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Laser Damage Database at 1064 nm

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In conjunction with our diversification of laser damage testing capabilities (see "Expanded Damage Test Facilities at LLNL" this conference), we have expanded upon a database of threshold measurements and parameter variations at 1064 nm. This includes all tests at low pulse-repetition frequencies (PRF) ranging from single shots to 120 Hz. These tests were conducted on the Reptile laser facility since 1987 and the Variable Pulse Laser (VPL) facility since 1988. Pulse durations ranged from 1 to 16 ns. The table below summarizes the test data scaled to 10-ns pulses.

Sample type	Number of tests	Damage thresholds (J/cm^2) scaled to 10 ns at 1064 nm		
		Min.	Average	Max.
AR coatings	164	0.8	19	> 56
HR coatings	283	0.7	18	56
Polarizers	47	0.8	8	41
Layers (1 or more, 1 material)	169	0.7	12	34
Metals (bare & enhanced)	49	0.4	6	40
Bare surfaces	226	1.6	26	61
Bulk material	175	0.8	21	61

Key words: anti-reflective (AR) coatings; bare substrates; bulk damage; damage; highly reflective (HR) coatings; laser-induced damage; metallic coatings; polarizers; reflectors; sol-gel coatings; thin films.

1. Introduction

For over fifteen years, the Lawrence Livermore National Laboratory (LLNL) has been actively involved in the development of damage-resistant optical coatings and materials and in the measurement of their laser-induced damage thresholds. In the course of that time we have conducted over 10,000 damage measurements, the results of which have been reported extensively at proceedings of the Boulder Damage Symposium as well as in technical

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journals. Typically, these reports have concentrated on a specific topic with data culled from a large database. In recent years more extensive publication of general databases have been made available in order to provide an overview of damage measurements covering a wide variety of materials, fabricated by numerous vendors, utilizing many different fabrication processes, and tested under countless different laser-parameter conditions. [1], [2]

This variety lends itself to the usefulness of a computer-based database but at the same time sets certain limitations to the user. In general there are often more caveats that must be appended to laser damage measurements than are practical within a tabular database. Hence, results of specific experiments are reported and elaborated on in journals and proceedings based on a compilation of data. The database will not of itself allow one to simply select the best optical component meeting a particular requirement without adherence to many of these hidden caveats. Moreover, the proprietary nature of much of the work by commercial vendors often prevents a total dissemination of the necessary information required in order to design or select a particular optical component.

2. Database parameters and conventions

Because of these limitations, the data we present here provide, to a first degree, only an index of measurements that have been conducted at LLNL during the past two or more years. The database is being enlarged on a daily basis as measurements are currently being conducted as well as relevant past measurements are added as time and program demands require. It must be strongly emphasized that these measurements do not necessarily represent the state-of-the-art nor necessarily a cross-section of what is achievable in terms of damage thresholds for a particular type of optical component. In virtually all cases, the data show a high preponderance of thresholds grouped near the lower end of the threshold range. Since the database does in fact list <u>all</u> measurements within a particular category, many of the research samples will naturally show poor performance. Not even the median thresholds should be construed as representing what one should expect within a particular category. Once we, or the vendors under contract to us, have developed a product that has achieved acceptably high damage thresholds we typically conduct sufficient tests to verify that the results are repeatable. Highlights of measurements taken at LLNL in support of high-peak-power lasers are presented in the companion paper at these proceedings. [3]

Comparing measurements taken under a variety of laser parameter conditions is difficult unless one takes into consideration the effects that the parameters and irradiation conditions may have on damage thresholds. The data presented here consist solely of recent measurements conducted at 1064 nm with pulse durations ranging from 1 to 16 ns. The data are always listed with the pulse durations used in the tests. Nearly all samples we have tested show a pulse-length scaling of between 0.2 and 0.5. In order to provide some capability of comparing these data we have also scaled the thresholds to 10-ns values by a value of 0.35 which is nominally the average temporal scaling factor according to the following relationship:

$$\text{Damage threshold} = k\,(\text{pulse duration})^{0.35}.$$

In table 1 we list the typical test-laser parameters which are based on laser capabilities and experimental requirements. Descriptions of the laser systems are presented in a companion paper at these proceedings. [4] Besides absolute damage threshold and laser parameters we also note the the type of irradiation and damage morphology at each site location as detailed in table 2.

Table 1. Laser parameters recorded with damage measurements

Pulse duration (ns)	1 - 65 depending on laser
Wavelength (nm)	1064, 532, 355, 351, 266, 248
PRF (Hz)	0 (single shot), 1, 6, 10, 15, 18, 30, 60, 100, 120, 6000
Polarization	Typically P; also S or mixed
Incident angle	0° to grazing; typically 10°, 45°, 57°
Spot diameter ($1/e^2$) (mm)	0.3 - 3 depending on required fluence; typically about 1

Table 2. Sample irradiation conditions and observations

Site location	Front or incident surface Rear or exit surface Bulk material within the first 10 mm	
Irradiation per site	1-on-1	1 shot only
	N-on-1	N shots with increasing fluence, usually on a single shot basis
	S-on-1	S shots in PRF mode at the same fluence
	R-on-1	R shots in PRF mode ramped from near zero to the desired maximum fluence
	Scan	Sample moved through a PRF beam
Damage morphology	Description of damage at threshold at each applicable location (front, rear, bulk) Comparable morphology typically at fluences exceeding threshold to characterize damage growth	

An abbreviated sample of the computer database is shown in the appendix in table 3. Each test result is usually printed on one line of a large table in a reduced type format. To display this sample database in a readable fashion we have broken it up into four segments. In tables 4a and 4b we provide detailed information to the user about the variety of samples, techniques and vendors that have already been included in the current database. We also supply information on how to interpret the data.

3. Overview of testing at 1064 nm

During the past two years we have have conducted over 1300 laser damage measurements, mostly at 1064 nm with 1- to 16-ns pulses at pulse repetition frequencies (PRF's) ranging from single shots up to 120. An overview of these tests is shown in figure 1.

The major portion of our efforts have been concentrated on the development of high threshold sol-gel coatings (AR's, HR's and single layers), HR's fabricated by physical vapor deposition (PVD), and optically polished bare surfaces and bulk materials of non-linear crystals and substrate materials. We list below summaries of our tests conducted on seven broad categories of optical materials. For each category we show a general histogram of all laser damage tests conducted at 1064 nm with pulse durations scaled to 10 ns. Depending on

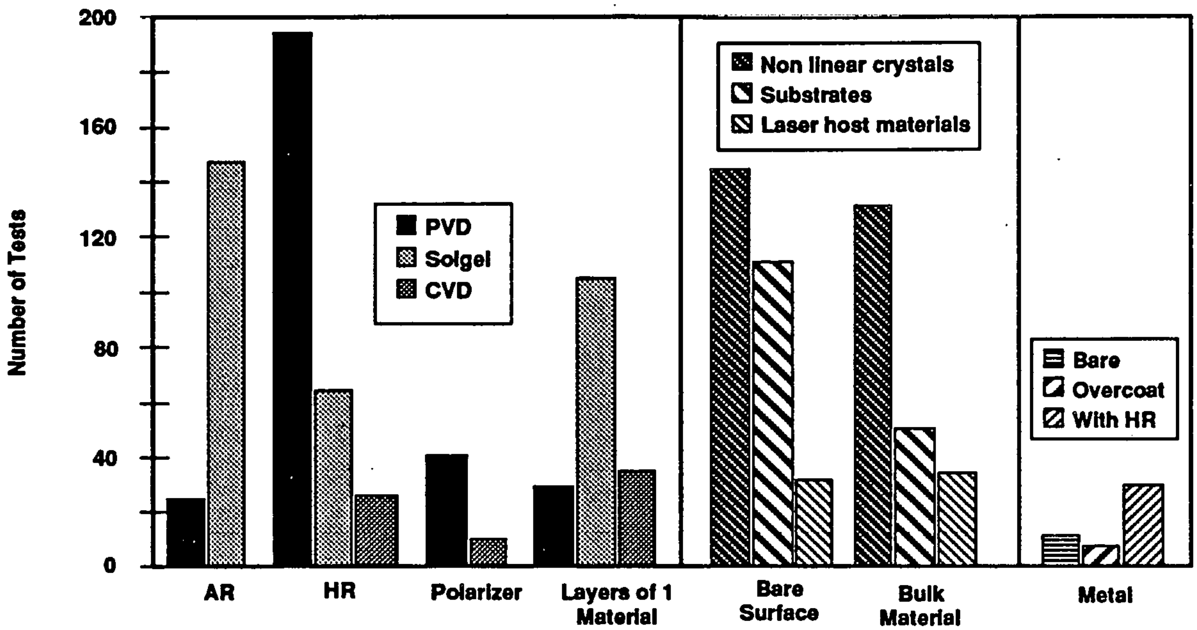

Figure 1. Two-year summary of laser damage tests at 1064 nm with 1- to 16-ns pulses.

the category type we also list applicable details such as substrate materials, coating materials, process types, and vendors of coatings, bulk materials and surface processing. Since these tests cover such a wide variety of optical components, material combinations, processes and proprietary data, we do not itemize these details in most histograms. Related figures for each category show pertinent important highlights that are germane to the programmatic laser development efforts at LLNL.

