Neutron Activation of NIF Final Optics Assemblies

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Abstract. Analyses were performed to characterize the radiation field in the vicinity of the Final Optics Assemblies (FOAs) at the National Ignition Facility (NIF) due to neutron activation following Deuterium-Deuterium (DD), Tritium-Hydrogen-Deuterium (THD), and Deuterium-Tritium (DT) shots associated with different phases of the NIF operations. The activation of the structural components of the FOAs produces one of the larger sources of gamma radiation and is a key factor in determining the stay out time between shots to ensure worker protection. This study provides estimates of effective dose rates in the vicinity of a single FOA and concludes that the DD and THD targets produce acceptable dose rates within 10 minutes following a shot while about 6-days of stay out time is suggested following DT shots. Studies are ongoing to determine the combined effects of multiple FOAs and other components present in the Target Bay on stay-out time and worker dose.

1. Introduction
Construction of the National Ignition Facility (NIF) has been completed and early phase experiments leading to eventual controlled self-sustaining nuclear fusion energy gain have commenced at the facility. The neutrons generated by these experiments activate various components and structures present in the facility. A good understanding of the level of residual radiation present at various locations in the facility is important in determining the stay out time between shots to ensure worker protection.

Final Optics Assemblies (FOAs) provide beam conditioning, frequency conversion, focusing, and debris protection in a compact module. There are four optics modules per FOA with forty eight FOAs attached to the target chamber wall. They focus the 192 laser beams to the target chamber center. Since they are in direct line of sight of the target, the FOAs experience some of the highest neutron fluences outside the target chamber. This study will focus on the activation of the large structural components in the FOA and estimate the effective dose rates in the vicinity of a single FOA. An earlier study [1] was performed with a simpler model of the FOA. While, a more recent study [2] used the same detailed computational model described here to examine the contact dose rates associated with optical elements in the FOA, this study focuses on dose contributions of the massive structural components of the FOA.

2. Computational Model
The radiation transport code, MCNP [3], was used to obtain the neutron flux spectra in various structural components of the FOA. These fluxes were then used to activate these components using the activation code, ALARA [4]. The gamma sources from ALARA for the various structural components of the FOA were then used in a second MCNP calculation to obtain effective contact and 1-ft dose...
rates from each of the FOA components. ICRP-74 [5] flux-to-dose rate conversion factors were used to obtain the dose rate estimates.

Targets representing different phases of NIF operation were used in the models. For the Deuterium-Deuterium (DD) shots, a yield of $1 \times 10^{13}$ neutrons/shot was used with a shot schedule of 4 shots per day for 50 days. The DD source spectrum used for the neutron calculations was 99% 2.45 MeV and 1% 14.1 MeV. The Tritium-Hydrogen-Deuterium (THD) shot was assumed to yield $2 \times 10^{14}$ neutrons/shot with a shot schedule of 2 shots per day for 50 days. A full THD neutron source spectrum based on 2% deuterium content was used for the calculations. The Deuterium-Tritium (DT) shot was assumed to yield $7.45 \times 10^{18}$ neutrons per shot with a shot schedule of 60 shots per year with a six day interval between shots. A full DT source spectrum with a 14.1 MeV peak was used in the calculations.

A detailed model of the FOA (Figure 1) was used in the MCNP neutron flux spectrum calculations. All 48 FOAs were included in this model as well as details of the target chamber walls, the floors and structural columns inside the Target Bay (TB) (Figure 2). The MCNP gamma calculation used a simplified model of the FOA that was voided out and divided into eight axial regions each with its own gamma source. Thus, having no self shielding, this model yielded conservative estimates of the dose rates.

**Figure 1.** Final Optics Assembly: MCNP model (left), CAD model (right)

**Figure 2.** MCNP model of the Target Bay (FOAs shown in blue)
3. Effective Dose Rates from an FOA
This section contains a summary of the calculated dose rates for the three target types at various decay times following the last shot in each shot sequence. This will allow for the accounting of isotopes that may accumulate or decay over the time span of the shot schedule. The tables presented for each target type contain both the contact dose rate and the dose rate at 1-ft from the region of the FOA that produced the highest value. It must be noted that in the cases of the THD and DT shots, different regions of the FOA were bounding at contact and 1-ft away.

