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S. Brereton, F. Papp, E. Packard, C. Mac Kenzie, R. Thacker, P. Datte, M. Eckart, M. Jackson, H. Khater, S. Manuel, M. Newton, R. Reed, J. C. Bell, V. Draggoo, T. R. Kohut, R. L. Beale, J. T. Dillon, S. Reyes, M. Dunne, K. Kramer, T. Anklam, M. Havstad, A. L. Mazuecos, R. Miles, J. Martinez-Frias, B. Deri, L. Dauffy, J. Hall, L. Hansen, S. Kim, B. Pohl, S. Sitaraman, J. Verbeke, M. Young

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Disclaimer

Overview of the National Ignition Facility[1]

Sandra Brereton

L-454, Lawrence Livermore National Laboratory

PO Box 808

Livermore CA, 94551-9900

Fax: 924-42x-xxxx

Telephone: 925-422-4671

e-mail: brereton1@llnl.gov

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is the world's largest and most energetic laser system for inertial confinement fusion (ICF) and experiments studying high energy density (HED) science. The NIF is a 192- beam, Nd-glass laser facility that is capable of producing 1.8 MJ, 500 TW of ultraviolet light, over fifty times more energetic than other existing ICF facilities. The NIF construction began in 1997 and the facility, which was completed in 2009, is now fully operational. The facility is capable of firing up to 192 laser beams onto a target placed at the center of a 10 m-diameter spherical target chamber.

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Experiments involving the use of tritium have been underway for some time. These experiments present radiological issues: prompt neutron/gamma radiation, neutron activation, fission product generation, and decay radiation. This paper provides an introduction to the NIF facility and its operation, describes plans for the experimental program, and discusses radiological issues associated with the NIF's operations.

Key words: National Ignition Facility, NIF, neutrons, fusion, lasers, tritium

INTRODUCTION

The National Ignition Facility (NIF) is a laser-driven inertial confinement fusion experimental facility recently completed at the Lawrence Livermore National Laboratory (LLNL). LLNL is located in Livermore, 45 miles east of San Francisco. LLNL is a federally-funded national laboratory operated for the National Nuclear Security Administration (NNSA) by the contractor Lawrence Livermore National Security (LLNS).

The NIF is a 192-beam Nd-glass laser facility capable of producing 1.8 MJ and 500 TW of ultraviolet light for use in Inertial Confinement Fusion (ICF) and High Energy Density (HED) experiments. The facility is poised to produce fusion ignition in the laboratory for the first time (Ref. 1, 2, 3). The NIF is the world's preeminent facility for performing ICF and HED science experiments, being over fifty times more energetic than previous lasers such as Nova and Omega.

The NIF was conceived in the early 1990s, with design well underway by the mid-1990s. Construction started in mid-1997, was completed in March of 2009. Since then, the facility has become fully operational, executing hundreds of shots per year.

One of the major goals of the NIF experiments is to achieve fusion ignition. Fusion is the process whereby nuclei of low atomic number elements are combined, with the release of energy. Fusion is difficult to achieve because of the repulsive force between nuclei. In order to achieve the temperature and pressure conditions necessary for fusion to occur, an input of energy is required. In the case of the NIF, that energy comes from the laser. The NIF, now the most energetic laser facility in the world, is capable of firing ~2 MJ of ultraviolet laser energy (0.35 μm) on target, within a few nanoseconds, corresponding to ~500 TW of power.

The least difficult or highest cross section fusion reaction is that between deuterium (D) and tritium (T), two isotopes of hydrogen. Upon fusing, an alpha particle and a neutron are released (see Figure 1). A total of 17.6 MeV (2.8×10^{-12} J) of energy is released per reaction, with 80% of the energy (14.1 MeV) being carried off by the neutron, and 20% (3.5 MeV) of the energy remaining with the alpha particle. Success is most often expressed in terms of the total number of neutrons released, or the total fusion energy (carried by the neutrons plus alphas) released. For example a shot releasing 1×10^{16} neutrons can be described in terms of the total fusion energy produced, about 30 kJ, while a shot releasing 7×10^{18} neutrons produces about 20 MJ of fusion energy. In achieving ignition, a self-propagating burn would occur in the capsule. Ultimately, the goal is to achieve energy gain – where more energy is created from fusion than put in to the target to achieve the conditions for the fusion reactions to occur.

The NIF became an operational facility in mid-2009. Initially, operations involved non-hazardous targets, for example gold foils. Very interesting science can be obtained using such materials at the high pressures and temperatures that the NIF can achieve. The NIF's first neutrons were produced in September 2009, from a deuterium containing target. DD fusion produces a 2.45 MeV neutron from one of the reaction branches:

$$^{2}_{1}D + ^{2}_{1}D \rightarrow ^{3}_{2}He + ^{1}_{0}n \text{ (2.45 MeV)}$$

$$^{2}_{1}D + ^{2}_{1}D \rightarrow ^{3}_{1}T + ^{1}_{1}p$$

In mid-2010, the first tritium targets were used on the NIF, producing the NIF's first DT neutrons. To date, the tritium throughput has been about 2000 Ci. The highest yield achieved has been about 8×10^{14} neutrons and a cumulative yield of 1×10^{16} neutrons has been exceeded.

The NIF is comprised of two Laser Bays, four Capacitor Bays, two Switchyards, and a Target Bay. The NIF laser beams are based on flashlamp-pumped 1.05-μm Nd-doped glass architecture that has been used in ICF laser facilities at LLNL for over 40 years. An initial seed pulse is generated in the Master Oscillator Room (MOR). This represents about one nJ of 1053 nm light (in the infrared). This pulse is split and sent to each of the laser bays. Here the light undergoes a pre-amplification stage, where the beam energy is increased by nine orders of magnitude. The beams are then injected into the main laser system. The main laser works by flashing bright white light onto the Nd-doped laser glass. The energy for the flashlamps comes from the Power Conditioning System in the Capacitor Bays. Once they flash and excite the laser glass, the energy is extracted by the seed pulse as it passes through the amplifiers. After being fully amplified, the beams have increased their energy by another six orders of magnitude. The beams are transported through two switchyards where they encounter a series of mirrors that reflect them towards the Target Bay (TB). Inside the TB is the Target Chamber (TC), a 10 m diameter aluminum alloy spherical shell within which targets are placed. In the TB, after reflecting off additional mirrors, the beams are frequency converted to the ultraviolet (351 nm), and focused onto a target at the center of the TC. A schematic of a beam line of the laser system is shown in Figure 2.

A facility layout overlaid with a model of the beam transport system is shown in Figure 3. The NIF building is approximately 70,000 m^2 in size. Each beam has a clear aperture of about 40 $\times$ 40 cm and the facility contains about 8,000 large optics. The NIF is by far the largest and most complex optical system ever built.

The NIF optics and electronics are installed as Line Replaceable Units (LRUs). Optical elements are placed into frames, each assembly being called an LRU. They have been designed for ease of maintenance and replacement. A sampling of the optical LRUs used in the NIF is shown in Figure 4. To install the LRUs into the laser system, robotically controlled transporters are used (see Figure 5). Each of the LRUs must be kept very clean, and the transporter functions as a portable clean room. For an LRU transaction, the transporter mates to the laser beampath, opens the cover, and either installs or removes the LRU.

Figure 6 is a view of one of the laser bays in the facility. There are 96 individual laser beams in each laser bay, grouped in two clusters, each cluster comprising 6 bundles of 8 beams. Figure 7 is a view of the Target Bay, which extends over seven stories. The photo in Figure 7 has two of the floors removed so that the expanse of the space can be seen. Visible in this figure is the Target Chamber (TC). The TC wall is 10 cm thick, with many penetrations for beams and diagnostics. The blue borated concrete shield, 40 cm thick, is also visible on the chamber. Each of the beam tubes contains four individual beams, known as a quad.

The NIF can use many different types of targets. A few examples are shown in Figure 8. The target in the bottom left of the figure is the ignition target. This target is fueled with DT, and cooled down as low as ~ 18K to form a hydrogen ice layer. When a shot occurs, extreme conditions are created:

- Matter temperatures > 10^8 K
- Densities > 10^3 g/cm^3

- Pressures > 10^{11} atm

These conditions allow the exploration of the science of high energy density physics, astrophysics, fusion energy, and materials science.

For the set of experiments focusing on fusion ignition, tritium is used as a fusion fuel in the capsule; typically around 10 Ci (1 mg) of tritium per target. This is comparable to the amount of tritium in a commercially available tritium powered exit sign (~ 20 Ci). The Cryogenic TARget POSitioner (CryoTARPOS) provides the cryogenic cooling systems necessary to complete the formation of the ignition target's fuel ice layer, and it also provides the positioning system that transports and holds the target at the center of the NIF chamber during a shot (see Figure 9). To form DT ice layers of sufficient uniformity, the target must control temperature symmetrically to within +/- 0.5 mK. (Ref.4). Many hours before an ignition shot, the target assembly, containing the fuel reservoir and capsule, is mounted to the cryogenic cooling system within the CryoTARPOS. Just prior to layering, the DT fuel is transferred, using temperature differentials, from the fuel reservoir into the capsule through a fine 10-m-diameter fill tube. The cooling system ultimately cools the target to 18 - 19 K. The DT will freeze and form a thick ice layer on the interior surface of the capsule. Beta particles from tritium decay facilitate the formation of a uniform ice layer by causing more localized heating and sublimation of fuel in thicker regions, which then re-condenses on cooler surfaces elsewhere. This "beta-layering" process creates the smooth, uniform ice layer required for ignition.

Capsules fielded for an ignition experiment require a 75-µm thick DT ice fuel layer (Ref. 4). The CryoTARPOS provides a target characterization tool that is used to provide feedback during the ice layer formation process. The Layering & Characterization Station is mounted to the forward portion of the CryoTARPOS as shown in Figure 9. This system ultimately determines when the ice has met the thickness and roughness specifications. The characterization system is based on phase contrast x-ray imaging and provides three orthogonal views of the target. This technique results in good contrast at the edges of even extremely low absorbing materials like hydrogen ice (Refs. 5 and 6). At the conclusion of a successful fuel ice layer formation process, the imaging system is stowed, and the target is transported on the boom to target chamber center. The CryoTARPOS positions the capsule and holds it steady to within a few microns at the chamber center, while maintaining the temperature within mK to preserve the carefully formed ice layer.

The NIF has a variety of diagnostics to examine what the target during the shot. There are over 50 target diagnostics currently installed. A few examples are shown in Figure 10. These diagnostics examine x-ray emissions, gamma emissions, track shock velocities, and detect neutrons. All of these diagnostics gather data for obtaining a better understanding of what occurs during these experiments.

On the NIF, after each shot, the old stalk is removed and a new target is installed. Each shot is followed by extensive analysis before the next one occurs. Shots occur as frequently as twice a day or as infrequently as once per week, depending upon the nature of the shot, the characteristics of the target and its impact on the facility. The laser pulse is very short, around 20 ns. If the facility executes as many has 500 shots in a year, the laser would be on for less than 10 μs.

The NIF project completed construction in 2009. Recently, additional support systems have been deployed leading to a more capable user facility. A key focus in recent years has been achieving ignition through the National Ignition Campaign. These types of experiments create a set of radiological conditions that need to be managed. These conditions are summarized in the next section.

RADIOLOGICAL HAZARDS IN THE NIF

Ignition experiments have been underway at the NIF since the fall of 2010. The goal is to achieve a self-propagating fusion burn in an ignition target. A graphic of an ignition target is shown in Figure 11. The target is comprised of a hohlraum, a small metal cylinder with laser entrance holes on the ends, containing a fuel capsule. The hohlraum is made of gold, sometimes lined with a thin layer of depleted uranium (DU), and measures about one cm long. The capsule within may be made of plastic or beryllium, a few mm in diameter. The capsule may be doped with a small amount of other materials, such as Si or Ge and inside is the DT fuel, which is cooled to extremely low temperatures to form a solid fuel layer on the interior of the capsule.

On a shot, the laser beams enter the hohlraum through laser entrance holes above and below, and shine onto the interior surface of the can. This configuration is known as indirect drive. The laser energy is absorbed and re-emitted as x-rays, which impinge upon the surface of the capsule. The x-rays heat the surface of the capsule, creating an outward thrust of material as it vaporizes. The resultant inward reactive force compresses and heats the fuel to the conditions required for fusion. This happens within a few billionths of a second. Figure 12 illustrates the indirect drive process.

Shots on the NIF may generate prompt radiation. This can range from x-rays only, if the lasers impinge onto a metal target, to a burst of prompt neutrons and gamma rays for deuterium or tritium fueled capsules. For the highest yield shots, about 7.1×10^{18} neutrons will be produced, corresponding to 20 MJ of total fusion energy. This energy is released over a few ns, so the power level is extremely high. For the highest yield shots, an energy gain of about 10 is expected –20 MJ of energy out, for 2 MJ of laser energy input.

Anticipated radiation levels in and around the facility have been studied in detail. Figure 13 presents a prompt dose map of the radiation levels (neutron and gamma) within the NIF for a 20 MJ shot. This is a plan view of the facility, with the Target Bay (TB), Switchyards (SY), and Laser Bays (LB) identified. This dose map illustrates the estimated values at ground level of the facility. Doses in the SYs are significantly less than in the TB due to the mitigating effect of the shield walls and doors. There are some localized areas of higher dose due in the SYs due to radiation streaming through penetrations. There is also streaming from the SYs into the LBs due to beam tube penetrations from the SYs to LBs. The TB, SYs and LBs are exclusion areas during these types of shots. There is significant shielding around the facility that mitigates the dose in occupied spaces both inside and outside the facility to less than 50 μSv.

Material in the target bay is subject to neutron activation, and there will be a decay radiation field that persists for some time, depending on the shot yield. Many components within the facility contain aluminum or aluminum alloy, so the radiation field decays at a rate generally determined by Na-24, one of the dominant radionuclides produced in aluminum.

Several days after a 20 MJ shot, the dose rate in most spaces within the TB is expected to fall below 50 μSv h^{-1}, the level of a Radiation Area. However, there will be some localized hot spots. Figure 14 is an example of a decay radiation dose map. A few localized hot spots are evident. These are tips of entrant devices that were inside the TC at the time of the shot, shown pulled back into their vessel as would be the case after a shot. The hot spot could be the remnants of the target that will need to be changed out, or the snout of a diagnostic that will need to be removed. Figure 15 shows how the dose rate decays as a function of time in a location near a debris shield, which is in the area where the beamtubes mate with the target chamber. About five days after a 20 MJ shot, the dose rate has fallen below 50 μSv h^{-1}. The goal for worker doses is to maintain them As Low As Reasonably Achievable (ALARA). This is accomplished by mandating a stayout time after shots, tightly controlling access to the TB, planning work in the TB to be efficient so that task durations are minimized, and carefully monitoring the doses of those who have entered the TB.

Another radiological issue to manage is the dispersion of radioactive material within the target chamber and associated systems. This contamination derives from unburned tritium, as well as activated material from the target, or ablated activated material from the chamber or devices entrant in the chamber. Also expected are some fission products from the DU (~ 40 mg) in the hohlraum. A schematic of the NIF confinement envelope and contamination control systems, which work to confine the contamination created in the NIF shots, is shown in Figure 16. The confinement envelope consists of components belonging to numerous subsystems within the facility that combine to provide the first line of protection against the uncontrolled release of these contaminants into the occupied areas of the NIF. It is not a single stand-alone system, but consists of the vacuum or pressure boundary of components in a large number of subsystems (e.g., Final Optics Assemblies (FOAs), diagnostics and positioners (e.g., CryoTARPOS), vacuum systems) that are connected to the target chamber and have the potential to receive contaminants directly from the target chamber. These components, by virtue of their boundary function, act to “confine” hazardous and radioactive contaminants and prevent release to the adjacent occupied spaces of the NIF. The contamination control systems receive contaminated gas streams and equipment from the confinement envelope and confines and processes the contaminants. This includes vacuum pump exhaust piping that is routed to the Tritium Processing System (TPS), or to the stack. Other elements of the contamination control system (not shown in Figure 16) include enclosures: room-within-a-room enclosures that provide additional confinement of contamination, fume hoods for handling and storing contaminated material, and a number of specialized containers, including cabinets for purging optics of residual tritium, transport carts for moving diagnostics from the target chamber to refurbishment areas in the diagnostic building, and containers for transporting tritium gas and tritium-containing targets to and within the NIF. One of the challenges for the NIF is that regular access to these contaminated volumes is needed to perform routine operational activities, such as target change outs, diagnostic change outs, and other maintenance activities. These operations have been successfully completed by application of standard contamination control practices, using ventilation, PPE, draping, defining contamination areas, and monitoring.

PROGESS TOWARDS IGNITION AND BEYOND

The first cryo-layered target experiment was fielded on the NIF on September 29, 2010. The target used is shown in Figure 17. The gold-colored arms are the clamshell, which closes over the target to protect it from the buildup of condensate while deployed in the TC. Although the TC is at high vacuum, about 10^{-8} Pa, there is still a small amount of residual water vapor, enough that if it were to freeze onto the windows of the target, would present a problem for the transmission of light into the hohlraum. Inside the target is the capsule, containing the DT fuel, that has been cooled to about 18 – 19 K. For this target, the fuel was a mixture of all three hydrogen isotopes (hydrogen, deuterium and tritium). This effectively dudded the fuel to ensure that the yield was low for this first attempt.

The ignition campaign has focused on measuring and optimizing four key capsule performance parameters: drive symmetry during the foot and the peak of the laser drive, shock timing, implosion velocity, and hydrodynamic mix (Ref. 1, 2). It is desirable for the x-ray radiation field generated from the laser interaction with the hohlraum to compress the capsule symmetrically to a sphere with a central hot-spot diameter of approximately 80 μm. Control of the implosion shape has been achieved by directing the beams at various angles or cones within the hohlraum, balancing the power of the beams, and tuning the wavelengths to achieve symmetry (Ref. 1, 2, 3) .

During the shot, a carefully timed series of shocks is sent through the frozen DT fuel. If the shocks are too closely spaced, they coalesce within the DT ice; if too widely spaced, the DT ice decompresses between shocks. Shock timing experiments are design to test the effects of timing and rise of the laser pulses and set the shock speed and timing in the fuel (Ref. 2). This will optimize the pressure on the fuel during the implosion. The impact of various ablator (capsule shell) thicknesses has also been explored.

High fuel velocities are required to compress and heat the center of the fuel capsule (forming a "hot spot") faster than the energy is dissipated via mass transport and radiation. Achieving high fuel velocity involves a balance between two competing requirements: blowing off most of the ablator mass to maximize the fuel kinetic energy, and preserving sufficient ablator mass to keep both instabilities at the ablator-fuel interface and fuel preheat effects low. Experiments have focused on achieving this optimum (Ref. 2).

Controlling the amount of ablator material that mixes with the hydrogen fuel during implosions is key to successful fusion ignition experiments (Ref. 1, 7.) The mixing of ablator material into the fuel dilutes the fuel and reduces its compressibility. If the mix penetrates into the hot spot, the central gas region of the imploded target, cooling and a subsequent reduction of yield occur. Experiments have focused on increasing the understanding of how mix varies as a function of laser parameters, ablator thickness, capsule imperfections, ablator dopants, and other laser plasma interactions.

Figure 18 shows progress in terms of one of the key parameters of interest, pressure. This plot shows the increase in pressure as the experimental campaign has progressed. Pressures have increased by more than a factor of 10; pressures in excess of 10 PPa[2] (100 Gbar) have been

[2] Peta (P) = 10^{15}

achieved. A factor less than ten is all that remains for the NIF to enter the regime where ignition is possible.

Figure 19 presents another way of viewing the progress towards a burning plasma (Ref. 2). The vertical axis is a product of fuel pressure (P) and the burn confinement time (τ). The data points on the plot are the result of measurements of stagnation pressure and ion temperature during DT implosions. Considerable progress has been made in increasing temperature and pressure, moving closer to the space where a burning plasma can exist.

Achieving ignition will take us down the pathway towards fusion as a viable energy source. Concepts are under developments that take advantage of the NIF technologies and what has been learned from these experiments. One such concept is Laser Inertial Fusion Energy, LIFE. LIFE adapts technologies from the NIF, and the increased understanding of the science of achieving fusion, to create a fusion power plant design. LIFE is a laser driven system that will use NIF-like ignition targets.   These targets will be fed at high frequency into the chamber, producing GWs of electric power. A summary of the concept is provided in Figure 20. More details on the LIFE concept are provided elsewhere in this issue.

SUMMARY

The NIF is a fully operational laser fusion experimental facility, currently focused on achieving ignition. The experimental program is well underway, exploring the key elements of the implosion and how to improve it: shape, implosion dynamics, mix and alpha heating. As a consequence of the experiments, there are a number of radiological issues that have been briefly described in this paper. The technologies developed for the NIF will allow direct progression to a fusion power plant. Further details in these areas will be provided throughout the body of this journal issue.

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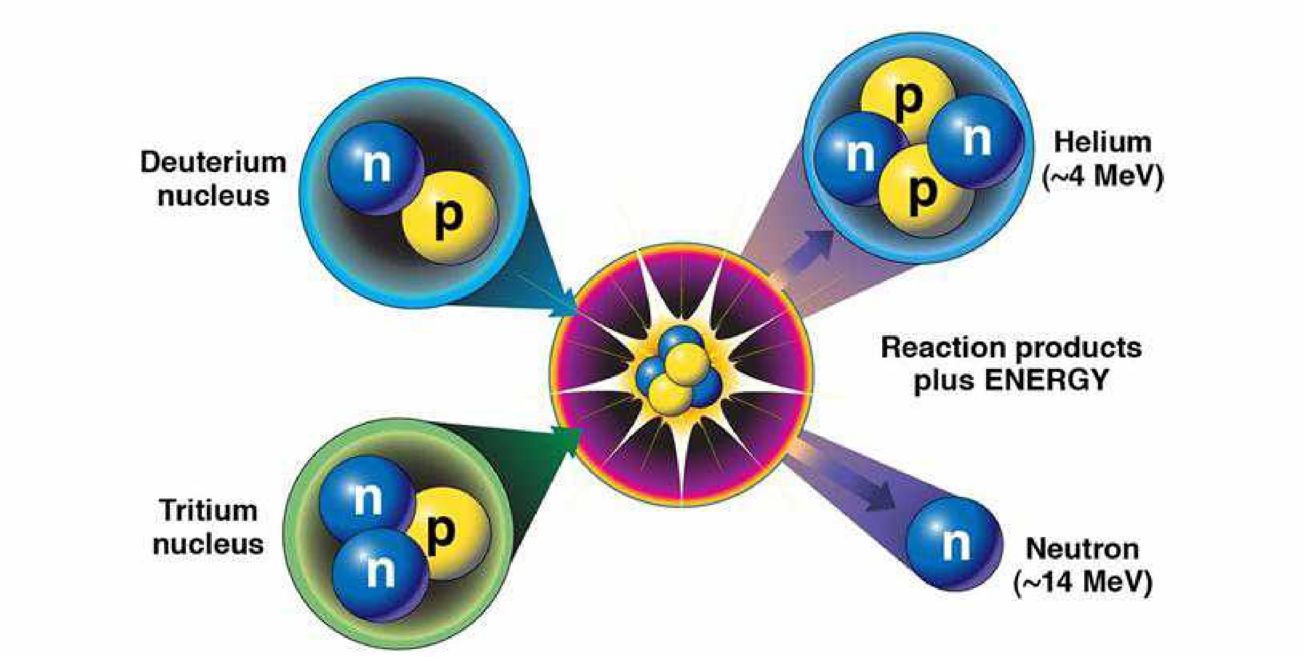


Figure 1. The nuclear fusion reaction between deuterium and tritium releases a total of 17.6

MeV per reaction. The bulk of the energy is carried off by the neutron (14.1 MeV), with the balance (3.5 MeV) remaining with the alpha particle.

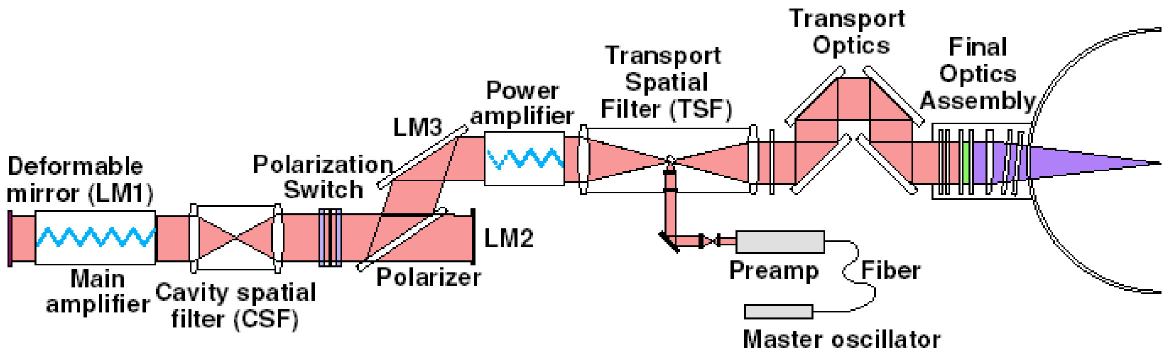


Figure 2. Schematic of one beam line of the NIF laser system. The seed pulse is generated by the master oscillator and sent into the pre-amplification system. After increasing the energy by nine orders of magnitude, the beams are injected into the main laser system. In this figure, the beams travel to the left through the Power Amplifier. After reflecting off a mirror (LM3) and polarizer, the beams are trapped for four passes in the Main Amplifier. With each pass, the beams also travel through a spatial filter, which focuses the beams through a pinhole, thereby smoothing

the rough edges of the beam. After four passes, the beams are switched out by the polarization switch, and pass once more through the Power Amplifier and the Transport Spatial Filter. At this point, the total energy of all beams has increased by 15 orders of magnitude. The beams are then transported through the Switchyard beampath and reflect off a series of mirrors arriving at the Final Optics Assembly on the Target Chamber. Here, the beams are frequency converted from 1053 nm (IR) to 351 nm (UV), and focused to Target Chamber Center.

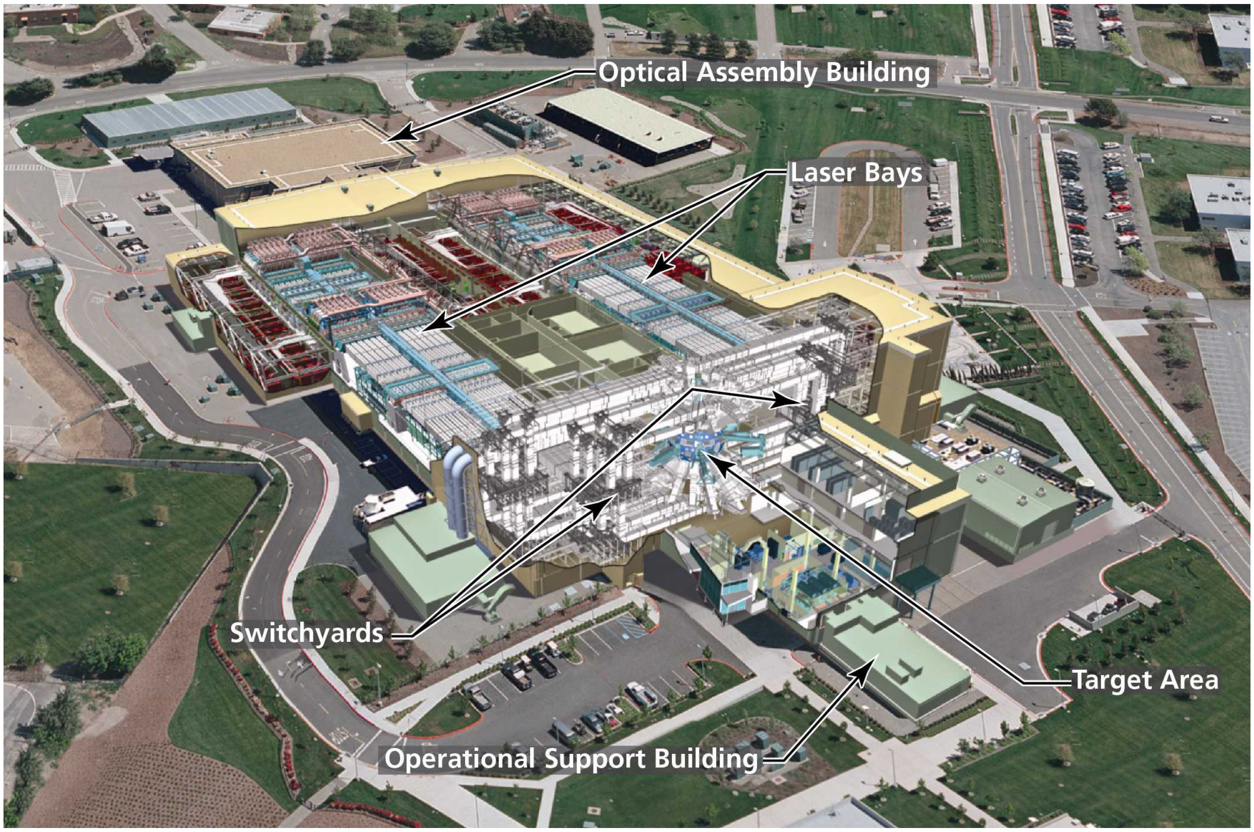

Optical Assembly Building
Laser Bays
Switchyards
Target Area
Operational Support Building

Figure 3. Layout of the NIF facility with an overlay of the laser beampath. Shown are the two Laser Bays, the two Switchyards, and the Target Bay, along with the Optical Assembly Building and Operational Support Building.

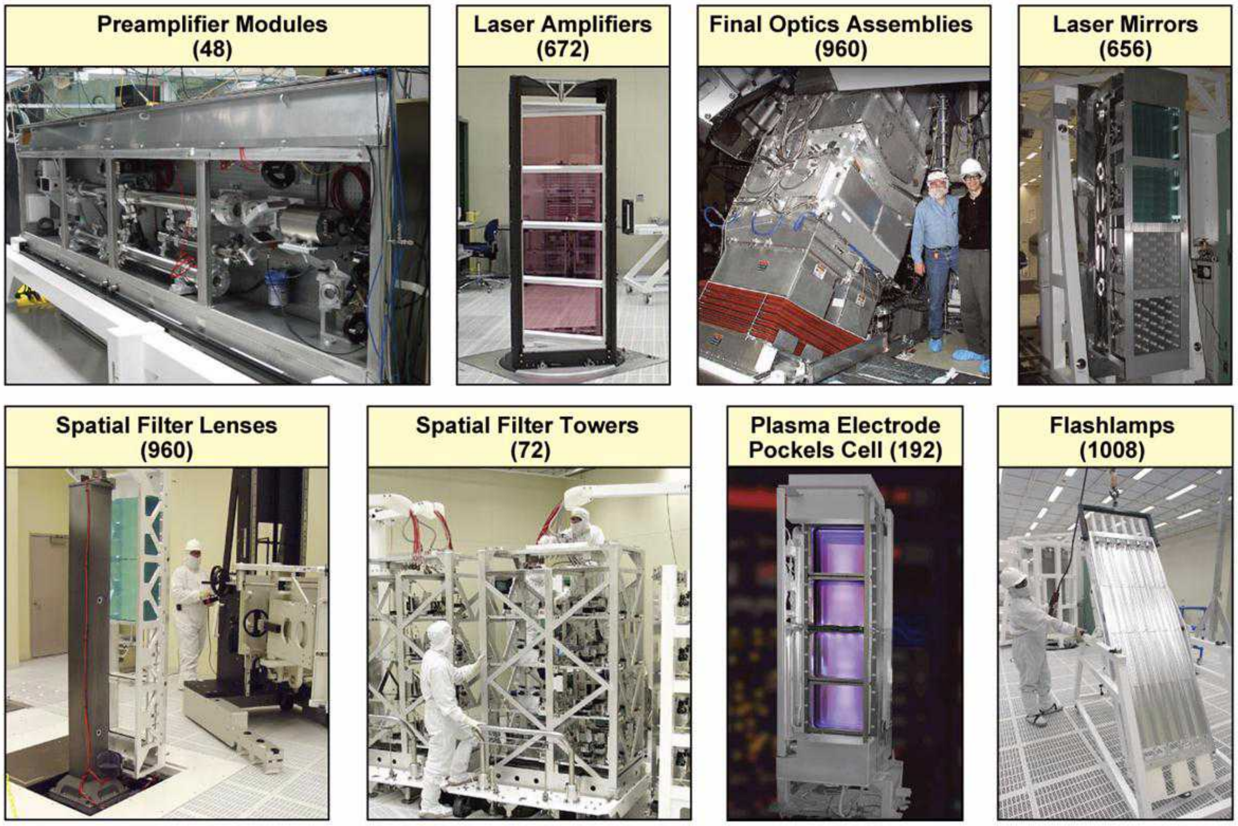

Preamplifier Modules (48)
Laser Amplifiers (672)
Final Optics Assemblies (960)
Laser Mirrors (656)
Spatial Filter Lenses (960)
Spatial Filter Towers (72)
Plasma Electrode Pockels Cell (192)
Flashlamps (1008)

Figure 4. Optical elements within their frames are known as Line Replaceable Units (LRUs). A sampling of LRUs used in the NIF is shown above. The numbers in parentheses indicate the number of this type of LRU within the entire NIF beampath.

Figure 5. LRUs are installed into the NIF using a robotic transporter that acts as a portable clean room. In this photo, the transporter has mated the canister to the beampath, allowing the LRU to be installed or removed while maintaining the clean environment.

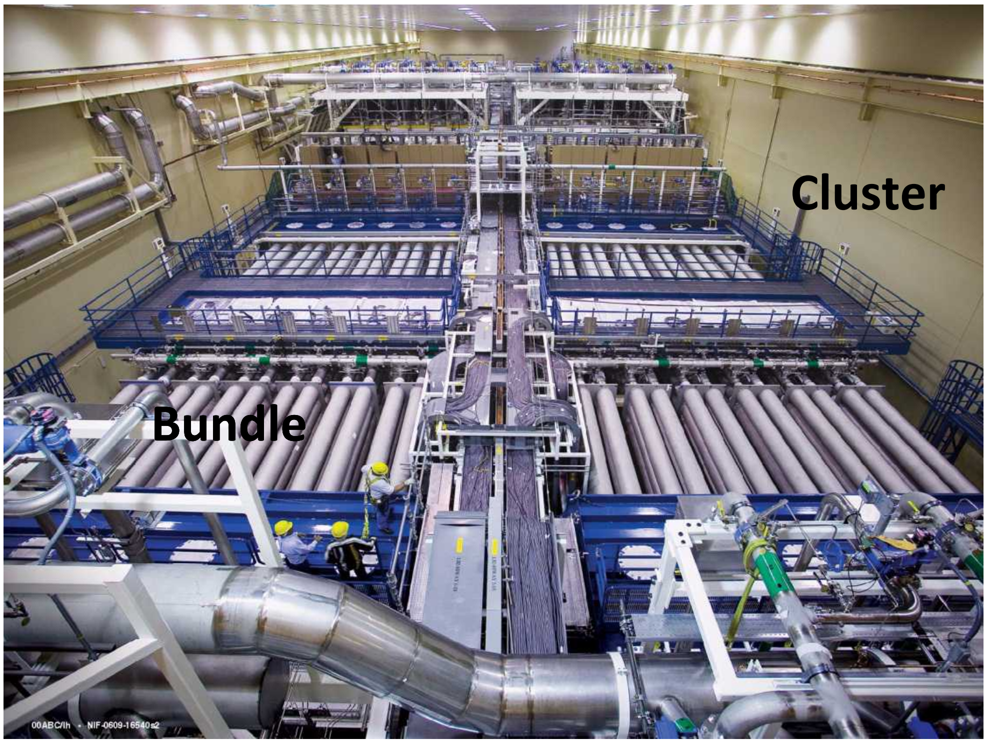
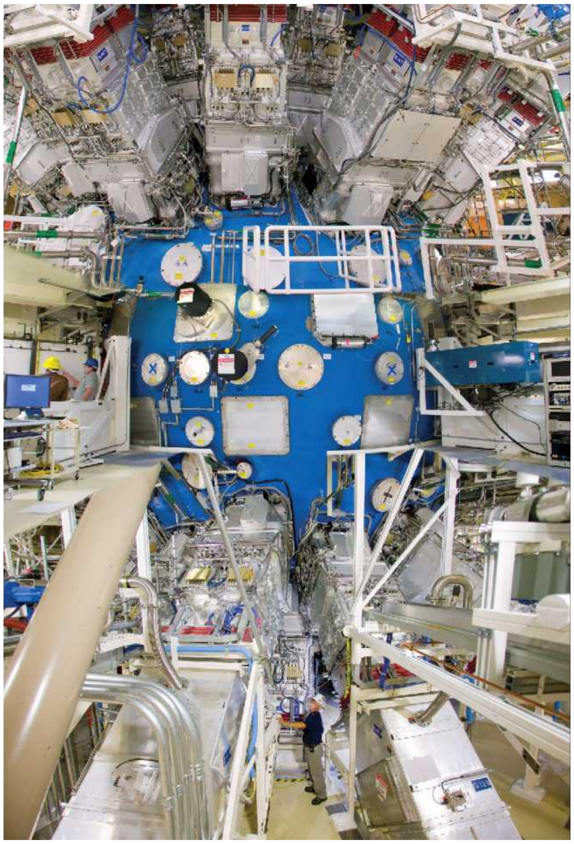

Cluster
Bundle
00ABC/lh • NIF-0609-16540s2

Figure 6. View of one of the NIF laser bays. Each cluster is comprised of six bundles of eight beams. The bundles shown here are two beams wide (visible) by four beams deep.



Diagnostic port

floor

Quad of (4) beams

Figure 7. View of the NIF Target Bay, with two floors removed. Evident are the quads of beams mating to the TC from above and below, and the many diagnostic ports.

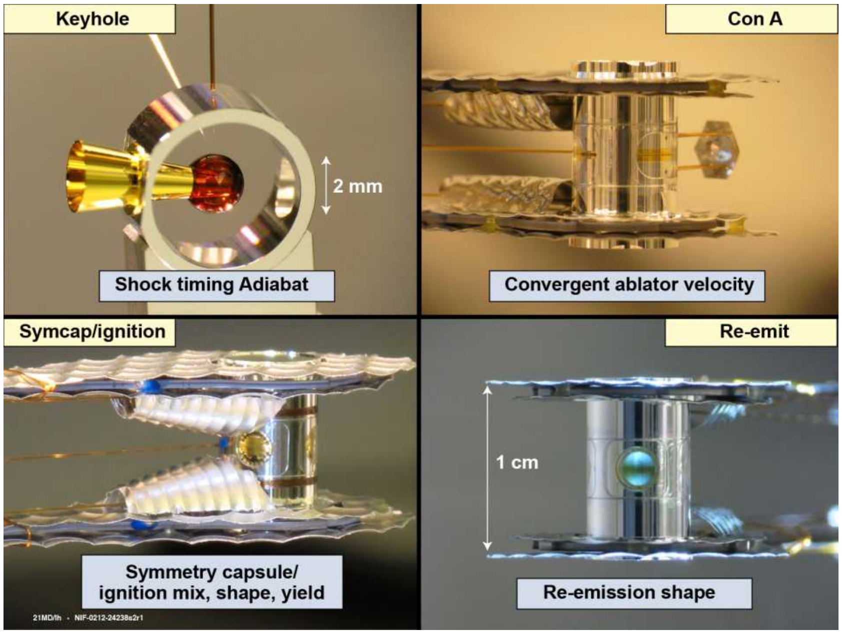


Figure 8. Examples of the wide range of targets and platforms used to study ICF physics on the NIF. The ignition target is shown in the bottom left.

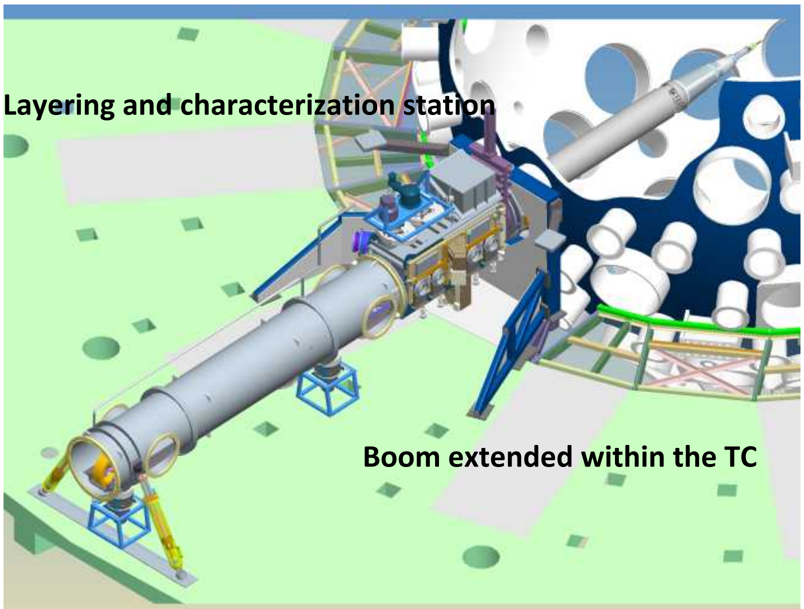


Figure 9. The CryoTARPOS provides the capability to cool the fusion fuel and to characterize it (Layering and characterization station), as well as the capability to transport it and hold it stably

at the center of the target chamber. In this graphic, the target assembly is mounted to the end of the boom, shown extended into the target chamber.

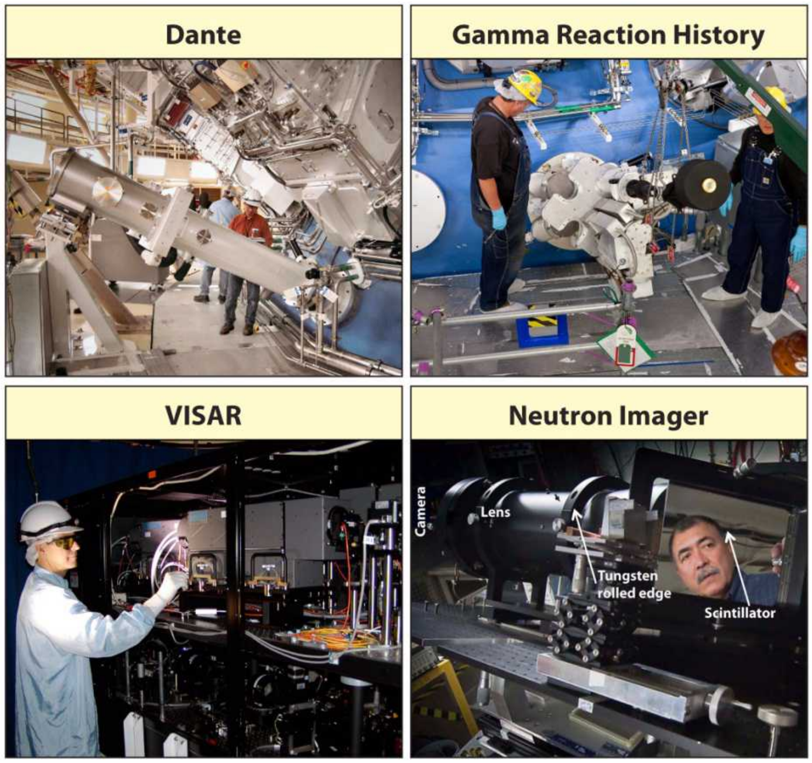


Figure 10. Examples of the wide range of diagnostics used on the NIF experiments, measuring x-ray emissions (Dante), gamma emissions (Gamma Reaction History), velocities of shock waves

(VISAR), and neutrons (Neutron Imager).

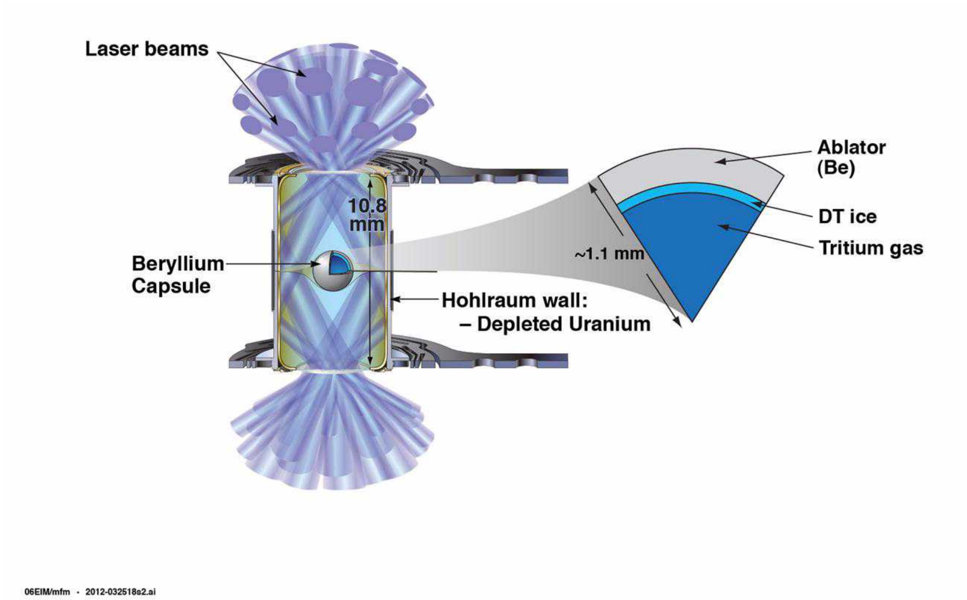
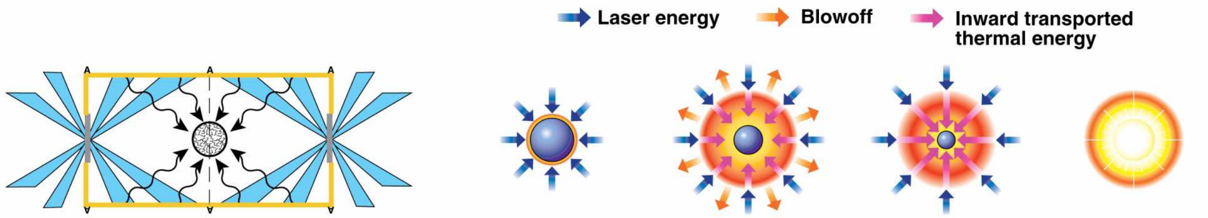


Figure 11. Schematic of the cryogenic ignition target showing the 48 “quads” of laser beams entering the hohlraum from above and below. There are four laser beams to each quad.



X-ray generation

Laser beams rapidly heat the inside surface of the hohlraum surrounding the capsule with a uniform field of x rays

Atmosphere formation

X rays rapidly heat the surface of the fusion capsule forming a surrounding plasma envelope

Compression

Fuel is compressed by the rocket-like blowoff of the hot surface material

Ignition

During the final part of the laser pulse, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 K

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy

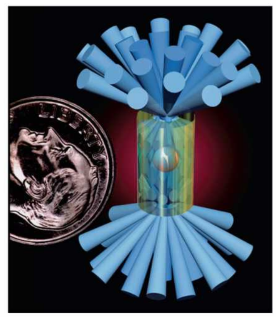
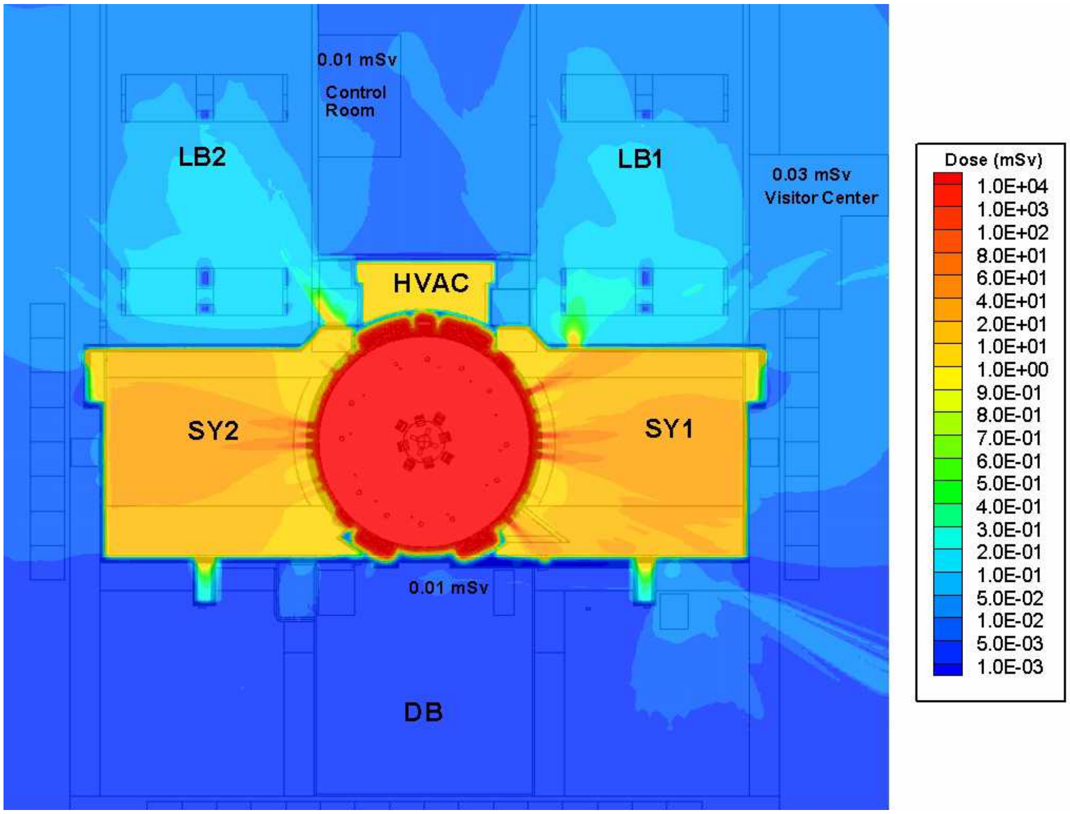
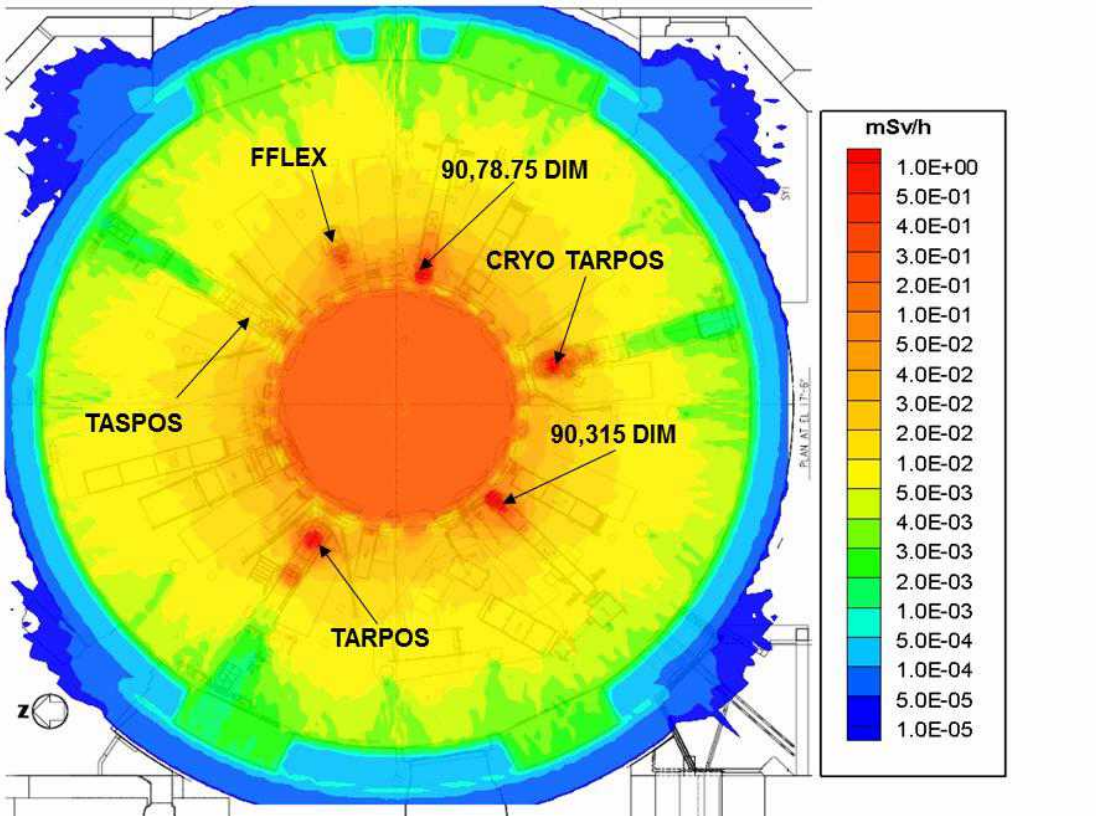


Figure 12. Schematic illustrating the indirect drive process.



0.01 mSv
Control Room
LB2
LB1
0.03 mSv
Visitor Center
HVAC
SY2
SY1
0.01 mSv
DB
Dose (mSv)
1.0E+04
1.0E+03
1.0E+02
8.0E+01
6.0E+01
4.0E+01
2.0E+01
1.0E+01
1.0E+00
9.0E-01
8.0E-01
7.0E-01
6.0E-01
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
5.0E-02
1.0E-02
5.0E-03
1.0E-03

Figure 13. Prompt radiation dose map showing estimated radiation levels within the facility at ground level during a 20 MJ shot. The shielding around the facility mitigates the dose in occupied spaces both inside and outside the facility to levels < 50 μSv.



FFLEX
90,78.75 DIM
CRYO TARPOS
TASPOS
90,315 DIM
TARPOS
Z
mSv/h
1.0E+00
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
5.0E-04
1.0E-04
5.0E-05
1.0E-05

Figure 14. Decay radiation dose map showing estimated radiation levels within the Target Bay (TB, at the mid-plane) five days after a 20 MJ shot. By this time, the dose rate in most spaces within the TB has fallen below 50 μSv h^{-1}.

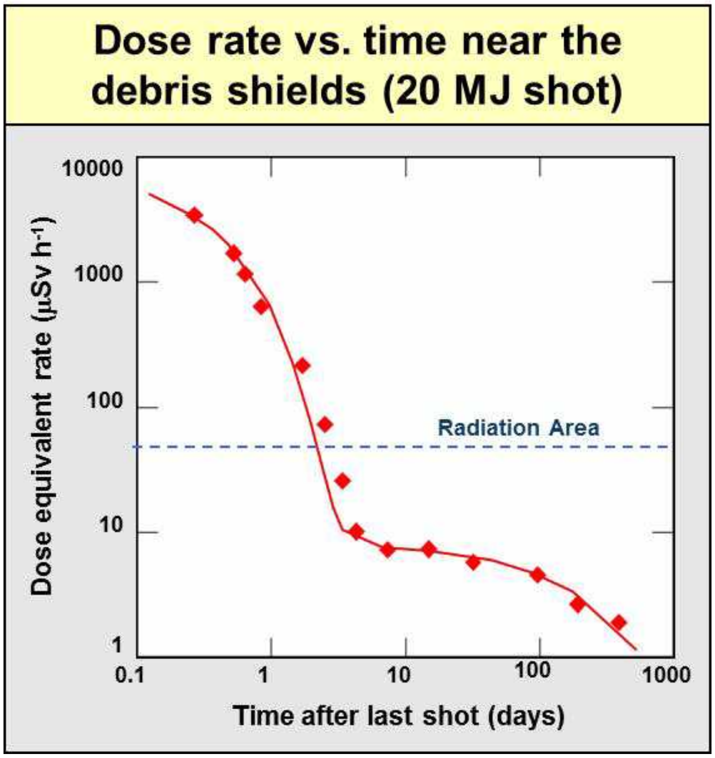


Figure 15. Decay radiation dose rate as a function of time at a location where a quad of beams mates with the Target Chamber (location of the debris shield, one of the optical

components). After ~ five days, the dose rate has fallen below 50 $\mu Sv\ h^{-1}$.

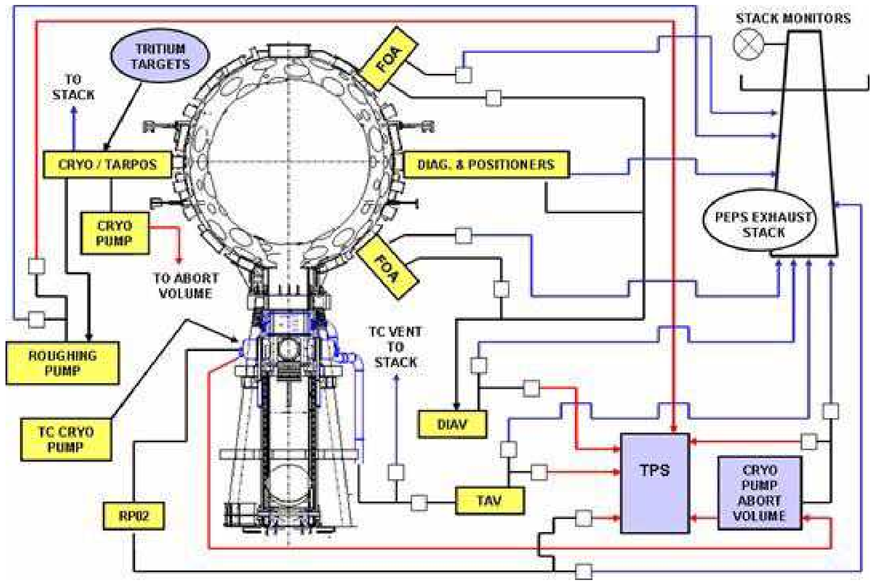


Figure 16. A confinement envelope has been defined; this is essentially the vacuum envelope including the TC, attached devices and associated vacuum systems. These interface downstream with additional systems at ambient pressure that work to confine the contamination. This includes interconnecting piping and pumps, and the Tritium Processing System (TPS), which oxidizes and captures any unburned tritium in exhaust streams.