4.1 Bare polished surfaces

We record bare surface damage thresholds of most substrate materials that we test for bulk damage as well as for samples which may have an AR coating on one surface but not the other. We observe rear surface damage if the results are not obscured by either front surface or bulk material damage. Typically well-polished bare surfaces have among the highest thresholds that we measure and are usually only exceeded by bulk damage to some materials. In figure 2 we show the aggregate test results of all bare surface measurements in recent years for over 20 different substrate types from over 20 different vendors. The vendor supplying the substrate was, however, not always the one who actually performed the surface processing. Most samples were lap polished but we also list the other surfacing techniques that we have investigated.

We have found that for several of the more commonly used substrate materials with refractive indices near 1.5, the optimized polishing techniques have yielded 1064-nm damage thresholds which scale relatively independent of the material types by a pulse-duration scaling factor of $\tau^{0.4}$. This is demonstrated in figure 3 for six materials (fused silica, BK-7, CVD glass, ULE glass, LG-750, and fluorophosphate glass) at seven different pulse durations ranging from 150 ps up to 40 ns. These measurements are average values of the best results obtained over a span of more than 12 years from at least six different laser systems.

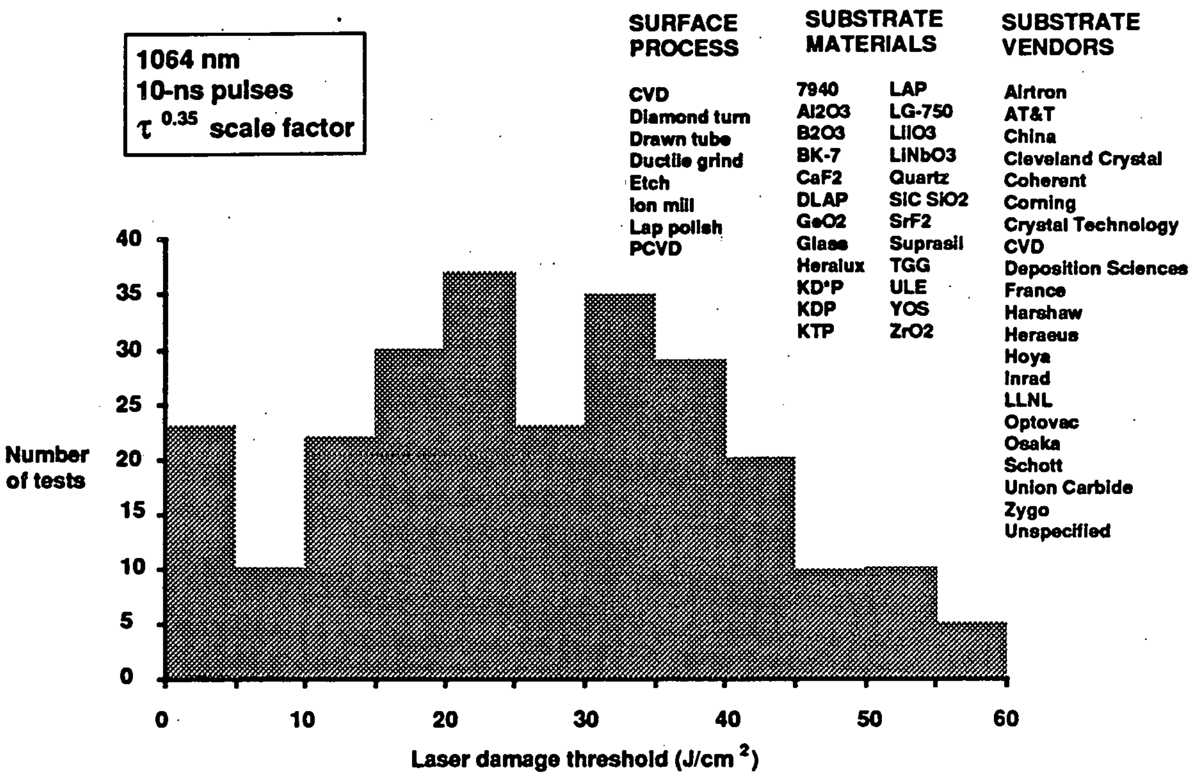

Figure 2. Summary of laser damage tests conducted on bare polished surfaces.

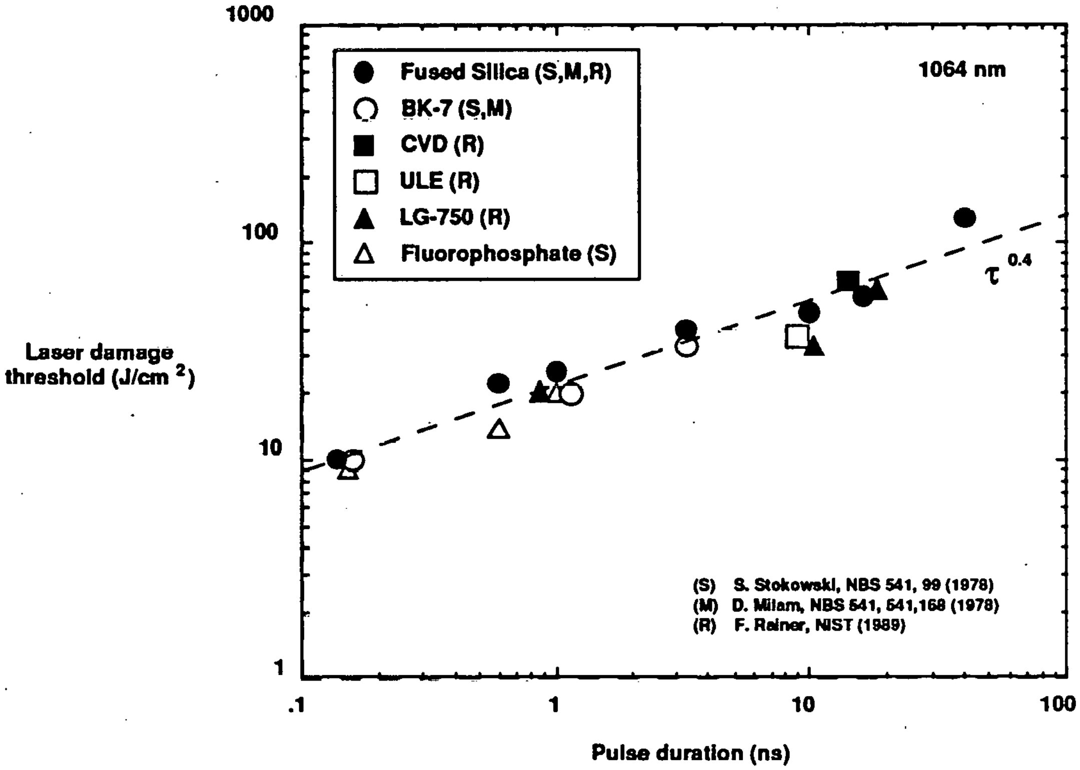

Figure 3. Damage thresholds of optimized polished surfaces scale as $\tau^{0.4}$ between 150 ps and 40 ns and are independent of glass type for a variety of common laser glasses having refractive indices near 1.5.