3.1. Dose Rates following DD Shots
The main contribution to the dose rate in the short term comes from $^{28}$Al with the longer term contribution from $^{56}$Mn and $^{24}$Na. The contribution to the dose by $^{24}$Na is not very significant at earlier decay times since the predominant DD neutron energy is well below the threshold of the production cross section of the isotope via an (n, $\alpha$) reaction in $^{27}$Al. These dose rates are negligible at 10 minutes after the last shot. The limiting dose rate in the case of the DD shot was from the part of the FOA containing the disposable debris shield. Table 1 presents the results from DD shots.

| Time after last shot (minutes) | Contact Dose Rate (mrem/h) | 1-ft Dose Rate (mrem/h) |
|-------------------------------|----------------------------|--------------------------|
| 10                            | 2.39e-2                    | 1.95e-2                  |
| 30                            | 2.06e-3                    | 1.77e-3                  |
| 60                            | 1.52e-3                    | 1.23e-3                  |
| 360                           | 6.24e-4                    | 6.03e-4                  |

3.2. Dose Rates following THD Shots
The main contribution to the dose rate in the short term comes from $^{28}$Al, $^{24}$Na, and $^{27}$Mg. The longer term contributions come mainly from $^{24}$Na and $^{56}$Mn. The THD neutron spectrum has a low energy tail that promotes the production of both $^{56}$Mn and $^{27}$Mg via (n, $\gamma$) reactions in $^{55}$Mn and $^{26}$Mg, respectively. In addition, the high energy portion of the THD neutron spectrum produces $^{24}$Na from $^{27}$Al. Effective dose rates at 10 minutes after the last shot are at acceptable levels of approximately 1 mrem/h. In the case of the THD shot, the limiting component of the FOA was the vacuum/valve assembly that is in contact with the target chamber. Table 2 presents the results from the THD shots.

| Time after last shot (minutes) | Contact Dose Rate (mrem/h) | 1-ft Dose Rate (mrem/h) |
|-------------------------------|----------------------------|--------------------------|
| 10                            | 1.38                       | 6.21e-1                  |
| 30                            | 3.43e-1                    | 1.31e-1                  |
| 60                            | 1.74e-1                    | 6.64e-2                  |
| 720                           | 8.56e-2                    | 3.03e-2                  |

3.3. Dose Rates following DT Shots
The DT yield shots correspond to 20 MJ of energy and produce the highest amount of activation. The dose rate at 6 days after the last shot on contact with the FOA is approximately 6 mrem/h and over 2 mrem/h at a distance of 1-ft. Thus a minimum 6-day stay-out time is recommended for these shots. This is consistent with the cooling time required for handling individual optics components [2]. In the case of the optical components, the highest dose rates were also caused by activation of the aluminium
frames. The limiting component in the case of the DT shot was the vacuum/valve assembly that is in contact with the target chamber, which is predominantly made of aluminium but also has stainless steel components. The main contributions to the dose rates come from $^{24}$Na, $^{54}$Mn, and $^{58}$Co. The DT neutron spectrum with a large component of high energy neutrons lends itself to the production of both $^{54}$Mn (via (n,p) reaction in $^{54}$Fe) and $^{58}$Co (via (n,2n) reaction in $^{59}$Co) which contribute to the dose rate at the long decay time of approximately 6 days. Table 3 presents the results at decay times following the last of the 60 shots.

| Time after last shot | Contact Dose Rate (mrem/h) | 1-ft Dose Rate (mrem/h) |
|----------------------|-----------------------------|-------------------------|
| 1 hour               | 4.96e3                      | 1.99e3                  |
| 12 hour              | 2.19e3                      | 8.03e2                  |
| 1 day                | 1.23e3                      | 4.51e2                  |
| 6 day                | 5.82                        | 2.35                    |
| 10 day               | 1.1                         | 6.02e-1                 |

4. Conclusions
Structural components of the FOAs produce dose rates that are low enough to allow entry into the TB at 10 minutes after DD and THD shots. However, more realistic entry times (for other reasons) will be closer to an hour after the shots making the radiation levels even lower. For the full yield DT shots, a stay-out time of days will allow radiation levels to reach acceptable values that will minimize radiation exposure to maintenance personnel. This study evaluated the radiation field in the vicinity of a single FOA after shots with different targets. In reality, the radiation levels in the TB will be the cumulative value from multiple FOAs and other structures present at the same floor level. Studies are being conducted to estimate these cumulative radiation levels at various locations within the TB while taking into account the reduction of dose rates associated with most maintenance tasks which take place at larger distances from highly activated components. Preliminary results indicate that for the most part the FOAs would contribute the largest fraction to the dose rate on the floors where they are present.

Acknowledgement
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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