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TITLE: CATASTROPHIC VERSUS MICROSCOPIC DAMAGE: APPLICABILITY OF LABORATORY MEASUREMENTS TO REAL SYSTEMS

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Catastrophic versus Microscopic Damage: Applicability of Laboratory Measurements to Real Systems*

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At ultraviolet wavelengths, damage to both coatings and bare surfaces is dominated by the presence of discrete localized defects. During multiple-shot irradiation, the overwhelming majority of these defects are damaged by the first or first few shots. Initially, damage morphology is that of a crater of approximately 10 microns in diameter; however, upon continued irradiation, one of two events can occur: either the crater grows to catastrophic dimensions or it remains unchanged. In the latter case, the damage is only observable under a microscope, it may be indistinguishable from cosmetic defects before irradiation, and it is likely that any related degradation in optical performance is unmeasurable.

In view of the generally accepted definition of laser damage (i.e. any visible change in the surface), it is important to consider the implications for real systems. These are discussed in the context of ultraviolet test results for both coatings and surfaces.

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Key words: catastrophic damage; damage morphology; laser-induced damage; microscopic damage; multiple-shot irradiation.

1. Introduction

The subject of catastrophic versus microscopic damage is not new to these proceedings [1]. In this paper we offer results of a preliminary investigation in which it was found that a rigid definition of damage may be unrealistic, may unfairly constrain the design of practical systems, and may mislead investigators attempting to optimize a production process. A major question remains, however, regarding the actual optical degradation associated with microscopic damage. A possible solution is the establishment of an objective damage criterion.

2. Catastrophic versus Microscopic Damage: Definitions and Discussion

2.1. Catastrophic Damage

Figure 1. is a micrograph of catastrophic damage on a 351nm reflector[1]. On the first shot, a few barely visible pits were formed. On succeeding shots these pits grew, merged, and became the 1-mm wide footprint that is shown. Although variable, this particular damage site has grown to the 25% intensity contour of the elliptical test spot - clearly a catastrophic failure. The peak fluence in this test was slightly over threshold and the damage at the edge of the footprint has occurred at a fluence well below the threshold level.

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[1] Test conditions for all present results are: λ=351nm, τ=12ns, and prf=35 pulses/sec. Testing was n-on-n where, at each test fluence, ten sites were irradiated for 140 shots or more.

This form of catastrophic damage, pitting followed by growth, is observed primarily in multilayer dielectric reflectors - over 90% of the uv reflectors tested at Los Alamos have damaged in this mode. Another form of catastrophic damage is illustrated in figure 2. In this case, usually observed at fluence levels well above threshold ~~for~~ on AR's and bare surfaces, a dense collection of pits has formed but no growth is observed during continued irradiation. In that a significant fraction of the irradiated area has been disturbed, it is certain that an actual component thus damaged would be rendered useless, hence the designation catastrophic. The designation is, at this point, subjective. To quantify the degree of damage would require a measurement of optical degradation[2] such as a change in reflectance or scatter. In a practical sense, damage may eventually be evaluated on the basis of comparing such measurements to system requirements rather than on the basis of visual observations.

2.2. Microscopic Damage

Figure 3. illustrates the morphology of microscopic damage. The two damage pits (circled to distinguish them from surrounding cosmetic defects) were produced in a 351nm AR coating irradiated at slightly above the damage threshold. At much higher fluence values, these pits would evolve into catastrophic damage, but at an intermediate level, no further change was observed during irradiation for 10^4 shots. This behavior is typical of most but not all uv AR coatings tested at Los Alamos.

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[2] There are preliminary indications [2] that the energy loss associated with a damage pit is far greater than would be expected from simple consideration of the amount of visibly damaged surface area.

Features of microscopic damage are summarized below.

* Small pits, usually less than 20um diameter.
* Indistinguishable from cosmetic defects (pinholes, dust) at 100x magnification.
* Low surface density - fewer than $10mm^{-2}$.
* Does not grow under continued irradiation except at very high fluence levels.
* Observed primarily on bare surfaces and antireflection coatings.

