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SHIELDING ANALYSIS FOR X-RAY SOURCES GENERATED IN TARGET CHAMBER OF THE NATIONAL IGNITION FACILITY

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SHIELDING ANALYSIS FOR X-RAY SOURCES GENERATED IN TARGET CHAMBER OF THE NATIONAL IGNITION FACILITY

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Prompt doses from x-rays generated as result of laser beam interaction with target material are calculated at different locations inside the National Ignition Facility (NIF). The maximum dose outside a Target Chamber diagnostic port is ~ 1 rem for a shot utilizing the 192 laser beams and 1.8 MJ of laser energy. The dose during a single bundle shot (8 laser beams) drops to ~ 40 mrem. Doses calculated outside the Target Bay doors and inside the Switchyards (except for the 17'-6" level) range from a fraction of mrem to about 11 mrem for 192 beams, and scales down proportionally with smaller number of beams. At the 17'-6" level, two diagnostic ports are directly facing two of the Target Bay doors and the maximum doses outside the doors are 51 and 15.5 mrem, respectively. Shielding each of the two Target Bay doors with ¼" Pb reduces the dose by factor of fifty. One or two bundle shots (8 to 16 laser beams) present a small hazard to personnel in the Switchyards.

I. INTRODUCTION

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory will be the world's largest and most powerful laser system for inertial confinement fusion. NIF is a 192 laser beam facility that will produce 1.8 MJ, 500 TW of ultraviolet light. As shown in Fig. 1, NIF consists of three buildings; Laser and Target Area Building (LTAB), Diagnostics Building (DB), and Optics Assembly Building (OAB). The main laser systems are installed in two laser bays inside the LTAB. Each laser bay delivers 96 beams into one of two Switchyards. Sets of turning mirrors in each Switchyard (SY) redirect the beams into the Target Bay (TB). Additional sets of optics in the TB will align and focus the beams onto the target in the center of the Target Chamber (TC). NIF will use indirect-drive targets. In such targets, laser beams enter a metal can (hohlraum) and create thermal x-rays that heat the surface of the fusion capsule. The 192 beams enter the TC through 48 indirect-drive beam ports. In addition, in order to accommodate for the possibility of future utilization of direct-drive targets, where the laser beams are focused directly on the fusion capsule, the NIF TC includes additional 24 direct-drive beam ports.

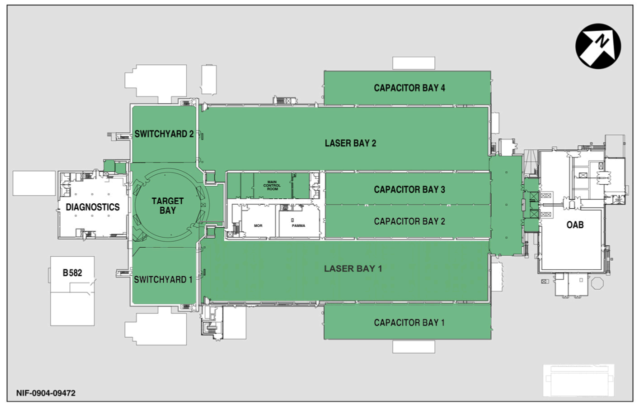

Fig.1. Top view of the NIF facility.

The Target Bay has a semi-cylindrical design with an inner radius of 50', 6'-thick concrete walls and 4.5'-thick concrete roof. A total of 175 and 44 utility penetrations are present in the TB and SY walls, respectively. There are six floor levels within the TB at elevations of -33'-6", -21'-9", -3'-6", 17'-6", 29'-6" and 50'-6" with respect to the ground level. The TC is located in the middle of the TB with its center at elevation of 23' from the ground level. Twenty TB doors connect the TB and the two SY.

The NIF operation is divided into four different phases.[1] Phase 1 includes laser operations with up to 192 beams. The main radiation hazard in this phase is caused by x-rays generated due to 3ω laser and high-energy petawatt laser (Advanced Radiographic Capability "ARC") interactions with different target materials. Phase 2 includes all Phase 1 operations and a maximum of 200 deuterium-deuterium (D-D) shots per year with maximum yield of $1x10^{13}$ neutrons/shot. Phase 3 includes Phase 2 operations and deuterium-tritium (D-T) shots for a maximum annual yield of 30 kJ ($1x10^{16}$ neutrons/year). Finally, Phase 4, which represents the full NIF operations, includes Phase 3 operations and D-T shots with routine 20 MJ yield per shot, and ≤ 1200 MJ per year.

This paper summarizes results of analyses performed to evaluate the radiation environment expected inside NIF during the first two phases of operation. Prompt dose values due to conservative x-ray source assumptions are calculated at different locations inside the Target Bay, Switchyards and Diagnostics Building.