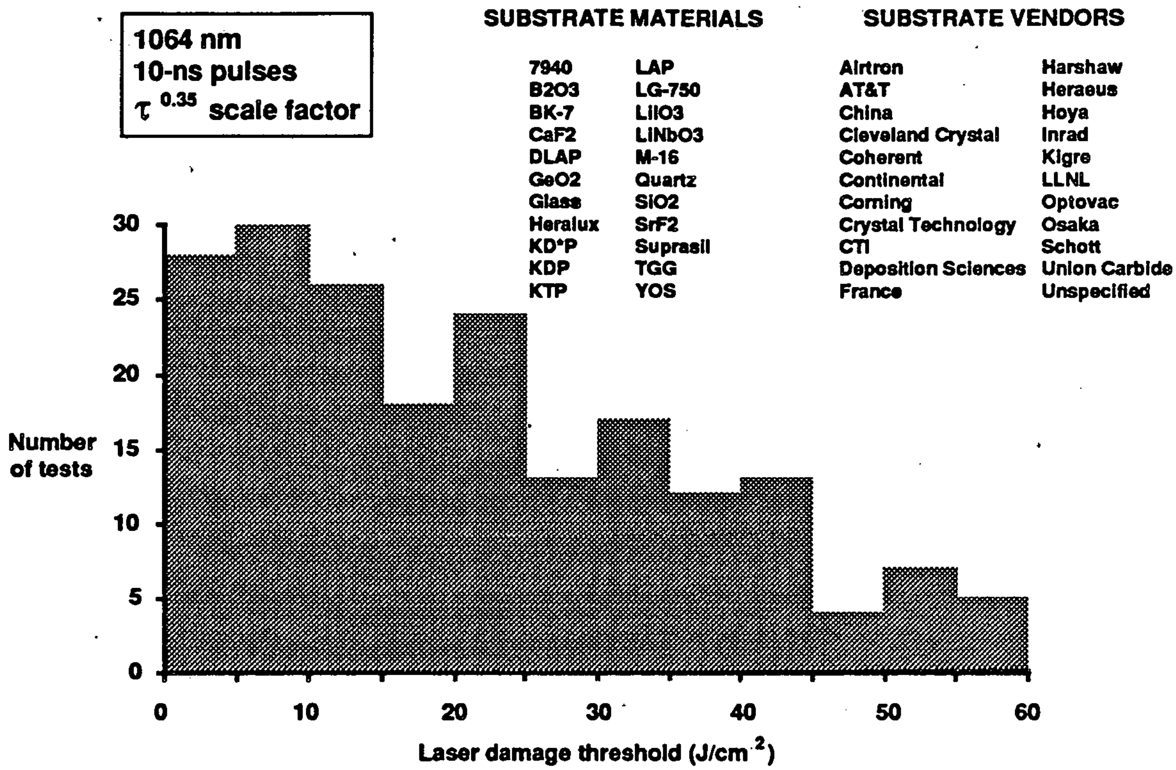

Figure 4. Summary of laser damage tests conducted on bulk materials.

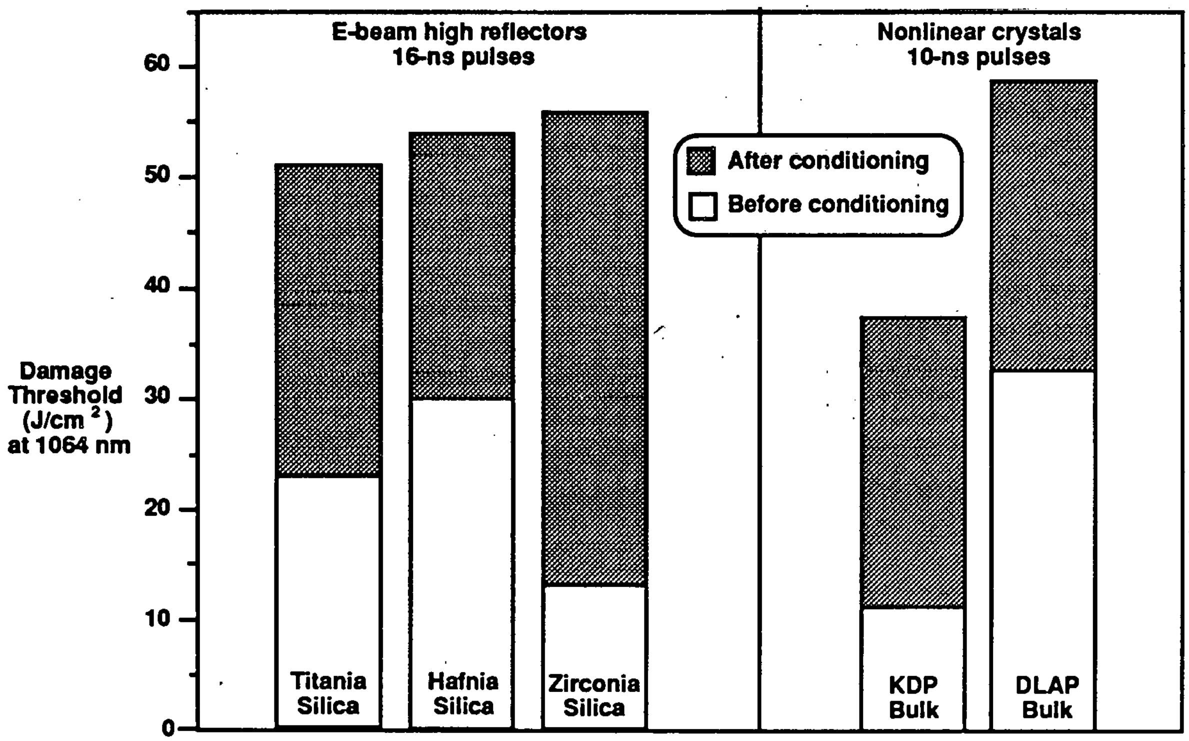

Figure 5. Pre-irradiation of PVD-fabricated HR coatings and non-linear crystals with sub-threshold laser pulses (conditioning) increases their damage thresholds above unconditioned thresholds.

4.2 Bulk materials

In figure 4 we summarize the measurements we have conducted on over twenty different types of bulk materials including non-linear crystals, laser host materials and substrates. Many of the entries at the higher fluence ranges actually represent lower limits of the thresholds. This was either because we ceased irradiation when massive damage occurred to the bare or coated surfaces or because we could not extract higher fluences from the laser. Our laser irradiation in the bulk material is conducted with a gently focusing beam using 2.5- to 5-m focal length lenses. We typically limit ourselves to a test volume over which the beam fluence changes $\leq 1\%$. We also find it useful to work within a depth of field which can be readily examined by Nomarski microscopy. Finally, within the constraints of the available laser fluence, we attempt to utilize as large a cross-section beam as possible. By this means we determine the threshold of a macroscopic volume of material with potential microscopic defects rather than the intrinsic threshold of a defect-free material. We irradiate with beams on the order of 1-mm diameter for a depth not exceeding 10 mm.

Of particular interest to us at LLNL is the improvement in damage thresholds of frequency conversion crystals to levels approaching those of substrate materials such as fused silica. We have pursued the development of a variety of high threshold materials such as deuterated and undeuterated potassium-dihydrogen phosphate (KDP) and ℓ-arginine phosphate (LAP). In 1981 we reported increases in bulk thresholds of KDP crystals by pre-irradiation of the material with a succession of sub-threshold laser shots. [5] This laser conditioning has been reported at these proceedings for several years both for non-linear crystals and optical coatings. Typical results of continued improvement are shown on the right half of figure 5.

4.3 High reflective (HR) coatings

Figure 6 summarizes the tests that we have conducted in recent years for a variety of HR coating techniques from 15 different vendors We list the assortment of materials used both for substrates and the coatings. All of the coatings consisted of muli-layer stacks of two or more materials. We list only the unique individual materials since the variety of material combinations is too numerous to elaborate upon. In this figure we combine the results of tests on single wavelength, multi-wavelength, and partially reflecting mirrors.

We are investigating three major options for improved damage thresholds in HR coatings. These include laser-conditioned PVD coatings, sol-gel coatings, and plasma assisted chemical-vapor-deposition (PCVD) coatings. The latter two techniques and their results are reported upon in companion papers at this conference. [6], [7], [8] Examples of typical improvements in damage thresholds by laser conditioning to PVD HR coatings are shown on the left side of figure 5. Improvement usually has been found to range from 1.5 times to greater than 3 times unconditioned thresholds. We have found that the degree of improvement was often dependent upon the number and sequence of sub-threshold irradiation shots. Once conditioned the samples were found to retain their elevated thresholds permanently. [9], [10]

