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Design and fabrication of high damage threshold turning mirrors for the Nova Laser*

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ABSTRACT

Laser induced damage to optical components severely limits the operating fluence of high peak power lasers used for fusion research such as the Nova laser at the Lawrence Livermore National Laboratory. In particular, surfaces and optical thin films often damage at a lower fluence than bulk materials in large aperture, high quality optics. We have designed and are fabricating new 94 cm turning mirrors for Nova as part of the "Precision Nova" program to improve beam quality. A new design has been optimized for updated optical performance specifications including increased damage resistance. The new mirror design will operate at all turning angles required by the ten Nova beamlines. This flexibility reduces mirror inventory and fabrication cost. A process of "conditioning" the mirror coating has been developed that is permanent and increases the damage threshold by as much as a factor of 2-3x.

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1. INTRODUCTION

Over the past several years our optical thin film design and fabrication work has been directed toward two objectives. First, we are planning to replace the current turning mirrors on Nova as part of the "Precision Nova" program. Our objective is to upgrade Nova with the high performance, damage resistant turning mirrors at a reasonable cost. Our second objective has been to improve upon our fabrication technology to enable us to produce large aperture mirrors suitable for the next generation of fusion lasers. To accomplish this objective we have simplified the new coating design and have developed a "conditioning" process for thin films. We have found that using this process the damage thresholds of large aperture mirrors can be increased by factors of 2-3x over current Nova mirrors.

2. NOVA REQUIREMENTS

The 100% turning mirrors on Nova are used to direct the output beams of 1.053 μm light to the target chamber. This is shown schematically in figure 1. The performance specifications of the current turning mirrors on Nova are shown in table 1. The specifications that have been modified for the re-work Nova mirrors are shown in table 2. These modifications have not sacrificed performance but have reduced cost and extended our fabrication technology.

The most significant changes in mirror specifications are:

i. a single design will satisfy all incident angles,
ii. reflectance at 2nd and 3rd harmonic has been reduced or eliminated and
iii. damage threshold at 1.064 μm has been increased.

Due to physical limitations, Nova turning mirrors must operate over a range of incident angles, from 13.6° to 33.0°. Originally, to achieve highest performance, several thin film designs were made to satisfy the six incident angles. Over the years, this conservative approach has proved awkward and resulted in a need for a large spare mirror inventory for Nova. To avoid this our re-work mirrors are all designed at the same angle and optimized to perform to specification at all incident angles. This results in one mirror stocked in inventory. We have also simplified the required reflectance of the re-work vs. the current mirrors. The actual reflectances of the current and re-work mirrors are shown in figures 2a and b. There is now no reflectance requirement at the 2nd harmonic and the relaxed requirement at the 3rd harmonic remains for target alignment purposes only. The damage threshold of the re-work mirrors is also, significantly improved. As will be discussed further below, we have developed new coating materials and a conditioning process for optical thin films that results in an improved threshold for the re-work mirrors of as much 2-3x that of the current Nova mirrors.

3. DESIGN APPROACH

Our design approach has been to attempt to satisfy multiple angles of incidence required by Nova with a minimum number of multi-layer coating designs. As a result of extensive theoretical calculations, we have found that a single design can satisfy performance specifications at all required incident angles.

We used a simple design approach starting with a quarterwave stack at 1.053 μm modified to control phase retardance. We varied the design angle in small increments from 13.6° to 33.0° and numerically refined the layer thickness at each design angle. We then evaluated the theoretical performance of the refined designs at the six incident angles of interest (match angles). By a repetitive process of design and analysis, we arrived at an optimized design for all incident angles. "Monte Carlo" simulations were run allowing individual layer thickness to vary by +/- 3%, to simulate manufacturing reproducibility. Typical reflectance and phase retardance calculations performed in this way are shown in figures 3 and 4.

4. OPTICAL PERFORMANCE

The current Nova mirrors are "trichroic" with high reflectance at the laser wavelength and at the 2nd harmonic. At the time Nova was designed, the 2nd and 3rd harmonic reflectance was also needed for target alignment. However, high reflection at the 3rd harmonic was not required, only partial reflection of an alignment beam was necessary. In addition the possibility of strong back-reflections of 3rd harmonic light from the target chamber into beam diagnostics was also a potential problem to be avoided. The high reflectance at the 3rd harmonic was therefore partially frustrated. This added some complexity to the multi-layer film design at that time, but could not be avoided. The resulting optical performance of the turning mirrors is as shown in Figure 2a. An extensive discussion of the design and fabrication of original Nova optical coatings can be found in [1].

The optical performance of the re-work Nova turning mirrors is shown in Figure 2b. Since the time of the original Nova design, the reflectance requirement at the 2nd harmonic has been removed. High reflectance at the laser wavelength and partial reflectance at the 3rd harmonic remain however. As described above, our goal in the design of the re-work turning mirrors was to satisfy as many angles of incidence as possible with a single design. This approach and the requirement of only partial reflectance at the 3rd harmonic naturally suggested a design approach using a modified quarterwave stack. Such a multi-layer has strong reflectance at the 1st and 3rd harmonic when the incident angle is the design angle (Figure 2b). The reflectance is quite narrow at the 3rd harmonic, and we make use of this fact in the new design.

When a multilayer mirror is rotated away from it's design angle (to higher or lower incidence), the optical performance shifts (to shorter or longer wavelength, respectively). This shift in performance is small and therefore the reflectance at the principle wavelength is not effected, since the reflectance bandwidth at that wavelength is broad. On the other hand, reflectance at the 3rd harmonic is effected by slight mirror rotation, since the reflectance bandwidth at that wavelength is narrow.

The use of a "simple" multi-layer design has also reduced fabrication costs. Simplicity in design increases fabrication yield, reduces the number of mirrors required and shortens the coating cycle. By having fewer layers the mirror is easier (quicker and higher yield) to fabricate. This design satisfies all 100% turning mirror needs on Nova, thereby substantially reducing the spare mirror inventory required for normal operation.

5. DAMAGE THRESHOLD MEASUREMENT

The facilities and method of damage threshold measurement at LLNL has recently been described in detail by Rainer [2] and Morgan [3]. Damage is defined as any visual change in the sample after laser irradiation that is visible by 100X Nomarski illumination. All damage testing and conditioning reported here were performed at a wavelength of 1064 µm. Two laser shot sequences are most frequently used to measure damage thresholds. These sequences are shown in Fgure 5. The S on 1 test uses a series of constant fluence shots; each on a fresh site (an area of the coating with no prior history of irradiation). The unconditioned damage threshold is measured in this way. The R on 1 test also uses a series of shots, but the fluence is varied from zero to a pre-set upper bound in a linear ramp. The conditioned damage threshold is determined in the R:1 test. In both cases the time between shots is short (equal to 1/PRF). Uncertainty in the threshold measurement is typically $^{+}/_{-}$ 15%.

"Conditioning", as we use the term here, involves exposing a coating to a fluence of laser light below the S on 1 damage threshold. This treatment has been found to increase the S on 1 damage threshold significantly [4]. The specifics of how this is done and our attempts to optimize the process so as to achieve the greatest damage threshold increase is the topic of [4, 5] and is summarized in Section 6.2 below.