II. NIF FACILITY MODELING FOR PROMPT RADIATION

In order to accurately evaluate the prompt radiation environment within the NIF facility, a detailed 3-D model of NIF has been developed using the MCNP radiation transport code.[2] The Target Chamber is made of a 10-cm-thick aluminum wall surrounded by 40-cm of borated concrete. In addition to 48 indirect-drive and 24 direct-drive laser beam ports, the TC includes 120 diagnostic ports. While each of the 48 indirect-drive ports is connected to a Final Optics Assembly (FOA), not all of the direct-drive and diagnostic ports are connected to any hardware (e.g., for diagnostics). All indirect-drive ports are modeled as being covered with a layer of glass representing the average density and thickness of optics in the FOA. On the other hand, unused diagnostic and direct-drive ports are covered with aluminum port covers that vary in thickness between 35 and 48 mm. Used ports are usually shielded with hardware providing more effective shielding than that provided by the port covers. In this analysis, as a conservative assumption, all diagnostic and direct-drive ports are assumed to be covered with only 35 mm of aluminum. The only exceptions are the d113 and d117 diagnostic ports (at the 17'-6" floor level), which are directly facing the D155 and D151 TB doors and potentially resulting in the highest dose values inside the two switchyards. Simplified models are developed for the Opposed Port Alignment System (OPAS) and Diagnostic Instrument Manipulator (DIM) diagnostics connected to the d113 and d117 ports, respectively. Finally, all of the nine top plate diagnostic ports were assumed to be covered with 25 mm aluminum (actual thickness of their port covers). None of the TB shield doors, except for the only door connecting TB to DB (TOTIM), is installed during Phases 1 and 2 of NIF operation. Mesh tallies are used to produce prompt dose maps of the entire facility. Dose values outside the TB doors (at locations with highest doses) are also calculated.

III. X-RAY SOURCE TERM

The two x-ray sources present during Phases 1 and 2 of NIF operation are:

1. X-ray generated by hot electrons due to laser beam interaction with target materials;
2. X-ray generated by petawatt laser interaction with back-lighters.

The first x-ray source term assumes a conservative conversion of 33% of the laser energy (≤ 1.8 MJ) into high energy "hot" electrons.[3] Electrons interact with a gold target generating the x-ray bremsstrahlung source. Actual radiation intensity measurements performed at Laboratory for Laser Energetics (LLE) at University of Rochester showed that < 6% of laser energy converted into hot electrons. Nevertheless, this analysis used the conservative source of x-rays as an upper bound. Figure 2 shows the spectrum of x-rays that was used in the analysis. The average energy of x-rays is about 55 keV. The spectrum is based on measurements performed at the OMEGA facility (Rochester).[4] Actual measurements are scaled up to the NIF assumptions and a point source located at the center of the TC is used in the calculation.

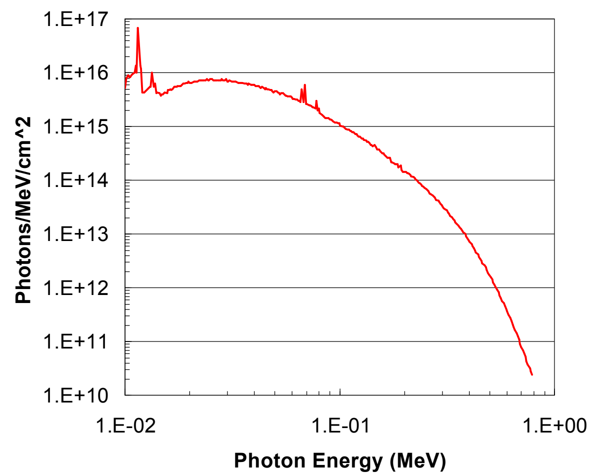

Fig. 2. X-ray spectrum due to conversion of 33% of laser energy (1.8 MJ) into hot electrons.

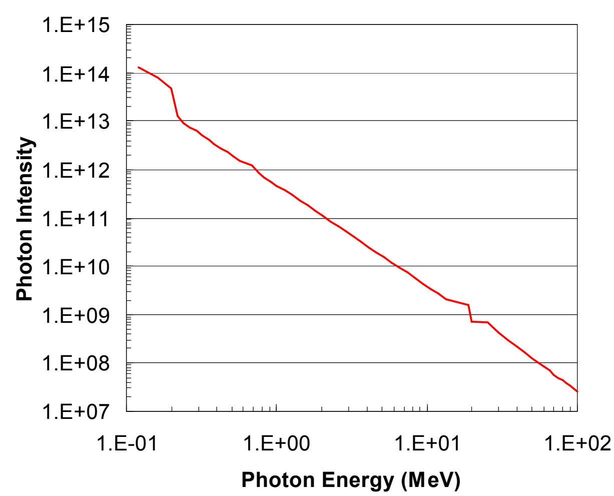

Fig. 3. X-ray spectrum due to ARC operation (1.5 kJ).

