N86-12773 $\mathcal{D}/4$

GLASS BREAKING STRENGTH--THE ROLE OF SURFACE FLAWS AND TREATMENTS

Donald Moore
Jet Propulsion Laboratory
Pasadena, California 91109

ABSTRACT

Although the intrinsic strength of silicon dioxide glass is of the order of 10^6 lb/in.^{2}, the practical strength is roughly two orders of magnitude below this theoretical limit, and depends almost entirely on the surface condition of the glass, that is, the number and size of flaws and the residual surface compression (temper) in the glass. Glass parts always fail in tension when these flaws grow under sustained loading to some critical size.

Over the past eight years, research associated with glass-encapsulated crystalline-Si photovoltaic (PV) modules has greatly expanded our knowledge of glass breaking strength and developed a sizeable data base for commercially available glass types. A detailed design algorithm has been developed for thickness sizing of rectangular glass plates subject to pressure loads. This algorithm employs nomographs based on sophisticated non-linear finite-element stress analyses to determine the maximum stress in a glass plate. This stress is compared with the practical strength of glass plates derived from a large body of existing glass breakage data. Additional studies have examined the strength of glass under impact-loading conditions such as that caused by hail.

Although the fundamentals of glass breakage are directly applicable to thin-film modules, the fracture strength of typical commercial glass must be replaced with data that reflect the high-temperature tin-oxide processing, laser scribing, and edge processing peculiar to thin-film modules.

This paper reviews the fundamentals of glass breakage applicable to thin-film modules and presents preliminary fracture-strength data for a variety of 1-ft-square glass specimens representing pre-processed and post-processed sheets from current amorphous-Si module manufacturers.

DISCUSSION

The objective of this presentation is to examine the applicability of current knowledge of glass breakage strength to the structural design of glass-supported thin-film PV modules. To this end, the research associated with glass-encapsulated crystalline-silicon PV modules is briefly reviewed. The applicability of this knowledge to thin-film glass modules is examined. Finally, the results of preliminary tests to characterize the mechanical strength of glass-supported thin-film PV modules are summarized.

The intrinsic strength of glass is on the order of 10^6 lb/in.^{2} The strength of large rectangular, commercially available, soda-lime glass sheets falls in the range of 3,000 to 20,000 lb/in.^{2} depending on the surface condition and temper of the glass. This huge discrepancy between the intrinsic and usable strength of glass is due to the fact that glass is a brittle material. As such, it always fails in tension at pre-existing surface

flaws. The brittle failure mechanism of glass is helpful in explaining the dependency of the measured strength of glass on the factors delineated below:

(1) Strength increases with increased residual surface compression (temper) because applied tensile loading is reduced by the amount of the residual surface compression.

(2) Strength decreases with increased time duration of loading, because under a sustained load pre-existing flaws grow to some critical size, at which failure occurs.

(3) Strength decreases with increased stressed area due to tne greater probability of a flaw existing within the stressed area.

Because the strength of glass depends on the number and size of flaws in the specimen tested, it is not surprising that apparently identical test specimens and loading conditions exhibit widely different measured strengths. For this reason, the strength of glass must always be cited for a given probability of failure.

In connection with the research devoted to glass-encapsulated crystalline-silicon PV modules, a design algorithm for thickness sizing of rectangular glass plates subject to pressure loads, such as wind, has been developed. This algorithm employs nomographs based on sophisticated non-linear finite-element stress analysis to determine the maximum stress in a glass plate. The maximum applied stress, so obtained, is compared with the strength of glass plates derived from a large body of empirical glass breakage data. Highlights of this design algorithm are shown in the figures that follow this text.

Thin-Film Glass Strength Tests

As discussed above, it is desired to establish the strength of the glass used for thin-film PV modules as a function of the processing to which the glass is subjected; i.e.,

(1) Edge treatment

(2) Thermal treatments

(3) Coatings applied

(4) Scribing

To accomplish this, burst-pressure tests were done on 1 x 1-ft-square glass specimens. The apparatus designed to do this is shown in a figure. Essentially, it consists of a rigid aluminum frame that provides simple support to the four edges of the square glass plates. Tap water, a pressure regulator and a needle valve are used to slowly pressurize the glass plate. A pressure transducer and a linear-motion transducer, with a strip chart recorder, are used to record the pressure and displacement versus time.

