UCRL-JC-135650
PREPRINT

Debris Shield Survivability and Lifetimes for NIF

M. Tobin, D. Eder, I. Thomas, J. Latkowski, S. Brereton, B. MacGowan, R. Horton, T. Duewer, F. Zaka, S. Davis and J. Ertel

This paper was prepared for submittal to the
First International Conference on Inertial Fusion Sciences and Applications
Bordeaux, France
September 12-17, 1999

September 1999

Debris Shield Survivability and Lifetimes for NIF

M. Tobin, D. Eder, I. Thomas, J. Latkowski, S. Brereton, B. MacGowan, R. Horton, T. Duewer, F. Zaka, S. Davis, J. Ertel

Abstract

The survivability and performance of the NIF debris shields on the National Ignition Facility are a key factor for the successful conduct and affordable operation of the facility. Estimates of debris shield lifetime in the presence of target emissions indicate severely shortened lifetimes. We have tested a new coating design that improves debris shield cleaning. A combination of modeling and continuous data collection on NIF is described/recommended to allow cost effective debris shield operation.

1. Introduction

The increased required performance of debris shields for NIF will require a substantially larger operations budget than for Nova. Extending debris shield life through more benign target emissions and intensive debris shield management could reduce the operating budget for debris shields. Further, cleaning of shields must be faster than for Nova to further keep costs down. A new coating design is presented that experiments show may be fast and efficient for NIF. Two threats to NIF debris shields, non-volatile residue (NVR) and target shrapnel are discussed. While NVR is unlikely to have a big impact on NIF debris shields due to self-cleaning processes in the chamber, target shrapnel will significantly reduce debris shield lifetimes if the impacts are not reduced by improved low impact target designs.

2. Goal Debris Shield Performance for NIF Compared to Nova

The 192 debris shields on NIF will provide 99.5% transmission when newly installed on the NIF and support as many as 15 shots in a single week of experiments. They will be replaced with a new or cleaned/re-coated shield at the end of each week. The removed shields are cleaned and re-coated during the following week to be ready for installation the following weekend. This is twice the change-out rate used on Nova where shields were left in the chamber for up to two weeks at a time supporting as many as 30-35 shots, on average. It is also more than 20 times the clean/re-coat rate in cm^2 per week. When a re-coated debris shield could not achieve 95% transmission, the debris shield was refurbished, if it was the first time, and discarded if it was the second. The main reason for the re-coated debris shield not being able to achieve 95% transmission was the damage induced by the laser fluences coupled with Nova target emissions that obscured more than 5% of the shield surface area. The 'two week rule' was developed over years of observations of Nova debris shields and was believed the time period that economically extended the life of the shield while balancing the operations cost of frequent cleaning. On NIF, it is planned, that after 2 months of continuous service, the shields will be discarded and replaced with new ones. It is uncertain whether refurbishment can be done on NIF, despite its economic advantages, because of concern for removing the deeply embedded damage sites. A comparison of Nova and NIF debris shield performance is shown in Table I.

Feature	Nova	NIF

Size	65 cm diameter (round)	43 x 43 cm (square)
Number	10	192
# Shields Changed per Wk	5	192
Transmission (new)	99.5%	99.5%
Transmission (reject)	95%	96.5%
Shield Lifetime	~6 months	~2 months
Refurbishment Rate	~ one time per shield	unknown
Installation Time (each)	~1 hour	15 minutes (goal)

Table I. A comparison of Nova and goal NIF debris shield performance

3. Annual Operating Costs of NIF Debris Shields

The annual acquisition cost of debris shields has been estimated, assuming six replacement sets of shields are bought each year. Reasonable costs for debris shield removal and installation, cleaning, re-coating, and refurbishment (if used) have also been estimated. We established figures-of-merit (FOM) for different cases of frequency of purchase, refurbishment, and cleaning of debris shields on NIF. For a baseline plan of simply replacing the debris shields every 2 months and cleaning, re-coating, and re-installing them the other weeks, the total annual cost (figure of merit) is taken at 1.00 (Case 1). If shields must be replaced on a monthly basis, the total cost (FOM) rises to 1.47 (Case 4), and to 1.94 if the interval is only 2 to 3 weeks (Case 7). The cost benefits of refurbishment is shown in cases 2, 3, 5, 6, 8, and 9 where each of the three