The second source term is generated during the operation of the Advanced Radiographic Capability (ARC), which provides petawatt laser capability using up to 4 NIF beams. Laser interactions with solid targets (back-lighters) produce much higher energy electrons. Approximately 40-50% of ARC laser energy is converted into hot electrons.[5] Electron interactions with the back-lighter results in the production of high energy x-rays that are used for diagnosing fuel density and symmetry of fusion targets. Figure 3 shows the spectrum of x-rays that were used in the ARC analysis. The x-ray intensity is based on a 1.5 kJ pulsed 1 W laser beam onto gold target (back-lighter). The average energy of x-rays in this case is about 160 keV. The spectrum and intensity are based on measurements performed at a Petawatt Laser system at LLNL.[5] Photon intensity is derived from a recorded measurement of ambient dose of 15 mrem at a distance of 20 m from the source. A point isotropic source located at the center of the TC is also used in the calculation. This is a conservative assumption because measurements showed a factor of five reduction in x-ray production in the backward direction with respect to the direction of laser target interaction. Photon intensity is estimated based on the maximum ambient dose value measured in the forward direction.

IV. ANALYSIS AND RESULTS

Each of the two source terms previously described is used in a separate MCNP calculation. Photon cross sections are derived from the ENDF/B-VI.8 data library and Effective dose values are calculated using ICRP-74 Anterior-Posterior (AP) dose conversion factors.[6,7]

IV.A. Laser Interaction with Target (up to 192 Beams)

Prompt dose values are calculated inside the TB (no personnel are allowed during shots) as well as outside TB doors leading to SY1 and SY2. The maximum dose outside a TC diagnostic port is ~ 1 rem for a shot utilizing the 192 laser beams and 1.8 MJ of laser energy. The dose during a single bundle shot (8 laser beams) drops to ~ 40 mrem. The high dose values inside the TB require classification of the TB as high radiation area for shots with more than 2 bundles (16 laser beams).

Except for at the 17’-6” floor level, the maximum doses outside the TB doors range from a fraction of mrem to about 11 mrem. The highest dose occurs at the -3’-6” floor level in SY2, for 4 clusters or 192 laser beam case, and scales down proportionally with a smaller number of laser beams. The situation at the 17’-6” floor level is different due to fact that the two diagnostic ports d113 and d117 are directly facing the D155 and D151 TB doors, respectively. While personnel standing outside all other doors will only see scattered radiation passing through penetrations in the TC, doses outside the two doors at the 17’-6” level are caused by x-rays emitted from the TC and stream through the two diagnostic ports while only interacting with the OPAS and DIM diagnostic hardware. The OPAS structure at the d113 port (90°, 315°) has an outside steel box that is 1/8"-thick. The DIM aluminum structure associated with d117 port (90°, 45°) is about 1.5"-thick except for the center region which is in line with TC (with only glass window). The maximum doses outside the D155 and D151 TB doors are 51 and 15.5 mrem, respectively. Shielding the D151 and D155 doors with ¼” Pb will reduce the doses outside the doors by about factor of fifty. Keeping the third door (TOTIM) at the 17’-6” floor level open will result in a dose of ~ 65 mrem inside the DB for the case of 192 laser beam operation. Most of the dose is due to x-rays passing through the DSWA diagnostic port (the largest port in the TC). Closing the 6’-thick concrete door, as planned, will reduce the dose to only 3.1 μrem for the 192 beam shot.

Dose maps of the all main floors of the NIF facility are developed to assist in fully understanding the dose environment throughout all potentially occupied areas during shots. The maps are produced for the 192 laser beam case. Dose values that are < 0.005 mrem are not assigned any color on the maps. In the two underground floors, -33’-6” and -21’-9” levels, 50% and 75% of the dose inside each SY is caused by x-rays streaming through the in-direct drive ports, respectively.

Figure 4 shows the dose behavior at the -3’-6” floor level (ground floor level) with dose contribution from x-rays passing through the direct-drive and diagnostic ports starting to have a large impact on dose values inside the SY. About 25 to 35% of the dose in the switchyards is due to x-rays passing through the in-direct drive ports. The largest contributors to the dose outside the TB door leading to SY1 and SY2 are the two diagnostic ports d83 and d92, respectively. Dose values in the DB as well as outside the NIF facility are very small (< 0.05 mrem).

