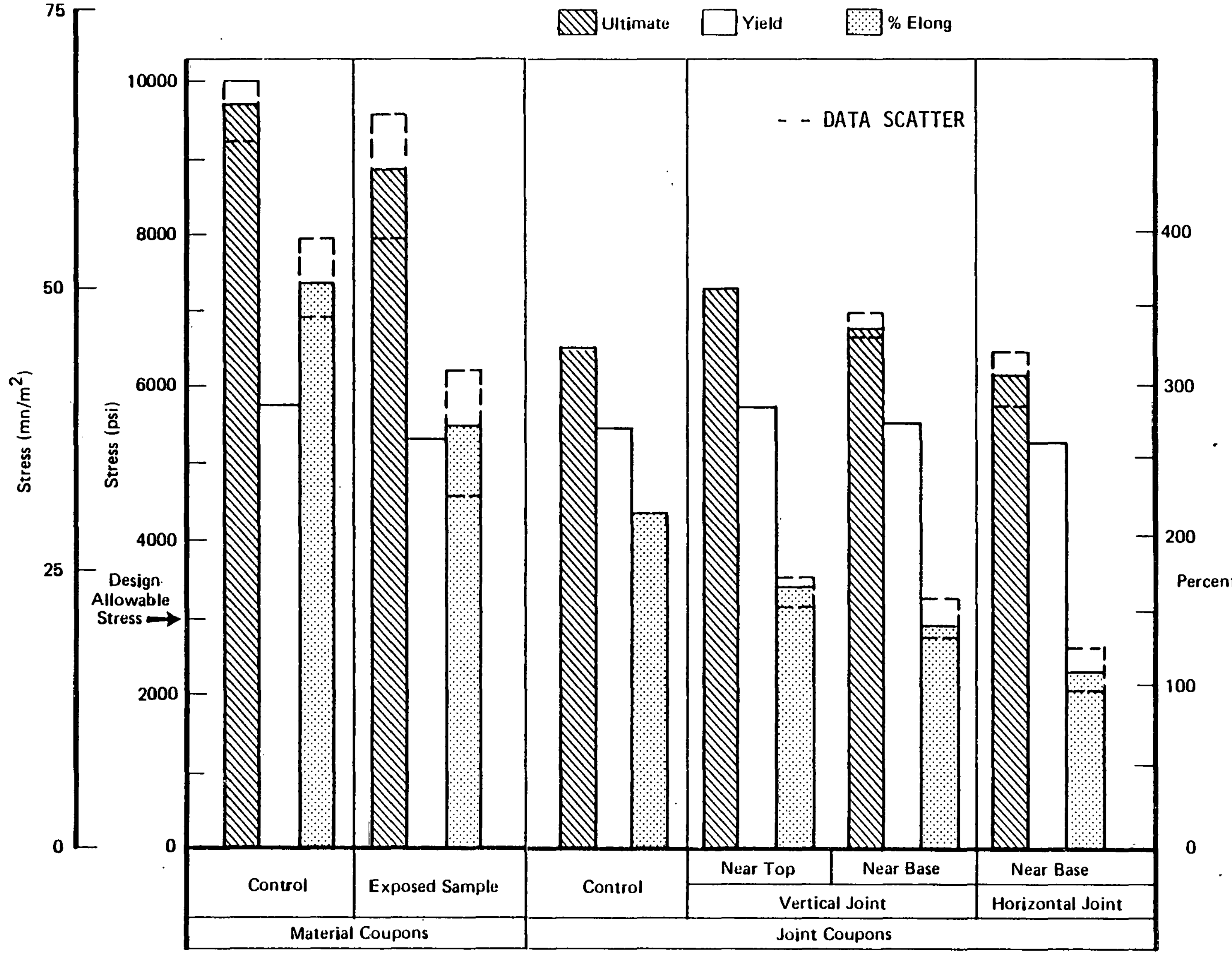

Figure 3-4 HO Enclosure Tensile Test Data

Because the failure of the enclosures occurred in a gusting wind condition, the possibility of increased strain rate sensitivity with exposure was considered. Joint samples were subjected to strain rates of .5, 5 and 20 inches per minute on a tensile test machine. Figure 3-5 and 3-6 present the results. The curves show two effects. One effect is the apparent higher strength corresponding to the higher strain rate. The other effect was a slight decrease in strength at all strain rates for the exposed material. However, all curves are well above (1.6:1) the material allowable of 20.7 mn/m^2 (3000 PSI), and reveal no significant decrease in elongation attributable to strain rate variation.