So far, 51 of 1 x 1-ft-square glass plates have been tested. These are described below by the number tested, thickness, temper, edge and surface

236

treatments. Note that the surface for which the surface treatment is described was placed in tension (convex) during the test.

Number Tested	Description
11	0.125 in.-thick annealed float glass with as-cut edges tested with tin side in tension
21	0.125 in.-thick annealed float glass with sanded edges tested with tin-side in tension
4	0.125 in.-thick annealed glass with as-cut edges obtained from manufacturer after TiO conductive coating had been applied
10	0.042 in.-thick annealed glass with carefully rounded edges obtained from manufacturer after TiO conductive coating had been applied
5	0.042 in.-thick annealed glass with carefully rounded edges obtained from manufacturer after scribing

Photographs are included for three fractured glass specimens:

(1)   0.125 in.-thick annealed glass with as-cut edges.

(2)   0.042 in.-thick annealed glass with carefully rounded edges and TiO conductive coating.

(3)   0.042 in.-thick annealed glass with carefully rounded edges, TiO and Si coatings, and scribed.

The burst-pressure data obtained from these tests were converted to strength data using the non-linear design nomograph. These strength data are plotted on a graph included here that shows glass strength versus probability of failure. Also shown on this graph is the glass strength obtained from previous burst-pressure tests made by other investigators. Although somewhat on the low side, the strength values obtained in the current tests are in reasonable agreement with previously obtained results for glass strength. As is often the case when studying glass breakage data, the results of the current tests defy simple explanation. It would be expected, for example, that the specimens of annealed 1/8 in.-thick glass with ground edges would exhibit higher strength than the specimens with as-cut edges, but the test results show a higher strength for the specimens with as-cut edges. Another unexpected result is that the scribed 0.042 in.-thick specimens exhibited a higher average strength than their unscribed counterparts.

Hail Impact Resistance

It is also desired to ascertain the hail impact resistance of glass-supported thin-film PV modules. Preliminary hail-impact tests have been conducted on thin-film modules from two manufacturers using the hail gun

developed for testing of crystalline-silicon PV modules. The hail gun uses
air pressure to propel a frozen ice ball at a test specimen. These
exploratory tests showed that the 0.125 in.-thick annealed-glass modules from
one manufacturer were marginally inadequate for 1-in.-dia ice balls at
52 mi/h. Failure occurred in 2 of 42 impacts made near the edges of three
modules. It is thought that the as-cut edges of these modules was a
significant contributor to these failures. Photographs of two of these
failures are included. The other module tested consisted of a 0.042 in thick
front glass-cover bonded to a 0.125 in.-thick back cover glass by a thin layer
of a soft encapsulant material. This module survived 16 edge impacts of
1-in.-dia ice balls at 52 mi/h. It was not tested for larger ice balls.
Finally, a bar graph shows the hail-impact resistance of PV modules for
various module constructions.

CONCLUSIONS

The analytical and empirical tools developed over the past eight years to
characterize the mechanical strength of crystalline-silicon PV modules are
applicable to the structural design of thin-film glass-supported PV modules.
Preliminary test results indicate that glass-supported thin-film modules will
be structurally adequate, but additional testing is mandatory to characterize
further the strength of glass used for thin-film modules as a function of the
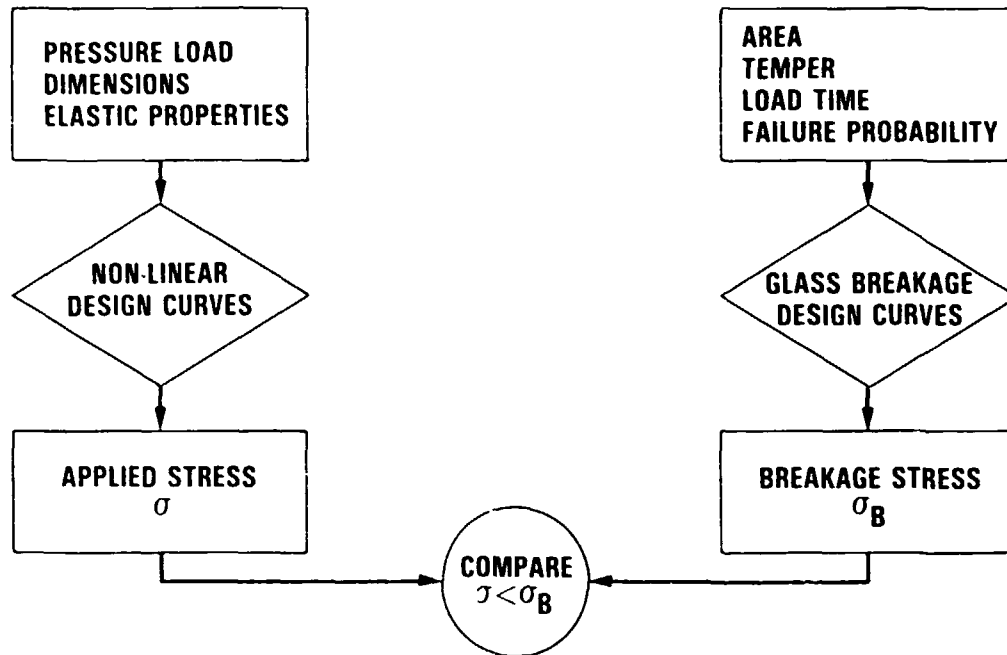surface treatments and processes to which it is subjected.