6. THRESHOLD IMPROVEMENT BY CONDITIONING THIN FILMS

In all multilayer coatings discussed here, SiO_2 was used as the low index dielectric material. The most reproducible and generally the highest damage thresholds were obtained for films using HfO_2 as the high index dielectric material. Inconsistent damage thresholds were measured for films using ZrO_2 and TiO_2 as the high index dielectric, as described in [4]. We found that the unconditioned and conditioned thresholds of HfO_2/SiO_2 HR coatings were very reproducible and showed the same factor of improvement due to conditioning over a broad pulse length range (1 ns to 16 ns), as shown in Figure 6. The improvement of the threshold was consistently between 2 - 3X. Based on the data in Figure 6 for the HfO_2/SiO_2 coatings, the damage threshold scales with pulse-length as approximately:

$$\text{unconditioned:} \quad D_t \approx 7\, t_p^{0.35}$$

$$\text{conditioned:} \quad D_t \approx 19\, t_p^{0.30}$$

were D_t is in Joules/cm^2 and t_p is the laser pulse length in ns.

The films used in the tests above were R&D coatings made during 1988-89. We also performed conditioning studies on the current Nova turning mirrors made in 1983. The unconditioned damage thresholds of the recent R&D HFO_2/SiO_2 HR coatings, compare quite well with the unconditional thresholds of our current Nova turning mirrors which are made of ZrO_2/SiO_2. This is shown in Figure 7. An important difference appears when conditioned thresholds are measured. The threshold of the Nova mirrors is only increased slightly (about 1.5X), while the threshold of the HfO_2/SiO_2 coatings is increased to a greater degree (about 2.7X), see Figure 7.

6.1 Elimination of some possible conditioning mechanisms

Laser conditioning of thin films has been linked in the literature to the removal of water or other atmospheric contaminants. When such "cleaning" mechanisms have been reported, the enhancement of the damage threshold by conditioning was often found to be temporary.

We have conducted experiments that show that the conditioning effect we report is not related to the presence or removal of water in the thin films. To demonstrate this, HfO_2/SiO_2 HR's made by e-beam evaporation were allowed to equilibrate with ambient air (20 C, ≈ 50% RH) and were then damage tested at 1064 nm. Both unconditioned and conditioned thresholds were determined. The same samples were then desiccated to remove physically absorbed water and the thresholds were again determined. The data shown in Figure 8 shows that no significant change in threshold was observed that can be related to the presence, or removal, of water from the thin films.

In the dried coatings, the removal of water was observed as a shift in reflectance to shorter wavelengths. The reflectance at 950 nm was used to monitor the change in film performance because a pronounced minimum occurred at that wavelength. This structure allowed the slight change in reflectance to be accurately monitored. When the dried coatings were re-exposed to ambient air, the reflectance shifted back to longer wavelengths and the original performance was recovered. Figure 9 shows the reflectance shift of the '950 nm' minimum for one of the dried mirrors as it was re-equilibrated with ambient air. (Subsequent measurement of water absorption at 3350 cm^{-1} verified that the change in reflectivity was accompanied by a change in water content in these multilayer coatings.)

Besides the laser conditioning and the drying experiments described above, we also attempted to raise the damage threshold by flashlamp illumination. We subjected a series of HR coatings, whose unconditioned damage threshold were known, to the multiple pulses of broadband flashlamp light. The fluence was approximately 10 J/cm^2 and pulse length was 0.5 ms. No change in the damage threshold was observed as a result of this treatment.

X-ray analysis of the HfO_2/SiO_2 HR coatings also indicate that conditioning does not involve any obvious phase change. Diffractometer scans of these coatings shows that, while the SiO_2 is amorphous, the HfO_2 is as mixture of amorphous, monolithic and cubic phases. Scans of conditioned and unconditioned coatings were found to be identical. We therefore conclude that no phase change, that is measurable by this method, accompanies laser conditioning of these coatings.

6.2 Conditioning of large aperture optical components

We have devised a practical process to make use of the laser conditioning phenomenon described above. We plan to use this process to condition large aperture optical thin films for the Nova Laser [5].

In the R-on-1 conditioning described above, an area only the size of the test beam (~0.2 mm in diameter) was conditioned. In contrast, we are interested in laser conditioning coatings the size of the Nova mirrors (1.1m diameter), therefore other, more practical, methods of laser conditioning were studied. Here we present the results of conditioning studies performed by rastering a large coating surface with a small area beam (~0.2 mm in diameter) at laser fluences below the S-on-1 damage threshold. The rastering was done using the damage test laser and a programmable x-y stage. The x-y stage velocity was chosen such that the sample was shot every 0.1 mm in both the x and y directions.

This scan rate corresponds to four shots/site for a 0.2 mm diameter beam. Areas of ~4 cm^2 were rastered with various fluences below the S-on-1 damage thresholds of HR coatings. Four types of conditioning programs were examined in this study (in which the fluence of the damage test laser was varied):

a) raster at 10% of the S-on-1 threshold
b) raster at 63% to 55% of the S-on-1 threshold
c) raster at 85% to 55% of the S-on-1 threshold
d) consecutive rasterings at five fluences increasing from 37 to 85% of the S- on-1 damage threshold (hereafter referred to as "step conditioning").

These conditioning programs, along with that for ramp conditioning, are shown graphically in Figure 10. For the 5-step conditioning, the time between individual illuminations was approximately 1 hr. This is in contrast to the ramp conditioning where the time between shots is ~0.1s. Note also that the increment in fluence between shots in the ramp is only ~0.05% of the S-on-1 damage threshold.

For both the R&D (HfO_2/SiO_2) coatings and Nova turning mirrors (ZrO_2/SiO_2), single or multiple fluence raster conditioning resulted in an increase in the S-on-1 threshold. The average damage thresholds measured for the different conditioning programs are shown in Figure 11. Conditioning increased the damage threshold of the current Nova mirror by a factor of 1.2 to 1.3x. For the R&D coatings, however, conditioning increased the thresholds by a factor of 1.2 to 2.4x. The slight conditioning of Nova turning mirrors relative to that of R&D HfO_2/SiO_2 coatings was previously shown in Figure 7 for small aperture R-on-1 conditioning.
It is not clear at this time which type of raster conditioning program would provide the largest increase in the damage threshold. It appears, however, that no clear advantage is gained by step conditioning.

The most important conclusion reached by this work was that for both coatings <u>all</u> raster conditioning programs resulted in a damage threshold increase <u>less</u> than obtained by the ramped fluence technique (i.e. R on 1).

Using the beam size and raster rate used above, it would take nearly two months to raster a 1m diameter mirror. Obviously a more practical large area conditioning technique is required for optics of this size. We therefore examined the effectiveness of using a large aperture beam from the Nova laser (1ns, 1064 nm) for the conditioning illumination. If this method were effective, Nova mirrors could be conditioned <u>in-stiu</u>. Two 2" diameter R&D samples were examined for this purpose: a HfO_2/SiO_2 HR and a ZrO_2/SiO_2 HR.

It has been shown that the S on 1 damage thresholds for these two coatings at 1064 nm are both ~7 Jcm^2 at 1 ns. For this experiment the coating samples were mounted down line from a condensing lens which focussed a mid-chain Nova beam down to a 4 cm diameter spot.

A total of seven laser shots were fired at the HfO_2/SiO_2 and one at the ZrO_2/SiO_2 coating. Figure 12 shows the illumination history in terms of the average fluence for each shot (beam modulation was approximately $\pm 30\%$). In the case of the HfO_2/SiO_2 coating, we slowly increased the laser fluence after each shot from an initial value of about 3.5 J/cm^2 up a final value of about 12 Jcm^2; 12 Jcm^2 is about 1.5 to 2 times the S on 1 damage threshold. Microscopic and large area inspection of the HfO_2/SiO_2 coating after each shot showed no change. The final Nova shot was fired on the ZrO_2/SiO_2 coating. This single shot, having a mean fluence of about 10.6 J/cm^2 was significantly above the single-shot damage threshold (7 J/cm^2). As expected, the sample damaged. These results show that large areas optics can be conditioned using the large aperture Nova laser beam.

