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Abstract — During peak operation, the National Ignition Facility (NIF) will conduct as many as 600 experiments per year and attain deuterium–tritium fusion yields as high as 1200 MJ/yr. The radiation effective dose equivalent (EDE) to workers is limited to an average of 0.3 mSv/yr (30 mrem/yr) in occupied areas of the facility. Laboratory personnel located outside the facility will receive EDEs ≤ 0.5 mSv/yr (≤ 50 mrem/yr). The total annual occupational EDE for the facility will be maintained at ≤ 0.1 person–Sv/yr (≤ 10 person–rem/yr). To ensure that prompt EDEs meet these limits, three-dimensional Monte Carlo calculations have been completed.

I. INTRODUCTION

Construction of the world's most powerful laser, the National Ignition Facility (NIF), has begun at the Lawrence Livermore National Laboratory. During peak operations, the NIF will conduct as many as 600 experiments per year and attain fusion yields as high as 1200 MJ/yr to produce up to 4.3×10^{20} 14 MeV neutrons per year. To ensure the safe operation of the NIF with high neutron yields, several radiological design limits were set forth in the NIF Preliminary Safety Analysis Report (PSAR) [1] and the Programmatic Environmental Impact Statement (PEIS) [2] for Stockpile Stewardship and Management. The effective dose equivalent (EDE) within occupied areas of the facility are limited to an average of 0.3 mSv/yr (30 mrem/yr). Those outside the facility are limited to 0.5 mSv/yr (50 mrem/yr) after accounting for occupancy. The total annual occupational dose will be maintained at ≤ 0.1 person–Sv/yr (≤ 10 person–rem/yr).

To reduce exposure of personnel and the public to radiation, the NIF Target Bay and Switchyards will make use of thick concrete shields, but these shields will contain many penetrations for beamlines, utilities, and personnel access. Detailed, three-dimensional Monte Carlo modeling of the NIF geometry has been completed to ensure that the radiological design limits will be met. This modeling has considered many different design features and modifications that have been made as the Title I and Title II designs have progressed. The effects of penetration size and location as well as wall and roof thicknesses within the NIF Target Bay and Switchyards have been investigated. The effects of using an approximate model for the forty-eight beam penetrations within the target chamber have also been determined and incorporated into our analyses.

Annual prompt doses have been calculated for many different locations inside and outside the facility, and the annual dose at the nearest site boundary has been scaled from previous results. These doses all meet the radiological design limits for annual prompt doses. Of the 0.1 person–Sv/yr limit for occupational doses, only 5×10^{-3} person–Sv/yr will be due to prompt doses received by workers within the NIF.

II. COMPUTATIONAL METHODS

Three-dimensional Monte Carlo particle transport has been accomplished using the TART96 [3] transport code. TART96 along with its TARTCHEK geometry plotting code, enables accurate and timely calculation of energy-dependent neutron and γ-ray fluences at many locations of interest. A typical model contains about 1000 zones and requires the transport of 50 million particles. In all, approximately forty separate calculations were completed using nearly 2000 hours of computer time over the course of twelve months. In several cases, confirming calculations were completed with the COG [4] transport code. These calculations demonstrated excellent agreement with the TART96 results.

Once energy-dependent neutron and γ-ray fluences were obtained, they are converted into effective dose equivalents using the fluence-to-dose conversion factors recommended by the International Commission on Radiological Protection (ICRP) and approved by the American National Standards Institute (ANSI) [5]. Since doses in all occupied locations are dominated by scattered radiation, the conversion factors for isotropic geometry have been used. In general, these conversion factors tend to be 2× lower than those for anterior-

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annular rings of open space while conserving the total open solid-angle fraction. More complicated calculations, performed with COG, have shown that the annular ring model produces conservative results. For example, Fig. 2 shows the normalized fluence as a function of energy at the inlet to the HVAC ducts. The annular ring model overestimates the fluence by about an order of magnitude. Other work [8] has suggested that the annular ring model may produce results that are high by a factor of two for the Target Bay–Switchyard–Laser Bay pathway. In the interest of conservatism, results are presented without taking credit for either of these factors.