Agenda

- Review of current knowledge of glass breakage
    - Theoretical considerations
    - Empirical results
- Application of this knowledge to thin-film glass modules
- Examine problems peculiar to thin-film glass modules
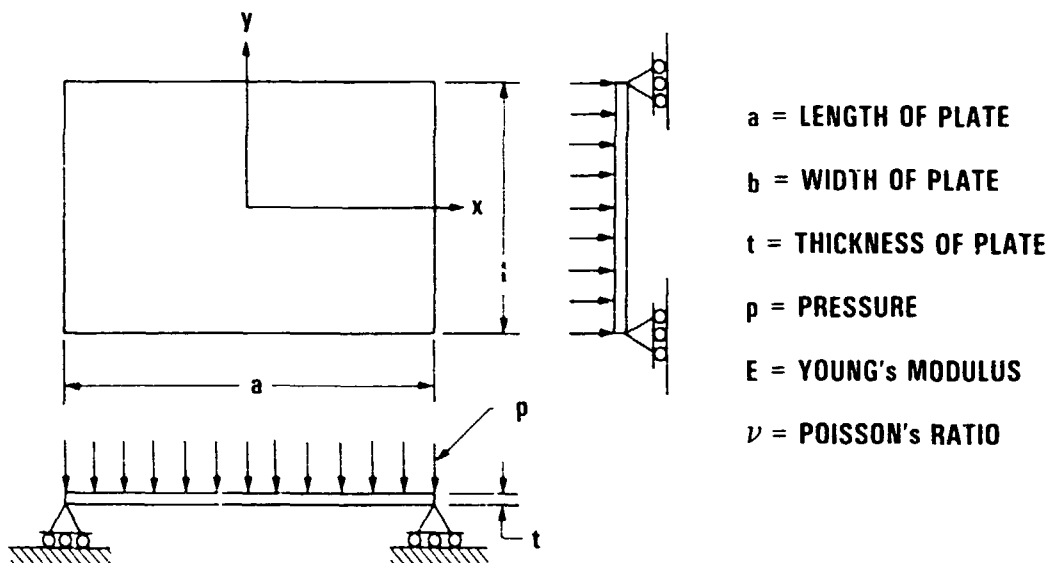   - Especially surface treatments of glass