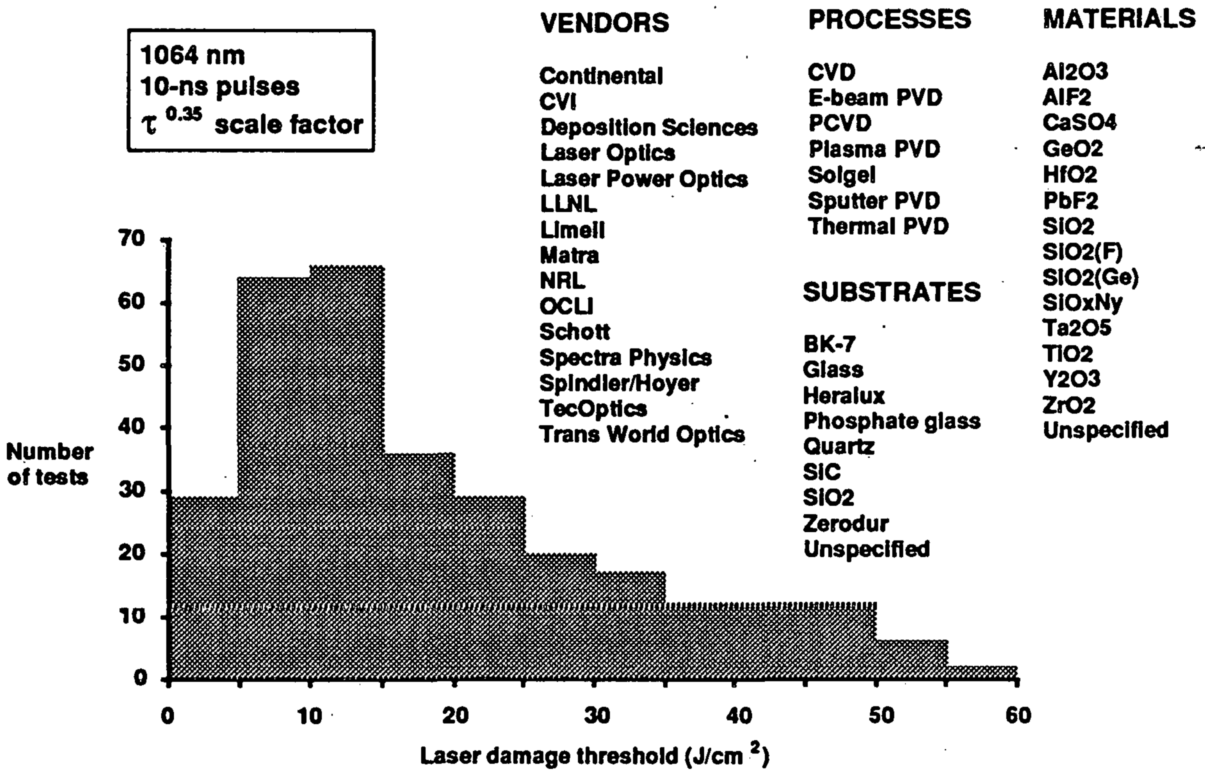

Figure 6. Summary of laser damage tests conducted on HR coatings.

4.4 Anti-reflective (AR) coatings

Figure 7 summarizes the extent of our recent AR coating testing. The bulk of this represented testing of research samples both for LLNL as well as outside vendors. Hence, many of the early results are concentrated at the lower threshold range. As with the case of the HR coatings we list both the variety of substrate and coating materials but do not elaborate on all of their combinations.

The major emphasis in this category has come from the development and implementation of the sol-gel process to produce damage-resistant AR coatings for fused silica substrates and lenses ranging up to 1-meter diameter and for large area arrays of KDP crystals for frequency conversion. Both of these applications have been extensively implemented on LLNL's Nova laser system. The extent of improvement in this technology in just the last few years is demonstrated in figure 8. The shaded portions of these histograms show all high threshold test results conducted in 1989 versus the best results (unshaded) obtained for the previous year. Blocks of tests with an arrow in them indicate that the sample thresholds were at least as great as the levels shown in the figure. Few tests were conducted at 355 nm since that testing capability had just been recently brought on line. Production of sol-gel AR coatings has become routine and reliable enough so that very little future testing of them is anticipated.

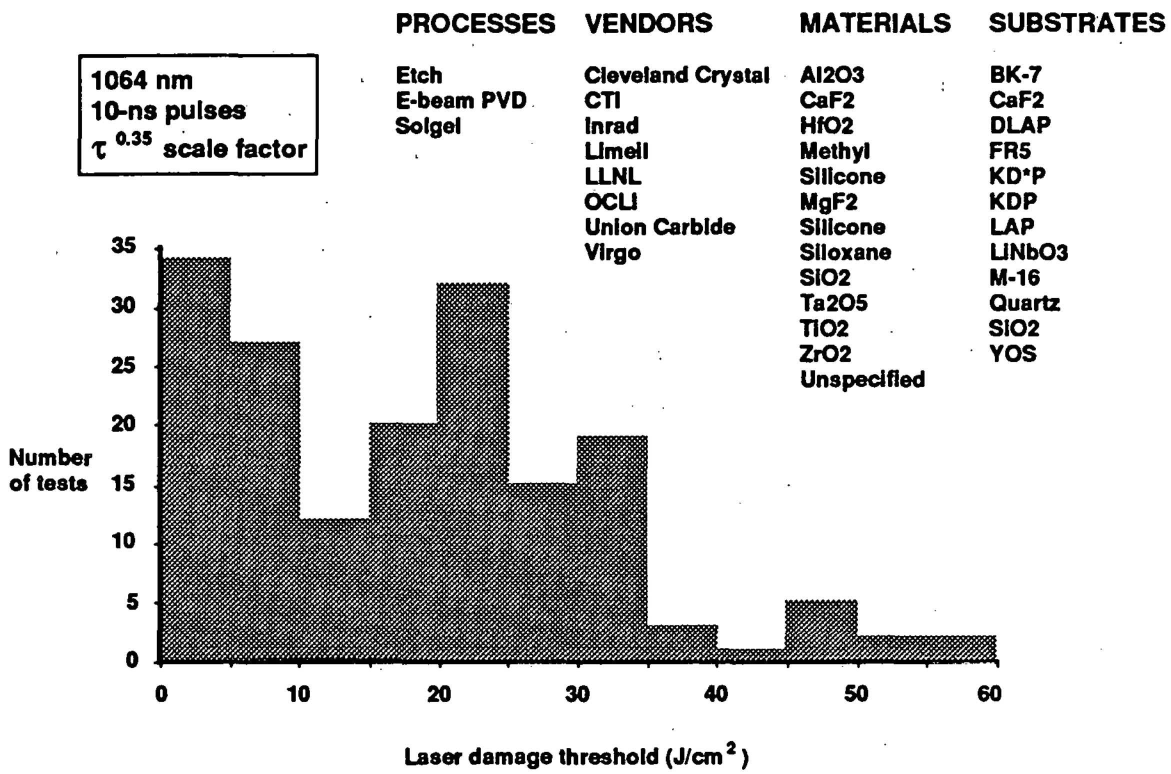

Figure 7. Summary of laser damage tests conducted on AR coatings.

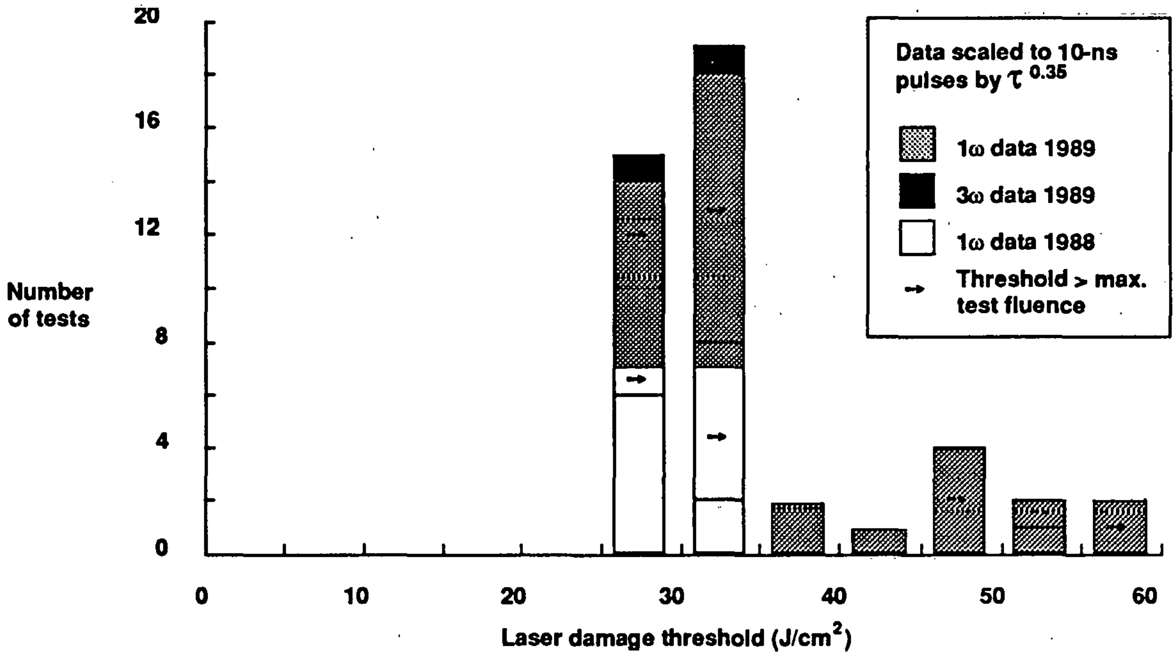

Figure 8. We have made significant improvements in laser damage thresholds of the best sol-gel AR coatings measured during the past year compared to those of the previous year.