	# Times DS Replace	Replace Cost FOM	# Times DS Refurbish	Refurbish Cost FOM	# Times DS Clean	Clean Cost FOM	Total FOM
Case 1	6	0.53	0	0.00	44	0.47	1.00
Case 2	3	0.27	3	0.15	44	0.47	0.88
Case 3	2	0.18	4	0.20	44	0.47	0.84
Case 4	12	1.07	0	0.00	38	0.40	1.47
Case 5	6	0.53	6	0.30	38	0.40	1.24
Case 6	3	0.27	9	0.45	38	0.40	1.12
Case 7	18	1.60	0	0.00	32	0.34	1.94
Case 8	9	0.80	9	0.45	32	0.34	1.59
Case 9	6	0.53	12	0.60	32	0.34	1.47

Table II. Cost of NIF Debris Shield Operations for Various Scenarios

replace-only scenarios are modified with either one or two refurbishments between replacements of debris shield.. The refurbishment options shown can save approximately 20% of the costs of the baseline plan. In addition, savings may also be realized if target emission damage can be reduced and if debris shields are removed, cleaned, and re-coated or re-furbished at the 'optimum' time that economically extends their lifetime (as on Nova). The range in total operations costs for the nine cases was $10M to $30M.

Since Nova had only 10 beams, each with a similar orientation to the target (50° cone angle), the shields were assumed to degrade uniformly during the two weeks in which they were in the chamber. However, ICF chamber studies over the years have shown substantial anisotropy in all of the target emissions that can damage debris shields – shrapnel, debris, and x-rays. NIF employs, in effect, two different cone angles (centered at about 27° and 48°). The difference in shrapnel 'fluence' between these angles from a target can be an order of magnitude or more. The difference in x-ray fluence can be 30% or more, and for debris fluence factors as great as three orders of magnitude. Therefore the rate of degradation between cone angles will be quite different with an obvious major impact on beam balance. There would be an additional benefit to NIF operations (although an additional not currently planned cost) to being able to remove and clean debris shields to preserve beam balance in addition to extending debris shield lifetime. These factors suggest that a combination of modeling and data from frequent chamber environment measurements, along with minimum damage target designs, may allow cost efficient maintenance of NIF debris shields and also support achieving target requirements such as beam balance.

4. NIF Debris Shield Status Modeling

The modeling envisioned to support cost-effective debris shield operations would include the following: (1) a code or codes that adequately predict the x-ray, debris, and shrapnel emissions in three dimensions including the size and number of craters for shrapnel; the mass, Z, and state of material (particle sizes) for debris; and the effects to the coating of x-rays (ablation or sintering). These codes would then be used to 'certify' the emissions from the planned targets and diagnostics for NIF – that is, the target outputs would be understood sufficiently well that the *change in the surface of each debris shield* after a shot would be sufficiently well known. (2) A few debris shields would be removed on a daily basis, perhaps two per cone angle, and examined to confirm and/or allow adjustment to what the analytical model suggested was the state of all of the debris shields. (3) A model that predicts damage growth in fused silica debris shields as a function of laser power and the type of damage site, either particulate contamination or craters. This capability would be used to determine when the shield should be removed to prevent further accelerated damage to the shield so that after proper cleaning and coating and perhaps some inexpensive refurbishment it could be used for more shots. This last function would be accomplished by using a database that would track each target and its effects during the week of operation. It would also be used to optimize the shot schedule to minimize debris shield damage and place shots that may not need the beam quality of other shots in the schedule when debris shields can support those shots but not precision shots. In short, this combination of modeling and data collection on NIF will serve to support minimal shrapnel targets and maintenance of debris shields so as to get the longest possible (and most cost effective) life out of them. *One impact of such a system as this is targets for NIF will have to be constructed using common guidelines and approved well in advance of their use on the facility.*