3. Damage Morphology

The morphology of a precursor to catastrophic damage is shown in figure 4, at various SEM magnifications. The frame in the upper left shows the pits as seen in the test facility viewing system. The 49-layer coating has been removed down to the substrate and a commonly observed crater in the fused silica is visible. The author of reference [1] finds size to be a critical parameter for damage growth related to absorbing defects under cw irradiation; we suggest that electric field enhancement at the broken edges of the coating is a possible growth mechanism here.

The absence of these rough edges in a microscopic damage site is shown in figure 5. A cosmetic defect appears in the frame at lower right to demonstrate the similarity between the two, and also to illustrate that, in contrast to the statement of section 2.2, damage sites <u>are</u> distinguishable from pinholes by virtue of the discoloration that surrounds them.

4. Test Results and Discussion

Figure 6. is the result of separating catastrophic from microscopic damage events on uncoated CaF_2 at 351nm. The curves are normalized to the catastrophic damage threshold. As fluence was gradually increased, microscopic damage was first observed at about 30% of the catastrophic threshold. The shallow slope of the probability curve, and the resulting high level of statistical noise, indicate a relatively low density of defects responsible for microscopic damage. At the catastrophic threshold, a transition occurs to a higher density of defects that are now responsible for damage accompanied by growth. Whether this is a result of the presence of two different types of defect, or simply a different response at higher fluence levels by a single class of defect is, at this point, unknown.

Figures 7. and 8. are curves generated in a similar manner, but now the emphasis is on the optimization of deposition rates for antireflection coatings. The results are summarized in table 1.

Table 1. Influence of Deposition Rate upon Damage Thresholds[a]

Deposition Rate	Microscopic Threshold	Catastrophic Threshold
2Å/sec	4.7 J/cm^2	5.9 J/cm^2
7Å/sec	3.9 J/cm^2	8.7 J/cm^2

[a] Al_2O_3/SiO_2; 4-layer AR's at 351nm; R≈0.3%

As can be seen, if microscopic damage proves to be optically detrimental, slightly better performance is available at the lower deposition rate. Alternately, if only concerned about catastrophic damage, the higher deposition rate offers better performance. Admittedly, these considerations ignore other factors such as durability or optical performance that may also vary with deposition rate. The point, however, is that depending on the type of damage being considered, completely different results are obtained in the attempt to optimize this coating parameter.

5. Conclusions

We have examined two different types of laser-induced damage behavior. One type is nongrowing, possibly harmless, and is primarily observed on uncoated surfaces and antireflection coatings. The other type involves growth to catastrophic dimensions with continued irradiation, and is generally seen on reflectors. The significance of microscopic damage remains to be determined; it clearly will always have a place in coating research, but may eventually be neglected in the design of real systems.

6. References

[1] Bennett, H.E. Insensitivity of the Catastrophic Damage Threshold of Laser Optics to Dust and Other Surface Defects. Nat. Bur. Stand. (U.S.) Spec. Publ. 620; 1980. 256 p.

[2] Marrs, D., Naval Weapons Center (private communication).

FIGURE CAPTIONS

Figure 1. Catastrophic damage in a 351nm reflector. At slightly over threshold, the initially small damage sites grew with continued irradiation to the 25% intensity contour of the beam.

Figure 2. This type of catastrophic damage is stable under continued irradiation, but, due to the size and density of pits, optical performance has been degraded.

Figure 3. The microscopic damage (circled) is nearly indistinguishable from cosmetic defects. Even at fluence levels above threshold, these sites did not grow for 10^4 shots. The effect upon optical performance is unknown.

Figure 4. Precursors to catastrophic damage in a 49-layer reflector. One possible growth mechanism is electric field enhancement at the broken edges of the coating.

Figure 5. Microscopic damage in a 351nm AR. At lower right is a cosmetic defect for comparison. Under certain viewing conditions, damage sites are found to be surrounded by a discoloration.

Figure 6. Damage probability curves for uncoated CaF_2 at 351nm. Two distinct curves result from separating catastrophic and microscopic damage.

Figure 7. Damage curves for an antireflection coating produced at a slow deposition rate.

Figure 8. Damage curves for an antireflection coating produced at a higher deposition rate than that of figure 7. While the slower rate gives a higher microscopic threshold, a higher catastrophic threshold results from a higher deposition rate.