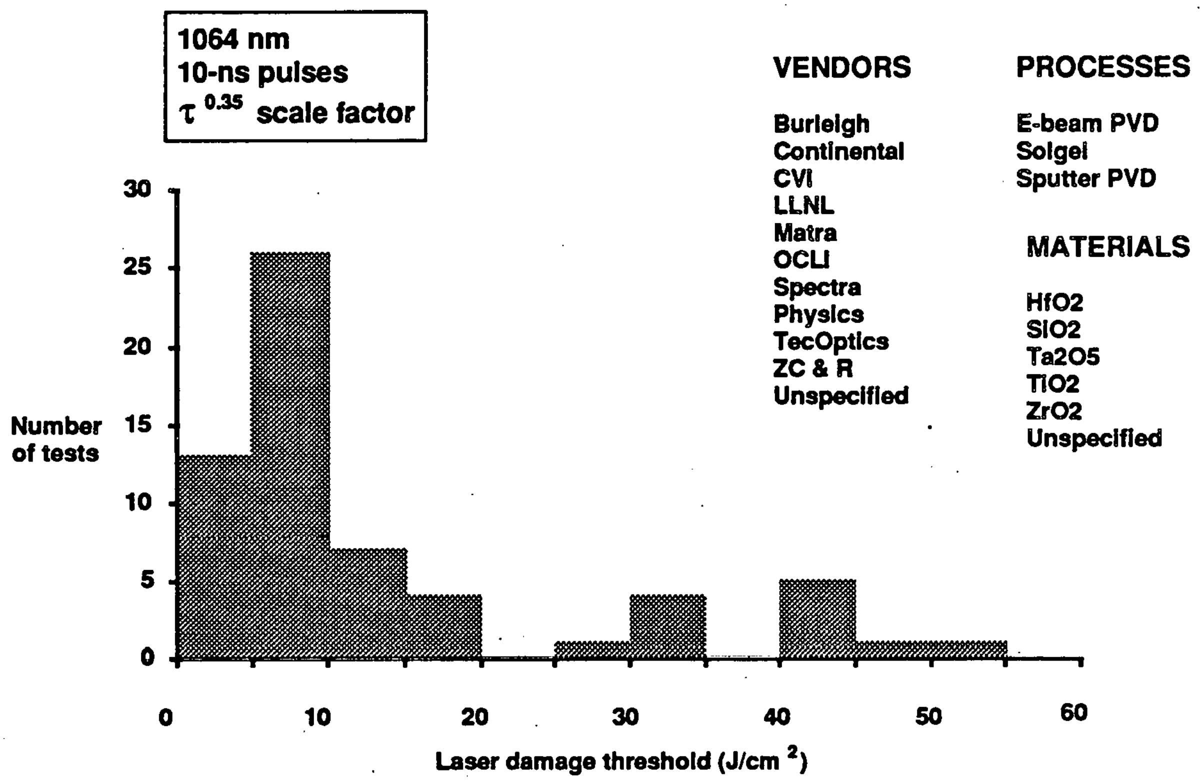

Figure 9. Summary of laser damage tests conducted on polarizers.

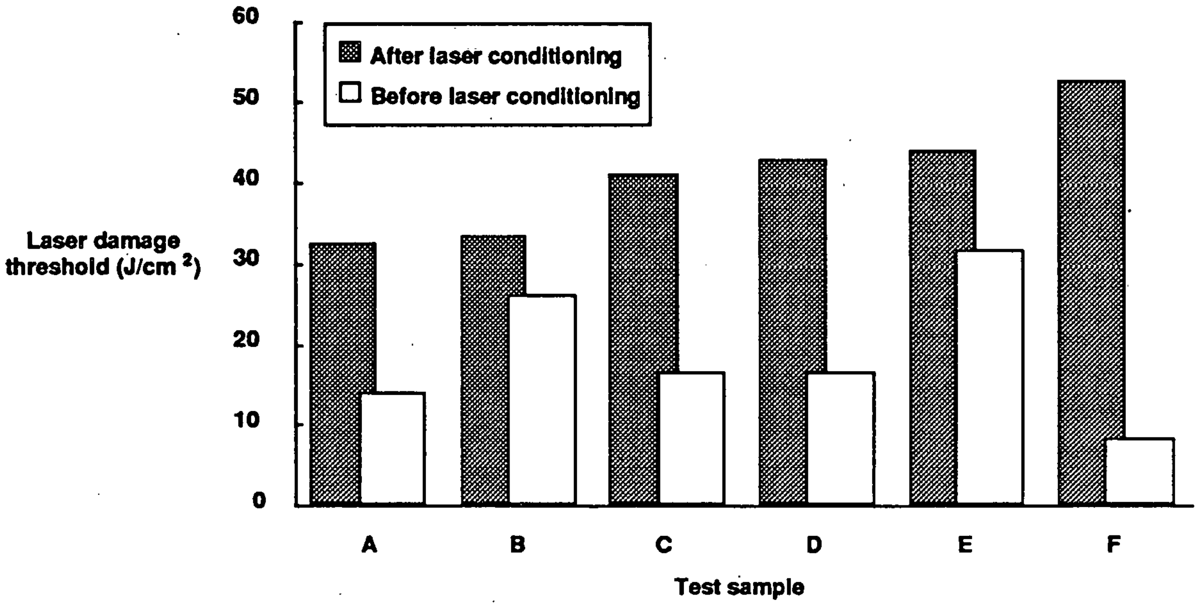

Figure 10. Laser conditioning of commercial PVD-fabricated polarizers improves their damage thresholds by an average factor of two.

4.5 Polarizers

Multi-layer stack polarizers are typically fabricated with more complex coating designs using more layers than those used for comparable HR coatings. Unlike HR coatings, the coating-substrate interface of polarizers sees the full intensity of the transmitted laser beam. By their very nature, polarizers will also have greater angular sensitivity to each polarized component of the laser beam. These characteristics have usually combined to yield among the lowest thresholds for multi-layer coatings as is shown in figure 9. We have not conducted as many tests on polarizers in recent years as on AR and HR coatings but the distribution of thresholds at the lower fluence range of this figure is typical of polarizers. We have, however, recently also conducted conditioning tests on a variety of samples from several vendors. In figure 10 we show that, as with HR coatings, we can expect to find a significant improvement in thresholds by implementing laser-conditioning. From a limited database of conditioned polarizer tests we have observed average rises in thresholds of about a factor of two.

4.6 Single material coatings

Much of the research that we and many of our vendors have done in the development of multi-layer coatings began with testing of single layers or multiple layers of the same material by all of the standard deposition processes. In figure 11 we show the aggregate result of these tests on 25 different materials applied by PVD, CVD or sol-gel processes. These coatings were often half-wave thick layers at 1064 nm but not exclusively so. We list most of these materials specifically in figure 12 to illustrate the spread that one can expect in damage thresholds. One cannot specifically use these data in order to pick optimum material combinations for fabricating high-threshold multi-layer AR's, HR's or polarizers. This database represents a compilation of many research and development samples with a great variety of deposition parameters including process type, thickness, number of layers, cleanliness, substrate type, and deposition conditions.

4.7 Metal mirrors

Of all of the commonly used optical components in the laser industry, metal mirrors have consistently yielded the lowest damage thresholds. From a limited database we had reported thresholds no higher than 4 J/cm^2 for 16-ns pulses at 1064 nm. [1] The higher thresholds were usually obtained by enhancing the bare metal substrate or plated metal coating with a dielectric overcoat or a multi-layer dielectric HR stack. This produced a rise in threshold by a factor of two at best. A summary of those earlier tests and more recent tests shows a small database in figure 13. We have seen some minor improvement in bare metal thresholds but in general they still lie below 5 J/cm^2 at 1064 nm for 10-ns pulses. We attributed the failure of HR-overcoated metal mirrors to two factors. First of all, possible pinholes in the dielectric HR would allow energy to propagate through the HR stack to the metal itself. Secondly, defects on the metal could propagate corn growth on subsequent dielectric layers so that they do not behave as true HR's where the defects print through. With dielectric substrates any leaked energy through the HR stack would be dissipated by transmission through the substrate. A metal coating or substrate would, however, trap this leaked energy at this interface and cause catastrophic failure to the metal. Recent coatings that have been fabricated for us appear to have yielded superior dielectric HR stacks as is

