IRRADIATION EFFECTS ON DIELECTRIC MIRRORS IN INERTIAL FUSION POWER REACTOR APPLICATION

L. L Snead, K. Leonard, and G. E. Jellison Jr.[1]
Mohamed Sawan[2]
Tom Lehecka[3]

[1]*Materials Science and Technology Division, Oak Ridge National Laboratory.*
Oak Ridge Tennessee, SneadLL@ORNL.gov
[2]*Fusion Technology Institute. University of Wisconsin. Madison. Wisconsin. Sawan@engr.wisc.edu.*
[3]*Penn State E-O Center. Penn State University. Freeport, PA 16229. TLehecka@eoc.psu.edu.*

OBJECTIVE

The objective of this work is to experimentally screen the irradiation stability of dielectric mirrors against an inertial fusion application, specifically the High Average Power Laser Program.

SUMMARY

This paper discusses the neutron exposure expected in the HAPL dielectric mirrors and an experimental program comprised of fabrication of advanced dielectric mirrors and testing of these mirrors exposed to prototypical irradiation environment. Specifically, three dielectric mirror types were fabricated to reflect in the KrF laser wavelength of 248 nm and these mirrors irradiated at ~ 175°C in the dose range of 0.001 to 0.1 x 10^{25} n/m^2 (E>0.1 MeV.) This dose range spans the range calculated with a recently developed 3-D Monte Carlo code. Mirrors were visually inspected following irradiation and reflectivity and laser induced damage threshold measured. All mirrors were intact following irradiation and did not appear to degrade significantly either in reflectivity or damage threshold. This finding is somewhat in contradiction to earlier work on dielectric mirrors, which suggested poor performance of dielectric mirrors at an order of magnitude lower neutron dose. Moreover, the current finding suggests the possibility for using dielectric mirrors to much high dose levels.

PROGRESS AND STATUS

`

I. APPLICATION OF DIELECTRIC MIRRORS IN THE HAPL PROGRAM

The High Average Power Laser (HAPL) program aims at developing laser inertial fusion energy based on direct drive targets and a dry wall chamber. [1] Power plant designs are assessed with 350 MJ yield targets driven by forty KrF gas (or Diode Pumped Solid State) laser beams at 5 Hz repetition rate. The final optics system that focuses the laser onto the target includes grazing incidence metallic mirrors (GIMM) located at 24 m from the target with 85° angle of incidence. A focusing dielectric mirror (M2) and a plane dielectric turning mirror (M3) to direct and focus the incoming laser beam. The turning mirror is inclined at a 45° angle relative to the laser beam. The optical beam cross section is rectangular, with a high aspect ratio of 6. The dielectric mirrors are placed out of the direct line-of-sight of the target. However, secondary neutrons resulting from interactions of the streaming source neutrons with the GIMM and the containment building can result in significant flux at the dielectric mirrors. The GIMM is embedded within the biological shield and neutron traps are utilized directly behind the GIMM and M2 in the concrete shield, as shown in Figure 1, to reduce neutron streaming through the beam line.

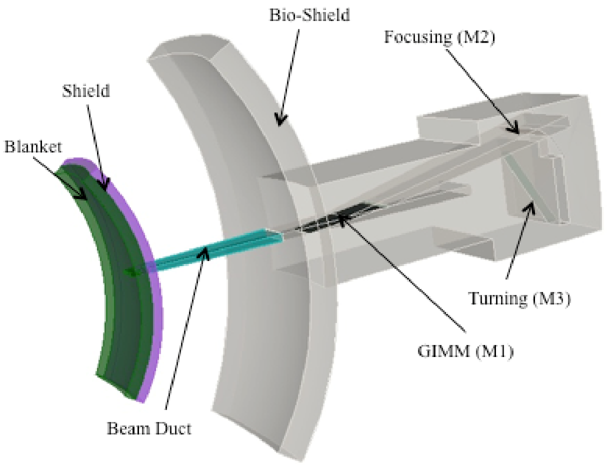


Figure 1. Schematic 3-D image for HAPL final optics.

As part of the HAPL program a robust program has been underway to develop GIMM options, which are currently focused on the alloyed aluminum system[2]. These efforts have included selection of optimized materials systems, determination of the laser induced damage threshold (a function of the deposited heat), and the effect of surface dust and debris on long-term performance of the mirrors. More recently, multilayered dielectric mirrors have been explored as a possible lower fluence, higher reflectivity option. The remainder of this paper discusses issues related an irradiation performance study of dielectric mirrors for the HAPL program.

II. NUCLEAR ENVIRONMENT FOR HAPL OPTICS

Three-dimensional (3-D) neutronic calculations were carried out using the recently developed DAG-MCNP Monte Carlo code [3] that allows calculations to be performed directly within the CAD model. The impact of the GIMM design options on neutron streaming and nuclear environment at the dielectric final optics was thereby assessed. [4] Three substrate materials, SiC and the Al alloys AlBeMet162 and Al-6061 for the GIMM were considered. The SiC GIMM with foam density factor of 0.125 was found to yield the lowest flux values at the dielectric mirrors with the AlBeMet GIMM yielding a factor of 1.6 higher values. The fast neutron flux decreases by about two orders of magnitude as one moves from the GIMM to the focusing mirror with an additional two orders of magnitude attenuation at the turning mirror accompanied with significant spectrum softening. The fraction of the neutrons above 0.1 MeV changes from 97% at the GIMM to 86% at M2, and 41% at M3.

