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Abstract. Nuclear reaction measurements are performed at the National Ignition Facility in a high energy density plasma environment by adding target materials to the outside of the hohlraum thermo-mechanical package on an indirect-drive exploding pusher shot. Materials are activated with 14.1-MeV neutrons and the post-shot debris is collected via the Solid Radiochemistry diagnostic, which consists of metal discs fielded 50 cm from target chamber center. The discs are removed post-shot and analyzed via radiation counting and mass spectrometry. Results from a shot using Nd and Tm foils as targets are presented, which indicate enhanced collection of the debris in the line of sight of a given collector. The capsule performance was not diminished due to the extra material. This provides a platform for future measurements of nuclear reaction data through the use of experimental packages mounted external to the hohlraum.

1. Introduction

The National Ignition Facility (NIF) is an Inertial Confinement Fusion (ICF) research facility located at Lawrence Livermore National Laboratory (LLNL). During a typical ICF shot, a plastic capsule filled with an equimolar mixture of deuterium and tritium (DT) is compressed to high densities and temperatures by high energy lasers [1,2,3]. The resulting fusion between the two hydrogen isotopes produces alpha particles and a significant yield of neutrons with a narrow energy distribution centered around 14.1 MeV. For a given implosion, increased capsule compression results in a higher fuel areal density (ρr), which produces an increased number of neutrons that have scattered off residual DT fuel to lower energies before escaping the capsule. Both the 14.1 MeV and lower-energy scattered neutrons interact with materials in proximity to the capsule, resulting in nuclear activation reactions and induced radioactivity [4]. By placing specific materials in and surrounding the capsule assembly, nuclear reaction rates can be determined by collecting the resulting debris and measuring the amount of reaction product produced. Through the use of the suite of nuclear diagnostics at NIF [4-12], the corresponding neutron spectrum is determined, resulting in the evaluation of nuclear activation cross sections. This method has applications in investigating nuclear reactions in the high energy density

plasmas produced during ICF shots, where plasma screening may affect neutron- and charged-particle reaction rates compared to equivalent accelerator-based measurements [13].

Based on early results measuring gold isotope ratios produced via neutron interactions with the gold hohlraum [4], adding materials to the outside of the thermo-mechanical package (TMP) that surrounds the target and hohlraum assembly should provide enough target atoms for measuring cross sections from neutron activation reactions. We will discuss the first experiment designed to evaluate how addition of materials to the TMP affects capsule performance and the distribution of solid debris resulting from the interaction of the lasers with the capsule assembly. If a significant quantity of reaction products can be retrieved from the NIF chamber, this platform could be used on subsequent DT shots for measuring nuclear reaction cross sections in support of national security missions or fundamental nuclear science.

2. Experimental configuration

2.1. Shot implementation

NIF shot N141130-001 was an indirect-drive exploding pusher (IDEP) [14] capsule. A 1075-μm outer radius CH plastic capsule with a wall thickness of 120 μm was filled with a 50:50 mix of DT gas at a nominal density of 7.5 mg/cc. The capsule was mounted in a 5.75-mm diameter gold hohlraum filled with He at 16 torr. The laser delivered 910 kJ of 351-nm light in a 4.5-ns pulse with a peak power of 330 TW. Neutron yield was 5.8×10^{14} at a measured ion temperature of 5.1 keV.

2.2. Modified thermo-mechanical package

The NIF hohlraum was surrounded by an aluminum (Al) TMP, was used to hold the assembly in place in the target chamber. The TMP features a diagnostic band around the center that has windows for x-ray diagnostics. A standard TMP was used with the addition of 0.5-mm thick foils of thulium (Tm) and neodymium (Nd) metals (>99% pure) fixed to the outside around the circumference above and below the diagnostic band (Figure 1). The rare earth foils were coated with several nm of Al to prevent oxidation and flaking of the material during handling. The foils were configured such that the Nd foils were facing the Diagnostic Instrument Manipulator (DIM) located on the equator of the NIF target chamber at coordinates (90,78), and the Tm was facing the DIM at (90,315). The total mass of added material was 70.8 mg of Nd and 98.8 mg of Tm.

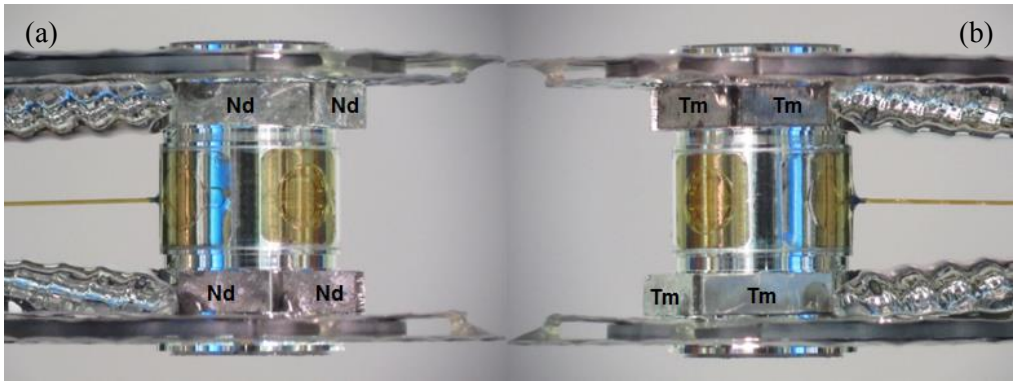

Figure 1. Modified TMP for shot N141130-001 with (a) 0.5-mm Nd foils (70.8 mg total) facing the DIM at (90,78) and (b) 0.5-mm Tm foils (98.8 mg total) facing the DIM at (90,315).