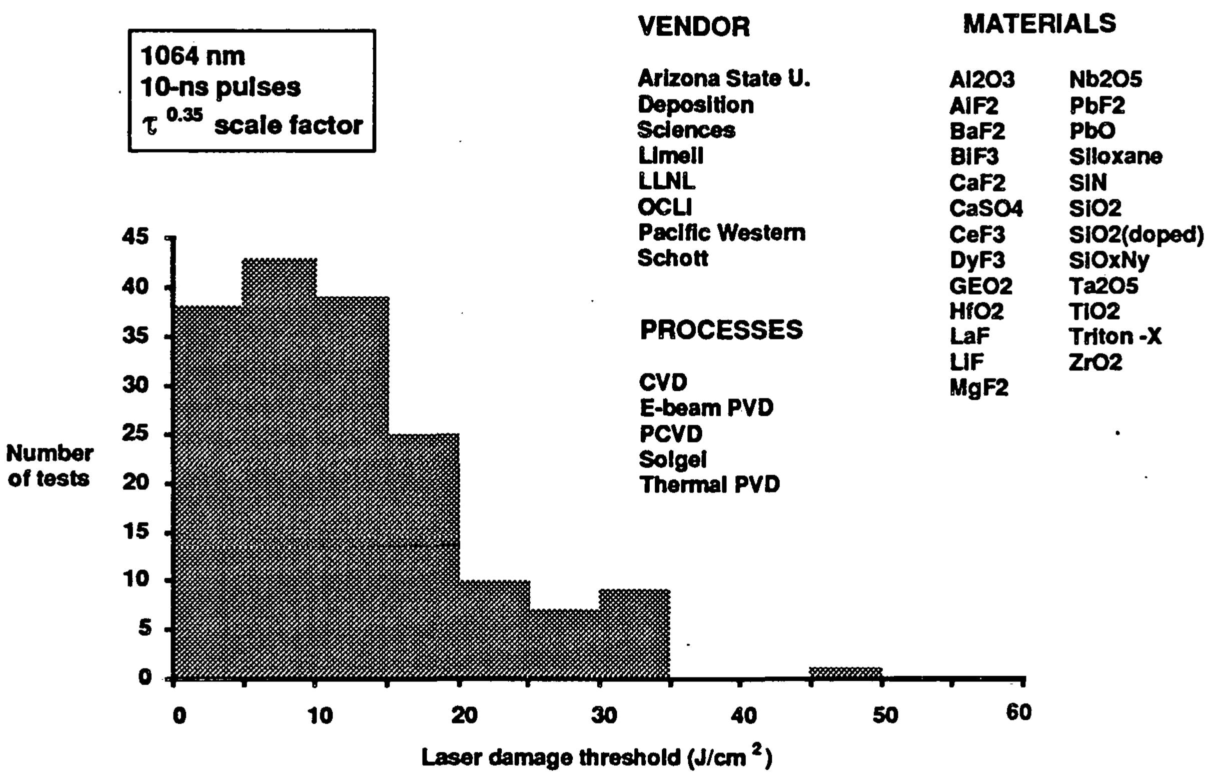

Figure 11. Summary of laser damage tests conducted on single or multiple layers of the same material.

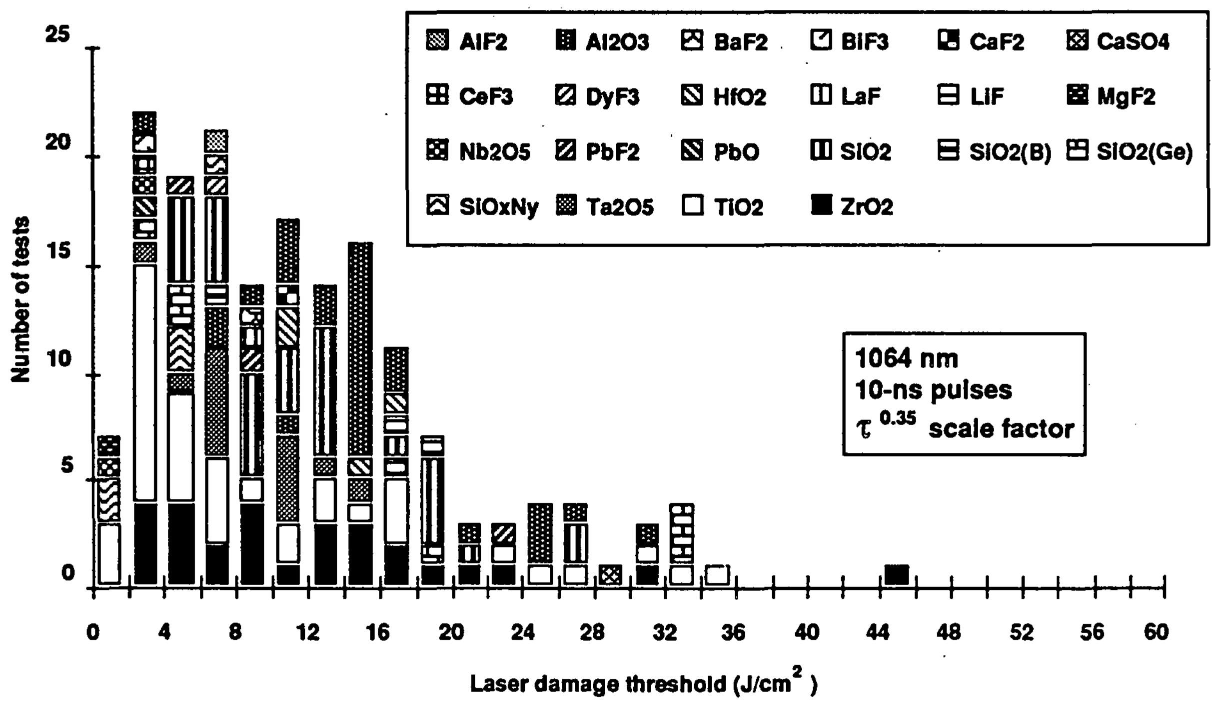

Figure12. Ranking of laser damage thresholds for a variety of single material coatings fabricated by PVD, CVD and sol-gel processes (except single-layer silica sol-gel AR's which are listed under the AR category).

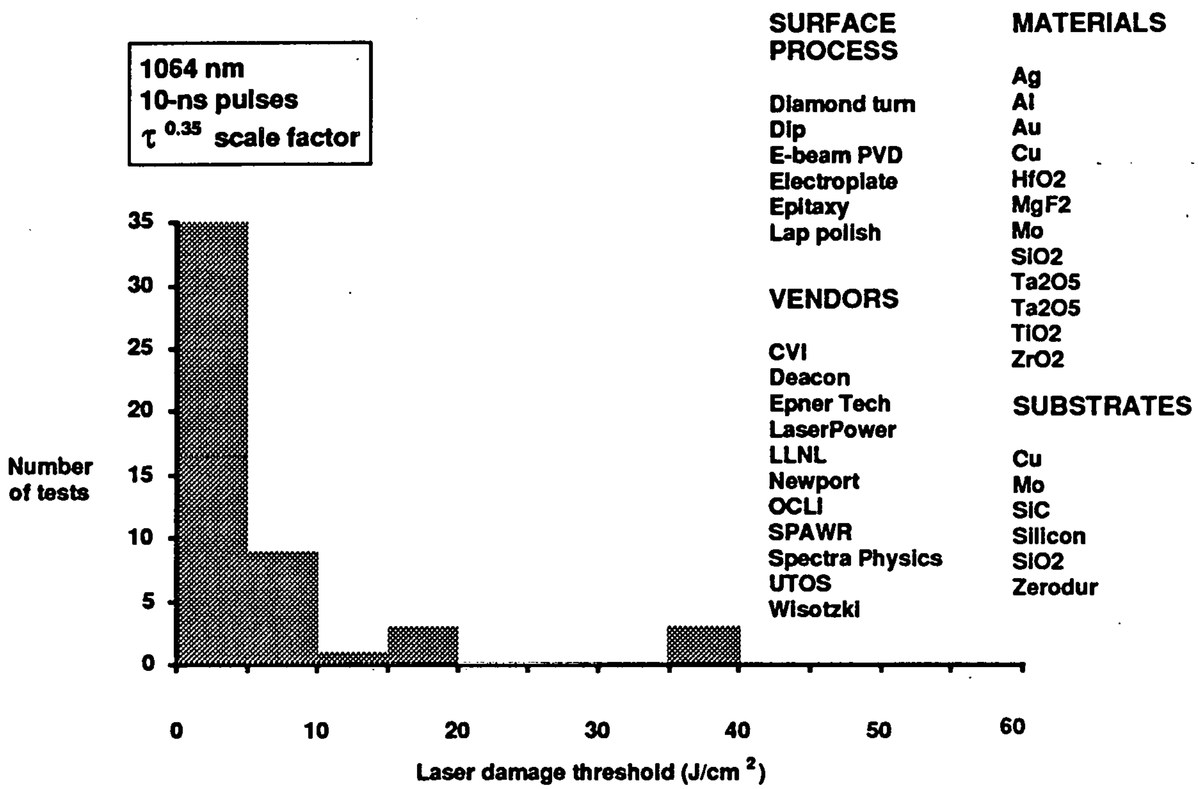

Figure 13. Summary of laser damage tests conducted on bare and enhanced metal mirrors.