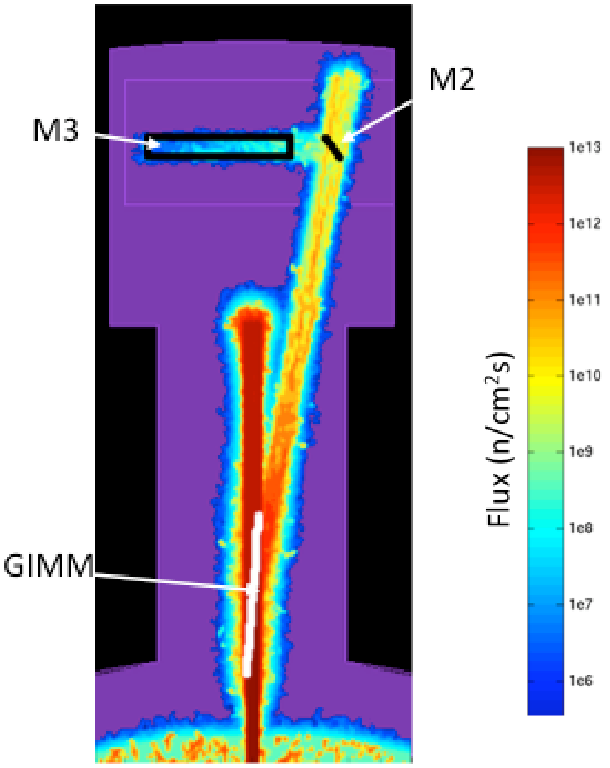


Figure 2. Fast neutron flux distribution in the final optics system.

Figure 2 gives a high-resolution map of the fast neutron flux (E>0.1 MeV) along the beam line for the SiC GIMM design option with 0.125 foam density factor. The fast neutron flux is reduced significantly at the turning mirror M3 due to the sharp bend in the penetration at M2 and utilizing a neutron trap behind M2. Table I gives the highest fast neutron fluence per full power year (FPY) in the GIMM and dielectric mirrors. For a plant lifetime of 30 FPY, the values for fast neutron fluence at the dielectric mirrors M2 and M3 are 2.2×10^{23} n/m^2 (~0.022 dpa) and 4.1×10^{21} n/m^2 (~0.00041 dpa). The GIMM is expected to be replaced every 2 FPY with fluence level of 9×10^{24} n/m^2 (~0.9 dpa).

Table I. Fast neutron fluence per FPY at final optics

	Fast Neutron Fluence per FPY (m^{-2} per FPY)
GIMM (M1)	4.54×10^{24}
Focusing Mirror (M2)	7.18×10^{21}
Turning Mirror (M3)	1.37×10^{20}

III. EXPERIMENTAL

III.A Materials and Irradiation

Dielectric mirrors consisting of alternating layers of Al_2O_3/HfO_2, HfO_2/SiO_2, and SiO_2/Al_2O_3 were deposited on sapphire substrates through electron-beam vapor deposition with ion assist by Spectrum Thin Films, Inc. In addition to the mirrors, single layer coatings were deposited onto sapphire substrates for later evaluation of the substrate/film interfaces. The dielectric mirrors were designed for maximum reflectance at a wavelength of 248 nm and consisted of ¼ l thick films of 36, 27 and 40 nm for the Al_2O_3, HfO_2 and SiO_2 layers respectively. The mirrors consisted of 14 bi-layers for the Al_2O_3/HfO_2 mirrors, 11 for the HfO_2/SiO_2 and 26 bi-layers SiO_2/Al_2O_3 mirrors. Sapphire substrates of 6 mm diameter by 2 mm thick were used having a surface roughness less than 1.0 nm with 10/5 scratch dig value over sample and a surface figure of l/10.

Samples were irradiated in the hydraulic tube facility of the High Flux Isotope Reactor (HFIR) at ORNL. The neutron flux for the position utilized was $1.7x10^{19}$ n/m^2-s (thermal) and $5.8x10^{18}$ n/m^2-s (E>0.1 MeV). The mirrors, single layer coating samples and substrate-only samples were encapsulated in specially designed 1100 grade aluminum holders that secure the samples in position by their edges to prevent damage to the optical surfaces. At each irradiation condition three of each mirror type and a single bar (0.3 x 0.3 x 2 cm) of GE-124 fused silica was irradiated. An illustration of the holder containing the mirror samples only is shown in Figure 3. The samples were sealed under ultra high purity Helium gas. Each capsule contained a SiC bar forced in contact with the backside of the sample used to determine the irradiation temperature, post-irradiation. The technique used to determine irradiation temperature from these monitors was the change in electrical resistivity upon isochronal annealing.[5] Samples were irradiated to doses of 10^{22}, 10^{23} and 10^{24} n/m^2 (E>0.1 MeV) corresponding to approximate displacement doses of 0.001, 0.01 and 0.1 dpa. This conversion is typical for ceramic materials and assumes sublattice-average displacement energy of 40 eV. [6] From analysis of the temperature monitors the mirror temperature during irradiation was determined to be in the approximately 175°C.

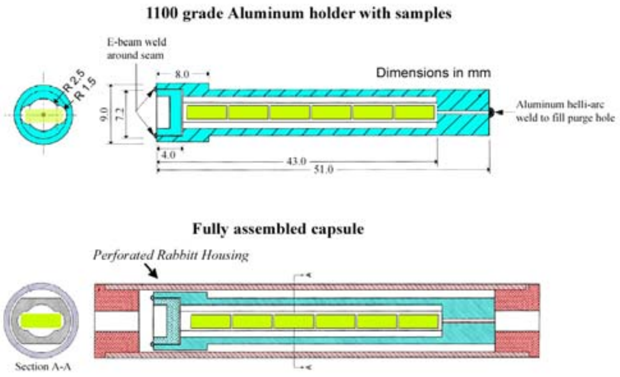


Figure 3. Schematic of HFIR irradiation capsule containing six mirror samples. Capsule design containing GE-124 bar not shown.

