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NEUTRONICS AND SHIELDING ANALYSIS OF THE NATIONAL IGNITION FACILITY

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ABSTRACT

The Department of Energy (DOE) is proposing to construct the National Ignition Facility (NIF) by the year 2001 to embark on a program to achieve ignition and modest gain in the laboratory. The NIF will use 1.8 MJ of 0.35 μm laser light, nearly a fifty-fold increase in energy over the Nova laser at Lawrence Livermore National Laboratory (LLNL). A 5-m radius spherical aluminum chamber will contain the target experiments and allow access to diagnostics for data collection. Based on a projected maximum annual yield of 385 MJ (1.4×10^{20} 14 MeV neutrons), prompt annual doses will be $< 1.2 \mu\text{Sv}$ at the nearest site boundary, $< 0.43 \text{ mSv}$ immediately outside the Target Area, and $< 30 \mu\text{Sv}$ in the warroom and control room. The target chamber material has been selected in a trade-off between its mechanical properties and its neutron activation qualities. External target chamber shielding has been selected such that the total annual occupational dose to Target Area workers will be $\leq 5 \text{ mSv}$. Finally, some Target Area systems have been redesigned based on their neutron activation and residual dose rates. The operation of the NIF will have an insignificant impact to workers and the general population.

I. INTRODUCTION

For the first time in the history of Inertial Confinement Fusion, enough D-T fusion neutrons will be produced to cause significant prompt doses and neutron activation of nearby materials. In the NIF, up to 7×10^{18} (14 MeV) neutrons may be produced in a single experiment. Radioactive decay of exposed materials, without proper shielding, could result in the need to restrict personnel access within parts of the Target Area. This paper describes the radiological analysis of the NIF target area done to ensure that the facility will be safe and environmentally benign.

Several assumptions have been made in this analysis. Annual design yield of the NIF will be 385 MJ (1.4×10^{20} 14 MeV neutrons) during the 30-year lifetime of the facility. This annual yield will be distributed as 100 experiments at 100 kJ, 35 experiments at 5 MJ, and 10

experiments at 20 MJ. The facility will conduct many more experiments, but these will have significantly less than 100 kJ D-T yield. The design goal is 1/10 of DOE occupational radiation protection standards (DOE 5480.11 and 10CFR835).^{1,2} To support post-shot Target Area activities, it is assumed that six-hour blocks of access time to the Target Area will be required between experiments.

The NIF will use materials in which neutrons produce predominantly short-lived radionuclides, and thus, have low radioactive inventories after a relatively short period of time (e.g., hours to days). Therefore, aluminum alloys rather than steels will be used whenever possible and cost-effective. Aluminum alloys produce primarily ^{27}Mg ($T_{1/2} = 9.5$ minutes) and ^{24}Na ($T_{1/2} = 15$ hours) when irradiated with high-energy neutrons. Steels lead to the production of such nuclides as ^{54}Mn and ^{59}Fe , with half-lives of 312 days and 45 days, respectively. These nuclides, while not a concern early in the lifetime of the facility, will build up to high equilibrium levels. The activity of ^{54}Mn would grow to 4800 times that produced in the first 100 kJ experiment, while the activity of ^{59}Fe would be 650 times greater. Consequently, after a few years of experiments, dose rates from activated steel components (chamber, structures, etc.) would exceed desired levels, even after long decay times.

II. COMPUTATIONAL METHOD

All calculations for this analysis have been performed using the TART³ Monte Carlo transport code. TART provides the neutron flux as a function of energy in each region of interest. Next, ORLIB⁴ is used in conjunction with the ACTL⁵ neutron cross section library to calculate one-energy-group neutron cross sections for the region. Then, FORIG⁶ is used to calculate the buildup of radioactive products within the region. Finally, the activities are used to transport decay gamma rays from each radionuclide of importance. The calculated photon distribution provides the dose rate in a desired location.

A design criterion of $\leq 5 \text{ mSv}$ (500 mrem) annual occupational dose has been chosen. This criterion is used to establish the shielding thickness, such that the average

dose rate 24 hours after a 100-kJ yield is $6.5 \mu\text{Sv/h}$ (0.65 mrem/h). For six hours residence time after 145 shots of the previously stated yields, the cumulative annual dose is $\sim 5 \text{ mSv}$. Decay of ^{24}Na , responsible for approximately 80% of the dose, is accounted for in setting this value.