In order to compare the damage thresholds obtained by Nova and raster conditioning, we damage tested (S on 1), at 8 ns, the Nova conditioned sample. Figure 13 shows that the Nova conditioned sample has a damage threshold in the range obtained by raster conditioning. Note once again that all the large-area conditioned thresholds are lower than that obtained by ramp conditioning, (R on 1).

The HfO_2/SiO_2 coating that was conditioned on Nova was further damage tested to determine if the conditioning effect was permanent. These damage tests were done at 1064 nm and 10 ns; the results are shown in Figure 14. Test conducted over a period of about 10 weeks showed no drop in the conditioned damage threshold.

7. CONCLUSIONS

We have changed the multilayer coating design and materials used in the 100% turning mirrors on Nova. In doing so, we have reduced the fabrication cost without sacrificing optical performance. In addition, we have developed a conditioning process for thin films that increases the damage threshold by as much as 2-3x. This process is permanent and is applicable to the large aperture coatings on the Nova laser.

8. REFERENCES

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Table 1
Specifications of Nova 100% Turning Mirrors

(AAA-78-115226-06)

Incident Angle (separate designs are required at each individual angle):		13.6, 20.0, 22.5, 24.8, 29.4		33.0
Diameter (cm):		94		109
Thickness (cm):		12		16
Mass (kg):		209		375
Substrate Material:		BK-7		
Surface Finish:		λ/10 in reflection at 0.63 μm with < λ/35 per cm gradient		
Coating Material/ Design:		ZrO_2/SiO_2; 2:1/1:1; λ/4		
Reflectance:	at	1.053 μm 0.527 μm 0.351 μm	R_{ave}	≥ 99.0% ≥ 95.0% ≥ 37.0% and ≤ 54.0%
Phase Retardance:		$\phi_p - \phi_s$ < 6 nm at 1064 nm		
Damage Threshold:		≥ 8.0 J/cm² for a 1 ns pulse at 1064 nm		

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Table 2
Specifications Modified for
Nova Re-work 100% Turning Mirrors

Incident Angles (all satisfied by a single design)	13.6, 20.0, 22.5, 24.8, 29.4, 33.0
Surface Finish	$\lambda/4$ in reflection @ 0.633 µm with < $\lambda/15$ per cm gradient
Coating Material/Design	HfO_2/SiO_2 modified 1:1 $\lambda/4$
Reflectance	@ 1.053 µm R_{ave} > 99.0% 0.351µm > 30.0%
Phase Retardance	$(\O_p - \O_s) \leq 2.5°$
Damage Threshold	> 16.0 J/cm^2 conditioned threshold for 1 ns pulse at 1064 nm

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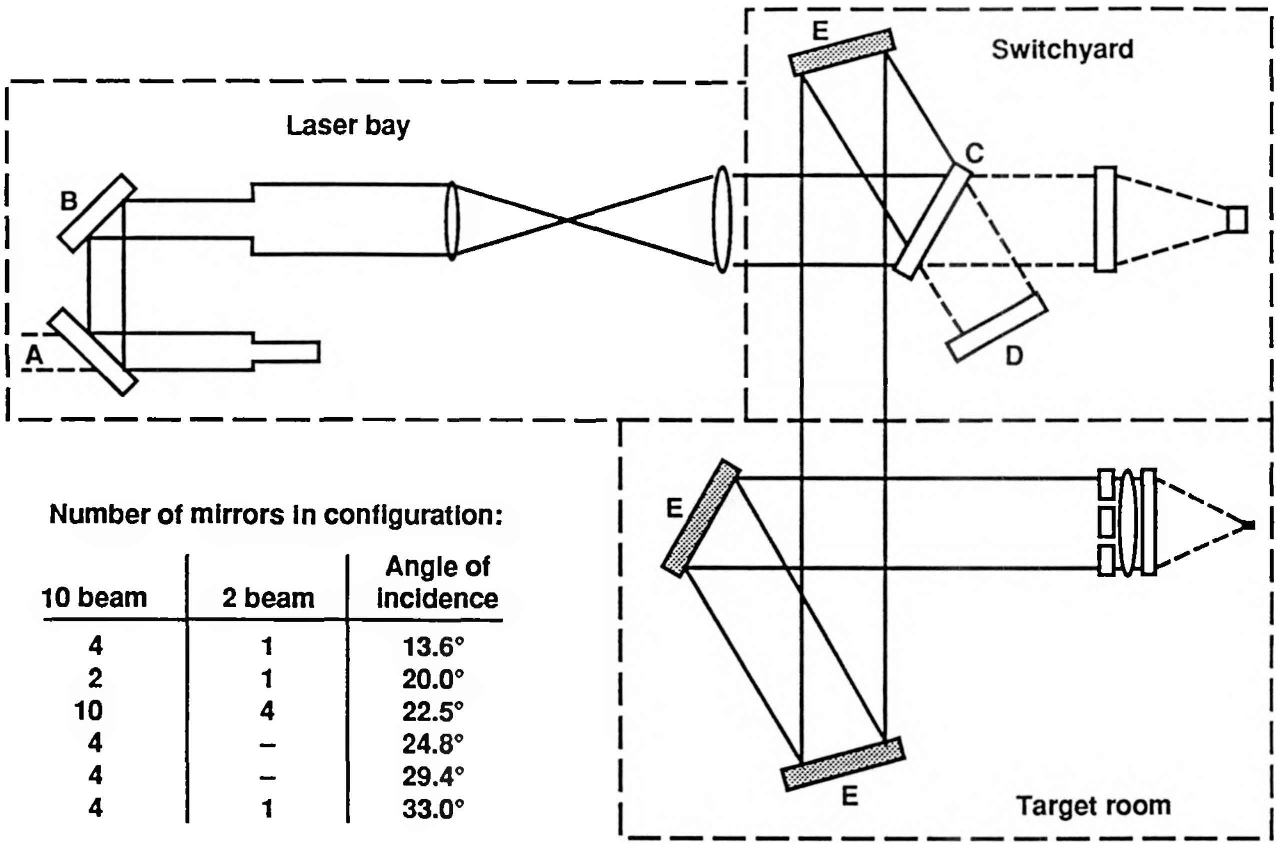

Number of mirrors in configuration:

10 beam	2 beam	Angle of incidence
4	1	13.6°
2	1	20.0°
10	4	22.5°
4	–	24.8°
4	–	29.4°
4	1	33.0°

Figure 1. Nova 100% turning mirrors direct laser light (1.053 μm) to the target chamber