As mentioned earlier, the failure mode was tearing along the seam. Data has verified that the enclosure material and seams had more than adequate strength to withstand the wind velocities experienced during failure. Examination of the failed seams reveals that the material tore along the seam edge rather than within the seam. Tear samples were cut from exposed material and joints and tear tested per ASTM D1004 (Graves). This test is primarily useful for determining tear initiation. The results are shown in Figure 3-7. Apparently the exposure had no effect on the tear initiation strength. Furthermore, the joints are no weaker than the base material for tear initiation. (However, once the tear is started the joint is observed to be weaker than the base material. This is believed to be the result of the heat sealing process, which locally thins the material as well as removing some of the tear propagation resistance). The testing discussed above reveals nothing that clearly indicates the cause of failure.

It is felt that fatigue in the material adjacent to heat sealed joints is the most likely mechanism of failure. However, because of limited funding no experiments were performed to verify this hypothesis. It is recommended that a research program be undertaken to develop an understanding of the mechanism of failure of Tedlar domes. The research work should include long term exposure of statically and dynamically loaded joint samples to environments of moisture and ultraviolet radiation (individually and combined). Periodic non-destructive and destructive tests would be performed on samples immediately after unloading to avoid suspected "healing effects".

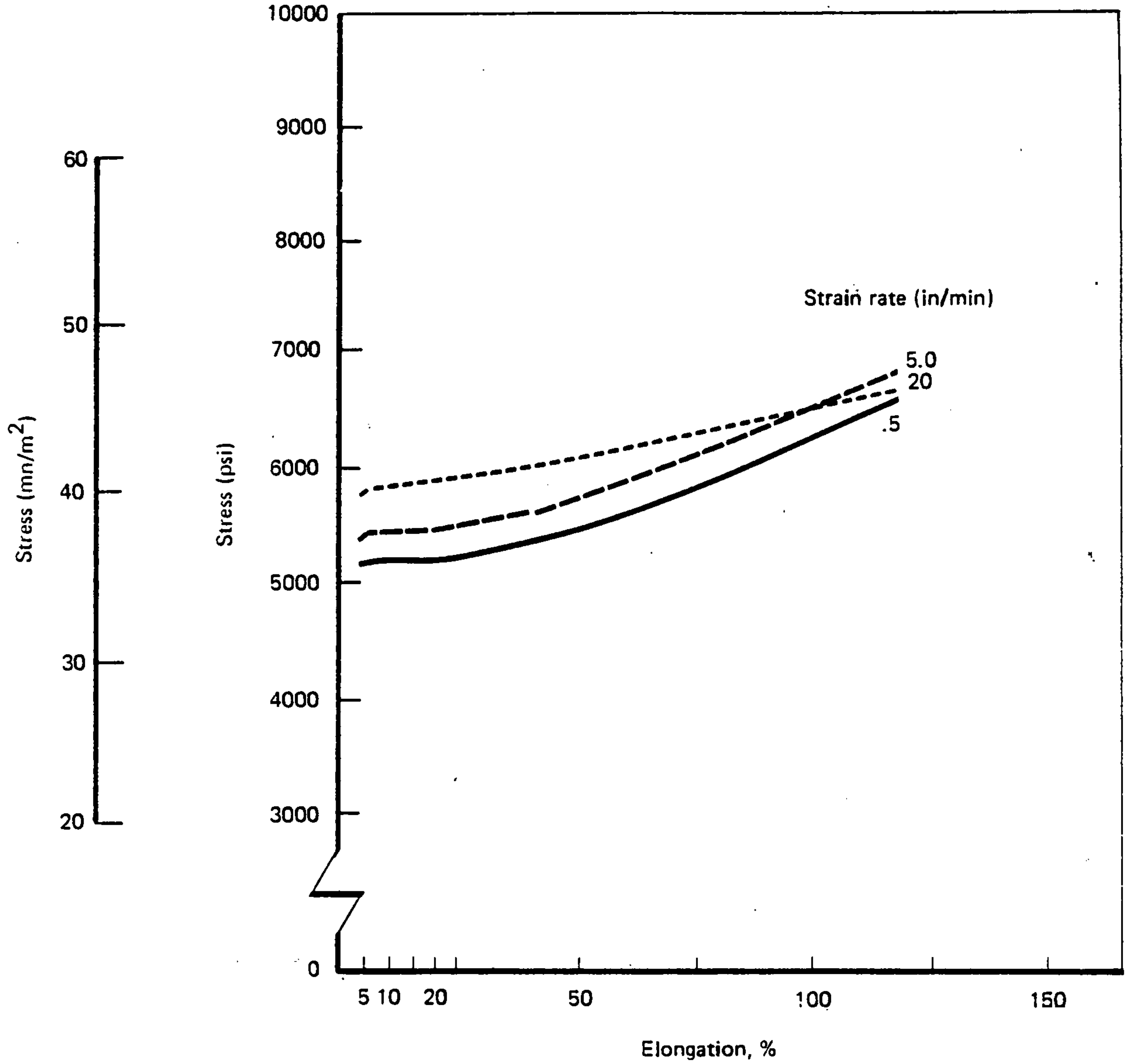

Figure 3-5 Unexposed Tedlar Joint Stress/Elongation Data Variable Strain Rate

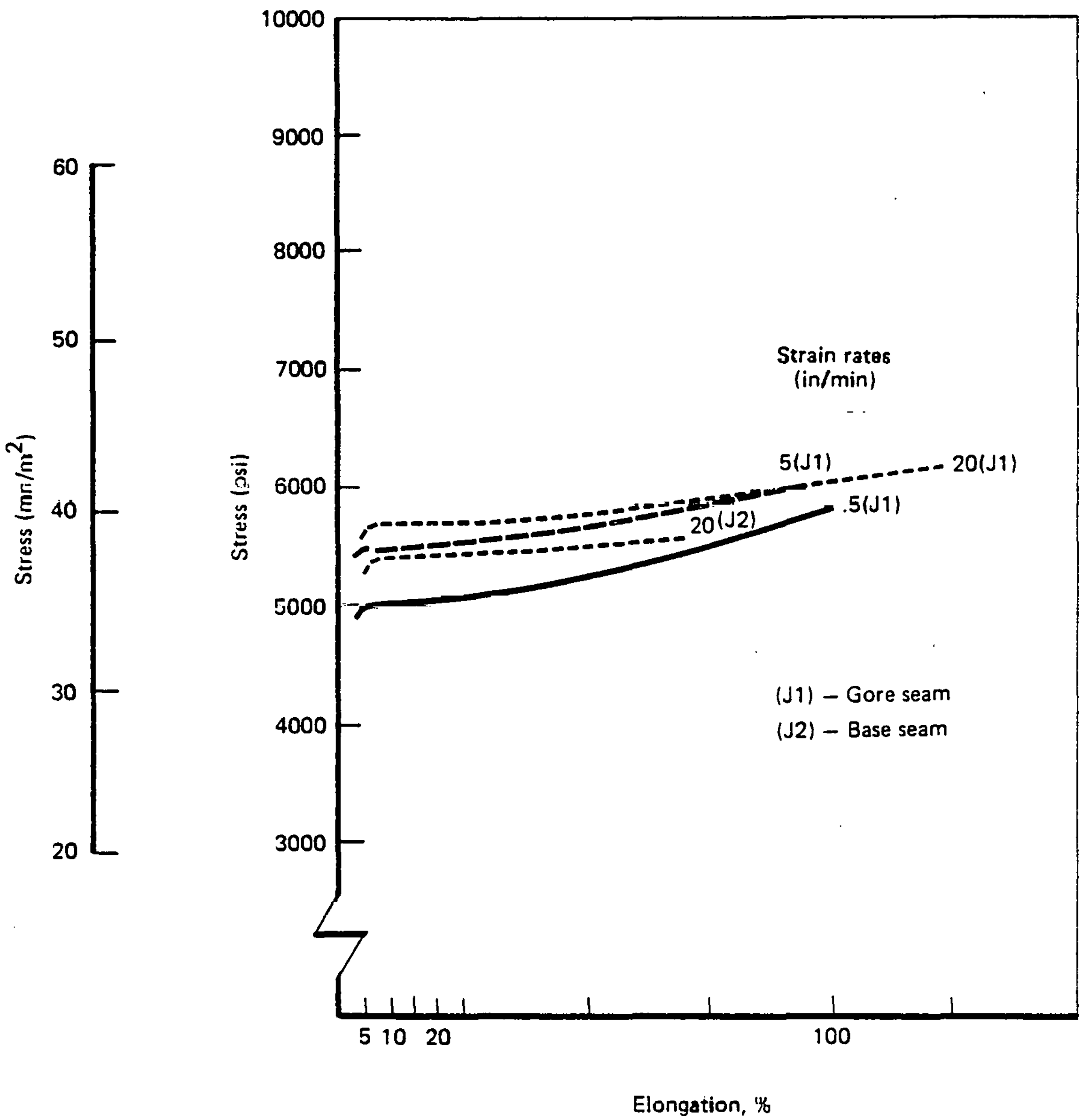

Figure 3-6 Exposed Tedlar Joints Stress/Elongation Data Variable Strain Rate

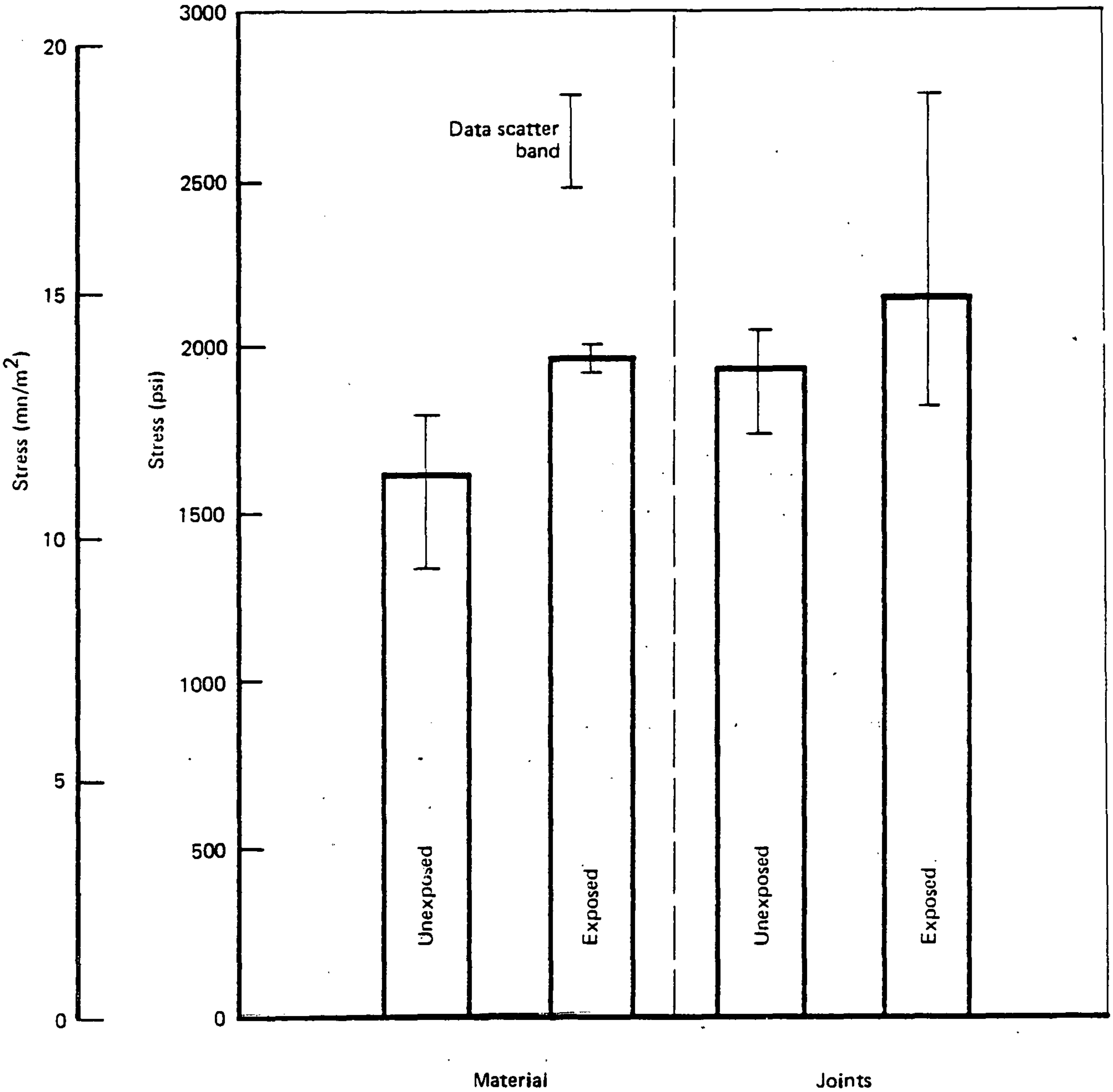

Figure 3-7 Average Tear Initiation Strengths

3.2 REFLECTOR MATERIAL

3.2.1 Mechanical Properties

Table 3-2 shows the mechanical property test results for the two time intervals (October 11, 1977 and April 12, 1978) and the control values. It should be recognized that this reflector did not track the sun (no active gimbal). It was positioned roughly south-facing and near vertical for most of the 21 months. In addition to continuous diffuse backlighting, some direct backlighting occurred during early morning or late afternoon hours, depending on exact orientation. The data reveals embrittlement and indicates the need for membrane stabilization.

3.2.2 Membrane Tension

To assist in evaluating the change in reflector membrane tension with time and environmental exposure, reference measurements were taken. The distance between the underside of the membrane, near center, and the backside of the interface plate was measured for heliostat HO on May 10, 1977, October 11, 1977, and again on April 12, 1978. The results of these measurements and ambient conditions are shown in Table 3-3.