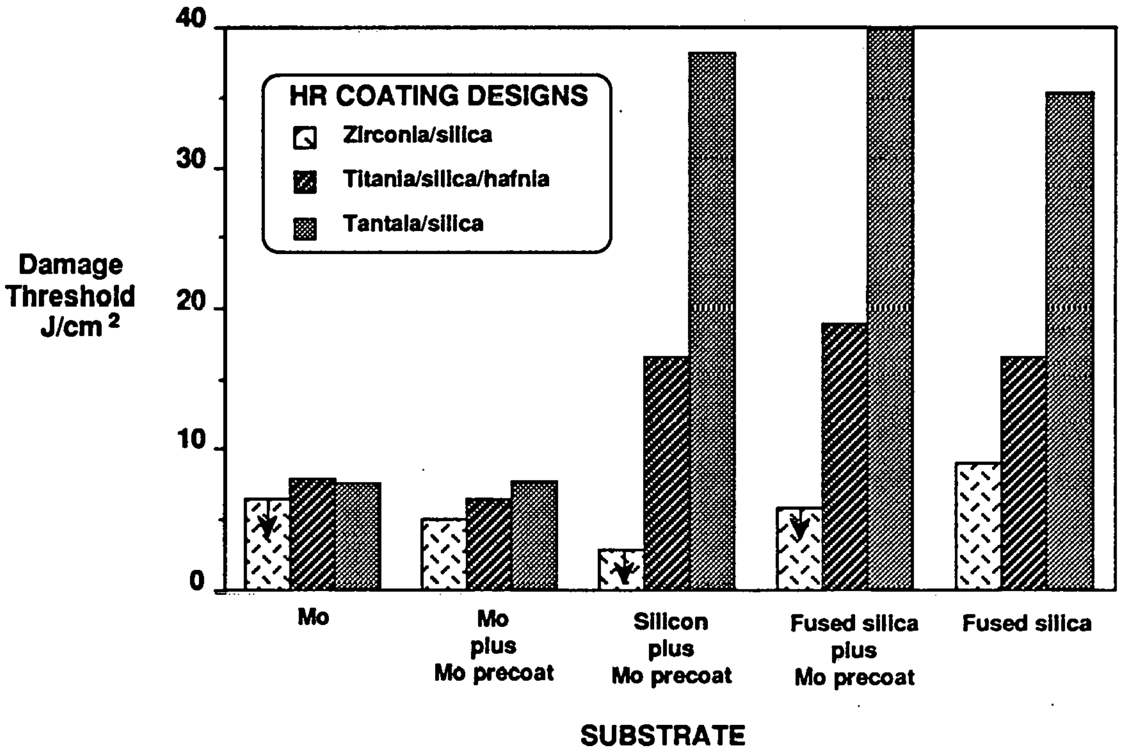

Figure 14. Metal mirrors enhanced with pinhole-free dielectric HR stacks can have thresholds comparable to those of the stacks on dielectric substrates. The arrows indicate that the thresholds for those particular samples were less than the minimum test fluences shown.

shown in figure 14. Although damage thresholds have improved for bare molybdenum substrates, print-through of defects from the substrates through the HR still caused thresholds to be low. However, when Mo coatings were plated on defect-free silicon or fused silica we found thresholds to equal those of the same HR's deposited on fused silica alone.

5. Conclusions

We have expanded upon our database of laser-damage tests at LLNL to include over 1300 tests conducted at 1064 nm in the last few years. This represents a small fraction of over 10,000 tests that we have conducted during the past 15 years. We have used a variety of laser systems to enable us to study the effects of spot size, pulse duration, PRF, polarization and incident angle. As time permits this database will be expanded to include relevant past data as well as all current testing. In addition, the database is currently being expanded to include tests at the second, third and fourth harmonic of 1064 nm.

We have broken our tests down into seven broad categories of optical samples including AR's, HR's, polarizers, single and multiple layers, metals, bare surfaces, and bulk material. We, or our vendors, have achieved 10-ns-normalized thresholds that reach or exceed 40 J/cm^2 in all of these categories . This has been accomplished by a variety of techniques worked on by LLNL and by our vendors including laser conditioning, sol-gel coatings and PCVD coatings.

The database provides us with an effective tool in being able to cull information from many test covering a large parameter space of sample fabrication and laser testing techniques. It is, to a first degree, an interactive computer tool rather than just a printed list of test data. To that extent it has a somewhat limited use when simply printed as a whole. The value of the database stems from our ability to be able to sort and search from a high volume of data. Unfortunately we are currently not at liberty to be able to publish a detailed database for general external use. To first order the database represents primarily research in optical component development by LLNL and its vendors. It does not guarantee to include all vendors and processes or even the best ones. At a later date we may be able to provide for distribution a cross-referenced database which approaches such a goal but which must of necessity be limited by proprietary information from our vendors.

6. References

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7. Appendix

Table 3. Sample of a computer-generated database table. The table has been broken into four parts to aid in presentation

1	2	3		4			
TEST & #	TEST Date	SAMPLE #	OTHER ID #	COATING (or Bare, or Bulk) Vendor	Type	Process	Materials
R 508 A	7/13/89	A279B	1-YOS-4#2	L-Thomas	AR 1	Solgel	AlO(OH)
R 508 B	7/13/89	A279B	1-YOS-4#2	L-Thomas	AR 1	Solgel	AlO(OH)
R 508 C	7/13/89	A279B	1-YOS-4#2	L-Thomas	BU LK	Solgel	AlO(OH)
R 508 D	7/13/89	A279B	1-YOS-4#2	L-Thomas	AR 1	Solgel	AlO(OH)
R 508 E	7/13/89	A279B	1-YOS-4#2	L-Thomas	AR 1	Solgel	AlO(OH)
R 508 F	7/13/89	A279B	1-YOS-4#2	L-Thomas	BU LK	Solgel	AlO(OH)

5					6					
SUBSTRATE Type	Source	Polish by	Process	LxW(or D)xT mm	LASER PARAMETERS nm	ns	Hz	pol	°	mm
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1
YOS	Vendor	L-Prochnow	Lap	23dx7	1064	10	10	P	10	1.1

7		8							9		10
THRESHOLD Loc	J/cm2	MORPH.(thresh />thresh) M	µ	#	M	µ	#	@	Shots/Site Meth.	#	REPORTS
F	38.2 ±5.7	M	999	1					S/1	30	LDG89-117
R >	20.9	M	999	1	M	999	1	34	S/1	600	LDG89-117
B	17.9 ±2.7	A	?	2	M	999	1	21	S/1	600	LDG89-117
F	43.1 ±6.5	A	5	1	N			47	R/1	600	LDG89-117
R >	47.1	N			N			47	R/1	600	LDG89-117
B	43.6 ±6.5	A	?	2	A	?	1	47	R/1	600	LDG89-117

11	12
SAMPLE DESCRIPTION & COMMENTS Before test ◊ After test	10-ns thresh
Nd3+:Y2SiO5 crystal ◊ Massive R&B dmg @ lower fluences	38.2
Nd3+:Y2SiO5 crystal ◊ Massive R&B dmg @ lower fluences	> 20.9
Nd3+:Y2SiO5 crystal ◊ Massive R&B dmg @ lower fluences	17.9
Nd3+:Y2SiO5 crystal ◊ Slight improve w/anneal	43.1
Nd3+:Y2SiO5 crystal ◊ No dmg	> 47.1
Nd3+:Y2SiO5 crystal ◊ Clean B areas survived above thresh	43.6

Table 4a. Explanation of database table entries

1 TEST numbers are prefixed by a LETTER which signifies the test laser or facility:

A — Air Force XeF Excimer	H — Chameleon	N — Nova
B — Raster Blaster	I — Isotope Separation	O — OCLI
C — Cyclops	K — Kilroy	R — Reptile
D — Comparative Damage	L — ILS	V — VPL
F — Felix XeF Excimer	M — Montana Laser	X — KrF Excimer

TEST NUMBERS follow chronologically for each laser.

LETTER SUFFIXES distinguish separate results obtained under the same test number such as location: front, rear surface, or bulk material; irradiation type: conditioned or unconditioned; etc.

2 DATE when test was begun — entries are in chronological order.

3 SAMPLE NUMBER (hopefully unique) assigned by us or the materials development group.

Any OTHER ID number that came with the sample (often not unique). Very long numbers may be partially hidden in print-outs but are extractable from the computer database.