Vacuum annealing treatments at 300 and 400°C were conducted on the irradiated mirrors following initial optical testing. Samples were heated at 3º/minute to temperature and held for 1.5 hours under < $1x10^{-6}$ torr followed by furnace cooling.

Laser induced damage threshold was measured was measured using the system transported from the Penn State EOC and installed into the LAMDA facility at ORNL and depicted in Figure 4. It was comprised of a GAM Laser operated at the KrF frequency of 248 nm with an ~ 130 mJ/puls output, ~ 18 ns pulse length and d125 Hz maximum rep rate. The position of the lens, along with the laser energy, is use to determine the ultimate energy to the dielectric mirror sample as shown in Figure 5. Due to beam non-uniformities at the 0, 10 and 20 mm focal position only focal distances greater than 30 mm were considered for this work.

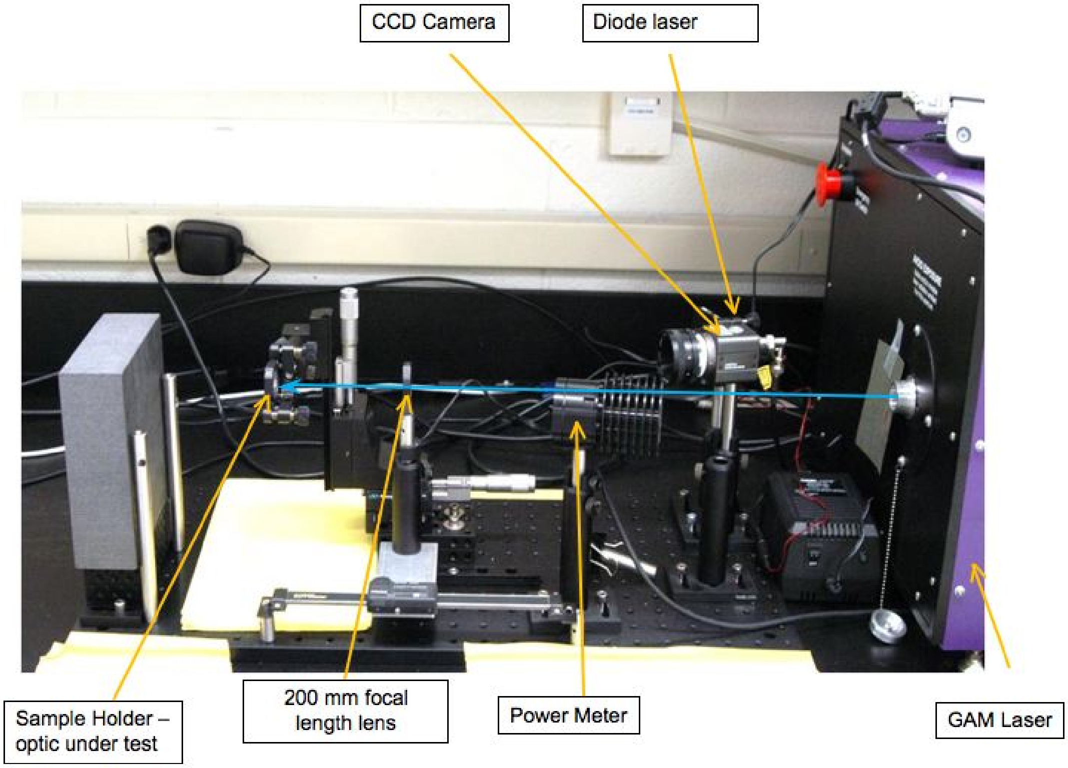
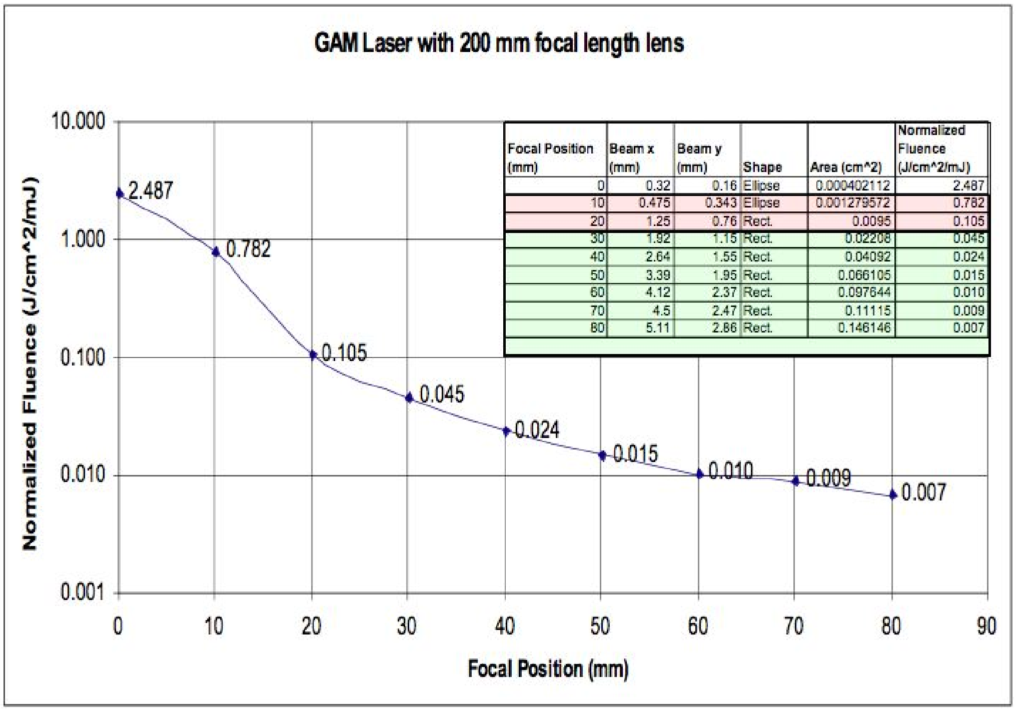


Figure 4. Bench-top set-up of LIDT measurement equipment temporarily installed by Tom Lahecka in the LAMDA facility at ORNL.