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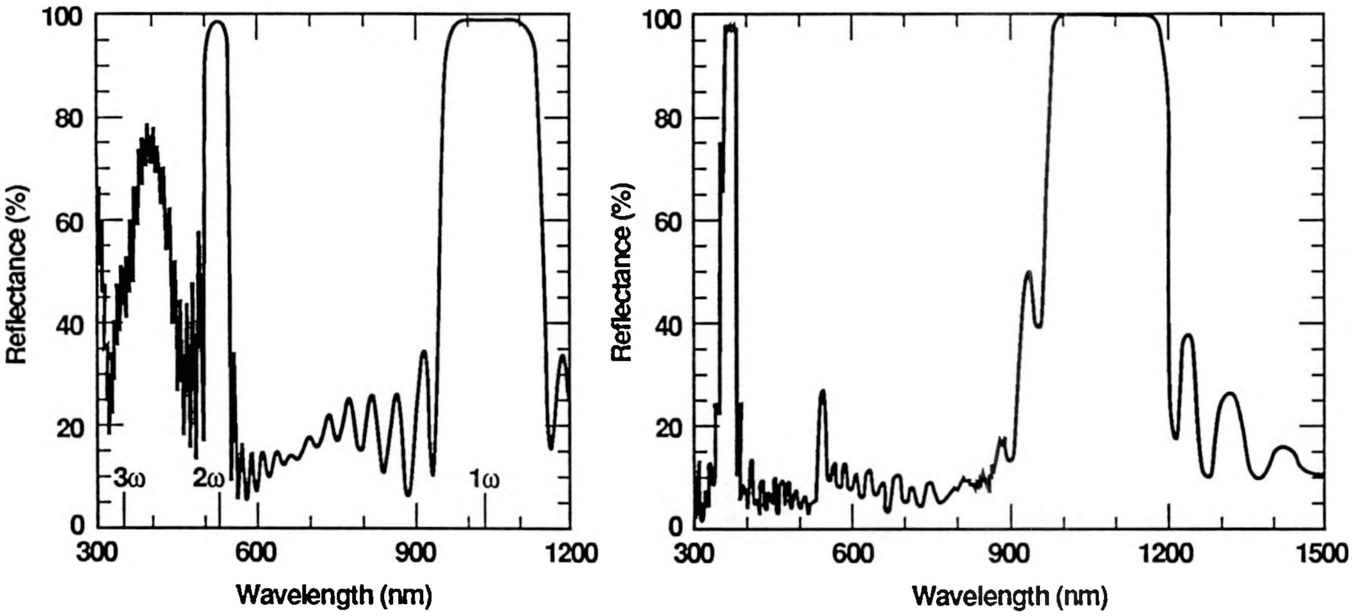

a) Current turning mirror

- Trichroic
- Complex multi-layer design

b) Re-work turning mirror

- Simple design
- Reflectance at 3rd harmonic "de-tuned" by rotation

Figure 2. Spectral reflectance of Nova 100% turning mirrors

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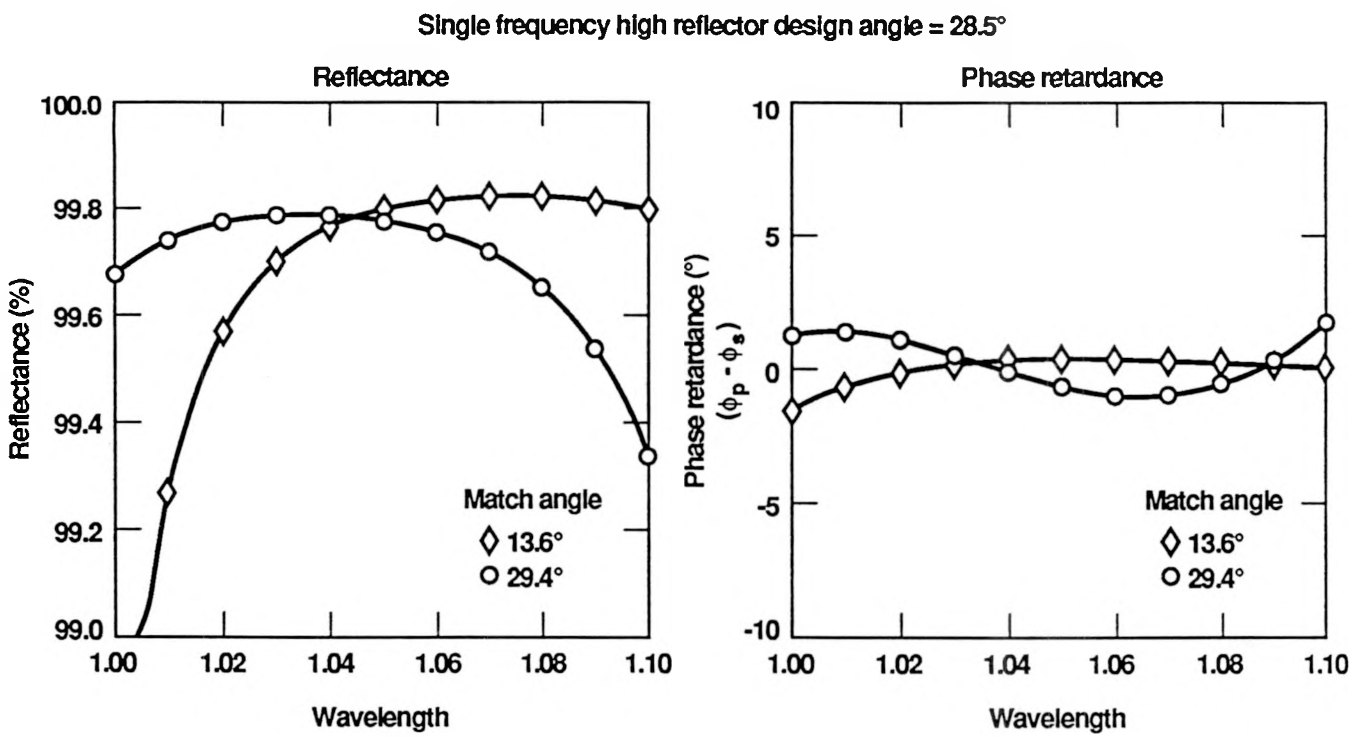

Figure 3. The theoretical reflectance and phase retardance were calculated vs. incident angle for each design

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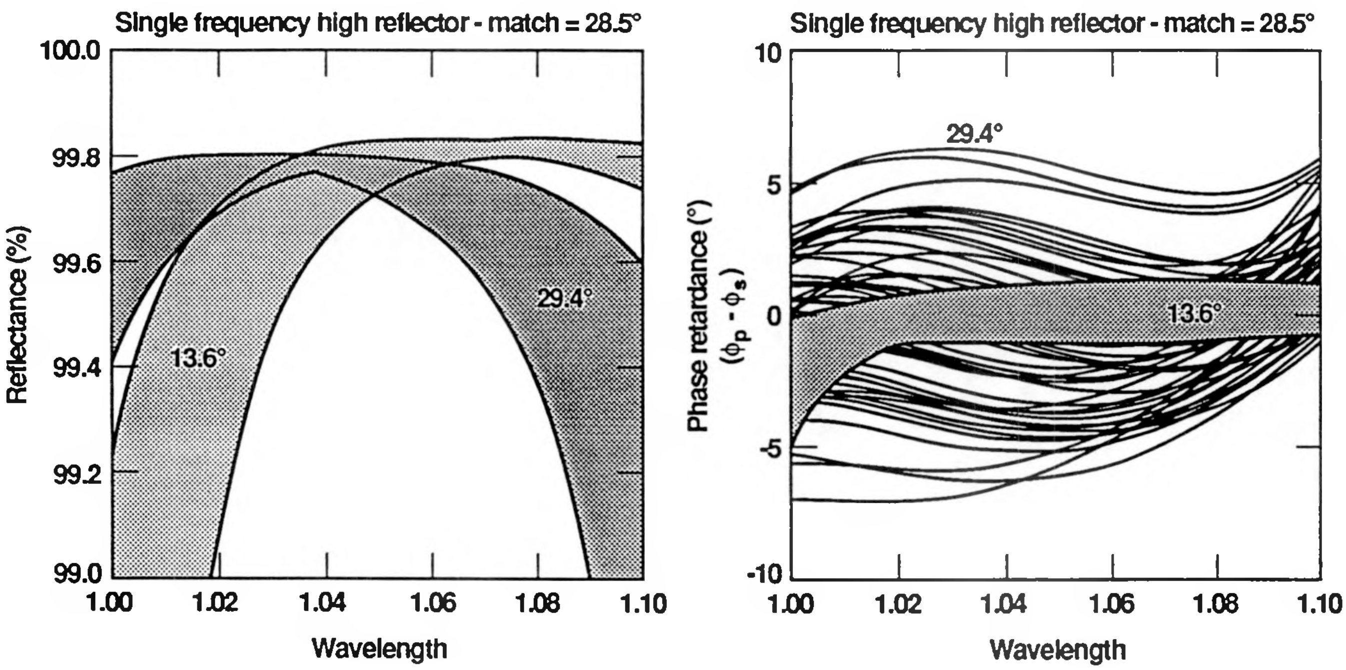