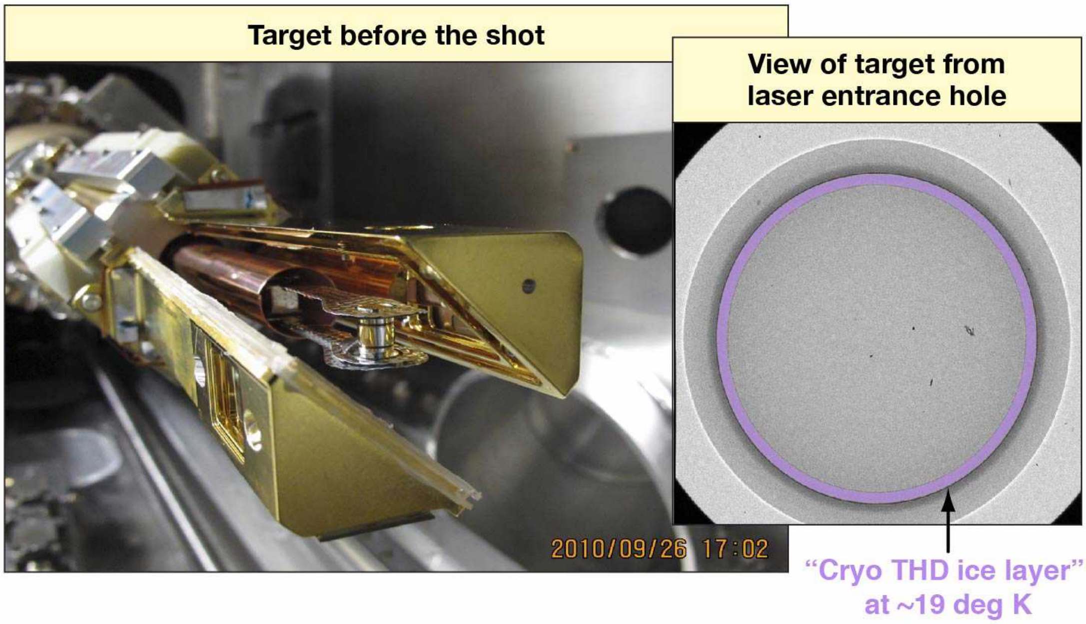
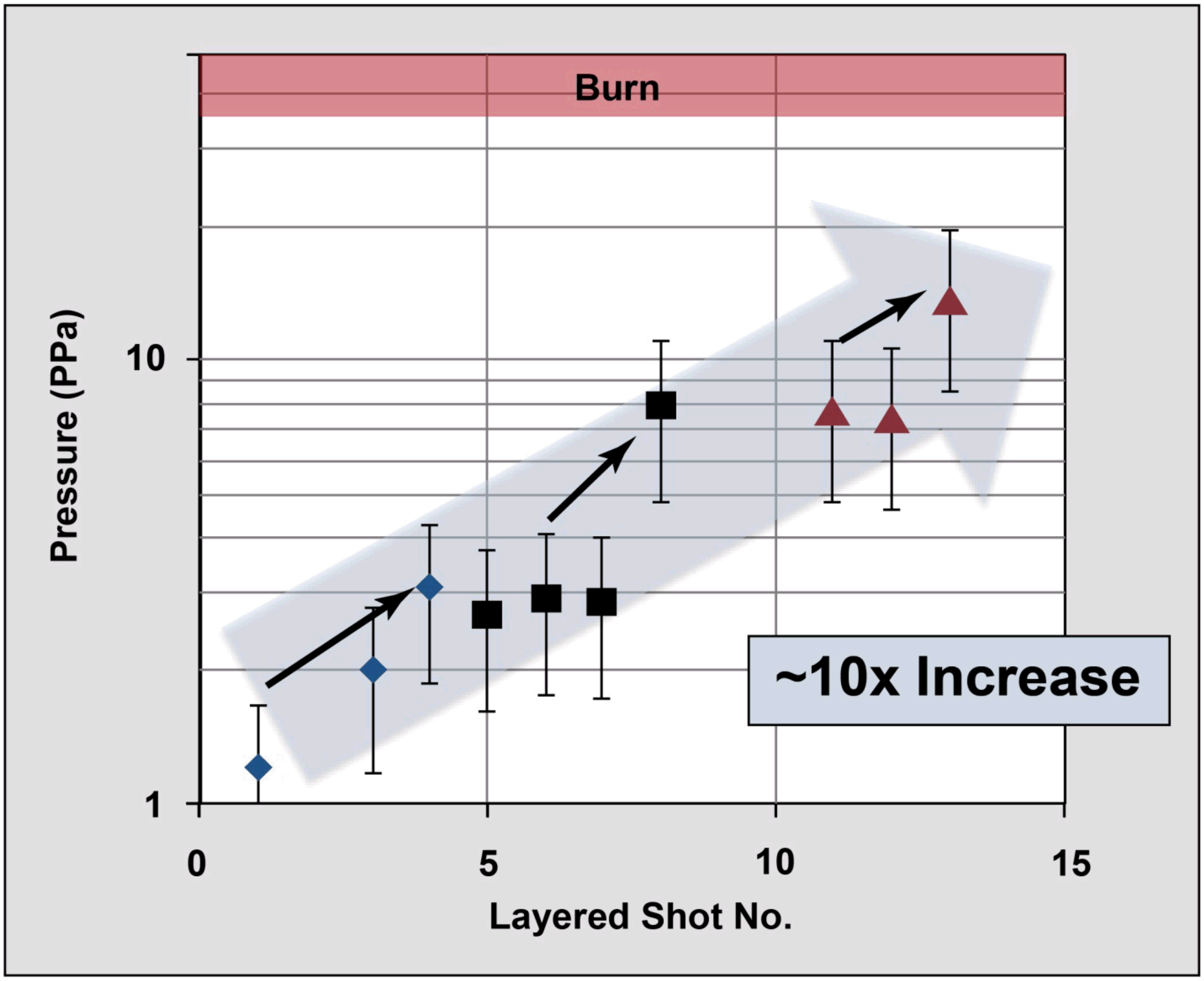

Target before the shot
2010/09/26 17:02
View of target from laser entrance hole
"Cryo THD ice layer" at ~19 deg K

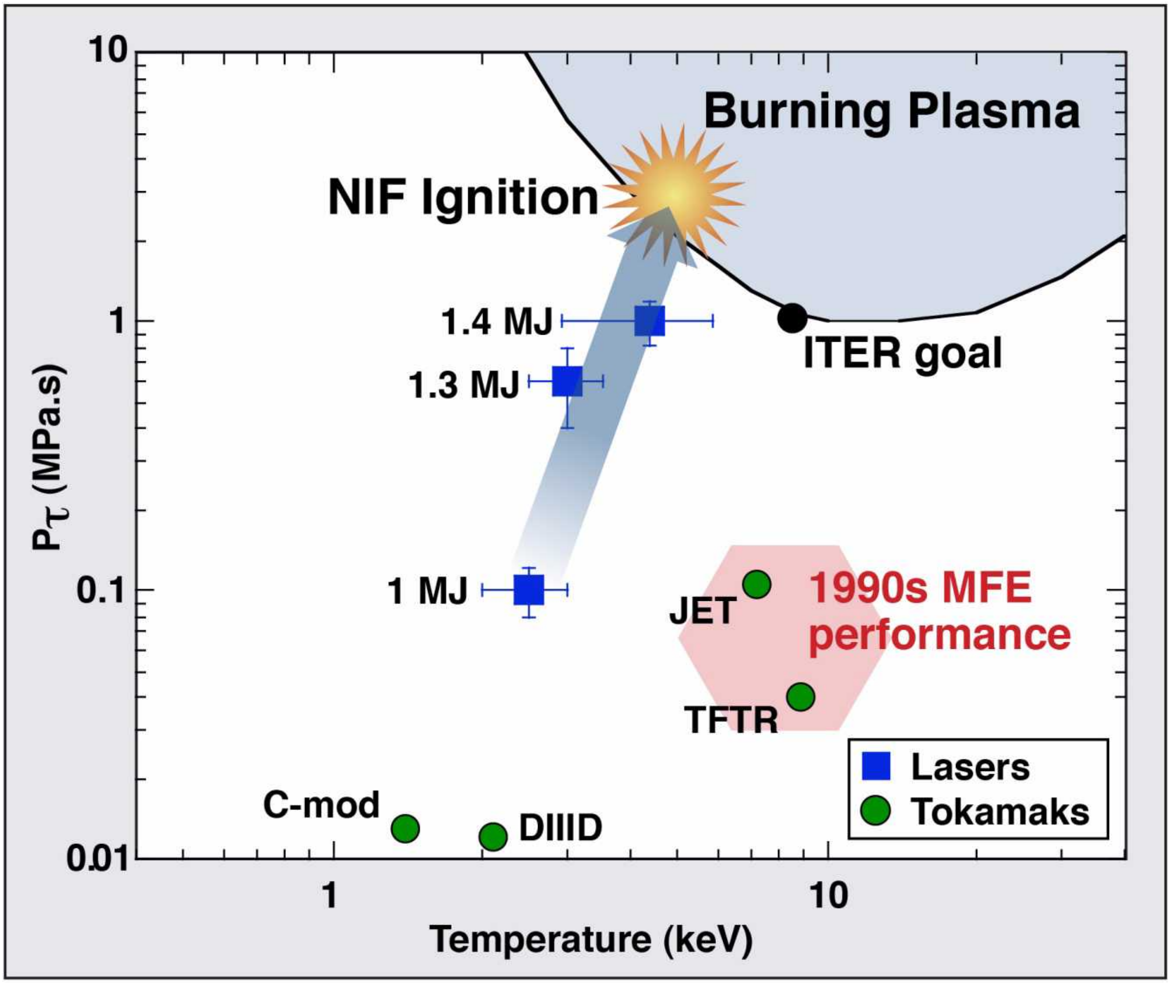
Figure 17. View of the cryo-layered target used in the NIF's first ignition experiment. The gold colored clamshells protect the target laser entrance windows from condensation while in the Target Chamber environment. They are opened at the last second before the shot, allowing the laser beams access to the target. Also shown is a radiograph of the fuel ice layer (pink) within the target capsule.



peta (P) = 1x 10^{15}

Figure 18. Pressures achieved during the NIF shot campaigns have increased by a factor of 10, to over 10 PPa[3] (100 Gbar). To achieve ignition relevant pressures, less than a factor of 10 increase remains.

[3] Peta (P) = 10^{15}



Burning Plasma
NIF Ignition
1.4 MJ
1.3 MJ
1 MJ
ITER goal
1990s MFE performance
JET
TFTR
C-mod
DIIID
Lasers
Tokamaks
Pτ (MPa.s)
Temperature (keV)
10
1
0.1
0.01
1
10

Figure 19. Progress towards ignition expressed in terms of the product of pressure and confinement time (P_T) and ion temperature (keV) (Ref. 2). The NIF experiments are edging closer to the burning plasma regime.

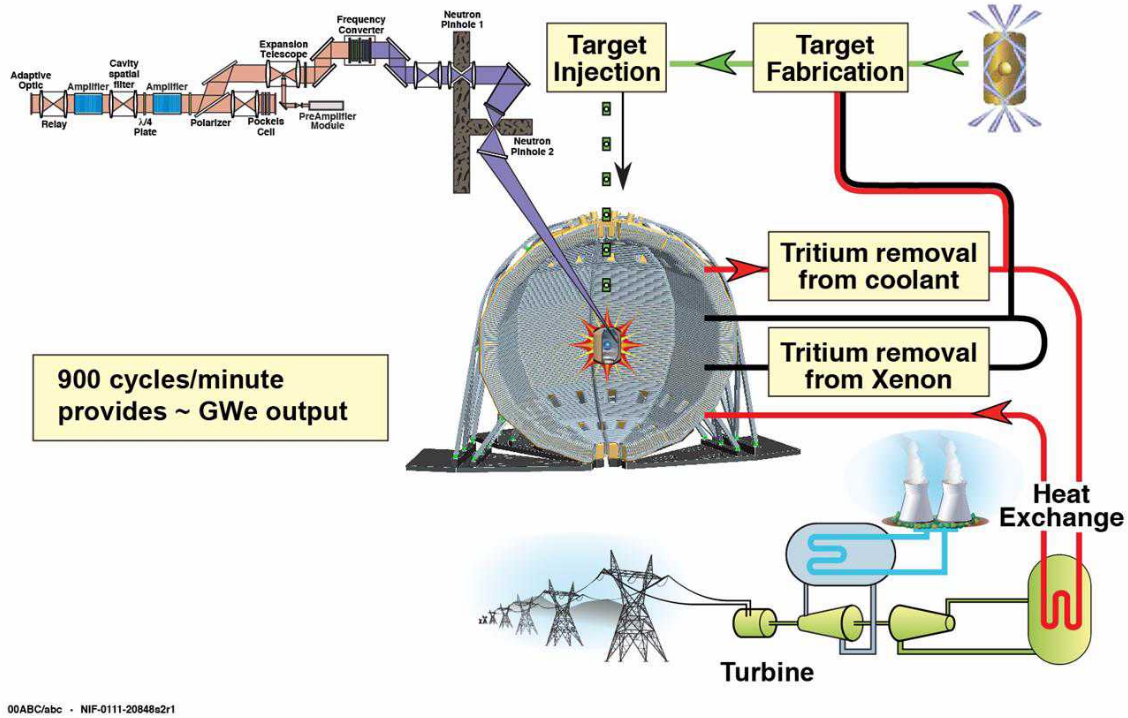


Figure 20. Simplified schematic of the Laser Inertial Fusion Energy (LIFE) power plant. Targets are injected at a high frequency into a target chamber and hit with a precisely timed laser pulse (adapted from the NIF technologies). Energy is extracted from the coolant,

producing GWs of electric power.

Assuring Operational Readiness of the National Ignition Facility[4]

Sandra J. Brereton and Frank Papp

L-454, Lawrence Livermore National Laboratory

PO Box 808

Livermore CA, 94551-9900

Fax: 924-42x-xxxx

Telephone: 925-422-4671

e-mail: brereton1@llnl.gov

[4] This work was performed under the auspices of the Lawrence Livermore National Security, LLC, (LLNS) under Contract No. DE-AC52-07NA27344.

National Ignition Facility experiments involve the use of a variety of materials that generate a number of radiological issues. Along with the use of tritium and depleted uranium, shots generating neutrons create prompt radiation fields, as well as fission and activation products. In order to assure readiness for these hazards, a series of readiness reviews was conducted as the hazards were introduced. Each step was built upon the previous steps, as well as the basic infrastructure and operating capability of the laser facility. A detailed preparation plan for the introduction of these hazards was developed. This included ensuring required equipment was in place and ready, all plans and procedures were developed, and personnel were trained and qualified to perform work in the environment. The approach for preparing the facility for operations under the new set of conditions, the preparations for the readiness reviews, the review process, as well as the approach to initial operations is discussed.

Key words: National Ignition Facility, NIF, start up, Readiness Assessment, Management Prestart Review, operational topics

INTRODUCTION

The National Ignition Facility (NIF) began as a project in 1995 and was completed in 2009. The Project consisted of 192 laser beams, supporting systems and utilities, an optical bench to support the laser components, an interaction chamber to fire the laser into (i.e., the Target Chamber (TC)), and an environmentally controlled building to house all of this equipment. After completion of the building and the beam path, optical systems and electronics were installed. Finally, commissioning of the beams to target chamber center was completed. The NIF lasers have demonstrated that they can deliver over 500 TW and 1.85 MJ of 0.35 μm light, making NIF the only operating megajoule-class laser system in the world.

A Safety Basis Document (SBD) was developed evaluating the safety of operations in the National Ignition Facility (Ref. 1). This document addressed impacts of NIF operations outside of the facility, i.e., it ensured that hazards are mitigated so that the risks to co-located workers in nearby facilities and the public are acceptably low. The document described the ramp up operations at the NIF in phases, crediting certain systems and administrative controls, as new and increasing hazards were introduced (Table 1).

The Safety Evaluation Report (SER), the mechanism by which the National Nuclear Security Administration (NNSA) approved the Safety Basis Document (Ref. 2), identified conditions of approval. With this and the NIF Project Completion Criteria, the Department of Energy (DOE)/National Nuclear Security Administration (NNSA) mandated that certain types of reviews would be necessary before entering each phase of NIF operations. An internal readiness process known as a Management Prestart Review (MPR) was invoked for introduction of tritium and low yield operations. An MPR is an internal NIF process for examining equipment, personnel, plans and procedures, and evaluating readiness to proceed with a prescribed scope of work. This type of review is normally required by NIF to determine readiness whenever a significant new ES&H hazard is introduced; NNSA determined that this would be an acceptable approach prior to operations in Phases 2 and 3, as listed in Table 1. The MPR team can be internal to NIF, but often takes advantage of other expertise at Lawrence Livermore National Laboratory (LLNL). A Readiness Assessment (RA) is a higher level review. Although an RA is very similar in nature to a MPR, it is more rigorous and typically conducted by an independent panel of experts. NNSA required this higher level of review for Phases 1 and 4 of NIF operations. The types of reviews required for each phase in the ramp up of NIF operations are summarized in Table 1.

The RA required as part of NIF Project completion (Phase 1) confirmed that the management systems, staff, and procedures needed to safely operate NIF project systems were in place. A significant effort was necessary to develop the plans and procedures, to prepare the personnel for operations, and to ensure safety equipment was in place and operable. A series of 33 Management Self-Assessments (MSAs) was conducted prior to the RA to evaluate readiness and to identify gaps. These MSAs covered Management Systems, (e.g. Maintenance, Configuration Management, etc.), Safety Programs (e.g., Laser Safety, etc.), and critical equipment (e.g., safety interlock system, etc). The RA Team concluded that the facility was in a state of readiness to safely conduct basic operations (Phase 1) in accordance with the safety basis, the management control programs were in place to ensure safe operations can be sustained, and personnel were trained and qualified.

In the case of the RA for NIF Project completion, a second RA performed by NNSA was also required. The purpose of this second review was to confirm the adequacy of the initial RA performed by LLNL. Completion of these two RAs and the associated confirmation of readiness allowed the facility to perform operations involving up to 192 laser beams with non-hazardous target materials. Introduction of radiological hazards, including the use of tritium and depleted uranium (including production of small amounts of fission products), and the production of neutrons with associated prompt and decay radiation required completion of additional reviews. This paper focuses on the review process that occurred prior to the introduction of these hazards with Phases 2, 3, and 4 operations.

STARTUP PLAN

One of the key operational goals of the National Ignition Facility is to achieve fusion ignition. Under these conditions, a self-sustaining, propagating fusion burn is created in the imploding capsule. Key materials are required for success:

- Deuterium-tritium fuel mixture, as a frozen ice layer inside the capsule;
- A high-Z hohlraum, that efficiently converts incident laser light into xrays that impinge upon the capsule;
- A low-Z capsule material, such as plastic or beryllium; when subjected to xray heating, the capsule material ablates, blowing off and outward, resulting in an inward compressive force.

A graphic of the ignition target is shown in Figure 1. The target materials introduce hazards, requiring engineered systems, plans, procedures and trained personnel to successfully operate. Details of the hazards are described elsewhere in this issue.

The startup of the NIF paralleled the phases of the SBD (Table 1). Operations with hazardous materials built upon the infrastructure and operating model developed for basic operations of the facility (operations involving up to 192 beams with non-hazardous target materials). As new hazards were introduced, existing systems and operational approaches were augmented. In accordance with the SER, reviews of readiness to proceed were conducted prior to each step. The reviews for hazardous materials introduction and yield generation built upon the early reviews for Project completion and focused specifically upon those preparations necessary for advancing into the hazardous materials and yield operations. This was a measured, stepped approach that allowed for feedback and learning during the ramp up. The reviews were focused, performance-based reviews that evaluated NIF's readiness to proceed confirming that: (1) the facility was in a state of readiness to safely conduct the subject operations in accordance with the safety basis; (2) the plans and procedures were in place to ensure the safe operations could be sustained; and (3) that personnel were trained and qualified.

The time line for performance of the reviews and introduction of the hazards followed the programmatic plan. As necessary, early experiments influenced that plan, resulting in some change in the timing of the reviews. The actual timeline on which the reviews were conducted is summarized in Figure 2, along with the time when the specific hazards were authorized.

The review for tritium introduction was conducted in two parts. Because there were many challenging technical issues associated with developing cryogenic fuel layers, it was desirable to get experience with the layering equipment in the NIF as soon as possible, and establish this capability. This first Management Prestart Review was conducted to examine readiness to introduce tritium into the Cryogenic Target Positioner (CryoTarpos) for target hydrogen ice layer formation only (Phase 2). This review occurred in May of 2010 (Ref. 3). A second Management Prestart Review was conducted to examine readiness to shoot targets containing tritium. The scope of this second MPR also included use of beryllium and depleted uranium, and considered low yield operations (< 1 x 10^{16} neutrons/shot) as well. The MPR for beryllium, depleted uranium (DU), tritium, and low-yield operations (Ref. 4) was conducted in July 2010. For both MPRs, the committees recommended granting conditional authorization to proceed with the scope of work under review once the prestart findings were resolved. The prestart findings from both reviews were closed with concurrence from the DOE/NNSA NIF Project Division, enabling these operations to commence on September 3, 2010. The Program has not yet required that beryllium be introduced. One pre-start item related to the use of beryllium remains open. This item will be closed just prior to the need for introducing that material.

After authorizing the use of tritium, a tritium handling performance test was completed, this included injecting tritium into the target chamber. Tritium gas was injected from a manifold containing five bottles of 100 mCi each. All systems behaved as expected. A second injection of tritium followed and was also successful. This introduction of tritium into the facility marked the beginning of operations with hazardous materials. Subsequently, target shots with tritium producing yield were performed using the hazardous material protocols reviewed during the MPRs.

After several months of operating in the regime described by Phase 3 of the SBD, the contractor RA for ignition operations was completed. On March 4, 2011, the contractor RA for ignition experiments concluded that facility systems and equipment, training, and management controls were in place for NIF to safely perform experiments with yields of up to 10^{19} neutrons. In their report (Ref. 5), the RA team recommended granting authorization to proceed with ignition operations once the single prestart finding was closed. This item was closed out and verified by NNSA on May 23, 2011.

Three key reasons that enabled the successful completion of the startup reviews for NIF were being thoroughly prepared, planning a well-coordinated review, and having a well prepared review team. These aspects will be discussed in the subsequent sections.

PREPARING FOR HAZARDOUS OPERATIONS

In order to properly prepare for successful operations, it is critical to have an understanding of the hazards and material behavior as well as an understanding of regulatory requirements. In addition to engineered controls, administrative controls such as procedures and training, as well as Personnel Protective Equipment (PPE) are necessary. By reviewing the hazards, material behavior, regulatory requirements and intended operations, the set of required engineered systems, documentation, training and supporting equipment and controls is identified, ensuring safe operations.

For NIF, required items for readiness were identified on a task list which evolved into the complete list of required items for readiness. A dedicated manager was identified to develop and coordinate these preparations. As the startup plan was developed, the required systems, plans and procedures, and personnel readiness became increasingly apparent; the detailed task list grew. The magnitude of the effort was recognized, and the support of NIF management was essential. In addition, the step-wise introduction of hazards allowed a managed increase in operating experience. This, in turn, provided feedback that influenced preparations and readiness for the subsequent phase(s), contributing to the evolution of the tasks list and the overall success. A summary of key requirements for readiness is provided below.

Engineered Systems

Critical systems required for safety were either identified in the SBD or from a thorough hazards analysis of operations. The SBD was developed from the perspective of impacts outside the facility, on co-located workers and the public. This necessarily identifies the highest level systems required to ensure safe operations, but may not identify systems important to worker safety within the facility. The worker safety systems were identified from the hazards analysis. Detailed Failure Modes and Effects Analyses (FMEAs) were developed for both safety basis and worker safety systems, to understand the critical components of these systems necessary to ensure the safety function. These key systems became known as Configured Systems. Their continued functionality is ensured by a heightened configuration management program that was reviewed as part of the initial Project RA. To be ready for any given operation, the relied upon Configured Systems needed to be installed and commissioned, with all supporting operations and maintenance procedures in place, along with trained personnel to perform the operations and maintenance. More details regarding the performance of each system are provided elsewhere in this issue. Systems required for each phase of the startup of the NIF are summarized in Table 2. In many cases, evaluations or assessments were needed to fully understand what was required to prepare for operations. The number of these evaluations, along with the number of activities specifically related to commissioning or operationally qualifying equipment, the number of plans and procedures to be developed, and the number of training activities (e.g., development of training, delivery of training) are identified in Table 3.

Plans, procedures and work processes

A key set of procedures related to operating and maintaining the critical engineered systems was necessary. Also, procedures describing how to interface with any equipment that would either be located in a radiation environment, or potentially become contaminated had to be modified to integrate with the Radiation Protection Program.

In addition to this, an entire set of procedures and processes needed to be prepared to support the developing Radiation Protection Program. Procedures and processes were necessary to flow down administrative requirements from the SBD, such as inventory limitations and change control/configuration management requirements. The highest level document, the Safety Plan, included an overall description of the Radiation Protection Program, with operational limitations. This was supported by detailed procedures, for example swipe and re-entry procedures. The NIF work control process was modified to include the use of Radiation Work Permits, which extracted the controls specific to a job from the overall radiation protection Program. All in all, nearly 650 plans and procedures were developed or modified (due to increasing magnitude or type of hazard) during the preparation phase. This represents an extraordinary amount of work.

Training program

A detailed training and qualification program was developed and implemented to ensure that workers understood the hazards and controls associated with their work and were qualified to work safely in the environment at NIF. The program built upon institutional generic training already in place at LLNL, and incorporated specifics of the hazards in their operational context at the NIF. General, specific, and hands-on training courses for various worker levels (Radiation Worker 1, Radiation Worker 2) were established; these workers in particular underwent extensive training and qualification.

Over 600 workers were qualified as radiological workers. These workers are supported by a team of radiological control technicians (RCTs), who are specialists in radiological safety. These RCTs also underwent a rigorous training program: first to become generally qualified as an RCT, then to be specifically trained on the unique aspect of the NIF environment.

Finally, general training of all personnel having access to the NIF was necessary. This required the development of a general course for a broad audience to given them an awareness of the new hazards at the NIF. Over 1200 Workers were trained for NIF site access.

It took considerable time and coordination to prepare the training materials, deliver it to appropriate audiences, and qualify the set of workers before the reviews took place.

Tracking Progress

As with any project, tracking progress, defining priorities and driving tasks to completion is essential for success. Once the preparations were underway, two dedicated managers worked to track progress and manage the preparations. As the detailed task list was developing, regular meetings were held with contributors and stakeholders. This ensured that the scope of any particular deliverable was understood, interfaces were clear and completion dates agreed to. As was often the case, it became apparent during the status meetings that additional resources were necessary, a new interface was recognized, or assistance was required to overcome some unexpected problem. Therefore in addition to tracking and statusing progress, the regular status meetings enabled the completion of deliverables. The total number of deliverables for each review is summarized in Table 3.

An example of a subset of tasks on the detailed task list is shown in Figure 3. For each task, a task owner and due date were assigned. When the estimated completion date, and the previously agreed upon due date diverged, this information was noted in the task list. Progress charts, such as the one shown in Figure 4, provided a graphical view of progress towards completion. At any point along the way, progress with respect to completing deliverables due on any given day was evident, as was overall progress toward completing all tasks and being ready for the review. This statusing approach was invaluable in managing the preparations to completion.

PREPARING FOR THE REVIEWS

An important element for an effective review is the identification of qualified and knowledgeable review team members who can dedicate enough time to prepare for and to execute the review. The key areas to be reviewed determined the subject matter expertise needed: radiological protection, configuration management, shielding, tritium systems, for example. In forming the review team, an effort was made to seek out knowledgeable personnel from across the DOE complex, nuclear industry and academia, as well as internal to our laboratory, and from the pool of laboratory retirees. Review committees ranged in size from 8 to 15 members, depending on the scope of the review.

Once the participation of the appropriate expertise for the review was secured, sessions were set up to provide the review team with necessary background. This included briefings on the facility, the intended operations, the associated hazards, specifics of key equipment/systems, and an overview of key programmatic elements such as radiation protection and configuration management. This pre-work was necessary so that the review team could establish appropriately targeted review criteria, and so that they could start the review prepared and knowledgeable. They could then spend the review period looking in more detail at readiness for operations, rather than familiarizing themselves with the basics of the facility, how it was to be operated, and key issues. This approach was essential for an efficient review, lasting only 1-2 weeks.

Early identification of acceptance criteria, personnel to be interviewed and areas for work observations also helped focus the preparations. Periodic checking in with the review team on focus areas helped ensure that the facility and operations personnel were preparing in accordance with expectations.

EXECUTING THE REVIEWS

Because of the large scope of the reviews, and the limited review window, it was essential that the execution of the review be well planned. The review teams were each assigned a dedicated room as their home base, with supplies, computers and administrative support. A set of key documents was maintained in the review team room. These were used as references for the team. Other documents were made available as requested.

In order to ensure efficient and effective use of time during the review window, a detailed plan for each day of the review was developed. An example is provided in Figure 5. Often multiple reviewers were interested in talking to a person in a specific role, but for different reasons. Similarly, multiple reviewers were often interested in seeing the same work observation, but for different reasons. Sometimes the review team split into multiple groups to allow multiple parallel review activities. A detailed plan was developed to coordinate all of this, allowing the most to be accomplished in the allotted time, with the least impact to ongoing NIF operations and personnel. It also ensured the availability of personnel of interest at the desired time.

Every day, a subset of the NIF management team met with the review team to review any issues of concern, identify any needs, and to review and finalize the plan for the next day. This allowed the team to efficiently follow their lines of inquiry, and get the information they needed to assess their area. This proved to be a very efficient manner for executing the review.

On the last day of the review, the review team provided an outbriefing. This summarized key issues resulting from the assessment that needed to be addressed prior to starting the new operation (i.e., pre-start findings; e.g., qualify the minimum number of personnel to operate a certain piece of critical equipment), or other issues that wouldn't preclude starting up, but that should be closed at some time in the near future (i.e., post-start findings; e.g., long-term maintenance procedure incomplete).

Once all pre-start items related to a particular scope were completed, management was in a position to start up that activity.

DELIBERATE OPERATIONS

After successful completion of the first two MPRs for Phases 2 and 3 of NIF operations, and closure of associated pre-start items, NIF management made the decision to introduce tritium and commence low yield operations. To ensure a successful startup, NIF went through a period of deliberate operations upon first introduction of tritium. Although all of the workers had been extensively trained, most were new radiation workers, with limited, if any, experience in radiological or contaminated environments. To mitigate the risk of inexperience, each work team was assigned an experienced "mentor" to coach them during the initial operations; ensuring appropriate practices were being followed. The mentors were experienced radiological workers from elsewhere at LLNL, and from outside organizations.

The mentors oversaw the work teams, coaching them on radiological practices, such as when to change gloves, how to doff PPE, etc. At that same time, only a limited number of new activities were allowed to start up. This period of deliberate operations continued for approximately two months, gradually adding more operations, and gradually relaxing the oversight as confidence grew.

During this time, a continuous feedback loop was in place. An environment had been created where the radiation workers were comfortable asking questions if they were unsure. This allowed for the creation of a set of "frequently asked questions" that were distributed across work teams. We also discovered that although the radiation protection program defined requirements appropriately, in many cases, there were multiple ways to accomplish certain things. Once these became apparent operations were standardized to ensure consistency in implementation. The expected practice was communicated through the "frequently asked questions", as well as directly to work teams through the mentors. Subsequently, the Radiological Controls Steering Committee was developed to discuss issues that arise and to provide consistent guidance. This group continues to meet.

After about two months, it became apparent through the collective judgment of the mentors, that the set of NIF radiation workers were sufficiently proficient that they no longer needed daily oversight. Periodic oversight by the RCTs, as had been planned, would be adequate.

Beryllium has yet to be introduced; a plan for limited duration deliberate operations after its first use has been developed. Since many of the practices already in place for contamination control will apply to beryllium, there are limited new controls. The primary new controls are use of respirators and personal air samplers, as well as swiping specific to beryllium. Deliberate operations will focus on practices around the uses of these new controls to make sure the work teams are employing best practices.

SUMMARY

NIF is well into hazardous operations, having utilized over 2000 Ci of tritium and produced a cumulative yield in excess of 1e16 neutrons. Considerable work was necessary to prepare for these operations. Proper preparation requires an understanding of:

- operations and associated hazards,
- operating facility expectations,
- startup process and
- expectations of the regulator.

Coordination of these preparations and proper planning by dedicated personnel, along with a supportive management team is required. Regular statusing and early identification of problems is critical to driving preparations to completion. Finally, a prepared and qualified review team, as well as a planned and coordinated review period are key to a successful review.

ACKNOWLEDGEMENTS

The authors would like to thank and acknowledge the entire NIF team for their contributions to the successful startup of hazardous materials operations.

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Table 1: NIF Operational Phases and Startup Requirements

Phase of NIF Operations	**Scope**	**Startup Review Required**
1: Basic Operations of the NIF	Laser operations with up to 192 beams and non-hazardous target materials	Contractor RA plus NNSA RA
2: Introduction of tritium for Cryolayering	Introduction of tritium into the CryoTarpos for layering operations only	MPR
3: Low Yield Operations	Experiments involving tritium, beryllium and depleted uranium containing targets, with neutron yields up to 1e16 neutrons/shot	MPR
4: Ignition Operations	Experiments involving tritium, beryllium and depleted uranium containing targets, with neutron yields up to 1e19 neutrons/shot	Contractor RA

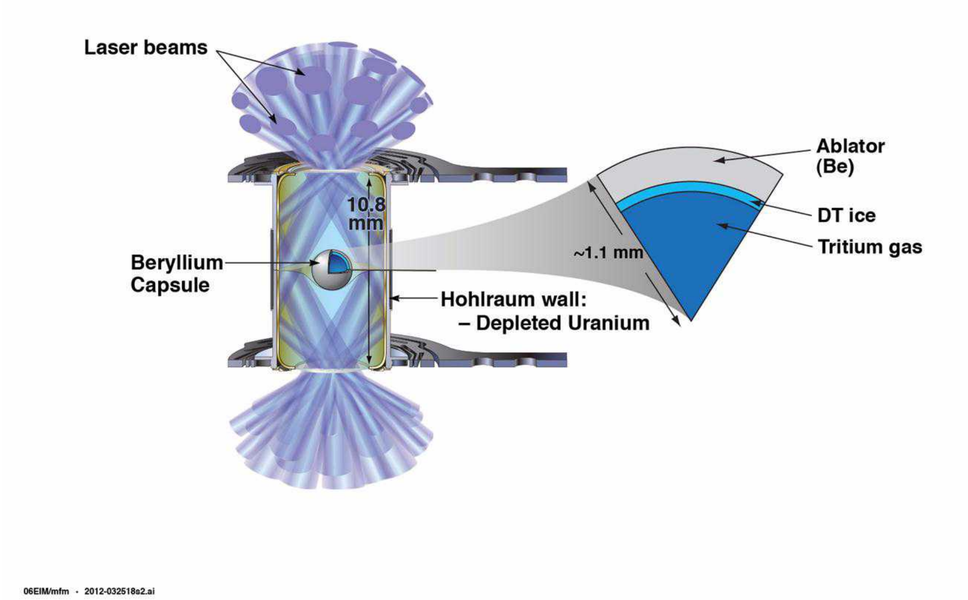


Figure 1. Schematic of the cryogenic ignition target showing the 48 “quads” of laser beams entering the hohlraum from above and below. There are four laser beams to each quad.

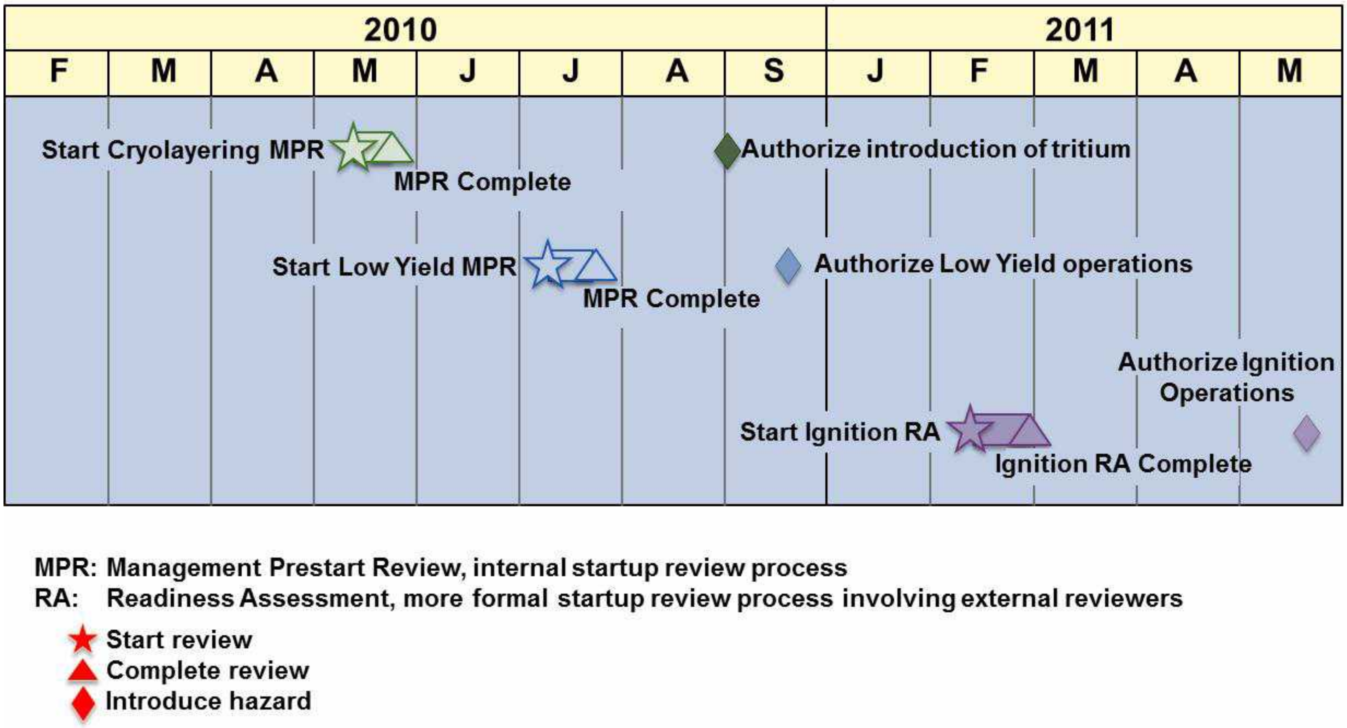


Figure 2. Timeline for NIF Startup Reviews and introduction of related hazards

Table 2: Summary of Required Items for Each NIF Startup Review

Review	Engineered Systems	Function
Cryolayering MPR (Phase 2)	• Confinement Envelope	• Components, by virtue of their boundary function, act to "confine" hazardous and radioactive contaminants and prevent release to the adjacent occupied spaces of the NIF
	• Contamination Control Systems	• Receive contaminated gas streams and equipment from the confinement envelope and confines and processes the contaminants
	• Ventilation System	• Provides air flows and pressures with the intent of maintaining a sufficiently large differential pressure to prevent spread of airborne contaminants to uncontrolled areas of the facility
	• Tritium Monitoring System	• Permanently installed monitoring system to detect airborne tritium and stack effluents
	• Monitoring and Alarm System	• Interfaces with the radiation monitoring system providing alarms when allowable thresholds are exceeded

Low Yield MPR (Phase 3)	• Confinement Envelope (augmented) • Contamination Control Systems (augmented) • Ventilation System (augmented) • Tritium Monitoring System (augmented) • Radiation Shielding • Safety Interlock System • Monitoring and Alarm System (augmented)	• Listed above • Listed above • Listed above • Listed above • Facility elements designed to protect facility workers, co-located workers, and the public from external radiation hazards generated during NIF operations • Works in conjunction with administratively controlled procedures to protect personnel from exposure to high-voltage, laser light, radiation, asphyxiation, and other hazards, and where feasible, minimizes equipment damage in the event of a failure in a monitored component in the NIF • Listed above

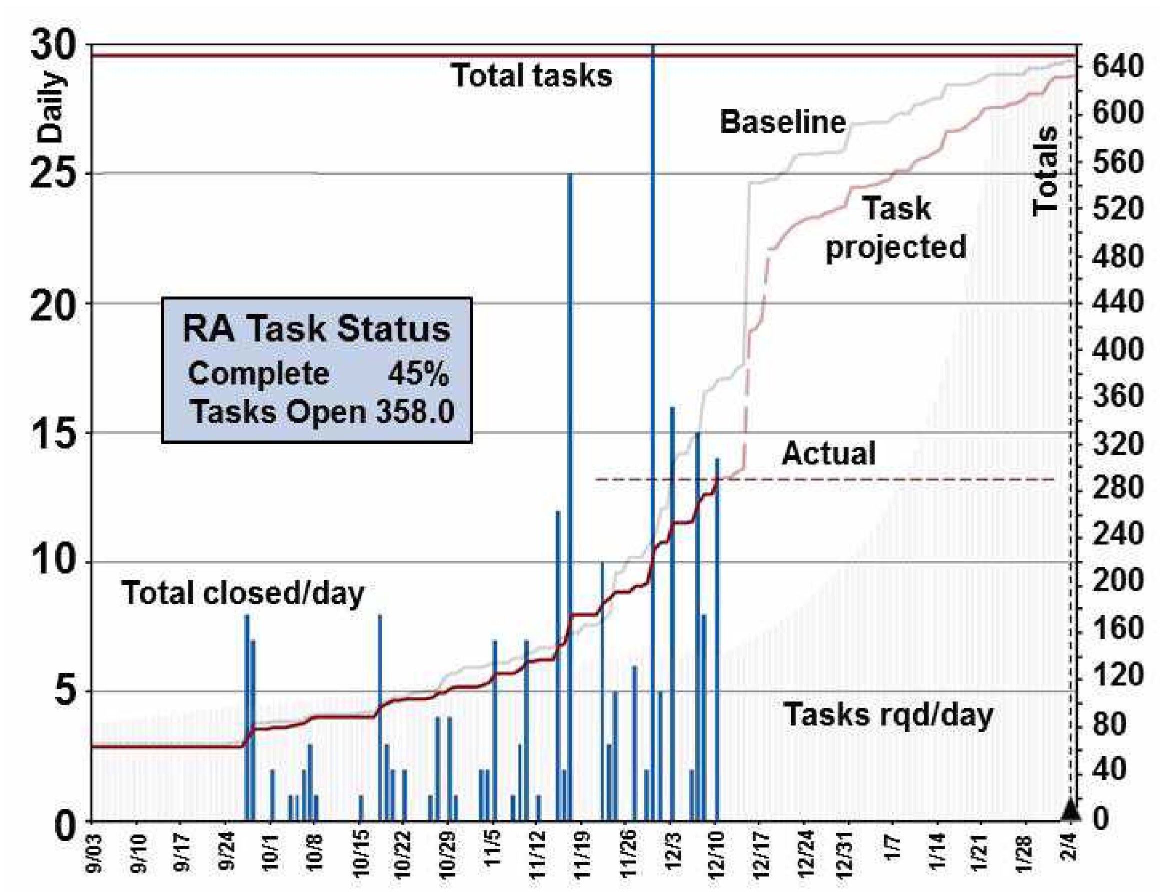
Ignition RA (Phase 4)	• All above • Radiation Shielding (expanded) • Gamma Monitoring System • Monitoring and Alarm System (expanded)	• Listed above • Listed above • Permanently installed monitoring system to detect decay gamma radiation • Listed above

Table 3: Number of Deliverables for each NIF Startup Review

	Task Totals				
	Training	Procedures	Equipment	Evaluation	
Cryolayering MPR	17	115	45	68	
Low Yield MPR	57	323	345	271	
Ignition RA	19	210	250	171	
	93	648	640	510	1891

Item	Task	Owner	APM	Due Date	Est. Comp	Act Comp	Daily meeting	RYG	Action
3200	Complete TP1 skid OQ w/full automation	Reitz	Weber	8/20	8/27		8/23	R	8/19: Srs 8/20; code 8/23am, draft CTP8/23, do CTP8/24-8/26, QA review 8/24-8/26; create CTR8/27; apv CTR8/27; review CTR results daily
3053	Update target Bay access list	Reed	Bruno	8/25	8/25				8/4: added per TK, SB 8/16: Bruno/Kohut to have Michelle update list when ready
3093	Release revised Shot Safety Checklist	Kohut	Bruno	8/25	8/25				8/6: Added per Kohut, (last minute item)
1860	Release HMMA optics purge cabinet operating procedure	Folta	Wegner	6/30	7/9	7/11		G	6/28: draft in review; to ECMS by 7/1
1914	Complete labeling on shield items	robertson	bruno	7/9	7/9	7/12		G	7/7: 7/9 CI stickers complete; x/x labels complete 7/12: 4 to go; due 7/12
3010	Post RMAs, RMMAs, BZs	Beale	Bruno	8/25	8/25				8/20: ready to execute

Figure 3. Sample excerpt from the detailed task list, which identified all deliverables for the reviews



RA Task Status
Complete 45%
Tasks Open 358.0
Total tasks
Baseline
Task projected
Actual
Total closed/day
Tasks rqd/day
Daily
Totals
30
25
20
15
10
5
0
640
600
560
520
480
440
400
360
320
280
240
200
160
120
80
40
0
9/03
9/10
9/17
9/24
10/1
10/8
10/15
10/22
10/29
11/5
11/12
11/19
11/26
12/3
12/10
12/17
12/24
12/31
1/7
1/14
1/21
1/28
2/4

Figure 4. Example progress chart showing status of preparations for the Ignition Readiness Review (Phase 4). The bar chart shows the actual number of daily deliverables completed (blue bars), compared to the plan (grey bars). The line graph shows (1) cumulative number of deliverables completed to date (dark red line) compared to the baseline plan (grey line); (2) projected cumulative number of deliverables to be completed (light red line) compared to the baseline plan (grey line).

MPR Schedule, 7/12-7/22

Wednesday, 7/14

Time		
8	MPR Committee Working Session	
8:30		
9		Tritium Processing System SSM Interview (482, 2178)
9:30		
10	Environmental Interviews (482,2274)	Confinement Envelope CSM Interview (B482,2178)
10:30		
11	Visit LSC, Be analysis in HP lab	Inv Mgmt System (RIMS) demo (B482, 2178)
11:30		
12	**Lunch**	
1:00	Radiation Safety Officer Interview (B482,2274)	Software QC Mgr Interview (B482, 2178)
1:30		
2:00	Radiation Monitors CSM Interview (482,2274)	
2:30		
3:00	Safety Analyst Interview (482,2274)	Ventilation System CSM Interview (B482, 2178)
3:30		
4:00	Pre-obs Prep (B482,2108)	
4:30	Observation sweep/shield door closure and re-entry (B581)	

Figure 5. Example daily schedule during the Low Yield MPR (Phase 3)

Application of the National Ignition Facility Distinguishable from Background Program to Accelerator Facilities at Lawrence Livermore National Laboratory

Eric D. Packard[5] and Carolyn Mac Kenzie[‡]

Name and address for correspondence:

Jon T. Dillon, L-449

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925 423-8049

Telephone: 925 423-6167

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[5] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

[‡] Lawrence Berkeley National Laboratory, Berkeley, CA 94720-1150

The authors declare no conflict of interest.

e-mail: dillon10@llnl.gov

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Abstract— **Lawrence Livermore National Laboratory must control potentially activated materials and equipment in accordance with Department of Energy Order 458.1, *Radiation Protection of the Public and the Environment*, which requires Department of Energy approval of the process used to release volumetrically contaminated personal property, and establishes a dose constraint of 10 μSv year^{-1} (1 mrem year^{-1}) for clearance of such property. The National Ignition Facility at Lawrence Livermore National Laboratory developed a technical basis document and protocol for determining the radiological status of property that is potentially activated from exposure to neutron radiation produced via fusion of tritium and deuterium. The technical basis included assessment of the neutron energy, the type of materials potentially exposed and the likely activation products, and the sensitivity of radiation detectors used to survey the property. This paper evaluates the National Ignition Facility technical basis document for applicability to the release of property from Lawrence Livermore National Laboratory's various accelerator facilities, considering the different types of particles accelerated, radiations produced, and resultant activation products.**

Extensive process knowledge regarding the accelerators operations, accompanied by years of routine surveys provides an excellent characterization of these facilities. Activation studies conducted at the Stanford Linear Accelerator and the High Energy Accelerator Research Organization in Japan corroborate that the long-lived radionuclides produced at accelerator facilities are of the same variety produced at the National Ignition Facility. Consequently, Lawrence Livermore National Laboratory concludes the release protocol developed for the National Ignition Facility can appropriately be used at all its accelerator facilities.

Key words: neutron activation; radioactivity, residual; accelerators; instrumentation; surveys; detector, scintillation

Introduction

Radioactivation of materials and equipment (M&E) is an inherent issue and a major concern associated with accelerator facilities that produce high-energy neutrons or photons. In electron accelerators, accelerated electrons can be lost from the primary beam during machine operations and introduce electromagnetic cascades when they collide with materials such as the accelerator magnets or beam tubes. The resultant high-energy bremsstrahlung can induce photonuclear reactions if the bremsstrahlung energy is greater than 6 – 13 MeV. When heavier particles (protons, deuterons, alpha particles, other ions) are accelerated, neutron activation commonly prevails through reactions such as (α, n) and (p, n). Regardless of the mode of production, the Department of Energy (DOE) classifies activated materials as "volumetrically contaminated" or "potentially volumetrically contaminated" and requires radiological control of such material in accordance with DOE Order 458.1, *Radiation Protection of the Public and the Environment*. This order requires DOE-approval of the process used to release volumetrically contaminated personal property (i.e., contractor-owned material and equipment), and establishes a dose constraint of 10 μSv year^{-1} (1 mrem year^{-1}) for clearance thereof. The American National Standards Institute (ANSI) report N13.12 – 1999, *Surface and Volume Radioactivity Standards for Clearance,* provides isotope-specific concentration values corresponding to this dose threshold.

Assessing the level of activation of potentially-activated materials becomes complicated due to the volumetric nature of the activation and the fact that some of the radionuclides produced are not easy to detect. Because of the large volume of potentially-impacted material, it is important to establish a protocol for determining when M&E might potentially be activated; when it is in-fact activated; and appropriate disposition avenues based on the level of activation.

The Lawrence Livermore National Laboratory (LLNL) National Ignition Facility (NIF) creates activated M&E via the laser-induced fusion of tritium and deuterium in a BB-sized target, which results in the isotropic release of 14 MeV neutrons. The NIF developed a protocol for managing potentially-impacted M&E that includes identifying when the M&E is 'potentially activated' (based on total neutron production, Monte Carlo modeling using MCNP, and proximity to the Target Chamber), and when the potentially-activated M&E is actually activated (based on type of material and radiation measurement). M&E that are shown not to be distinguishable from background (DFB) and below the thresholds specified in the ANSI N13.12 – 1999 are released from radiological control.

The technical basis document for the NIF DFB protocol (i.e., the NIF-DFB-TBD) evaluated neutron energies ranging from thermal to 14 MeV as the source term and focused on the primary types of M&E utilized at NIF (e.g., carbon steel (e.g., hand tools), stainless steel and aluminum (e.g., components and structures), and copper (e.g. power distribution and components). The TBD demonstrated that the concentrations of radioactive materials associated with the 10 $\mu Sv\ y^{-1}$ (1 $mrem\ y^{-1}$) dose constraint could be easily detected using a commercially-available 1-in x 1-in (or larger) sodium iodide (NaI) detector.

Given the in-depth analysis conducted for NIF operations, it was advantageous to apply the technical basis to other LLNL facilities and operations, if appropriate. The question at hand was whether or not the activation products produced at NIF were qualitatively the same as produced at LLNL's various accelerator facilities.

Background on LLNL facilities capable of producing activation

Since the late 1950's, LLNL's research and development activities have included the use of a wide variety of differ types of radiation-generating devices (RGDs). As shown in Table 1, LLNL has six RGDs (five accelerators and NIF) that have, or have had in the past, operated with sufficient energy to cause activation of M&E [6]. These RGDs operated both at the LLNL main site and at Site 300 (15 miles east of the main site), and three are still operational; three are non-operational and exist in various stages of decommissioning. LLNL has extensive process knowledge of how these RGDs were used, and routine surveys have established the areas in these facilities where potential activation was, or is, a concern.

Following is a brief description of each of the RGDs listed in Table 1.

B194 LINAC 100 MeV, 15 A electron Beam

The B194 LINAC was built in the 1960s as a 100 MeV machine to accelerate ions to produce pulses of photons and neutrons. The ongoing research programs at the facility include basic research projects, technology transfer activities, and defense-related programmatic research. The LINAC is located below ground on the main LLNL site, and includes the magnetic beam transport systems, and six experimental "caves" or target areas, four of which can receive the primary electron beam, and one of which includes two high power lasers.

At full beam power, the B194 LINAC can generate nearly 2×10^{14} neutrons and bremsstrahlung radiation fields of up to 5×10^{8} Rad/hr. The neutrons generated are from photonuclear reactions via giant-resonance effect in the photon energy region between 10 and 30 MeV, and the quasi-deuteron effect between 30 and 100 MeV. Residual radioactivity is produced in targets, beam dumps, accelerator components and shielding materials.

B581 National Ignition Facility (NIF)

The NIF is the world's largest and most energetic laser system, which has the goal of achieving self-sustaining nuclear fusion resulting in the release of more energy than it takes to initiate the fusion reaction. The NIF focuses the intense energy of 192 laser beams on millimeter-sized targets filled with hydrogen in the forms of tritium and deuterium. The fusion experiments at the NIF result in the emission of neutrons, energetic particles, x-rays and gamma-rays. The energetic particles, x-rays and debris are confined by the 10-meter diameter spherical aluminum alloy Target Chamber. Neutrons and gamma radiation travel through the Target Chamber wall into the seven levels of the Target Bay. Additionally, some pass through the Target Bay outer wall shielding structure and into the Switchyards and Laser Bays, primarily through penetrations and equipment ports. The M&E, structures and systems in these areas have the potential to become activated. The length of time the materials remain activated depends on the elemental composition of the material and the unique radiological decay characteristics of each activated element.

B801 Contained Firing Facility 18 MeV and 3 kA pulsed beam

The Flash X-ray (FXR) machine was dedicated in April 1982 as the nation's most powerful linear-induction electron beam accelerator. The beam from the FXR was directed to an outside firing table until the year 2001, when it was enclosed into a building and renamed the Contained Firing Facility. The building is a concrete, steel-reinforced firing chamber that contains blast effects. Flashes of highly energetic x-rays—capable of penetrating and producing radiographs of explosively driven assemblies—are produced by impinging pulses of electrons from microwave or linear induction accelerators onto a metal target. The FXR allows scientists to see into the heart of test objects at the very moment they are detonated. Small amounts of residual radioactivity are produced in the targets, beam dumps, accelerator components and shielding materials after the shots are completed.

B292 Rotating Target Neutron Source (RTNS-II), 400 keV and 45-150 mA (Non-operational)

The Rotating Target Neutron Source in B292 was in operation from 1979-1987. It was built as a national facility for the US fusion program with the purpose of investigating high intensity 14 MeV neutrons on a variety of materials. The machine accelerated a pulsed beam of deuterons onto a tritiated-titanium disk that rotated at the end of the target assembly, producing 14 MeV neutrons via the ^{3}H (d, n) ^{4}He reaction. Residual radioactivity was produced in the targets, beam dumps, accelerator components and shielding materials.

B851 LINAC, 100 MeV and 2 A

At Site 300 in Building 851, a 100 MeV pulsed Flash X-Ray accelerator was located with a bullnose that projected out onto an open-air firing table. It was built in 1960 and operated until 2008. It accelerated electrons for the purpose of creating flashes of highly energetic x-rays—capable of penetrating and producing radiographs of explosively driven assemblies. Residual radioactivity was produced in the targets, beam dumps, accelerator components and shielding materials.