2.3. Solid radiochemistry diagnostics

Post-shot capsule debris is collected using the Solid Radiochemistry (SRC) diagnostic [4], which consists of 5-cm diameter, 1-mm thick metal discs that are housed in a cap attached to the snout of a

DIM via a quick-release bracket. Up to four SRC collectors can be fielded on each of the three DIM locations, two above the snout and two below, at a distance of 50 cm from target chamber center (TCC). This gives three individual lines of sight for the collectors at coordinates (90,78) and (90,315) (collectors facing the target assembly) and at (0,0) (collectors facing the north laser entrance hole on the top of the hohlraum). After a shot, the DIMs are retracted from the NIF chamber and the quick-release brackets are removed. The SRC collectors are then disassembled from the housing and delivered to the LLNL Nuclear Counting Facility (NCF) for gamma radiation counting. For this shot, all 12 of the SRC collectors were vanadium (V) foils.

After radiation counting, the collectors were treated with 9M HCl / conc. HNO_3 acid mixture to remove the resulting debris along with the first ~10 μm (~78 mg) of the surface of the V collectors. In addition, unused collectors and collectors previously exposed to the inside of the NIF chamber were processed as blanks. The lanthanides of interest (Nd and Tm) were separated from the excess V through cation-exchange chromatography and recovered in 1% high-purity HCl. These samples were then analyzed via ICP-MS to determine the absolute amounts of Nd and Tm collected. The (n,2n) activation products from the collected debris (^{147}Nd and ^{168}Tm) were used as internal tracers for determining the radiochemical yields from leaching, separation and recovery. The uncertainties in the reported collection yields include counting statistics from gamma spectroscopy (1σ), a 2% absolute efficiency of the HPGe detectors, the standard deviation of five individual measurements from mass spectrometry (2σ) and reported uncertainties in nuclear data.

3. Results

The active collection surface of any given SRC collector (12.566 cm^2) corresponds to 0.04% of the total 4π solid angle. Each of the individual 12 collectors was processed as a separate sample in order to determine the distribution of debris in the chamber. Table 1 gives the amounts of materials recovered for Nd and Tm in terms of the fraction of the total ingoing mass that was collected. The DIM samples from (0,0) collected almost none of the TMP materials and it appears that under these experimental conditions the polar positioner had no sensitivity to collection of the target assembly.

Table 1. Percent of the initial Nd and Tm mass collected on the SRC collectors as a function of DIM position.

TMP material	DIM (0,0)	DIM (90,78)	DIM (90,315)
Nd	$(3.04\pm0.51)\times10^{-5}$ %	0.692±0.066 %	$(1.31\pm0.17)\times10^{-4}$ %
Tm	$(1.22\pm0.39)\times10^{-5}$ %	$(3.17\pm0.75)\times10^{-5}$ %	0.471±0.011 %

Results from the equatorial DIMs suggest that the SRC collectors are most efficient at collecting material in their direct line of sight. The Nd foils were placed on the side of the TMP facing DIM (90,78), where the bulk of the Nd was observed. Likewise, Tm was measured only on the collectors on DIM (90,315), which were facing the Tm foils. In addition, the fraction of material collected on each of the equatorial lines of sight was typically greater than the geometric 0.04% solid-angle collection area. Therefore, the debris collection was enhanced in the equatorial direction over what has been observed in shots that did not include extra mass on the TMP.

The nuclear reaction products identified in the gamma spectra of the debris collectors included ^{169}Tm(n,2n)^{168}Tm ($t_{1/2}$=93.1±0.2 d), ^{142}Nd(n,2n)^{141}Nd ($t_{1/2}$=2.49±0.03 h), ^{148}Nd(n,2n)^{147}Nd ($t_{1/2}$=10.98±0.01 d) and ^{150}Nd(n,2n)^{149}Nd ($t_{1/2}$=1.728±0.001 h) [15]. The production cross sections for these reactions are 1.5-2 b [16]. The IDEP platform has very little capsule compression (downscattered ratio (DSR) < 0.2%), so the majority of the neutrons interacting with the rare-earth foils were 14.1 MeV, with very few lower energy neutrons present in the neutron spectrum.

4. Discussion and future work

Based on these results, it was concluded that material was collected from the TMP with efficiency greater than what was expected from solid angle alone (0.04%) for collectors in the same line of sight as the material on the outside of the TMP. In addition, NIF shot performance was unaffected by the additional mass. These results suggest that target materials can be added to the TMP to perform nuclear data measurements in "ride-along" fashion. As long as the DT yield of the capsule is high enough to produce sufficient reaction products for collection and analysis ($\geq 10^6$), a wide variety of materials could be used to field nuclear data measurements on any DT shot.

The IDEP platform offers an advantage in that all of the neutrons can be considered to have an energy of 14.1 MeV. Fielding similar experiments on a high-compression capsule will result in neutrons with a mixture of energies, 14.1 MeV as well as lower energy neutrons from down-scatter off unreacted DT fuel, other fusion reactions (i.e., DD and TT) and breakup reactions. Reaction products will therefore be produced both by activation at 14 MeV and via moderated neutron capture, which is most sensitive to lower energy neutrons, but does have a non-negligible cross section at 14 MeV as well. Selecting materials that are monoisotopic, or where the (n,2n) production rates are well known, will distinguish between products produced from a mixture of high and low neutron energies. Ultimately, this technique will be used for measuring unknown nuclear reaction data through the use of external target materials added to the hohlraum.

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