Reflectance at 13.6° and 29.4° incidence

Phase retardance at 13.6° and 29.4° incidence

(Layer thickness was allowed to varying ±3% in a random manner)

Figure 4. "Monte-Claro" numerical analysis was used to estimate fabrication yield

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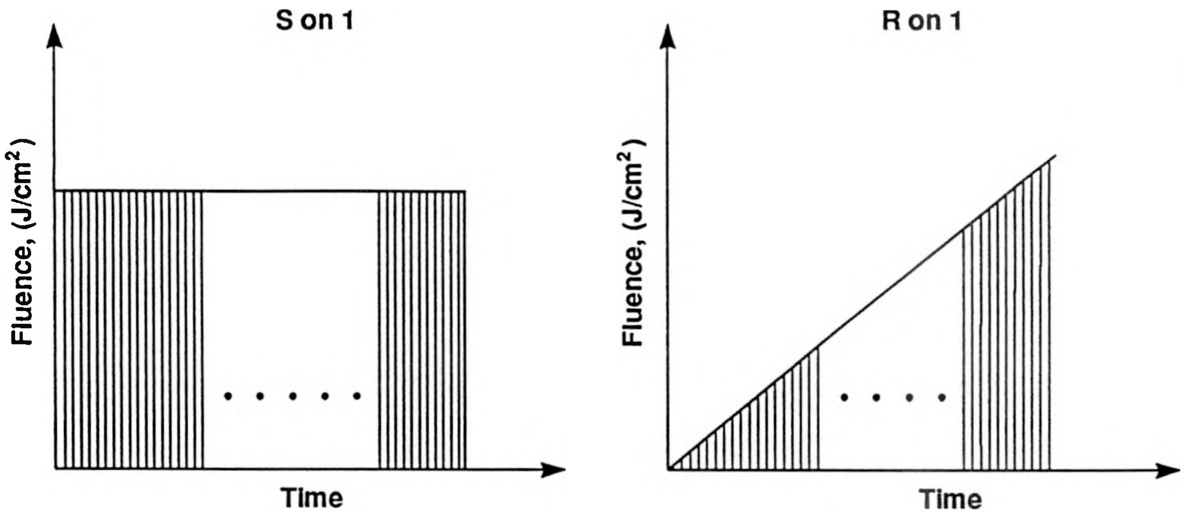

Figure 5. Two methods used to measure damage threshold: (a) multiple shots per site at constant fluence (S on 1), and (b) multiple shots per site with a ramped increase in fluence (R on 1).

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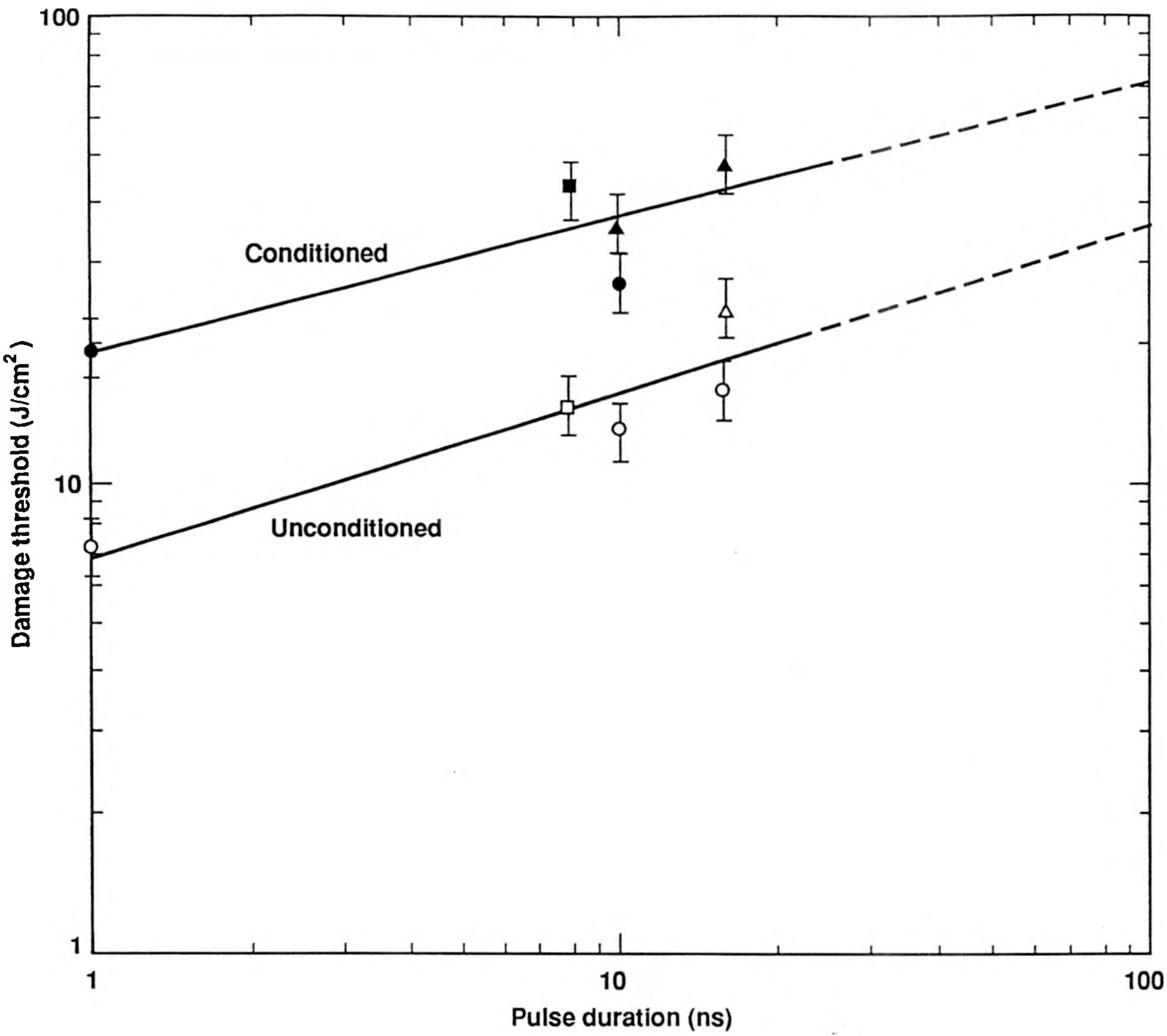

Figure 6. Measured pulselength scaling for conditioned and unconditioned damage thresholds of HfO_2/SiO_2 HR coatings at 1064 nm. The solid line represents a least squares fit to the data.