B865 Advanced Test Accelerator (ATA) 50 MeV and 10 kA

The ATA was built in 1980, dedicated for use in 1981 and officially retired in 1996. Its purpose was to support the Strategic Defense Initiative by evaluating the potential of electron beam technology for defensive weapons. ATA operated with a 50 MeV pulsed beam of particles in air which resulted in bremsstrahlung and neutron radiation. The neutron beam output was on the order of 10^{13} neutrons. Residual radioactivity was produced in the targets, beam dumps, accelerator components and shielding materials.

applying the NIF DFB approach to LLNL's accelerator facilities

Since the NIF-DFB-TBD was developed for a discrete source term focusing on specific materials of interest, the NIF-DFB-TBD needed to be evaluated to ensure it could be appropriately applied at LLNL's accelerator facilities. NIF initially produces 14 MeV neutrons via the ^{3}H (d, n) ^{4}He fusion reaction. Once produced, this initially mono-energetic neutron spectrum goes on to interact with other matter in the vicinity producing a spectrum of neutron energies that are eventually absorbed. While this is the same neutron production/interaction mode as the B292 Rotating Target Neutron Source, LLNL's other accelerator facilities accelerate electrons, creating neutrons in a different way and potentially at energies much higher than 14 MeV. That is, with the electron accelerators, neutrons are primarily produced when the accelerated high-energy electrons collide with target materials or accelerator components, resulting in high-energy electromagnetic cascades (bremsstrahlung) that subsequently produces neutrons (assuming the energy of the incident photon is greater than the minimum binding energy of the neutron in the target material).

Before the NIF-DFB-TBD could be applied at other facilities, the following questions had to be addressed:

1. Given that higher-energy neutrons produced by the accelerators would presumably penetrate materials more deeply than the spectrum of neutron energies up to 14 MeV produced by the NIF, would activation products be adequately detected using the surface survey approach developed for NIF?

2. Would the radionuclide inventory of interest at the accelerator facilities (or the ratios of radionuclides) be the same as at NIF?

To address these questions, a variety of DOE and international accelerator facilities that already had TBDs for release of potentially activated equipment were evaluated. While the TBD for Stanford Linear Accelerator Center (SLAC) and the High Energy Research Organization in Japan are the referenced documents for this paper, other facilities approaches were also evaluated for additional confirmation.

NIF used Monte Carlo modeling to establish zones/areas of influence from neutron radiation and assessed the M&E that may become activated in these zones. As discussed in the paper, *Implementing an Operational Program for Determining the Radiological Status of Material and Equipment* (Dillon), "Extensive activation modeling at the NIF has shown, as expected, that the predominant activation products stem from the activation of common metals. Silica glass and the Potassium Di-hydrogen Phosphate (KDP) and DKDP (Deuterated KDP) optic crystals become activated to a much smaller degree than metals due to the materials much lower neutron cross section. In addition, polymers (plastics) also were determined, as expected, to have a low propensity for activation. In the case of NIF components, most materials located in the Target Bay can be characterized as carbon steel, stainless steel, aluminum, and copper."[3] The types of metallic M&E used at NIF are generally consistent with those materials used at accelerator facilities (e.g. carbon steel, stainless steel, aluminum and copper). This statement in general holds true for the LLNL accelerator facilities. A review of the SLAC technical basis for detection thresholds and measurements of volumetric radioactivity corroborates this assertion. The long-lived activation-produced radioisotope inventory found in M&E at SLAC is essentially the same as that found in the NIF facility.

The NIF-DFB-TBD effectively dealt with the issue of "hard-to-detect" radionuclides such as ^{3}H and ^{55}Fe since other gamma emitting radionuclides (proxy radionuclides) were always produced when the hard-to-detect radionuclides were produced. Also, none of the hard-to-detect radionuclides are alpha emitters for the typical M&E. SLAC came to the same conclusion for their accelerator facilities. Table 2 (developed by SLAC) lists the common long-lived (>200 day half-life) radioisotopes for M&E and concrete within an accelerator facility; a notation is included for those nuclides used as proxy radioisotopes. Like NIF, SLAC was able to establish that the proxy radioisotopes contribute the vast majority (if not all) of the surface dose rate due to their high-energy and high-intensity gamma rays. The hard-to-detect radioisotopes ^{3}H and ^{55}Fe can exist in metals and particularly in concrete, but their dose consequences when normalized to the ANSI screening level values are at least 10 times smaller than the proxy radioisotopes, and their potential existence can be indirectly estimated by the measurements of proxy radioisotopes. The detection threshold using a 1-in x 1-in sodium iodide probe is 0.037-0.37 Bq g^{-1} (1-10 pCi g^{-1}) for the proxy radionuclides ^{22}Na, ^{54}Mn, ^{60}Co, and ^{152}Eu, which well below the ANSI/HPS N13.12 minimum screening level of 1.11 Bq g^{-1}(30 pCi g^{-1}). [7].

SLAC's method for survey techniques involved similar instrumentation and survey techniques to that implemented in the NIF DFB approach. SLAC used the Monte Carlo code MCNP along with gamma spectroscopy to characterize accelerator-produced activation products in metals and concrete for various energy accelerators and concluded that the induced activity in an object was volumetric and presents its maximum activity near the surface that faces beam loss points[7].

The High Energy Accelerator Research Organization in Japan[10] performed a study of activation products in concrete shielding at various depths in accelerators at a variety of energies (45 MeV, 220 MeV and 1.3 GeV) in preparation for decommissioning these facilities. As shown in Figure 7, the same high-energy gamma-emitting proxy radioisotopes were present in each of these accelerator facilities just as at SLAC and at the NIF. The various accelerator energies also provide a reasonable comparison to the accelerating potential found at the various LLNL accelerator facilities. In all of the accelerator facilities studied by the High Energy Accelerator Research Organization in Japan, the maximum activity was found from 0-10 centimeters from the surface of the concrete. Figure 7 displays the activity of various nuclides at concrete depth.

The NIF-DFB-TBD demonstrated the adequacy of using a 1-in x 1-in Sodium Iodide crystal for a 1-minute count to determine at the 95% confidence level when induced radioactivity is present; other instrumentation and count times could be used and still achieve the required statistical confidence. For example, larger scintillation probes (e.g., a 2-in x 2-in or 3-in x 3-in) would increase the sensitivity, and therefore would also be acceptable instruments for use in this IFB process. Similarly, the 1-minute count time could potentially be varied either shorter or longer based on the background and the instrument's efficiency without affecting the statistical basis of the NIF-DFB-TBD approach.

conclusions

LLNL has established that the NIF-DFB-TBD and the associated release protocol can appropriately be applied to any of its accelerator facilities. The protocol includes process knowledge to identify areas with potentially-activated M&E, conducting a radiation survey using instrumentation that is capable of detecting activity below the ANSI N13.12 screening levels (corresponding to the DOE Order 458.1 screening criteria of 10μSv y^{-1} (1 mrem y^{-1})), and releasing from radiological control potentially-activated M&E that is demonstrated not to be DFB.

Application of the NIF DFB release process is appropriate at LLNL's accelerator facilities since the LLNL accelerator areas with potentially-activated M&E are well known, and the potentially-activated M&E is very similar to that present at NIF, as well as other DOE accelerator facilities. SLAC, the NCRP, The High Energy Accelerator Research Organization in Japan, and the NIF-DFB-TBD have clearly characterized the long-lived activation products in metals and concrete for various energy accelerators and conclude the following:

- No alpha emitters are produced.
- Beam operations do not result in surface contamination in metals and other solid materials.
- The induced activity in an object is volumetric and presents its maximum activity near the surface that faces beam loss points, validating that surface measurements are sufficient when assessing volumetric activity resulting from activation
- Certain radionuclides (e.g., ^{3}H and ^{55}Fe) that are difficult to detect with hand-held instrumentation due to their low-energy emissions, are accompanied by higher energy gamma emitting radionuclides (e.g., ^{22}Na, ^{54}Mn and ^{60}Co) that are easy to detect and can be used as proxy radioisotopes.

Variations of the NIF survey protocol such as the survey time and size of the Sodium Iodide crystal are acceptable so long as the primary measurement objectives are met (DOE Order 458.1 screening criteria of 10 μSv y^{-1} (1 mrem y^{-1})).

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Table 1: LLNL RGD Facilities with Potentially Activated M&E

Facility	Energy	Current	Status

B194 Linear Accelerator (LINAC)	100 MeV	15 A electron beam	Operational
B581 National Ignition Facility (NIF)	Up to 20 MJ	NA (Laser induced fusion)	Operational
B801 Contained Firing Facility	18 MeV	3 kA pulsed electron beam	Operational
B292 Rotating Target Neutron Source (RTNS-II)	400 keV	45-150 mA deuteron beam	Non-operational
B851 LINAC	100 MeV	2 A electron beam	Non-operational
B865 Advanced Test Accelerator (ATA)	50 MeV	10 kA	Non-operational

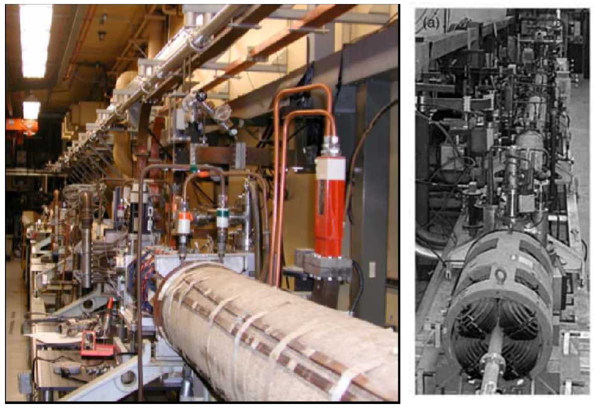


Figure 1: B194 LINAC

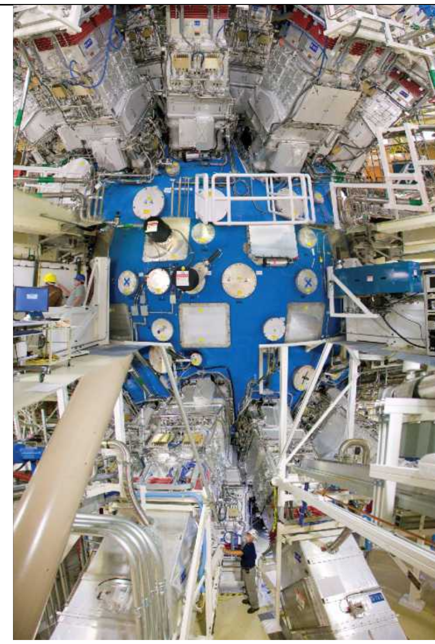
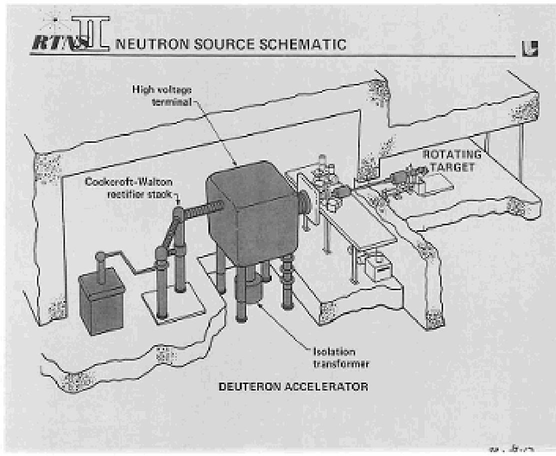
	
Figure 2a: NIF Laser Bay	**Figure 2b: NIF Target Chamber**

Figure 3: B801 FXR accelerator at the Contained Firing Facility (CFF)



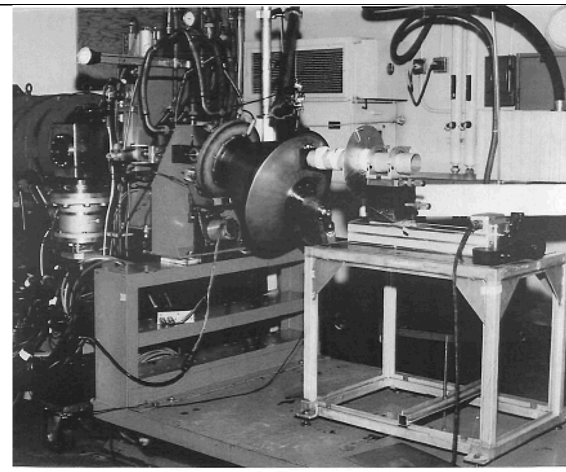


Figure 4: B292 Rotating Target Neutron Source (RTNS-II) facility

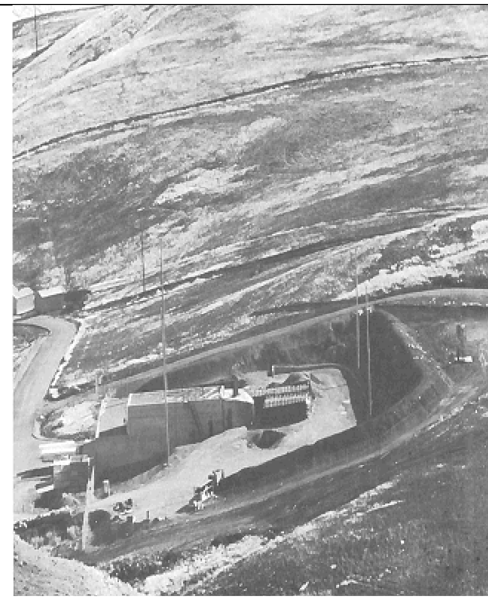
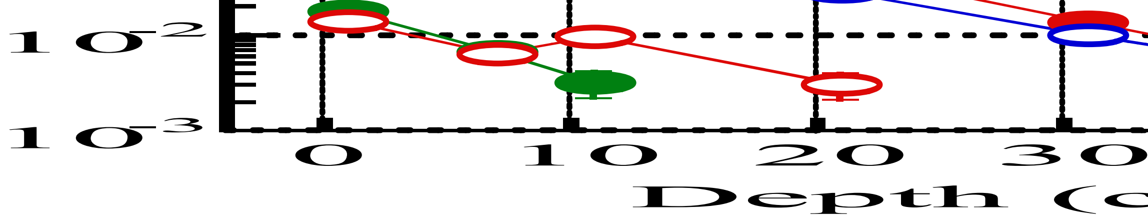


Figure 5: B851 LINAC facility

Figure 6: B865 Advanced Test Accelerator

Table 2: Long half-lived activation products in typical accelerator M&E[7]

Material	Radionuclide	Half-life
Carbon steel (Fe, C); Cast iron (Fe, C, Si, Mn)	**^{22}Na (*proxy*)**	**2.6 y**
	^{54}Mn (*proxy*)	**312 d**
	^{55}Fe (5.9 keV x-ray)	**2.73 y**
	^{57}Co	**272 d**
Aluminum	**^{22}Na**	**2.6 y**
Copper	**^{55}Fe (5.9 keV x-ray)**	**2.73 y**
	^{57}Co	**272 d**
	^{60}Co (*proxy*)	**2.6 y**
	^{65}Zn (NCRP Report #144)	**244 d**
Concrete	**^{3}H (pure beta)**	**12.3 y**
	^{22}Na (*proxy*)	**2.6 y**
	^{54}Mn (*proxy*)	**312 d**
	^{55}Fe (5.9 keV x-ray)	**2.73 y**
	^{57}Co	**272 d**
	^{60}Co	**5.26 y**
	^{152}Eu	**13.5y**
	^{154}Eu	**8.59 y**



45 MeV

Figure 7: Radionuclides present in concrete at various depths due to activation at different energy accelerator facilities.

Experiences Managing Radioactive Material at the National Ignition Facility

Rick L. Thacker*

Name and address for correspondence:

Rick L. Thacker, L-449,

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925 422-7791

Telephone: 925 422-6339

e-mail: thacker3@llnl.gov

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***Abstract*—The National Ignition Facility at Lawrence Livermore National Laboratory is the world's largest and most energetic laser system for inertial confinement fusion and experiments studying high energy density science. Many experiments performed at the National Ignition Facility involve radioactive materials; these may take the form of tritium and small quantities of depleted uranium used in targets, activation products created by neutron-producing fusion experiments, and fission products produced by the fast fissioning of the depleted uranium. While planning for the introduction of radioactive material, it was recognized that some of the standard institutional processes would need to be customized to accommodate aspects of NIF operations, such as surface contamination limits, radiological postings, airborne tritium monitoring protocols, and personnel protective equipment. These customizations were overlaid onto existing work practices to accommodate the new hazard of radioactive materials. This paper will discuss preparations that were made prior to the introduction of radioactive material, the types of radiological work activities performed, and the hazards and controls encountered. Updates to processes based on actual monitoring results are also discussed.**

Key words: contamination; fusion; lasers; maximum contaminate level; neutrons; operational topics; radioactive materials; surface contamination; tritium

Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory is the world's largest and most energetic laser system for inertial confinement fusion (ICF) and experiments studying high energy density (HED) science. Many experiments performed at NIF utilize or produce various types of radioactive material. Tritium and depleted uranium (DU) are used in the targets. When fusion experiments are performed, neutrons are produced, resulting in fission of the DU, fission products, and activation of systems, structures, materials and equipment (M&E). Fusion experiments also result in a prompt radiation hazard, which is discussed elsewhere in this journal. Radioactive contamination will be the primary radiological hazard discussed in this paper, including tritium, activation product contamination, and fission product contamination.

Most of the radioactive material used at NIF is related to fusion targets. Fusion targets typically contain a fuel mixture consisting of various isotopes of hydrogen, and may include tritium, deuterium, and protium. Briefly, a typical fusion target consists of a cylindrical "can" (called a hohlraum) with holes on the top and bottom to allow laser light to enter. As shown in Fig. 1, the hohlraum makeup is typically a core of aluminum coated with a layer of gold, although a small amount of depleted uranium (DU) may also be included. Inside the hohlraum is a small BB sized capsule which contains the fuel mixture of hydrogen-isotopes. The laser light is aimed to strike the interior surface of the hohlraum where it is converted to x-rays. The x-rays then impinge upon the capsule, ablating the surface. This ablation causes a compression of the fuel which continues until the temperatures and pressures are high enough to cause fusion of the hydrogen isotopes in the fuel. Varying the mixture of the hydrogen isotopes impacts the neutron yields. A typical capsule in a fusion target contains approximately 4 x 10^{11} Bq (10 Ci) of tritium, although when the fill system is also considered, the total tritium activity involved is somewhat higher (e.g., up to 2 x 10^{12} Bq (60 Ci)). The predominant reaction for high yield fusion shots is the deuterium-tritium reaction:

$$^{2}D\quad ^{3}T\quad ^{4}He\quad ^{1}n\ (14.1\ MeV)$$

NIF is currently authorized to create experimental neutron yields of up to 20 MJ, which equates to approximately 7.1 x 10^{18} neutrons per fusion target shot. As a consequence of neutron yields of this magnitude, activation of materials within the facility is an additional radiological hazard that must be considered. Materials of concern include structural materials, experimental and diagnostic components, equipment such as scaffolding, toolboxes, and hand-held power tools, and debris created from the target during the shot. Prior to fusion operations, NIF used the Monte Carlo code MCNP to model the projected activation products, which included predominately ^{196}Au, ^{198}Au, ^{239}Np, ^{24}Na, ^{54}Mn, and ^{55}Fe.

The introduction of DU as a component of the fusion target hohlraum creates additional radiological hazards. Small quantities of DU (typically on the order of 40 mg) can be incorporated in the wall of the hohlraum to increase the laser conversion (to x-rays) efficiency. The radiological hazard of the DU itself is minimal; however, high energy neutrons produced during the fusion reaction can cause fast fissions to occur in the DU. Due to the small quantity of DU that fissions, the direct radiation hazard from the fission products is of nominal concern; however, the fission products that are created and dispersed during a shot can result in a contamination hazard. Prior to fusion operations, MCNP modeling was used to project the expected fission products, which included predominately ^{131}I, ^{133}I, ^{140}Ba, ^{99}Mo, ^{142}Te, and ^{143}Pr.

As of the time of the writing of this paper, NIF's experimental shot schedule has not progressed to the higher yield capabilities. The radiological controls experiences described in this paper are based on neutron yield of approximately 8×10^{14} neutrons per shot, or about four orders of magnitude less than the design capabilities. At these yields, the predominant radiological hazard for early NIF operations is the contamination hazard; direct radiation levels are not yet significant.

STARTUP CHALLENGES

In planning for radiological operations at NIF, it was determined that certain practical aspects of NIF radiological operations would not be adequately or efficiently addressed by existing institutional processes. Therefore, NIF developed unique controls and processes, several of which related to contamination controls as discussed below.

Surface Contamination Control Levels

One of the first challenges was to determine an administrative surface contamination control level. Institutionally, LLNL abides by the Department of Energy's control levels specified in Part 10 CFR 835, *Occupational Radiation Protection*, Appendix D. For tritium, the initial and largest radiological contaminant expected at NIF, the Appendix D value is 2×10^4 Bq m^{-2} (10,000 dpm 100 cm^{-2}). When considering the values to choose for an administrative surface contamination control level, NIF radiological operations personnel wanted to ensure the ability to adequately control tritium contamination. Based on modeling, components that are present in the Target Chamber during a shot are expected to have the highest levels of tritium contamination on them due to their proximity to tritium filled fusion targets. Many of these components are frequently removed and handled in adjacent posted Contaminated Areas and therefore, some spread of tritium contamination to work surfaces in the area is expected. The low energy beta radiation emitted from tritium, compounded by an anticipated elevated ambient levels of radiation, makes it challenging to have real time feedback on contamination controls; thus, indirect monitoring is frequently performed (e.g., routine swipes analyzed via a Liquid Scintillation Counter).

NIF workforce's inexperience in working with radioactive materials was also a factor. Radiological work had not previously been performed in the NIF facility, and therefore the majority of the workforce was not experienced in contamination control practices. Because of this, NIF Radiological Operations management chose a conservative value less than the DOE limit for the administrative surface contamination control levels. A NIF-specific value of 2×10^3 Bq m^{-2} (1,000 dpm 100 cm^{-2}) (i.e., 10 % of the Appendix D value) was chosen for the tritium administrative surface contamination control level. Similarly, other administrative surface contamination control values were reduced to 50% of the 10 CFR 835 Appendix D value. See Table 1. The NIF-specific administrative surface contamination control values were considered to be initial control levels that would be evaluated as actual contamination control experience in the facility was gained. Additionally, a method was established to allow exceptions to be made on a case-by-case basis if the facility health physicist and facility Radiation Safety Officer agreed to invoke a higher contamination control level (up to the 10 CFR 835 Appendix D value).

Radiological Postings

Radiological postings for contamination controls are typically straightforward, with impacted areas frequently posted as Contamination Areas or Radiological Buffer Areas. Shortly after the introduction of radioactive materials, dispersible beryllium was also expected to be introduced into NIF operations. The dispersible beryllium was expected to be concomitant with radioactive contamination. Dispersible beryllium in the workplace also has required signage, which resulted in a concern that a single area could be overburdened with signage. To consolidate the required signage, NIF coordinated with the institutional radiation protection and industrial hygiene programs to create a combined sign that incorporated both the radiological and beryllium contamination hazards. The combined contamination hazard signs incorporated the Contamination Area and Radiological Buffer Area from the radiological control program. Since these areas would now be controlled for combined hazards, new titles were created to describe the areas: Buffer Zone (BZ) and Contamination Zone (CZ). The Buffer Zone sign consists of a Radiological Buffer Area and Beryllium Buffer Area along with the appropriate controls. The Contamination Zone sign consists of the traditional radiological Contamination Area and the Beryllium Work Area sign along with appropriate controls, as shown in Fig 2. The intent of the combined signs is to make it easier to post areas as well as effectively communicate the hazards and requisite controls.

Protective Clothing

Protective clothing used for contamination control purposes was an issue to be considered prior to initial operations, as the clothing had to function both as clean room garb (for cleanliness of the laser system) and contamination control garb for both radiological and beryllium contamination. The precision optics and diagnostics in use at NIF mandate a high level of cleanliness. To support this, the NIF Target Bay, where many radiological operations occur, operates as a cleanroom environment. Standard reusable (launderable) protective clothing was considered, but ultimately rejected since clothing made from linen cloth would not meet cleanliness requirements. Conversely, standard cleanroom apparel could not be laundered through a cleanroom laundry service because of the radiological contamination potentially present in the clothing. NIF Radiological Operations management therefore made the decision to utilize single-use (disposable) protective clothing that met the cleanliness requirements required for facility operations.

The level of radiological protective clothing required in BZs was also an issue to be addressed.. To compensate for the inexperience and question regarding the ability of facility workers to aggressively control tritium contamination and unknown tritium migration characteristics, it was decided to require disposable shoe covers and gloves when accessing BZs. Additionally, a decision was made to require frisking when exiting the CZs and BZs. While tritium was initially the predominant radionuclide (which cannot be detected by frisking), it was expected that DU hohlraums (resulting in fission products) would be introduced in a matter of a few months. With many inexperienced radiological workers, the radiological operations team decided that the most effective process would be to initially train the workers to frisk, rather than initially not requiring frisking and then adding it as a requirement only a few months later. After several months of practicing (and DU not yet having been introduced), the decision was made to not require frisking until detectable radioactivity was present.

Tritium Air Sampling

NIF fusion targets typically contain approximately 4×10^{11} Bq (10 Ci) of tritium, with up to an additional 2×10^{12} Bq (50 Ci) in the fill system. As a result of fusion shots (where some fraction of the tritium is consumed and the other fraction energetically distributed), the Target Chamber atmosphere can have elevated airborne concentrations of tritium. NIF has many contained volumes that communicate with the Target Chamber atmosphere, thus those contained volumes also have the potential for elevated airborne tritium concentrations. These volumes are maintained at vacuum during the shot, and therefore confinement of tritium at this time is not a significant concern. However, these volumes are routinely brought to air, so that their interiors can be accessed to perform target changeouts or diagnostic maintenance, for example, and therefore it is desirable to be able to measure the airborne concentrations prior to opening the contained volumes. To support this, the radiological operations group requested that a pair of quick-connect ports be installed on the contained volumes, with isolation valves between the volume and quick connect coupling as shown in Fig. 3. The quick connect couplings allow a portable tritium air monitor to be connected. The tritium monitor (in this case, an Overhoff Model 400SBDγC, Overhoff Technology Corporation, 1160 US Route 50, Milford, OH 45150) will then draw air from the potentially contained volume, monitor it, and discharge the air back into the contained volume. This process provides a method for determining airborne tritium concentrations, and any compensatory actions needed to be taken prior to access by personnel.

RADIOLOGICAL WORK ACTIVITIES

The major radiological work activities performed at NIF can be broken down into four major tasks areas:

- Optics Exchanges
- Target Manipulations
- Diagnostic Exchanges

- Target Chamber Entries

This section will explore these activities. Each major task area will be described, the radiological hazards and controls associated with the task discussed, and typical radiological conditions presented.

Optics Exchanges

As the laser beam enters the Target Chamber, it passes through a Final Optics Assembly (FOA), where frequency conversion and additional focusing occurs. This is accomplished through various optics located within the Integrated Optics Module (IOM) portion of the FOA as shown in Fig. 4. The optics are approximately 40 cm x 40 cm and varying thicknesses. Some of the optics are made of crystalline materials; others are made of silica glass. The optics need to be periodically switched either to support the changing optical properties required for the particular experiment, or because of small damage sites on the optic. Damage to the optic can occur when the high power laser beam interacts with dust or other material on an optic and creates a nucleation site for damage to grow. NIF inspects installed optics for damage and, when damage is noted, schedules the optic to be exchanged. Optics can then be transported to another NIF facility to be refurbished onsite. The optics in the IOM are serially positioned in slide-in slots and some are exposed directly to the Target Chamber atmosphere as shown in Fig. 5. This results in the optic closest to the Target Chamber volume having the most exposure to the contaminated atmosphere in the Target Chamber. The IOM slots and optics do not form a hermetic seal; however they do create a labyrinth pathway for contaminants to traverse, thus each subsequent upstream optic has less and less potential for contamination. The first three optics are the most radiologically significant. The optic closest to the target chamber is the Disposable Debris Shield (DDS) which functions as the primary debris shield (and is the most contaminated). The next upstream optic is the Grating Debris Shield (GDS) which aids in laser beam power balancing, and functions as a secondary debris shield. The third upstream optic is Wedge Focus Lens (WFL) which provides a focusing function.

The process for exchanging an optic involves removing a cover plate from the IOM vessel, attaching a case to the side of the IOM to withdraw the optic into, removing the case, and re-attaching the cover plate, as shown in Fig. 6. As previously discussed, the IOM volume communicates with the Target Chamber atmosphere. The main radiological concern is therefore the potential for airborne tritium and tritium contamination on internal components. Because of the cleanliness requirements for the optics, additional challenges are introduced. One such challenge relates to the ventilation requirements for the IOM. Prior to the introduction of radioactive material, optics exchanges occurred with positive ventilation in the IOM volume (i.e., air blowing out) to prevent dust and other particulate material from entering the IOM volume to support cleanliness. After the introduction of radioactive material, it was desirable to have negative ventilation in the IOM volume (i.e., air drawn in) to help contain any airborne or dispersible tritium. Because of the competing desires, a compromise was reached where the ventilation was left static, with no air flow in or out of the IOM. While static conditions were not the most desirable for radiological control purposes, it did eliminate the active discharge of the internal air volume to the worker's breathing zone.

A second challenge related to the cleanliness requirements involved the performance of contamination monitoring swipes. It was previously mentioned that optics upstream of the DDS are refurbished in other NIF facilities (DDS optics are disposed). For programmatic reasons, it was highly desirable maintain these facilities as non-radiological, thus requiring an unrestricted (free) release survey prior to their removal from the NIF. Developing a protocol to free release the optic was challenging because the face of the optic could not be directly swiped as any contact with the face of the optic has the potential for damaging the optic. An alternate protocol for release was developed where a metal frame around the perimeter of the optic was swiped and assumed to be representative of the overall optic contamination levels. Since the source of contamination was mostly elemental tritium, which would be dispersed by diffusion through the IOM, it was expected that the surface contamination level on the optic and its frame would be relatively uniform; therefore, swipes taken on the optic frame (perimeter) are considered to be representative of the overall surface, and free release actions are taken based on these swipes.

When preparing for optics exchange operations, expected contamination levels were estimated to be on the order of 1 to 100 times the DOE free release levels (i.e., 2×10^4 to 2×10^6 Bq m^{-2} (10,000 to 1,000,000 dpm (100 $cm^2)^{-1}$)). Two processes were developed to mitigate these expected contamination levels: a water wash process, and a process to continuously flow moist air past the optic surface. Each method was expected to reduce the contamination levels by approximately a factor of ten, thus potentially achieving free release levels.

Surface contamination was the only radiological hazard expected during the changeout activity; any airborne tritium was expected to be adequately mitigated by maintaining static ventilation conditions. Radiological controls for the surface contamination included the establishment of a CZ work area and the required used of anti-contamination clothing (coveralls, shoe covers and gloves). Swipes are taken in the work area for contamination monitoring and on the optics frame for free release evaluation. Additionally, portable tritium air monitors are used when removing the optic access covers on the IOM volume to monitor the internal tritium airborne concentration. After the initial year of operation, optic contamination levels were much lower than expected, and no airborne tritium was noted outside of the IOM volume. Optics upstream of the DDS were typically less than 8×10^2 Bq m^{-2} (500 dpm 100 cm^{-2}), and usually near the detection limit of the LSC. These levels allowed the optics to be free-released without requiring use of the mitigation processes. With a history of over a year's worth of data with no elevated results, optics upstream of the DDS are now being treated as non-contaminated. Swipes are still being taken on the first upstream optic (GDS) to continuously validate the non-contaminated status.

Target Manipulations

Targets are typically placed into the target chamber by one of two target positioners. The positioners essentially consist of an extendable and retractable boom, the end of which has a target mounted. When extended, the target is placed at Target Chamber Center, where the lasers can be accurately aimed. When retracted, a gate valve can isolate the target chamber (which is at vacuum) from the positioner. The retracted target at this point is in a vessel which will allow personnel access to exchange targets or perform other manipulations. There are two target postitioners (TARPOS); one that typically fields ‘warm’ targets (i.e., not cryogenically cooled), and a second positioner that typically fields cryogenically cooled targets (CryoTARPOS). Each positioner has a door on its vessel to access the target, as can be seen in Fig. 7. The CryoTARPOS vessel also has glovebox capabilities as shown in Fig. 8. Ignition targets are cryogenically cooled so that the fuel (typically a deuterium/tritium mixture) forms an ice layer on the interior surface of the capsule. The target assembly typically consists of a mounting base containing electrical and gas connections, a stalk projecting out from the mounting base, and the hohlraum/capsule assembly attached to the stalk, as can be seen in Fig. 9.

Work activities on the target positioners include target installation and removal, and various maintenance activities. Such maintenance activities could include work on the boom drive mechanism, cabling, electronics, or end effector. For the majority of the work evolutions, workers will stand at the vessel door and reach into the contaminated volume to perform the desired activities.

There are several radiological hazards associated with target manipulations. The tritium hazard is multifold for the target manipulation task. Prior to a shot, there is a discrete source of tritium (i.e., the fuel in the target and fill system) of 7×10^{11} – 2×10^{12} Bq (20-60 Ci). The tritium fill sources for the targets are loaded in a separate facility at LLNL and then transferred to NIF. There is potential for leakage or rupture of the fill source prior to installation in the positioner. Once installed, if an abnormal condition arises resulting in the target or fill system leaking or breaking, the tritium inventory of a target (elemental tritium gas) could escape into the positioner volume (approximately 7 m^3), and subsequently expose a worker to elevated levels of airborne tritium. Post-shot tritium hazards are related to the distribution of tritium in the target chamber and attached volumes. The potential for airborne tritium exists in both particulate and vapor forms. Particulate tritium is considered a possible hazard due to the debris created from the energetic distribution of the tritium filled target during a shot. Airborne tritium vapor is a continuing potential hazard. After numerous tritium target shots have distributed tritium throughout the target chamber and attached volumes, tritium vapor continues to evolve from the surfaces. Tritium contamination is also a hazard, and surfaces of the positioners have the potential for high contamination levels due to their very close proximity to the target source term. Additionally, as neutron yield goes up, activation of the positioner parts occurs and direct radiation doses can become a potential hazard.

Numerous controls are employed to mitigate the radiological hazards associated with target manipulations. To ensure no leakage occurs in the discrete tritium fill source during transport from the supply facility, a hermetically sealed transport container is used. This container has anti-shock features to lessen impact forces, and also provides a barrier to contain tritium that may have leaked out. Once at the NIF facility, this container is only opened in a hood or other ventilated enclosure.

Ventilation systems within the positioner volume are used to control the airborne tritium concentration. To lower the airborne concentration prior to opening the positioner vessel, a vent and pump process can be utilized. When the positioner is extended into the target chamber for a shot, the positioner vessel volume is at the same vacuum as the target chamber (approximately 1×10^{-4} Pa ($1 \times 10^{-}$

^{6} Torr)). When retracted, and the positioner vessel volume is isolated from the target chamber, the positioner volume can be vented to atmosphere, and then pumped down to a vacuum again. This process can be repeated until the tritium concentration in the positioner volume, as measured by an installed process tritium monitor, is at an acceptable level for opening, which is normally less than or equal to 1 DAC (7.4×10^5 Bq m^{-3} (20 µCi m^{-3}) for tritium vapor). After reducing the airborne tritium concentration, constant-flow negative ventilation can be initiated, which permits the positioner vessel to function as a ventilated enclosure, thus ensuring airflow into the vessel and allowing the door to be opened. When personnel access is needed in this configuration, personnel air monitoring for particulate tritium is prescribed. Optionally, the positioner volume can be used in glovebox mode, with manipulations made through installed gloves. In this mode, personnel are not exposed to the positioner atmosphere.

To address the radiological hazard associated with activation issues, dose rates are monitored on the positioner and extremity dosimetry is prescribed when contact with the positioner is part of the work scope.

Prior to opening the positioner vessel for target manipulation activities, a 'process tritium monitor' is used for airborne tritium monitoring. Portable tritium air monitors and personal air samplers are used to monitor for personnel exposure. Typical airborne tritium concentrations in the positioner prior to opening are approximately 7.4×10^6 to 1.1×10^7 Bq m^{-3} (200 to 300 µCi m^{-3}), however infrequent values in excess of 3×10^7 Bq m^{-3} (800 µCi m^{-3}) have been noted. After mitigation by the vent-and-pump method, an open positioner vessel will typically expose a worker to less than 3.7×10^5 Bq m^{-3} (10 µCi m^{-3}) (conservatively assumed to be tritium vapor, which has a DAC of 7.4×10^5 Bq m^{-3} (20 µCi m^{-3}). Workers are also monitored for particulate tritium via personal air samplers. The typical particulate tritium concentration observed is approximately 3.7×10^{-1} Bq m^{-3} (1×10^{-5} µCi m^{-3}) (DAC = 7.4×10^4 Bq m^{-3} (2 µCi

m^{-3})). With over a year's worth of data indicating such low tritium particulate concentrations, the requirement for personal air sampling for every task has been reduced. Personal air sampling is now required only for the first entry into the positioner vessel after a shot with a tritium target.

During target manipulation work activities, swipes are taken on components in the positioner vessel and in the local work area. Routinely, swipes are taken on the interior walls of the vessel, the positioner boom and end effector, and the floor in the local work area. Observed tritium contamination levels have been less than expected. For swipes taken on the vessel interior walls, average results have been approximately 2×10^4 Bq m^{-2} (10,000 dpm 100 cm^{-2}), with peak results typically no higher than approximately 1×10^5 Bq m^{-2} (60,000 dpm 100 cm^{-2}). Contamination levels on the positioner and end effector are expected to be higher due to the close proximity of the tritium filled target during a shot. Average results on the positioner itself have been approximately 3×10^4 to 5×10^4 Bq m^{-2} (20,000 to 30,000 dpm 100 cm^{-2}), with peak results typically no higher than approximately 1×10^6 Bq m^{-2} (600,000 dpm 100 cm^{-2}). The floor in the general work area is monitored as well. The area surrounding the vessel, while controlled as a CZ, has not exceeded 2×10^4 Bq m^{-2} (10,000 dpm 100 cm^{-2}). This data indicates that engineering controls and well implemented contamination control practices are effectively limiting the spread of contamination outside of the positioner vessel.

Diagnostic Exchanges

A large number of diagnostics are used to make scientific observations of the experiments conducted at NIF. Diagnostics are used to evaluate parameters such as laser performance, x-ray and gamma ray emission, and neutron production and are located throughout the target bay. As shown in Fig. 10, some diagnostics may be entrant to the target chamber, some may be mounted directly on the target chamber, and some may not be associated with the target chamber (and thus not associated with the target chamber's contaminated environment). Three special diagnostics, called Diagnostic

Instrument Manipulators (DIMs) are entrant into the target chamber. Two of these are located at the equator of the target chamber, and one is located at the upper polar area. These DIMs have interchangeable diagnostics (usually called a snout) that are attached to a boom that can be extended to position the diagnostic near the target during a shot. Because of this proximity to a tritium target during a shot, the snouts are subject to elevated tritium contamination levels, in addition to activation concerns. When retracted, a gate valve can isolate the DIM snout from the target chamber. The retracted DIM can then be positioned in its associated vessel which will allow personnel access to exchange snouts or perform other manipulations.

The target chamber has a diameter of approximately 10 meters, therefore other diagnostics that are mounted on the target chamber ports are positioned a minimum of 5 meters from the tritium filled target during a shot. This geometry results in much lower levels of tritium contamination reaching these diagnostics. Similarly, the levels of activation are much less on diagnostics that are not entrant than those of the snouts, which are often only centimeters from the tritium filled target during a shot.

Work activities associated with diagnostic exchanges are varied and include activities such as exchanging imaging media, exchanging various optical and x-ray filters, and exchanging snouts on the DIMs. Additionally, refurbishment or re-engineering of diagnostics which have been removed from the system is a routine activity.

Work activities associated with diagnostic exchanges have numerous radiological hazards. Similar to the target positioner, airborne tritium and tritium contamination are the major hazards. In the DIM vessels, airborne tritium is a hazard in both vapor and particulate form. As with the target positioner, particulate tritium is a potential hazard due to the close proximity of the DIM snout to the tritium target during a shot. Tritium contamination and airborne tritium in vapor form are expected throughout the target chamber and any attached volume. For non-entrant diagnostics that are attached to target chamber ports (which are at least 5 meters from the target at shot time), the airborne and contamination hazards are less than those associated with the entrant DIM. Additionally, activation of the DIM snouts and resultant direct radiation doses can become a potential hazard with high yield experiements.

Radiological controls for diagnostic activities are similar to other tasks. Prior to accessing the DIM vessel volume, airborne tritium activity can be measured by attaching a portable tritium air monitor to the installed sample ports. If elevated airborne tritium is observed, a vent-and-pump cycle can be initiated and repeated until the vessel tritium concentration is at an acceptable level. Upon removal of the access panel to exchange the DIM snout, negative ventilation is utilized, thus allowing the DIM vessel to function as a ventilated enclosure with air flowing into the vessel. When accessing a freshly exposed DIM snout, personal air sampling is also initiated to monitor for particulate tritium. Standard contamination controls are invoked for DIM snout exchanges, including posting the area surrounding the DIM vessel as a CZ.

As previously mentioned, contamination levels for non-entrant diagnostics are less than the levels observed for the DIMs. In the case of non-entrant diagnostics mounted on a target chamber port, very low levels of airborne tritium are expected. Although the contamination levels are not expected to be as high, the areas are still posted and controlled as CZs. When the non-entrant diagnostic is not connected to the target chamber volume, airborne tritium is not a consideration, and tritium contamination is unlikely.

Because DIM snouts can be both activated and have high levels of contamination, certain additional controls are provided for refurbishment activities. To mitigate dose consequences of activated DIM snouts, the refurbishment activities are not allowed to take place until an acceptable dose rate is achieved. DIM snouts are loaded into a hermetically sealed storage tube and placed into storage until the dose rates have decayed to less than 50 μSv h^{-1} (5 mrem h^{-1}). Once activation dose rates are at an acceptable level, actions to mitigate the contamination levels are taken. These actions may include working on the item in a hood or an enclosed ventilated room dedicated to contaminated work processes. Contamination levels may also be mitigated through decontamination by water wash in an ultrasonic bath.

Airborne tritium is well managed for diagnostic exchanges. Both entrant and non-entrant diagnostic exchanges are monitored, and in both cases, results average less than 7.4×10^{5} Bq m^{-3} (20 μCi m^{-3}). Concentrations for non-entrant diagnostics are well less than this value. Personal air samples for particulate tritium are also taken. For DIM snouts, typical particulate airborne concentrations are approximately 3.7×10^{-1} Bq m^{-3} (1×10^{-5} μCi m^{-3}), and for non-entrant diagnostics, typical particulate airborne concentrations are approximately 3.7×10^{-2} Bq m^{-3} (1×10^{-6} μCi m^{-3}). With over a year's worth of data indicating such low tritium particulate concentrations, the requirement for personal air sampling for every task was reduced to being required only for the first entry into the DIM vessel after a tritium target shot. Particulate tritium air monitoring for non-entrant diagnostics was eliminated completely.

During diagnostic exchange work activities, swipes are taken on components in and around the diagnostic and in the local work area. For the DIMs, swipes are taken on the interior walls of the vessel, the DIM snout, and the floor in the local work area. For swipes taken on the vessel interior, including the snout, average results have been approximately 5×10^{4} Bq m^{-2} (30,000 dpm 100 cm^{-2}), with peak results typically no higher than approximately 5×10^{5} Bq m^{-2} (300,000 dpm 100 cm^{-2}). For non-entrant diagnostics, the average results on the diagnostic itself have been approximately 2×10^{3} Bq m^{-2} (1,000 dpm 100 cm^{-2}), with peak results typically no higher than approximately 5×10^{4} Bq m^{-2} (30,000 dpm 100 cm^{-2}). The floors in the general work areas around the diagnostics are monitored as well. The areas surrounding the diagnostics (both entrant and non-entrant), while controlled as a CZ, do not exceed 2 ×

10^4 Bq m^{-2} (10,000 dpm 100 cm^{-2}). This indicates that contamination control practices are well implemented by the workers, thus limiting the spread of contamination outside of the diagnostics. With over a year's worth of data indicating such low tritium contamination levels for non-entrant diagnostics, certain diagnostics are no longer being worked as contaminated jobs.

Target Chamber Entries

Periodically (typically 2-3 times a year), maintenance or operational activities necessitate personnel entry into the target chamber. When this need arises, the target chamber, which is normally at vacuum, is brought up to atmosphere. During this process, the chamber is vented and pumped several times to reduce the airborne tritium concentration. The target chamber is accessed from an access port located on the bottom of the target chamber vessel. The port cover, known as the plenum plug, can be removed with special tooling from the bottom, and lowered to the floor. Once opened, negative ventilation is initiated which maintains airflow into the target chamber. Personnel access is accomplished through the plenum plug opening via a special personnel lift called the Target Chamber Service System (TCSS) as shown in Fig. 11. This dedicated lift elevates personnel into the target chamber, and once inside, the TCSS can articulate to allow personnel to reach all surfaces of the target chamber interior.

Because the target chamber contains the debris and residual material from shots, it has the highest source term for contamination and airborne tritium. Additionally, material present inside the target chamber is subject to the neutron environment produced during shots. The interior of the target chamber has a replaceable louvered surface made of stainless steel called the first wall. The purpose of the first wall is to limit laser light reflections and protect the aluminum surface of the target chamber vessel. The stainless steel first wall and other materials present in the target chamber, including debris, are subject to activation and can provide whole body as well as extremity exposures. Activated particulate from debris is also considered as a contamination source and has potential for re-suspension as an airborne hazard.

Special radiological controls have been developed for removal of the plenum plug. It is expected that the plenum plug serves as a collection point for some of the debris from shot targets and contamination that falls to the bottom of the target chamber. Thus, when the plenum plug is removed, high levels of contamination on the inner surfaces are potentially exposed. Additionally, with the plenum plug removed, the target chamber is exposed to atmosphere. To mitigate contamination and airborne radioactivity concerns, an enclosure was built around the lift, the storage area for the removed plenum plug, and the resultant opening in the target chamber. This permanent structure, the Plenum Plug Contamination Control Enclosure (PPCCE), is constructed from Plexiglas and is designed to limit the spread of contamination to inside its boundaries. See Fig. 12. The PPCCE has an installed tritium air monitor and is separately ventilated to maintain a negative pressure relative to its surroundings. It also contains local task ventilation that is used for the plenum plug while it is removed and in storage.

Due to the high contamination levels expected, once opened for personnel entry, the target chamber is controlled as an airborne radioactivity area as well as a high contamination area. When making entry to the target chamber, a double set of disposable coveralls and Powered Air Purifying Respirator (PAPR) are prescribed. The respirator is used to protect against potential airborne activation products and tritium particulate. Personal air samplers are also issued to workers making entry into the target chamber. In addition to the routinely worn TLD, exposures to the whole body are monitored by alarming electronic dosimeters, and to the extremities by ring dosimetry worn on the hands.

During entries into the target chamber, swipes are taken on both the plenum plug itself, and on articles and surfaces inside the target chamber that are to be accessed. Swipes taken on interior surfaces of both the plenum plug and interior of the target chamber have an average range of 2×10^5 to

8×10^5 Bq m^{-2} (100,000 to 500,000 dpm 100 cm^{-2}). Typically, the maximum contamination levels are approximately 2×10^6 Bq m^{-2} (1,000,000 dpm 100 cm^{-2}). Contamination levels on the floor inside the PPCCE area also monitored. Typical contamination levels do not exceed 3×10^4 Bq m^{-2} (20,000 dpm 100 cm^{-2}), indicating the high contamination levels of the target chamber are being adequately controlled.

Bulk activation of materials resulting in dose rates is also a potential radiological concern. Dose rates from the first wall and other interior components are taken upon entry. No dose rates greater than 50 µSv h^{-1} (5 mrem h^{-1}) have been noted during target chamber entries with the yields achieved in the first year of operation.

Routine Operations

In addition to the radiological controls and monitoring for the specific work activities discussed above, routine area monitoring is performed. Area swipes are taken both in and outside of radiologically posted areas to monitor the effectiveness of the contamination control practices employed by the workers. Swipes taken within radiologically posted areas include the general areas of CZs, BZs, and Radioactive Materials Areas (RMAs). Swipes taken outside of RMAs include just outside of access points, walkways, break areas, and meeting rooms. For the calendar year of 2011, over 17,300 routine area monitoring swipes were taken. Of these, no swipe indicated greater than 8×10^2 Bq m^{-2} (500 dpm 100 cm^{-2}) tritium, confirming that work practices were effective at minimizing the spread of contamination both within posted CZs, as well as outside. After approximately a year of work observation and survey data, NIF Radiological Operations management reviewed the administrative surface contamination control level that was initially established at 2×10^3 Bq m^{-2} (1,000 dpm 100 cm^{-2}). Based on the observed ability of the workforce to maintain good contamination controls, it was decided to increase the tritium administrative surface contamination control level to 8×10^3 Bq m^{-2} (5,000 dpm 100 cm^{-2}) (i.e., 50% of the 10 CFR 835 Appendix D value). For radiation types other than tritium, the surface contamination control levels were established at the 10 CFR 835 Appendix D values.

CONCLUSION

NIF experiments now include the use of radioactive material. While a variety of radionuclides are expected as neutron yield continues to increase (hence increasing the amount of fast fission products from DU, and activation products), at current levels of neutron yield, the only radionuclide of significance is the tritium used in many NIF targets. Prior to the introduction of radioactive materials into NIF, the radiological protection management team determined that several issues related to contamination control warranted a unique approach. This was influenced by the work force's inexperience as radiological workers and the somewhat unique challenge associate with performing radiological work in a clean room environment. Protocols, many of which were intentionally initially conservative, were established and implemented to address these factors.. In most cases, after experience and radiological data were gained, the controls were relaxed to a more appropriate level commensurate with the observed hazard. After performing radiological work activities for over a year, the level of contamination on items entrant to the target chamber during a shot has been observed to be lower than the projections used during the planning process. Additionally, worker contamination control practices and effectiveness of engineered controls, as evidenced by the minimal spread of tritium contamination, have been better than expected.

ACKNOWLEDGMENTS

The author would like to thank Sandra Brereton, Kenneth Kasper, and Kathleen Shingleton for their invaluable comments on the manuscript.

Fig. 1. (A) Cutaway view of hohlraum showing lasers entering top and bottom and internal fuel capsule. (B) Picture of target hohlraum showing top laser entry hole.

Table 1. Department of Energy's contamination control levels specified in Part 10 CFR 835, *Occupational Radiation Protection*, Appendix D compared to administrative control levels chosen by NIF.

Radionuclide	App D Removable Bq m^{-2} (dpm $100cm^{-2}$)	App D Total Bq m^{-2} [Fixed + Removable] (dpm $100cm^{-2}$)	NIF release goal Bq m^{-2} [Removable] (dpm $100cm^{-2}$)
Depleted-U, U-Natural, ^{238}U, ^{235}U, and associated decay products	2,000 (1,000) α	8,000 (5,000) α	800 (500) α
Transuranics, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{231}Pa, ^{227}Ac, ^{125}I, ^{129}I	30 (20)	800 (500)	(same as App D)
Th-Nat, ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U, ^{126}I, ^{131}I, ^{133}I	300 (200)	2,000 (1,000)	200 (100)
β/γ emitters except as noted above. Includes mixed fission products that include ^{90}Sr.	2,000 (1,000) β/γ	8,000 (5,000) β/γ	800 (500) β/γ
Tritium and tritiated compounds	20,000 (10,000)	NA	2,000 (1,000)

Fig. 2. Example of signs incorporating both radiological and Beryllium hazards. (A) shows a Buffer Zone consisting of a Radiological Buffer Area and Beryllium Buffer Area. (B) show a Contamination Zone

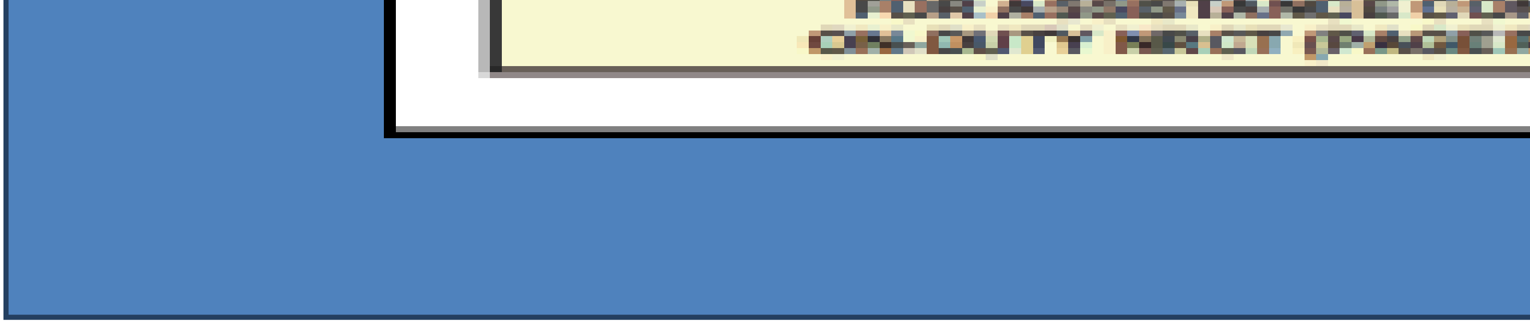

Fig. 3. Ports for performing air samples on contained volumes. (A) shows the quick connect couplings with isolation valves. (B) shows a worker connecting a tritium monitor to sample ports on a diagnostic

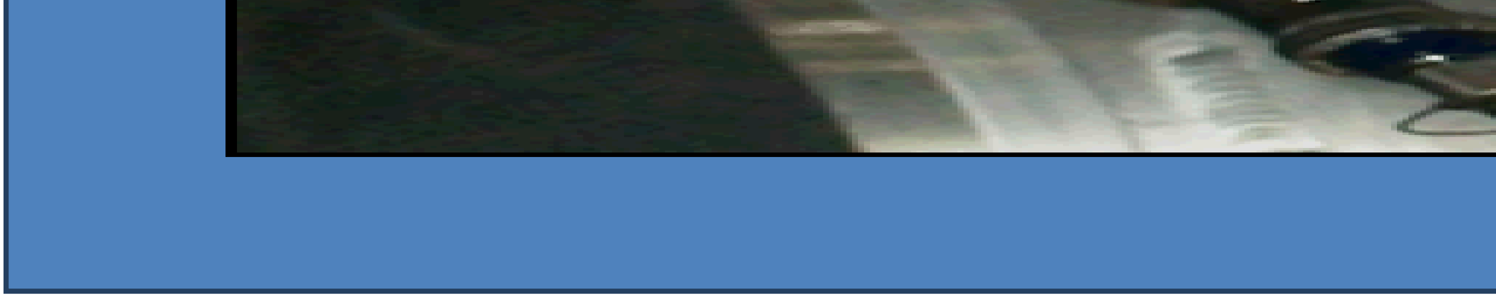

Fig. 4. NIF Final Optics Assembly showing optical components in the Integrated Optics Module.

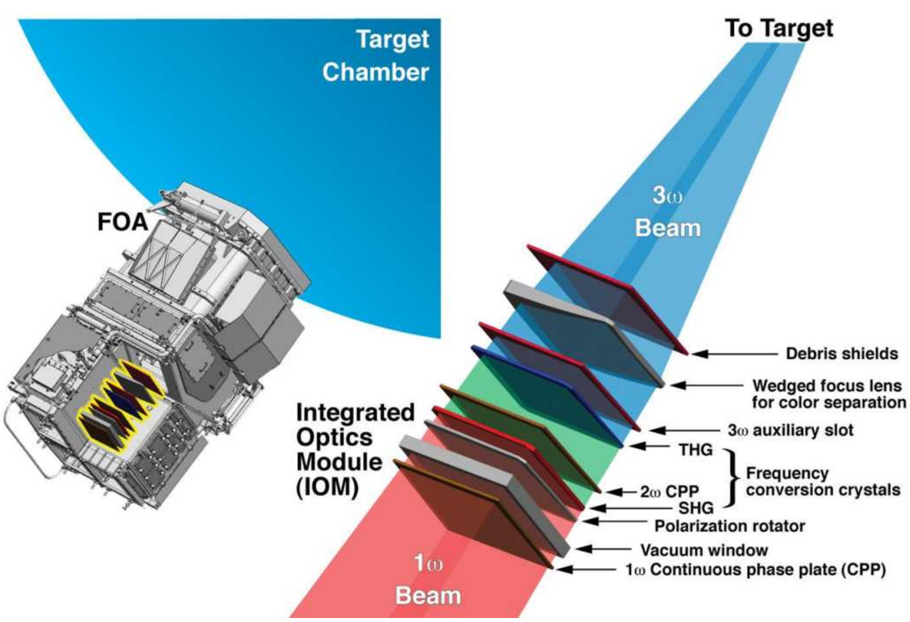

Fig. **5**

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ntegrated Optics Module showing position of optics.