5. Nova Experiments to Support NIF Chamber Modeling

To test whether this idea of 'simple' target modeling had merit, we measured the debris that had deposited on two Nova debris shields (Beamlines 3 and 4) from March 1 to 12 of this year using wipes that were soaked in an acid solution. The wipes were then examined by Inductively Coupled Plasma-Optical Emission and Mass Spectroscopy to measure the mass of each element in the sample. The composition of the wipe was subtracted out, as was the contribution of the gloves used when obtaining the sample. An evaluation of wipe efficiency was also made and included to account for material left on the debris shield. The center of the debris shield (19 cm diameter) did not have light passing through it – and therefore provided an excellent witness

Element	BL#4 Measured ng/cm^2	BL#2 Measured ng/cm^2	Calculated ng/cm^2	% Difference Calculated to Measured

Au	493	540	675	24%
Cu	51	69	153	61%
Al	67	80	73	<1%
C	Not measured	Not measured	63	–
Ta	Not measured	Not measured	30	–
Fe	25	35	16	88%
Be	0.34	1.2	0.66	14%
Ti	0.69	2.4	0.55	183%
U	0.071	0.091	0.16	49%
Sc	Not measured	Not measured	0.13	–
Ge	Not measured	Not measured	0.003	–
Ag	17	16	Not calculated	–
Ce	3.8	0.0	Not calculated	–
Cr	4.8	4.7	Not calculated	–
Pb	6.6	6.2	Not calculated	–
Ni	3.9	5.3	Not calculated	–
Mo	1.5	1.5	Not calculated	–
Mn	0.9	0.9	Not calculated	–

Table III. Comparison of predicted and measured debris shield contamination on Nova.

plate of unperturbed direct target debris for the 31 shots. A spreadsheet was created for each target type used, and using the detailed modeling done for other targets, a simple scaling was used to estimate the material that deposited on each shield. For shine shields ('wings' on the hohlraum used to block unconverted light from reaching the target), the amount of vaporized material depended on the ablation depth and exposed area to unconverted light. For hohlraums, we required the energy needed to vaporize the material be only a small fraction of beam energy that was deposited. We used a simple expression for ablated depth with two possible scalings with fluence (F)/intensity (I):

$$D_{abalation} = \alpha\, F^{2/3},\ \text{or}\ D_{abalation} = \alpha\, I^{2/3}\Delta t = \alpha\, F^{2/3}\Delta t^{1/3},$$

where α is in range 2-7 μm/(kJ/cm^2). The results are shown in Table 3 above. The agreement generally is good between calculated and measured values. The shields were also measured for transmission losses before and after introduction to the chamber. The contamination at the center of the shield, an average thickness of 0.7 ng/cm^2 in the center region of the shield, resulted in a transmission reduction of 6%. This relation between particulate loading and transmission loss must be better understood and likely empirically measured to create the necessary 'look-up' table this database will need to understand debris shield performance during NIF experimental campaigns. There may have been some contribution from shrapnel damage to this transmission reduction, but since the debris shield was brand new when put in, we suspect that this contribution was quite small. These two debris shields saw no further shots on Nova. They will be a good record of the shrapnel damage of the 31 shots when measured. A similar spreadsheet is being created for shrapnel to confirm that similar results can be created fairly simply, further lending credibility to the model strategy laid out above. The cratering damage on these two debris shields will be measured and used to check the accuracy of the model that predicted it.