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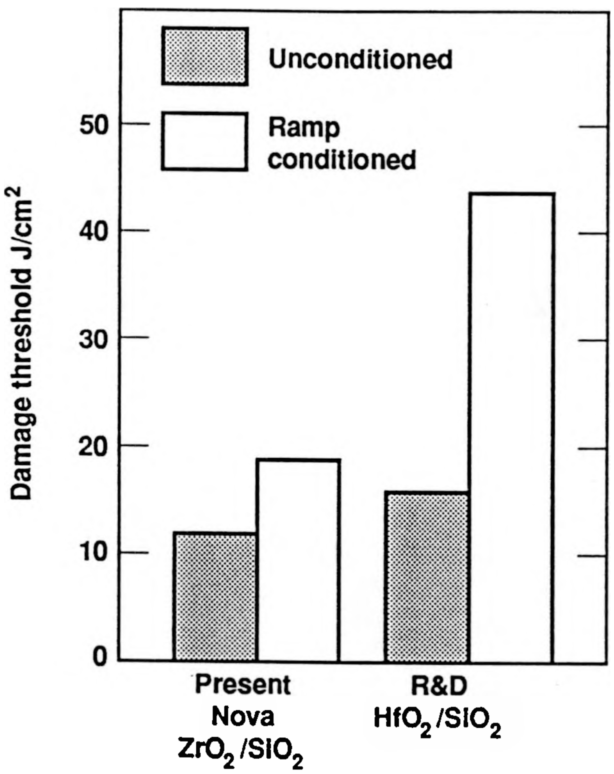

Figure 7. Unconditioned (S on 1) and ramp conditioned (R on 1) 1064 nm damage thresholds (18 Hz, t_p = 8ns) of Nova ZrO_2/SiO_2 and R&D HfO_2/SiO_2 HR coatings. Conditioning performed using damage test laser.

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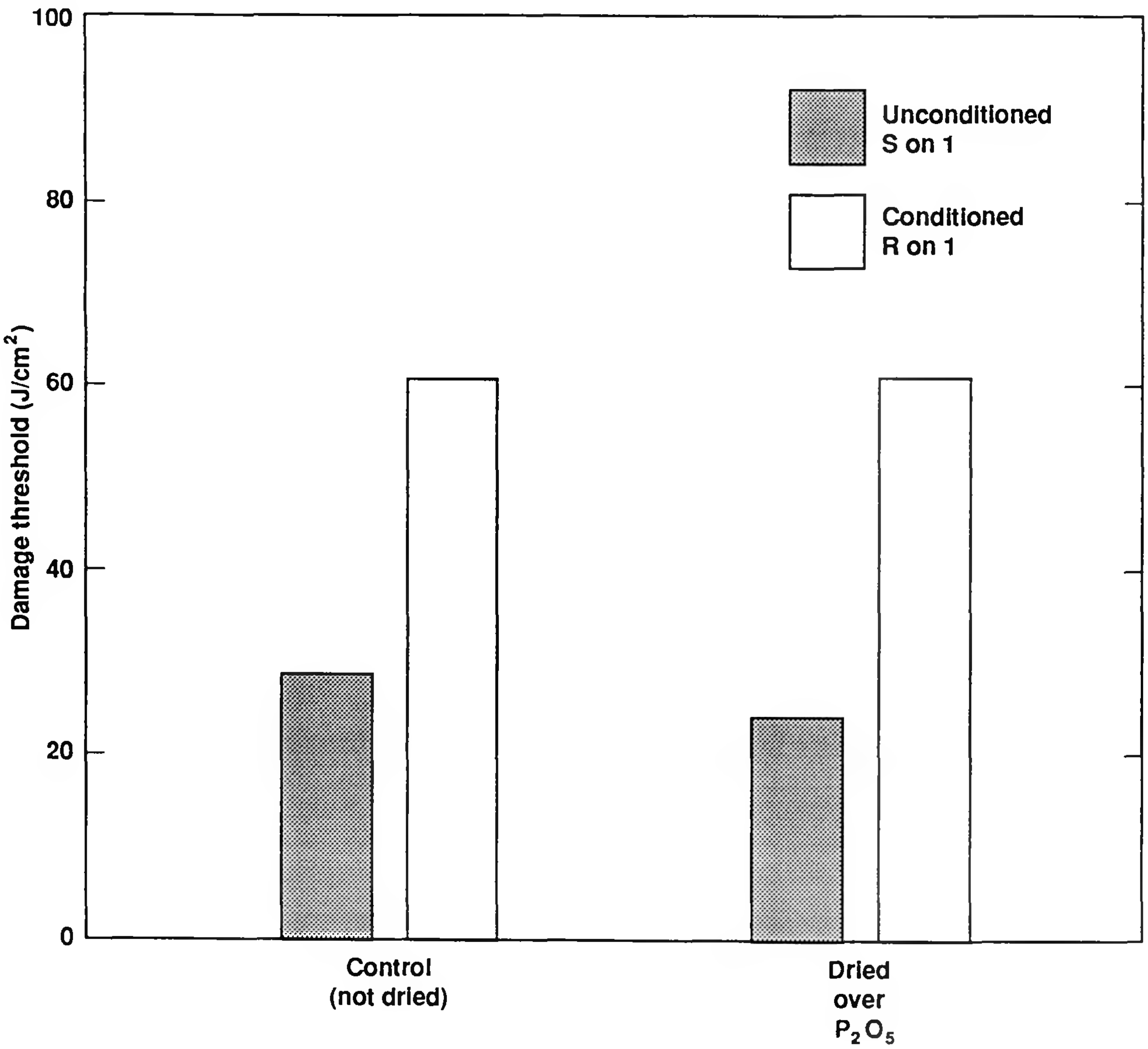

Figure 8. Conditioned (R on 1) and unconditioned (S on 1) damage thresholds (1064 nm, 16 ns) for HfO_2/SiO_2 HR coatings equilibrated in ambient air and desiccated over P_2O_5.

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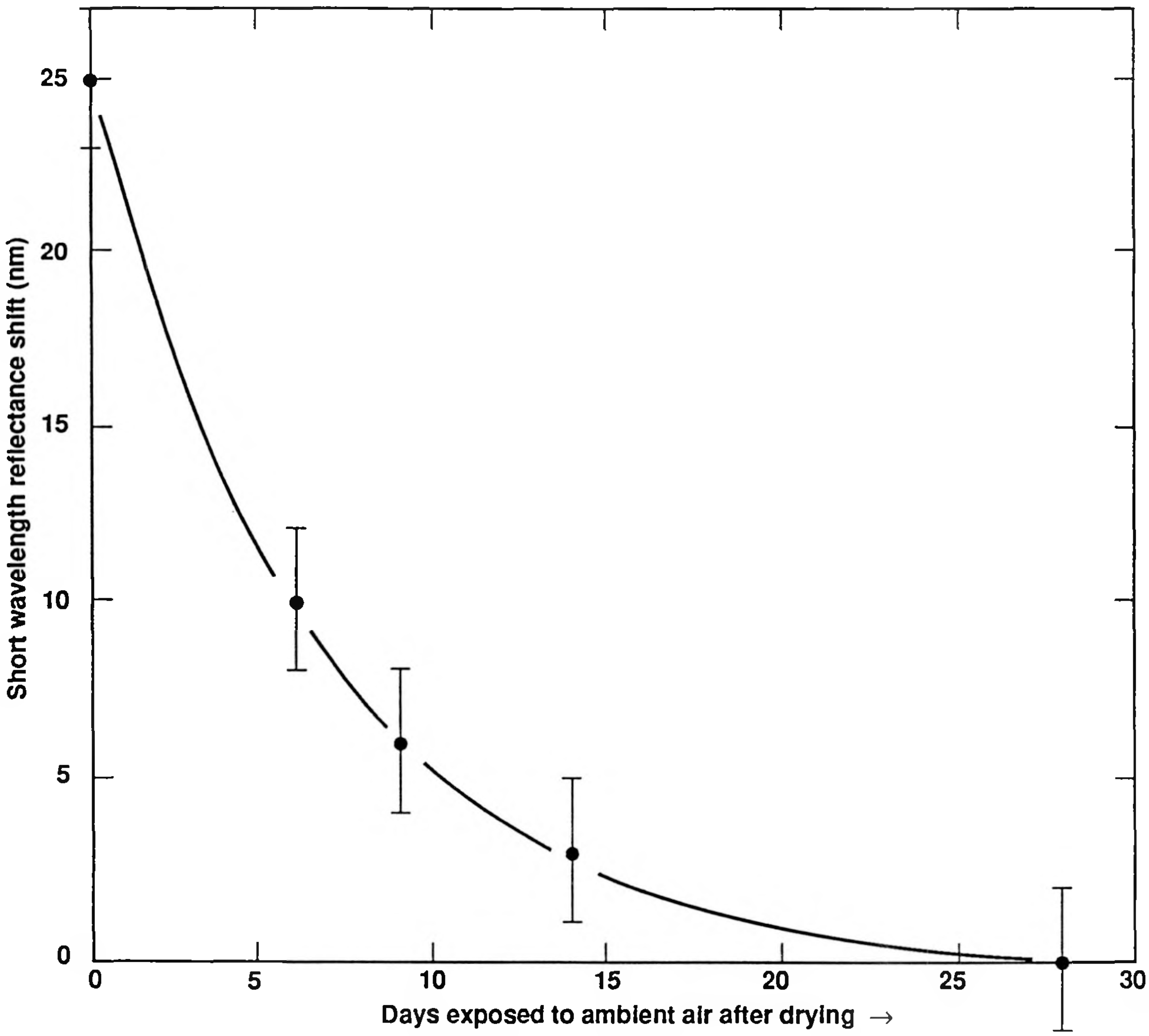