Focal Position (mm)	Beam x (mm)	Beam y (mm)	Shape	Area (cm^2)	Normalized Fluence (J/cm^2/mJ)
0	0.32	0.16	Ellipse	0.000402112	2.487
10	0.475	0.343	Ellipse	0.001279572	0.782
20	1.25	0.76	Rect.	0.0095	0.105
30	1.92	1.15	Rect.	0.02208	0.045
40	2.64	1.55	Rect.	0.04092	0.024
50	3.39	1.95	Rect.	0.066105	0.015
60	4.12	2.37	Rect.	0.097644	0.010
70	4.5	2.47	Rect.	0.11115	0.009
80	5.11	2.86	Rect.	0.146146	0.007

Figure 5. Normalized laser fluence as a function of focal position.

III.B Results

The irradiated capsules were disassembled and dielectric mirrors, SiC thermometry, and fused silica bars removed for inspection and analysis. Samples were cleaned in isopropyl alcohol to remove any debris resulting from the capsule disassembly process. Dielectric mirrors showed no visible signs of surface abrasion, film delamination, cracking, or pitting following irradiation and handling. Figure 6 gives an example of the condition of the mirrors in the control and irradiation condition as a function of the vacuum anneal. The mirrors on the left are tilted so the smooth surfaces reflect the overhead (visible spectrum) lighting to reveal the integrity of the films. Upon irradiation the samples as visualized in the “flat” condition have an apparent darkening which increases with increasing neutron dose. Annealing of the irradiated materials at 300 and 400ºC for 1.5 hrs resulted in a reduction in the irradiation-induced darkening. These observations were consistent for all mirrors studied and reproducible for the triplicate-irradiated mirrors. A slight speckling was observed in some of the mirror surfaces following annealing, however, this appeared randomly in the visual observation and showed no specific trend with regards to mirror type, dose or thermal treatment.

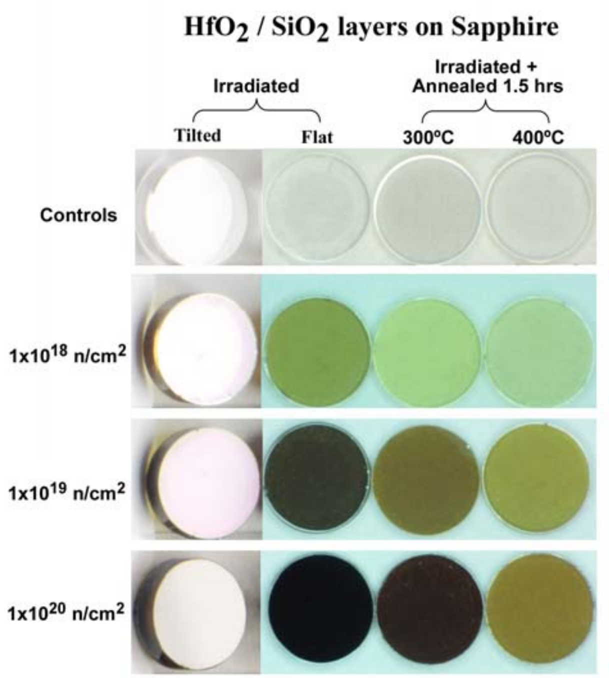


Figure 6. Optical inspection of HfO_2/SiO_2 mirrors in the non-irradiated and neutron irradiated condition as a function of post-irradiation annealing temperature.

The GE-124 fused silica bar samples also underwent a slight discoloration with irradiation, though the darkening was not as pronounced as in the mirror samples of figure 6. Results on the densification of the fused silica irradiated in this experiment is shown in Figure 7 for each irradiation dose. For the upper dose of this study (1e25 n/m2) the material underwent a 2.26% compaction. While this data set data is limited, the rate of compaction has dramatically slowed and perhaps reached a saturation level at the uppermost dose level. As will be discussed later, saturation in compaction for amorphous silica at this dose is expected.

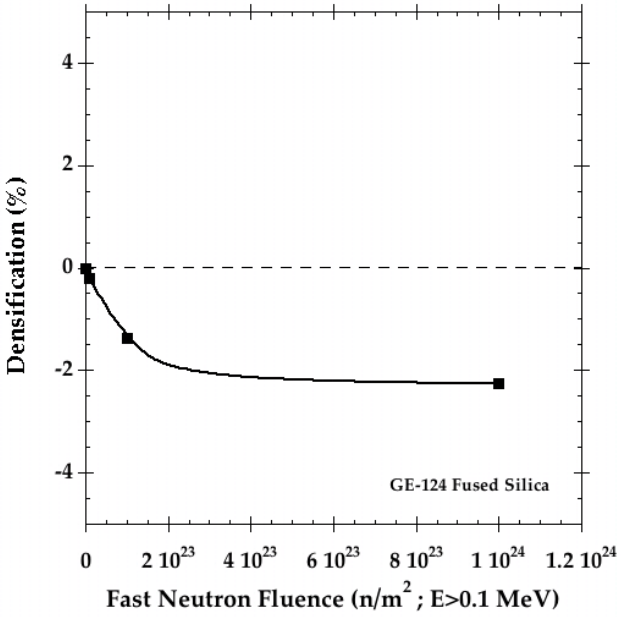


Figure 7. Densification of GE-124 fused silica irradiated with dielectric mirrors.