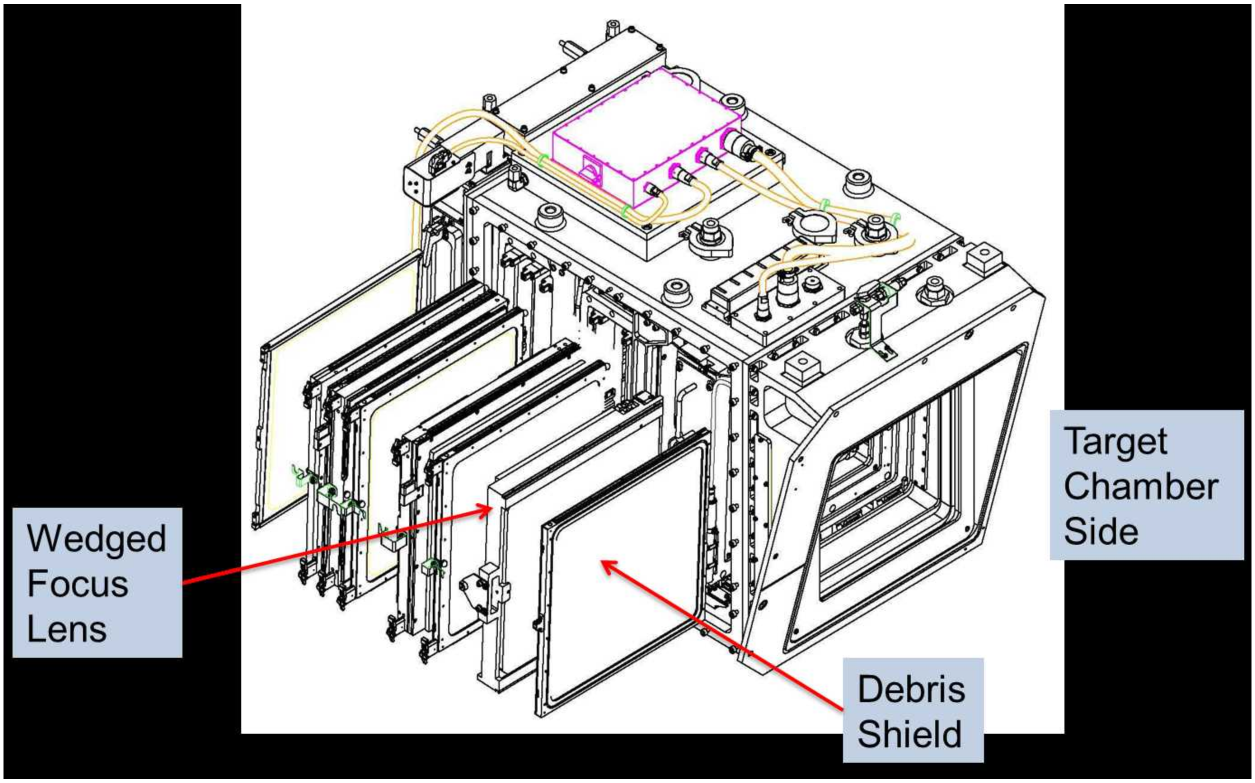

Fig. 6. An optics exchange occurring on the Integrated Optics Module. After a cover panel is removed, a case is attached into which the optic is withdrawn

Fig. 7. CryoTARPOS Target Positioner vessel with door open.

Fig. 8. CyroTARPOS Target Positioner with door closed in glovebox mode.

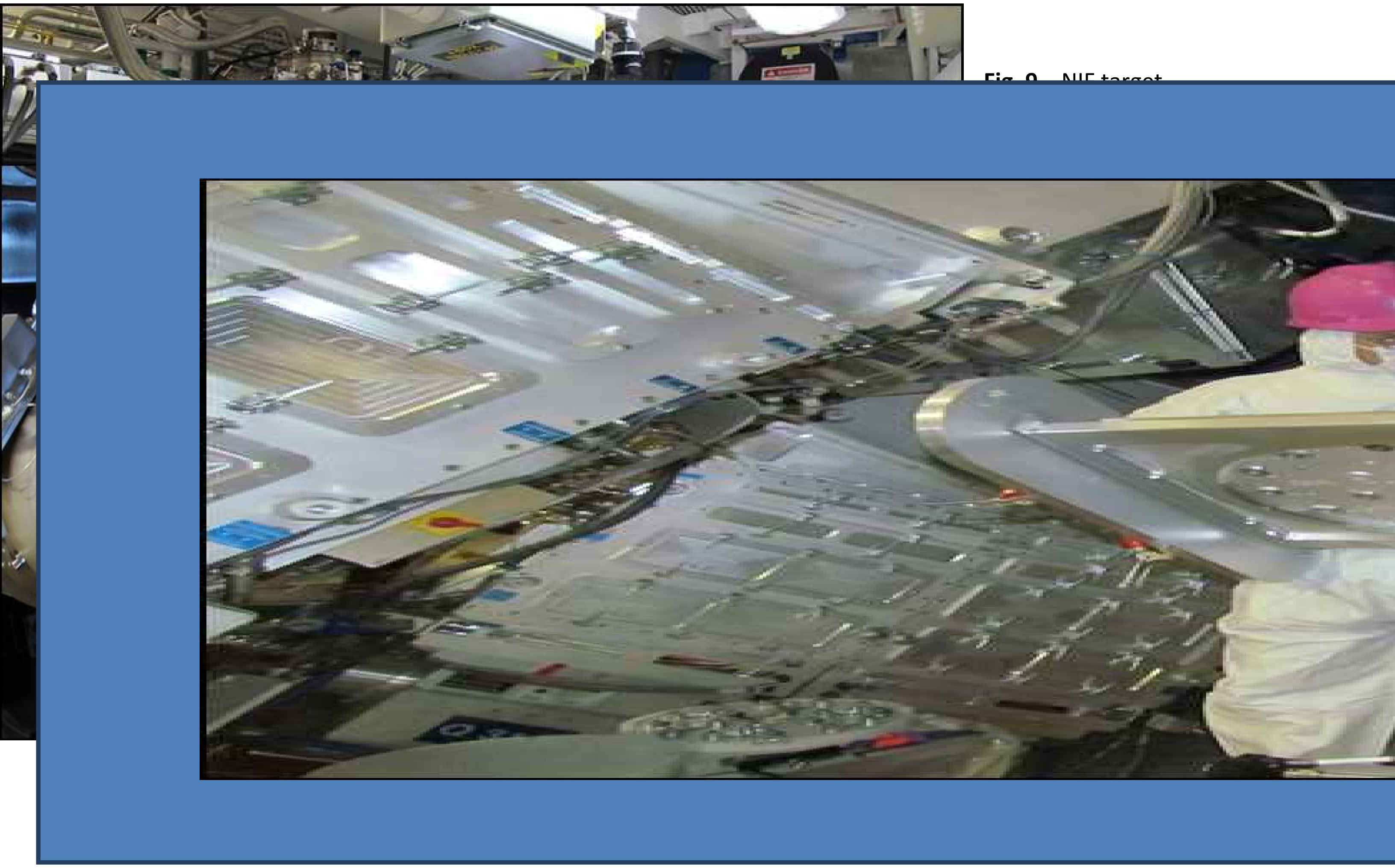

Fig. 9 – NIF target

Fig. 11. Interior of Target Chamber showing personnel in the Target Chamber Service System.

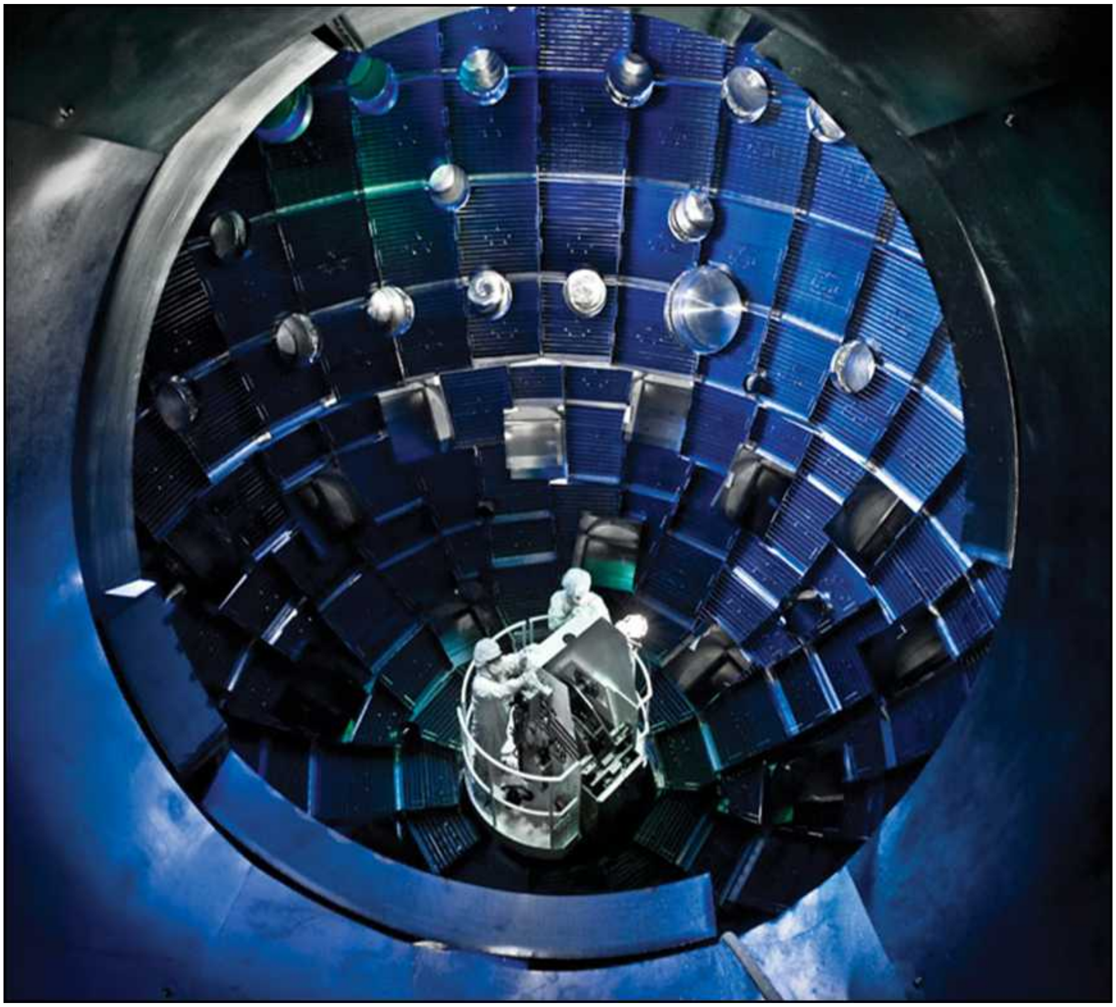

Fig. 12. Looking into the Plenum Plug Contamination Control Enclosure as workers prepare to enter the Target Chamber Service System lift.

Managing NIF Safety Equipment in a High Neutron and Gamma Radiation Environment§

Philip Datte, Mark Eckart, Mark Jackson, Hesham Khater, Stacie Manuel, Mark Newton*

Name and address for correspondence:

Philip Datte, L-440

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX 925-422-9554

Telephone: 925 422-8819

e-mail: Datte1@llnl.gov

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Abstract

The National Ignition Facility (NIF) is a 192 laser beam facility that supports the Inertial Confinement Fusion program. During the ignition experimental campaign, the NIF is expected to perform shots with varying fusion yield producing 14 MeV neutrons up to 20 MJ or 7.1×10^{18} neutrons per shot and a maximum annual yield of 1200 MJ. Several infrastructure support systems will be exposed to varying high yield shots over the facility's 30 year life span. In response to this potential exposure, analysis and testing of several facility safety systems have been conducted. A detailed MCNP (Monte Carlo N-Particle Transport Code) model has been developed for the NIF facility and it includes most of the major structures inside the Target Bay. The model has been utilized in the simulation of expected neutron and gamma fluences throughout the Target Bay. Radiation susceptible components were identified and tested to fluences greater than 10^{13}(n cm^{-2}) for 14 MeV neutrons and gamma ray equivalent. The testing includes component irradiation using a ^{60}Co gamma source and accelerator based irradiation using 4 and 14 MeV neutron source. The subsystem implementation in the facility is based on the fluence estimates after shielding and survivability guidelines derived from the dose maps and component tests results. This paper reports on the evaluation and implementation of mitigations for several infrastructure safety support systems including video, oxygen monitoring, pressure monitors, water sensing systems and access control interfaces found at the NIF.

Keywords: Neutron Activation, Radiation Damage, Neutron Mitigation, Occupational Safety

Introduction

The National Ignition Facility (NIF) is a 192 laser beam facility that supports the Inertial Confinement Fusion program. The facility described in Fig. 1 consists of two laser bays, their associated switch yards and the Target Bay that includes the Target Chamber. During the ignition experimental campaign, the NIF is expected to perform shots with varying fusion yield (up to 20 MJ or 7.1 x 10^{18} neutrons per shot) and a maximum annual yield of 1200 MJ. A deuterium-tritium (D-T) target shot will generate primarily 14 MeV neutrons at Target Chamber Center (TCC) that propagate outward from the center of the Target Chamber in a pulse of approximately 25ns wide. The neutrons pass through the chamber wall and into the Target Bay with multiple scatters resulting in a high fluence, broad energy band of neutrons and gamma rays. When the scattering process results in energy deposition into the material, the deposited energy can lead to permanent changes resulting in damage to that material. At shot time, several infrastructure support systems will be exposed to the high yield shots over the facility's 30 year life span. During this process, the scattering neutrons will interact with various electronic components located in the target bay causing operational concerns including "upsets", (memory corruption in electronics, communication errors, false alarms) and permanent damage to a subsystem. In response to this potential radiation exposure, analysis and testing of several facility safety systems have been conducted to establish management guidelines for these systems. The guidelines include operational risk based on location, sensor longevity, and conduct of operations for each safety system. Each system will have a unique type of mitigation depending on the risk of failure with the goal to assure continued reliable operation.

The TB shown in Fig. 2 contains many of the facility safety systems that require some sort of mitigation. The six foot thick target bay wall is part of the radiation shielding system that is designed to reduce radiation levels outside the Target Bay to below the level of concern. Examples of equipment that are exposed to neutrons, include but are not limited to, are the positioners, advanced fusion diagnostics, alignment instruments, monitoring systems, seals and o-rings, optical fibers, optics, motors, air handling systems and safety systems. This paper will emphasize the radiation dose effects and mitigations related to the safety systems located inside the Target Bay.

The exposed safety systems include oxygen monitors and pressure sensors to monitor argon, fire alarms, air ventilation systems controls, and video surveillance cameras. Oxygen monitors are used to measure the oxygen content in and around beam tube locations that contain argon and pressure sensors are used for HVAC control. Argon is used in the laser beam tubes to prevent beam degradation through Stimulated Rotational Raman Scattering (SRRS) ref.[2] that would occur if the tube contained air. If the argon escapes the beam tube, it will displace the local oxygen in the area potentially causing a health hazard for the workers in the immediate vicinity. Fire alarms are part of the standard infrastructure in the facility. A unique feature with the NIF alarms is that they are in direct contact with the local onsite fire station. The alarms are in operation 24 hours per day seven days a week and have the potential to false alarm when a NIF shot occurs due to the neutron field. Air ventilation in the facility is required to maintain a fixed ambient temperature to prevent thermal fluctuations of the beam tube optical systems and the precision optical alignment system. In addition, the air handling system provides pressure differentials to assure that any airborne contaminants are not dispensed throughout the facility. Further, the air exhaust rate is sufficiently long to allow for significant decay of activated species before any residual is discharged through the monitored, elevated release point. Although this activation is short lived, management of the air flow is an important part of the overall safety strategy of the facility. The NIF Target Chamber has several video systems that monitor prior to and during post shot activities. The video systems are directly mounted to port locations and are in the direct line of sight of the unshielded neutron field. The requirement that the system be mounted on the port and that it must be operational before and after a shot requires a robust system that has the most stringent radiation tolerance demands.

All of the aforementioned systems can be described as commercial off the shelf (COTS) hardware or based on the mitigation requirements could be a modified COTS system without loss of functionality. Table 1 provides is a summary of the various systems of interest that are currently deployed in the facility and their associated quantities. The required mitigation has several components that may be addressed. The major goal is to increase the longevity of the subsystem, and if applicable to be operational during a shot, and be easily replaceable if damaged. The mitigation plan is to establish “upset” and “damage” levels for the NIF systems and verify these levels with 14 MeV neutrons at NIF fluences if possible. Action would then be taken before the “upset” level is reached to assure continued reliable operation.

Detailed Monte Carlo radiation transport calculations were performed to establish the expected radiation field in the Target Bay and Target Chamber area. The instrument locations were identified on the maps to establish the local dose levels in which the system would be expected to operate. The shot history of a system is tracked and cumulative dose levels are monitored and compared to the expected levels for upset and damage. Based on this comparison a system can be managed though an operational plan. Finally an upset or damage metric is tracked and fed back in the dose level models as part of the overall upset and damage predictions for the system.

Subsystem Evaluation

In anticipation of the expected varying yields on NIF, a program was undertaken to assess the radiation effects on various installed components and systems, and develop a path to operate these systems in a radiation environment. For a typical shot guidance, there are at a minimum five entities that go into providing the subsystem shot guidance. These include component effects guidelines, environment simulations, component vulnerability of the subsystem, cumulative dose and the expected dose. Fig. 3 is a shot guidance diagram that represents the various inputs that go into determining the guidance for a given shot and the conduct of operation for a safety subsystem.

The evaluation process begins with the component effects guidelines. An extensive literature search was conducted to establish a baseline for various thresholds relating to upsets and damage of electronics and supporting systems. The results of this literature search showed several short comings related to the relevance of existing COTS parts used on NIF. The search identified components that are now obsolete or parts that were fabricated in a transistor feature size that is not scalable to the NIF type components. Also there is difficulty identifying the relevant energy scaling related to 14 MeV neutrons versus the abundant thermal neutron data that currently exists. These short comings were investigated though a testing program describe below.

Experimental Testing

To establish a baseline for the COTS systems that are planned or deployed on the NIF, a testing program was developed to evaluate the subsystem using fluences and neutron energies that a system would experience in operation. The details of the testing facility and processes are described in the “Electronic Testing Examples” section of this article. The testing consisted of irradiating a variety of electronic and fiber systems with 14 MeV neutrons in the power ON and power OFF state. The performance was measured during the irradiation process to establish the upset and damage thresholds. If the exact system could not be tested a similar system was used as a surrogate. The electronic systems were grouped in categories; for example, digital electronics would include memories, microprocessors, EPROMs, FPGAs etc., ADC and DAC devices and analog electronics would include, capacitors, resistors, discrete transistors, transformers, displacement sensors. CCD and CMOS sensors were measured for their pixel performance as well as the ability to communicate and transfer data. Results from these tests when combined with the values from the fluence maps were used to establish the general operational guidelines for each system. Fig. 4 is the representation of a typical grouping for electronic systems. These groups are used to determine a class of electronic system that have similar upset or damage thresholds.

Once the thresholds are established, the shot performance results from individual shots are compared to the upset and damage predictions for the system and location. Mitigation would be implemented based on performance history and conduct of operation strategy. This may include operating on a shot and accepting performance degradation, or removing a vulnerable part during the shot and reinstalling it after a shot.

Radiation Transport Simulation

Accurate fluence maps are another key element to the conduct of operations for a particular instrument. The maps, which have approximately 1ft resolution, provide the estimated fluence values an instrument can expect to experience during a yield shot. An example of a fluence map, for the target bay location 17ft 6in equator level is shown in Fig. 5. The map is established from detailed models integrated into the MCNP (Monte Carlo Neutral Particle) codes Ref[1]. The example map displayed describes the predicted fluence for a 20MJ shot that will produce 7.1×10^{18} neutrons. The resulting fluence is linear with yield, and is used to scale any expected shot yield.

With the equipment damage thresholds established and fluence maps developed for the facility, the subsystem performance can be predicted for a given NIF shot. The evaluation considers the subsystem location and the measured subsystem behavior at a unique location in the neutron field.

The final area of review for the subsystem is related to the type of components that are part of a subsystem and the impact this part has on the overall system performance. For example, electronic components are of higher damage risk than the optic components. In considering the type of mitigation applied to a subsystem, a priority is given to a particular component, based on the relative vulnerability of the component in the subsystem. Guidance is based on the most vulnerable component first and usually defines the conduct of operations

Electronic Testing Examples

As mentioned in the previous section, the electronic upset and damage thresholds must be established for each subsystem in the facility. Several COTS components were tested in a neutron field to establish these limits. The Edwards Accelerator Facility Ref [3] located at the Ohio University campus was used for the component testing program. The facility offers (D-T) 14 MeV ± 0.6 MeV neutrons at a flux of 1.85×10^{7} (n Sr^{-1} C^{-1}), at zero degrees. At these levels only the most vulnerable system components could be tested when compared to the expected NIF levels.

Example test results for the oxygen monitor is discussed and the data is displayed in Fig. 6. For this test the oxygen monitor controller with the sensor was tested as an assembly and then separated and tested as individual components. The first upsets from the controller and sensor combination occurred at the fluence level of ~$2x10^9$ (n-cm^{-2}) or 2 (Rad-Si). This yielded similar results for four consecutive tests. The upset condition occurs when the monitor output fluctuates between the ON and OFF state as displayed in the data recording in Fig. 6. For the system to be functioning properly a DC voltage reading is represented on the graph as a flat line. As the cumulative radiation dose is increased the "upsets" begin to occur. The upset for this system is described as the unit resetting observed by the voltage level change in the recording. This phenomenon is not permanent damage as the system recovers to the original voltage level over time or on a power reset. The sensor was then separated from the controller and the tests were repeated for only the controller and comparable upset values were recorded. Testing of the oxygen sensor separated from the controller was completed in four independent runs and only one upset was observed at ~$8x10^9$ (n cm^{-2}) or 7 (Rad-Si).

This information was combined with a fluence map for the oxygen monitor in the Target Bay and shown in Fig. 7a. The maps show that regardless of where the sensor is physically located, the neutron field is too high for long term operation. Based on the location and the test results from the accelerator data, this system was modified to allow the safety monitors to be removed during a shot shown in Fig. 7b. During a NIF shot, personnel are restricted from being in the target bay, and therefore removal of this safety system is an acceptable solution. This required changes to the monitoring software, mechanical assembly and the electrical interfaces. The software changes allowed the measurement to function in a non-continuous manner and provides the capability to turn the instrument off for a shot without alarming. The mechanical additions included new connector locations and quick connect mounting hardware integrated into the overall enclosure assembly. The electrical changes included quick disconnect connectors with socket guides for an alignment aide.

Another example of a microcontroller based safety system is the facility access panels that read the personnel badge information when an individual is accessing a specific floor of the Target Bay. Fig. 8a illustrates the possible locations where the panel could be mounted. This system used throughout all of NIF contains a magnetic card reader, a liquid crystal display (LCD) and contains a local microcontroller that interfaces to a larger facility access control system. This facility access panel is the main control point for access in and out of the Target Bay. It provides access into a particular area and also logs personnel access information as to who and when an individual was granted entry into a particular location. In addition, the panel also displays the various Target Bay status messages relating the safety conditions at the location that is being requested. Several radiation damage related failure modes could exist without taking proper mitigation steps. The failure modes include LCD failure preventing or mislabeling status messaging and access data logging failures preventing personnel tracking and access feedback. Information collected from the fluence maps and testing program was used to establish radiation exposure limits anticipated for this control panel. Fig. 8 also shows an example of the mitigations that were taken based on the physical locations and the vulnerable components that existed in the unit. The mitigation for the panels used in the Target Bay was to remove the microcontroller and replacing the LCD with individual radiation hard LED status display windows.

Similar test were completed for several types of subsystem components including charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS) cameras, digital oscilloscopes, pressure sensors and several types of microprocessor based controllers. The extensive testing showed that regardless of the system, any COTS subsystem that includes digital components, upset or failed above ~$2x10^9$ (n cm^{-2}). Table 2 provides a summary of the subsystem failures when exposed to 14 MeV neutrons. The analog systems that were tested did not exhibit any failures below the cumulative fluence of $1x10^{11}$ (n cm^{-2}).

The limited time operating on the neutron source prevented testing at higher fluence levels.

Based on the results from these neutron tests, guidelines for operating the NIF safety systems in the Target Bay are established. In addition, the testing information is used to provide input into the initial safety system designs to extend the operability of the unit or to allow easy access for replacement or removal of susceptible subsystems. For the oxygen sensors, this includes separating the sensor head from the microcontroller and where appropriate providing quick disconnect connectors and access points to physically remove the unit during a shot. Table 3 lists of several safety systems and the type of mitigation taken in order to field the particular subsystem. Some mitigation is more extensive than others with the overall goal of providing operational functionality pre and post NIF shot.

Conclusion

The NIF Target Bay contains several types of safety systems that must be managed in order to assure proper operation during a high yield shot cycle. After extensive component testing, neutron mitigation guidance has been established to allow for functional operation prior to or post shot activities. The mitigation involves modification to COTS systems or designing features into the subsystem that allows for quick removal and installation before or after a shot. Some types of mitigation are simply allowing the subsystem to be powered down during the shot to prevent a false alarm trigged by an erroneous radiation event. Other mitigations take advantage of the natural concrete structures of the building to provide shielding to extend the lifetime of the unit. There is no single mitigation that encompasses all the different systems found in the NIF and each subsystem requires upfront planning and analysis that takes into account the effects of radiation emanating from the target during a shot.

References

[1] "Stimulated rotational Raman scattering in nitrogen in long air paths", Optical Letters, November 1985, Vol. 10 No. 11, pp.565-567.

[2] X-5 Monte Carlo Team, *MCNP - A General Monte Carlo N-Particle Transport Code, Version 5*, LA-UR-03-1987, Los Alamos National Laboratory (LANL) (2003).

[3] "The Ohio University Beam Swinger Facility", Nuclear Instruments and Methods, 198 (1982) pp. 197-206. R.W. Finlay, C.E. Brient, D. E. Carter, A. Marcinkowski, S. Mellema, G. Randers-Pehrson, and J. Rapaport.

Fig.1 Sectional view of the National Ignition Facility. The facility includes the Main Lasers, two Switch Yards, Target Bay, Target Chamber and supporting buildings.

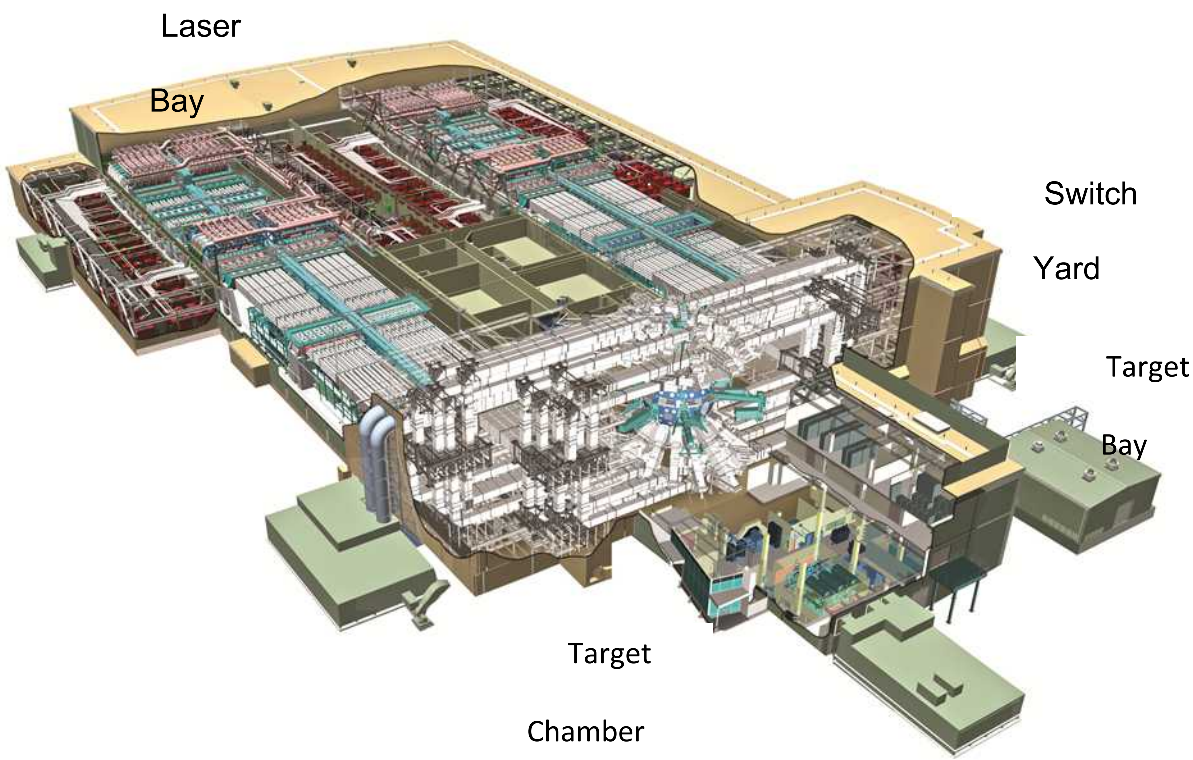


Fig. 2 Shows the 17’6” (equator) sectional view of the NIF Target Bay. The red stars indicate the nominal locations of various systems that require neutron mitigation.

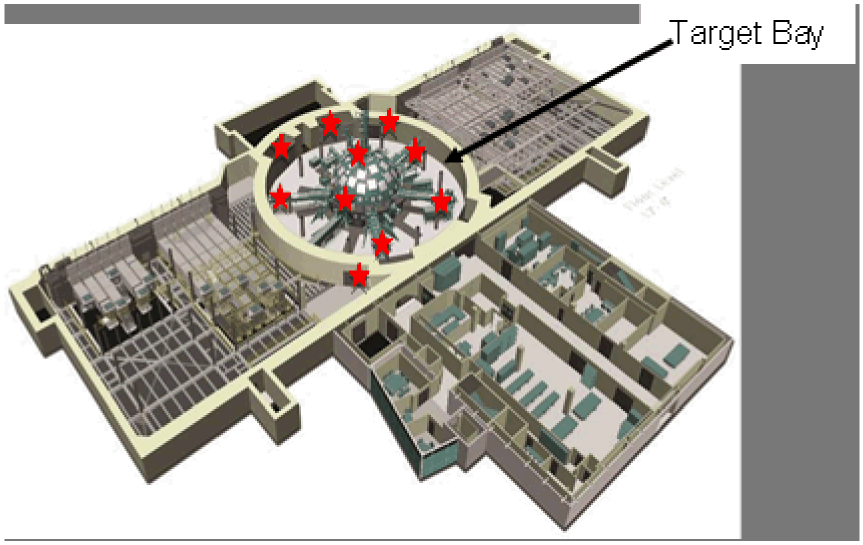


Fig. 3 Shot guidance diagram illustrating the various aspects that define the conduct of operations for a typical NIF safety system.

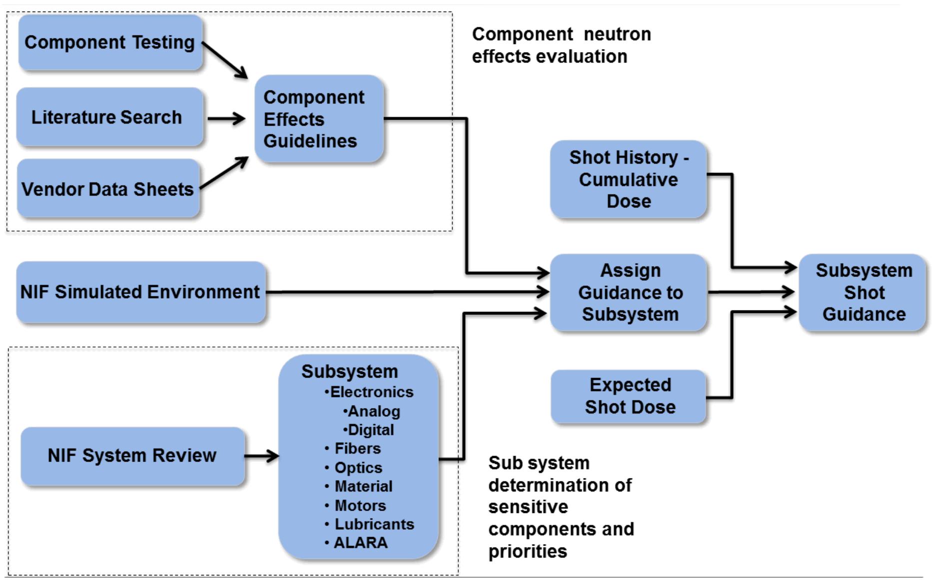


Fig. 4 Is a list of groups that contain various electronic systems that exhibit similar upset and damage thresholds.

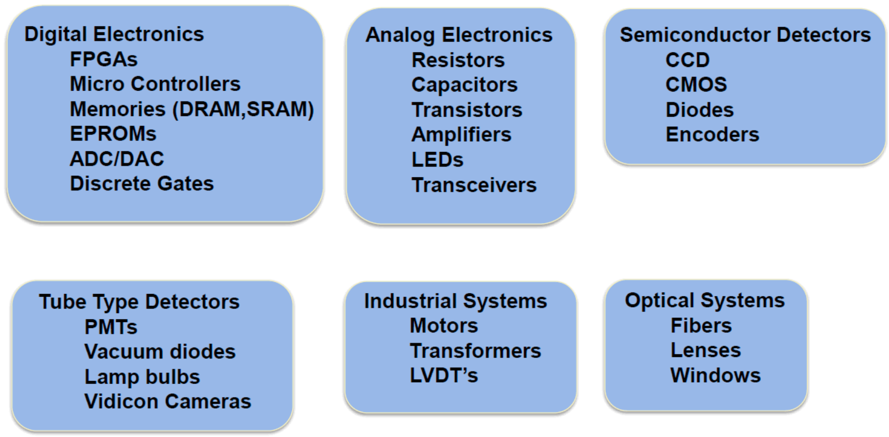


Fig. 5 shows a typical fluence map based on single 20MJ NIF shot that produces 7.1 $x10^{18}$, 14 MeV neutrons.

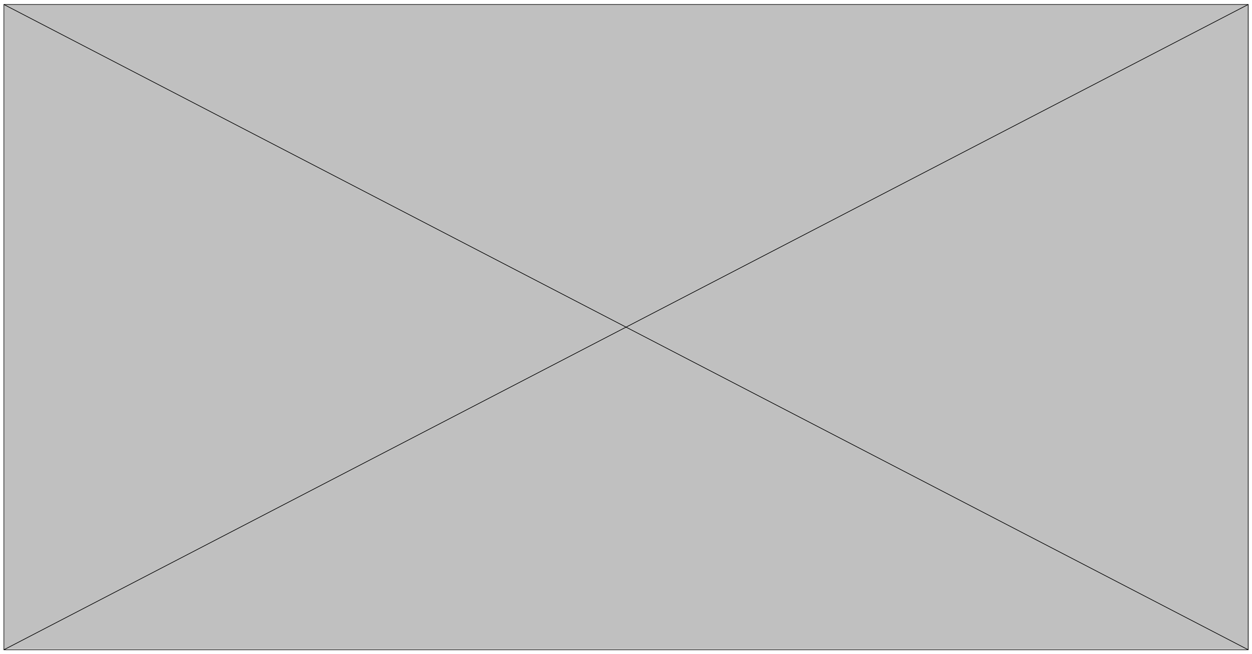
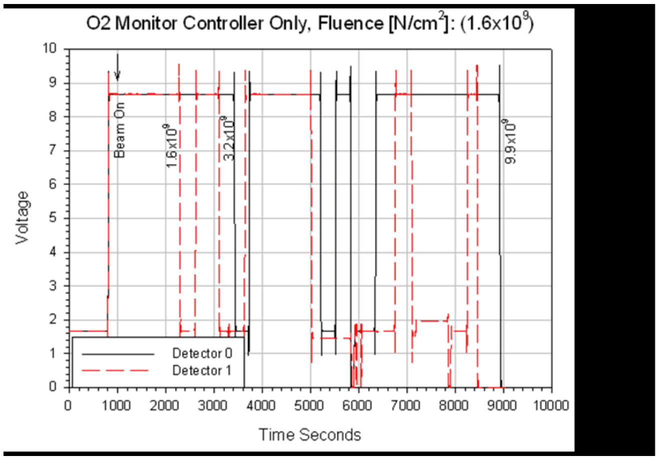


Fig. 6a and 6b display the test results for two oxygen monitors both with the controller/sensor as one complete unit and the sensor separated from the controller.



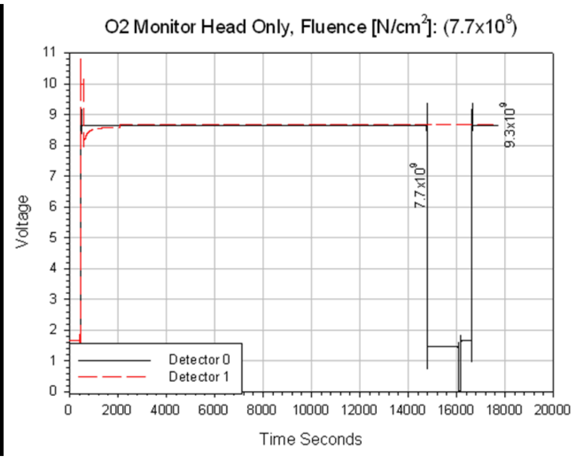


Fig. 7a shows nominal locations of the Oxygen safety monitors (left). There are two monitors per floor and they are located along the back wall of the Target Bay and in close next to the Target Chamber as illustrated by the red stars.

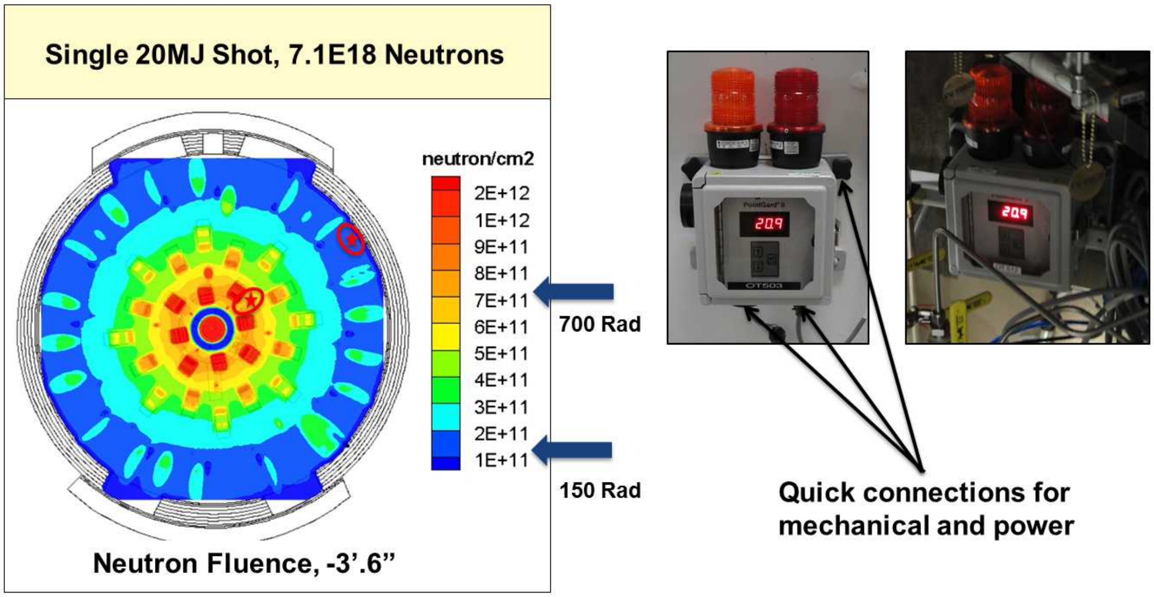

Single 20MJ Shot, 7.1E18 Neutrons
neutron/cm2
2E+12
1E+12
9E+11
8E+11
7E+11
6E+11
5E+11
4E+11
3E+11
2E+11
1E+11
700 Rad
150 Rad
Neutron Fluence, -3'.6"
20.9
OT503
Quick connections for mechanical and power

Fig. 8a is the fluence map that represents predicted fluence levels for a 20 MJ high yield shot in the Target Bay and the red band shows where the access panels are located. Fig. 8b is an image of the before and after modifications to the target bay access panel to increase the operability in a radiation environment.

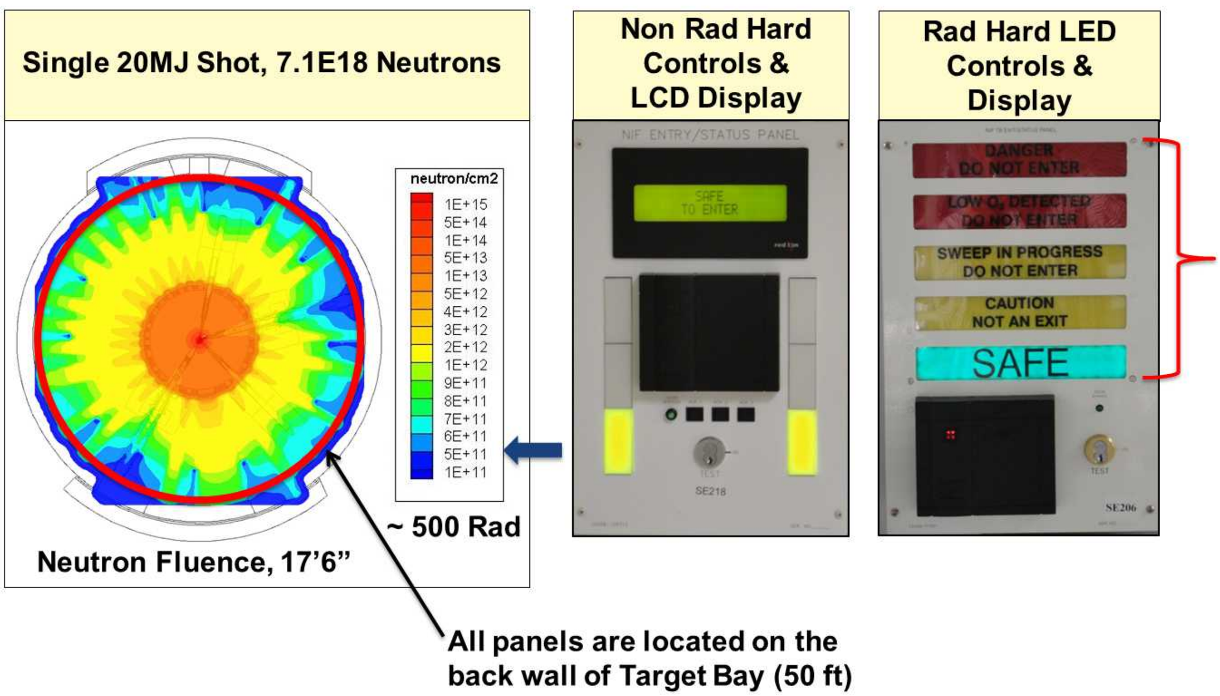


Table 1: List of NIF Target Bay safety systems that could be affected by radiation.	
System	**Quantity**
Safety oxygen monitors	10
Beam tube oxygen monitors	48
Chamber interior video system	9
Pressure sensors	9
Water sensors	1
Facility and emergency lighting	>50
Air handling monitors	12

Table 2: List of subsystem components there were tested using a 14MeV neutron beam at the Ohio University Edwards Accelerator Facility and the level of upset and failure observed.

Subsystem	**Circuit Type**	**Fluence at Failure ($n\ cm^{-2}$)**	**Dose at Failure (Rad-Si*)**	**Dose at Failure (Gy)**
CCD cameras[a]	Analog/Digital	~$4x10^9$	4	0.04

CMOS cameras[a]	Analog/Digital	~4x10^{9}	4	0.04
Oxygen Monitors[a]	Analog/Digital	~2 x10^{9}	2	0.02
Pressure Sensors	Analog	N/A	N/A	N/A
X-ray generator controllers[a]	Analog/Digital	~3 x10^{9}	3	0.03
LED Illuminators	Analog	N/A	N/A	N/A
Digital Oscilloscope[a]	Analog/Digital	~4 x10^{9}	4	0.04

[a]The primary failure was a digital failure.

*1 Gy = 100 Rad-Si (14MeV) = 1x10^{9} (n cm^{-2})

Table 3: List of neutron mitigation actions taken for several NIF systems located in the Target Bay.

Safety System	Action Taken
Oxygen Monitors	Removed controller and left only the sensor head exposed to the neutron field.
Oxygen Monitors (Safety System)	Made removable for each shot. Updated connectors and added mounting hardware that allows quick disconnects.
Fire Alarms	Administratively gate the alarm signal during a shot.

Pressure Sensor	Replaced digital sensor with an analog type.
Water Sensors	Shielded inside the building concrete infrastructure.
Air Handling Sensors	Moved air handling sensors to take advantage of the natural shielding of the building
Interlock Systems	Replaced LCD panel and controller with LED backlighting and moved controller outside the target bay.
Building Lighting	Replaced solid state electrical ballast with a transformer type electrical ballast
Emergency Lighting	Separate the battery and control circuit from the light source
Chamber Interior Video Systems	The use of analog tube camera systems and some sacrificial higher resolution CCD cameras.
General Electronics	Removed controller and left only the sensor head, also made removable for each shot.

Safety Systems and Access Control in the National Ignition Facility

Robert K. Reed* and Jayce C. Bell[6]

Name and address for correspondence:

Robert K. Reed, L-760

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925 422-9528

Telephone: 925 423-6089

e-mail: reed7@llnl.gov

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[6] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

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Abstract— **The National Ignition Facility (NIF) is the world's largest and most energetic laser system. The facility has the potential to generate ionizing radiation due to the interaction between the laser beams and target material, with neutrons and gammas being produced during deuterium-tritium fusion reactions. To perform these experiments several types of hazards must be mitigated and controlled to ensure personnel safety. NIF uses a real time safety system to monitor and mitigate the hazards presented by the facility. The NIF facility Safety Interlock System (SIS) monitors for oxygen deficiency, and controls access to the facility preventing exposure to laser light and radiation from the Radiation Generating Devices. It also interfaces to radiation monitoring and other radiological monitoring and alarm systems. The SIS controls permissives to the hazard generating equipment and annunciates hazard levels in the facility. To do this reliably and safely, the SIS has been designed as a fail-safe system with a proven performance record now spanning over 10 years. This paper discusses the SIS, its design, implementation, operator interfaces, validation/verification, and the hazard mitigation approaches employed in the NIF. A brief discussion of**

the Failure Modes and Effect Analysis supporting the SIS will also be presented. The presentation ends with a general discussion of SIS dos and don'ts, and common design flaws which should be avoided in SIS design.

Key words: computers; lasers; occupational safety

Introduction

In order to mitigate the hazards presented to personnel, the National Ignition Facility (NIF) uses a Safety Interlock System (SIS) and a separate Access Control System (ACS) that functions in conjunction with the SIS to control access into the facility. The purpose of the NIF Safety Interlock System (SIS) is twofold: 1) to work in conjunction with administratively controlled procedures to protect personnel from exposure to high-voltage, laser light, radiation, asphyxiation, and other hazards, and 2) where feasible, to minimize equipment damage in the event of a failure in a monitored component in the NIF. The NIF ACS is a commercially available Access Control System from Hirsch Electronics, known as their "Velocity" system which employs an on-line database configured to identify personnel qualified to enter the facility and to track their location within the major operational areas of the NIF.

The SIS provides permissive signals for the operation of process power supplies, alignment lasers and other devices necessary to perform target shots. It monitors the status of safety related elements in each bay of the facility, including shutters, doors, crash buttons, sweep status, oxygen levels, radiation alarms, etc. The safety interlock system does not control any process devices, but simply provides a permissive signal for each device interlocked by the system. If the interlock logic chain for a device is not satisfied, the permissive signal will not be enabled, operation of the device will not be permitted, and it will stay in its fail-safe state or position. If the interlock logic chain for a device is satisfied, the permissive signal will be enabled, and operation of the device will be allowed. The actual operating state of the device is determined by the process control system within the constraints imposed by the SIS.

The NIF ACS and SIS consist of varying types of systems and procedures designed to limit personnel entry into specified areas. These consist of safety interlocks, mechanical barriers and locks (either local or remotely controlled electronic locks), or lesser methods. These controls are intended to prevent personnel from entering the target bay and other areas in which the potential for radiation exposure or other hazards exist, so that they are protected against prompt radiation and/or residual radiation due to decay of activated components and other hazards. The important functions that the NIF ACS and SIS must accomplish are: 1) Establish the various entry states, such as Controlled and Restricted Access using appropriate interlocks; 2) Ensure orderly searching of an area before shots through the use of appropriate controls; 3) Operate annunciator displays and audio warning systems throughout the facility; 4) Control access to certain areas outside the beam enclosures using physical barriers and controlled locks and keys; 5) Verify that perimeter entry points to an area are closed prior to allowing operation of hazardous equipment. Operation of the main laser for target shots is permitted or denied by controlling permissives to the laser flashlamp capacitor bank charging power supplies. A list of acronyms used in this paper is provided in table 1.

Materials and Methods

Functionality

The SIS provides personnel safety interlocks for the entire facility. It continuously displays the hazard level in each area of the facility, and annunciates changes in hazard level. The SIS monitors door and shutter positions. It also monitors crash buttons, radiation alarms, oxygen levels, and controls visual status displays in the facility. It provides permissive signals to power conditioning, safety shutters, and other components as necessary to protect personnel, and warn them of hazards in the area. It provides a digitized voice annunciation of hazard level changes and conditions in the facility, and audible alarms as required. A simplified view of the SIS architecture is shown in figure 1.

The SIS is a distributed Programmable Logic Controller (PLC) based system, based on Allen-Bradley's "ControlLOGIX" line of PLCs. It consists of four PLCs, one controlling interlocks for Laser Bay #1, Switchyard #1, Capacitor Bay #1 & #2. The second controls interlocks in Laser Bay #2, Switchyard #2, Capacitor Bay #3 & #4. The third controls interlocks for the Target Bay. The fourth "Master" PLC coordinates activities of the other three, performs additional error checking, controls the digitized voice warning system, interfaces oxygen alarms to the Fire Alarm Control Panel, and handles interlocks for the balance of the facility. The zones each PLC covers are shown in figure 2. The approximate device count for the SIS is shown in table 2. Note that these are composite points or devices. The system also provides a Graphical User Interface (GUI) for control room operators to provide input, observe system and permissive status and other data.

Status Panels

The SIS provides Crash and Status panels located throughout operational areas of the facility. The Crash and Status panels have the following features (see figure 3):

- An alphanumeric message display unit that can be backlit in red, yellow, or green and capable of displaying a minimum of two lines of text. In the case of the Target Bay these message units are replaced by a radiation hardened backlit display panel
- Red, yellow, and green lights to indicate relative hazard status.
- A sweep key for use in executing sweep sequences.
- A test key to temporarily bypass the panel and allow for online testing.
- An emergency shutdown button that latches in the actuated position and has redundant sets of contacts.

The SIS provides Entry Status panels located at controlled entry doors throughout the facility. The Entry Status panels have the following features (see figure 4):

- An alphanumeric message display unit that can be backlit in red, yellow, or green and capable of displaying a minimum of two lines of text.
- Red, yellow, and green lights to indicate relative hazard status of the area.
- A test key to temporarily bypass the panel and allow for online testing.
- A badge reader interfaced to the Access Control System to read users badges.
- An indicator light to indicate door bypass state
- Three acknowledge buttons to enter user responses to gain entry

Backlighting of the text display and panel hazard indicators adhere to the color usage defined in table 3.

Shot Modes

The SIS supports three shot modes to the Target Bay (see table 4), selected based on maximum credible neutron yield for the experiment being executed. Shot Category A is defined as no or low yield. Shot Category B is defined as moderate yield. Shot Category C is defined as high yield. Depending on the shot mode, SIS requires various combinations of shield doors to be closed and various areas of the facility to be swept.

Shield Doors

For each shield door the SIS monitors the closed position of the door and the engaged position of the seismic pin. For a valid closed signal SIS must see both (redundant) position switches indicating closed and the seismic pin switch indicating that the seismic pin is in the engaged position. In the NIF there are 19 primary shield doors for the Target Bay and 28 secondary shield doors located in/on the switchyards. Additionally, the SIS provides a permissive to each shield door allowing it to be operated, based on permission granted by control room operators via GUI input.

Facility Sweeps

A critical function of the SIS is to implement the sweep function for operational areas of the facility and to monitor the perimeter of those areas. Engineered sweeps controlled by the SIS require personnel to physically enter an area to ensure that a sweep of the area has been conducted and that it is unoccupied. This requires a sweep team to traverse the area being swept in a predefined pattern actuating the sweep key-switch in each status panel in an area. The sweep key-switches may be thought of as being analogous to a watchman's key box. Completion of the required actions, in the specified sequence and time, is required prior to issuing permissives for hazardous operations.

SIS enforces engineered perimeter control for operational areas of the facility that are subject to sweep. Control of all personnel access points to an area is maintained by mechanical locks or electronic locks requiring permissives from the ACS through the SIS to allow access. Once the perimeter is established, the system provides an alarm indication in the control room if the perimeter has been violated, and drops any associated permissives.

Areas of the facility subject to sweeps include:

1. Capacitor bays (4 each)
2. Laser bays (2 each)
3. Switchyards (2 each)
4. Target bay (7 levels)
5. Diagnostic mezzanines (4 each)
6. Viewing gallery
7. Target Bay mechanical rooms (2 levels)
8. Core elevator vestibules (2 each)
9. Entry lobby
10. Facility Roof

Permissive Generation

The SIS generates the shot permissives to perform all target shots in the facility as well as the permissives required to generate alignment light and to perform rod (low laser energy test) shots. Typical items that SIS monitors in order to generate permissives include: Selected shot mode; Perimeter status; Sweep status; Position of various beam line devices; Area personnel door status; Shield door status; Permissive key status; and SIS health status. If any of these devices are faulted or not presenting valid status, permissives will be withdrawn and the condition must be rectified before permissives may be issued. An example of the logic required to generate shot permissives to target chamber center is shown in figures 5 and 6. Live status of these logic diagrams is provided to the operator on GUIs to aid in understanding permissive status and troubleshooting of issues.

Alarms

The SIS monitors conditions throughout the facility and annunciates alarms as required. Alarm annunciation may include the following (depending on the alarm): Display on the SIS user interface; Audible and visual display on the backlit alarm annunciator panel in the control room; Automated pager notification to selected personnel; Automated notification to the LLNL fire department; Automated announcements and/or klaxons within the facility via the facilities public address system; Automated closure and access restrictions to affected areas of the facility; Display of status on the SIS status panels. SIS alarms are defined in the SIS Alarm Response Procedure which is used by control room operators to respond to SIS alarms. The procedure defines the alarm, details the response generated by SIS, and instructs the operator on what needs to be done to respond to the alarm and return the facility to normal operation. Examples of alarms annunciated by SIS include: Stack monitor hi tritium; Hi tritium alarms by area; Hazardous Materials Management System (HMMS) fault; Stack fault; Water leak detected; Crash button active; Oxygen deficiency by area; Fire alarm active; Heating, Ventilation, Air Conditioning (HVAC) fault; SIS fault; Perimeter violation, etc.