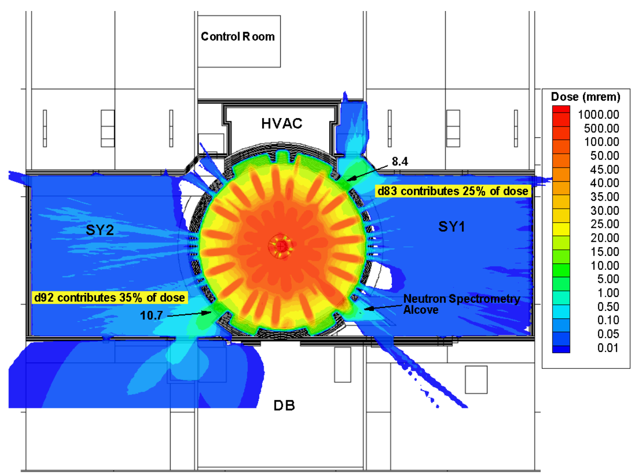

Fig. 4. Prompt dose map of the -3’-6” floor level.

Figure 5 shows the dose values at the 17’-6” floor level, which includes center of the TC. As expected, due to the fact that a large number of direct-drive and diagnostic ports exist at this level, contribution to the dose from x-rays passing through the in-direct drive ports drops to only 2% of the total dose in the SY. The highest doses inside SY1 and SY2 are caused by x-rays passing through the two diagnostic ports d117 and d113, respectively. As shown in the figure, radiation passing through the D155 door (SY2 side) will also result in a relatively higher dose value (30 mrem) inside elevator 1.

Shielding the D155 door with ¼" Pb will reduce the dose values outside the door and in elevator 1 by about a factor of fifty. Dose values inside the DB remain quite small. Shielding D151 on SY1 side with ¼" Pb will reduce the dose outside this door to < 1 mrem.

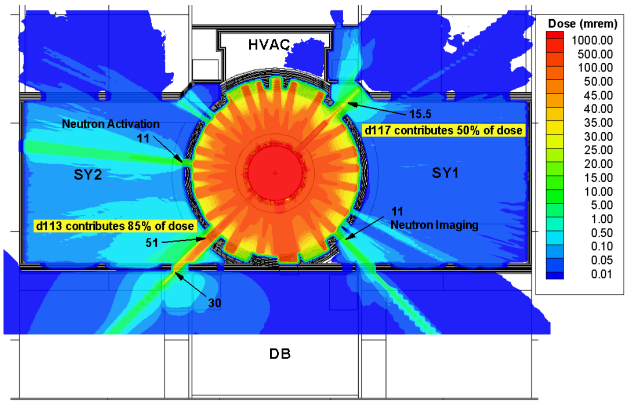

Fig. 5. Prompt dose map of the 17'-6" floor level.

Dose values inside each SY at the 29'-6" floor level are about half of what has been shown for level -3'-6". About 50% of the dose is caused by x-rays passing through the in-direct drive ports with the other half passing through the different diagnostic ports. The view port "d26" which is facing two of the TB doors is responsible for about half of the dose outside these doors. Dose values inside SY1 and SY2 at the remaining floor levels, 40'-0" and 50'-6" are somewhat similar to the dose values at the -21'-9" level. Radiation streaming through the laser beam path in TB walls at the -21'–9" and 50'–6" floor levels are small in comparison to radiation passing through the TB doors. Once again, most of the dose is caused by x-rays passing through the in-direct drive ports. In all cases, dose values inside the DB remain small.

IV.B. Petawatt Laser Interaction with Back-lighters

The second analysis is performed using the x-ray spectrum generated by the ARC quad (4 beams) shot. Prompt doses outside the TB doors in the SYs range from a fraction of mrem up to about 2.4 mrem at all floor levels except for the 17'-6" floor level. The maximum doses outside the D155 and D151 doors without the additional lead shielding are 11 and 3.4 mrem, respectively. Installing the lead doors reduces the dose at each location by about factor of seven. Notice that the Pb attenuation is about factor of seven less effective for the ARC shots due to the fact that these shots generate higher energy x-rays. Keeping the TOTIM door open results in a dose of about 14 mrem inside the DB. Closing TOTIM door results in a dose of only 0.68 µrem per shot outside the door.

In general, dose values expected during ARC shots are about a quarter of dose values shown in the dose maps generated for the 192 beams. Access control measures during ARC shots are expected to be similar to controls implemented during shots using a cluster (48 laser beams).

V. CONCLUSIONS

Detailed analysis of prompt doses generated inside the NIF facility during x-ray generating shots is completed. Conservative x-ray source terms that are based on experimentally measured values are used in the analysis. The first source assumes that 33% of the laser energy is converted into hot electrons. The second source uses a peak x-ray intensity (based on measured ambient dose) during ARC shots. Shots using up to two bundles represent a very small hazard to personnel working inside the switchyards during the shots (no personnel are allowed in the Switchyards during shots utilizing more than two bundles). In the case of ARC shots, dose values outside the Target Bay are similar to dose values generated during a single cluster shot. Finally, dose values in all floor levels of the Diagnostics Building as well as to co-workers and the public outside the facility shield walls are very small (<0.05 mrem for 192 beam shot).

ACKNOWLEDGMENTS

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