Results on the relative dielectric mirror reflectance are given in Figures 8, 9, and 10, for the Al_2O_3/SiO_2, HfO_2/SiO_2, HfO_2/Al_2O_3 mirrors respectively. It is stressed that this is relative reflectance. Due to the size of the sample and the preliminary nature of the study the absolute reflectance of the mirrors is not known at the time of this publication. Measurement of absolute reflectance of these mirrors is ongoing. As will be seen later, it is likely that these mirrors are well short of the ideal >99% reflectance. Figures 8-10 are normalized to each other specifically to demonstrate the frequency response. By inspection of these figures, a real shift in the working range (flat top) occurred. The direction of this shift was towards lower wavelengths with increasing irradiation dose. It is noted that the HfO_2/Al_2O_3 mirrors were fabricated out of specification, with its working range below the 248 nm specified. However, this is not thought to impact the general findings of this paper.

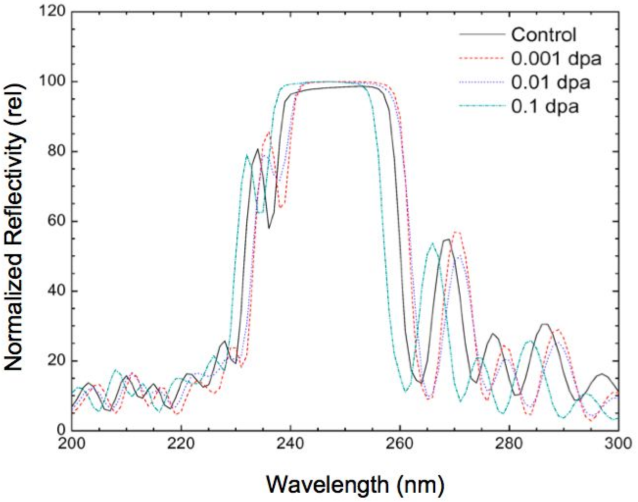


Figure 8. Effect of neutron irradiation on the relative reflectance of Al_2O_3/SiO_2

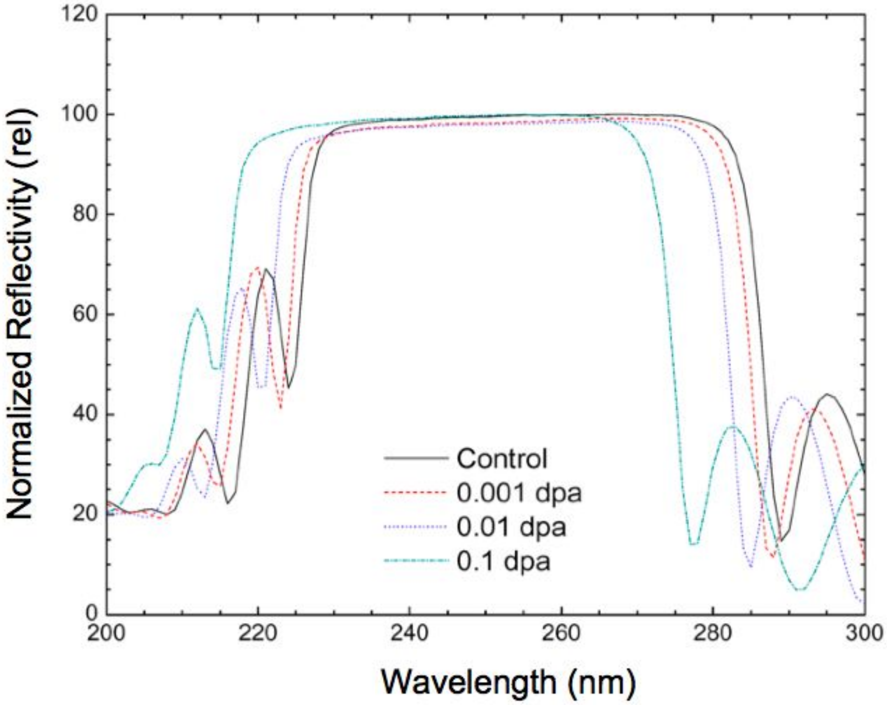


Figure 9. Effect of neutron irradiation on the relative reflectance of HfO_2/SiO_2.

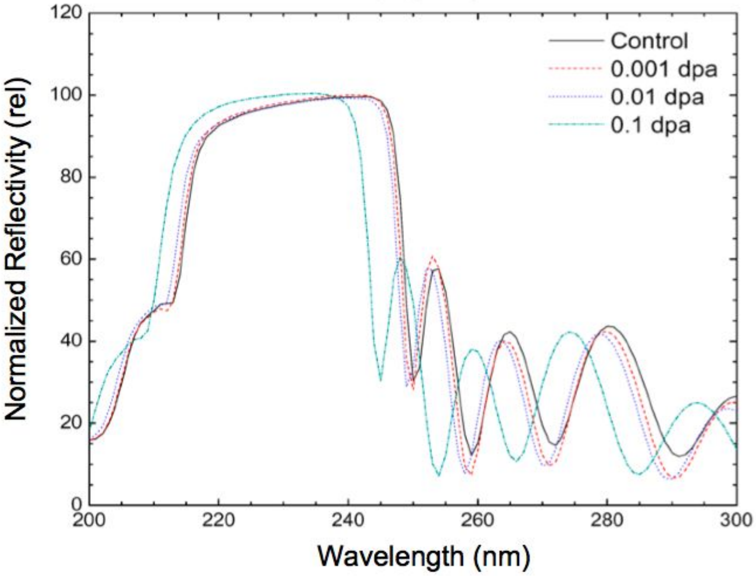


Figure 10. Effect of neutron irradiation on the relative reflectance of HfO_2/Al_2O_3.