Special Requirements for High Yield Shots (Category C)

Prior to engaging in high yield shots several additional protocols are followed for gaining access to the Target Bay. This is to further reduce the likelihood that someone could be accidently left in the area during a high yield shot when the consequences are much greater. At least seven hours prior to a high yield shot the Target Bay is placed in Restricted Mode. In this mode the SIS entry panels are backlit in yellow and indicate that the bay is in Restricted Mode. To gain access while the Target Bay is in Restricted Mode an entrant must:

1. Call the control room from the door which they desire entry
2. Control room operator observes the entrant on the entry surveillance monitor
3. Control room operator verifies each entrant has an Access Key Station token
4. Control room operator verifies each entrant has a valid Rad Work Permit (RWP) and electronic dosimeter
5. Control room operator buzzes the entrant(s) in through the selected door
6. Control room operator verifies that each entrant scans their ACS badge and that they are entered in the ACS transaction log
7. Control room operator verifies that no one tailgates in with the entrant(s)

8. Control room operator verifies that the Target Bay door closes after the entry

The SIS employs Access Key Stations (AKS) based on Morse Watchmans "KeyWatcher" system that are used in the entry process for the Target Bay prior to and after high yield operations (see figure 7). The AKS contains tokens that are checked out by an operator prior to gaining access to the Target Bay. The AKS maintains an on-line database that may be queried by the control room operator to determine how many tokens are checked out and who has them. The AKS also furnishes a signal to the SIS which that is true when all AKS tokens are present. The SIS uses this signal in its permissive generation logic.

A part of the re-entry procedure for the Target Bay after high yield shots includes testing of all the SIS devices in the Target Bay that may be susceptible to damage by radiation to ensure that they remain operational.

Discussion

One of the primary premises of the SIS is that it is designed as a fail-safe shutdown system. When a failure is detected, permissives are removed and operations requiring those permissives halted until the issue has been corrected. SIS incorporates redundancy through key components of the system. Doors (shield doors and personnel doors) are monitored with redundant switch pairs. Emergency shutdown buttons incorporate two sets of contacts that function redundantly. In all cases any pole of a redundant device is capable of initiating the shutdown function. The SIS also incorporates redundant 24Vdc power supplies supporting its field devices. The SIS is powered by Uninterruptable Power Supplies (UPS) backed by a standby generator which allows the system to remain operational in the event of an extended power failure. The SIS uses diagnostic input/output modules on critical points to allow for additional error checking such as open circuit detection.

An extensive Failure Modes and Effects Analysis (FMEA) was conducted to search out single points of failure that required mitigation. This analysis is updated when changes are made to the SIS and has been used to guide the SIS design.

An extensive Fault Tree Analysis (FTA) was conducted to confirm that the probability of someone being left behind in any of the operational areas was at an acceptable level, and to ascertain if additional controls were required. Some additional controls that were implemented as a result of these analysis include: a) Continuous sounding of klaxons in the Target Bay while shot permissives are issued; b) Addition of two strobe lights on each level of the Target Bay that are illuminated while permissives are present.

The NIF SIS is subject to strict configuration management and critical devices are tested quarterly in order to reveal covert faults. Regression tests are executed when programming changes are made on the system.

Conclusions

The NIF SIS has been in operation for over 10 years, operating 24/7/365. It has a logic scan time of <50ms. Its technology is proven with a large installed base worldwide. The system has been optimized for operations over its lifetime and continues to be optimized. The system has reached a mature level with minor changes occurring a couple of times a year. The system has been exhaustively reviewed by both internal and external reviewers. Analysis has confirmed that it is a fail-safe system and that the probability of someone being injured due to being in a swept area is at an acceptably low level.

During its operations to date the fail-safe response of the system has been as designed. The system is under strict configuration management and is tested regularly. The system is in place and is ready to support high yield experiments at the National Ignition Facility.

Table 1. Acronyms

Acronym	Definition
ACS	Access Control System
AKS	Access Key Station

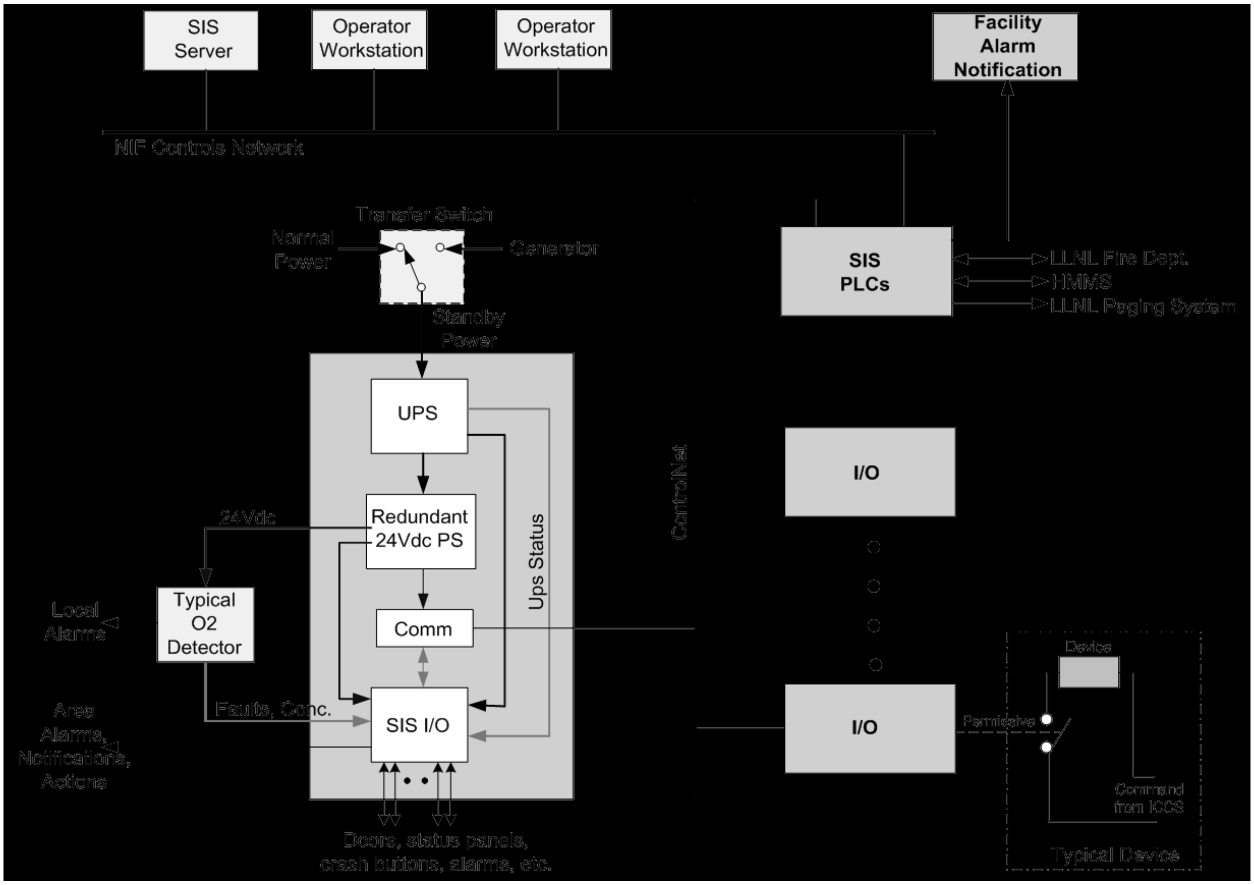
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
GUI	Graphical User Interface
HMMS	Hazardous Materials Management System
HVAC	Heating, Ventilation, Air Conditioning
ICCS	Integrated Computer Control System
LLNL	Lawrence Livermore National Laboratory
NIF	National Ignition Facility
PLC	Programmable Logic Controller
RWP	Rad Work Permit
SIS	Safety Interlock System
UPS	Uninterruptable Power Sypply

Table 2. Approximate SIS device count

Crash & Status Panels	Monitored Doors	Controlled Doors	Permissives	Oxygen Sensors	Radiation Alarms

253	70	99	250	44	17

Figure 1. Simplified SIS Architecture



SIS Server
Operator Workstation
Operator Workstation
Facility Alarm Notification
NIF Controls Network
Transfer Switch
Normal Power
Generator
Standby Power
SIS PLCs
LLNL Fire Dept.
HMMS
LLNL Paging System
UPS
Redundant 24Vdc PS
24Vdc
Ups Status
ControlNet
I/O
Local Alarms
Typical O2 Detector
Comm
Faults, Conc.
SIS I/O
Area Alarms, Notifications, Actions
I/O
Device
Permissive
Command from ICCS
Typical Device
Doors, status panels, crash buttons, alarms, etc.

Figure 2. SIS zones in NIF

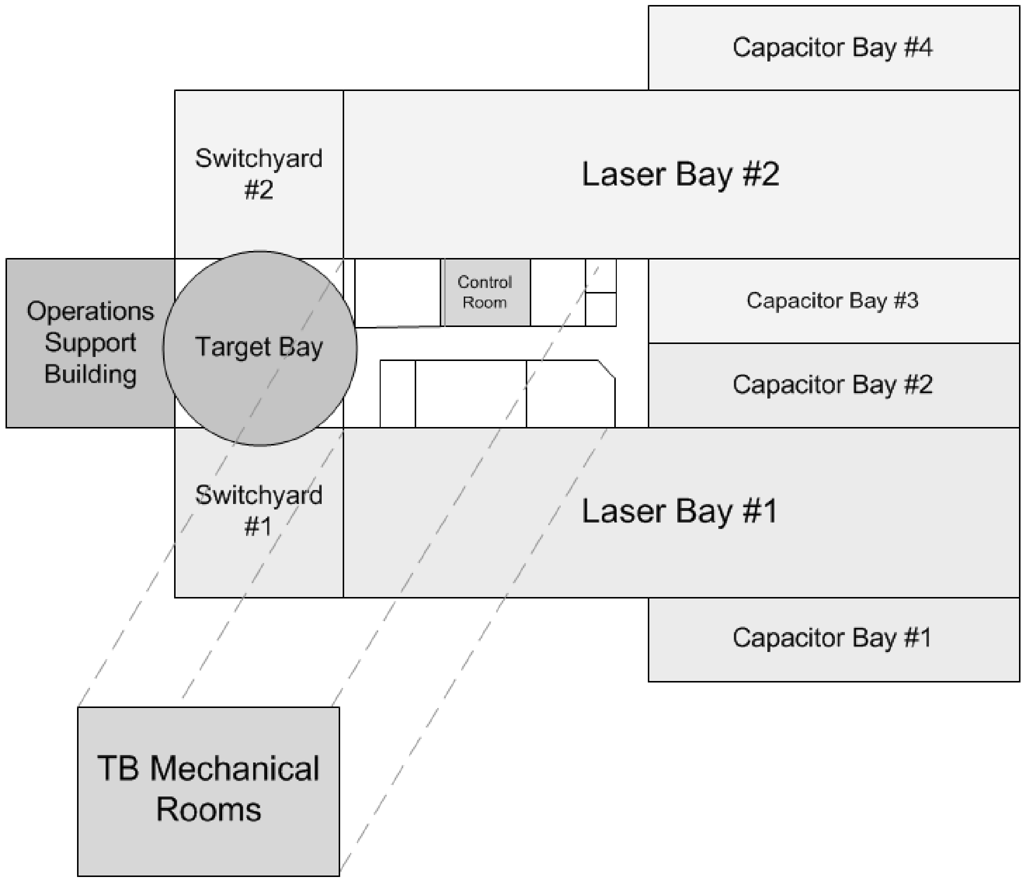

Capacitor Bay #4
Switchyard #2
Laser Bay #2
Operations Support Building
Target Bay
Control Room
Capacitor Bay #3
Capacitor Bay #2
Switchyard #1
Laser Bay #1
Capacitor Bay #1
TB Mechanical Rooms

Table 3. Status Panel Backlighting Definitions

Color	Use
GREEN	**SAFE, No hazards present, SIS shot permissives removed**
YELLOW	**CAUTION, operations in progress. Personal Protective Equipment or special procedures required, or sweep in progress**
MAGENTA	**High tritium level detected, leave the area/do not enter**

RED	**DANGER, hazardous operations in progress, or hazard detected (such as oxygen deficiency), NO admittance or occupancy allowed**

Figure 3. NIF Crash and Status Panels

Rad Hardened Crash & Status Panel for Target Bay

Standard NIF Crash & Status Panel

Figure 4. Standard SIS Status Entry Panel

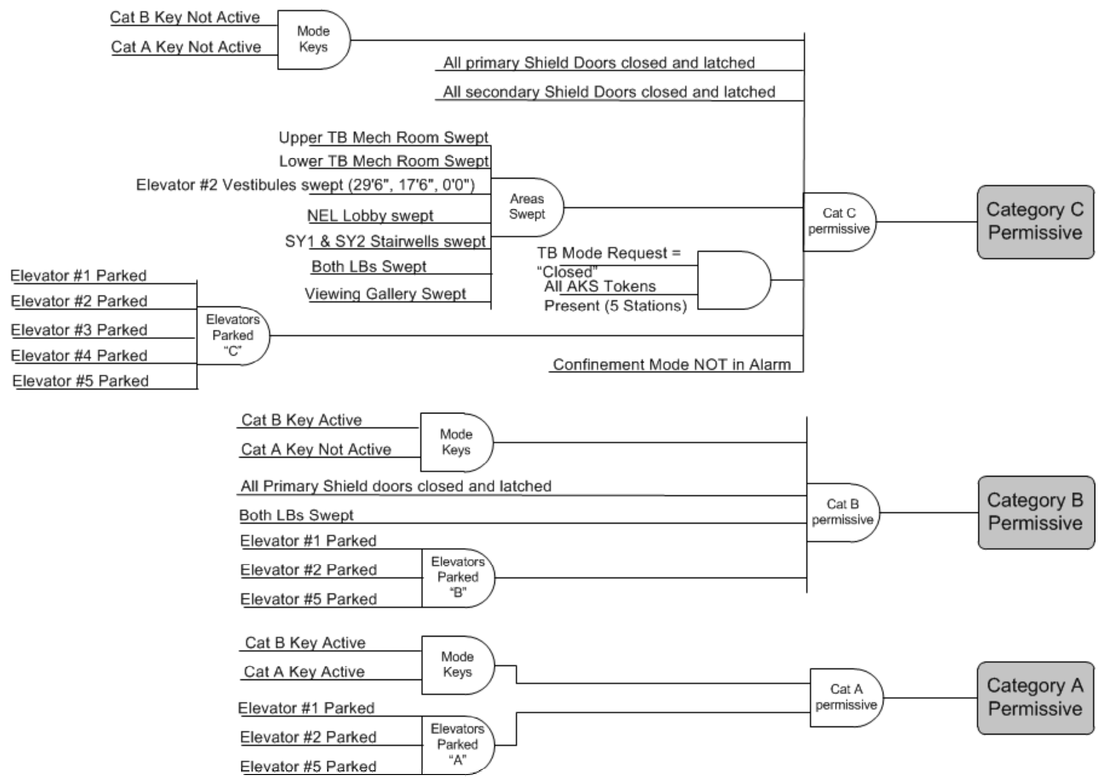

NIF ENTRY/STATUS PANEL
SAFE
TO ENTER
ACS Badge
Reader
DOOR
BYPASS
ACK 1
ACK 2
ACK 3
ON
TEST
SE 412
LEA98-129712
SER. NO.

Table 4. Facility Configuration by Shot Mode

Shot Category/Mode	**Maximum Credible Yield**	**Configuration**
A	Low or none $< 10^{14}$ neutrons	No shield doors closed except the primary shield door between the Target Bay and Operations Support Building (door D165). Capacitor Bays, Laser Bays, Switchyards, and Target Bay Swept.

B	Moderate >= 10^{14} and <= 10^{16} neutrons	All Primary shield doors (Target Bay) closed. Capacitor Bays, Laser Bays, Switchyards, and Target Bay Swept.
C	High > 10^{16} neutrons	All Primary and Secondary shield doors closed and all ancillary areas swept (mechanical rooms, etc.) Capacitor Bays, Laser Bays, Switchyards, Target Bay, Viewing Gallery, Lobby, Target Bay Mechanical Rooms, and Core Vestibules swept.

Figure 5. Logic example: SIS Mode Select Logic



Cat B Key Not Active
Cat A Key Not Active
Mode Keys
All primary Shield Doors closed and latched
All secondary Shield Doors closed and latched
Upper TB Mech Room Swept
Lower TB Mech Room Swept
Elevator #2 Vestibules swept (29'6", 17'6", 0'0")
Areas Swept
NEL Lobby swept
SY1 & SY2 Stairwells swept
Both LBs Swept
Viewing Gallery Swept
TB Mode Request = "Closed"
All AKS Tokens Present (5 Stations)
Elevator #1 Parked
Elevator #2 Parked
Elevator #3 Parked
Elevator #4 Parked
Elevator #5 Parked
Elevators Parked "C"
Confinement Mode NOT in Alarm
Cat C permissive
Category C Permissive
Cat B Key Active
Cat A Key Not Active
Mode Keys
All Primary Shield doors closed and latched
Both LBs Swept
Elevator #1 Parked
Elevator #2 Parked
Elevator #5 Parked
Elevators Parked "B"
Cat B permissive
Category B Permissive
Cat B Key Active
Cat A Key Active
Mode Keys
Elevator #1 Parked
Elevator #2 Parked
Elevator #5 Parked
Elevators Parked "A"
Cat A permissive
Category A Permissive

Figure 6. Logic example: Main Laser Permissive to TCC Logic

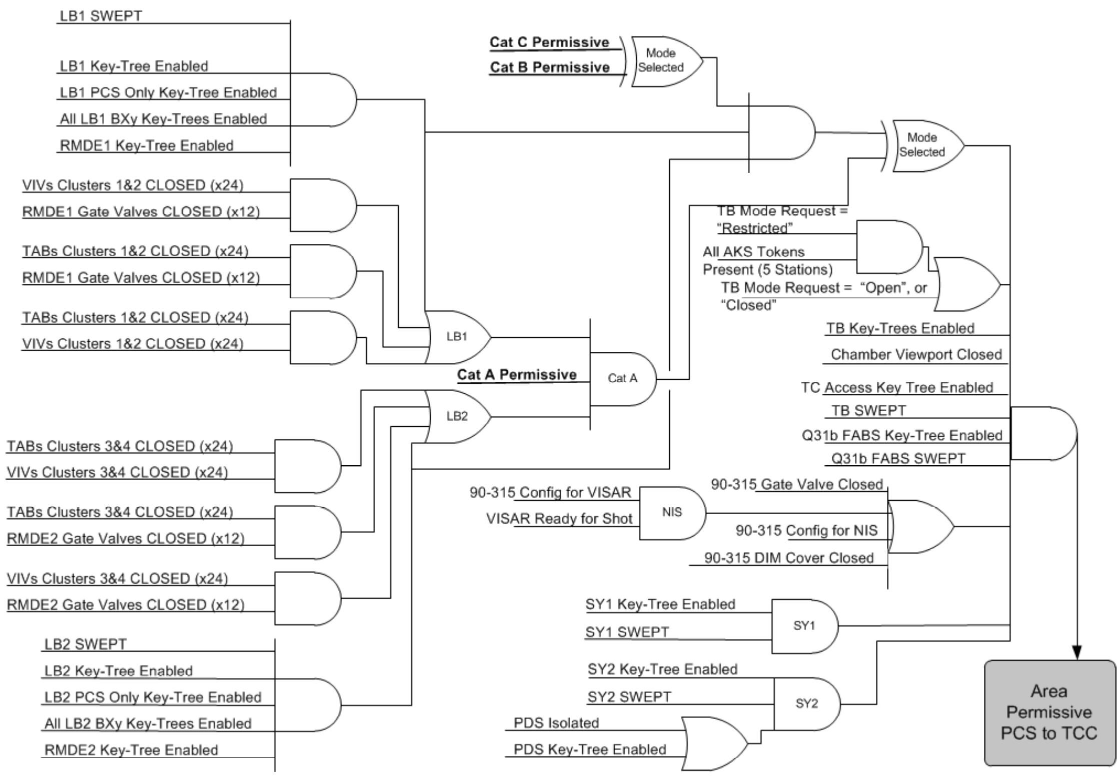
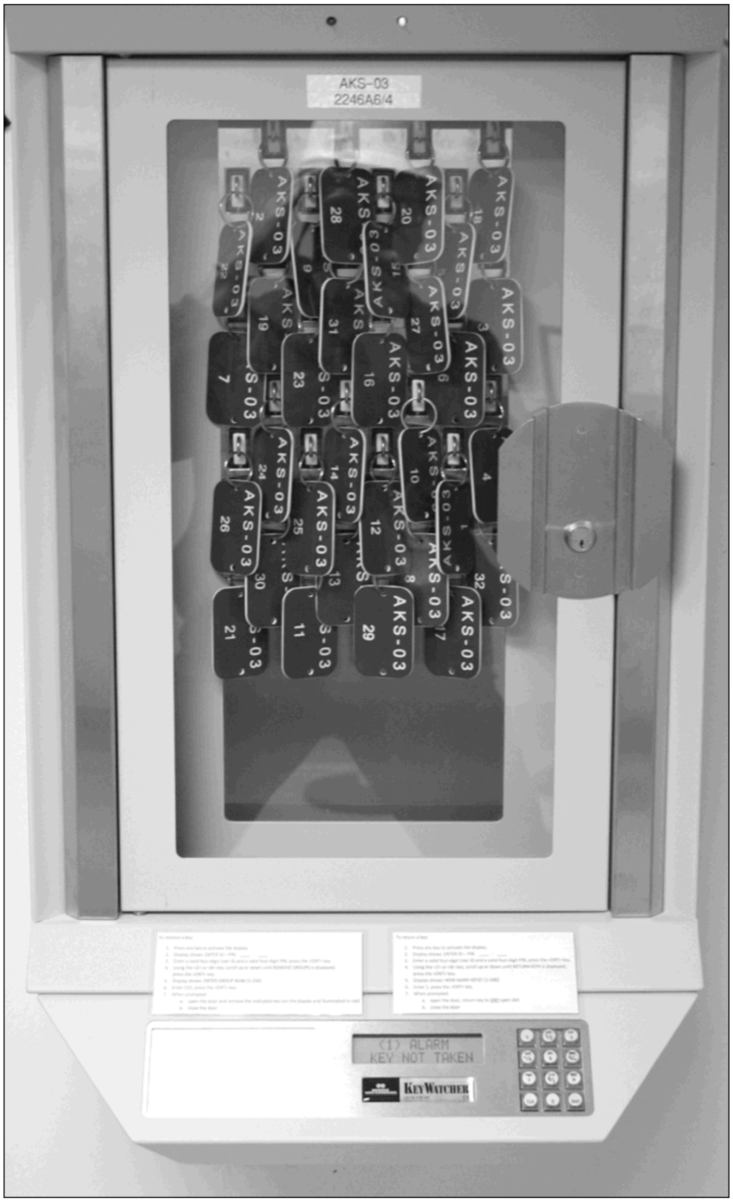

LB1 SWEPT
LB1 Key-Tree Enabled
LB1 PCS Only Key-Tree Enabled
All LB1 BXy Key-Trees Enabled
RMDE1 Key-Tree Enabled
VIVs Clusters 1&2 CLOSED (x24)
RMDE1 Gate Valves CLOSED (x12)
TABs Clusters 1&2 CLOSED (x24)
RMDE1 Gate Valves CLOSED (x12)
TABs Clusters 1&2 CLOSED (x24)
VIVs Clusters 1&2 CLOSED (x24)
LB1
Cat A Permissive
Cat A
LB2
TABs Clusters 3&4 CLOSED (x24)
VIVs Clusters 3&4 CLOSED (x24)
TABs Clusters 3&4 CLOSED (x24)
RMDE2 Gate Valves CLOSED (x12)
VIVs Clusters 3&4 CLOSED (x24)
RMDE2 Gate Valves CLOSED (x12)
LB2 SWEPT
LB2 Key-Tree Enabled
LB2 PCS Only Key-Tree Enabled
All LB2 BXy Key-Trees Enabled
RMDE2 Key-Tree Enabled
Cat C Permissive
Cat B Permissive
Mode Selected
Mode Selected
TB Mode Request = "Restricted"
All AKS Tokens Present (5 Stations)
TB Mode Request = "Open", or "Closed"
TB Key-Trees Enabled
Chamber Viewport Closed
TC Access Key Tree Enabled
TB SWEPT
Q31b FABS Key-Tree Enabled
Q31b FABS SWEPT
90-315 Config for VISAR
VISAR Ready for Shot
NIS
90-315 Gate Valve Closed
90-315 Config for NIS
90-315 DIM Cover Closed
SY1 Key-Tree Enabled
SY1 SWEPT
SY1
SY2 Key-Tree Enabled
SY2 SWEPT
SY2
PDS Isolated
PDS Key-Tree Enabled
Area Permissive PCS to TCC

Figure 7. SIS Access Key Station


AKS-03
2246A6/4
(1) ALARM
KEY NOT TAKEN
KEYWATCHER

Tritium and Ignition Target Management at the National Ignition Facility

Vaughn Draggoo

Name and address for correspondence:

Vaughn Draggoo, L-462

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925 422-5099

Telephone: 925 423-0185

e-mail: Draggoo1@llnl.gov

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Abstract

Isotopic mixtures of hydrogen constitute the basic fuel for fusion targets of the National Ignition Facility (NIF). A typical NIF fusion target shot requires approximately 0.5 mmoles of hydrogen gas and as much as 750 GBq (20 Curies) of ^3H. Isotopic mix ratios are specified according to the experimental shot / test plan and the associated test objectives. The hydrogen isotopic concentrations, absolute amounts, gas purity, configuration of the target, and the physical configuration of the NIF facility are all parameters and conditions that must be managed to ensure the quality and safety of operations. An essential and key step in the preparation of an ignition target is the formation of a ~60 micron thick hydrogen "ice" layer on the inner surface of the target capsule. The Cryogenic Target Positioning System (Cryo-Tarpos) provides gas handling, cyro-cooling, X-ray imaging systems and related instrumentation, to control the volumes and temperatures of the multi-phase (solid, liquid and gas) hydrogen as the gas is condensed to liquid, admitted to the capsule and frozen as a single spherical crystal of hydrogen in the capsule. The hydrogen fuel gas is prepared in discrete 1.7 cc aliquots in the LLNL Tritium Facility for each ignition shot. Post shot hydrogen gas is recovered in the NIF Tritium Processing System (TPS). Gas handling systems, instrumentation and analytic equipment, material accounting information systems, and the shot planning systems must work together to ensure that operational and safety requirements are met.

Key words: National Ignition Facility, NIF, tritium, cryo-layering, operational topics

INTRODUCTION

An isotopic mixture of hydrogen is the basic fuel for fusion/ignition targets. The physical form of the hydrogen fuel prior to laser excitation is as a thin hydrogen "ice" layer within the precision target capsule. This sets the required initial conditions of amount, density and shape for compressing and heating the fuel required for fusion burn. Quality and safety of the facility operations is managed through: fuel gas isotopic analysis, fuel gas purity, target configurations, gas handling system of NIF, physical configuration of the NIF Facility, and tritium accounting equipment and systems. This article provides an overview of the technical and administrative systems related to tritium and targets in support of the inertial fusion experimental campaign at the National Ignition Facility.

NIF TARGETS

There are four basic target configurations used in the NIF fusion experimental campaign. These target types are designed to test different performance indicators related to the inertial confinement event, Table 1 and Figure 1.

The Symcap / Ignition Target is the primary focus in this article because the appropriate management of the hydrogen fuel gas is critical to the performance, safety and quality of the experimental campaign.

The design concept for NIF targets includes a generalized "platform", or Thermo-Mechanical Package, to provide important functional aspects including mechanical support, thermal conduction to a cryostat, auxiliary heaters, and thermal instrumentation, for the target "physics package". The physics package includes elements designed to evaluate key parameters associated with the inertial confinement fusion concept. In the most general sense, an ignition target always includes a hollow fuel capsule. This capsule and the supporting target system are designed to provide a mechanical and thermal environment to form a thin and precisely spherical shell of hydrogen ice on the inside surface of the capsule.

The capsule is nominally 2mm in diameter with the hydrogen ice layer of 60 microns. Fuel is admitted to the capsule through a 5-micron glass fill tube. At fill time, the capsule is cooled to condensation point for the isotopic gas mixture and fuel is added to the capsule as a liquid. The amount of liquid is precisely controlled to provide the proper thickness of the resulting solid hydrogen ice shell.

Depending on the experimental objectives for a given shot, the isotopic composition of the hydrogen fuel gas may be adjusted for maximum deuterium/tritium (DT) fusion yield, a 50/50 mix, or it may be "duded" using a mixture of protium and deuterium with tritium (THD) to suppress the neutron yield for improved diagnostics performance.

As the formation of a single crystal of hydrogen ice is required for smooth highly spherical hydrogen ice shell, the fuel gas must be free of contaminant gasses. High levels of contaminant gases, like nitrogen, argon, water and methane, can lead to defects in the ice layer as it forms.

Accordingly, preparation and management of the purity and isotopic mix of the fuel gas is important for the quality and safety of the ignition target operations.

THE CRYO-TARGET POSITIONING SYSTEM (CRYO-TARPOS)

The NIF Cryo-Tarpos is a dual functional system that provides the cryogenic cooling and diagnostic systems necessary to form the ignition target's fuel ice layer, and provides the positioning systems that transports and holds the target at the center of the NIF chamber for the shot, Figure 5. In the figure, the target positioning boom is shown fully extended and is supporting the target and the Ignition Target Inserter Cryostat (ITIC). The initial operation of the Cryo-Tarpos begins with the boom fully retracted into the Target Positioner vacuum vessel behind the NIF Target Chamber Vacuum Isolation valve. The target cycle begins with loading a new target and a fuel gas reservoir onto the ITIC. Following preliminary mechanical and electrical checks, the external fuel gas reservoir is manually opened, vacuum vessel door closed and the system is evacuated. At this point the target assembly is positioned in the three axis X-ray imaging system and cryo-cooling of the system begins. The X-Ray imaging system provides essential visualization of filling the capsule with liquid DT and the subsequent formation of a single crystal hydrogen ice layer on the interior of the capsule.

Prior to the shot, a precise single crystal of fuel ice must be formed in the target capsule. In this process, the target fuel reservoir is cooled and the fuel is allowed to flow into the capsule as liquid hydrogen through the fill tube. Once the required amount of liquid is in the capsule, as determined by precision measurement of the x-ray image, the process to form the ice layer begins. Initial freezing of the fuel mix results in a highly disorganized polycrystalline layer. This form of the ice is far too rough meet the requirement for the implosion process; a single crystal of hydrogen ice is required to line the inner surface of the capsule. The temperature of the capsule is then raised to near the triple-point for the gas mixture and the polycrystalline formation melted. Only small seed crystals remain at the fill tube. The temperature of the capsule is then manipulated to allow single crystal growth from the fill tube. This process may have to be repeated often until a single crystal is observed in the x-ray image. With a single crystal in place the system continues to slowly cool and grow ice layer to the required thickness.

Imperfections in the ice layer may form during the crystal growth process. These may be caused by mechanical disturbances of the equipment, cooling the crystal too quickly, imperfections capsule or impurities in the source gas. These imperfections may appear as grooves or bumps on the ice layer as viewed in the x-ray images. To mitigate these difficulties, the target gas supply systems are designed to purify the gas before it enters the capsule using cold trapping techniques on the target, and minimization of mechanical vibrations in the cryo-target systems have been critical to ensure quality layers. The growth of the ice layer is painstakingly monitored throughout the 20-hour growth cycle to assure high quality crystal.

Larger scale imperfections in the thermal environment of the target may also exist due to subtle differences in the target design and assembly, and the thermal environment around the target. These larger scale perturbations result in an asymmetric shape of the ice layer. To manage and account for this, the target systems provide auxiliary heaters on the target to gently shape the thermal environment to more precisely position and shape the ice layer. This thermal “shimming” of the position and shape of the ice layer typically occurs as the final adjustment to the cryogenic target. The time line for the layer formation process is shown in figure 5.

The beta-decay of the tritium facilitates the formation of the a uniform ice layer by causing local heating and sublimation of the DT fuel which then re-condenses on cooler surfaces elsewhere, typically at thinner, regions of the ice shell. This “beta-layering” process, illustrated in Figure 6, greatly facilitates the creation of the smooth and uniform ice layer required for ignition.

A key element of the characterization system is a phase contrast x-ray imaging system that provides three-axis orthogonal views of the target capsule and ice layer. This technique results in sharp contrast at the edges of even extremely low absorbing materials like hydrogen ice. (see J.K. Hoffer and L.R. Foreman, PRL 60, 1310 (1988)). This approach has allowed quantitative evaluation of the quality of the THD/DT ice surface in optically opaque materials of the capsule, e.g. beryllium or plastic. Figure 7 shows an x-ray image projection of solid THD in a capsule with a resolution of approximately 3-microns. Images are continuously taken at ~one-minute intervals to monitor the ice formation process. The system provides key data regarding the ice layer attributes and ultimately the basis of technical review prior to proceeding with the shot.

At the conclusion of a successful fuel layer formation process, the imaging system is withdrawn and the target is transported on the Cryo-Tarpos boom to target chamber center.

Having the layering and characterization capability integral with the positioning system allows the target to be moved into the target chamber with minimum vibration or time delays. The Cryo-Tarpos positions the capsule and holds it steady to within a few microns at the target chamber center, all the while maintaining the temperature to within milli-Kelvins of the set point to preserve the carefully formed ice layer.

Figure 8 shows the Ignition Target Inserter Cryostat (ITIC) mounted on the boom of the Cryo-Tarpos. In this photo the access door of the Cryo-Tarpos vacuum chamber is open, the target has been mounted on the ITIC and the technician is opening the fuel gas reservoir to admit gas to the ITIC gas handling system. This is the last manual operation prior to closing the vacuum chamber and initiating vacuum operations.

TRITIUM CYCLE AT LAWRENCE LIVERMORE NATIONAL LABORATORY IN SUPPORT OF NIF IGNITION

The quality and safety of the ignition shot campaign is, in part, ensured through the fuel gas supply, handling, and analytic systems that prepare and quantitatively determine and maintain the key attributes. For the National Ignition Campaign (NIC), isotopic mixtures of hydrogen gas are prepared and analyzed at the Tritium Facility at LLNL, Figure 9.

Fuel gas is transported to NIF as individual aliquots of fixed volume, ~1.7cc. Typically two identical aliquots are prepared and transported; one is held as a spare should there be an upset in the fuel handling and layering process. These vessels, called External Reservoirs, are quite simple vessels consisting of precision manual valve assemblies with blind volumes that provide precision amounts of gas with appropriate isotopic composition and pressures consistent with technical, safety and reliability requirements, Figure 10.

Gas mixtures are prepared in either of two gas handling systems located in the LLNL Tritium Facility; the Tritium Science Station, and the Tritium Processing Station. These systems each include two sets of uranium-hydride and palladium-hydride "bed" pairs to serve as sources of pure tritium gas or prepared mixtures of tritium with deuterium and/or protium. And, each station includes a separate uranium-hydride bed to capture and hold residual gas left over from the gas preparation process as well as unused gas returned from target operation at NIF. This "scrap" is later recovered and returned to Savannah River Site for purification and recovery of the tritium.

The Tritium Processing Station was designed and commissioned to meet some of the special gas requirements for NIF, including very low protium concentrations, and timely rejection of helium-3 due to tritium radioactive decay using Pd diffuser technology. Generally, the Tritium Processing System provides pure tritium gas or 50/50 mixtures of tritium/deuterium gas, the ideal mix for high yield ignition shots on NIF, Figure 11

The Tritium Science Station is a functionally more agile system that can provide a broader range of hydrogen isotopic mixes albeit at lower pressure and total delivered mass. Generally, the Tritium Science System provides ranges of THD gas mixtures, and are prepared using Pressure/Volume/Temperature (PVT) and gas mixing techniques.

The fuel gas requirements for the ignition testing campaign can vary widely depending on the experimental objective. Generally, however, the gas mixes, gas volumes and impurity gases can be characterized as shown in Table 2. Hydrogen isotopic mixes control the maximum yield of the shot, the ingrowth of ^{3}He must be managed to assure gas purity in the capsule, and other impurities must be minimized to assure proper movement of the gas at cryogenic temperatures. For example too much atmospheric gas (oxygen and nitrogen) can freeze and plug the small bore gas lines of the cryogenic target.

Isotopic and molecular determination of the fuel gas constituents, including trace impurity gases, is accomplished with a sector magnet mass spectrometer and associated gas handling and sampling system. The mass spectrometer is a Thermo-Scientific / Finnigan model MAT-271 and is tuned for low molecular weight gas species to mass 85. The attendant gas handling system includes a heated gas sample admitting system and a multiple source calibration gas handling system. Hydrogen isotopic gas calibration sources are provided by Savannah River Nuclear Solutions from Savannah River Site, while non-radioactive calibration gases are procured from certified vendors. Figure 12 shows the sector-magnet mass spec system; the gas inlet system is to the left and a Faraday Cup / Electron Multiplier detector system to the right.

Stable and calibrated operation of the Sector-Magnet Mass Spectrometer as a precision analytic instrument is required to assure the technical performance and safety of operation of the ignition shot campaign. These data form the basis for safety and technical considerations. The accuracy and precision is assured through certified calibration standards, and statistical methods to collect and characterize the performance. Standard operation of the instrument includes a calibration regimen and replicate measurements to determine accuracy and precision. A standard mass spectrometer analysis data set is shown in Figure 13. This Mass Spec report captures fractional components of molecular hydrogen species; H2, HD, D2, HT, DT and T2, and the calculated atomic fraction of the hydrogen fuel. Also provided in the standard analytical report are any observable contaminant gases, especially atmospheric species, waters and methanes (the terms “waters” and “methanes” refer to the multiplicity of molecular species formed with multiple species of isotopic hydrogens.) Methanes are a common contaminant species in tritium gas supply and transport systems. The cryogenic target system is tolerant to these contaminants if the concentrations are small.

Operational safety and efficiency is assured through fuel gas isotopic determination. As the experimental campaign uses a variety of target types and fuel gas compositions, the range of neutron yield will also vary. Accordingly, the range of maximum credible neutron yields for a given shot have been grouped into three categories. Planning the shot campaign according to shot yield category provides for efficiently and safely configuring the many experimental systems and diagnostics and for certain safety systems of the facility. This is particularly true for configuration of the facility Shield Doors.

The safety basis for this approach is founded on the physics of fusion event and the maximum credible neutron yield for the planned test. A fundamental determinant for the maximum credible yield is the isotopic mixture of the fuel gas. Analysis has shown and an operational plan has been established for ignition target testing a threshold using 11-atomic percent deuterium in tritium/protium gas mixes. Accordingly, management of the pedigree of the reservoir fielded for a shot event is carefully managed through technical precision of the process and analytical equipment, and logistics planning and documentation for the preparation, transport and fielding of the target fuel gas, target and configuration of the facility and experimental systems (Table 3).

Initial cryo-layering testing in support of the NIF Ignition Campaign began in September of 2010, and the first ignition test shot on September 29, 2010. Figure 14 illustrates the testing timeline showing individual fuel gas transactions in terms of Curie content of the reservoir aliquots. Most of the fuel gas was used for development and characterization of the fuel ice layering process. Specific ignition tests are also shown as red indicators. For this period, over 110 gas transactions were completed and 29 ignition tests performed using DT/THD fuel.

SUMMARY

An isotopic mixture of hydrogen is the basic fuel for the ignition targets at the National Ignition Facility. The experimental program of the National Ignition Campaign relies on careful preparation and management of the fuel gas to ensure quality and safety of operations. Timely and agile operation of the tritium supply systems is fundamental to meet the demand for cryo-target development and the ignition shot

schedule. Precision and robust equipment and the associated operational infrastructure have been successfully implemented to meet the technical and safety requirements. This experience now forms the basis for continued development of more demanding target designs and fuel gas requirements.

Target Platform Type	Ignition Parameter
Keyhole	Assesses the efficacy of the timing of the laser pulse in compression of the capsule
Con A	Measures the speed of the compression of the capsule
Re-Emit	Evaluates the x-ray illumination uniformity within the hohlraum
Sym Cap / Ignition	Assesses the shape and symmetry of the capsule implosion and the neutron yield of the fusion event.

Table 1: Target types used in the National Ignition Campaign

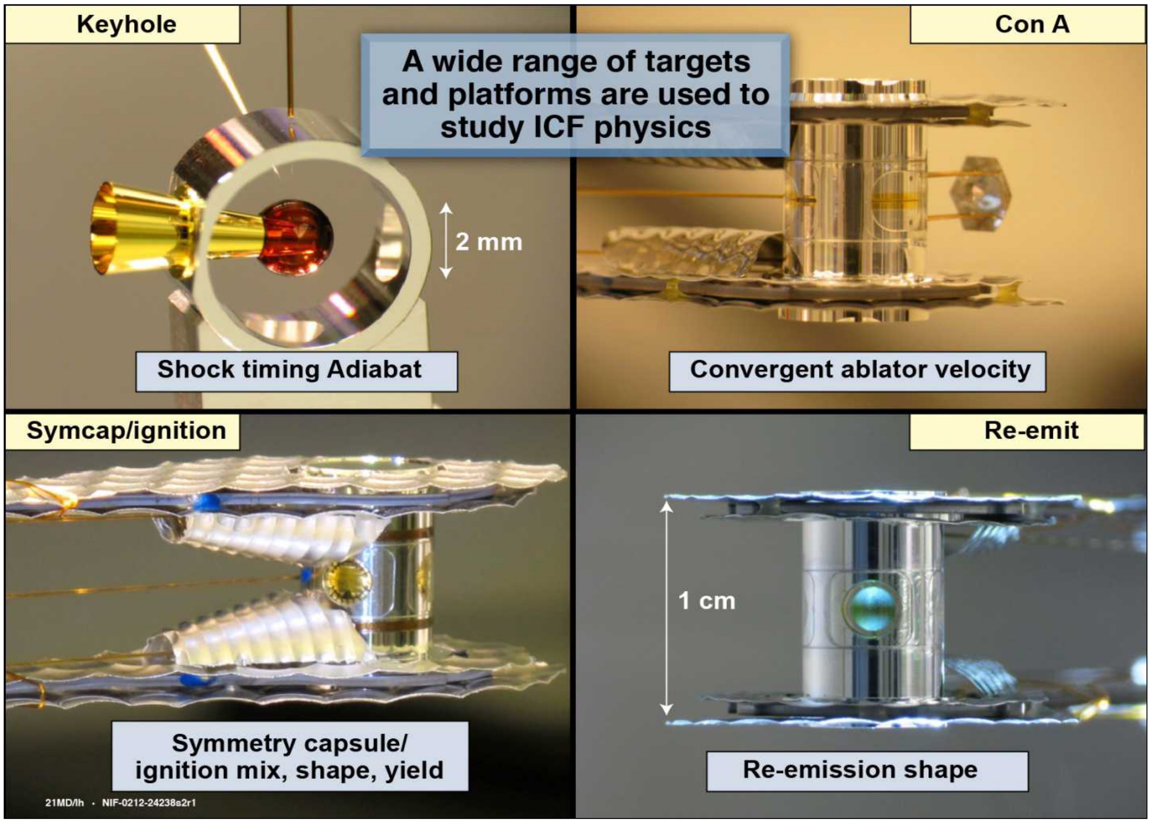


Figure 1: Types of targets used in the National Ignition Campaign

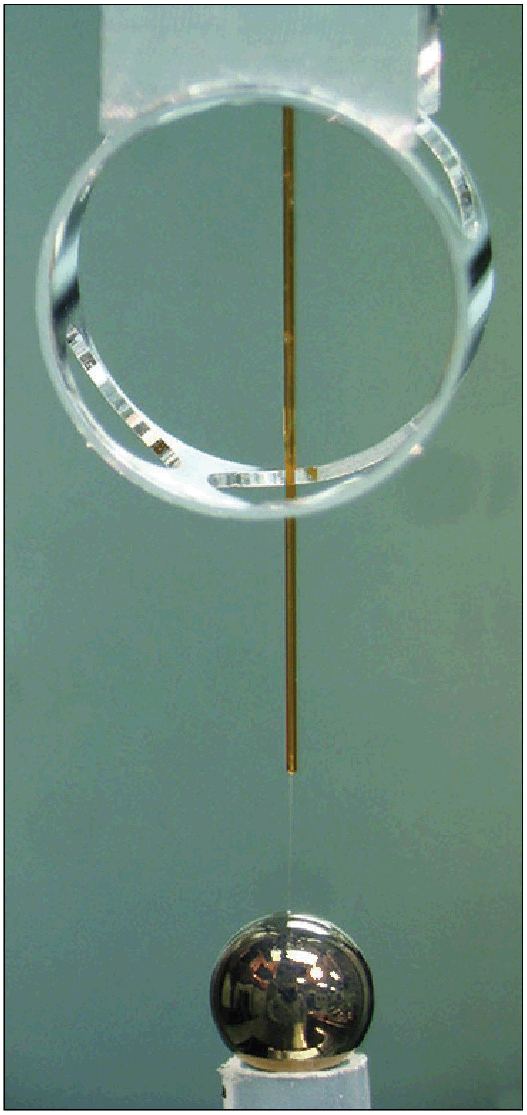
Physics

Laser Entrance

Package

Hole

Figure 2: Schematic of ignition target showing the Thermal Mechanical Package, the Hohlraum, and the Fuel Capsule. The Hohlraum and Fuel Capsule assembly is called the Physics Package



Diagnostic Band of Hohlraum

5 µ Capsule Fill tube

2 mm Capsule

Figure 3: Photograph of an Ignition Capsule attached to a 5-micron ID glass fill tube. The capsule is being threaded into the Diagnostic Band of the Hohlraum assembly

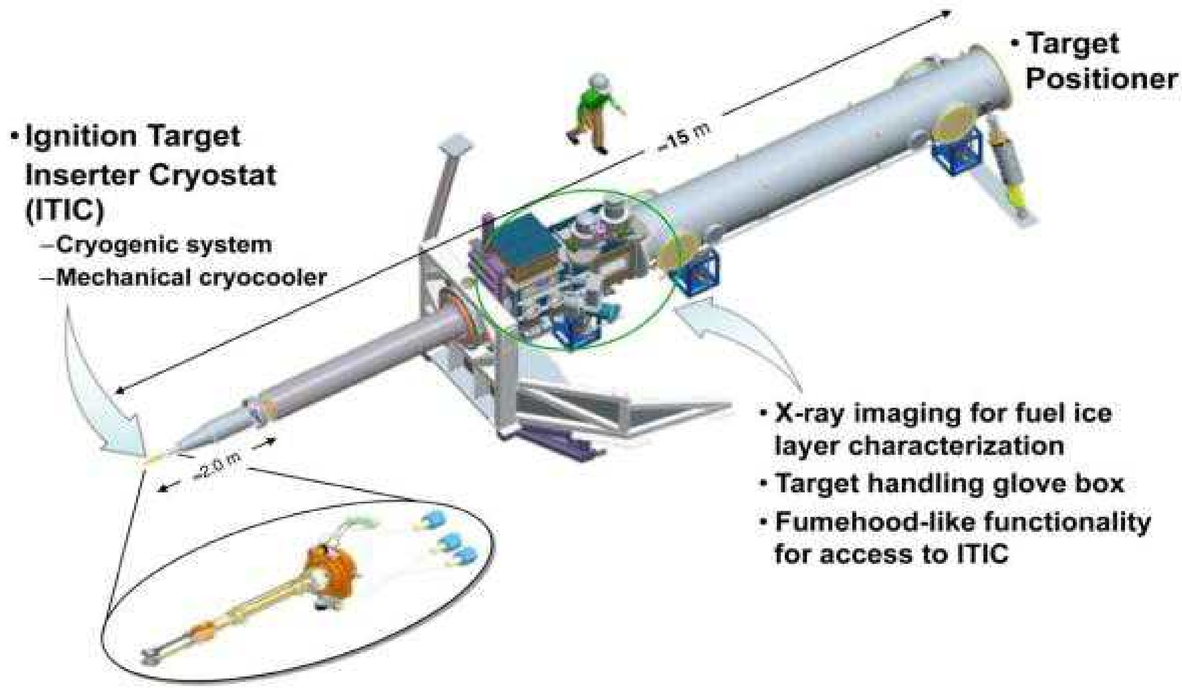


Figure 4: Schematic of the Cryo-Tarpos system

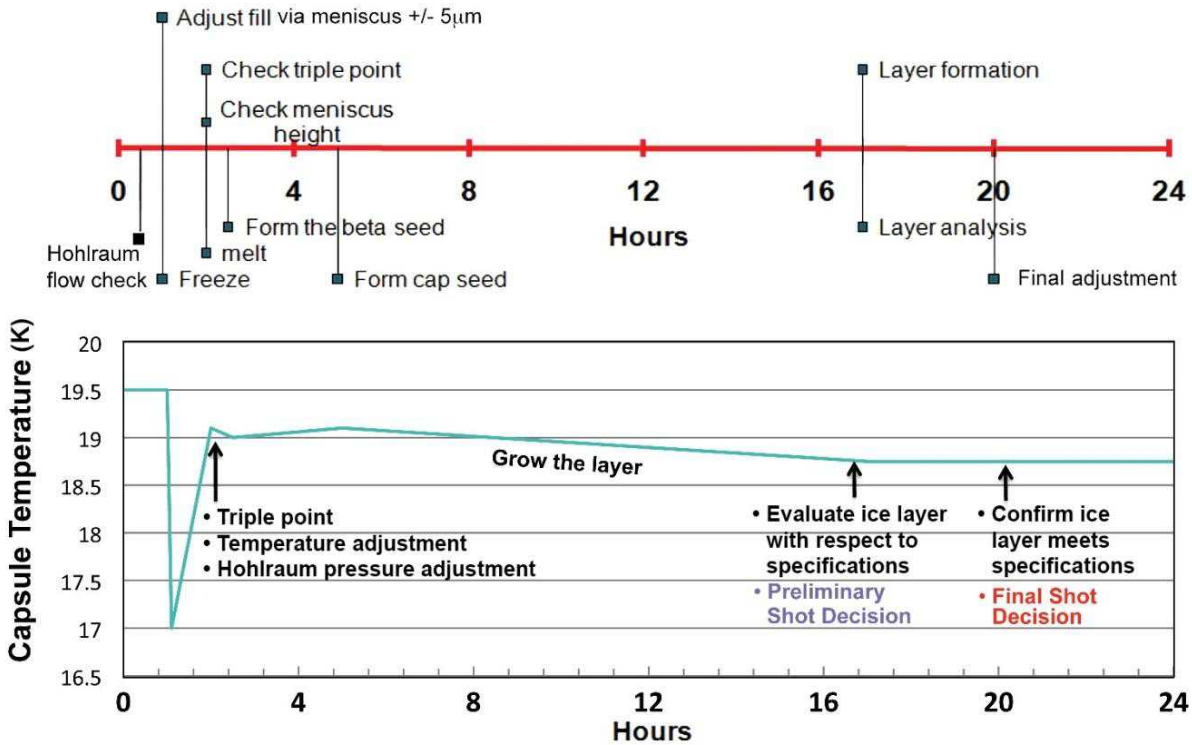
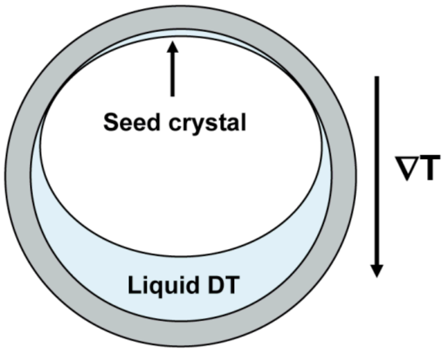


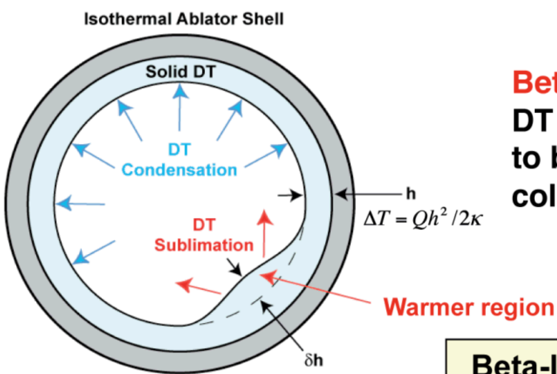
Figure 5: Layering timeline for a cryogenic ignition target.



Liquid self heating provides thermal gradient during formation that helps limit rate of solid growth

The power generated by the DT divided by the heat of sublimation gives a natural time constant

T ~ 1500 J/mole/(0.977 watts/mole) = 25.6 min



Beta-layering* reduces the bump height as DT sublimes from the warmer region (due to beta-decay of tritium) and condenses on colder surfaces

* *J. K. Hoffer and L. R. Foreman, PRL 60, 1310 (1988)*

Beta-layering helps produce a spherical shape, but does not smooth small-scale roughness

Figure 6: Beta Layering; radioactive decay of tritium helps in formation of uniform ice layers.

The Cryo-Tarpos also provides a target characterization tool that is used to monitor and control the formation of the ice layer. This equipment is mounted in the forward portion of the Cryo-Tarpos shown in Figure 7.

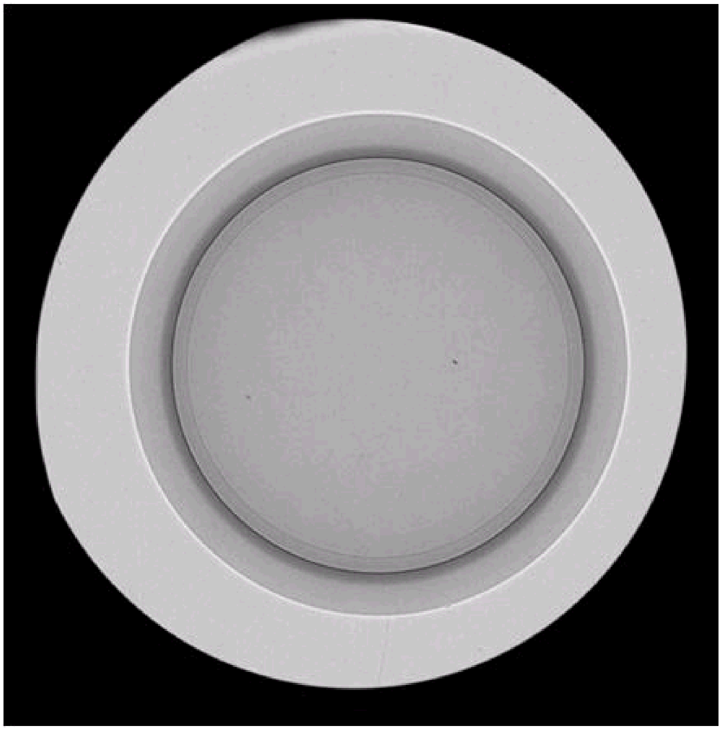


Figure 7: Phase contrast x-ray image of a fully formed DT ice layer with in the target capsule. This view is through the laser entrance hole.

Figure 8, Photo of Cryo-Tarpos vacuum vessel showing the Ignition Target Inserter Cryostat (ITIC) and associated fuel gas handling systems. The technician is opening the manual valve of the fuel gas reservoir. This is the last manual operation prior to closing the vacuum vessel door.

Figure 9 Main Site of Lawrence Livermore National Lab. Fuel gas for NIF ignition experiments is prepared at the LLNL Tritium Facility (lower left) and transported to the NIF (upper right).

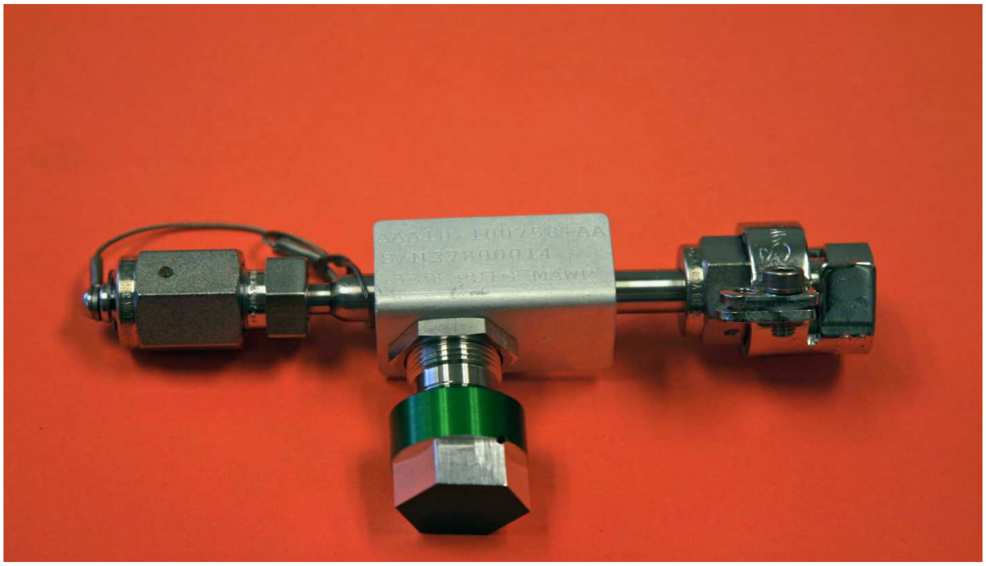


Figure 10, Photo of typical NIF fuel gas External Reservoir. These vessels provide for precision gas composition, accurate material accountability, and containment of the radioactive materials.