Figure 9. Time dependence of the spectral shift, to short wavelength, of a desiccated HfO_2/SiO_2 HR upon exposure to ambient air.

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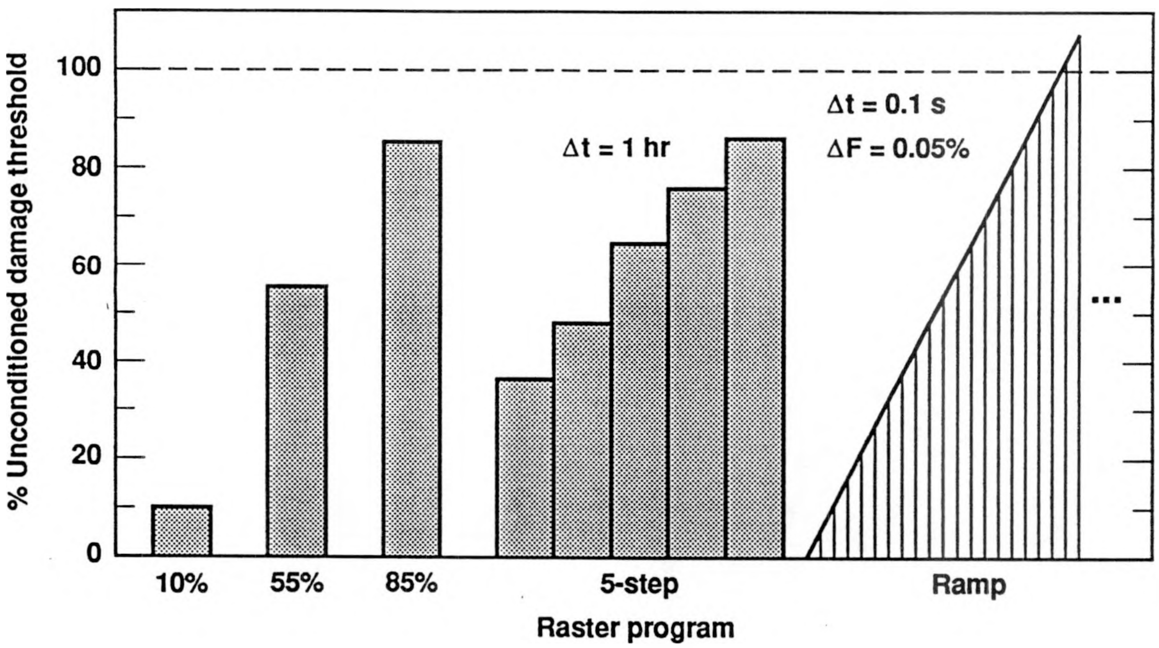

Figure 10. Laser conditioning program used in raster conditioning and ramp conditioning experiments.

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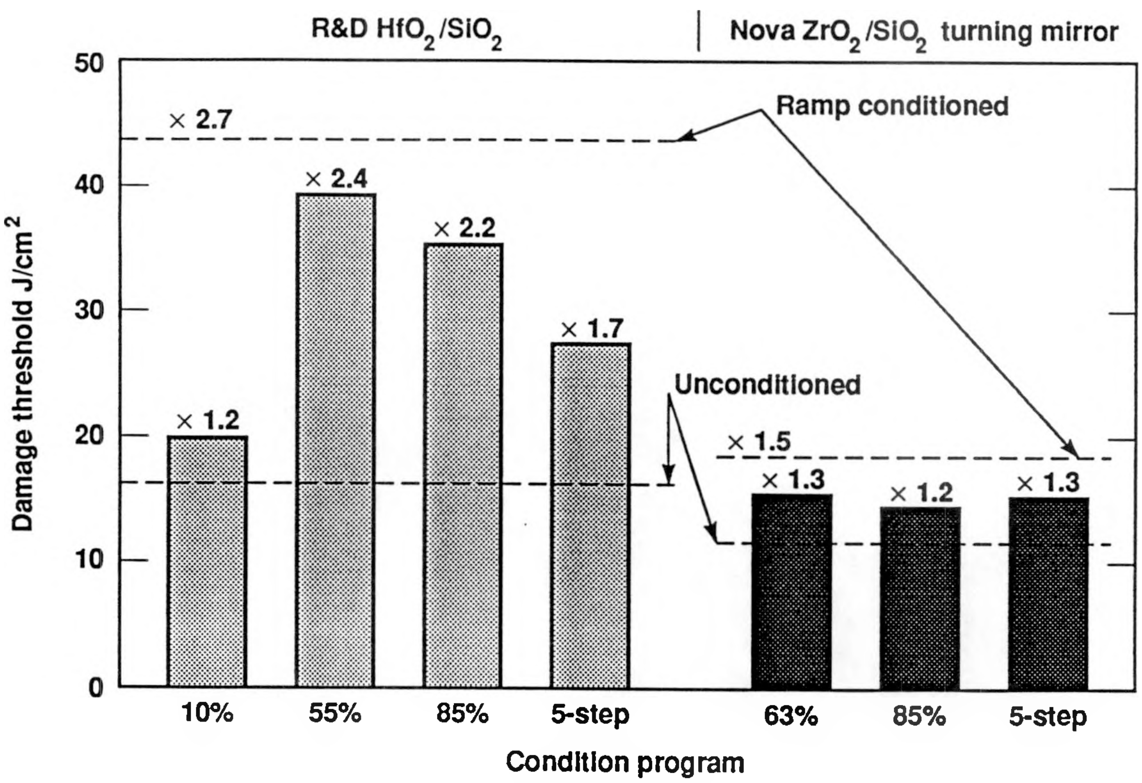

Figure 11. Conditioned 1064 nm damage thresholds (18 Hz, t_p = 8 ns) of Nova ZrO_2/SiO_2 turning mirror and R&D HfO_2/SiO_2 HR coatings for various raster conditioning programs. Unconditioned and conditioned thresholds are included for reference.