Each of the mirror types were annealed in vacuum and visually inspected. Following annealing, no apparent change occurred, though a minor frequency shift in the working range did occur.

Testing of laser induced damage threshold was carried out on all non-irradiated mirrors and a complete series of as-irradiated alumina/silica mirrors. With this set-up an estimate of the reflectivity was also possible. It was found that both the hafnia/silica and hafnia/alumina mirror has very low laser induced damage thresholds in the virgin condition and therefore not tested in the irradiated condition. Moreover, the *approximate* reflectance of these mirrors was also unacceptably low. However, the alumina/silica mirror did have fairly good approximate reflectance (see Table II) and the reflectivity did not apparently degrade as a function of irradiation. As seen in Table III the laser induced damage threshold (LIDT) for the hafnia/silca and hafnia/alumina mirrors was less than 1 J/cm^2 , which is considered a target value for the HAPL program. However, the alumina silica mirrors behaved in both the non-irradiated state (LIDT>1 J/cm^2) and did not appear to degrade upon irradiation. It is important to note that these tests were carried out on a single sample and therefore any conclusions are statistically limited.

Table II. Results of reflectivity using the LIDT set-up.

Mirror	**Reflectance**				**Note**
	Virgin	**0.001 dpa**	**0.01 dpa**	**0.1 dpa**	
Control Mirror	93%	NA	NA	NA	Spectrophotometer measured R form company was 99.7%
HfO_2/SiO_2	41%	NT	NT	NT	Possible damage before reflectivity measurement completed
HfO_2/Al_2O_3	52%	NT	NT	NT	Possible damage before reflectivity measurement completed
Al_2O_3/SiO_2	86-87%	84-86%	78-83%	80-84%	

NA: not applicable; NT: not tested

Table III. Results of laser induced damage threshold

Mirror	**Laser Induced Damage Threshold**				**Note**
	Virgin (J/cm^2)	**0.001 dpa**	**0.01 dpa**	**0.1 dpa**	
Control Mirror	0.9<d<1.2	NA	NA	NA	Agrees with standard
HfO_2/SiO_2	d<0.43	NT	NT	NT	Clearly damaged before alignment completed at lowest fluence available (80 nm, 11kV)
HfO_2/Al_2O_3	d<0.9	NT	NT	NT	Appeared to survive alignment, but damaged at 80 nm, 16 kV
Al_2O_3/SiO_2	1.3<d<1.95	1.3<d<1.95	1.2<d<1.3	1.2<d<1.3	Both non-irradiated and 0.001 dpa damaged after ~ 10 second at fluence listed (50 nm). 0.01 and 0.1 damaged after ~ 60 seconds at the high fluence.

NA: not applicable; NT: not tested

IV. DISCUSSION

By alternating thin transparent dielectric materials of differing refractive index this class of mirror can be capable of reflecting greater than 99% of incident laser light. This is in contrast to GIMM's, which typically range from <40% reflectivity in the UV range (for silver or gold) to as high as 80-90% for the HAPL candidate aluminum alloy system.

Unfortunately, the early work on the neutron irradiation of dielectric mirrors by Farnum et al. [7] was not encouraging. For the long-wavelength mirrors of his work, DC magnetron sputtered bi-layers of hafnia/silica, zirconia/silica, and titania/silica were deposited onto silica substrates. In each case the thickness of the layers ranged from 332-642 nm, or about and order of magnitude thicker than those of this study. The spallation neutron producing LASREF facility was used to produce uniform displacement damage through the mirrors for a reported irradiation temperature of 270-300°C as inferred from a similar capsule design. The reported total integrated neutron fluence was 1.1×10^{23} n/m^2. In addition to the neutron dose, Farnum reports an associated gamma dose of 1.1×10^9 Gy. While Farnum did not report on reflectivity of his long-wavelength mirrors he did report that three of the five mirrors suffered either film crazing or total film flaking, with the fourth possibly suffering film damage as well. One mirror, a TiO_2/SiO_2 plate polarizer did not show visible degradation.

The neutron dose of the Farnum work was of similar magnitude to the HAPL M3 mirror (2.2×10^{23} n/m^2, see Section II,) and for this reason the seemingly negative results of his work were of concern. However, more recent work in support of the ITER diagnostic program[8,9] for similar dose appeared more promising. Specifically, Orlovskiy[9] reports on multilayer dielectric mirrors deposited by evaporation on the high-purity KS-4V silica glass. The bi-layers chosen were titania/silica and zirconia/silica. At the lower irradiation dose of that study (1×10^{21} n/m^2, E>0.1 MeV) neither mirror type exhibited visible damage. For the higher irradiation dose (1×10^{23} n/m^2 , E>0.1 MeV) only the titania/silica mirror was irradiated. The reported irradiation temperature was "near ambient water temperature 50°C." This higher dose irradiated mirror showed no visible signs of irradiation damage and no reduction in spectral reflection, though did show a movement in the working range to lower wavelengths similar to that seen in the current study.