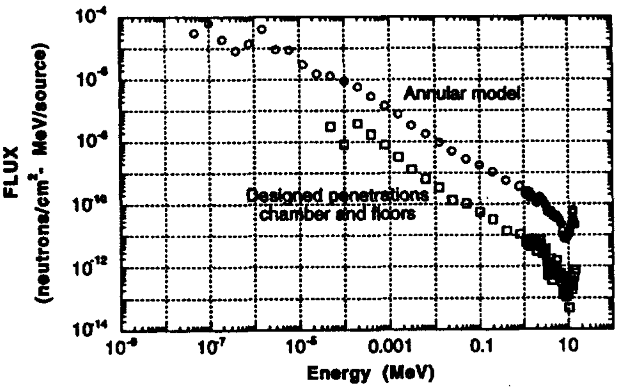

Fig. 2. A plot of the neutron spectra obtained using the annular ring and actual penetration models shows that the annular ring model produces conservative results.

Fig. 3 is a schematic of the NIF that shows the results of our analyses. Prompt doses are given for a year with 1200 MJ of fusion yield. Values in italics indicate exclusion areas. Other values have been scaled by the occupancy factors (1/3 inside and 1/16 outside). Average annual prompt EDE will be about 30 μSv/yr in the Main Control Room. The results suggest that the NIF will easily meet the radiological design limits set forth in the PSAR and PEIS.

Despite the apparent ease with which the NIF design will meet the radiological requirements for prompt EDE, a study of the uncertainties in our analyses has been completed [9]. Areas that have been investigated include the neutron source term (including the annual yield, neutron spectrum from the source, and angular distribution of emitted neutrons), the geometric approximations that have been made in modeling the facility, and the method of solution and nuclear data. Consideration has also been given to benchmarking that has been undertaken in previous studies.

The individual margins of uncertainty for each area investigated were combined to form an overall estimate of the uncertainty in our results. Our analysis indicates that the actual prompt EDE may vary by a factor of 3.5 in the nonconservative direction and by as much as a factor of twenty in the conservative direction. That is, a result that is reported as being 0.1 mSv (10 mrem) may actually be as high as 0.35 mSv (35 mrem) or as low as 5 μSv (0.5 mrem).