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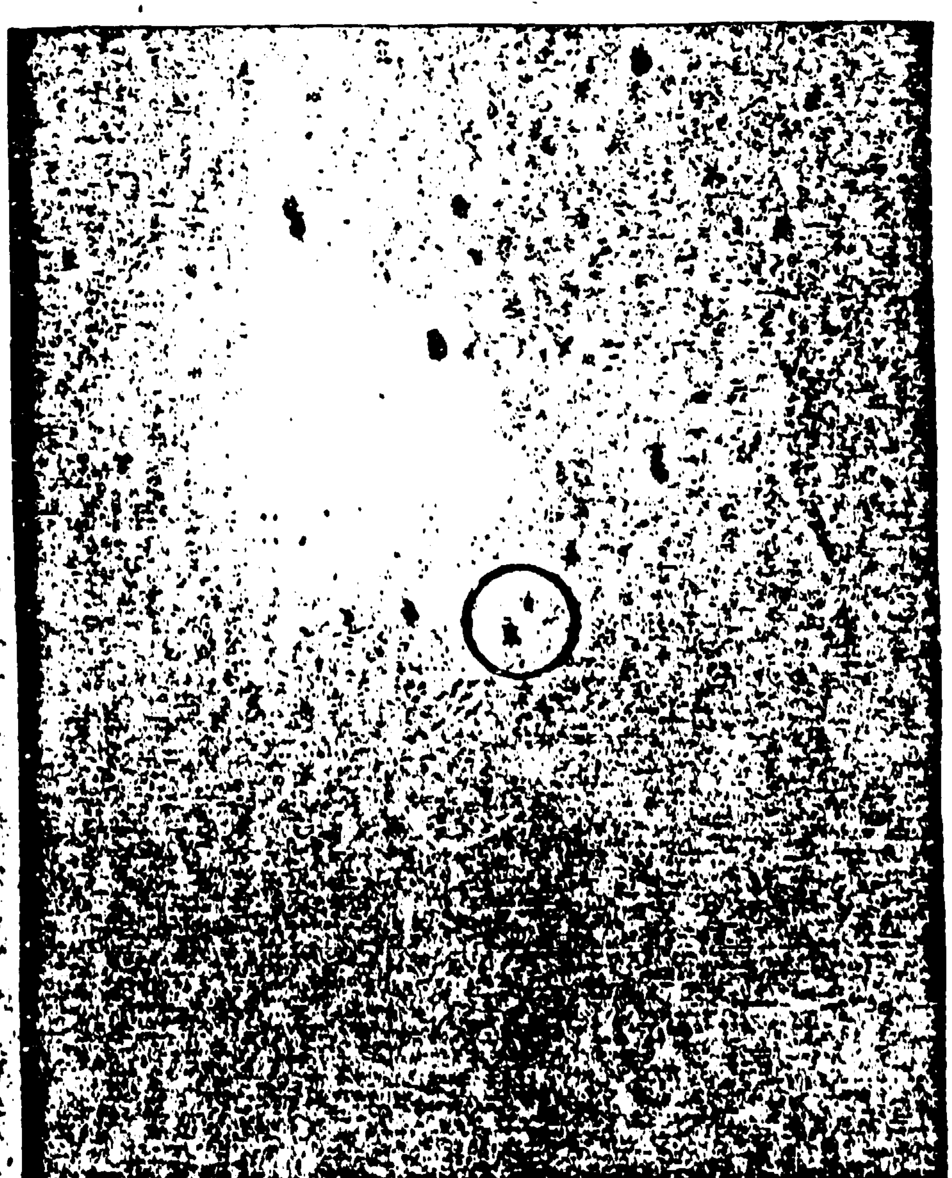
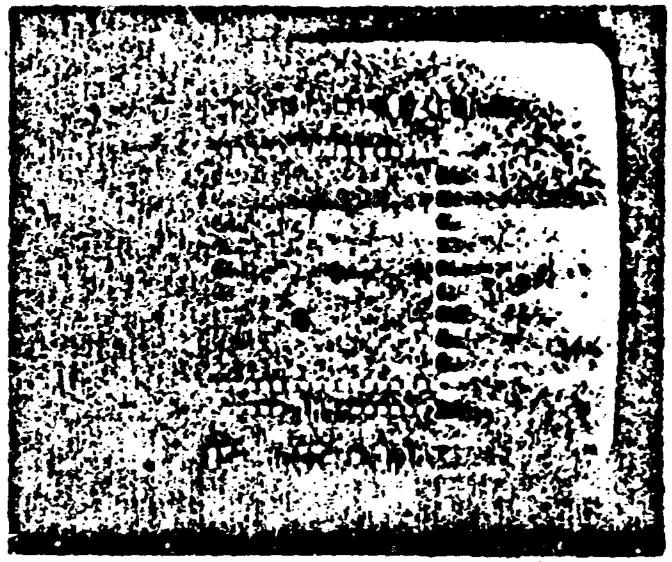