Given that the mirrors of the present study have not indicated any visible degradation (film decohesion) or spectral reflectivity degradation, there is a clear trajectory of improvement in these materials from the work of Farnum (0.01 dpa, visible film degradation), to Orlovskiy (0.01 dpa, no visible or spectral reflectance degradation for titania/silica), to this work (0.1 dpa, no decohesion or spectral reflectance degradation for a range of materials.)

When considering the irradiation effects in high quality dielectric mirrors, the three most likely effects of irradiation are:

- altered refractive index of material.
- altered thickness of layers.
- interfacial stress due to differential swelling in layers or between layers and substrate.

The first and second points will primarily impact the reflection but will also influence the working range of the mirror. Unfortunately, there is not a large body of work on the effect of irradiation on the optical properties of many of the materials comprising these dielectric mirrors. For instance there is essentially no information on the effects of neutrons on swelling or optical properties of hafnia. However, there is information on silica and alumina to draw on. For the case of silica (amorphous SiO_2, like the SiO_2 bilayers of all materials discussed here and the KS-4V glass of the Orlovskiy work and the substrate of the Farnum work) irradiation causes pronounced densification.[10,11] In the current work this is demonstrated in the densification of the GE-124 fused silica (see Figure 7.) Previously, Primak[10] demonstrated that the refractive index is proportional to silica densification following a general Lorentz law. Primak showed that a nominal change in 2% density of silica resulted in about a 0.75% change in refractive index. Unfortunately, the irradiation-induced refractive index of the other mirror materials used in the present study is not known. However, there is a body of work on alumina swelling. It is clearly understood that polycrystalline Al_2O_3 (one of the bilayers for this study), and single crystal Al_2O_3 (the substrate for this study) will both undergo volumetric expansion under neutron irradiation. At the irradiation temperature for which dielectric mirrors are to be used this swelling is caused by point defect strain within the crystal and is a function of both irradiation temperature and dose. A comparison of the expected swelling of polycrystalline (which closely matches single crystal) alumina[12] is given in Figure 11 along with the GE-124 fused silica. It is noted that the microstructure of the Al_2O_3 bilayer of this study has not been characterized though is assumed to be microcrystalline, low-density Al_2O_3 typical of other optical grade alumina.

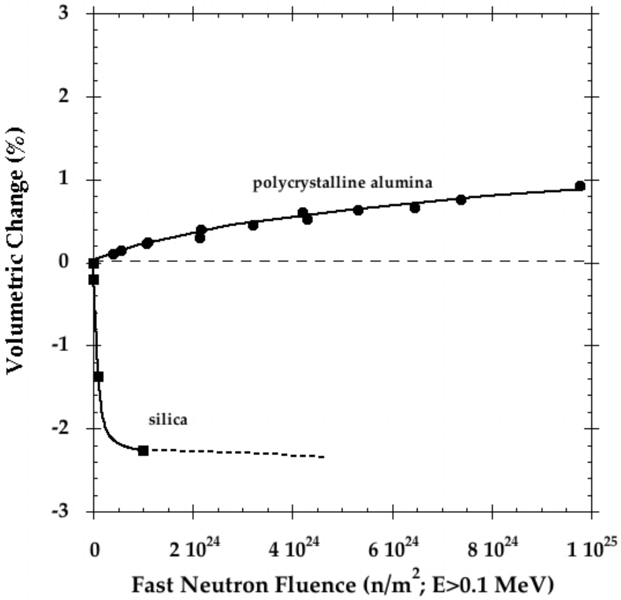


Figure 11. A comparison of literature data on swelling in polycrystalline alumina with compaction in GE-124 fused silica.

The behavior shown in Figure 11 underlines a potential issue facing the dielectric mirrors. In both of the previous studies discussed the substrates used were amorphous silica, and both combined ceramic and amorphous silica as the bi-layers. As these mirrors are irradiated, differential dimensional change (as example, Figure 11) of constituents can result in an stress buildup within the multilayers whose magnitude is a competition between the rate of irradiation-induced differential swelling and the rate at which irradiation-induced creep can mitigate the developing stresses. Reduced viscosity (essentially irradiation-creep) due to displacive irradiation is known to occur in glassy materials, with the first discussion of this phenomenon reported as early as 1960 (Mayer, 1960.) A clear indication of the significant effect irradiation can have on the viscosity of glass is given by Zhu (Zhu, 1994), who irradiated Herasil 1 with 10 MeV protons in the temperature range of 220°C to 600°C. The dose rate for these experiments was 2.3×10^{-7} dpa/s, which compares well with the displacement rate of this study (5.8×10^{-7} dpa/s.) The Herasil 1 silica was tested in tension during irradiation in the applied load range of 5-100 MPa with the sample initially undergoing a rapid reduction in length due to the irradiation-induced silica compaction. Following this, sample elongation due to irradiation-reduced viscosity was clearly observed. While the experiment was carried out at a few hundred degrees, the irradiation-reduced viscosity was equivalent to thermally-induced viscosity of ~ 1200°C. In other words, the displacive irradiation reduced the silica viscosity by several orders of magnitude to a value of ~ 10^{13} Pa-s. This level of viscosity is associated with the annealing point (point at which internal stress is relieved in ~ 15 minutes.) Irradiation-creep has been seen in crystalline ceramics such as SiC[13]though the report by Zhu which documented enhanced viscosity in silica did not find evidence for irradiation creep in Al_2O_3 or SiC. At least for those experimental conditions vitreous silica was more capable of deformation under applied strain during irradiation.

While there is only limited information on irradiation-reduced viscosity in silica and irradiation-creep in ceramics, from those findings it is a reasonable conclusion that closely matching the irradiation-induced dimensional change of the mirror substrate with the non-silica constituent of the multilayer mirror is prudent. While silica appears to be more capable of response to applied stress than the ceramic materials, the fact that the substrate is so much thicker than the coatings, if the substrate was silica its densification would dominate, possibly resulting is large stresses in combination with the ceramic bilayers. Therefore, a matched substrate and ceramic layer with a more compliant silica layer (or a paired ceramic layer) may prove more resistant to irradiation.