6. NIF Debris Shield Damage Site Growth Rates and Implications for Shrapnel Damage

Substantial work has been done to try to quantify the rate at which damage sites grow as a function of laser fluence. Estimates of *laboratory* damage site growth rates range from 1.4 μm/shot at 3 J/cm^2 to 13 μm/shot at 5 J/ cm^2 to 30 μm/shot at 8 J/ cm^2 for a 3 ns 3ω pulse.[1]

Note that observed damage growth rates on Beamlet were significantly greater. These analyses include the growth rate for only pre-existing damage sites which are quite small (few nm) and do not treat the growth of damage sites induced by target emissions which can be quite large (many µm to even mm). The analyses also do not treat the damage induced by laser interaction with surface contamination. At these growth rate values, and assuming that a debris shield must be removed when the obscuration due to damage reaches 3%, then the number of shots that fused silica can survive ignoring the presence of target emissions is estimated and shown in Table IV.

Shrapnel damage to the 23.5° and 50° debris shields are shown in Table V below for the case of a 1.8 MJ shot into a hohlraum that employs large Cu disks as shine shields for the unconverted light.[2] The shields are 50-µm thick and 4-cm in radius. An *average* particle size is reported and

Mean Fluence (3 ns pulse) (J/cm^2) *scaled from 7.5 ns	Growth Rate (µm/shot) *scaled 10 Hz data	Shots to 3% Obscuration at Laboratory Damage Growth Rate	Shots to 3% Obscuration at Beamlet Damage Growth Rate
1.9	0.5	20,000	600
3.2	2.6	2000	15
4.1	7.1	800	5
4.7	11.3	400	2
6.3	20.2	95	0

Table IV. Estimates of number of shots to 'failure' as a function of fluence for 3ω light and fused silica.

is therefore quite large and few in number. The laser damage growth rate at 4 J/cm^2 is about 7 µm/shot. Since this growth is effectively an increase in the diameter of the crater site, the increase in size of large craters is slow for this case since the increment is quite small compared to the diameter. The rapid obscuration of the shield is mainly due to repeated exposure to large particles in this case. As replacement materials are selected that are more benign and large particle shrapnel is avoided, then laser induced damage growth can become a more dominant effect for shield obscuration. For example, if instead of six 1.8 cm craters produced on the 50° debris shields, we assume that five such craters are made along with 1,000 craters of 180 µm diameter. This conserves mass but results in an initial obscurance that is 15% less than for the only large crater case (only 0.7%). However, after 20 shots the laser induced damage accounts for 2.5% of the total damage which grows to 14.4%. If further target design improvements reduced the large craters to one but had to increase the small craters to 5,000 (again mass in conserved), then while the initial obscurance is now reduced by 75% (0.2%), after 20 shots laser induced damage accounts for 30% of the damage which has grown to 5.4%. The debris shield can now withstand 13 shots before reaching the 3% obscuration. The % obscured values for 23.5° and 50° again underscore the impact on beam balance where shields will experience substantial differences in degradation.

Row	**D_{crat}/D_{part}**	**Ave D_{part}**	**# / debris shield**	**% obscured**	**D_{crat}**
23.5°	100	300 µm	28	10 %	3.0 cm
50°	60	300 µm	6	0.83 %	1.8 cm

Table V. Example of possible target shrapnel emission effects on the debris shield for the two cone angles.

This analysis indicates that the 23.5° debris shields would have to be changed after only 1 shot (due strictly to shrapnel damage) and that the 50° debris shields would last only another 3 or 4 shots, compared to the 800 or so shots predicted for a debris shield without target damage. Note that the Beamlet experience would only support 5 shots *without any target damage consideration at all.* These results underscore that need for major reduction in shrapnel emissions and an intensive (but cost effective) debris shield management effort, as well as achieving debris shield performance similar to laboratory damage growth rates.