LASER DAMAGE MORPHOLOGY

Al_2O_3/SiO_2 MULTILAYER REFLECTOR



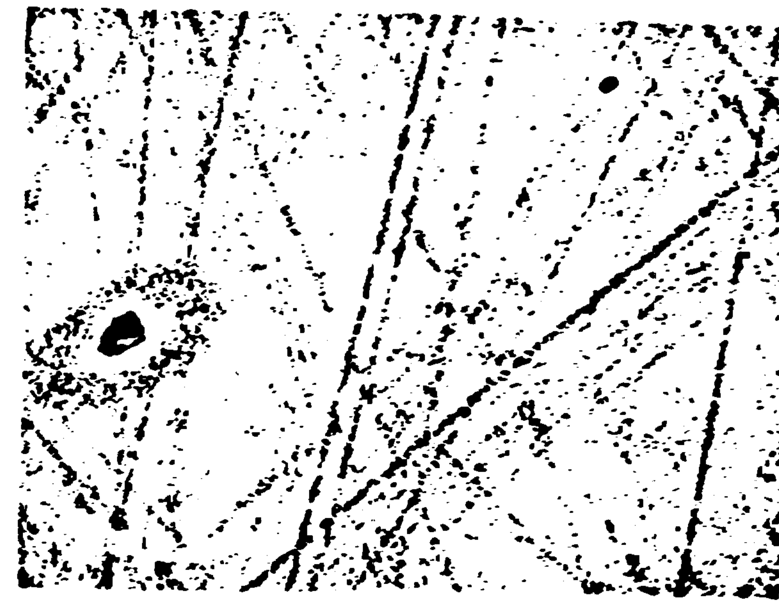
MICROSCOPE/VIDEO at ~ 100 x

SEM at ~ 1200 x

SEM at ~ 9000 x

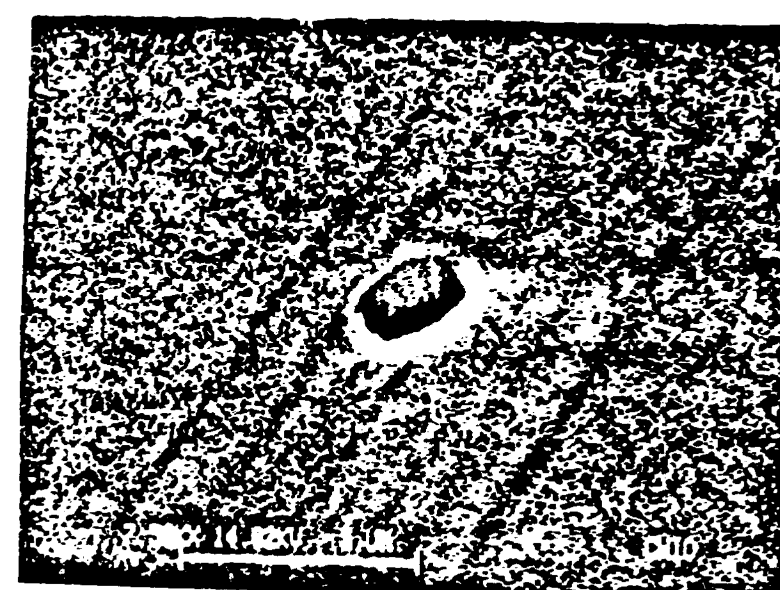
SEM at ~ 20 000 x

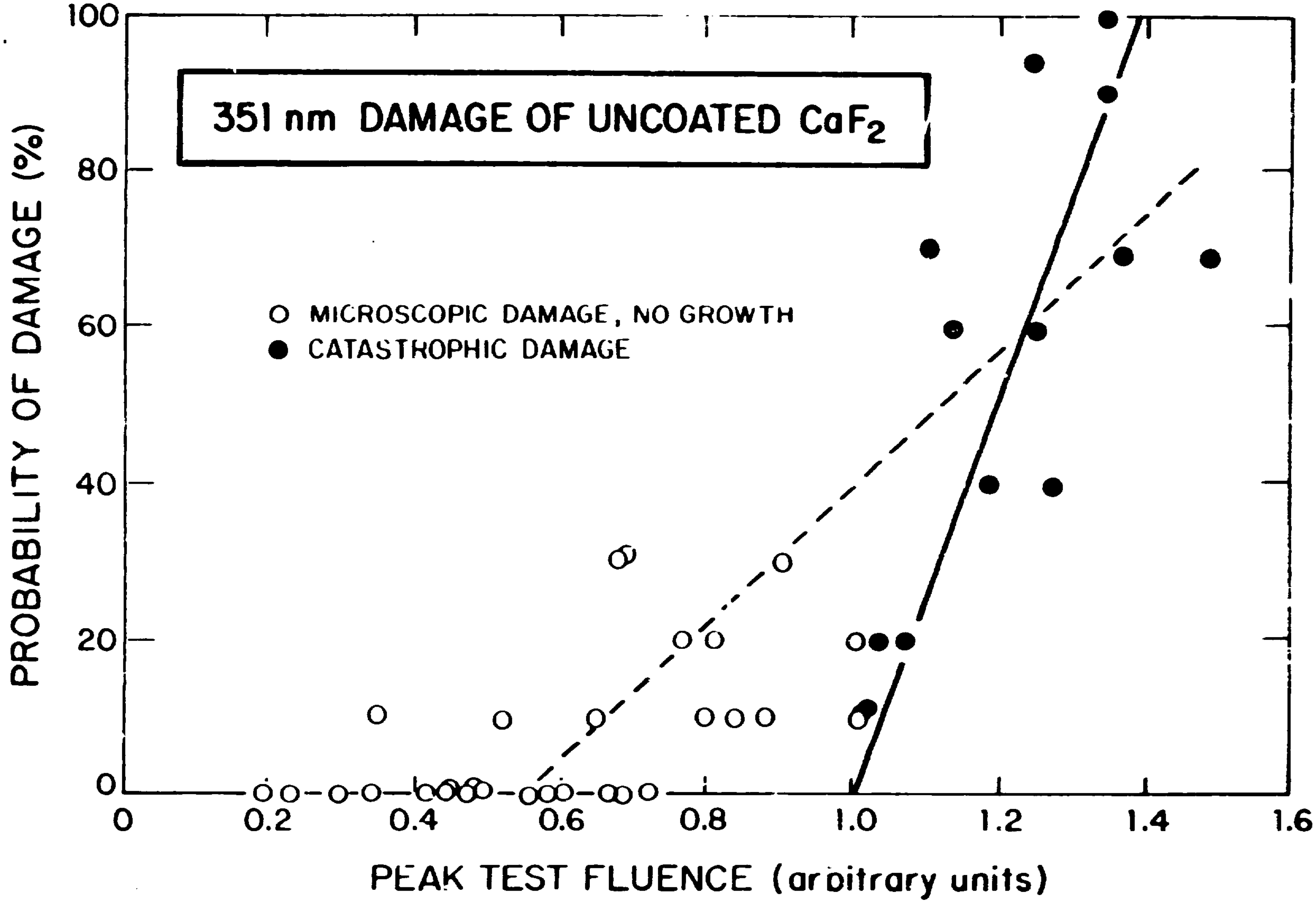
Damage Morphology