4 Coating VENDOR; further numbers identify subtasks or runs from a particular vendor. If the "vendor" is an LLNL employee his name is preceded by L-. For a bare surface, the vendor who polished or treated the surface is listed. For bulk material tests we list the front surface parameters in this section. The following surface vendors have been catalogued to date:

Airtron	Deacon	Laser Optics	PacificWestS.	Tinsley
Ariz.U.	Dep.Sci	Laser Power	Rochester	Trans World Optics
Burleigh	Epner Tech	Limeil	Schott	UnionCarbide
Cleveland	France	LLNL	Shandong	UTOS
Continental	Harshaw	Matra	SPAWR	UofNM
Corning	Hoya	NBS	Spectra Physics	Virgo
Crystal Tech	Inrad	Newport	Spindler/Hoyer	Wisotzki
CVD	Kodak	OCLI	TecOptics	ZC & R
CVI	Labsphere	Optovac	Thin Film Coat	Zygo

Optic TYPES are listed by the following general categories:

- AR — antireflective coating — following numbers indicate for which harmonics the design applies: 1=1w (1064,1053 nm), 2=2w (532, 527 nm), 3=3w (355, 351 nm) 4=4w (266, 263, 248 nm)
- BARE — bare surfaces which may have been polished, turned, extruded, etched, cleaved, etc., but without any applied coating.
- BULK — bulk material as opposed to bare surface or coating.
- HR — high reflector or partial reflector — following numbers indicate harmonics (see AR above).
- LA — layer(s) of only one material — following numbers indicate number of such layers
- MET — bare or deposited metal surface — following HR or OC indicates the metal is covered by a dielectric HR stack or a dielectric overcoat respectively.
- MISC — miscellaneous such as liquid, powder,paint,cement.
- POL — polarizer—following numbers indicate for which harmonics design applies (see AR above).

Coating PROCESSES cataloged to date are listed below. For bare surfaces some of these entries are the same as in the substrate section.

CVD	Epitaxy	PCVD	PVD-plasma	Solgel
Dip	Misc	Powder	PVD-sputter	
Electroplate	Paint	PVD-ebeam	PVD-thermal	

MATERIAL combinations have not all been catalogued consistently. In general, multiple layers are listed with a / between them. Dopants or mixtures are represented by { }. For cataloguing purposes a common material such as SiO2 is always listed last. UC = undercoat, OC = overcoat.

Ag	Cu	MgF2/Al	SiO2{l}/SiO2{h}	TiO2/Triton-x
Al/SiO2	DLAP	Mo	SiO2{N}	TiO2/HfO2/SiO2
Al/TiO2/SiO2	DyF3	Nb2O5	SiO2{N}/SiO2{N'}	TiO2/HfO2/SiO2/Mo
Al2O3	GeO2/P2O5/SiO2	Nd3:Y2SiO5	SiO2{P}	TiO2/Siloxane
Al2O3/AlF2	GeO2/SiO2	Opal	SiO2{Ti}	TiO2/SiO2
Al2O3/SiO2	Glass	PbF2	SiO2{Ti,F}/SiO2{F}	TiO2/SiO2/OC
Al2O3/TiO2/SiO2	Heralux WG	PbF2/AlF2	SiO2{silicone}	TiO2/SiO2/UC
AlF2	HfO2	PbF2/CaSO4	SiO2/silicone	TiO2/SiO2/HfO2
AlO(OH)	HfO2/SiO2	PbF2/SiO2	SiO2{siloxane}	TiO2/SiO2/ZrO2
AlO(OH){SiO2}	KD*P	PbO	Spectralon	ULE
AlO(OH)/SiO2	KDP	Phosphate	SrF2	ZrO2
AlO(OH)/TiO2/SiO2	KTP	Quartz	Ta2O5	ZrO2/MgF2/SiO2
Au	LAAC	Si3N4+d	Ta2O5/SiO2	ZrO2/SiO2
B2O3/SiO2	LaF	SiC	Ta2O5/SiO2/UC	ZrO2/SiO2/Mo
BaF2	LAP	Silicone	Ta2O5/SiO2/Mo	ZrO2/SiO2/HfO2
BaSO4	LG-750	SiN	TFF1	ZrO2/Y2O3
BiF3	Li-formate	SiO2	TGG	
BK-7	LiF	SiO2{B}	TiO2	
CaF2	LiIO3	SiO2{F}/SiO2	TiO2(anatase)	
CaSO4	LiNbO3	SiO2{Ge}	TiO2(rutile)	
CeF3	Methyl silicone	SiO2{Ge}/SiO2	TiO2/siloxane	
CH3OH	MgF2	SiO2{Ge}/SiO2{F}	TiO2/siloxane/Triton-x	

Table 4b. Explanation of database table entries

5 SUBSTRATE materials catalogued in the database to date are listed as follows:

7940	FR5	LAP	Phos.APG	TFF1
Al	GeO2{P}	LG-750	Quartz	TGG
Al2O3	GeO2/SiO2	Li-formate	SiC	TiO2
B2O3/SiO2	Glass	LiIO3	Silicon	ULE
BK-7	Heralux	LiNbO3	SiN	YOS
CaF2	Heralux WG	M-16	SiO2	Zerodur
Ceramic	KD*P	Mo	Spectralon	ZrO2
CH3OH	KDP	Nb2O5	SrF2	
Cu	KTP	None	Suprasil	
DLAP	LAAC	Opal	Suprasil F3	

SUBSTRATE AND POLISHING VENDORS OR SOURCES are listed as follows:

Airtron	CVI	Kodak	OCLI	UTOS
Applied Optics	Deposition Sciences	Labsphere	Optovac	Wisotzki
AT&T	France	Laser Power	Osaka	Zygo
China	Fujian	Limeil	Schott	
Cleveland	Harshaw	LLNL	Shandong	
Coherent	Heraeus	Matra	Spectra Physics	
Continental	Hoya	NBS	Spindler/Hoyer	
Corning	Inrad	Newport	Tinsley	
Crystal Technology	Kigre	NRL	Union Carbide	

POLISH or surface treatment PROCESSES used:

Beadblast	Drawn Tube	Fused	None	Super
Cleaved	Ductile	Ion mill	PACE	Unknown
Diam.T.	Etch	Lap	Replicate	

Substrate dimensions are in mm as length x width (or diameter if followed by d) x thickness.

6 Six laser parameters are specified:

WAVELENGTH in nm (1064, 1053, 532, 527, 355, 351, 266, 263, 248)

PULSE DURATION in ns (0.1 — 100).

Pulse repetition frequency (PRF) in Hz (0 — 8.6 k). All entries are in integers except high and low PRF values. Single shot is designated by 0.

POLARIZATION is given as P or S. Mixed or alternation polarization is listed as PS. Elaborations may follow in the comments section.

ANGLE OF INCIDENCE in degrees (0° — 85°) (fractions may be rounded off but stored in database).

SPOT DIAMETER (1/e^2) in mm.

7 Laser damage threshold LOCATIONS are:

F — at the front or incident surface of the sample

R — at the rear or exit surface of the sample. The entry is indented 1 space to aid in locating it.

B — within the bulk material of the sample (extensive surface damage may cause damage to propagate into the bulk material and vice versa). The entry is indented 2 spaces to aid in locating.

Thresholds are designated > or < if a full determination was not pursued because of lack of fluence, not of interest, severe damage elsewhere, or inability to measure.

THRESHOLDS and ERRORS are in J/cm2 to 0.1 J/cm2 but not necessarily accurate to that degree.

THRESHOLD COMMENTS may follow with R for retest, ? for doubtful measurement, etc.

8 Damage MORPHOLOGY comments are given in two sets of columns, the first at threshold, the second at a higher fluence (lower if no higher tests were taken) — listed under @ in J/cm2.

MORPHOLOGY under columns M is coded as:

A — artifact enhancement	M — massive damage	T — trail of bubbles or points
B — bulk damage	N — no damage	V — visual change (not seen by microscope)
C — crack or fracture	P — pinpoint damage	? — Not noted or unknown
D — delamination	R — coating removal	
F — foggy appearance	S — scald from plasma	

SIZE of largest damage at a site is given in μm in the μ columns (999 means ≥ 1 mm).

The NUMBER of observed damage phenomena is listed under #; note that many small damage points may be listed as 1 point when damage spreads to massive proportions (99 means ≥ 99).

9 IRRADIATION TYPE is coded as follows:

1/1 — ONE shot per site.

N/1 — NUMEROUS shots per site, 1 at a time with increasing fluences (conditioning or annealing).

S/1 — SEVERAL shots per site, each shot nominally at the SAME fluence with PRF irradiation.

R/1 — many shots per site, beginning near zero fluence and RAMPED up to highest stated fluence in PRF mode (conditioning).

scan — sample SCANNED along line through a PRF beam (conditioning by wings of beam).

rast — sample RASTERED in 2 dimensions through a PRF beam (conditioning by wings of beam).

The NUMBER OF SHOTS on the site which defined threshold is listed under #.

10 Identifying number of the REPORT in which the test results were written up. This is usually a Laser Damage Group Memo (LDG) (a + sign means more reports are listed but hidden in the print-out).

11 Abbreviated further details (sample description before the ◊, test results after). Abbreviations used for location and morphology apply. Coating stack described as [T/S]5 means 5 layer pairs of TiO2/SiO2. M F dmg @ 30 means massive front surface damage at 30 J/cm2.

12 If tests were conducted with other than 10-ns pulses, t, the threshold, T, is scaled to a 10-ns value by T=t^0.35. This is only a rough comparison aid. Scaling usually ranges between t^.2 and t^.5 if at all.

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