III. RESULTS

The results of all radiological calculations done in support of the NIF will be discussed in five major sections: (1) prompt doses, (2) target chamber and shielding, (3) air activation, (4) optics support, and (5) entrant equipment.

A. Prompt Doses in and around the NIF

Prompt dose includes skyshine dose and direct dose (uncollided neutrons, scattered neutrons, and neutron-induced gamma rays). Skyshine dose results from the interaction of radiation with the atmosphere surrounding the facility. Scattered neutrons and gamma rays and neutron-induced gamma rays deliver a dose to personnel surrounding the facility. Figure 1 shows the maximum skyshine dose rate as a function of distance from target chamber center for a 10-cm thick target chamber, 40 cm of shielding, and the 1.2-m thick concrete ceiling (about 15% of the chamber solid angle is open for beam penetrations).⁷ The doses are considered maximum skyshine doses, because personnel within other areas of the facility will have additional shielding provided by the building structure.

Figure 1. Skyshine dose rate from operation of the NIF at 385 MJ/year.

The 1.8-m thick concrete walls reduce the annual direct dose (scaled to a 40-hour work week) just outside the Target Area to 0.40 mSv (40 mrem).⁸ An additional 60 cm of concrete reduces the annual direct dose to

$5.0 \mu\text{Sv}$ (0.5 mrem) within the warroom and control room. Calculations show that the target chamber and shielding result in an approximate factor-of-ten reduction in the direct dose. Our results are validated by Rotating Target Neutron Source (located at LLNL) measurements⁷ of prompt dose through the facility walls.

The skyshine dose reaches a peak at approximately 50 m from the chamber center. At this peak, the skyshine contribution to the annual prompt dose is approximately 0.1 mSv (10 mrem). Thus, the highest annual prompt dose outside of the Target Area (scaled to a 40-hour work week) is approximately 0.43 mSv (43 mrem). The maximum annual prompt dose within the warroom and control room is $30 \mu\text{Sv}$ (3.0 mrem). The maximum annual prompt dose at the nearest site boundary (330 m) is approximately $1.2 \mu\text{Sv}$ (0.12 mrem).

B. Target Chamber and Shielding

The NIF target chamber must be capable of achieving a moderate vacuum, must remain stable within micron tolerances, must provide support for diagnostics, external shielding, and entrant equipment, must produce a minimum amount of debris under x-ray and laser light environments, and must have an acceptable neutron activation. The target chamber will be a 5-m radius sphere with its thickness determined by mechanical properties.

Three materials have been considered for use as a target chamber. These include stainless steel #316 (SS #316), 5083 alloy of aluminum (Al-5083), and Kevlar.[®] A comparison of contact dose rates as a function of time after 10 years of operation at 385 MJ per year is given in Figure 2. These dose rates are for the outer surface of the target chamber (not through any shielding). Dose rates inside the target chamber will be 2–3 times greater. Figure 2 shows that the end-of-life exterior contact dose rate of a Al-5083 target chamber is 30 times less than that of a SS #316 target chamber. A Kevlar target chamber has a virtually undetectable dose rate after less than one day but has questionable performance in the areas of vacuum compatibility and response to x-ray and debris.

In both the Al-5083 and SS #316 target chambers, the long-term (> several days) dose rate is dominated by the decay of ^{54}Mn . Al-5083 has been chosen as the target chamber material. Its selection is a trade-off between the shortest radioactive decay time and known engineering properties. It is the best choice considering both radiological safety and ability to be engineered.¹⁰

To date, eight materials have been considered for use as external shielding of the target chamber. These materials and the factors taken into account in the choice of a shielding material are shown in Table 1. Some key factors in the choice of a shielding material include flammability, thickness, mechanical stability, shield

activation, and cost. Each factor was ranked according to its importance in the overall shielding design. Then, each material was given a score for each factor. The product of the importance and the score gives an adjusted score for each issue. The sum of the adjusted scores gives a total adjusted score for each candidate material.

Figure 2. Dose rate vs. time for Al-5083, SS #316, and Kevlar® target chambers.

Early in the shielding design process, basic shielding concepts such as borated polyethylene and water with an Al-5083 support were considered. Polyethylene is unacceptably flammable. Although scoring fairly high, water raises concerns with its required thickness (~ 1 m), mechanical stability, and possibility of corrosion. As the design progressed, several materials manufactured by Reactor Experiments, Incorporated (R/X) were considered. Of the R/X materials, Catalog No. 277, "Heat Resistant Shielding," appeared to hold the most promise for our application. Finally, per M. S. Singh's suggestion, concrete with Al-5083 rebar was considered and appears so far to be the best material. Concrete is natural, non-flammable, mechanically stable, well understood, and inexpensive. The required thickness for a concrete shield is 40 cm.