AR coating at 351 nm

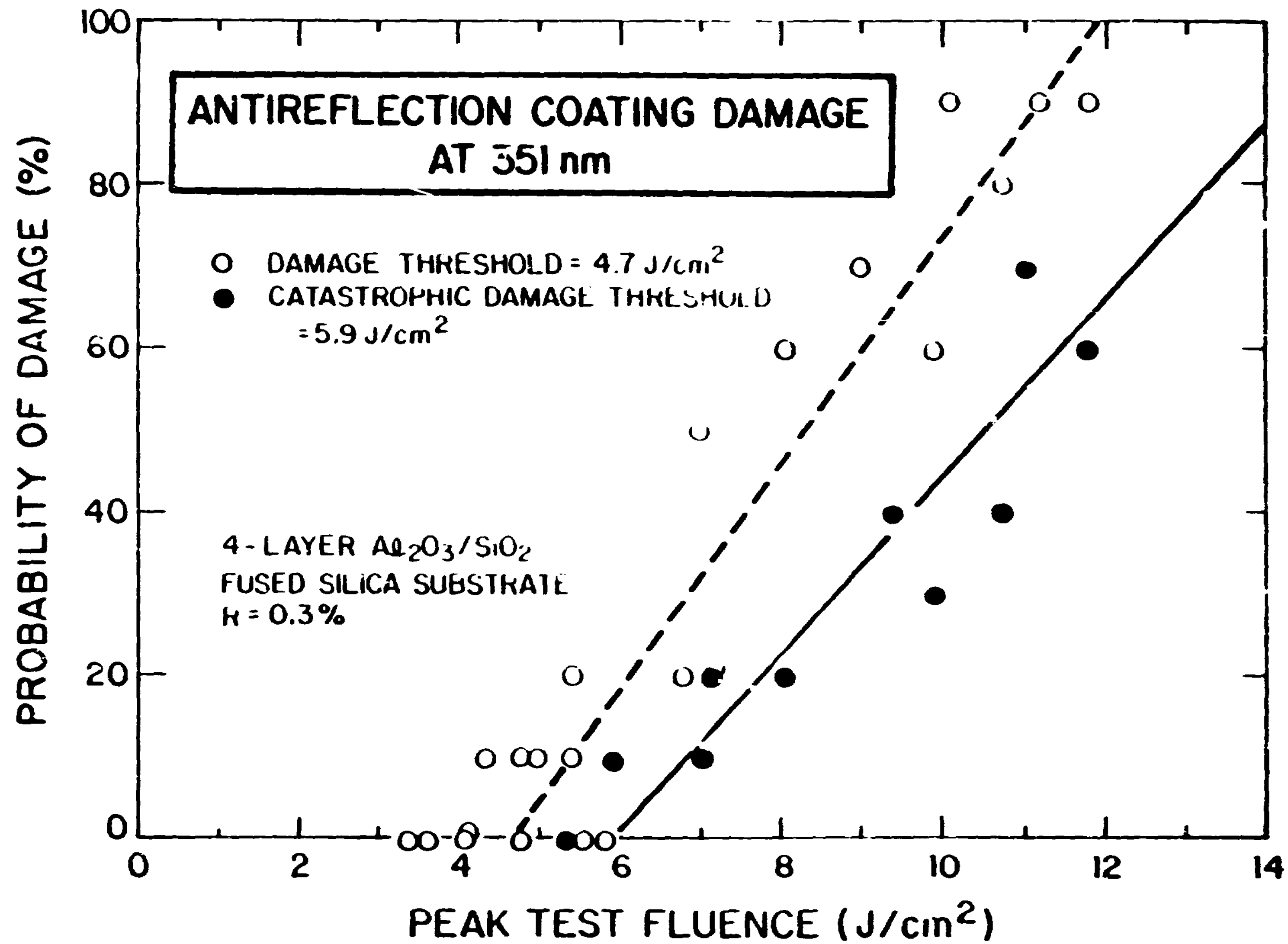


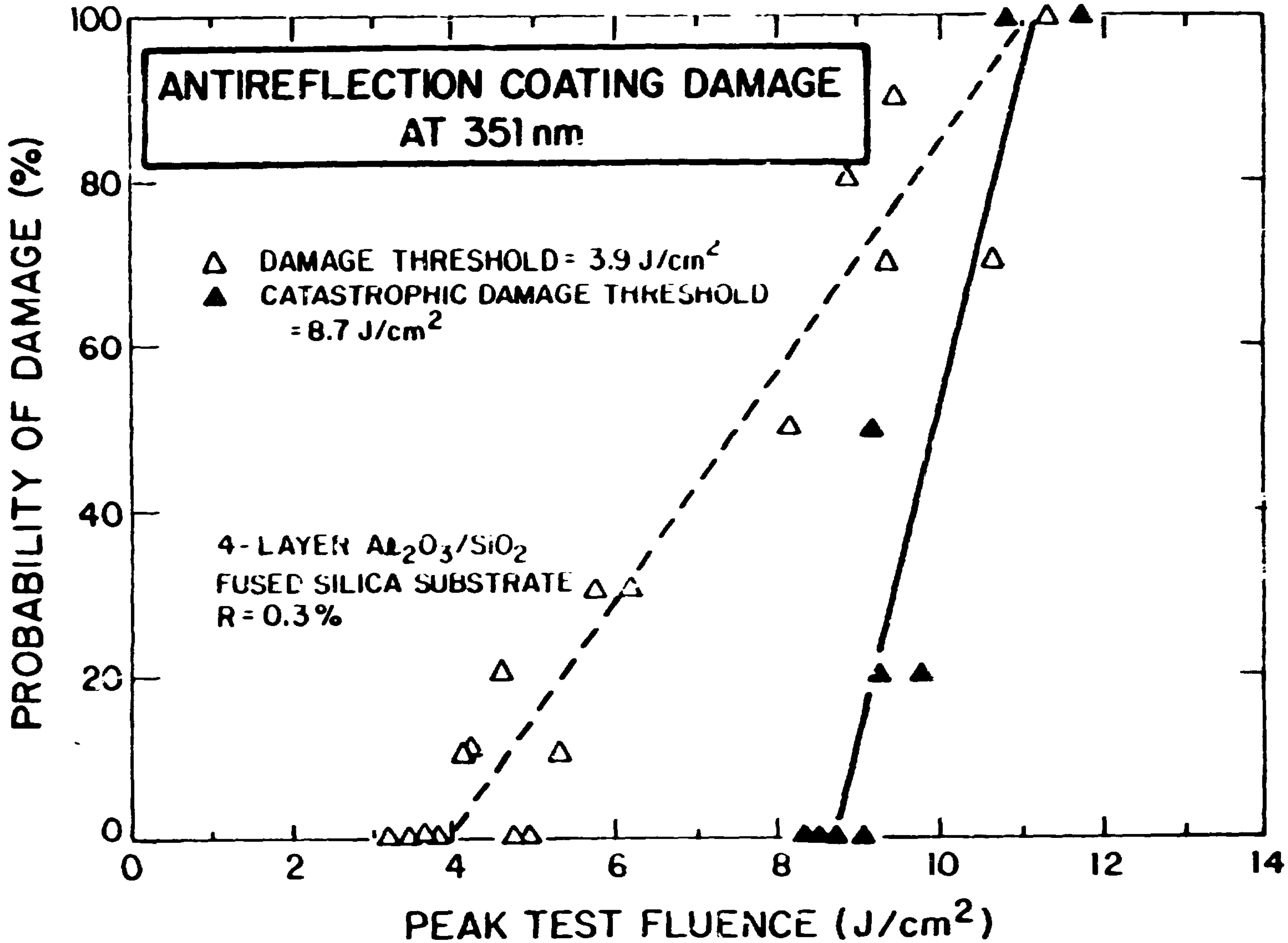
microscopic damage

coating pinhole?




351 nm DAMAGE OF UNCOATED CaF_2
MICROSCOPIC DAMAGE, NO GROWTH
CATASTROPHIC DAMAGE
PROBABILITY OF DAMAGE (%)
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
PEAK TEST FLUENCE (arbitrary units)


ANTIREFLECTION COATING DAMAGE
AT 351 nm
O DAMAGE THRESHOLD = 4.7 J/cm²
● CATASTROPHIC DAMAGE THRESHOLD = 5.9 J/cm²
4-LAYER Al₂O₃/SiO₂
FUSED SILICA SUBSTRATE
R = 0.3%
PROBABILITY OF DAMAGE (%)
PEAK TEST FLUENCE (J/cm²)
0
20
40
60
80
100
2
4
6
8
10
12
14


ANTIREFLECTION COATING DAMAGE AT 351 nm
△ DAMAGE THRESHOLD = 3.9 J/cm²
▲ CATASTROPHIC DAMAGE THRESHOLD = 8.7 J/cm²
4-LAYER Al₂O₃/SiO₂
FUSED SILICA SUBSTRATE
R = 0.3%
PROBABILITY OF DAMAGE (%)
PEAK TEST FLUENCE (J/cm²)
0
20
40
60
80
100
0
2
4
6
8
10
12
14