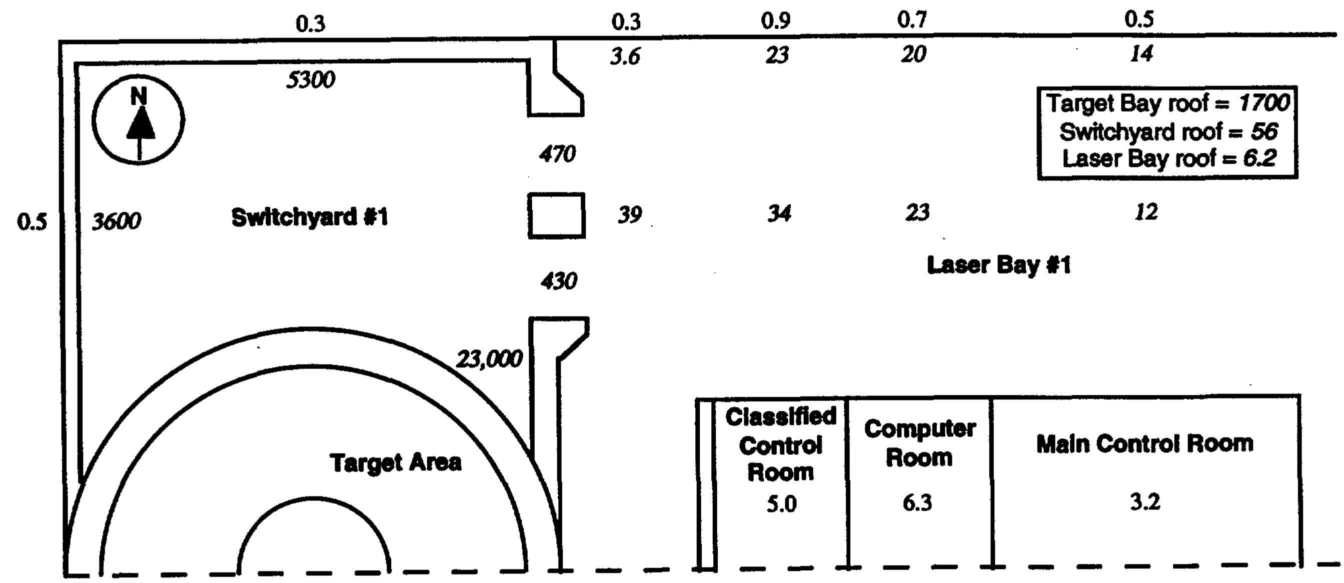

Fig. 3. Annual prompt doses (in units of 10 μSv = 1 mrem) inside and outside the NIF for a annual yield of 1200 MJ. Values in italics are for exclusion areas (will not be occupied during experiments). Other values have been corrected by occupancy factors of 1/3 in the control rooms and 1/16 outside the facility. Figure is not to scale.

posterior geometry, which have been used in previous analyses [6].

The prompt dose results also have been corrected to account for partial occupancy. For example, for occupied areas within the facility, the limiting *average* dose is 0.3 mSv/yr. Since the facility will be operated around-the-clock, the average prompt EDE to any individual worker will be only 1/3 of the total. For areas outside the facility, we have followed the National Council on Radiation Protection and Measurements (NCRP) recommendation [7] of an occupancy factor of 1/16 for "outside areas used only for pedestrians or vehicular traffic." All results are presented after these corrections have been made.

III. FACILITY DESIGN

The heart of the NIF is a laser capable of delivering 1.8 MJ of 0.35 μm laser energy to a target in a 3 ns pulse. The laser consists of 192 beams that are generated within two laser bays. Each laser bay delivers 96 beams into one of two Switchyards where the beams are redirected, via turning mirrors, towards the Target Bay. Within the Target Bay, the beams are redirected by three sets of turning mirrors, and they enter the target chamber, in groups of four, through forty-eight final optics assemblies. The entire facility will be about the size of a professional sports stadium.

The NIF Target Bay will be of cylindrical design. The inner diameter will be 30.48 m (100') with 1.83 m (6') thick concrete walls. The Target Bay height will be about 36.5 m (120'). The two roof sections will reduce skyshine doses and will have a combined thickness of roof thickness 1.37 m (4'6"). Within the Target Bay shell, six concrete floors and sets of steel gratings will support equipment and make personnel access possible.

The 10–m–diameter, 0.1–m–thick target chamber will be positioned near the center of the Target Bay. The target chamber will be covered with 0.40 m of "shotcrete" shielding. This shielding will reduce occupational exposures from the target chamber and neutron activation of outside components. Fig. 1 shows a cross-sectional view of the NIF Target Bay. In addition to the concrete structures, target chamber, and final optics assemblies, the figure shows the major diagnostics including the large Neutron Spectrometer.

Although the Target Bay will be constructed from thick concrete walls and floors, a large number of penetrations will allow neutrons and γ-rays to stream out of the Target Bay and into the Switchyards. The 192 laser beams are bundled into forty-eight penetrations — twenty-four that exit into each Switchyard. Each rectangular penetration will be roughly 1.09 × 1.17 m. To reduce the number of high-energy particles that escape into the Switchyards, the Target Bay wall has been locally thickened to a total of 3.66 m (12') around the beamports. This thickening is denoted as the addition of "collimators." Other penetrations for utilities and diagnostics have been dealt with on a case–by–case basis.