A sprayable form of concrete, called "shotcrete," will be used. Shotcrete will be sprayed onto Al-5083 rebar that has been welded to the target chamber. The overall shield composition is ninety-five weight percent concrete and five weight percent Al-5083 rebar. A shotcrete thickness of 40 cm was such that the average dose rate near the chamber is $\leq 6.5 \mu\text{Sv/h}$ (0.65 mrem/h) 24 hours after a 100 kJ yield shot.

The addition of lead (ten weight percent) to the concrete increases the shield density by nearly 40%. The resulting increase in density and average atomic number

results in improved gamma ray shielding properties. The resulting Target Area residual dose rate decreases from $6.4 \mu\text{Sv/h}$ to $4.0 \mu\text{Sv/h}$ (0.40 mrem/h). However, the addition of lead would force the shield to be classified as mixed waste upon decommissioning. A final shotcrete composition will be chosen during detailed design.

C. Target Area Air Activation

Activation of the air atmosphere within the Target Area makes a significant (20%) contribution to the site boundary dose during routine releases and following a bounding event accident.^{7,10} The maximum annual dose due to routine releases would be $0.075 \mu\text{Sv}$ (7.5 μrem).⁷ The air contribution to the bounding radionuclide release dose would be $98 \mu\text{Sv}$ (9.8 mrem).¹⁰

The desire to improve overall laser beam transport may result in the use of an argon or argon-oxygen atmosphere within the Target Area. The removal of nitrogen from the Target Area avoids high levels of Stimulated Raman Scattering. The best solution is 100% argon-filled tubes in the Target Area. For operational safety concerns, however, an argon-oxygen (80% Ar/20% O₂) atmosphere may be more desirable. The tubes could be made from high-density polyethylene with an inner surface coated with Teflon.TM

We have considered the radiological safety implications of argon-oxygen filled tubes. Our calculations show that the use of an argon-oxygen mixture in the beamtubes would actually result in a 13% reduction in the activated air contribution to both the routine and bounding accident release doses.¹¹

D. Optics Support Systems

Neutron activation is a concern for the final focus optics assemblies and final turning mirrors. Each of the 48 final optics assemblies will have an Al-5083 structure with a mass of approximately 3000 kg. In addition, each assembly will contain hardware totaling approximately 100 kg of carbon steel.

Preliminary calculations of the radioactivity of the final optics assembly have been performed. The results indicate that the contact dose rate of the Al-5083 structure in the final optics package will be approximately $4.0 \mu\text{Sv/h}$ (0.40 mrem/h) at 24 hours after a single 100-kJ yield. This dose rate is a significant fraction of the total Target Area post-shot dose rate. During the detailed design phase of the NIF, portions of the final optics assemblies may be redesigned to take advantage of the low activation characteristics of composites.

The final turning mirrors will be mounted onto Al-5083 plates that are approximately 1 m in diameter and 5-10 cm thick. The turning motors will each contain

		Borated Poly.	Water & Al Support	R/X 202 Pb-doped B-Poly.	R/X 237 Boro-Silicone	R/X 259 Poly. Cast	R/X 277 Heat Resistant.	R/X 277 & Pb	Concrete & Al Rebar
Factor	Mult.	Score	Score	Score	Score	Score	Score	Score	Score
Environmental concerns	5	4	5	3	4	5	4	2	5
Flammability	4	1	5	0	4	3	5	4	5
Thickness	3	2	1	4	2	2	2	3	1
Cost	4	3	5	2	1	3	4	3	5
Weight	3	1	2	3	2	2	2	3	5
Ease of fabrication	4	2	3	2	2	2	3	2	4
Support frame activation	2	4	4	3	3	4	3	2	4
Chamber gamma shielding	4	2	2	5	3	2	3	4	3
Mechanical stability	5	3	1	5	4	3	4	4	5
Knowledge of materials	3	3	5	1	1	1	3	2	4
Shield activation	3	4	3	4	1	5	1	1	2
Decommissioning & disposal	3	4	4	3	4	4	4	3	3
Total Adj. Score		117	143	127	116	130	142	122	171

Table 1. The choice of an effective shield material is influenced by many parameters.

approximately 1–2 kg of copper and steel. Based on our calculations, the motors and plates make a minimal contribution to the total Target Area dose rate. Although the plates are directly in the line-of-sight of 14-MeV neutrons, they are at an average of 14 m away from the chamber center and have a relatively small cumulative mass when compared with components that make large contributions to the Target Area dose rate.