7. Cleaning of NIF Debris Shields

Nova debris shields were cleaned by a rigorous process that took several hours per optic. The process was quite good — debris shields placed on Nova were measured to have only Ce as a contaminant at less than 1 ppb levels. All target debris was removed. However, an equally efficient process that is much faster is needed for NIF. We propose to use a new coating that retains transmission but supports automated cleaning of debris shields. The usual 70 nm sol-gel (SiO_2) coating would have under it a 0.5 µm layer of 95% dense silica followed by another 0.5 µm thick layer of an organic such as methyl cellulose or polyvinyl alcohol. Tests we have conducted on Nova indicate that all of the target debris is easily removed by rinsing the optic in a solution of 10% NaOH in water which dissolves the organic layer. This removes all contamination and would also, as a side benefit, remove all tritium when it is introduced on NIF as well, preventing proliferation of tritium into the optics processing area. The tests showed that several times the expected loading of debris on NIF is easily removed by this process. Also, the x-ray survivability appears to support operations even up to ignition target yield (~100 kJ) on NIF. Further x-ray testing is required to determine just when the coating will not survive the target x-rays beyond a few MJ of fusion yield. The peak x-ray loading (23.5° cone angle) on a NIF debris shield for a 5 MJ shot is 0.5 J/cm^2 in a 3-part blackbody spectrum of 240, 60, and 15 eV with 9, 60, and 60 ns pulse durations, respectively. At 20 MJ, this increases to about 1.2 J/cm^2 in a 4-part blackbody spectrum of 400, 200, 80, and 15 eV with 15, 15, 70, and 70 ns pulse durations, respectively. We believe that the coating may not survive this level but further testing on a Flash X-ray Machine (debris free) is required to confirm this.

8. Degradation of Sol-Gel Coating by NVR

Non-volatile residue (NVR) inside the NIF chamber can rapidly degrade the sol-gel coating on the debris shield on the target chamber side. A one to ten Torr pressure in the Integrated Optics Module (IOM) will retard migration of NVR. Eight different measurements on Nova have shown that the NVR level inside the chamber are consistently less than 1 µm/cm^2 – the selected NIF standard for the chamber because sol-gel degradation is quite small at this level, less than 0.5%. This result was a surprise because no special precautions (such as diagnostic bake-out) were taken on Nova. We propose that scattered laser light cleaned the chamber of NVR on each shot, volatizing several per cent of this layer with each shot. This observation agrees with measured chamber pressure increases immediately after shots – that is the magnitude of the rise in the pressure seems to agree quite well with the conversion of about 5% of the NVR which is know to be dioctylphthalate (DOP). Cleanliness standards for the NIF Target Chamber components should be Level 300 A except for the IOM, which must be maintained at laser component levels of cleanliness, and the Final Optics Assembly outside the IOM which should be kept at Level 200 A. This would indicate that periodic cleaning of the interior of the FOA should be done to prevent contamination of the NIF debris shield from a dirty and nearby FOA surface. Experiments should be conducted on Omega to confirm this 'self-cleaning' of NVR by laser light which should be more pronounced on NIF than on Nova.

9. Conclusions — The improved debris shield performance required for NIF over Nova represents a potentially large cost to NIF operations. We believe it is possible and cost effective to establish a modeling capability coupled with regular data collection from the NIF chamber to reduce debris shield operations costs by factors of a few. Proof-of-principle experiments on Nova have shown some success in simple modeling of debris contamination, for example, on debris shields. Established damage growth rates for fused silica and 3ω light indicate that target emissions will substantially reduce the number of shots debris shields can survive. A proposed new coating scheme will substantially reduce the effort to clean debris shields and also provide a means to efficiently decontaminate the shields of tritium. Suspected self-cleaning of NVR on Nova may indicate that NVR will not be an issue on NIF and unusual efforts to reduce it such as diagnostic bake-out may not be required. Work performed for DOE by LLNL (W-7504-Eng-48).

References

[1] Feit, M.D., "Statistical Description of Laser Induced Damage in UV Grade Fused Silica at 351 nm", LS&T Technical Seminar, May 3, 1999.
[2] Tokheim, R.D. et al, "Damage and Hardening Assessments for the National Ignition Facility Target Chamber Design", UCRL-CR-128686, February 1998.

Corresponding author:

Michael T. Tobin
Lawrence Livermore National Laboratory
P.O. Box 808, L-181
Livermore, California 94550
USA

Phone: (925) 423-1168
Fax: (925) 422-8471

Email: tobin2@llnl.gov