Glass Breakage Strength

- Inherent strength $\approx$ 1,000,000 lb/in.^{2}
- Apparent strength $\approx$ 3,000 to 20,000 lb/in.^{2}
- Brittle failure mechanism explains why
    - Glass always fails in tension at flaws
    - Strength increases with increased surface compression (temper)
    - Strength decreases with increased flaw size
    - Strength decreases with increased duration of load
    - Strength decreases with increased stressed area
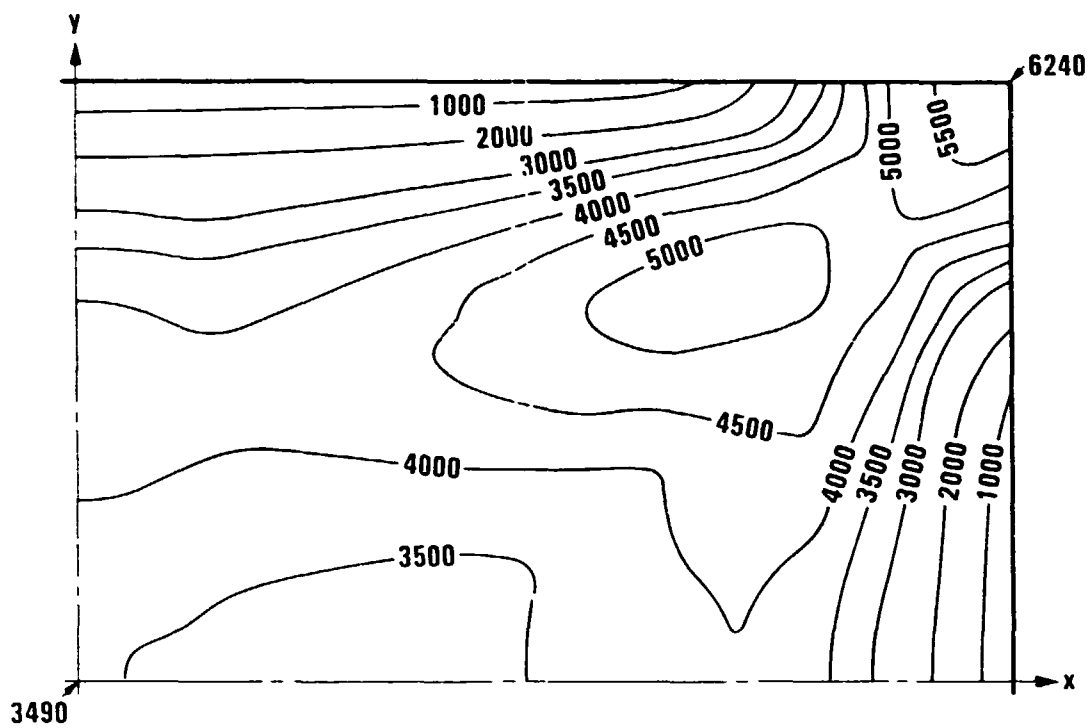- Strength of glass is therefore stated for a given probability of failure
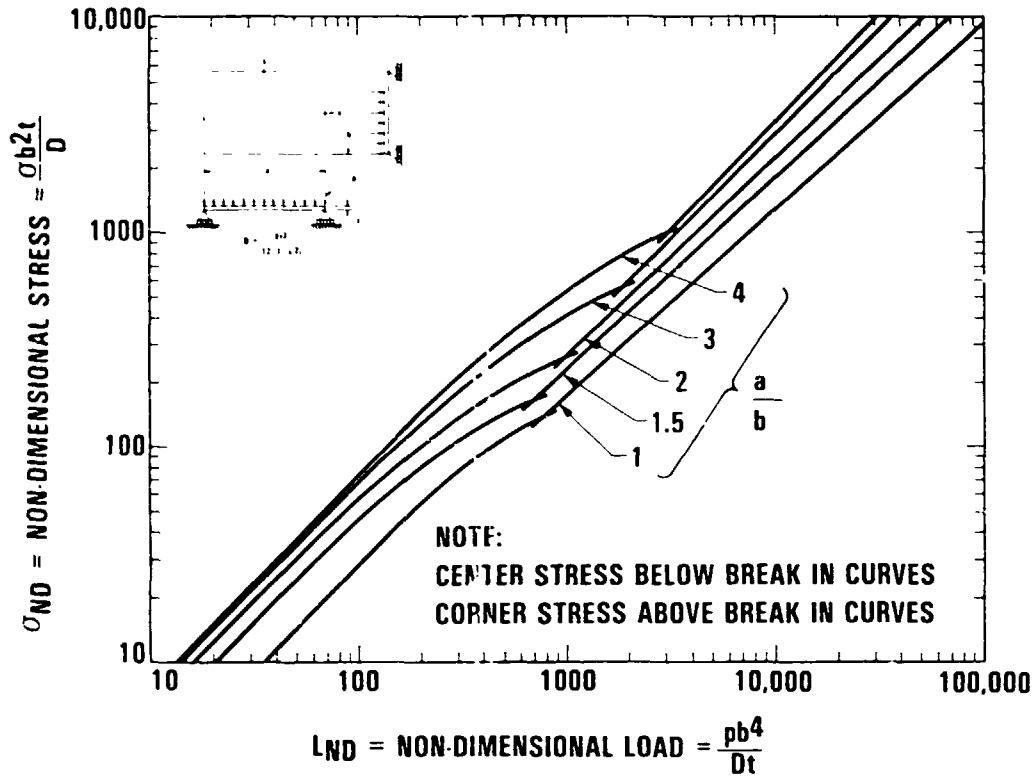
Glass Thickness Sizing Method