E. Activation of Entrant Equipment

A series of calculations have been completed to determine the contact dose rates of several pieces of equipment that may be inserted into the target chamber during high-yield experiments. These calculations include the target positioner, the diagnostic manipulator tubes, the hohlraum, and the cryogenic support system.

Calculations predict that the tip of an Al-5083 target positioner would have contact dose rates greater than 1 mSv/h (100 mrem/h) 24 hours after a 100-kJ yield. A SS #316 target positioner would have a contact dose rate of only 50 μ Sv/h (5.0 mrem/h) after a single experiment, but the buildup of ^{54}Mn would result in dose rates that are thirty times higher than those found in the Al-5083 target positioner at the end-of-life. Therefore, the last 2.5 m of the target positioner have been redesigned to incorporate a carbon composite. The redesign brings the end-of-life dose rate down to about 0.8 μ Sv/h (0.08 mrem/h).

Similar calculations for the activation of a Twelve-Inch Manipulator (TIM) tube (if one were to be inserted into the chamber during an ignition shot) indicate that both Al-5083 and SS #316 tubes will experience significant neutron activation. These calculations show that Al-5083 or SS#316 TIM tubes should not be allowed to enter the target chamber during high-yield experiments. If necessary, the TIM tubes may also be redesigned.

Although not a part of the baseline NIF design, a calculation of the activation of the cryosystem has been completed. In calculating the radiological effects of activated and vaporized cryosystem and target materials, a few key assumptions have been made. It is assumed that the hohlraum, liner, and copper heat transfer ring are completely vaporized. A portion of the stainless steel cryotubes are also vaporized by neutrons in high-yield experiments: the first 1 cm, 2 cm, and 3 cm of each tube for 100 kJ, 5 MJ, and 20 MJ yield shots, respectively. Finally, it is assumed that the vaporized material plates out evenly over the entire inner surface of the target chamber, resulting in a thin spherical shell that is a source of decay gamma ray radiation.

Calculations indicate that this shell of target and cryosystem materials will give a significant dose early in the lifetime of the facility. The interior dose rate due to the target chamber itself is 0.33 mSv/h (33 mrem/h) at 24 hours after a 100-kJ yield. The interior dose rate due to

the target and cryosystem materials reaches 0.21 mSv/h (21 mrem/h) after one year of operation and dominates the target chamber interior dose rate at approximately 0.43 mSv/h (43 mrem/h) after 5 years of operation. The radionuclides responsible have much longer half-lives than ^{24}Na , which dominates the target chamber residual dose rate, and therefore present concerns similar to those for a steel target chamber. Therefore, periodic decontamination of the interior of the target chamber is required to keep the buildup of radioactivity to acceptable levels. The activated hohlraum material contributes only a small amount to the total target and cryosystem material dose rate ($< 2\%$ for lead and 6% for gold).

IV. SUMMARY

The NIF will utilize a 5-m radius, 10-cm-thick Al-5083 spherical target chamber. Outside the target chamber there will be a 40-cm-thick "shotcrete" shield that will reduce the residual dose rates in the vicinity of the target chamber to $\leq 6.5 \mu\text{Sv/h}$ (0.65 mrem/h).

Prompt radiation will present no significant impact to personnel or the public. The annual prompt dose (scaled to a 40 hour work week) will be $\leq 0.43 \text{ mSv}$ (43 mrem) immediately outside of the Target Area and $\leq 30 \mu\text{Sv}$ (3.0 mrem) in the warroom and control room. The annual prompt dose at the nearest site boundary will be $\leq 1.2 \mu\text{Sv}$ (0.12 mrem), which is insignificant in relation to the current radiation protection standards for the public.

The use of beamtubes for beam transport within the Target Area somewhat reduces site boundary doses for both routine and accident releases of activated air. The final turning mirror mounting plates and motors make a minimal contribution to the Target Area residual dose rate, however, the contribution from the final optics assemblies is significant. Portions of the final optics assembly will be redesigned during the detail design. The target positioner has already been redesigned, and the TIM tubes may also be redesigned.

Periodic decontamination of the interior of the target chamber will prevent the unacceptable build up of radioactivity due to the deposition of vaporized target and cryosystem materials.

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