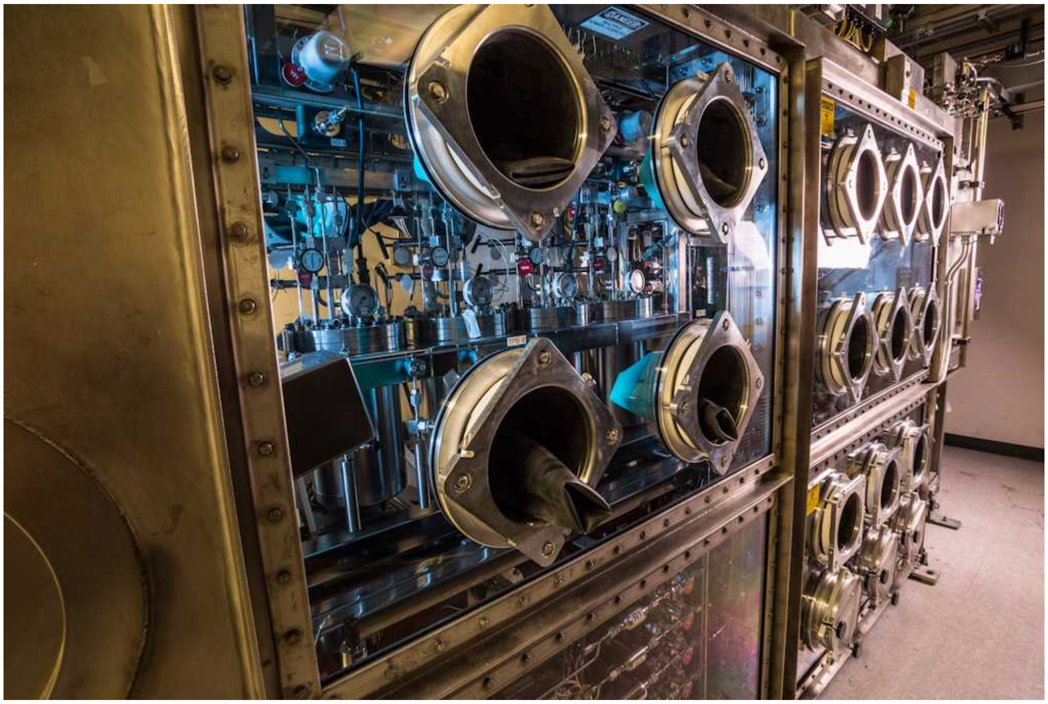


Figure 11 Tritium Processing System showing glove box system enclosing the uranium-hydride and palladium hydride bed pairs. This system provides high purity tritium gas for NIF cryo-target operations.

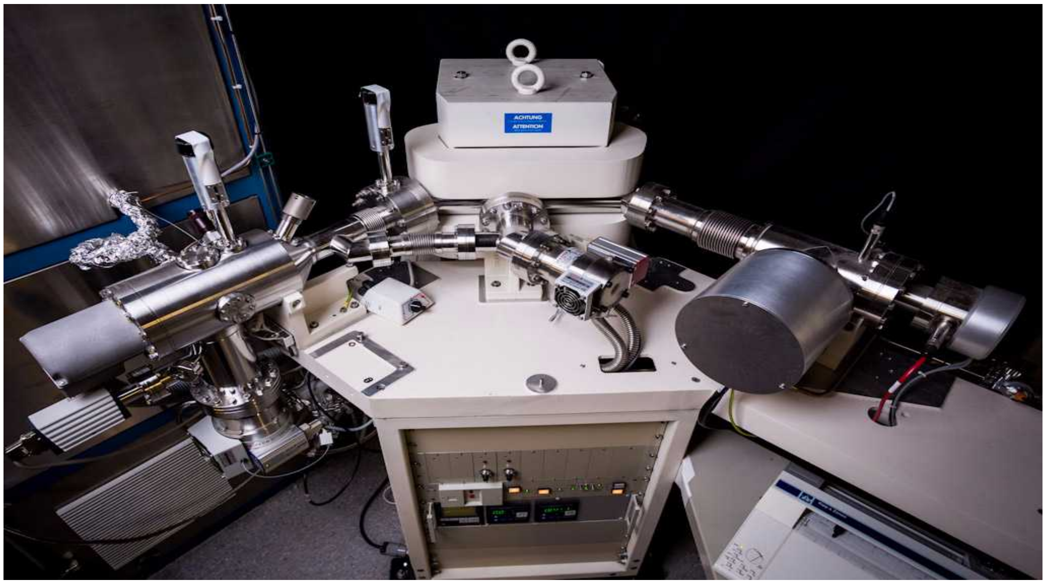


Figure 12 Sector-Magnet Mass Spectrometer. In this photograph, the gas inlet, ionization and acceleration section is to the left, the faraday cup and electron multiplier detection system to the right. Mass differentiation is provided through sweeping the acceleration voltage thereby changing the speed of the gas species traveling through the drift tube. These are then spatially separated as the charged species trajectories are bent by the magnetic field.

Mass Spectrometry Analysis

NIF Target Gas Analysis					
	Analyst	Chiarappa-Zucca	Analysis Date	05/09/12	
	Witness Sample S/N	EFS OQ 05092012 Test Reservoir 14 Only	Work Order & Reservoir Serial Numbers	PGAS118694	27800014
	Sample Bottle Fill Pressure	TPS fill; 27.2 psia		NA	NA

Gas Components	Replicate 1 mole %	Replicate 2 mole %	Replicate 3 mole %	Average mole %	STDEV	% RSD	95% CL	Lower 95% CL	Upper 95% CL
H_2	0.002	0.004	0.001	0.003	0.002	68.59	0.002	0.001	0.004
^3He	ND	ND	ND	NA	NA	NA	NA	NA	NA
HD	0.224	0.209	0.206	0.213	0.010	4.49	0.011	0.202	0.224
HT	0.193	0.184	0.183	0.187	0.005	2.85	0.006	0.181	0.193
D_2	25.63	25.61	25.11	25.45	0.294	1.16	0.333	25.12	25.78
DT	49.23	49.24	49.25	49.24	0.010	0.021	0.012	49.23	49.25
T_2	24.72	24.45	24.75	24.64	0.167	0.677	0.189	24.45	24.83
Total Atomic Components	**Replicate 1 Atom %**	**Replicate 2 Atom %**	**Replicate 3 Atom %**	**Average Atom %**	**STDEV**	**% RSD**	**95% CL**	**Lower 95% CL**	**Upper 95% CL**
H	0.211	0.201	0.195	0.202	0.008	3.79	0.009	0.194	0.211
D	50.36	50.34	50.34	50.34	0.012	0.023	0.013	50.33	50.36
T	49.43	49.46	49.47	49.45	0.019	0.039	0.022	49.43	49.48

Electron Multiplier Detector

Gas Components	Replicate 1 mole %	NCR required when mole % is ≥ 60 ppm
Helium	ND	NO
Total Waters	0.0023	NO
Total Methanes	0.0100	YES
Argon	ND	NO
Carbon Dioxide	ND	NO
Nitrogen	ND	NO
Total Ammonias	ND	NO

Figure 13 Standard fuel gas Mass Spectrometer report showing molecular species, calculated atomic fractions of hydrogen isotopes, and trace gas determinations.

Shot Category	Yield type	Neutron Yield neutrons / shot	Ignition Target Fuel Isotopics	Primary Shield Door	Secondary Shield Doors
A	None/low	<1E14	n/a	X	
B	Moderate	1E14< Y <1E16	< 11 at % D	X	
C	High	>1E16	> 11 at % D	X	X

Table 3, Shot maximum neutron yield and elemental deuterium of the fuel mix. The configuration of the facility shield doors for a given shot is based on deuterium concentration.

Gas Fuel Requirements for Ignition Targets		
Prepared in single aliquots of ~ 1.7 cc at ~10 atmospheres		
Hydrogen Isotopes are adjusted to control neutron yield for testing purposes		
Low Yield (typical)	2 atomic % D	74 % T : 24% P
High Yield (typical)	50:50 Deuterium:Tritium	< 1% Protium
Helium-3 Ingrowth	< 300 hours	
Other Contaminant Gases	Methanes	< 200 ppm
	Waters	< 60 ppm
	Carbon Dioxide	< 60 ppm

Table 2 Summary of Fuel gas requirements for ignition targets on NIF.

Figure 14, timeline of cryo-layering development and initial ignition test shots on NIF. This chart shows this history as the amount of tritium (in Curies) processed.

Standing Up The National Ignition Facility Radiation Protection Program

Thomas R. Kohut*, Rick L. Thacker[7], Richard M. Beale[8], and Jon T. Dillon[9]

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[7] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

[8] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

[9] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

Name and address for correspondence:

Thomas R. Kohut, L-760

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925-422-9528

Telephone: 925 424-3242

e-mail: kohut2@llnl.gov

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***Abstract*— Operation of the NIF requires a large and varied number of routine and infrequent activities involving contaminated and radioactive systems, both in servicing on-line equipment and off-line refurbishment of components. Routine radiological operations include: up to several dozen entries into contaminated systems per day, multiple laboratories refurbishing radiologically impacted parts, handling of tens of curies of tritium, and (eventually) tens of workers spending most of their day working in radiation areas and handling moderately activated parts. Prior to the introduction of radioactive materials and neutron producing experiments (capable of causing activation), very few of the operating staff had any radiological qualifications or experience. To support the full NIF operating program, over 600 radiological workers needed to be trained and a functional and large-scale radiological protection program needed to be put in place. It quickly became evident that there was a need to supplement the LLNL site radiological protection staff with additional radiological controls technicians and a radiological protection staff within NIF operations to manage day-to-day activities. This paper discusses the approach taken to stand up the radiological protection program and some lessons learned.**

Key words: radiation protection; operational topics

Introduction

While planning for radiological operations in the NIF was included at a high level from the start, detailed planning for implementing a radiological protection program began in earnest in 2008. At that time, the facility was essentially complete, and commissioning and operation of the laser and target systems had been proceeding for some time. The size, scope and complexity of planned radiological operations required significant planning to ensure that the transition to a radiological facility would be a smooth one.

In preparing to standup the radiological protection program, a number of things had to be considered, including: the initial conditions and associated limitations imposed by existing facility operations, the scope and breadth of the anticipated radiological hazards, and personnel availability. The NIF was already the largest and most energetic laser facility in the world, and laser operational requirements present some limitations. For example, the need to maintain the cleanliness of laser components (to prevent self-damage from high energy laser beams) presented many operational considerations such as air cleanliness and flow, cleanliness of personal protective equipment, and cleanroom protocols. Often compromises needed to be made between cleanliness considerations and standard radiological control practices. In addition, the hazards associated with operating the laser system (including laser light, high voltage and oxygen deficiency hazards), needed to be integrated with radiological controls to provide an overall safe working environment.

Planned experiments were anticipated to use modest quantities of tritium (few hundreds to thousands of GBq) and depleted uranium (few mg per target), and produce very high neutron fluxes (which would lead to significant activation of materials). In addition, provisions were to be made to use small quantities (mg) of Beryllium in targets, which would then become co-mingled with radiological contaminants. The nature of NIF operations would require frequent and routine access to these affected areas and systems. Operations were anticipated to occur on a 24 hour-per-day, 7 day-per-week (24/7) basis.

Staffing and training was an important planning aspect. Routine NIF operations require several hundred operations and support staff. Almost all of these personnel were already working on site, but few (<10%) had any previous radiological training or experience. The assigned health physics staff at the NIF at the time consisted of one health physicist and one multi-purpose health and safety technician. Clearly this staff required augmentation.

To start, an assessment was made of the full range of preparations that would be needed to stand up the radiological protection program, including required equipment (and software), personnel, and procedures.

Materials and Methods

Documentation

The most pressing need was for an overarching document that would describe the radiological hazards and controls for the facility. While the existing LLNL safety program documents provided generic radiological controls that would be used at NIF, details of how these would be applied to NIF-specific hazards and configurations needed to be specified.

This was documented in a single Integrated Worksheet/ Operational Safety Procedure that would apply to all radiological work that occurring in the facility (for simplicity and consistency of controls). It included things such as:

- The magnitude of hazards to be encountered
- Facility design requirements such as shielding and ventilation system operations and radiation monitoring systems
- Management of high yield operations
- Specifics on anti-contamination clothing and respiratory protection to be used
- Management of flow-down documents
- Dose management
- Training requirements

and a number of other topics. Dozens of other documents would be required that detailed commissioning and operation of radiological safety-related systems, personnel training, and hazard analysis.

One critical document developed was a Radiological Work Permit (RWP). NIF's RWP form was patterned after the one described in the Department of Energy Standard Radiological Control Manual (DOE-STD-1098-2008). When required, Beryllium controls would also be included in the RWP, since it was anticipated that any Beryllium contamination would usually be co-located with the radiological contamination, and controls would be similar and overlapping. This would provide a clear set of controls to the worker, without having to comply with two different (and potentially conflicting) safety documents. Because of the large number of workers and the number of varied tasks to be performed, RWPs provide the method for assigning workers specific radiological controls aligned closely to specific work tasks. RWPs were to be used in conjunction with NIF's previously existing work permit process. Essentially all work on NIF requires a work permit as part of the work package documentation; the RWP is included as part of this work package. Work teams execute the controls specified in the RWP, with periodic assistance and oversight of assigned Radiological Controls Technicians (RCTs).

Personnel

Personnel preparation consisted of two major groups: the health physics staff, and the general worker population.

Due to anticipated 24/7 operations, the standard LLNL facility health physics support paradigm would require augmentation and adjustment. Most LLNL facilities work on a weekday-only schedule, and have much smaller staffs than the NIF. To help manage this large operational scope efficiently, a radiation protection staff element was added to the NIF operations staff. Individuals with significant health physics experience and training were assigned within operations as Radiation Safety Officer (RSO) and Deputy RSO (DRSO). They would provide the day-to-day management of radiological operations, and provide the interface to the LLNL health physics staff, which provides guidance and independent oversight (Figure 1).

To provide field support, additional RCTs would be required. LLNL did not have a sufficient number of available RCTs, so a number were recruited from outside sources, including commercial nuclear power, other DOE labs, and the Navy nuclear power community. Experienced RCTs were brought in to assist with the training of radiation workers, and to provide quality oversight of radiological work. Since they had been previously trained, recertification as DOE RCT was much faster than the normal certification process. RCTs are hired, trained and qualified by the LLNL Environmental Safety & Health (ES&H) radiological control organization (reporting to the LLNL Radiological Controls Manager [RCM]), but are matrixed to the NIF RSO for daily tasking. The RSO/DRSO manage this tasking. RCTs also staff the NIF in-house health physics laboratory, which provides 24/7 survey support, including liquid scintillation counting and beryllium analysis.

The number of RCTs required for efficient operations was initially underestimated (by a factor of 2). This was due to three main causes: the number of radworkers staffing each shift was increased more than anticipated to meet operational schedules, the number of free-releases and down-posts of areas and equipment was larger than anticipated, and staffing the heath physics lab took more dedicated technician time than estimated. At the peak, 18 RCTs were ultimately required. Initially RCTs were borrowed from elsewhere in the laboratory and contract RCTs were brought in until the permanent staff could be adequately augmented.

Training of the required number of radworkers was also a significant undertaking. Due to the anticipated radiological conditions, most of the operations staff and a number of support staff (including engineers, scientists, component refurbishment teams) would need to be trained as radiological workers. Radworkers were classified as either a radworker 1 (potentially exposed to external dose, but not handling contaminated items), or the more highly trained radworker 2 (exposed to both external dose and qualified to handle contaminated components). In all, this added up to a total (combination of radworkers 1 and 2) of almost 600 people at the peak. This represented about a 30% increase in the total LLNL radworker population. Where possible, existing LLNL radiological training resources were used. However, workers needed to be trained on NIF-specific hazards, controls, and business practices (use of RWPs, interaction with RCTs, etc.). The difficult balance was in determining when to train workers. Train too early, and workers might forget their training prior to putting it to use; start training too late and risk not having enough trained individuals to support operations. As a result, a relatively fast ramp up in training was required, which strained training resources somewhat (Figure 2).

Software tools

In planning for operations, it was determined that four major functions would require obtaining or developing specialized software tools. These were radiological inventory management, survey management, dose and doe rate predictions, and dose management.

The NIF safety basis document[1] lists the maximum radioactive quantities allowed (by radionuclide) to ensure that NIF stays within its classification (as a non-nuclear facility) and be consistent with the safety analysis. Among the requirements specified there is the need to track an estimate of the amount of radioactive particulate within the target chamber, as well as the amount of tritium in the facility. Tritium is brought in as part of targets or fuel reservoirs, and is removed by fusion burn up, capture in the tritium processing system (and subsequent removal from the facility), or loss to the stack. Other discrete sources of radioactive material (such as sealed calibration sources) must also be tracked.

The target chamber contains particulate from material directly added (such as the small mg quantities of depleted uranium added by targets), and activated target chamber materials that subsequently become ablated by laser light and x-rays emitted by the target interactions. Such generated particulate can be as much as several grams for very high yield shots. In

[1] Tier 2 Safety Basis Document for the B581-582 Complex, NIF-5019666

addition, some of the nuclides have half-lives that make buildup and decay important to keep track of. A software tool was deemed necessary to calculate and keep track of these various nuclide sources. The NIF Information Technology (IT) team developed the Radiological Inventory Management System (RIMS) software tool to meet this need. This is a database tool with a web-based user interface, used by RCTs to record radioactive material entering and leaving the building. It also calculates the quantity of generated radioactive material added to the target chamber based on the details of the target and experiment parameters and shot yield. The tool provides a user "dashboard" which displays warnings relative to approaching specified limits, and cautions the user not to allow acceptance into the facility of material that might exceed the limits.

Due to the presence of tritium in most potentially contaminated systems and components, contamination swipe and airborne surveys are accomplished using Liquid Scintillation Counters (LSCs). Because of NIF's 24/7 operations, and the need to make routine process decisions and produce surveys to support changes in radiological postings, it was determined that an in-house health physics lab capability would be required. So a local lab was established in NIF, with 2 LSCs (among other capabilities).

Routine daily operations typically includes up to a few dozen work activities in contaminated systems. To accommodate survey data from up to several dozen surveys per day, it was clear early on that appropriate software would be required to manage these surveys. The NIF IT team developed the web-based Survey Information Management System (SIMS) to meet this need. SIMS interfaces with the LSCs directly to download data and perform periodic quality assurance checks, completes required unit conversions, provides electronic storage and search capability for surveys and survey maps, and manages survey review and approval. Early operations without this tool in place were challenging, and it has developed into an indispensable part of operations.

To provide operations with the necessary dose information to plan work in the target area after high yield shots, a tool was required which would allow predicting dose rates at various locations based on actual or projected yield profiles. This tool leveraged detailed neutronics modeling that had been constructed and made it accessible to operations in a user friendly web-based application, The NIF Exposure Estimating Tool (NEET[11]) assists in planning for re-entry after specific shots with measured neutron yields, and also allows for ALARA planning over longer periods when a proposed yield profile is entered. A user may select any time after an actual or proposed shot and have a detailed dose map for any level of the target bay produced in less than a minute. Plots of dose rate over time at any selected point may be similarly produced.

The final major software tool requirement was related to the ability to manage worker doses in real time. While average dose rates were expected to be relatively low (a few to a few tens of micro-Sieverts per hour), the long work times and large number of workers meant that high cumulative doses could occur if not managed closely. Thus Electronic Personal Dosimeters (EPDs) would be used to provide real-time dose data and dose and dose rate alarms for workers. RWPs specify the expected dose for each task and the dose and dose rate alarm settings. To manage this flow of information to workers and back to management, and to deal with issuing and retrieving of EPDs, it was clear that a robust software tool would be required. Since these software functions were common functions conducted in other radiological facilities, it seemed likely that a commercial software product could be found. After

[11] J. Verbeke, "NEET: NIF Exposure Estimation Tool," NIF-0116620, Lawrence Livermore National Laboratory (2010)

evaluating several options, the Sentinel Health Physics Information System software package by PTI Systems (PTI- Systems/Mirion Technologies (MGPI) Inc., 5000 Highlands Parkway, Suite 150, Smyrna, GA 30082) was chosen. As deployed on NIF, this package is accessed by self-service kiosks located throughout the facility and provides the following functions: RWP generations and management, including worker acknowledgments; issue, alarm setting, activation and return of EPDs; collection of dose by task and by worker; verification of worker radiological training status; worker information regarding estimated dose and proximity to dose limits, and dose reports to management.

Consumables and logistics

The large physical expanse of NIF radiological work areas, and the wide variety and quantity of routine activities made logistics challenging. Simply identifying locations to stock consumable materials, waste containers and the like took some effort. In addition, some aspects of operating the laser made the choice of materials and equipment more challenging.

For example, common launder-able cloth anti-contamination clothing could not be used since many of the work areas required cleanroom protocols be employed. Radiological laundries investigated could not meet the cleanliness requirements. Typical launder-able cleanroom garments also were not a good choice, since no cleanroom vendors could take radiologically contaminated garments. The solution was to use brands of disposable type cleanroom attire that met both the cleanroom and radiological requirements and provided acceptable comfort and durability. It turned out that the lifecycle cost of this solution was not dramatically different than re-usable garments.

Another example of a challenge was in selecting respirators for use. While most activities were not expected to require respirators, some (like target chamber entry and certain operations with Beryllium) would. Many target bay work locations would also require the use of laser protective eyewear during some of these radiological operations. Most respirator vendors contacted could not provide masks with laser eyewear inserts that met our requirements. Eventually a single vendor was found that met our requirements. This took almost a year to establish.

In the area of logistics, radioactive material storage areas needed to be set up to accommodate short term decay and storage of activated components before they could be worked on, as well as for other items that did not need to be stored for any particular period. These areas needed to be conveniently located and provide for drop off by operations personnel and pick up by refurbishment teams. Initially we underestimated the area required to do these tasks efficiently and had to expand the areas dedicated to these activities.

Health Physics Lab

In addition to the LSCs discussed earlier, the health physics lab provided a number of other capabilities. These included beta/gamma swipe counters, personal and area air samplers, various portable contamination, airborne tritium and radiation survey meters, sealed radioactive test sources (for calibration of health physics and diagnostic instruments), portable gamma spectrometer, and maintenance of EPDs, neutron bubble detectors, and personal contamination monitors.

One additional capability not typically found in a health physics lab was the ability to perform beryllium analysis. Since it was initially not possible for the LLNL industrial hygiene analytical laboratory to process rad-contaminated beryllium samples, and because NIF's operations required 24/7 support with fast turn-around, it was determined that an in-house beryllium analysis capability was required. The method chosen was a NIOSH (U.S. National

Institute of Occupational Safety and Health)-approved portable fluorescence method. Initially a completely manual commercially available method was used, but it was eventually determined that it was not practical to meet our throughput requirements with available staff. So NIF staff worked with a biochemical equipment manufacturer to use standard robotic laboratory equipment to produce an instrument that uses the fluorescence method, but can process up to about 70 swipe or air samples in less than about 4 hours. The process is mostly automated, requiring a single RCT to process the samples, and automatically interfacing results into the SIMS application. Developing and perfecting this capability took more than 18 months.

Deliberate Operations

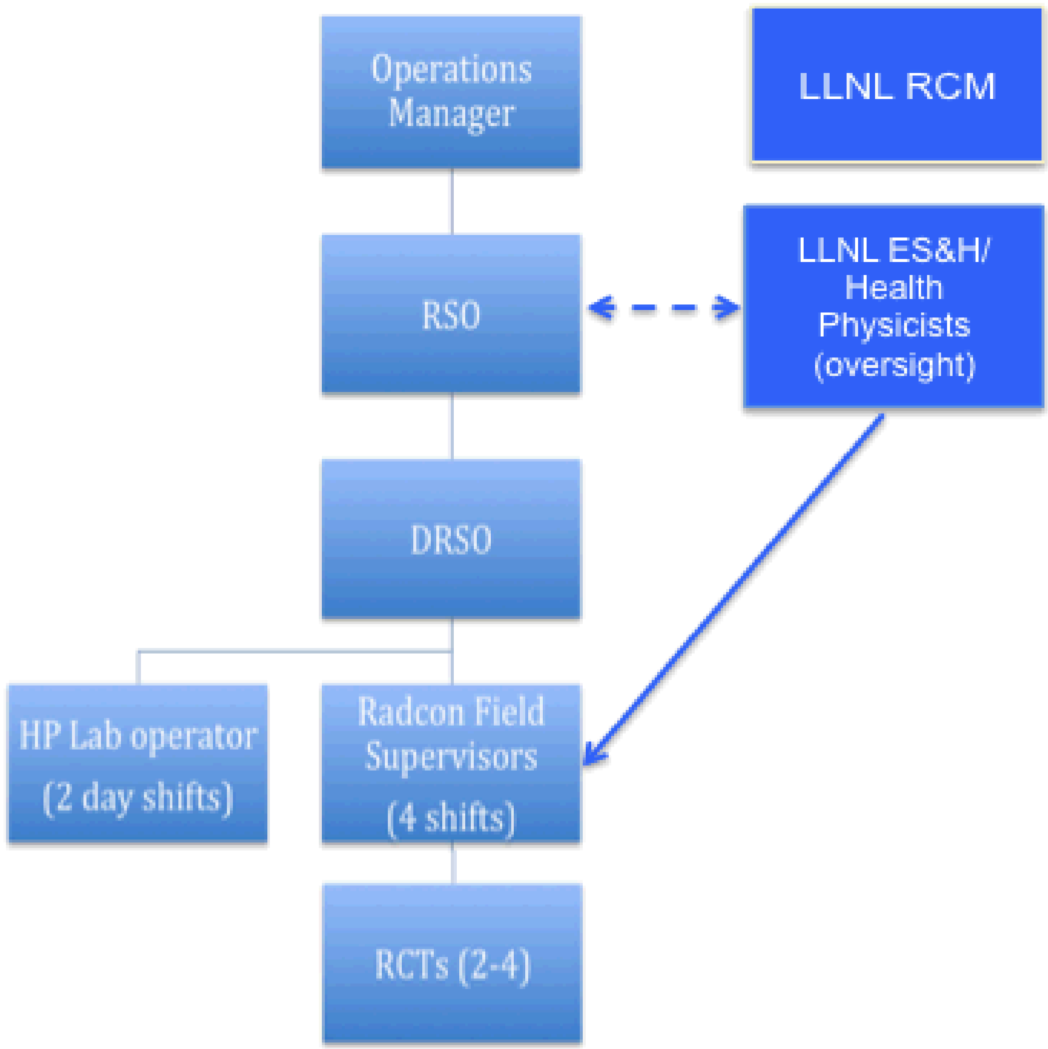
Due to the large number of workers with no radiological experience, we took a very deliberate approach to initial operations with radioactive materials. We started by permitting only a limited number of such tasks that allowed us to perform basic functions. Each work team was assigned an experienced monitor (typically a radiation protection professional) to observe and coach workers in common radiological control protocols. This also allowed us to provide feedback and clarification on our operating protocols, and led to further training.

To supplement the experienced NIF staff, other resources throughout LLNL and some temporary hire health physicists were used to provide 24/7 coverage. The level of work was slowly ramped up, and as confidence was gained in the work teams, they were released to work with only intermittent oversight. After about 2 months, all work teams were considered capable of routine work with only periodic assistance of RCTs.

Conclusions

Standing up a radiation protection program the size and complexity of NIF's was a significant undertaking that took significant forethought and attention to detail. It required thinking through the details of planned operations very early on to put in place actions to achieve the needed elements. For NIF, this took almost 2 years. Planning must include preparing the people, procedures and hardware, and must incorporate the smallest details and the unique operating considerations for the facility.

Figure 1. NIF radiation safety staffing.

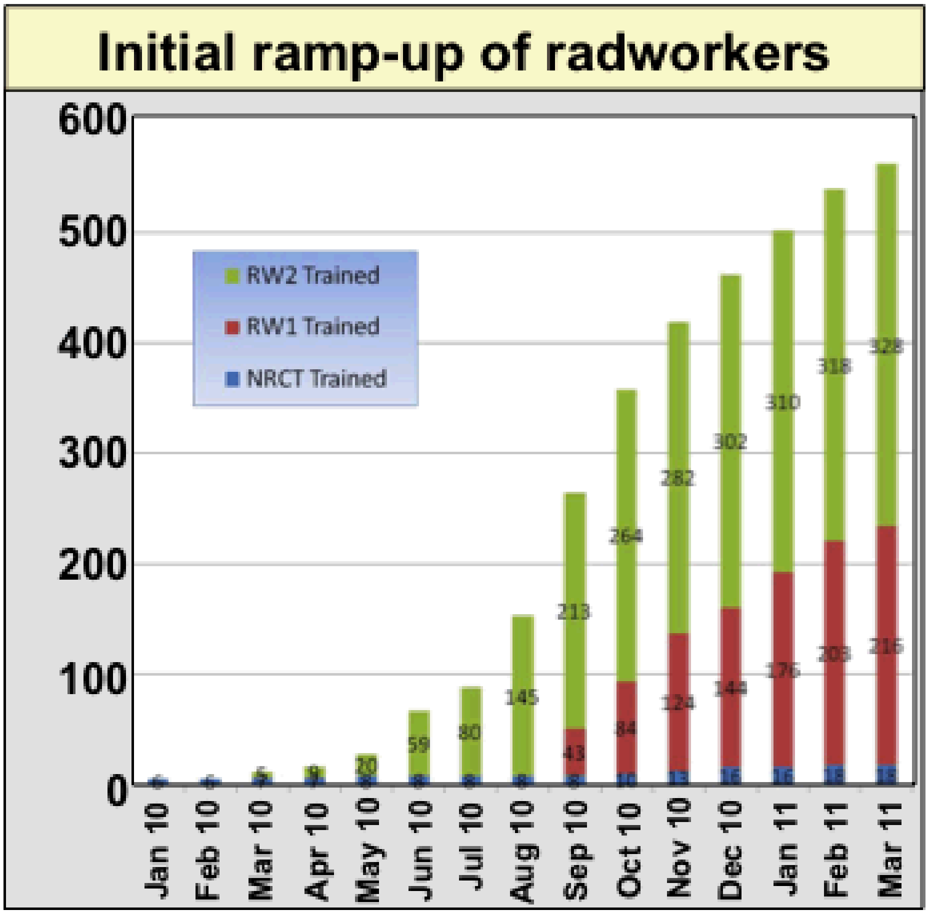

Operations Manager
LLNL RCM
RSO
LLNL ES&H/ Health Physicists (oversight)
DRSO
HP Lab operator (2 day shifts)
Radcon Field Supervisors (4 shifts)
RCTs (2-4)

D/RSO: Deputy/Radiation Safety Officer

RCT: Radiological Control Technician

RCM: Radiological Control Manager

Figure 2. Radworker training. Initial radiological operations started in September 2010.


Initial ramp-up of radworkers
600
500
400
300
200
100
0
RW2 Trained
RW1 Trained
NRCT Trained
59
80
145
213
43
264
84
282
124
302
144
310
176
318
203
328
216
Jan 10
Feb 10
Mar 10
Apr 10
May 10
Jun 10
Jul 10
Aug 10
Sep 10
Oct 10
Nov 10
Dec 10
Jan 11
Feb 11
Mar 11

Implementing an Operational Program for Determining the Radiological Status of Material and Equipment

Jon T. Dillon*

Name and address for correspondence:

Jon T. Dillon, L-449

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX: 925 423-6126

Telephone: 925 423-6167

e-mail: dillon10@llnl.gov

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Abstract— **The National Ignition Facility at the Lawrence Livermore National Laboratory has implemented a protocol for evaluating and releasing material and equipment that is potentially 'volumetrically contaminated' as a result of neutron activation, and shown not to be 'distinguishable from background'. This protocol is an important element of the National Ignition Facility's operational program as the Department of Energy's Order 458.1, *Radiation Protection of the Public and the Environment*, requires DOE-approval of the process used to release volumetrically contaminated personal property, and establishes a dose constraint of 10 μSv year^{-1} (1 mrem year^{-1}) for clearance of such items. The protocol utilizes process and historical knowledge to determine when material and equipment may be potentially impacted and field measurements to verify it has been impacted (i.e. is distinguishable from background). Material and equipment which does not meet the distinguishable-from-background criteria is considered to be non-impacted and outside the scope of the Order, and may be released from radiological control. This paper provides the technical basis and methodology for determining whether or not there is radioactivity distinguishable from background in the evaluated material and equipment, and**

documents that the measurement sensitivity exceeds the unrestricted release criteria specified in the American National Standards Institute report N13.12 – 1999, *Surface and Volume Radioactivity Standards for Clearance*. Pending Department of Energy approval, this protocol could be used as the basis for releasing materials and equipment that exceed the distinguishable-from-background criterion and are below the specified threshold for unrestricted release.

Key words: neutron activation; radioactivity, residual; instrumentation; surveys

Introduction

The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) has established a technical approach for determining the radiological status of materials and equipment (M&E) that has been exposed to neutron radiation, potentially resulting in activation. This approach demonstrates that when measured levels of radioactivity in M&E cannot reliably be distinguished from background levels of radioactivity, the M&E is not radiologically impacted and may be released without restrictions on future use. As defined in the Multi-Agency Radiation Survey and Assessment of Materials and Equipment Manual (MARSAME), distinguishable-from-background (DFB) is the radionuclide concentration or radioactivity that is statistically different from the background level of that radionuclide concentration or radioactivity in similar M&E. The NIF DFB measurement process uses sensitive, commercially-available instrumentation that is responsive to a broad range of gamma emissions anticipated from induced activation. (Note: the DFB process does not address potential surface contamination, which is a separate and well-established process used in parallel with DFB measurements.)

DOE Order 458.1, *Radiation Protection of the Public and the Environment* (02-11-2011), establishes a dose constraint of 10 μSv y^{-1} (1 mrem y^{-1}) for clearance of personal property (i.e., contractor-owned materials and equipment) and 250 μSv y^{-1} (25 mrem y^{-1}) for clearance of real property (i.e., land and buildings). The DFB determination process must be capable of identifying concentrations of radioactivity at or below these dose constraints. A consensus standard, American National Standards Institute/Health Physics Society (ANSI/HPS) N13.12-1999, ***Surface and Volume Radioactivity Standards for Clearance,*** provides the radioisotope-specific activity thresholds that correlate to 10 μSv y^{-1} (1 mrem y^{-1}) to potential future users of the subject materials.

NIF operations will create fusion of hydrogen isotopes, resulting in the production of 14.1 MeV neutrons. M&E will activate in proportion to the total energy released during the experiments, the neutron cross section of the M&E, and the proximity of the M&E to the Target Chamber. NIF used Monte Carlo modeling and source neutron energies ranging from thermal to 14 MeV to establish zones or areas of influence from potential neutron fields; assess metallic M&E that may become activated in these zones; and to show that non-metallic M&E are less likely to be activated by neutron fluxes than metals. Metallic M&E used at NIF (as well as other accelerator facilities) is typically made up of carbon steel, stainless steel, aluminum and copper.

Release of activated, or potentially activated, M&E is problematic since there is no DOE-defined threshold applicable to standard field measurements. The NIF developed a defined systematic process for conducting measurements to support release of M&E using the DFB process, and demonstrated that it can identify concentrations below the screening criteria given in ANSI/HPS N13.12-1999. Items are deemed to be DFB when there is a 95% confidence that activity (differing from background) is present. If the M&E

does not meet the DFB criterion, it is considered non-impacted and is no longer subject to radiological controls; that is, it is suitable for release without future restriction. For the time being, M&E exhibiting levels of radioactivity that are DFB are treated as radiologically-impacted and appropriate radiological control is maintained. Pending DOE review and approval, this process also supports the unrestricted release of M&E that has radioactivity exceeding the DFB criterion, but below the values given in ANSI/HPS N13.12-1999 and DOE O458.1.

background on the NIF

The NIF is the world's largest and most energetic laser system, which has the goal of achieving nuclear fusion and energy gain in the laboratory. The NIF focuses the intense energy of 192 laser beams on a BB-sized target filled with hydrogen in the forms of tritium and deuterium. The goal is inertial confinement fusion: the fusing of the hydrogen atoms' nuclei, resulting in the release of more energy than it takes to initiate the fusion reaction. See Figure 1 for a layout of the major areas of the NIF.

The fusion experiments at the NIF result in the emission of neutrons, energetic particles, x-rays and gamma-rays. The energetic particles, x-rays and debris are confined by the 10-meter diameter aluminum alloy Target Chamber (not shown in diagram, but centered within the Target Bay). Neutrons and gamma radiation travel through the Target Chamber wall into the seven levels of the Target Bay. Additionally, some pass through the Target Bay outer wall shielding structure and into the Switchyards and Laser Bays, primarily through beam line penetrations and equipment ports. When M&E absorb neutrons, those materials may become activated. The length of time the materials remain activated depends on the elemental composition of the material and the unique radiological decay characteristics of each activated element (half-life). The NIF Radiation Safety Analysis Group (RSAG) used the MCNP5 Monte Carlo code to predict the neutron flux through the volumes of interest to determine the potential for activation of M&E

with increasing neutron yield (see Figure 2).

The RSAG then used the Analytic and Laplacian Adaptive Radioactivity Analysis activation code to calculate the induced radioactivity in those volumes and to determine the point at which activation would be a concern within various areas of the facility. Zones for activation potential were established and the most sensitive M&E in the particular zone or area was identified by evaluating the material composition, neutron cross section, decay radiations and half-lives. The M&E was analyzed for activation products at time frames from 6 hours to 365 days post-shot, using a level of concern based on concentrations equating to the 10 μSv y^{-1} (1 mrem y^{-1}), as specified in ANSI/HPS and DOE O 458.1. Figure 3 shows pictorial views of the modeling predictions of neutron fluence during a 20 MJ shot (7.1 x 10^{18} neutrons) and the subsequent prompt radiation levels centered about the NIF Target Chamber. Note that the streaming seen in Figure 3 was purposely designed for neutron diagnostics.

Distinguishable from background (DFB) implementation

Approach

The NIF approach to the management of potentially-activated M&E is based on a combination of historical knowledge, process knowledge, and radiation surveys using a hand-held field detector. That is, when neutron yields at the NIF are achieved that result in the potential for activation at the level of concern, and when M&E is in a location where it might become activated, a radiation survey is required prior to release to demonstrate the M&E does not contain radioactivity which is DFB. M&E determined to be DFB is retained under radiological control; other M&E is determined to be non-impacted and may be released from radiological control.

To utilize a hand-held radiation detector for the DFB process, the net instrument count () *must be compared to a predetermined action limit (AL). The selected AL is set at the minimum detectable value of the net instrument count (), which is defined as the mean value of the net count that gives a specified probability (1 – β) of yielding an observed count greater than the instrument's critical* value, S_C. In the event that the minimum detectable value is exceeded, the M&E remains under radiological control (i.e., it is not released from radiological control).

In equation format, the foregoing logic is represented by Equations 1a and 1b:

Eq. 1a

Eq. 1b

where:

The net instrument count (gross count – background count).

=

= The action limit (i.e., the minimum detectable net instrument count), the mean net instrument count that gives a specified probability ($1 - \beta$) of yielding an observed count greater than an instrument's critical value, S_C.

Statistical Bases

As defined above, the DFB process involves a comparison of net sample results to an instrument- and measurement-specific AL, which requires determination of a representative ambient or material-specific background. Metrics (e.g. the AL) need to be established to delineate what is DFB. Measurement uncertainty and the background distribution often make it difficult to distinguish small amounts of radioactivity from background. An important part of the measurement process is to determine the instrument's detection capability, which is typically expressed as the smallest concentration of radioactivity that can be reliably distinguished from background.

As specified in MARSAME, Section 7.5, statistical decision-making is based on hypothesis testing. For the DFB approach, the "null hypothesis" (H_0) is: The M&E is below the LLNL-defined action limit and the "alternative hypothesis" (H_1): The M&E exceeds the action limit. The null hypothesis is presumed to be accepted unless there is sufficient statistical evidence to the contrary. If the evidence is strong enough, the null hypothesis is rejected in favor of the alternative hypothesis. Using the MARSAME Scenario B approach, the M&E are suitable for release only if the null hypothesis is not rejected.

Making a decision as to whether M&E is DFB relies on the evaluation of both the critical value and the minimum detectible net count. According to MARSAME, the critical value, S_C, is defined as the lowest value of the net instrument count that is too large to be compatible with the premise that there is no radioactivity present. Further, the minimum detectable net count, S_D, is defined as the mean value of the net instrument count that gives a specified probability, $1 - \beta$, of yielding an observed net instrument count greater than its critical value S_C. When a sample result is less than S_C, the sample is considered to have radioactivity at background levels, leading one to conclude that there is no radiation or radioactivity present. The relationship between the critical value of the net count, S_C, and the minimum detectable net instrument count, S_D, is shown in Figure 4.

The net instrument count obtained for a blank sample, or representative background material, will be distributed around zero, as shown in Figure 4. The probability of obtaining a background result with net counts above S_C is given by the choice of α, shown as the lightly shaded area in Figure 4. Smaller values of α result in larger values of S_C and vice versa. The minimum detectable value of the net instrument count, S_D is the value of the mean net instrument count that results in a detection decision with the probability 1 – β. That is, the probability of having a false negative (i.e., an observed net instrument count which is less than the critical level) when it has radioactivity at levels greater than background is equal to β, shown as the darkly shaded area in the figure. Smaller values of β result in larger values of S_D and vice versa.

It is important to note that both the background and sample data are not discrete points, but a distribution of data that needs to be compared when making a decision regarding DFB. The comparison of two distributions must incorporate a specified confidence level such that discrete measurement data used in making decisions to release (or not) can be evaluated.

The previously defined critical level (S_C) is the lowest value of the net instrument count that is too large to support the premise that the M&E is indistinguishable from background. The most commonly used approach for calculating the critical level of the net instrument count, S_C, is given by Equation 2:

Eq. 2

Where:

N_B = Number of background counts

t_S = Time for the sample count

t_B = Time for the background count

$z_{1-\alpha}$ = $(1 - \alpha)$-quantile of the standard normal distribution

If $\alpha = 0.05$ (corresponding to a 95% confidence level that the result is background) and $t_B = t_S = 1$, as is the premise for this approach, this equation leads to the well-known expression *for the critical net count,* S_C.

LLNL selected the Stapleton equation (Eq. 3) to derive the critical level (S_C) to provide flexibility in choosing instrumentation. The Stapleton equation is typically used for situations where the background is less than 100 counts and the background count time is equal to the sample count time. Note that the Stapleton form of the equation also works well in areas where background counts exceed 100. Evaluating the difference between *and Stapelton's equation for a background range of 100 to 1000* (N_B) resulted in a difference of only ± 2 counts, supporting the use of Eq. 3.

Eq. 3

Where:

N_B = Number of background counts

The critical level S_C, establishes the value that, when exceeded, yields the decision that the result is greater than background (i.e., DFB). However, when a measurement has a mean value at S_C, the probability that the M&E will be considered DFB is only 50%, as shown in Figure 5. Implementation of a survey procedure using S_C as the action limit (AL) would incorrectly identify up to 50% of M&E as containing excess radioactivity when it does not. It was necessary to establish the AL at a level where there is a higher confidence that the M&E is DFB, thus providing an appropriate risk-management approach that minimized the impact on operations and generation of radioactive waste, while controlling materials that are known to be impacted.

The AL is established as the minimum detectable value of the net instrument count (S_D) defined as the mean value of the net count that gives a specified probability, $1 - \beta$, of yielding an observed count greater than its critical value, S_C. Based upon the value selected for the Type II error (β), the confidence level that the M&E is DFB can be increased from 50% to 95%. For example, if the Type II error (β) is set at 0.05, the confidence level that the M&E is distinguishable from background is increased to 95%, reducing false positives to 5%.

In the context of decisions supporting M&E clearance, to make a Type I error (α) is to conclude that a sample contains radioactivity in excess of the AL when it actually does not. Similarly, to make a Type II error (β) is to fail to conclude that M&E contains radioactivity in excess of the AL when it actually does. Note that in any given situation only one of the two types of decision errors is possible. If the M&E does not contain radioactivity in excess of the AL, a Type I error is possible. If the M&E does contain radioactivity in excess of the AL, a Type II error is possible. For purposes of NIF's approach, Type I and II errors were set at 0.05 and both survey and background count times were set at 1 minute.

The minimum detectable value of the net instrument count (S_D) may be calculated by Equation 4:

Eq. 4

Where:

S_C = Critical value

R_B = Mean background count rate, $R_B = N_B/t_B$

N_B = Number of background counts

t_S = Count time for the sample count

t_B = Count time for the background count

$z_{1-\beta}$ = (1 − β)-quantile of the standard normal distribution

Based upon these selections for count times and errors, Eq. 4, the minimum detectable net count, becomes . *For consistency with Equation 3 (e.g. Stapleton equation) and when Type I and II errors are set at 0.05 along with the survey and background count times set at 1 minute,* the minimum detectable net count S_D may be calculated by Equation 5. The result is rounded up to the nearest whole number to ensure that the Type II (β) error is not exceeded.

Eq. 5

Example 1: Determine if an item of M&E meets the criteria for DFB, where the instrument has an average one-minute background (N_B) of 600 counts with only a 5% probability (β = 0.05) of identifying the M&E as not containing radioactivity in excess of the AL when it does. Assume the static measurement of the M&E was taken for one minute and resulted in a gross measurement of 715 counts.

Determining "release" versus "control" of the M&E can be accomplished by comparing the net instrument counts N_n to the *AL* using Eq. 1a:

Therefore the M&E is not DFB and may be released.

validation of the DFB approach

The DFB process described thus far focuses on counting statistics, without regard to whether the AL is sufficiently sensitive to meet the release thresholds specified in DOE O458.1 and ANSI/HPS N13.12-1999. The intention of the following validation is to determine if the selected DFB survey process is sufficiently sensitive to detect concentrations that correlate to the level of concern, or derived concentration values relating to doses in excess of 10 μSv y^{-1} (1 mrem y^{-1}), based upon the instrumentation used.

Basis for Selection of Instrumentation

According to ANSI/HPS N13.12-1999, survey instruments used for radiological measurements must be:

- Selected based upon the survey instrument-detection capability for each known or potential radionuclide or mixture of radionuclides.
- Capable of measuring the quantity of radionuclides on or in the item.
- Capable of detecting the presence of radionuclides at or below the screening levels established in Section 3.0 of the standard.
- Calibrated (NIST or internationally traceable, potentially using ISO reference radiations) for the known or potential radionuclide spectrum and distribution.
- Operated and maintained by qualified personnel, in accordance with an appropriate Quality Assurance program (e.g., including cross checks and response/operational checks).

Based on the required statistical robustness for clearing M&E, it was necessary to select an instrument that would provide integrated counts rather than count rate data. Additionally, the instrument had to be sensitive enough to provide sufficient background and sample counts in a reasonable amount of time. The desired goal was to select an instrument that would result in at least a 100 counts per minute in a low background area in order to support the use of Poisson statistical methods. Following the evaluation of several instruments, the NIF staff selected the Ludlum Model 44-2, 1×1 sodium iodide scintillation probe connected to a Ludlum Model 2241-3 scaler/ratemeter for the DFB process. Larger probes, such as a 2×2 or 3×3 sodium iodide, would increase the sensitivity and therefore are acceptable instruments for use.

Process Used to Evaluate DFB Capability

After identification of suitable instrumentation, the NIF staff took the following steps to determine if the selected decision criterion was sufficient to detect concentrations associated with the level of concern:

1. A standards document that identifies concentrations of concern was selected.
2. The potential radionuclide inventory of candidate M&E was determined.
3. Screening levels for the potential radionuclide inventories were determined based on the selected standard.
4. Emitted radiation of representative M&E was modeled using Monte Carlo codes.
5. Emissions of impacted M&E at the screening levels were evaluated with respect to the DFB AL.

Select a Standards Document that Identifies Concentrations of Concern

ANSI N13.12 provides guidance for converting volumetric activity (activity per gram) to dose per year, based on the dose criterion, above background, for the clearance of solid materials and items that contain surface or volume activity concentrations of radioactive materials. NIF selected ANSI N13.12 “Table 1 Screening levels for clearance”, which establishes 4 groups of radionuclides with volume screening levels in Bq g^{-1} (pCi g^{-1}).The Table 1 screening levels are consistent with both the DOE O458.1 dose constraint for personal property and the ANSI dose criterion of 10 μSv y^{-1} (1 mrem y^{-1}) and are the most restrictive of those found in the ANSI standard. NIF selected a screening level that corresponds to 10 μSv y^{-1} (1 mrem y^{-1}) because it is consistent with both the DOE dose constraint and the ANSI dose criterion.

Determine the Potential Radionuclide Inventory of Candidate M&E

Before an AL can be determined, a list of radionuclides to be measured must be prepared. The NIF staff developed a list of radionuclides of potential concern based on the M&E that is potentially activated. Extensive activation modeling at the NIF has shown, as expected, that the predominant activation products stem from the activation of common metals. Silica glass and optic crystals become activated to a much smaller degree than metals. In addition, polymers (plastics) also were determined, as expected, to have a low propensity for activation. In the case of NIF components, most materials located in the Target Bay can be characterized as carbon steel, stainless steel, aluminum, and copper. Radiation produced during a shot will be emitted mainly in the form of gammas and neutrons, the latter being mainly responsible for the activation of the materials. As a result, the environment will become activated, especially within the 30 m high, 30 m diameter, 1.8 m thick Target Bay wall, where the neutron flux is the highest. Instruments, diagnostics, pipes, and other M&E inside the target bay will have to be accessed for maintenance, change-out, or normal operation. Some of these objects will need to be cleared, if possible, for return to a vendor or for testing/repair in areas that are not radiologically controlled.

The NIF staff developed a neutronics model that produced activation estimates as a function of location, NIF shot history, and post-shot time for decay, for a number of components that may require clearance. NIF focused the scope of this model on common material contained in M&E in the facility, including carbon steel, stainless steel, aluminum, and copper. These materials make up the large majority of metallic M&E and are useful for evaluating the general efficacy of the DFB process.

To calculate the level of activation of M&E in the Target Bay, the RSAG built an accurate model of the Target Bay, dividing it into zones and cells. The RSAG model includes the concrete walls, floors and columns, the target chamber and its openings (ports), the chamber pedestal, and the 48 Final Optics Assemblies (FOAs).

The neutron flux through the volumes of interest was first calculated with MCNP5 (for neutron transport), and then used as an input for the Laplacian activation code that calculated the resulting gamma and beta activity in that volume. The activation data was compiled for each element of the model ("zone" or "cell") on an isotope-by-isotope basis at time intervals ranging from "shutdown" (t=0) to hours and days after the shot. Zone data were evaluated for proximity to the Target Chamber Center, the materials of construction and the propensity for the materials to activate. The activation data in each of the zones/cells were also evaluated for long-term activation from repeated exposure to neutron fields.

The RSAG modeling was used to determine the potential radionuclide inventory of various NIF components and materials. On an *a priori* basis, the following components/areas of the Target Bay were selected as conservative source terms for the listed, representative M&E to support the validation process:

- Carbon Steel – Target Bay Wall (rebar) to represent the radionuclide inventory of an activated carbon steel ingot (e.g., a hand tool) .
- Stainless Steel (SST) – Final Optic Assemblies and Mirrors to represent the radionuclide inventory of an activated SST-304 ingot (e.g., a small component).
- Aluminum – Optic frames to represent a scaled model of 25% Al-6061/75% Alumina components.
- Copper – Cabling to represent power distribution and small components.

Determine Screening Levels for the Inventory

While ANSI/HPS N13.12, Table 1 includes the principal radioisotopes commonly encountered in radiological environments, the RSAG evaluated approximately 300 isotopes for potentially activated material control at NIF. As part of this evaluation, isotopes not listed in ANSI/HPS N13.12, Table 1, but determined to have a half-life sufficient to have an impact on NIF operations, were assigned screening levels based on the following approach:

- Using ICRP 38, *Radionuclide Transformations*, and DOE-TIC-11026, *Radioactive Decay Tables*, the decay characteristics of the isotope were compared to the ANSI/HPS

N13.12 Table 1 groupings to determine the general category the isotope in question would best fall into.

- Using the same references, the energy of the decay radiations were compared to the other isotopes in the category to check for similarities (e.g., weak gamma, strong gamma.)

- Using the *Handbook of Health Physics and Radiological Health*, the specific gamma ray constants (for gamma emitters) of the evaluated isotopes were compared to those isotopes in each category to check for similarities.

- Finally, the evaluated isotopes were compared against the volumetric dose conversion factors (DCFs) of the listed isotopes in Federal Guidance Report 12, *External Exposure to Radionuclides in Air, Water, And Soil*, (EPA 402-R-93-81) and the International Commission on Radiological Protection (ICRP) Publication 60, *1990 Recommendations of the International Radiological of Commission Protection* (1991) to ensure that the assigned category was consistent with the dose potential for the existing isotopes in a given category.

Where the resources cited above did not indicate a clear category selection, the more restrictive selection was made. In all, five national and international standard references were used to assign screening levels to isotopes not listed in Table 1 of ANSI/HPS N13.12, based on similarities in decay mode, decay radiation, and potential to generate dose as listed isotopes.

Numerous M&E within NIF may become activated but will not contribute to the overall radiological clearance challenge. Radionuclides that decay through 10 half-lives in less than 24 hours were excluded from the overall evaluation.

Modeling of Emitted Radiation

Each of the four representative M&E materials were modeled in Microshield™ (MS). The approach was to build a three-dimensional model of the source volume (M&E) using the "rectangular volume" geometry in MS, and then to fill each volume with a singular source radionuclide uniformly distributed throughout that volume. Although the center edge and end of the modeled rectangle were originally evaluated, the center edge was selected as the geometry of choice because of the higher calculated field strength at that location. Care was taken to match the density and other material properties to American Society for Testing and Materials (ASTM) standards of actual NIF materials, on which previous MCNP modeling parameterizations were based. Each component radionuclide for each representative M&E was modeled in MS at its full ANSI/HPS N13.12 screening level of 0.11, 1.11, 11.1 or 111 Bq g^{-1} (3, 30, 300 or 3000 pCi g^{-1}). The exposure rate on-contact (1 cm) was calculated on the representative item at the center of the side of the object. The exposure rate-output of the MS program was then truncated to exclude the contribution of very low energy photons (<60 keV) since these would be shielded by the instrument casing during the measurement process.

The MS modeling was used to determine the dose rate from the M&E, which in turn was used to calculate the 1×1 inch NaI (e.g., Ludlum 44-2) instrument response. Since the selected instrumentation is typically calibrated to a ^{137}Cs radiation field, the instrument response was adjusted to account for the different emission energies of the expected component radionuclides from the MS modeling. The vendor-generated energy response curve was utilized to determine this adjustment and is identified as the sensitivity factor. This sensitivity factor (cpm μR^{-1} h^{-1}), combined with the expected radionuclide exposure rate in μR h^{-1} and the specific radionuclide fraction of 1 ANSI/HPS N13.12 screening level (SL) provides a net count rate (cpm) for each component radionuclide expected to be present in the M&E at specific times post-irradiation equating to the ANSI/HPS N13.12 SL.

Evaluate Emissions of Material impacted at the Screening Levels

Further analysis was completed to determine the expected net count rate profiles for the four common types of materials at various times post irradiation. The count rate was calculated for items at 1 times the SL by summing the contribution (cpm) of each radionuclide, and also summing the individual fractions of the ANSI SL. This data was used to predict instrument responses for the common types of materials at varying backgrounds and at varying times post irradiation. As an example, Figure 6 summarizes the relative values of DFB to the common materials modeled (e.g. carbon steel, stainless steel, aluminum and copper) at the release criterion of 10 μSv y^{-1} (1 mrem y^{-1}), based upon varied backgrounds at 10-days post shot. For the materials considered, the DFB level ranged from 3 to 9 times lower than the ANSI/HPS N13.12 release criterion.

summary and conclusions

The NIF has implemented a protocol for evaluating and releasing potentially-activated M&E based on process knowledge, historical knowledge, and direct radiation measurements using a hand-held NaI detector in scaler mode. The protocol is sufficiently sensitive to detect activation of the metals of concern (carbon steel, aluminum, copper, and stainless steel) at levels 3 to 9 times lower than the release criterion specified in ANSI/HPS N13.12-1999 and DOE Order 458.1. When measured levels of radioactivity in M&E cannot be reliably distinguished from background, the M&E is considered to be non-impacted, and may be released without restrictions on future use.

The NIF established an action limit (AL) as the minimum detectable net count (S_D) such that there is a 95% confidence of identifying the M&E as containing radioactivity in excess of the AL, and a 5% probability of falsely identifying M&E as containing radioactivity. A straightforward comparison of the net instrument response to the AL is used to determine whether the M&E must be continued to be controlled as radiologically impacted material or may be released from radiological control.