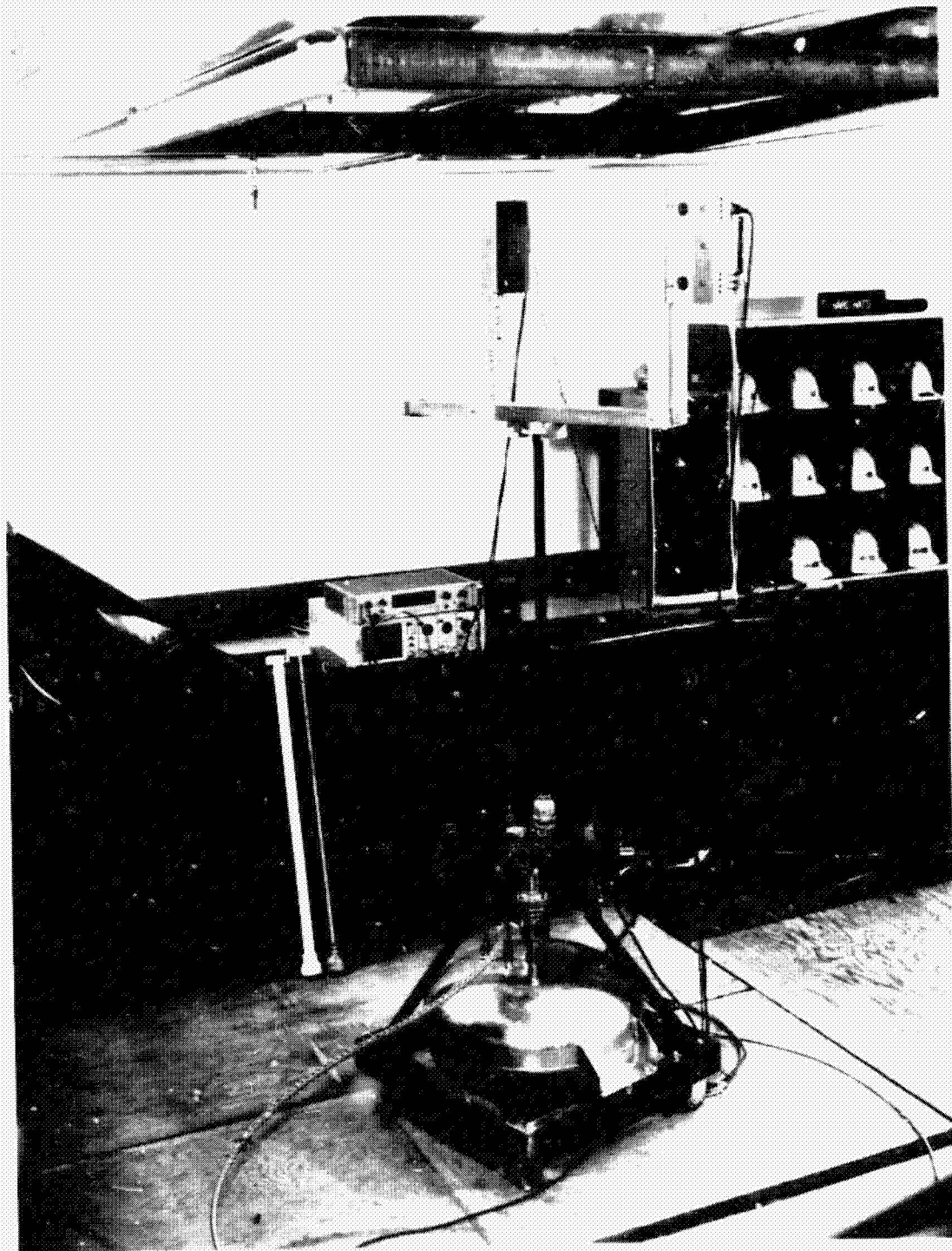## Uniformly Loaded, Simply Supported Rectangular Plate