For the case of the Farnum[7] mirrors, which consisted of much thicker bi-layers and a larger cool-down temperature from irradiation as compared to the current work or that of Orlovskiy, a larger induced stress would be expected, possibly explaining the resulting mirror failures. Upon annealing the irradiation-densified silica, or irradiation-swollen ceramics, the material is restored to near original density. For glass the relative recovery is proportional to annealing temperature, with glass exhibiting near complete restoration by ~ 1100°C,[10] while for alumina requires a somewhat higher annealing temperature (~1400°C.) [14] For the case of the silica/alumina mirror of this study, the 400°C vacuum anneal would have resulted in an *expansion* of silica of about 0.1% and an alumina *contraction* of about 0.02%.[10,14] (This assumes the behavior of the mirror bi-layers is similar to that of the fully dense materials.) For these post-irradiation annealing experiments the annealing temperatures are such that no thermal creep should have taken place, and with the absence of irradiation the result would be an increases stress similar to the stress which would occur due to the mismatch in coefficients of thermal expansion.

V. CONCLUSIONS

A series of neutron irradiations have been carried out on multilayer dielectric mirrors deposited by electron beam vapor deposition on sapphire substrates designed to operate in the KrF wavelength range of 248 nm. Multilayer combinations included the glass/ceramic combinations of silica/alumina and silica/hafnia as well as the ceramic/ceramic combination alumina/hafnia. Irradiations were carried out to a maximum dose of 0.1 dpa, corresponding to dielectric mirror fluence greater than currently considered for the High Average Power Laser inertial fusion power application.

All three mirror combinations survived the neutron irradiation without visible degradation. A shift in working range towards lower wavelength occurred upon irradiation becoming more pronounced with higher fluence. However, at the maximum dose of this study, 0.1 dpa, the shift was relatively minor, on the order of 10 nm.

The mirrors were vacuum annealed in the non-irradiated and irradiated condition to determine the integrity of the inter-layer strength and to determine whether significant irradiation-induced residual stress was present. Visual inspection of mirrors following annealing indicated no apparent film degradation. All mirrors were screened for laser induced damage threshold. The alumina/hafnia and silica/hafnia mirror had very poor LIDT as well as apparent reflectivity. However, the alumina/silica mirror had both good reflectivity and LIDT in the virgin condition, but retained these acceptable properties upon irradiation. The results of this study offer a clear improvement in mirror performance over previous dielectric mirrors studied under neutron irradiation. The superior performance is tentatively attributed to the selection of a more irradiation stable substrate (sapphire,) and the selection of very thin and very high purity dielectric layers. Moreover, it is speculated that the choice of a mirror substrate whose irradiation-induced changes are closely matched to the behavior of the ceramic components of the mirror leads to a more radiation tolerant system. Further work to better understand the behavior of the microstructures of these materials under irradiation and the study of the developing interlayer stress is anticipated and could lead even greater tolerance of this class of mirrors to neutron irradiation.

ACKNOWLEDGMENTS

The authors would like to thank Joel McDuffee, Bob Sitterson, and Marie Williams for help with construction of the irradiation capsules and Patricia Tedder for assistance with radiological aspects of this work. Irradiations were carried utilizing the High Flux Isotope Reactor, a Department of Energy user facility. This work was funded by the Department of Energy High Average Power Laser Program under a contract to the Oak Ridge National Laboratory. The Oak Ridge National Laboratory is managed by UT-Battelle under contract DE-AC05-00OR22725.

REFERENCES

1. J. D. Sethian, A. R. Raffray, J. Latkowski et al., J. Nuclear Materials **347** (3), 217 (2005).
2. M. S. Tillack and J. E. Pulsifer, Fusion Engineering and Design (submitted 2008).
3. M. Wang, D. L. Henderson, T. Tautges et al., Fusion Science and Technology **47** (4), 1079 (2005).
4. M. Sawan, A. Ibrahim, T. D. Bohm et al., Fusion Engineering and Design **Submitted**.
5. L. L. Snead, A. M. Williams, and A. L. Qualls, presented at the The Effects of Radiation on Materials: 21st International Symposium, 2003 (unpublished).
6. F. W. Clinard, Jr., G. F. Hurley, and L. W. Hobbs, Journal of Nuclear Materials **108&109**, 655 (1982); S. J. Zinkle and C. Kinoshita, Journal of Nuclear Materials **251**, 200 (1997).
7. E. H. Farnum, F. W. Clinard, Jr, S. P. Regan et al., Journal of Nuclear Materials **219**, 224 (1995).
8. K. Vukolov, presented at the 8th Meeting of the ITPO Topical Group on Diagnostics, Culham, 14-18 March 2005, Culham, UK., 2005 (unpublished).
9. I. I. Orlovskiy and K. Y. Vukolov, Fusion Engineering and Design **74**, 865 (2005).
10. W. Primak, Phys Rev **110**, 1240 (1958).
11. T. Yano, K. Fukuda, M. Imai et al., Journal of Nuclear Materials **367-370**, 730 (2007).
12. G.P. Pells, Journal of the American Ceramic Society **77** (2), 368 (1994).
13. Y. Katoh, L. L. Snead, T. Hinoki et al., J. Nuclear Materials **367-370**, 758 (2007).
14. B. S. Hickman and D. G. Walker, Journal of Nuclear Materials **18**, 197 (1966).