The NIF approach promotes the use of the prescribed DFB process to determine if materials are radiologically impacted from operations. The NIF demonstrated that common metals are easily identified by the DFB process when theoretically activated to 1 times the ANSI/HPS N13.12 concentrations (sum of the fractions including non-gamma emitters), which can also be viewed as a concentration of concern. This evaluation demonstrated the general efficacy of the DFB process, and that the DFB methodology may be applied to other types of potentially volumetrically contaminated M&E other than the specific material analyzed herein. That is, if an analysis and survey of candidate M&E produces a net count result that is less than the AL, then that M&E will be determined to be 'not DFB', and will no longer be subject to radiological controls (i.e., it will be suitable to release without restriction). Until addressed otherwise (e.g. via a DOE-approved authorized release), M&E exhibiting levels of radioactivity that is DFB will be treated as radiologically impacted and remain under radiological control.

acknowledgements

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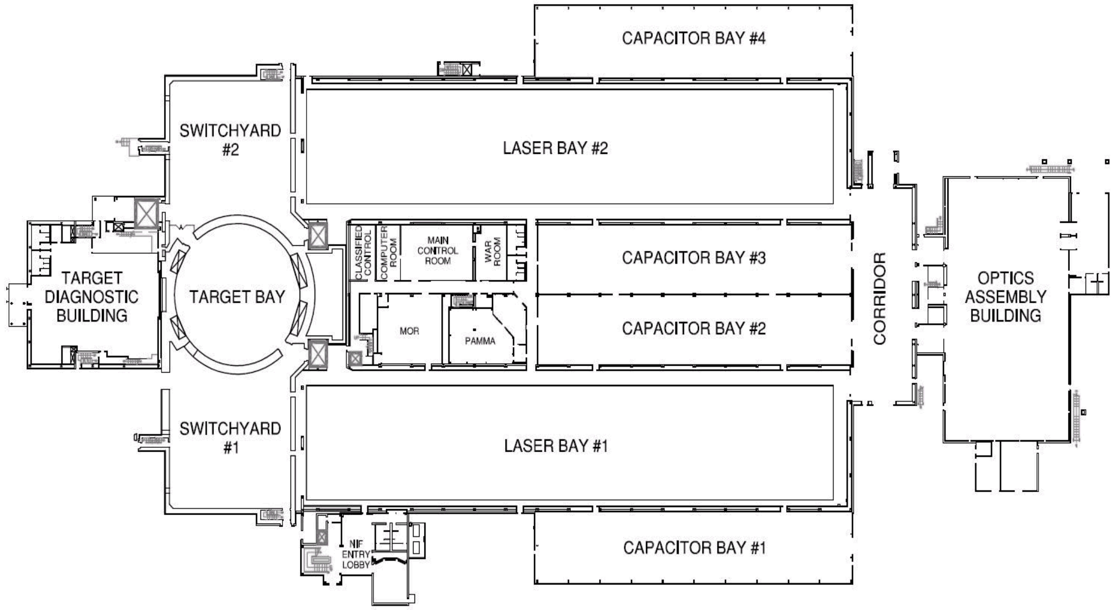


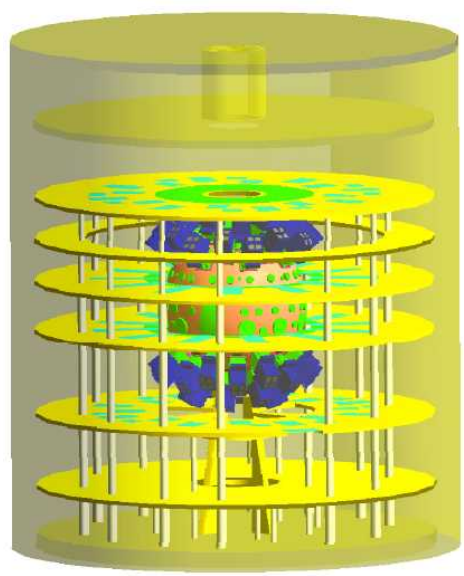
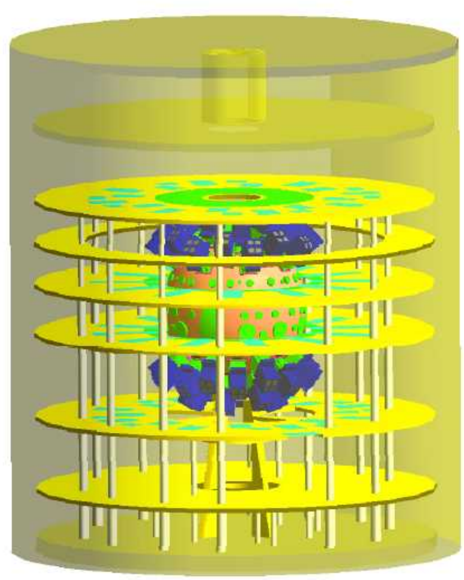
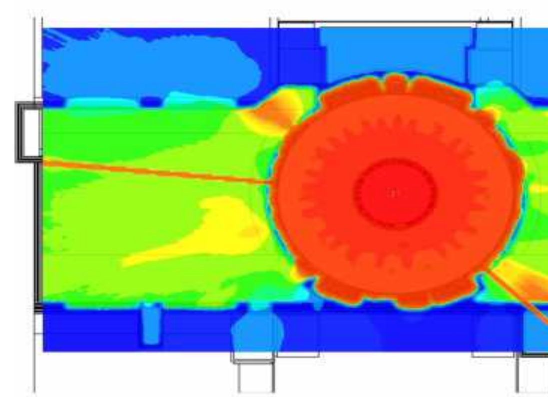


Figure 1: NIF Layout – the Target Chamber is a 10-meter Diameter Sphere in the center of the Target Bay

Figure 2: NIF Target Chamber MCNP Modeling





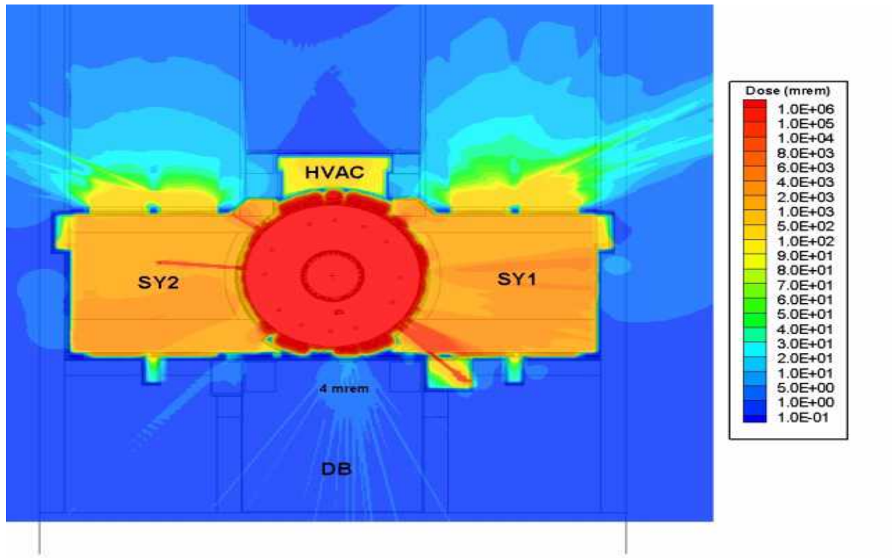


Figure 3: MCNP modeling for neutron fluence.

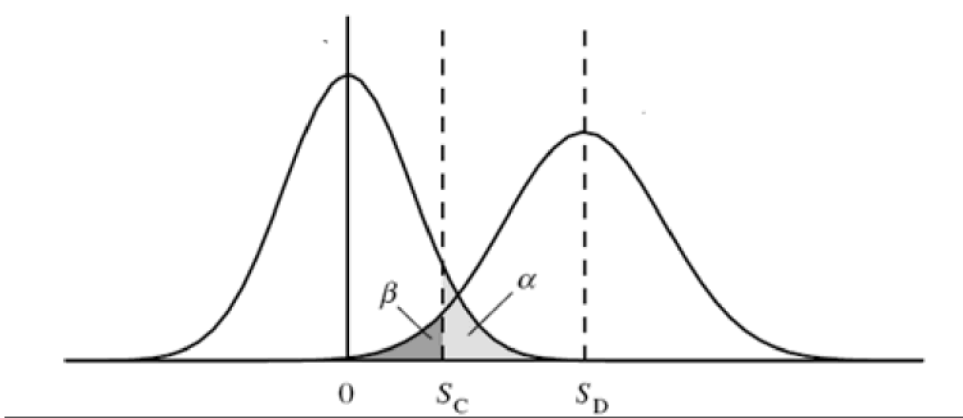


Figure 4: MARSAME Figure 7.6 The Critical Value of the Net Instrument Count (S_C) and the Minimum Detectable Count (S_D)

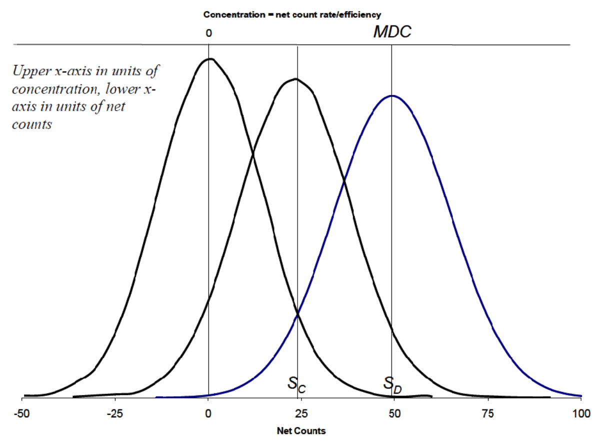


Figure 5: MARSAME Figure 7.7, Relationship Between the Critical Value of the Net Count, the Minimum Detectable Net Counts, and the MDC

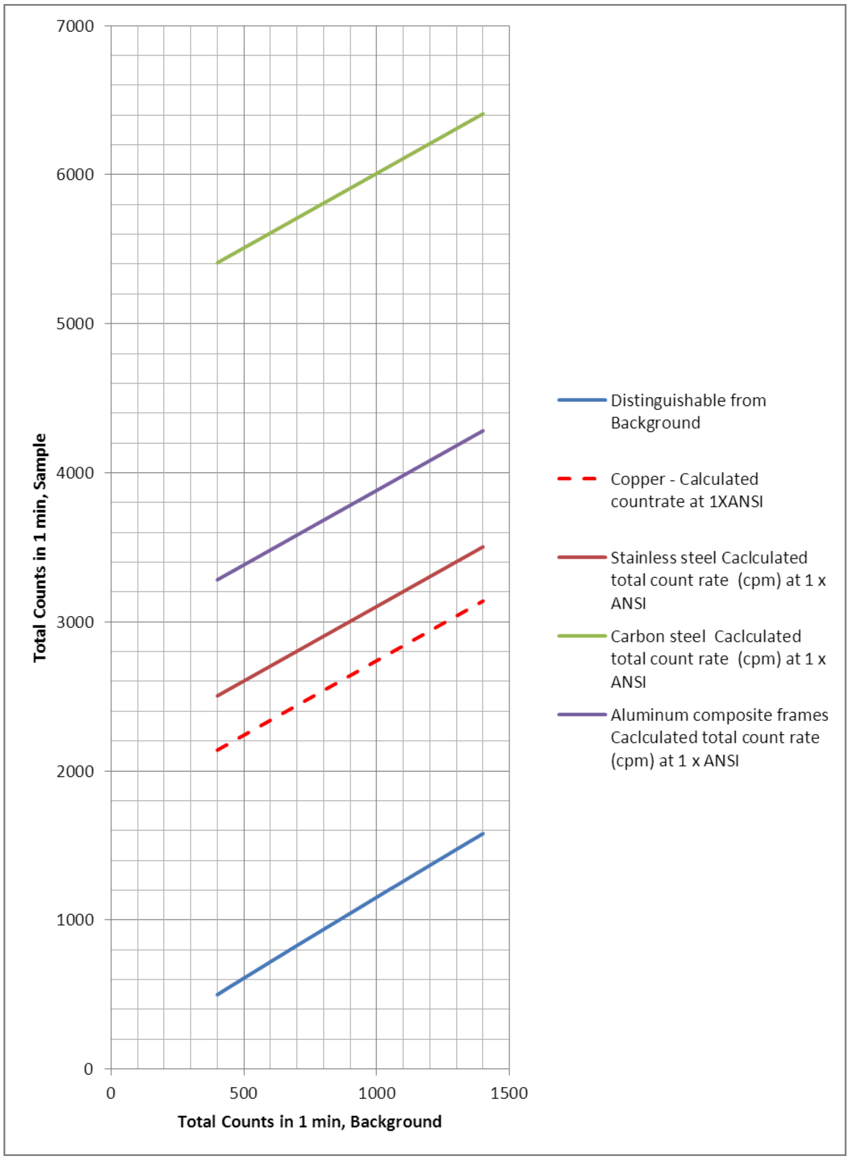

7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
Total Counts in 1 min, Sample
Total Counts in 1 min, Background
Distinguishable from Background
Copper - Calculated countrate at 1XANSI
Stainless steel Caclculated total count rate (cpm) at 1 x ANSI
Carbon steel Caclculated total count rate (cpm) at 1 x ANSI
Aluminum composite frames Caclculated total count rate (cpm) at 1 x ANSI

Figure 6: NaI Instrument Response for DFB in Comparison to Typical Materials Activated at ANSI/HPS N13.12 SL (10-days post shot)

LIFE: A Sustainable Solution for Developing Safe, Clean Fusion Power

Susana Reyes, Mike Dunne, Kevin Kramer, Tom Anklam, Mark Havstad, Antonio Lafuente Mazuecos, Robin Miles, Joel Martinez-Frias, Bob Deri*[12]

Susana Reyes, L-592

Lawrence Livermore National Laboratory

PO Box 808

Livermore, CA 94551-9900

FAX: 925 424-3295

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[12] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

Telephone: 925 423-0253

e-mail: reyes20@llnl.gov

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The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in California, is currently under operation with the goal to demonstrate fusion energy gain for the first time in the laboratory – also referred to as "ignition". Based on these demonstration experiments, the Laser Inertial Fusion Energy (LIFE) power plant is being designed at LLNL in partnership with other institutions, with the goal to deliver baseload electricity from safe, secure, sustainable fusion power, in a time scale that is consistent with the energy market needs. For this purpose, the LIFE design takes advantage of recent advances in diode-pumped, solid-state laser technology, and adopts the paradigm of Line Replaceable Units utilized on the NIF to provide high levels of availability and maintainability and mitigate the need for advanced materials development. The LIFE market entry plant will demonstrate the feasibility of a closed fusion fuel cycle, including tritium breeding, extraction, processing, re-fueling, accountability and safety, in a steady-state power-producing device. While many fusion plant designs require large quantities of tritium for startup and operations, a range of design choices made for the LIFE fuel cycle act to reduce the in-process tritium inventory. This paper presents an overview of the delivery plan and the pre-conceptual design of the LIFE facility, with emphasis on the key safety design principles being adopted. In order to illustrate the favorable safety characteristics of the LIFE design, some initial accident analysis results are presented that indicate potential for a more attractive licensing regime than that of current fission reactors.

Key words: fusion; energy transfer; power plant, nuclear

Introduction

The Laser Inertial Fusion Energy (LIFE) power plant [1] is a laser-based indirect-driven fusion energy system being designed to deliver a transformative source of safe, secure, sustainable electricity, in a time scale that is consistent with the global energy market needs. The approach is to adopt a power plant design that uses the physics scheme currently being tested on the National Ignition Facility [2] (NIF) at Lawrence Livermore Laboratory, in California, coupled to a laser technology using existing manufacturing capabilities, and a concept of plant operations and maintenance that eliminates the need to wait for advanced material development or intermediate step facilities.

A pre-conceptual design has been completed for the LIFE power plant, based on the requirement to fit within the footprint, operational characteristics and grid connectivity of a coal-fired or nuclear-powered baseload power plant. The design takes advantage of the factory-built, modular line replaceable nature of the specialized equipment, to allow for high plant availability and a competitive economics model. The design process for LIFE has been driven by end-user needs (through consultations with the utility sector and power plant vendors), coupled with an analysis of the likely economic context of fusion power delivery and the commercial impact of different technology options for the power plant. Additionally, other criteria such as minimization of tritium inventories, are used to drive fundamental design choices in the overall power plant architecture, sub-system configurations, and acceptability of certain technology options.

The LIFE power plant uses deuterium-tritium (DT) targets similar to those being tested in NIF [3] as fusion fuel, with a closed fuel cycle for the tritium. While many fusion plant designs require large quantities of tritium for startup and operations, a range of design choices made for the LIFE fuel cycle act to reduce the in-process tritium inventory. The high fractional fuel burn-up [3] relaxes the tritium breeding requirements, while the use of only milligram quantities of fuel per shot and choice of a pure lithium heat transfer fluid substantially reduce the amount of material entrained in the facility. Additionally, the high solubility of tritium in the lithium breeder is expected to mitigate the need for development of permeation barriers in the heat transfer systems, normally required to control routine releases within the allowable regulatory limits.

In the next sections we provide a general description of the LIFE delivery plan and of the LIFE design, an overview of the facility safety characteristics, and finally some initial safety analysis results that indicate the potential for a simplified licensing approach when compared to fission reactors.

LIFE DELIVERY

The LIFE project represents the next step right after demonstration of fusion energy gain (or ignition) in the NIF, with the delivery of a pre-commercial market-entry plant generating ~400 MW fusion power. Initial assessments of LIFE commercialization timelines show clear advantages of an early LIFE market entry [4]. For example, a scenario with commercial rollout from the 2030s would remove 90–140 gigatonnes of CO2-equivalent carbon emissions by the end of the century (assuming U.S. coal plants are displaced and the doubling time for roll-out is between 5 and 10 years). The same type of avoidance analysis can be done if LIFE is assumed to displace new light water reactors with a once-through fuel cycle. In this case, the metric is high-level nuclear waste avoidance. The analysis shows that, if first commercial operation were to commence in 2030, 230,000 to 360,000 MT of high-level nuclear waste can be avoided (3.0 to 4.5 additional "Yucca-Mountain-Equivalents").

The actual time for LIFE delivery will be strongly dependent on the technology development program requirements. Estimates of such requirements along with manufacturing and construction timescales indicate that the LIFE market entry plant could be commissioned and operational by the mid-2020s. Such a step would be designed to demonstrate all the required technologies in an integrated manner, providing the materials qualification and safety margin validation needed for the subsequent rollout of commercial power plants, which could take place from the 2030s onwards. It is recognized that delivery in the 2020s timeframe is possible only if driver characteristics and target illumination solutions demonstrated by NIF ignition are adopted, enabling a "single-step" facility. Nevertheless, later LIFE power plant designs could be adapted for alternate target designs based on experience from the NIF or other international laser fusion facilities [5].

Throughout the LIFE pre-conceptual design process, the rigor of a "facility point design" has been adopted, along with extensive consultation with the relevant industries [1]. A detailed (370-element) work breakdown structure (WBS) for the power plant was established, covering the main subsystems (conventional power block, plant support facilities, supervisory control system, fusion engine, target injection and tracking system, laser system, fusion fuel operations equipment, tritium plant, power conversion, and system integration). The technical solution adopted for each area had to demonstrate its compatibility and self-consistency with the rest of the plant. Design choices were then made based on the overall plant response to a proposed technology option, incorporating Monte Carlo assessment of performance and cost. Similarly, error budgets (for efficiency, availability, etc.) are distributed throughout the plant in a balanced manner.

It is recognized that much technical development work still remains if the required timeline is to be met. In this sense, a delivery plan is being prepared alongside the demonstration of ignition on NIF with the goal to enable timely analysis of the technical and economic case and establishment of the appropriate delivery partnership.

OVERVIEW OF THE LIFE FACILITY

The LIFE plant has been designed based on the requirement to fit within the operational characteristics and grid connectivity of a coal-fired or nuclear-powered baseload power plant. It is designed to make use of a conventional workforce on the plant site, taking advantage of the factory-build, modular plug-and-play nature of the specialized equipment needed for the thermal source (based on the physics scheme currently being tested on the NIF), coupled to a driver solution using existing manufacturing technology and a concept of plant operations that overcomes the need to wait for advanced material development. The design of each subsystem is consistent with performance levels using known technology options.

A schematic of the main parts of a representative LIFE plant is shown in Figure 1. The design and operation of a LIFE power plant can be considered as the combination of four distinct and decoupled technologies:

(i) a laser driver to convert electricity into a burst of light,

(ii) a fusion engine to harness this light to generate substantial energy to heat a circulating fluid,

(iii) a balance of plant to convert this heat into electricity,

(iv) a tritium fuel cycle, fuel fabrication and injection systems.

Figure 2 shows an artistic image of a representative LIFE plant. The core of the facility is the Fusion Operations Building (FOB). This building contains the fusion engine along with the laser and target delivery systems that are required for fuel delivery, ignition and energy capture.

Laser system

Advances at LLNL in beamline architecture show the ability to shrink the laser footprint and reduce the required power load by very significant factors compared to flashlamp-pumped systems such as NIF. These designs make use of the substantial progress made in high-average-power, diode-pumped, solid-state lasers over the past few years [6]. The LIFE laser design uses harmonically-converted, Nd:glass laser beamlines, which enables the reuse of much of the NIF technology and manufacturing base for LIFE. However, while the NIF laser slabs are pumped by flashlamps, the LIFE laser slabs are pumped by laser diodes. This allows for a much more compact laser architecture when compared to that of NIF. Another difference is that while NIF laser slabs are passively cooled, the LIFE laser slabs are actively cooled, by flowing helium gas at high velocity in narrow channels between laser slabs. Active cooling enables operation at high repetition rate, by removing waste heat produced by slab pumping processes.

The FOB contains four levels of laser bays that house the laser boxes and the laser beam transport system carrying the laser beams to the fusion chamber. The laser bays are environmentally controlled and support modular maintenance of the laser boxes and the beam transport systems, all designed as “line replaceable units” (LRUs).

Fusion engine

During power plant operations, fuel targets are injected into the LIFE interaction chamber in a manner conceptually analogous to the operation of a diesel engine (fuel injection, followed by laser-driven compression and ignition, followed by energy output, system exhaust, and cycle repeat). The fusion energy output is absorbed in the circulating liquid lithium that heats up to 575 ºC. A heat exchanger is used to drive a conventional power cycle for electricity or process heat applications. The engine-like mode of operation for LIFE (compared to the reactor-like operation of a nuclear power plant or concepts for magnetic fusion energy) results in very favorable operational, maintenance and availability characteristics for the plant. It also allows incremental improvement in plant performance as higher efficiency (or lower cost) fuel targets are designed and tested on the NIF or elsewhere.

To ensure continuous operation, the facility is designed such that the fusion engine components can be routinely removed from the FOB and replaced by standby units. This allows the engine and associated chamber to be constructed from conventional steel materials, removing the need for a multi-decade materials development program prior to plant construction. While the market entry plant would utilize a modified (low impurity) HT-9 steel and provide a chamber lifetime of ~ 1 year, the superior strength at temperature shown by 12YWT and other ODS-FS materials enables full commercial operations at a GWe scale. Although clearly more data is needed, the void swelling lifetime of ferritic-martensitic steels is likely to be at least 150 dpa or 6 fpy [7, 8].

Power conversion system

The facility also contains the technologies required for production of thermal energy from the fusion engine. The heat generated by the fusion chamber is transferred to steam via a primary lithium loop and secondary salt loop. The secondary salt loop is introduced as a conservative early design measure to minimize the potential for lithium/water interactions, which could impact plant availability. In consultation with utility customers and turbine manufacturers, Rankine cycle designs have been adopted for LIFE, based on demonstrated super-critical steam systems. More efficient designs using advanced ultra-super-critical steam cycles, or postulated closed Brayton cycle are possible, but are incompatible with the design philosophy of using readily available technology solutions. Nevertheless, future incorporation of these systems remains an option, taking advantage of ongoing research for the solar thermal, coal and Gen-IV fission communities.

Fuel cycle

The LIFE market entry plant will demonstrate the feasibility of a closed fusion fuel cycle, including tritium breeding, extraction, processing, re-fueling, accountability and safety, in a steady-state power-producing device [9]. The LIFE fuel cycle encompasses the engine equipment that recovers the un-spent fuel and the bred fuel from the engine systems, the tritium plant equipment that processes such fuel and conditions it for target manufacturing, and finally, the target manufacturing and target injection equipment. Some unique features of the LIFE fuel cycle include a high tritium fuel burn-up fraction, a relatively high tritium breeding ratio (through the use of a liquid lithium breeder), and low tritium permeation from the heat transfer fluid (due to the high solubility of tritium in lithium). The use of only milligram quantities of fuel per shot and choice of a pure lithium fluid substantially reduce the amount of material entrained in the facility. The design of LIFE fuel processing equipment is based on the concept of LRUs, allowing for high availability of the tritium systems and reduced tritium inventories in the facility. The pre-conceptual outline diagram of the fuel cycle is shown in Figure 3.

The LIFE engine is filled with a low density Xe gas that protects the structural walls from the fusion target emissions [7]. The chamber gas handling system (CGHS) must remove exhaust gas from the chamber, separate fusion debris from the gas stream and separate un-burned DT from the xenon chamber gas. In order to close the fuel cycle, tritium is primarily produced in the engine blanket by neutron absorption and transmutation of the Li^6 in the lithium breeder. The choice of a self-cooled lithium-breeding blanket (instead of a lithium bearing salt or alloy) is key for a sustainable fusion fuel cycle, as it allows for an optimum neutron economy and a tritium breeding margin large enough to cover potential losses and uncertainties. The lithium tritium recovery system must efficiently extract the bred tritium, so that the steady state inventory mobilizable in case of an accidental spill remains below the safety limits (achievable with a tritium concentration ~0.1 wppm).

The gas streams recovered from the chamber gas and the lithium blanket are directed towards the tritium plant, where the fuel is purified and processed in order to produce new targets. The tritium plant will be required to have high up-time and availability to process such gas streams, and will be used for tritium accountability and other functions even when the remainder of the plant is in maintenance. The following high level processing functions are performed by the LIFE tritium plant:

- receipt of tritiated gas streams (chamber exhaust, blanket extraction purge gas) during normal operations and other phases of operation (pump down, wall conditioning, maintenance),
- separation into two streams, hydrogen isotopes and detritiated impurities,
- conditioning of the impurity stream prior to its rejection to the environment,
- isotopic separation of the hydrogen stream, and
- storage and delivery of the deuterium and tritium fractions prior to sending them to the fuel manufacturing facility.

The tritium plant is also expected to handle incoming and outgoing gas shipments including tritium, and perform process monitoring, tritium accountability and inventory measurements as needed for operational and regulatory purposes.

LIFE SAFETY AND ENVIRONMENTAL CHARACTERISTICS

A principal benefit of LIFE are its inherent safety characteristics, especially compared with nuclear plants, coupled to the lack of emissions that could adversely affect the local or global environment. The intrinsically safe mode of operation of a LIFE plant arises from the very nature of fusion, which requires continuous delivery of laser energy to drive the operation – in contrast to fission, where reactions can continue to occur even after plant shutdown. Key safety characteristics include:

- Runaway reactions or meltdown are simply impossible. The system contains only tiny amounts of fuel (milligrams) at any point in time, and is only “on” for a few trillionths of a second per second (equivalent to a small fraction of a second per year).
- Fusion cannot occur when the system is off or suspends operations. This is in contrast to a fission reactor, in which nuclear reactions are sustained for an extended period.
- No cooling, external power or active intervention is required in the event of system shutdown or failure (deliberate or otherwise). This is because the residual decay heat is very low, with no need for external cooling. Upon system shutdown, the LIFE engine can be simply left standing.
- No fissile or fissionable material or spent nuclear fuel are generated. Fusion has a closed fuel cycle, with a by-product of inert helium gas. All waste streams generated during plant operation qualify as “low level” (and are therefore disposable via shallow land burial).
- The LIFE plant does contain lithium and tritium (both hazardous substances), but the consequences of even the most severe accident would be well within anticipated regulatory limits, requiring no off-site public action. This represents a major difference from nuclear power.
- As a result, preliminary work suggests that LIFE does not require any “safety class” structures, systems or components (SSC) and could utilize a performance-based licensing regime rather than the prescriptive design-based regimes required for any form of nuclear plant [10].

These safety and environmental attributes will likely become of paramount importance over the coming years. As such, LIFE could contribute significantly to international imperatives for enhanced energy security, assured public safety, and tackling the threat of nuclear proliferation.

LIFE hazards assessment

The main LIFE operating risks relate to a low probability release of radioactive materials (tritium or activation products) following an extreme accident. The hazards will primarily be controlled by the implementation of confinement zones in the facility. The confinement methodology is to identify hazardous materials and provide an appropriate level of protection based on the level of risk, i.e., provide sufficient confinement to meet the general safety objectives and further reduce potential impacts to the extent reasonably practicable.

To date, the US DOE Fusion Safety Standards [11, 12] are being used as part of the general safety strategy in LIFE and to provide guidance for fusion safety requirements. Although originally developed for experimental facilities, these standards were structured to be congruent with US Nuclear Regulatory Commission safety regulations so as to remain applicable up to the point of transition to commercial application and operations.

The main safety objectives for LIFE can be summarized as follows:

- To protect workers, public and environment from hazards
- To ensure that exposure to hazards within the premises and due to release of hazardous material is as low as reasonably achievable (ALARA)
- To prevent accidents with high confidence and implement passive safety features

wherever possible

- To ensure accident consequences are bounded and their likelihood small
- To demonstrate no need for public evacuation in any event
- To minimize radioactive waste hazards and volumes to ALARA

In particular, the handling of liquid lithium is being addressed in relation to the chemical reactivity of the material with air, water and other substances. The primary strategy for controlling lithium chemical reactivity hazards includes the following measures:

- Use of an inert cover gas (Argon) in the engine bay
- No water present in the engine bay and protection against external flooding
- Liners over all concrete surfaces potentially exposed to spilled lithium
- Low pressure lithium inventory and segmented design
- Use of multiple containment methods to lithium release (e.g. dump tanks)
- Minimized tritium inventory in the lithium to avoid radioactivity release in the event of a spill.

Initial accident analysis results

A preliminary safety assessment for the LIFE plant has been completed. The analyses of postulated events performed to date focus on bounding scenarios that have been specified based on a deterministic selection process, taking into account the major inventories at risks and the potential release pathways. The accidents considered to date are judged to be those leading to the worst possible consequences.

In order to estimate the activation of LIFE components, the MCNP Monte Carlo neutron transport code [13] has been used to calculate neutron fluxes throughout the facility. Results related to neutron activation of the materials, such as residual decay heat, have been obtained using the ACAB code [14]. Figure 4 presents the residual decay heat of the structures as a function of time, at the end of the fusion chamber lifetime. The chamber material is assumed to be a low-impurity version of the HT-9 ferritic martensitic steel [15].

To simulate the accident sequences, a version of the thermal-hydraulics code MELCOR developed by the Idaho National Laboratory (INL) has been employed that has been adapted for fusion and allows for the use of lithium as the working fluid [16]. MELCOR is capable of simulating a wide range of physical phenomena, which include heat transfer, aerosol physics and fusion product release and transport, and it has historically been applied to a variety of fission and fusion concepts, primarily for scoping accident scenarios and safety-related decision making. Therefore, a MELCOR model of the LIFE engine has been developed that specifies engine component volumes, flow paths between such volumes, solid structures, heat transfer conditions, decay and process heats and key control functions that govern normal and interrupted flow conditions. Such a model has been used to analyze the following bounding scenarios:

a) Complete loss of forced convection cooling of the LIFE engine due to lithium pump failure or loss of electrical supply to these pumps,

b) Complete loss of pumping coinciding with a double-ended in-vessel break of a large lithium pipe with a subsequent lithium spill and simultaneous air ingress leading to fire

c) Complete loss of pumping coinciding with a double-ended ex-vessel break of a large lithium pipe with a subsequent lithium spill and simultaneous air ingress leading to fire

Results of the initial safety analyses seem to indicate that even in the case of a major lithium spill with simultaneous air ingress the temperature excursion of all engine structures would be mild, and well below the level of concern for significant oxidation-driven steel mobilization. In these circumstances, the maximum hazard would be the release of the tritium contained in the spilled liquid lithium, as a consequence of a potential fire. The high solubility of tritium in lithium ensures extremely low permeability into other structures and enables the localized removal of tritium in a highly controlled manner. It has been estimated that any release from a LIFE power plant following a worst-case accident scenario would be below the limit that would require public evacuation, representing a fundamentally different scenario to any form of nuclear power plant. This is a key safety advantage that indicates the potential for a simplified and more attractive licensing pathway compared to that of current fission reactors.

Conclusions

Experiments being performed on NIF provide confidence that ignition may be achieved for the first time ever at laboratory scale. The starting point for the LIFE project is to assume success with the ignition campaign, such that a full-scale fusion energy source can be benchmarked directly on the NIF over the near term. The next step is a technology development program integrated with the detailed design and construction of a LIFE power plant in the 2020s. This plant is designed to provide the foundation for subsequent rollout of an international fleet, by demonstrating the feasibility of a closed fusion fuel cycle, including tritium breeding, extraction, processing, re-fueling, accountability and safety, in a steady-state power-producing device.

Some unique features of the LIFE fuel cycle include a high tritium fuel burn-up fraction, a relatively high tritium breeding ratio (through the use of a liquid lithium breeder), and low tritium permeation from the heat transfer fluid (due to the high solubility of tritium in lithium). The use of only milligram quantities of fuel per shot and the choice of a pure lithium fluid substantially reduce the amount of material entrained in the facility. Additionally, the leading criterion in the design of LIFE tritium processing systems is that the amount of inventory that could be mobilized in the case of any accident remains below the safety limit to avoid public evacuation. The results from initial hazards and safety analysis of the LIFE facility confirm that such a safety objective is achievable, indicating potential for a simplified licensing pathway when compared to that of fission reactors.

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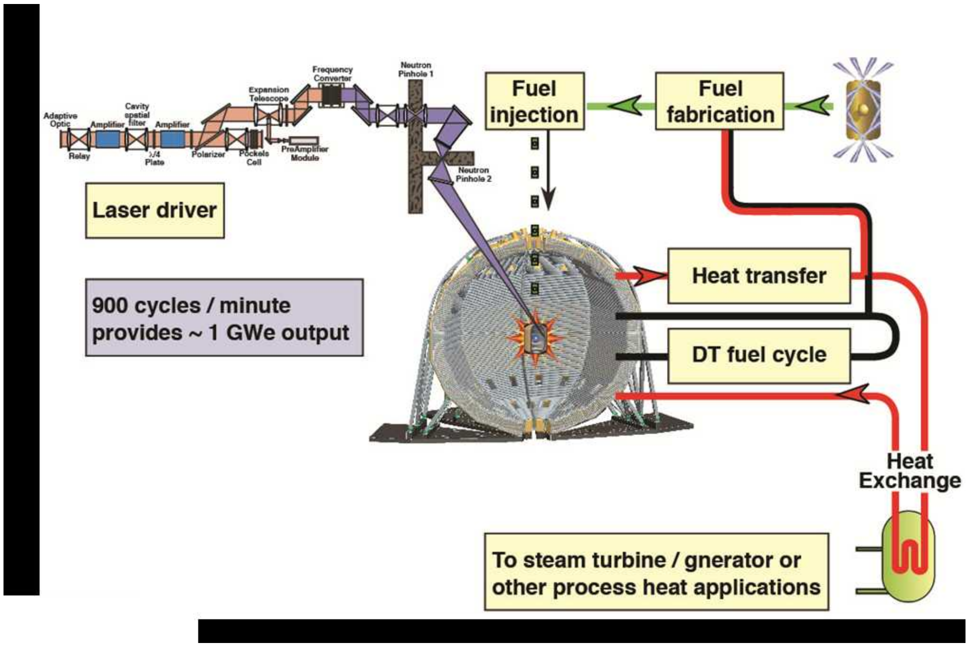

Figure 1. Schematic representation of the main components of a LIFE power plant.

Figure 2. Artistic representation of a LIFE power plant showing the central Fusion Operations Building, which includes the central LIFE engine surrounded by the laser, heat transfer, target injection and chamber exhaust systems.

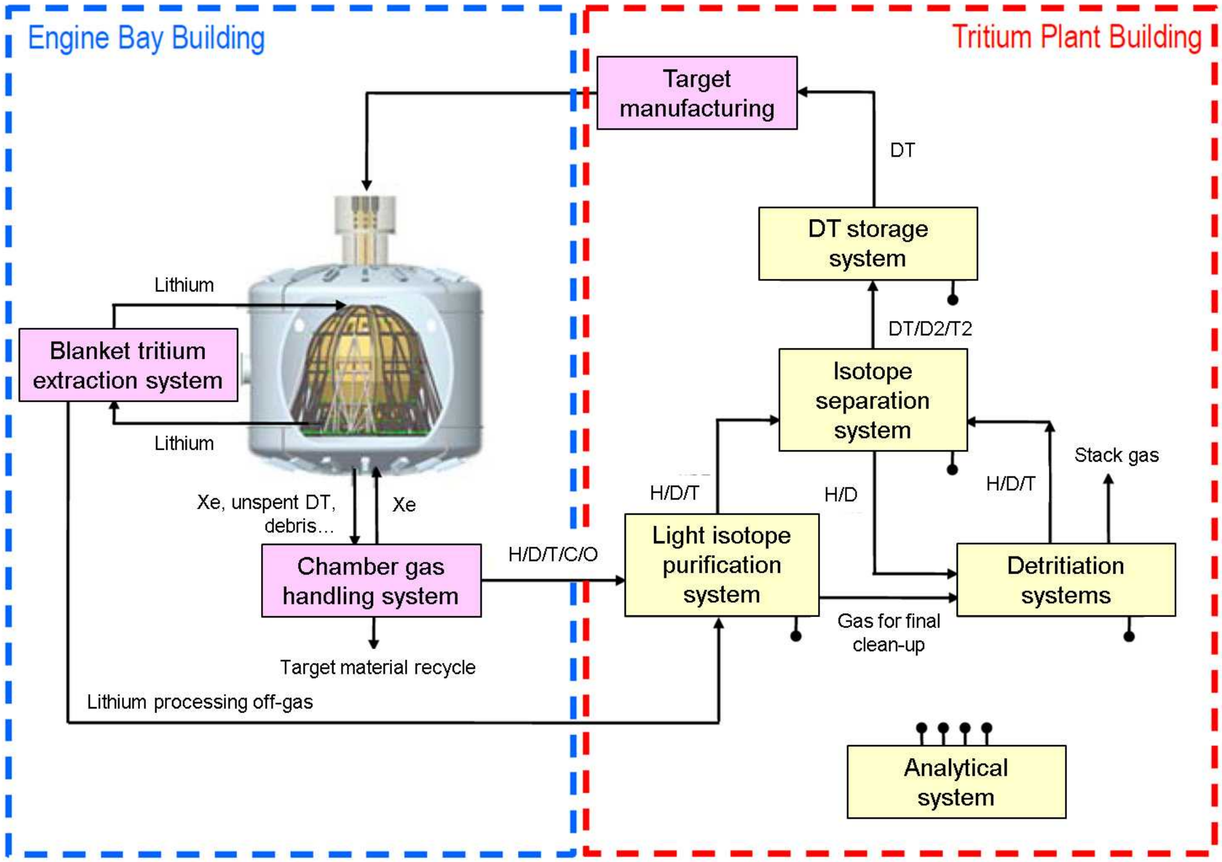
Engine Bay Building
Tritium Plant Building
Target manufacturing
DT
DT storage system
DT/D2/T2
Lithium
Blanket tritium extraction system
Lithium
Isotope separation system
Stack gas
H/D/T
H/D
H/D/T
Xe, unspent DT, debris…
Xe
Chamber gas handling system
H/D/T/C/O
Light isotope purification system
Detritiation systems
Gas for final clean-up
Target material recycle
Lithium processing off-gas
Analytical system

Figure 3. Simplified LIFE Fuel Cycle diagram.

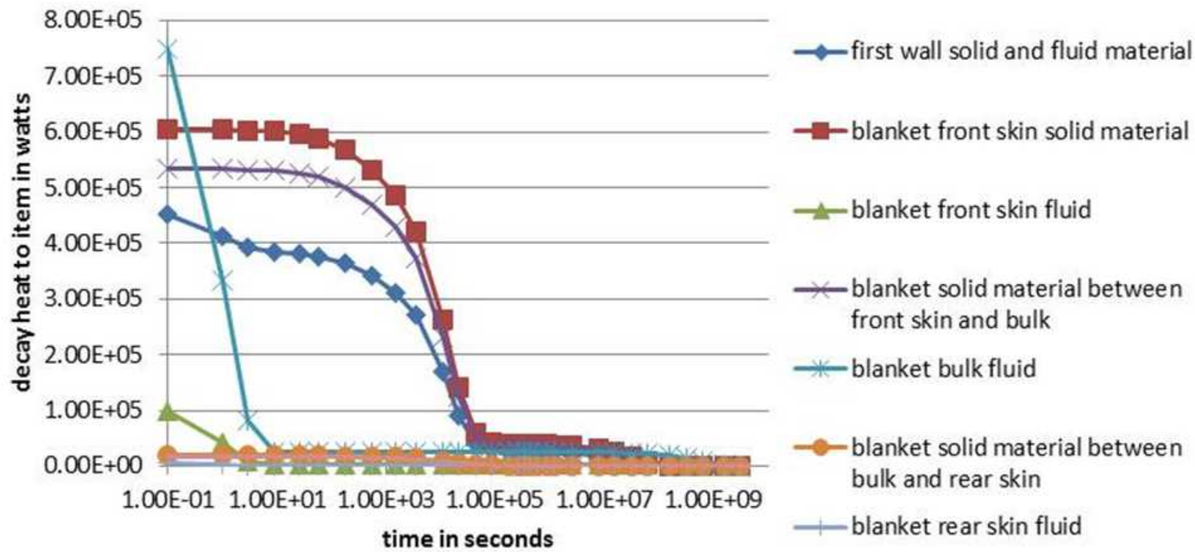

Figure 4. Decay heat of activated steel engine structures (first wall and blanket) at the end of its lifetime.

Radiological Design Aspects of the National Ignition Facility

Thomas R. Kohut*, Sandra L. Brereton[13], Hesham Khater[14]

Name and address for correspondence:

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[13] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

Thomas R. Kohut, L-760

Lawrence Livermore National Laboratory, Livermore, CA 94551-9900

FAX 925-422-9528

Telephone: 925 424-3242

e-mail: kohut2@llnl.gov

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***Abstract*— The National Ignition Facility (NIF) has been designed to accommodate some challenging radiological conditions. The high prompt neutron source (up to 1.6 x 10^{19} neutrons per shot) results in the need for significant fixed shielding. Concrete shielding approximately 2m thick is used for the primary (target bay) shield. Penetrations in this shield, including those required for 192 laser beams, utilities, diagnostics and 19 shielded personnel access doors, make the design challenging. An additional 28 shield doors are part of the secondary shield. In addition, the prompt neutron pulse results in activated air within the target bay, requiring special ventilation considerations. Finally, targets can use a number of hazardous and radioactive materials including Tritium, Beryllium, and Depleted Uranium (the latter of which results in the generation of small**

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[14] Lawrence Livermore National Laboratory, Livermore, CA 94551-9900.

The authors declare no conflict of interest.

quantities of fission products). Frequent access is required to the associated potentially contaminated volumes for experimental setup, facilitating the need for local exhaust ventilation to manage these hazards. This paper reviews some of these challenges, design considerations and the engineering solutions to these design requirements.

Key words: shielding; fusion; radioactivity, airborne; ventilation

Introduction

From the start, the design of the National Ignition Facility (NIF) building and supporting systems was significantly influenced by the anticipated radiological conditions produced by fusion experiments. Facility design assumptions included fusion neutron yields of up 1,200 mega-joule (MJ) per year, with routine experimental yields of up to 20MJ (7.1×10^{18} neutrons) per shot, and single shot yields of up to 45 MJ (1.6×10^{19} neutrons). This prompt neutron yield could result in potentially high personnel neutron doses at shot time if not properly shielded. The high yields can also result in neutron activation of systems, structures, and components in and around the target chamber, as well as the air in the target bay. The facility structure and support systems needed to be designed to manage these potential hazards.

In addition to the prompt neutron yield, the target materials themselves introduce potential hazard sources that needed to be addressed by facility systems. This includes the fusion fuel, a combination of two heavy isotopes of hydrogen, deuterium and tritium. Targets may also include small quantities of depleted uranium and (potentially) other hazardous materials, such as beryllium.

To manage these hazards, the facility has been designed with shielding systems, controlled ventilation systems and radiation monitoring systems to support planned fusion experiments and attendant radiological conditions.

Materials and Methods

Source Terms

Inertial confinement fusion experiments conducted at the NIF are based on indirect-drive targets (Fig 1) which use the energy of the 192 laser beams to create an intense x-ray field inside the outer target container (hohlraum) which then ablates the capsule material, causing it to compress the capsule and the deuterium-tritium fusion fuel within to create extreme temperatures and pressures. Under these conditions, fusion reactions occur. The primary reaction is the combination of deuterium and tritium. In this reaction (Fig 2), deuterium and tritium nuclei combine, and release an alpha particle (Helium nucleus) at about 3.5 MeV, and an energetic neutron at about 14.1 MeV. Other fusion reactions, such as D-D and T-T can occur, but the cross sections for these reactions under NIF conditions are much smaller.

Up to about 370 GBq of tritium are typically contained within each target. Only a few percent of the tritium is burned, the remainder being released into the target chamber environment, where most is removed by the target chamber vacuum systems and subsequently collected by the tritium processing system.

For a planned routine facility ignition experiment yield of 20 MJ, about 7.1×10^{18} neutrons are produced. The majority of these neutrons are released within the last few nano-seconds (10^{-9} sec) of the implosion. Almost all the alpha particles are captured in the dense fuel and aid in heating the burning plasma. A few percent of the neutrons interact with target materials and are down scattered to lower energies, but the majority of the neutrons remain at 14.1 MeV as they leave the target chamber. Of note, these relative high-energy neutrons (higher than the median energy of about 2 MeV in a fission reaction) are above the activation threshold for a number of common materials. As a result, some materials that would not become significantly activated in a fission reactor environment can become activated in a fusion facility.

In some experiments, the walls of the target hohlraum are lined with a small quantity (40 mg or less) of depleted uranium to increase the efficiency of converting the ultraviolet laser light into x-rays. Due to the high neutron flux from the D-T reactions during the implosion, some fast fissions of ^{238}U occur and produce small quantities of fission products, which are then mixed with other materials in the target chamber environment. Other target materials, including small amounts of aluminum, gold, copper, silicon and others, can be activated and become dispersed in the target chamber when the target is vaporized. Beryllium may also be used as a target material, and while it only becomes slightly activated, it can also become dispersed throughout the target chamber and associated systems.

Finally, unconverted laser light and x-rays from the target interactions can cause ablation of the first wall panels on the inside wall of the target chamber. The louver-like first wall panels are made of stainless steel and help protect the surface of the aluminum target chamber. The ablation of the stainless steel produces up to several grams of potentially dispersible activation products that add to the contaminants present in the target chamber.

Results

Shielding System

Since the source of neutrons is in the target chamber, the shielding system was designed in layers to provide protection against prompt neutron dose to personnel and to minimize activation of structures and subsequent decay dose to workers.

The target chamber is a sphere 5m in radius, 10 cm thick, made of a low-activation aluminum alloy (Al-5083). Aluminum was chosen for the target chamber and other major target bay structures in part because of its activation properties. While aluminum is susceptible to neutron activation, its primary activation product (^{24}Na) is fairly short-lived (15 hour half-life), allowing relatively rapid access after a high yield experiment.

The target chamber is covered with a 40 cm thick layer of borated concrete. This layer is intended to reduce the energy of exiting neutrons and allow for some capture of neutrons as close as possible to the source. However, the target chamber (Figure 3) has 192 penetrations, including ports for lasers, target diagnostics, target insertion, and maintenance access. Thus a significant portion of the neutrons leaving the target chamber cannot be intercepted.

The target chamber sits in the target bay; a cylindrical reinforced concrete structure about 30 m in diameter by about 36.5 m high. The walls of the target bay are typically 2m thick, and constitute the primary shield wall. The target bay wall contains a number of penetrations, including: 52 (1.5 m square) laser beamtube apertures, 175 utility ports, 10 diagnostic ports, and 20 access doors. As a result, the target bay wall does not provide full shielding, and a secondary shield is required. The walls of the two adjoining laser switchyards constitute the secondary shield, and are on average about 1m thick (Figure 4).

Shielding system modeling and analysis

Shielding analysis started with the facility design and the subsequent design validation. For example, an analysis was conducted in the mid-1990s to validate the facility contractors' shielding design met the prompt dose design criteria. The criteria specified a 0.3 $mSvy^{-1}$ dose in occupied areas of the facility, and a 0.5 $mSvy^{-1}$ dose outside the facility for a total annual yield of 1,200 MJ (taking into account appropriate occupancy factors). The analysis was conducted using MCNP4 (Monte Carlo N-Particle transport code) on 3 desktop Unix machines. This analysis used facility drawings as a reference to create a simplified model of the facility, and used simple round/annular penetrations to represent major target chamber and facility penetrations. Minor penetrations were ignored based on some scoping calculations that indicated that their affect was likely to be minimal. Even though greatly simplified, the analysis took several days to run.

In the late 2000s it was determined that more accurate modeling was necessary to analyze facility operations. This new effort resulted in a detailed model translated directly from facility as-built drawings, included the details of major equipment and structures, and included all target chamber, target bay and switchyard wall penetrations. The full facility prompt dose model now takes on the order of 1 million CPU (central processing unit) hours to complete. The model was run using MCNP5[1]. With the advent of ever more powerful computers, the calculations run in about the same amount of time.

The output from these models is detailed dose maps for the entire facility and surrounding area. This analysis demonstrated that the overall shielding system performance was adequate, but led to minor modifications to improve performance. One interesting point that became clear was that the details of the minor shielding penetrations could be important. Figure 5 shows an example of adding shielding to a single unused utility penetration in the target bay wall. The resultant prompt dose outside the facility goes from marginal to acceptable by making this one minor change.

Shield doors

One important use of the updated prompt dose model was optimization of the facility shield doors. The original facility design made provisions for a number of shield doors at the personnel and equipment access points at the perimeter of the primary and secondary shield walls. Doorframes were installed at all these locations, but the doors themselves were deferred until the start of yield operations required them. The revised prompt dose model allowed for optimizing the thickness of these doors to meet the overall shielding system goals. Many of the doors could be specified much thinner than was originally anticipated in the design, and a few were actually eliminated since their presence would have little effect on the net doses in the associated areas. This action resulted in a significant reduction in the door procurement and installation costs.

The doors are essentially steel cans filled with concrete. The doors were fabricated in pieces offsite, then staged in the facility, pieces were welded together, doors were aligned, then filled with concrete in situ. In all, 19 doors were installed in the primary shield, ranging from 0.3 m to 2.0 m in thickness (depending on location, Figure 6). In the secondary shield, a total of 27 doors were installed, ranging from 0.3 m to 0.6 m in thickness.

The doorframes are stepped on the top and sides, preventing any shielding gaps in these areas. However, to allow normal transit over the doorsills, a relatively tight gap was specified between the door and the floor. The as-built floors in some door locations required elevation adjustments to ensure that there was not an excessive gap (to minimize the possibility of radiation streaming through the gaps) and that the door could swing freely over the entire swing path.

Most of the doors are hinged and swing open. The mechanism provided by the vendor to operate these doors, which drove the door from the hinge point, was underpowered and unreliable. Ultimately NIF engineers replaced most of the swing door drives with an in-house developed wheel drive mechanism that applies force near the outer edge of the doors. This has proven to be a reliable design (Figure 7).

Ventilation Systems

The high prompt neutron flux is expected to produce activation of the air inside the target bay (Table 1). The key radionuclides produced in the approximate 30,000 m^3 volume of the target bay have short to moderate duration half-lives that affect how they are managed. Most of the activity is retained within the target bay long enough to decay in place. To minimize the release to the environment of the longer-lived radionuclides, the system is designed to exhaust <1% of the target bay volume per minute (<255 $m^3\ min^{-1}$).

The total dose for an individual immersed in target bay air following a high yield experiment has been estimated (Figure 8). Though the target bay is an exclusion area during shots and decay dose rates prevent entry for extended periods after high yield experiments, access is allowed (or is allowed after a short delay) to areas adjacent to the target bay. Thus the target bay Heating, Ventilation and Air Conditioning (HVAC) system must prevent the escape of activated air constituents to avoid immersion doses to personnel in these areas.

In addition, during maintenance operations, the potential exists for release of tritium gas from target assemblies or vacuum systems into the target bay. Tritium area alarms would detect such a release and warn workers to evacuate the area. The HVAC system is relied upon to contain such a release within the target bay and direct it to the stack to prevent affecting adjacent areas of the facility.

Additional functions of the HVAC system include maintaining stable conditions with tight tolerances on temperature, pressure, and particulate cleanliness to support the proper functioning of the laser and diagnostic systems. The system that was developed to achieve these varied requirements consists of a high flow rate recirculating system with High Efficiency Particulate (HEPA) filters (to maintain required cleanroom conditions). A recirculation rate of approximately 10,000 m^3 min^{-1} is maintained for these purposes. To support containment of airborne contaminants (as noted above) and to aid in preventing the spread of particulate contamination, the space pressure is maintained negative (about 12 Pascal) relative to surrounding areas (and the environment) by controlling the makeup and exhaust flows. All air from the target bay is exhausted from a single exhaust riser and is routed through exhaust HEPA filters prior to discharge from the facility elevated release point (stack) at 35m above ground. The target bay exhaust riser is maintained at approximately 1,000 Pascal negative pressure.

To assist with control of particulate and airborne contaminants from the target chamber and attached vacuum vessels (final optics assemblies, target positioners, target diagnostics, etc.) during routine maintenance access, these systems are provided with negative ventilation. Each vessel has ducting connected to the target bay exhaust riser and uses that pressure as its motive force. Flows are balanced to achieve a near fumehood-like face velocity of about 25-35 m min^{-1} at routine access locations. This system has been very effective at containing tritium airborne contaminants within these vessels.

The exhaust of the various vacuum systems supporting target area operations is controlled and can be aligned either to the Tritium Processing System (TPS)[2] (when relatively high concentrations of tritium are present) or directly to the stack. Similarly the room exhausts for major radiological refurbishment areas outside of the target bay, and the tritium processing system, are all directed to the stack.

Radiation Monitoring Systems

Facility radiation monitoring systems have been developed to monitor routine and off-normal operations. The exhaust stack is monitored to ensure compliance with the LLNL Site-wide Environmental Impact Statement (SWEIS)[3] as well as for operational reasons. The stack is monitored for tritium, general radioactive particulate, and radioiodines. Particulates and radioiodines are monitored by sample filters and activated carbon cartridges (respectively), and samples are exchanged weekly. Tritium is monitored for both elemental and oxide forms using an ORTEC model OS1700 Tritium Collector (*ORTEC Advanced Measurement Technology, Inc.,* 801 South Illinois Avenue Oak Ridge, TN 37831-0895*)*. This integrating system uses glycol bubbler samples that are retrieved weekly and read on a liquid scintillation counter.

The stack is also monitored for tritium with a real-time monitor for operational purposes. For this, a Femto-TECH Model GC224RM gamma-compensated ion chamber (Femto-TECH, Inc., 25 Eagle Court, P.O. Box 8257, Carlisle, Ohio 45005) is used. NIF engineers combined this ion chamber with a recirculating pump and mass flow controller into a standard package used throughout the facility. In the stack monitor application, the system has demonstrated the ability to detect and alarm reliably for point releases as low as about 0.37 GBq, with a typical stack flow rate of about 1,000 m^3 min^{-1}.

The same tritium monitor package is used throughout the facility to monitor work locations where significant tritium handling occurs, and as a process monitor in the tritium processing system. Analog outputs from these units are passed to the facility hazardous material management programmable logic controller (PLC) based system for display, trending and alarming as required.

Facility gamma area monitors as used to monitor post-shot decay radiation fields only, as the prompt radiation pulse is too fast to be monitored with standard instrumentation, and is not important from a health physics perspective since personnel are excluded from areas of high prompt dose. The values are used as an aid in confirming ambient conditions prior to attempting re-entry and formal characterization surveys.

Two types of monitors are used. A Mirion GIM-201k low-range gamma area monitor (Mirion Technologies, 3000 Executive Parkway, Suite 222, San Ramon, CA 94583) is used in the target bay. These ion chambers use a low-activation plastic detector housing. This should reduce the buildup of activated components, and therefore false signals, in the detectors. The detectors are turned off just prior to a shot and turned back on immediately afterward to prevent damage to the electronics due to the high neutron and gamma pulse that occurs during a shot. Outside the target bay, Ludlum Model 375 area monitors (Ludlum Measurements, Inc., 501 Oak Street, Sweetwater, Texas 79556) with a Geiger-Mueller detector are used.