Table 3-3
Membrane Tension

Date/Time	Ambient Temp.	Spacing
May 10, 1977	50°F	10.3 cm (4.06 inches)
October 11, 1977	71°F	10.1 cm (3.98 inches)
April 12, 1978	57°F	10.2 cm (4.00 inches)

Note: Mirror configuration was horizontal in all three cases

The maximum deflection change was 0.20 cm (0.08 inches) between measurements.

Table 3-2 Mechanical Test Results

SAMPLE IDENTIFICATION	YIELD STRENGTH MN/m^2 (PSI)	ULTIMATE STRENGTH MN/m^2 (PSI)	ULTIMATE ELONGATION %
CONTROL	82.1 (11,900)	130 (18,900)	81
REFLECTOR SAMPLE 10/11/77 (15 months)	96.6 (14,000)	102 (14,800)	29
REFLECTOR SAMPLE 4/12/78	96.6 (14,000)	101 (14,700)	12

This difference could be attributed to either temperature difference between days, or long term creep. The value is quite small and is not considered to be significant.

This data confirms that the concept of pretensioning and bonding of a membrane reflector to a support rim is satisfactory. Creep in the film and adhesives (at rim and joints) did not occur.

3.2.3 Membrane Joints

The reflector membrane seams were formed by butt joining with tape on the backside. The tape consisted of aluminized polyester with thermosetting polyester adhesive, with the aluminized side back facing. This placed the bare polyester film facing toward the sun. If the reflector membrane butt joint was not totally closed, the possibility of sun exposure through its slit and subsequent UV degradation existed.

Samples were cut across a seam and tensile tested. It was found that for joint gaps of a few mils, the joint was as strong as the base material. Joint gaps in excess of 6 mils (.006 inches) resulted in embrittled tape and weak joints.

Lap joining is recommended for future reflector seams to avoid the problem described above. In lap joining, the membrane panels to be joined are overlapped and bonded together in the overlapped area. No bare polyester is exposed to direct sunlight in this technique.

4.0 AIR FILTRATION/PRESSURIZATION SYSTEM

During the time period covered by this work the manometers were checked weekly, as a minimum. No adjustments with time or temperature were required except when work was performed on the inside of the enclosure or filter maintenance was conducted.

As described in Section 2.1, the filters required more frequent changing due to rodent damage during the latter part of the program. This resulted in dust settling on the reflector surface and internal dome surfaces. A reduction in the overall heliostat reflectance was subsequently detected. Future heliostat designs must address the need for reduced air flow and adequate dust filtration.

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