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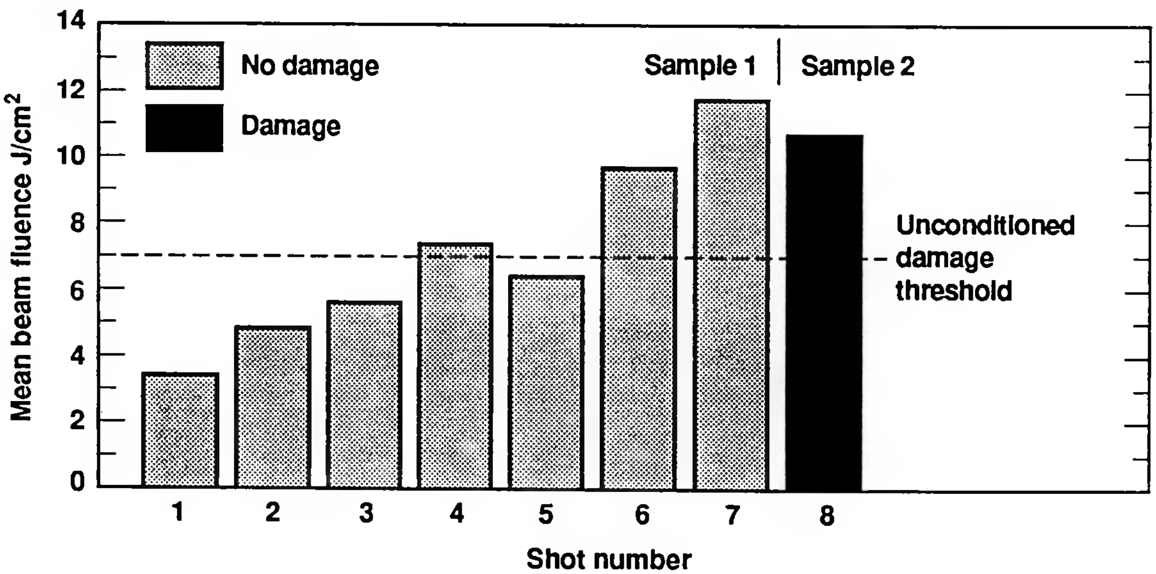

Figure 12. Beam fluence vs. shot number for large aperture Nova conditioning experiment $\lambda = 1064$ nm, $t_p = 1$ ns. Sample 1 = HfO_2/SiO_2 R&D coating. Sample 2 = ZrO_2/SiO_2 R&D coating.

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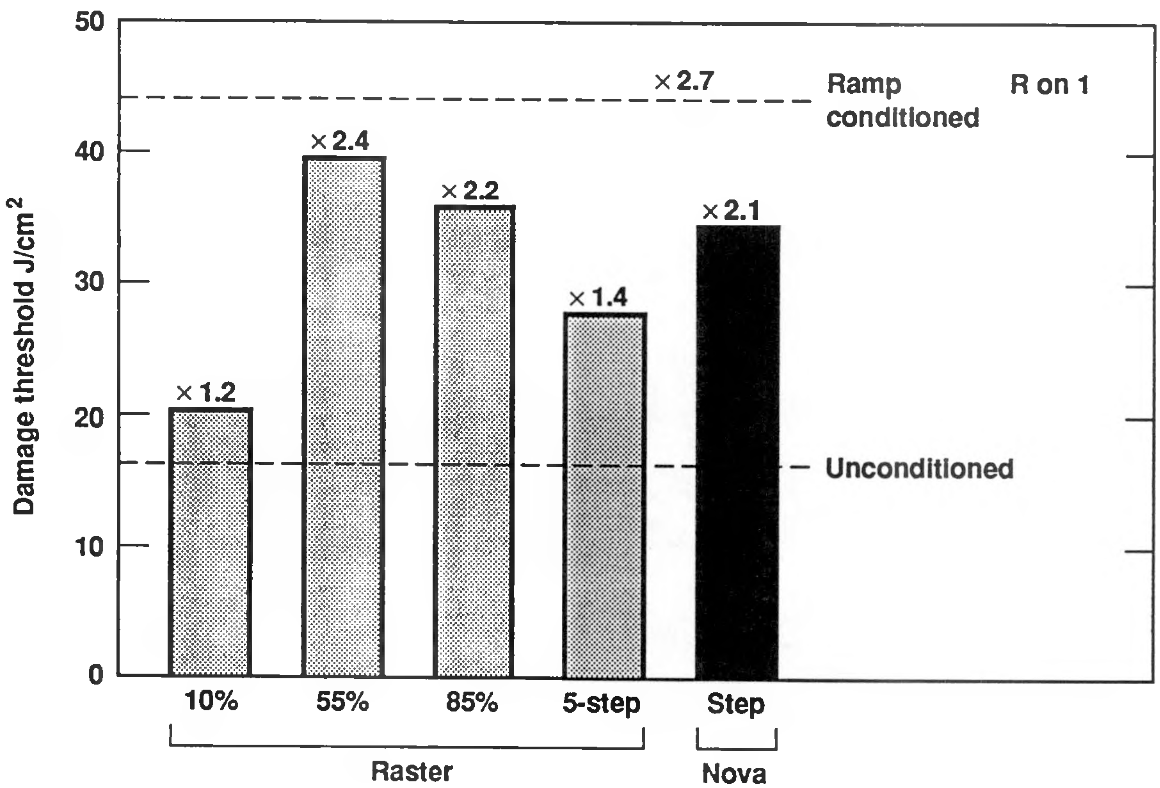

Figure 13. 1064 nm damage thresholds (18 Hz, t_p = 8 ns) of R&D HfO_2/SiO_2 HR coatings conditioned by raster scanning and large aperture Nova illumination.

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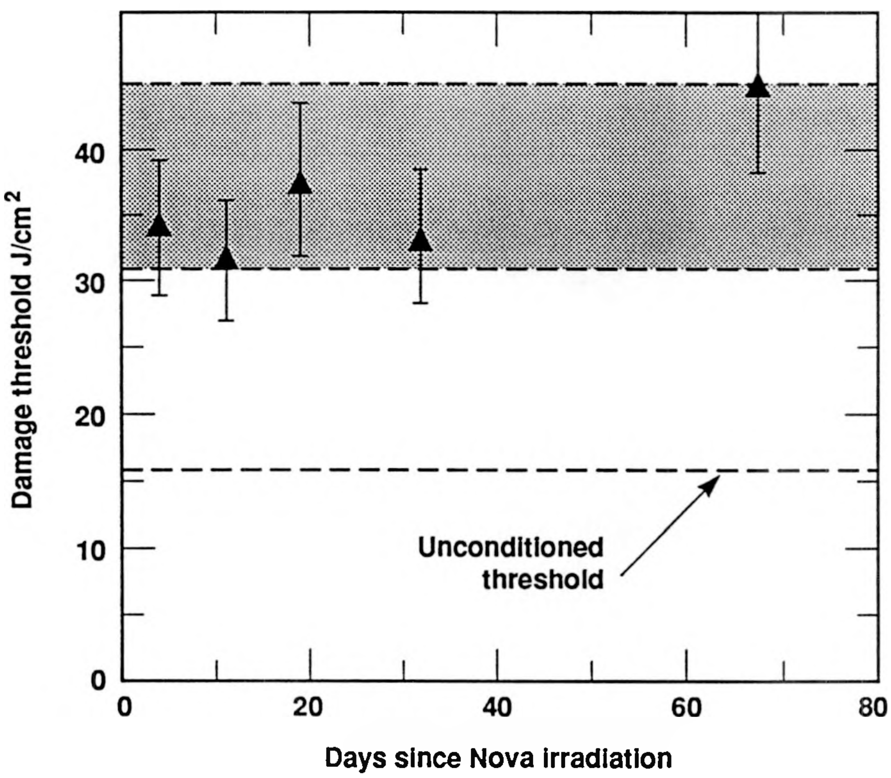

Figure 14. 1064 nm damage thresholds (t_p = 10 ns) vs. time after conditioning for the R&D HfO_2/SiO_2 HR coatings illuminated on Nova. From this data we conclude that for all practical purposes, conditioning is permanent.

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