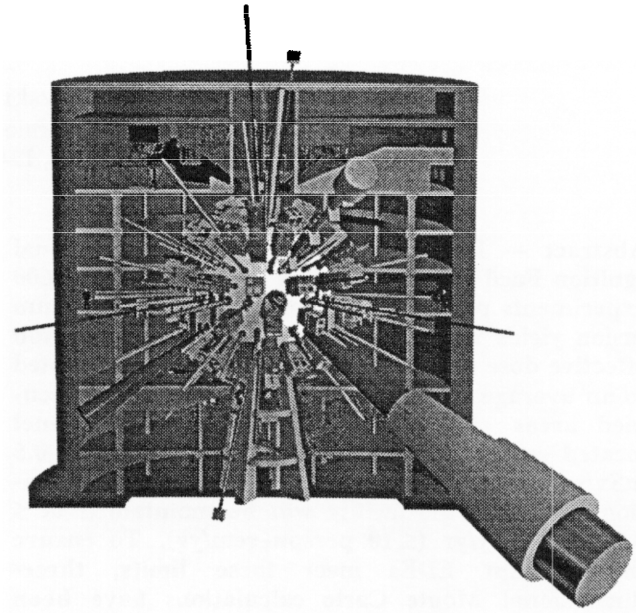

Fig. 1. A cross-sectional view of the NIF Target Bay shows the target chamber covered with forty-eight final optics assemblies and major diagnostics.

Despite the benefits of the collimators, the Switchyards still will have to provide significant shielding. The Switchyards roof thickness will be 0.46 m (1'6"), and the walls thicknesses will range from 0.84 m (2'9") to 1.14 m (3'9") in thickness. In each Switchyard, the twenty-four beam bundles will be combined into two clusters of beams. These clusters will penetrate the Switchyard walls through large (2.21 m × 9.14 m) openings. Due to radiation streaming through these large openings, prompt doses in the Laser Bays will be as high as 5 mSv/yr. Fortunately, particle fluences fall off significantly before reaching occupied areas.

Particles may also get to occupied areas by exiting the Target Bay through the heating, ventilation, and air conditioning (HVAC) ducts and penetrating through the HVAC chase and the Mechanical Equipment Room shielding walls. This pathway, however, does not result in sizable dose rates in the Main Control Room.

IV. ANALYSIS AND RESULTS

Due to the complexity of individually modeling the forty-eight target chamber beamports in their exact locations, a simplified model has been used for these calculations. Since the beamports are separated into four rings, we have combined the penetrations into four

Although the prompt EDEs, even increased by a factor of 3.5, would meet the radiological requirements, a measurement and retrofit plan has been developed [10]. Since NIF annual fusion yields will be increased gradually as the facility is brought to fully operational status, it will be possible for actual measurements to be taken. Between 2002 and 2004, measurements of the particle sprectra and flux will be made at key locations throughout the facility. While EDE cannot be measured directly, it can be calculated from these measurements. If these early measurements suggest that the prompt EDE calculations underestimated the actual doses, then simple retrofits will be made. Examples include the use of shielding blocks near shield doors or portable shield walls within the Laser Bays or Control Rooms.

V. CONCLUSIONS AND FUTURE WORK

Three-dimensional Monte Carlo prompt dose calculations have been completed for the final design of the National Ignition Facility. Prompt annual EDE has been calculated for both occupied and unoccupied areas inside and outside the facility. For areas outside the facility, an occupancy factor of 1/16 has been used. For those within the facility, corrections have been made to account for around-the-clock operations (3 shifts). During peak operation, NIF the will produce a maximum of 1200 MJ/yr of fusion yield.

Calculations have shown that annual prompt EDEs are significantly below the facility design requirements of 0.5 mSv/yr outside the facility and 0.3 mSv/yr (average) in occupied areas within the facility. Additionally, an uncertainty analysis suggests that the calculated results are more likely to be conservative than nonconservative. Nevertheless, a plan has been developed to take measurements throughout the facility and, if necessary, to make minor retrofits to the facility design in an effort to reduce prompt EDEs. We conclude that NIF operations will easily meet the design requirements set forth in the PSAR and PEIS.

As the NIF is constructed, it is likely that some design details will be modified. This will require continual updates to our models and reassessments of the prompt EDEs. New features in TART97, which allow surface cloning and simplify the rotation of surfaces and zones, will also make it possible to model the NIF in greater detail and with much more accuracy. Such models will reduce the uncertainties in our calculations.

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