a = LENGTH OF PLATE

b = WIDTH OF PLATE

t = THICKNESS OF PLATE

p = PRESSURE

E = YOUNG's MODULUS

ν = POISSON's RATIO

Maximum Principal Stress Contours

Stress vs Load

Figure: Plot of $\sigma_{ND} = \text{NON-DIMENSIONAL STRESS} = \dfrac{\sigma b^2 t}{D}$ (vertical axis, from 10 to 10,000) versus $L_{ND} = \text{NON-DIMENSIONAL LOAD} = \dfrac{p b^4}{D t}$ (horizontal axis, from 10 to 100,000). Curves are labeled 4, 3, 2, 1.5, 1 for $\dfrac{a}{b}$.

NOTE:
CENTER STRESS BELOW BREAK IN CURVES
CORNER STRESS ABOVE BREAK IN CURVES

Hail Gun Uses Air Pressure to Propel
Frozen Ice Balls at Spec men

Strength of Thin-Film Glass Modules

- **Problem:**
  - Establish breakage strength statistics for treated glass used for thin-film photovoltaic modules as a function of:
    - Edge treatment
    - Conductive coating (TiO)
    - Laser scribing

- **Approach:**
  - Conduct burst pressure tests of treated 1 x 1 ft. glass samples

Glass Burst-Pressure Test Apparatus
for 1 x 1-ft Glass Samples
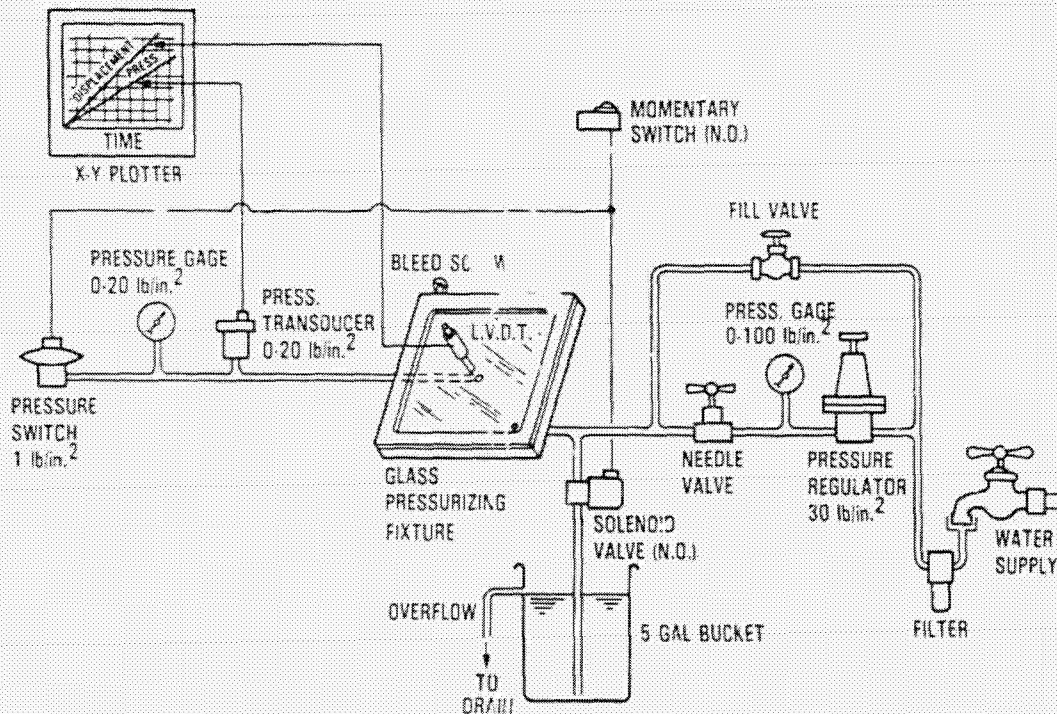
0.125 x 12 x 12-in. Annealed Glass Plate
With As-Cut Edges Failed at 4.67 lb/in.^{2}
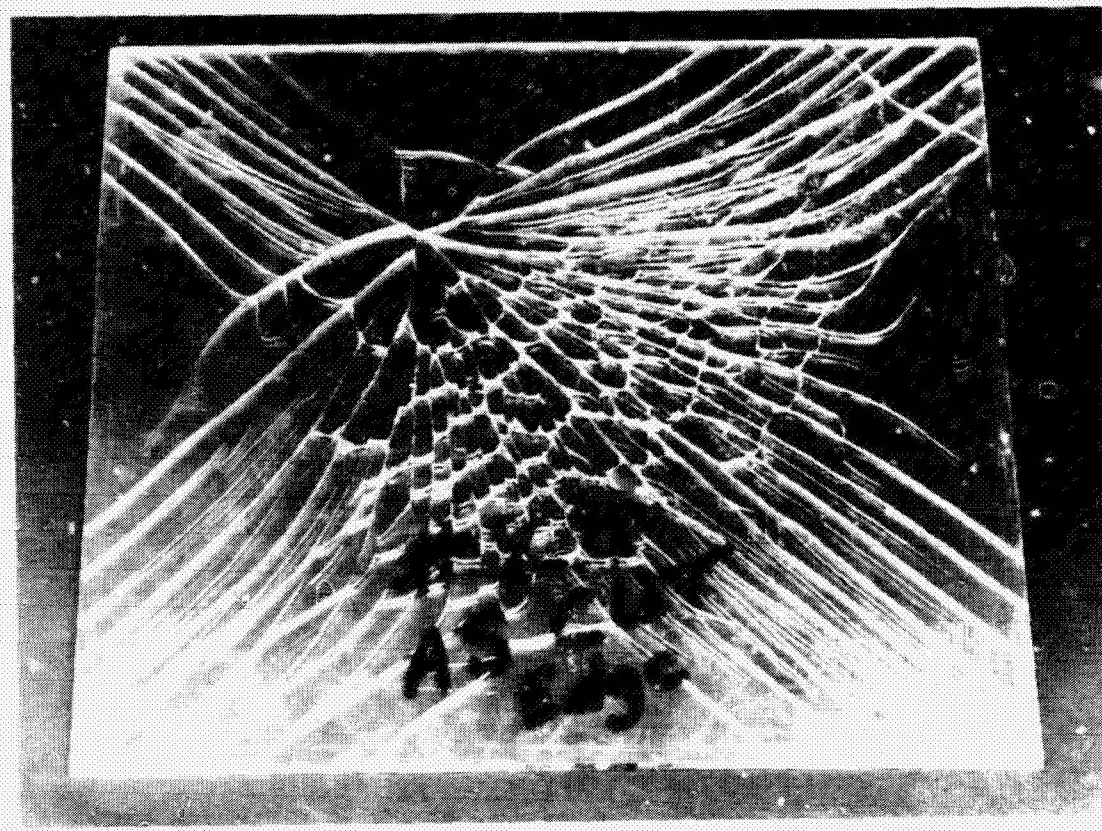
0.042 x 11.8 x 11.8-in. Annealed Glass Plate With
Rounded Edges and TiO Conductive Coating;
Failed at 0.90 lb/in.^{2}

0.042 x 11.8 x 11.8-in. Annealed Glass Plate With
Rounded Edges, TiO and Si Coatings, and Scribed;
Failed at 0.99 lb/in.^{2}

Hail Impact Resistance

TOP SURFACE MAT=RIAL	FAILURE MODE	CRITICAL HAILSTONE DIAMETER, in.
		¼ ½ ¾ 1 1¼ 1½ 1¾
ACRYLIC S::ET	BROKE ACRYLIC	
SILICONE RUBBER POTTANT	CRACKED Si SOLAR CELLS	Block V Requirement 1 in. diameter at 52 mi/h
ANNEALED GLASS	BROKE GLASS	
TEMPERED GLASS	SHATTERED GLASS	
THIN (0.042 in.) LASER-SCRIBED GLASS/ EVA/THICK GLASS	BROKE GLASS	
THICK (0.125) LASER-SCRIBED GLASS, NO BACKUP	BROKE GLASS	