Conclusions

The design of the NIF had to from the very beginning consider the anticipated radiological conditions for full ignition operations. The most significant impact was from the anticipated high potential prompt neutron dose resulting from the 14.1 MeV deuterium-tritium fusion neutrons. Shielding forms a major structural aspect of the facility. Due to the numerous penetrations required in the target chamber and target bay shields to allow for laser beam, utility and personnel access, shielding design is complicated. Since the initial design calculations were completed, more sophisticated design models and dramatically increased computing power has allowed the prompt dose model to obtain a very high degree of fidelity. This higher fidelity modeling has allowed for optimizing the shielding system, including the shield door parameters and utility penetrations. Optimizing the shield doors resulted in a significant cost savings. The detailed model also showed that relatively small penetrations could have a non-intuitively significant effect on overall shield performance; the details matter.

Ventilation system design was influenced by the need to confine activated air resulting from prompt neutrons during a shot, and to assist with control of airborne tritium and particulate contamination. Due to the cleanroom conditions required for NIF system cleanliness and stability considerations, a relatively complex HVAC system was developed. To support routine access to internally contaminated vacuum vessels, the ventilation exhaust system is used to provide a fume hood-like negative air system at routine access points.

The exhaust from the target bay ventilation and vacuum systems associated with the target chamber and associated contaminated systems are routed through the elevated release point (stack). Vacuum systems may be aligned to pass through the tritium processing system to remove almost all entrained tritium prior to reaching the stack. The stack exhaust is monitored to meet environmental requirements and to provide process feedback to operators. Weekly samples are obtained to provide information on released tritium, radioactive particulate and radioiodines. A real time tritium monitor is also provided. A commercial tritium monitor has been packaged with pumping equipment to provide a common assembly that is used throughout the facility where required for area and process monitoring and alarming. A gamma monitoring system is also deployed to provide post-shot information to assist with stay-out time and re-entry planning.

Overall, NIF systems have met requirements to date, and are ready to support future operations up through maximum expected radiological conditions.

Figure 1. Cutaway model of typical indirect drive ignition target

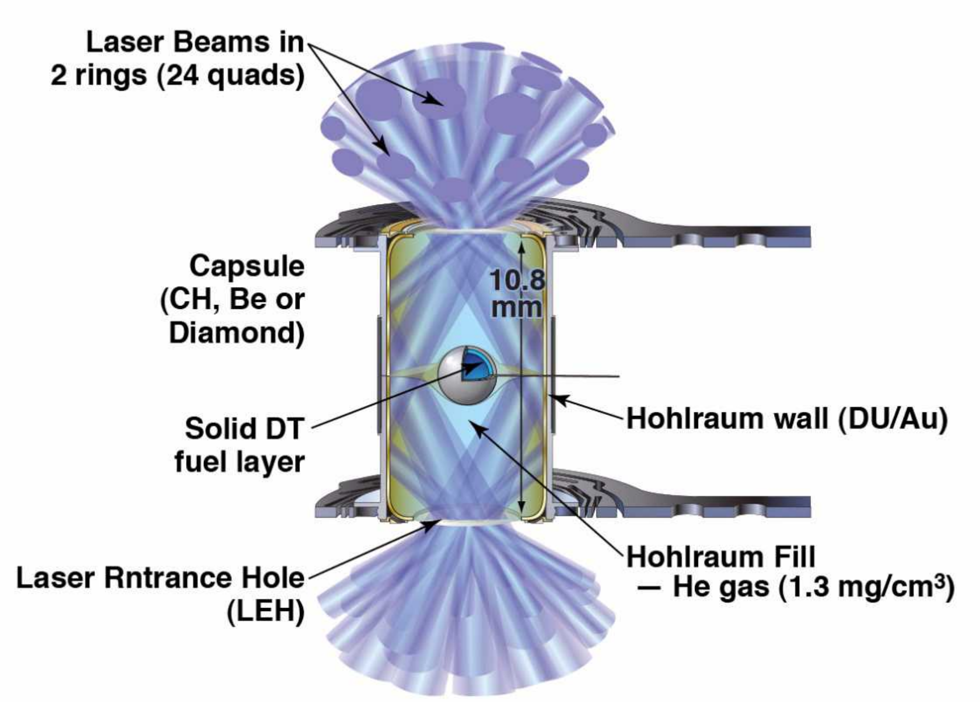


Figure 2. Deuterium-Tritium fusion reaction

D+T $\rightarrow$ He^4 (3.5MeV) + n (14.1MeV)

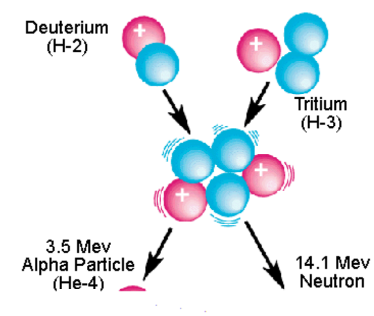


Figure 3. Target chamber and MCNP model representation.

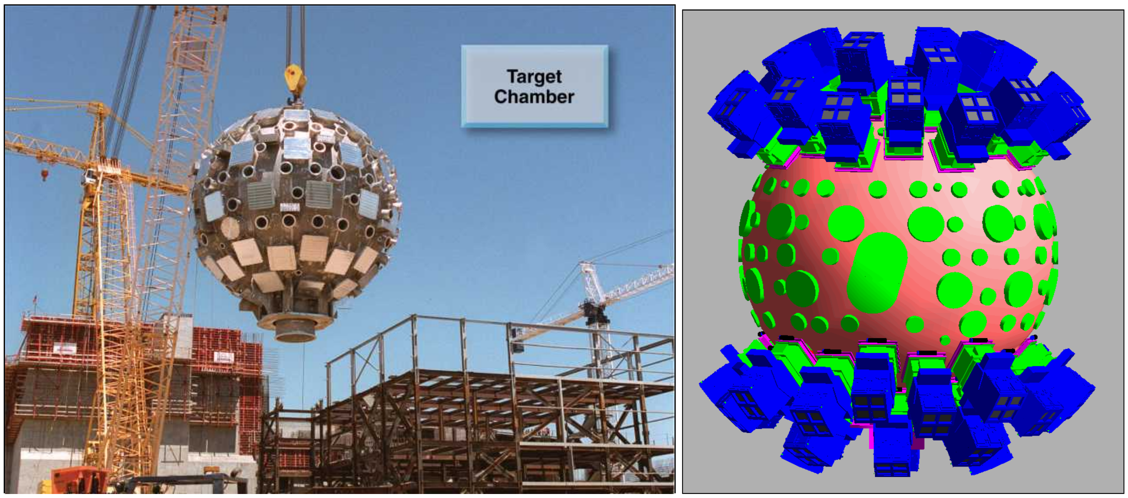


Figure 4. Cutaway model of the ground level of the facility, showing arrangement of key shielding system components.

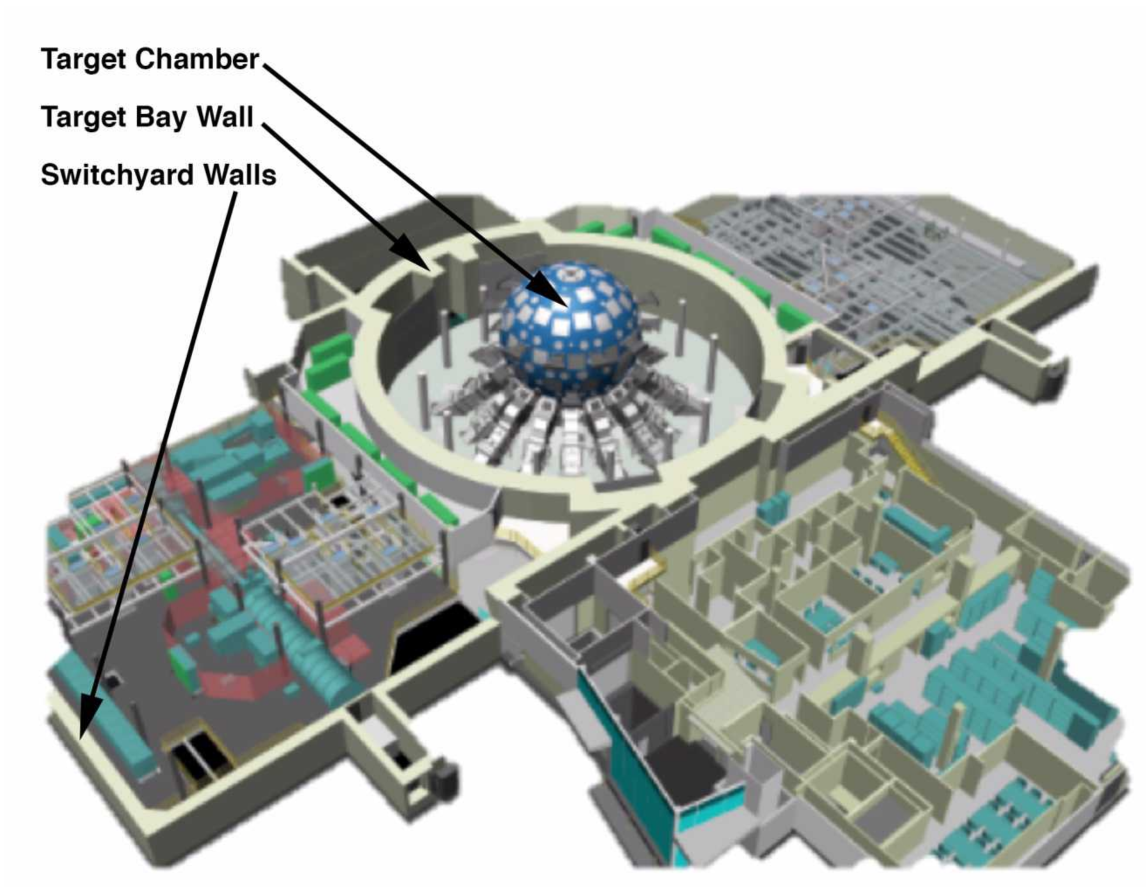
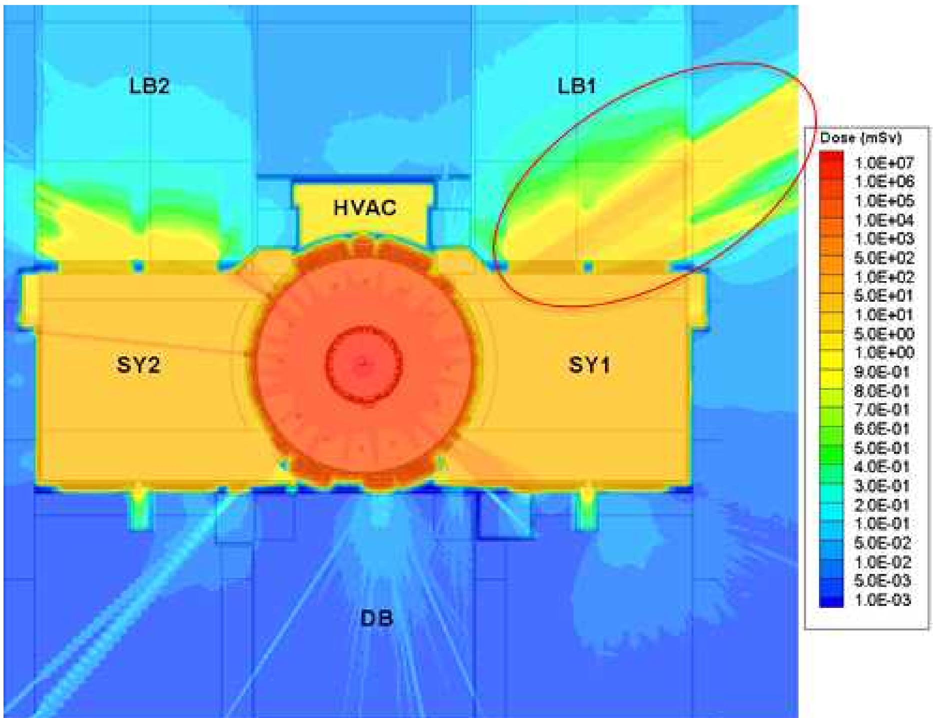


Figure 5. Affect on prompt dose outside the facility from adding shielding to one target bay wall utility penetration (dose per 20 MJ shot, elevation 6 m).



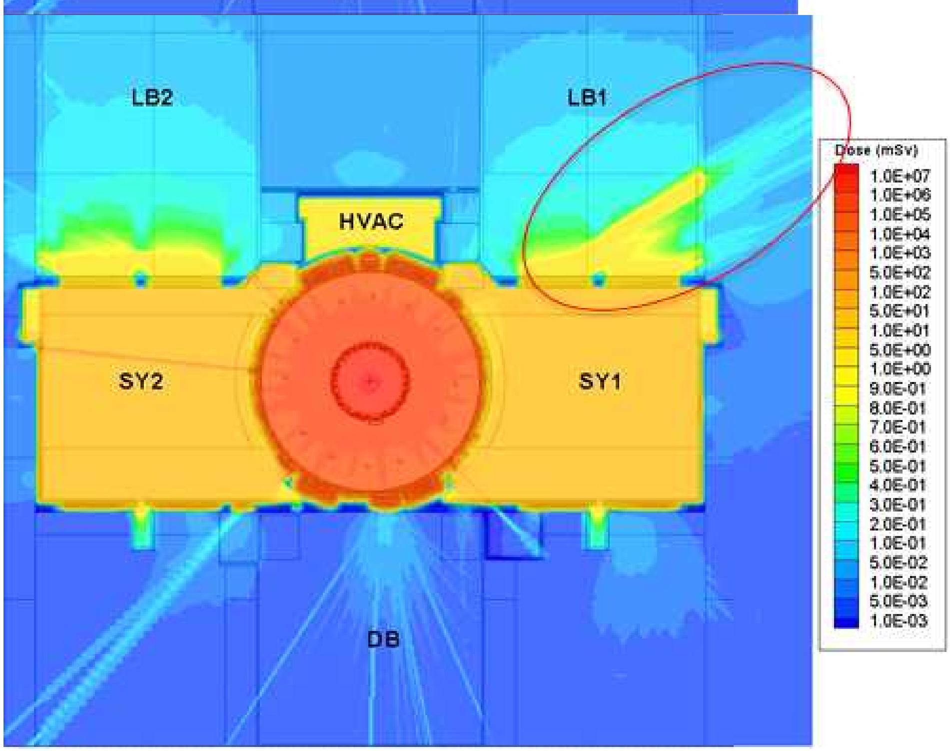


Figure 6. Shield door locations (multiple elevations stacked in this view). Circles indicate primary door locations, squares indicate secondary door locations.

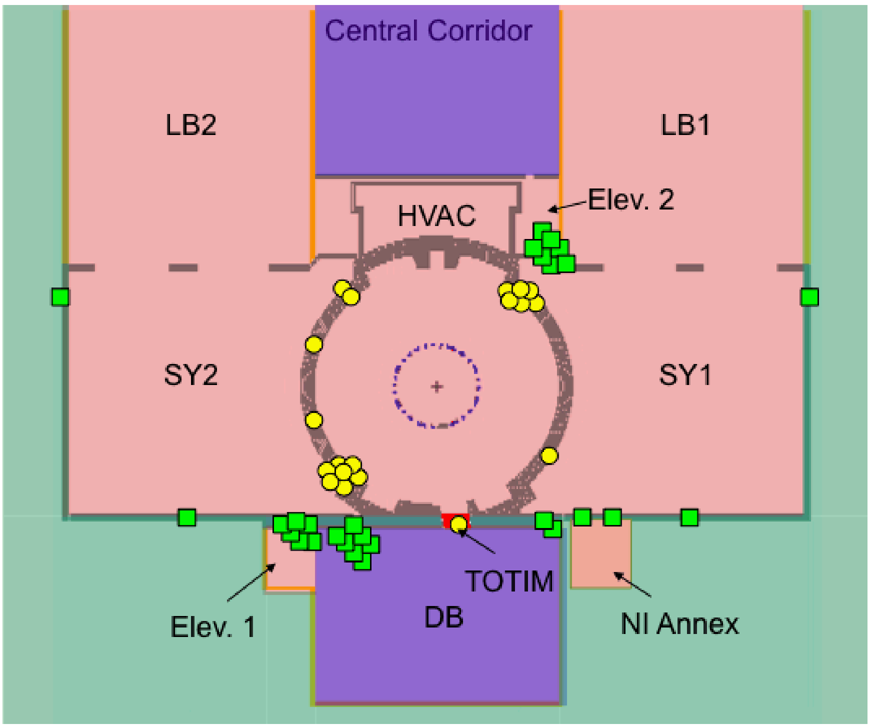


Figure 7. Primary shield door with wheel drive mechanism.

Table 1. Estimated activity produced in target bay air (per 20 MJ shot) for major nuclides.

Activation radionuclides (source nucleus)	Resulting decay products	Half-life of key nuclide	GBq Produced (per 20 MJ shot)
N-16 (from O-16)	O-16 + b- + g (6.1MeV)	7.1 seconds	31,700
N-13 (from N-14)	C-13 + b- (1.2 MeV)	9.97 minutes	200
Ar-41 (from Ar-40)	K-41 + b- (1.2 MeV) + g (1.3MeV)	1.83 hours	25

Figure 8. Estimated cumulative immersion dose in target bay for a given stay time after a 20 MJ shot.

Analysis of Decay Dose Rates and Dose Management in THE NATIONAL IGNITION FACILITY

Authors: Hesham Khater, Sandra Brereton, Lucile Dauffy, Jim Hall, Luisa Hansen, Soon Kim, Tom Kohut, Bertram Pohl, Shiva Sitaraman, Jerome Verbeke, and Mitchell Young

Corresponding Author: Hesham Khater

Lawrence Livermore National Laboratory

P. O. Box 808, L-550

Livermore, CA 94550

(925) 422-2620

khater1@llnl.gov

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ABSTRACT

A detailed model of the Target Bay (TB) at the National Ignition Facility (NIF) has been developed to estimate the post-shot radiation environment inside the facility. The model includes the large number of structures and diagnostic instruments present inside the TB. These structures and instruments are activated by neutrons generated during a shot and the resultant gamma dose rates are estimated at various decay times following the shot. A set of computational tools was developed to help in estimating potential radiation exposure to TB workers. The results presented in this paper describe the expected radiation environment inside the TB following a low-yield D-T shot of 10^{16} neutrons.

General environment dose rates drop below 30 μSv/h within three hours following a shot with higher dose rates observed in the vicinity (~ 30 cm) of few components. The dose rates drop by more than a factor of two at one day following the shot. Dose rate maps of the different TB levels were generated to aid in estimating worker stay-out times following a shot before entry is permitted into the TB. Primary components, including the Target Chamber, diagnostic and beam line components, are constructed of aluminum. Near-term TB accessibility is driven by the decay of the aluminum activation product; ^{24}Na. Worker dose is managed using electronic dosimeters (ED's) self-issued at kiosks using commercial dose management software. The software programs the ED dose and dose rate alarms based on the Radiological Work Permit (RWP), and tracks dose by individual, task and work group.

Introduction

In a facility like the National Ignition Facility (NIF), with high-energy neutron fluxes, it is important to analyze the radiation exposure due to the activation of surrounding materials. During the ignition campaign, the NIF is expected to generate shots with varying fusion yield (up to 20 MJ or 7.1 x 10^{18} neutrons per shot) with a maximum annual yield of 1200 MJ. The level of material activation inside the NIF Target Bay (TB) and the resulting dose rates associated with maintenance activities will depend on the target neutron yield as well as the shot schedule. Lower yield shots will allow for quick access to the TB following the shot. It is typically expected that access will be allowed inside the TB after a 3 hours decay period following a low yield shot (10^{16} neutrons). In contrast, a stay-out period of 6 days is expected following a high-yield 20 MJ shot). This paper summarizes the expected radiation environment inside the TB following a low-yield D-T shot of 10^{16} neutrons

A detailed model of the TB has been developed to estimate the post-shot radiation environment inside the facility. The model includes a large number of structures and diagnostic instruments that are present inside the TB during shots. These structures and instruments are activated by neutrons generated during a shot and the resultant gamma dose rates are estimated at various decay times following the shot. Some of these structures, like the snout assemblies of the Diagnostic Instrument Manipulators (DIMs) and Target Positioners (TARPOSs) are extended into the Target Chamber (TC) during the shot and hence are exposed to an intense neutron environment and subsequent high level of activation. The high level activation of these components results in localized hot spots in the vicinity of the components once they are retracted from the TC following a shot.

The complexity of the TB model required the development of automation tools that perform the various steps involved in creating the dose rate maps in an efficient manner that allows for a simultaneous analysis of the gamma decay of all activated structures present in the model. A set of computational tools (Verbeke et al. 2011) was developed to help in estimating potential radiation exposure to workers from activated materials inside the TB. In order to provide an efficient method for estimating dose rates, a coupling scheme between radiation transport and neutron activation codes was developed. A web-based application was also developed to use the calculated dose rates for estimating potential dose hazards associated with different maintenance activities following any given shot sequence. AAMI (Automated ALARA-MCNP Interface) provides an efficient, automated mechanism to perform the series of calculations required to create dose rate maps for the entire facility, and NEET (NIF Exposure Estimation Tool) is a web application that combines the information computed by AAMI with a given shot schedule to compute and display dose rate maps as a function of time following shots.

Facility Modeling

In order to accurately evaluate the decay radiation environment inside the TB, a detailed 3-dimensionsl model of the TB has been developed using the MCNP radiation transport code (X-5 Monte Carlo Team 2005). The TB has a semi-cylindrical design with an inner radius of 15.24 m, 1.83-m-thick concrete walls and 1.37-m-thick concrete roof. As shown in Figure 1, there are seven floor levels within the Target Bay at elevations of -10.29 m, -6.63 m, -1.07 m, 5.33 m, 8.99 m, 12.19 m, and 15.39 m (B2, B1, L1, L2, L3, L4 and L5) with respect to the ground level.. The Target Chamber (TC) is located in the center of the TB at an elevation of 7.01 m from the ground level (in TB level L2) and 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 48 FOAs are included in the model (see Figure 1). The unused diagnostic and direct-drive ports are covered with aluminum port covers that vary in thickness between 35 and 48 mm.

Models for major components attached to the TC were included in the TB model. The Cryogenic Target Positioner (CryoTARPOS) and the Target Positioner (TARPOS) are modeled in details. These models exist in two configurations, the first configuration shows the positioners extended into the TC during the shot. This configuration is used for the neutron flux spectrum calculation. The second configuration represents retracted positioners following the shot, and is used for the gamma transport analysis. Figure 2 shows the MCNP model of the retracted CryoTARPOS. A model for a third positioner, the Target Alignment Sensor Positioner (TASPOS) is also included in the TB model. The TASPOS is only extended into the TC to align the laser beams and the target before the shot and hence it is always modeled in the retracted position.

A Diagnostic Instrument Manipulator (DIM) is used to position different type of diagnostics close to the target at Target Chamber Center (TCC). A snout is attached at the end of the DIM and is the closest part of the assembly to the target. As a result, a DIM snout assembly is typically activated at a high level due to its exposure to a high neutron flux. The TB model includes three different DIMs, a polar DIM located in the north pole of the TC as well as two horizontal DIMs in the equatorial plane of the TC. These three components are also modeled with their snouts extended into the TC for the neutron flux calculations and in the retracted mode for the gamma dose rate calculations. The two equatorial DIMs were modeled with the assumption that when extended, the tip of the snout assembly is located at 8 cm from the TCC while the polar DIM was modeled with the snout assembly at 12 cm from the TCC. Figure 3 shows the MCNP model of a DIM in the extended configuration.

Another example of diagnostic equipment inserted inside the TC during a shot is the Static X-ray Imaging system (SXI). Two SXIs could be used in the NIF, one through the upper hemisphere and the other through the lower hemisphere. Each SXI system consists of a pair of nested (telescoping) arms with a removable x-ray pinhole assembly at the top end of the upper arm. For the neutron flux calculations, the telescoping arms are simulated as fully extended, placing the snout of the pinhole assembly at 82.9 cm from TCC. Like the CryoTARPOS, TARPOS, and the DIMs, the arms are modeled in the retracted position outside the TC following the shot.

Finally, a variety of diagnostics equipment is located outside the TC. The equipment is exposed to lower neutron flux levels and hence represents a lower level of radiological hazard to workers during maintenance activities following a shot. The TB model used in the analysis includes the following diagnostics equipment:

1. The FFLEX (Filter Fluorescer) x-ray diagnostic is located in the L2 floor level.
2. The Magnetic Recoil Spectrometer (MRS) located in the L3 floor level.
3. The Dante (soft x-ray diagnostic instrument for hohlraum temperature estimation) systems located in the L1 and L3 floor levels.

4. The Final Optics Damage Inspection (FODI) system located in the L3 floor level.

CALCULATIONAL METHODOLOGY

The calculations were performed in three steps. The first step involved the estimation of the neutron flux spectrum in a 175-group structure for all the components in the TB that would be activated. This calculation was performed with the Monte Carlo Radiation Transport Code; MCNP using continuous energy data from the Fusion Evaluated Nuclear Data Library FENDL-2.1 (Aldama and Trkov 2004). The source term for this run consisted of a D-T neutron source placed at the TCC. The neutron spectrum associated with each individual component in the TB model was then used to activate the component and produce gamma spectral data in a 25-group structure at different post-shot decay times using the activation and decay code, ALARA (Wilson and Henderson 1998). The gamma spectra generated in each component were used as sources in a new MCNP gamma transport calculation with ENDF-VI photoatomic data (Evaluated Nuclear Data File 2002). The gamma fluxes were converted to effective dose rates using ICRP-74 anterior-posterior conversion coefficients (International Commission on Radiological Protection 1997). A rectangular mesh tally scheme with a mesh size of approximately one cubic foot was used to cover the entire TB model with dose rates being calculated in each mesh.

The neutron transport calculation was performed using the ‘extended’ MCNP TB configuration, where the three different DIMs, TARPOS, CryoTARPOS and lower and upper SXI were extended into the TC during the shot. The gamma transport calculations were performed using the ‘retracted’ configuration, where the extended parts of these components are retracted to the outside of the TC (behind gate valves). All other components (TASPOS, FFLEX, MRS, FODI, and lower and upper Dante) were modeled outside the TC (retracted) for both neutron and gamma transport calculations.

Since the TB model is detailed and extremely complicated, an automation program, Automated ALARA MCNP Interface (AAMI) (Young and Verbeke 2010), was developed to link the three calculational steps. This program generates gamma source terms and spectra for a given post-shot decay time, which are used by a special version of MCNP that was modified to include a user supplied source subroutine. The large amount of data generated in these runs for each post-shot decay time was incorporated into a database which was accessed by a web-based tool that was developed to display effective dose rate maps inside the TB following a single shot or series of shots at any neutron yield. The tool, NIF Exposure Estimation Tool, NEET (Verbeke 2010), will be used for work planning following shots.

COMPUTATIONAL TOOLS

AAMI, automates the series of calculations required to create dose rate maps in the facility for a given neutron shot yield. The goal of this code is to produce data with minimal user input, henceforth minimizing human error. The three steps of AAMI logic are summarized in Figure 4. The first step consists of producing a MCNP model that contains all the components that are important from both radiation transport and material activation perspectives. A Monte Carlo continuous-energy simulation that emits D-T neutrons from the target is then carried out to tally the neutron flux spectra in all these components of interest. In the second step, AAMI takes the neutron flux spectrum computed for each MCNP cell and converts it into an inventory of radioisotopes and a γ-ray spectrum in a 25-group structure. The ALARA activation code and the FENDL-2.0 libraries (Pashchenko et al. 1997) are used to compute these time-dependent inventories and γ-spectra. Inventories of radioisotopes and γ-spectra for each MCNP cell are produced for the different decay times specified by the user. The third step generates the expected dose rates due to activated materials inside the entire TB.

As mentioned before, some activated components (e.g.; positioners and DIMs) which are inserted into the TC during the shot for diagnostics are retracted outside of the chamber following the shot. AAMI will work as long as the activated cell numbers and volumes do not change from the extended to the retracted model. The γ-rays will simply be emitted from the retracted location. A fine 3-dimensional grid is imposed on the MCNP model of the TB for γ-rays tallying purposes. Finally with a single simulation per decay time, the computed γ-ray spectra are sampled and emitted from each activated component, and propagated by a transport simulation through the entire MCNP model of the TB. Special care was taken to account for the different γ-ray intensities in the different activated cells. The output file of MCNP contains a detailed diagnostic table showing how well or poorly the geometry was sampled by comparing the expected cell volumes with the cell volumes as calculated by γ-ray source sampling. From this simulation, a 3-dimensional γ-ray flux map is obtained. The flux map is converted into a dose rate map using the ICRP-74 fluence to effective dose conversion coefficients. The final step is repeated as many times as the number of decay times. The generated dose rate maps are stored in a database, along with the initial radionuclide inventories for activated components that may require handling.

The MCNP code was modified to simultaneously and efficiently sample the γ-rays from all activated components. The major modification consisted of a custom source subroutine, in which locations are first sampled within user-defined sampling regions (boxes, cylinders, cylinder wedges, tubes, tube wedges, spheres and sections thereof, shells and sections thereof, potentially transformed), then checked against a set of user-defined cells to see whether they belong to one of these cells, upon which the code samples the appropriate activation γ-ray distribution to emit a γ-ray from that location. The user-defined sampling regions can be assigned different importance. This powerful feature enables the user to bias the emission of activation γ-rays towards regions of higher activation.

The second computational tool, NEET is a web application that can perform several types of radiation exposure calculations needed by health physicists for radiation protection. Its first purpose is to compute the dose rates after a single shot or set of shots. A shot schedule is entered in a table and combined with the dose rate information stored in the database to compute and display in situ dose rate maps as a function of time. For decay times that are not in the database, NEET generally interpolates the dose rate data for stored decay times.

DOSE MAPPING OF THE TB FLOORS

Detailed dose rate maps were generated for the different floors of the TB. The dose rate maps represent the expected dose rates on each floor as a function of time following a single D-T shot with 10^{16} neutron yield. The same dose rate map data is imported to the work planning tool NEET, such that the impact of multiple shots with different yields and longer or shorter decay times can be assessed. Figure 5 shows a 2-dimensional cut of the MCNP model of the TB equatorial plane (in the L2 level). The L2 level is the most important floor level because it contains components that will experience the highest levels of neutron exposure during the shot. The CryoTARPOS target assembly, ITIC and boom as well the TARPOS target holder and boom are within a few centimeters of TCC during the shot. These components will become highly activated during the shot and represent a major source of gamma decay after being retracted outside the TC. Similarly, the snouts associated with the two equatorial DIMs will represent other large sources of radiation exposure once they are retracted outside the TC. Other major components located outside the TC during the shot, like the TASPOS and FFLEX will represent a lesser source of activation and radiation exposure following the shot.

Figure 6 shows a dose map at the equatorial plane of the TC (an elevation of 7.01 m) at 3 hours following a shot. As shown in the figure, the dose rates in close contact of the highly activated (retracted) parts are on the order of 0.5 mSv/h. This is a higher dose rate value will require most personnel to minimize their exposure time and to keep a large distance from any of these components. In contrast, the dose rates near the TC but at a larger distance from the aforementioned retracted components are on the order of only 10 μSv/h. The dose rates drop as a function of distance from the TC and reach a level of ~ 2 μSv/h near the TB wall. Figure 7 shows the dose map for the same floor after a 1 day decay period. Since most of the dose near the TC is due to the decay of ^{24}Na ($T_{1/2}$=14.7 h), the resulting dose rates drop by about a factor of two. The snout regions of the two DIMs as well as the TARPOS and CryoTARPOS target holders are the most activated components due to their proximity to the target during the shot. Dose rates at various decay times in the vicinity (~30 cm) of the two equatorial DIMs are presented in Table I. The dose rates in the vicinity (~30 cm) of the two target positioners are presented in Table II.

Another TB floor of interest is the L4 level. The actual TB L4 floor is limited to an outer mezzanine near the TB wall which represents a section overlooking the L3 floor level. Near the TC at the L4 level elevation, special maintenance platforms allow for access to the area above the TC top plate. Access to this area allows for work associated with the retracted polar DIM snout and hence relatively higher dose rates are expected. In addition, a person working in this area will be surrounded by multiple FOAs. The FOAs are typically more highly activated due to their direct exposure to neutrons emitted from the target. Access to the retracted upper SXI snout is also possible at this level. Figure 8 shows the dose rate map at a distance of 5.79 m (in L4 level) from TCC at 3 hours following a 10^{16} shot. The dose rate near the tip of the retracted snout of the polar DIM shows a hot spot of ~2 mSv/h that occurs in contact with the DIM snout with the dose rate rapidly dropping off as the distance from the DIM snout increases. Dose rates of 10 to 30 μSv/h are seen in all other locations above the TC top plate. This is due to the fact that the TC aluminum top plate is not shielded by gunite and hence is exposed to a higher neutron flux. Table III shows the dose rates at different decay times for the north pole region of the TC and the L4 floor level. As shown in Figure 9, allowing for 1 day of decay following the shot, results in a lower dose rate of ~ 5 μSv/h for most locations above the TC top plate.

The main contributions to dose come from the activation of the various types of aluminum and steel components present in the TB. In the short term following a shot, the main contributions to the dose rate come from ^{28}Al ($T_{1/2}$ = 2.2 m; $<\gamma>$=1.78MeV), ^{27}Mg ($T_{1/2}$ = 9.5 m; $<\gamma>$=0.9 MeV, ^{56}Mn ($T_{1/2}$=2.6 h; $<\gamma>$=1.7 MeV), and ^{24}Na ($T_{1/2}$ = 14.7 h; $<\gamma>$=4.1 MeV). ^{28}Al, ^{27}Mg, and ^{56}Mn are produced via (n, γ) reactions in ^{27}Al , ^{26}Mg, and ^{55}Mn, respectively. The ^{24}Na is produced via the (n, α) reaction in ^{27}Al. In the longer term, there is a dose rate component from ^{24}Na in addition to contributions from ^{58}Co ($T_{1/2}$ = 70.9 d; $<\gamma>$=0.8 MeV) and ^{54}Mn ($T_{1/2}$ = 312.2 d; $<\gamma>$=0.8 MeV). The ^{58}Co is produced via both the (n, 2n) reaction in ^{59}Co and the (n, p) reaction in ^{58}Ni. ^{54}Mn is produced via the (n, p) reaction in ^{54}Fe.

Dose Rate Estimates for handling of DIM Snouts

A separate analysis was conducted to evaluate the potential dose to personnel due to the handling of DIM snouts and airboxes. Figure 10 shows the MCNP model of a polar DIM snout and airbox. Figure 11 shows expected dose rates as a function of time during the first day following a 10^{16} shot. As shown in the figure, after 3 hours of decay, the dose rate near the snout tip (~ 30 cm) is 45 μSv/h and drops to 17 μSv/h after 1 day. Most of the dose is due to the decay of ^{24}Na.

Finally, a storage and decay area has been designed for storage of irradiated DIM snouts after being removed from the TB. The storage area is located in the switchyard and assumed to hold up to 24 snouts. An analysis was conducted to define the boundaries (stay-out distance) for the storage area. The analysis assumed that up to three snouts could be removed from the TC after 3 hours of decay time following a 10^{16} shot. In addition, a shot schedule of one shot per day was assumed. The current storage and decay area is designed to hold a total of 24 snouts (8 day inventory). Figure 12 shows the expected dose rates as a function of distance from the storage area. Creating an exclusion zone of 3 m around the storage area will limit the dose to personnel in the switchyard to < 10 μSv/h. Most of the dose is due to the decay of ^{24}Na. Due to the rapid decay of ^{24}Na, 70% of the dose rate outside the area is due to decay of the last 3 snouts added to the storage area (with only 3 hours of decay time).

MANAGING WORKER DOSE

Once experiments that produce high yield have begun, managing worker dose will require attention by workers, the health physics staff and line management. While post shot stay out times will significantly reduce dose rates for workers entering the TB, workers will continue to be exposed to low dose rates during routine operation. A typical worker might spend 4-10 hours per day inside the TB, and even with relatively low general area dose rates of a few to a few tens of μSv per hour, cumulative doses could become significant if not closely controlled.

The web-based application tool; NEET is used to help plan for work in these low-level radiation fields. Specific tasks can be evaluated based on the task location and time after a specific shot or series of shots, and decisions can be made to defer tasks or figure out how to reduce task durations. Local shielding can be considered, but in most cases is not practical due to the general area radiation field and the dose that would be incurred to install and remove the shielding.

In more general terms, as shown in Figure 13, NEET is used to develop annual ALARA plans and set administrative dose limits for workers and work groups. To develop the annual ALARA plan, an estimate of experiments planned to produce significant yield is obtained. The approximate yield and experiment dates are entered into NEET. At that point, the predicted localized dose rates throughout the TB can be computed. Each work group provides estimates of their routine tasks, where they are located, how many workers are involved and the frequency or number of times the task is to be executed during the year. NEET is used to obtain representative dose rates for each of these tasks, assuming a typical entry pattern between shots. This data is entered into a spreadsheet that then produces the expected annual dose for the work group, and the average worker dose within that group. These are used to set the goals and administrative control limits for the year. The assumptions that went into developing these estimates (such as average dose rates at re-entry) are then included in the work controls for those tasks. Work controls are flowed down to the individual Radiological Work Permit (RWP) for that task.

To track worker dose throughout the year, Electronic Personal Dosimeters (EPDs) are used for most work inside the TB. The Mirion DMC 2000S electronic dosimeter (Mirion Technologies (MGPI) Inc, 5000 Highlands Parkway, Suite 150, Smyrna, GA 30082) is used for this purpose. These electronic dosimeters provide real-time feedback to workers of dose and dose rate, and tracking data to the health physics staff and line managers between quarterly reads of the thermoluminescient dosimeters that are used for dose of record.

To manage the issuing and reading of the EPDs, the associated dose data and the Radiation Work Permit (RWP) program, NIF uses self-serve kiosks running Sentinel Health Physics Information System software (PTI- Systems/Mirion Technologies (MGPI) Inc, 5000 Highlands Parkway, Suite 150, Smyrna, GA 30082). Workers enter their employee number and the RWP they are working under, and the EPD is programmed with the RWP values for dose and dose rate alarms, and the workers can see their estimated dose to date, and margin to their personal dose limit. After completing the work, they log the EPD back in, the data from the task is uploaded and saved for analysis and to update the worker’s estimated dose.

CONCLUSIONS

The post-shot radiation environment inside the TB of the NIF has been characterized. Dose rate maps of the different TB levels were generated to aid in estimating worker stay-out times following a shot before entry is permitted into the TB. Following a low-yield D-T shot, the general environment dose rate at the equatorial region of the TC drops to < 30 μSv/h at 3 h after a 10^{16} shot. General access could be allowed within an hour but specific tasks that require accessing locations with locally higher dose rates may benefit from additional decay time to allow dose rates to drop further. The dose rates drop by more than a factor of two at one day following the shot. The results presented in the paper are based on the conditions expected for a shot yield of 10^{16} neutrons and could be scaled down within the range of expected lower D-T neutron yields. The work planning tool NEET, uses this approach to scale dose rates for successive shots to estimate cumulative dose rates at any given time after a sequence of shots. NEET is used to develop annual ALARA plans and set administrative dose limits for workers and work groups. To track worker dose throughout the year, Electronic Personal Dosimeters (EPDs) are used for most work inside the TB.

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Figure 1. 3-D view of the MCNP TB model.

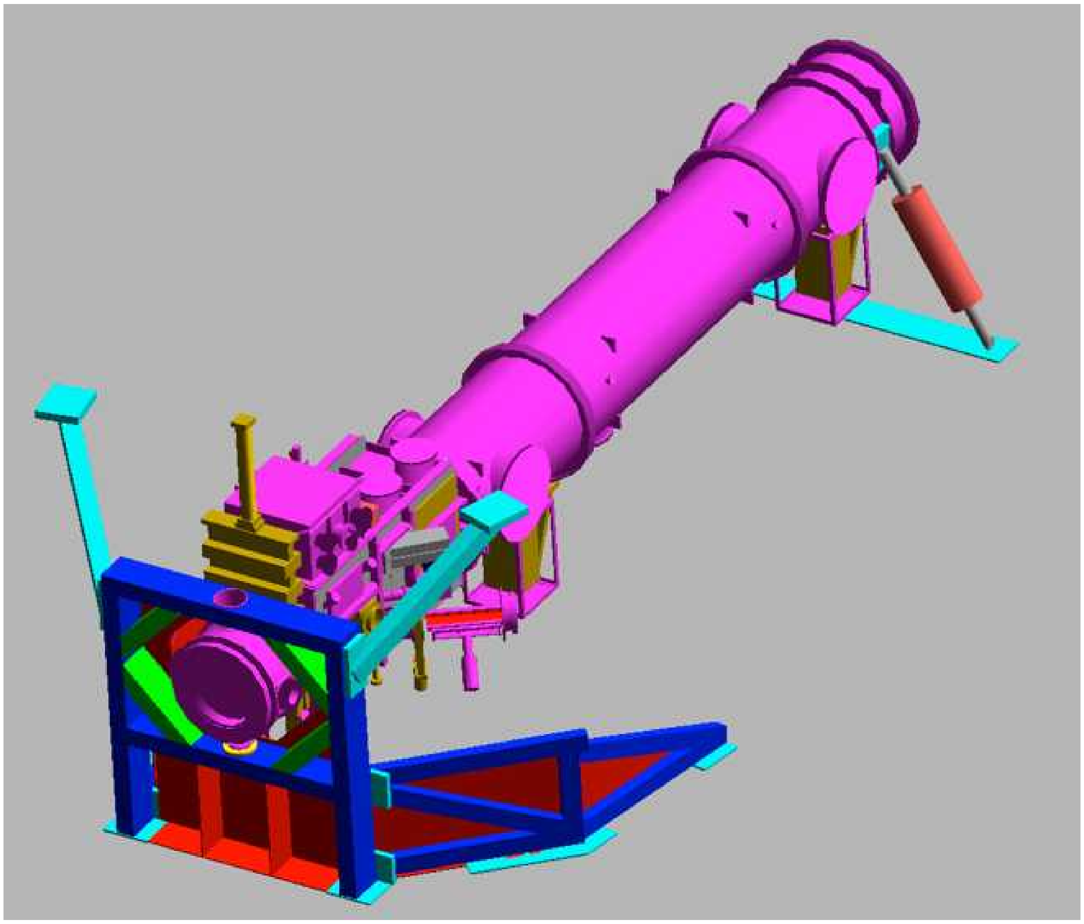


Figure 2. MCNP model of the retracted CryoTARPOS.

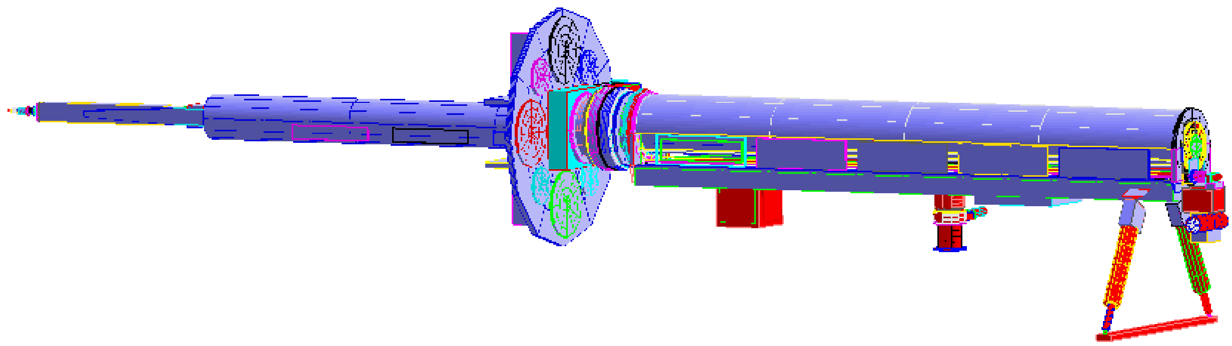


Figure 3. MCNP model of an extended DIM.

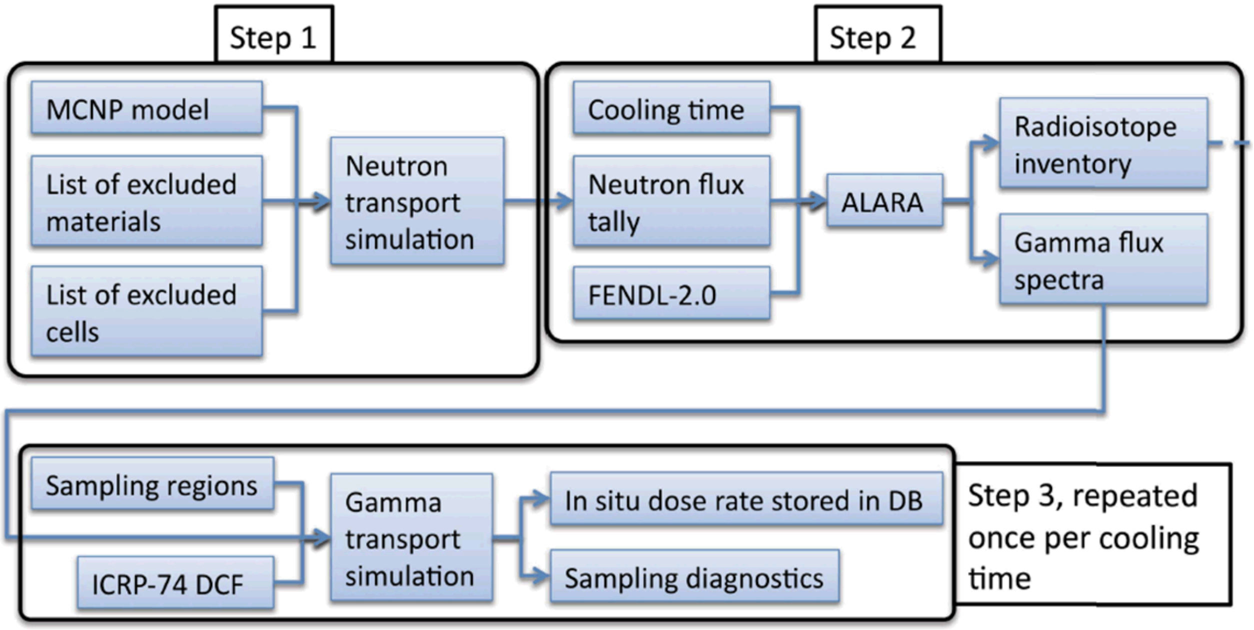
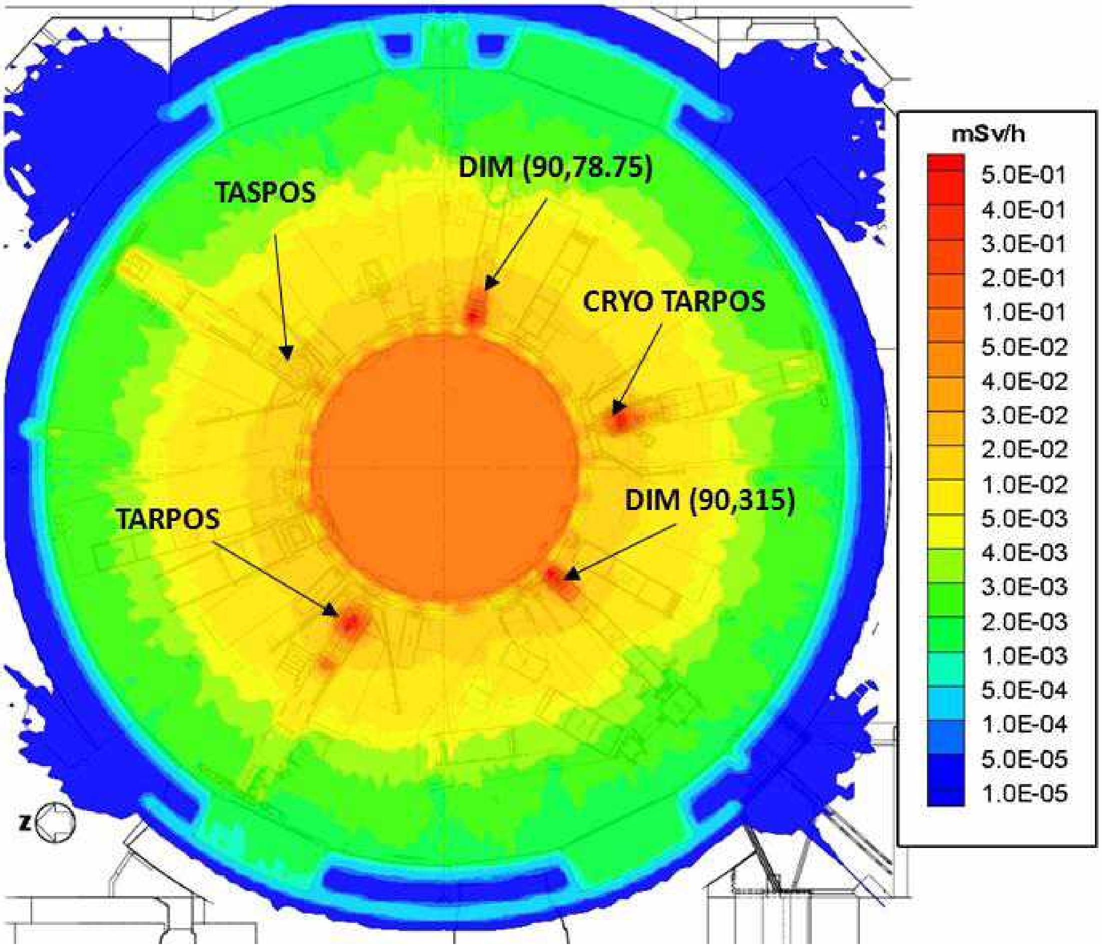


Figure 4. AAMI flow chart.

Figure 5. MCNP model of TB equator during a shot.



TASPOS
DIM (90,78.75)
CRYO TARPOS
DIM (90,315)
TARPOS
z
mSv/h
5.0E-01
4.0E-01
3.0E-01
2.0E-01
1.0E-01
5.0E-02
4.0E-02
3.0E-02
2.0E-02
1.0E-02
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
5.0E-04
1.0E-04
5.0E-05
1.0E-05

Figure 6. Dose rate map at the equatorial plane of the TC (L2 level) at a 3 h following a 10^{16} shot.

Figure 7. Dose rate map at the equatorial plane of the TC (L2 level) at a 1 d following a 10^{16} shot.

Figure 8. Dose rate map on maintenance platforms 5.79 m above TCC (L4 level) at a 3 h following a 10^{16} shot.

Figure 9. Dose rate map on maintenance platforms 5.79 m above TCC (L4 level) at a 1 d following a 10^{16} shot.

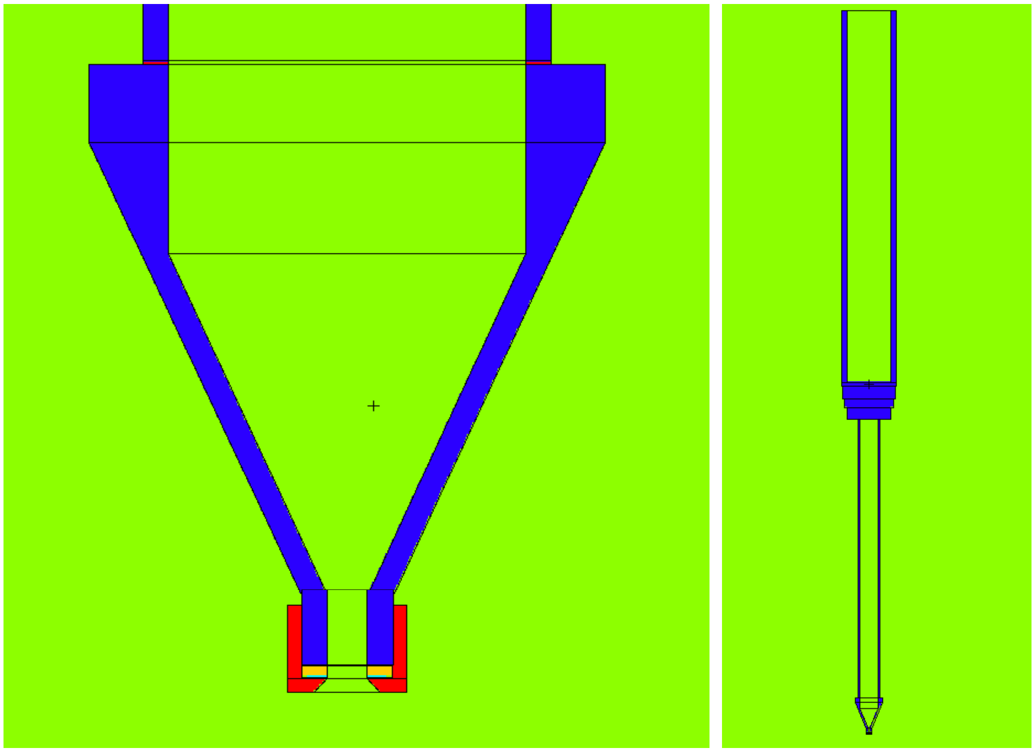


Figure 10. MCNP model of the Polar DIM snout and airbox.

Figure 11. Dose rates near the polar DIM snout and airbox following a 10^{16} shot.

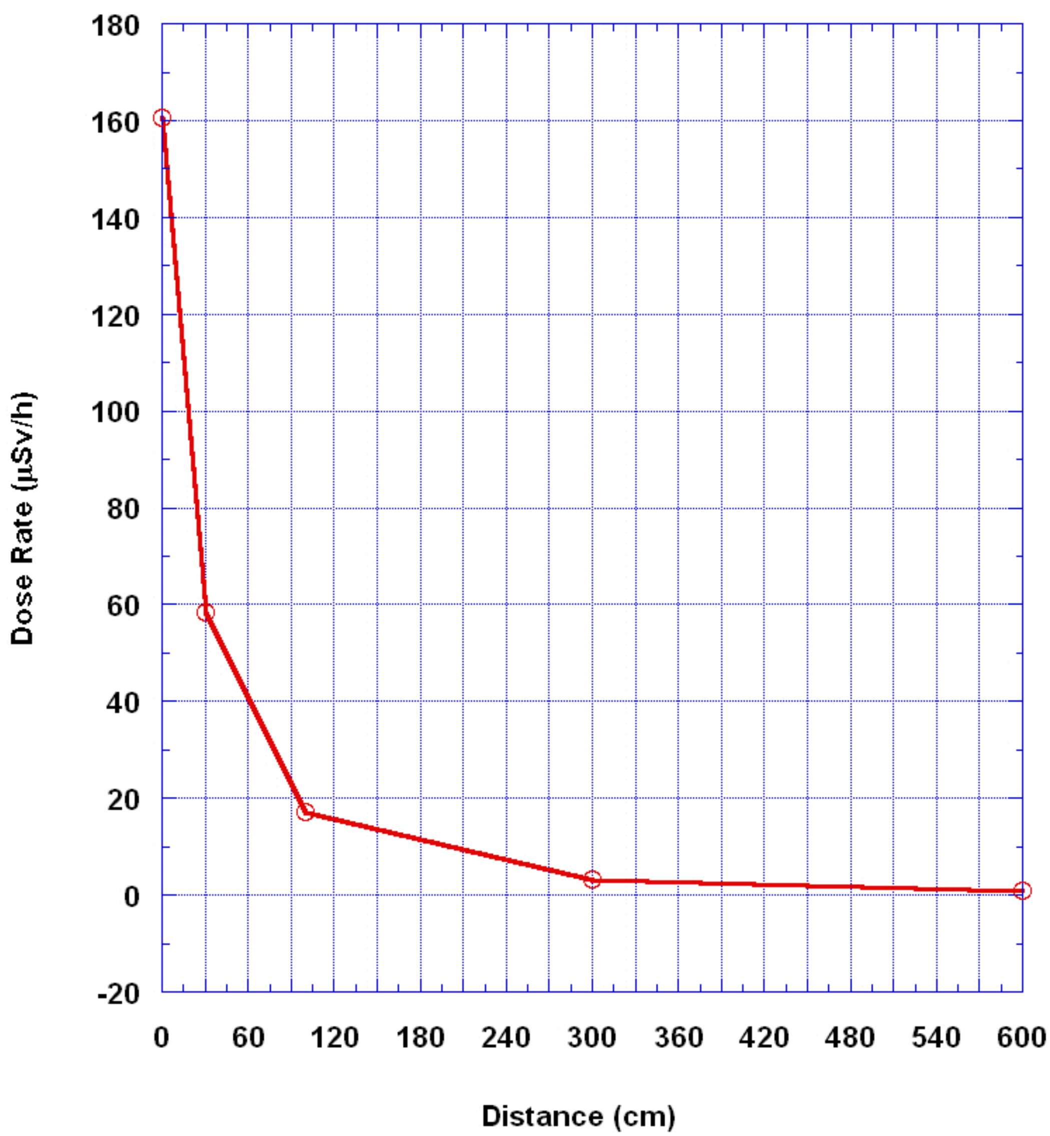

Dose Rate (µSv/h)
180
160
140
120
100
80
60
40
20
0
-20
0
60
120
180
240
300
360
420
480
540
600
Distance (cm)

Figure 12. Dose rates outside the DIM snouts decay and storage area.

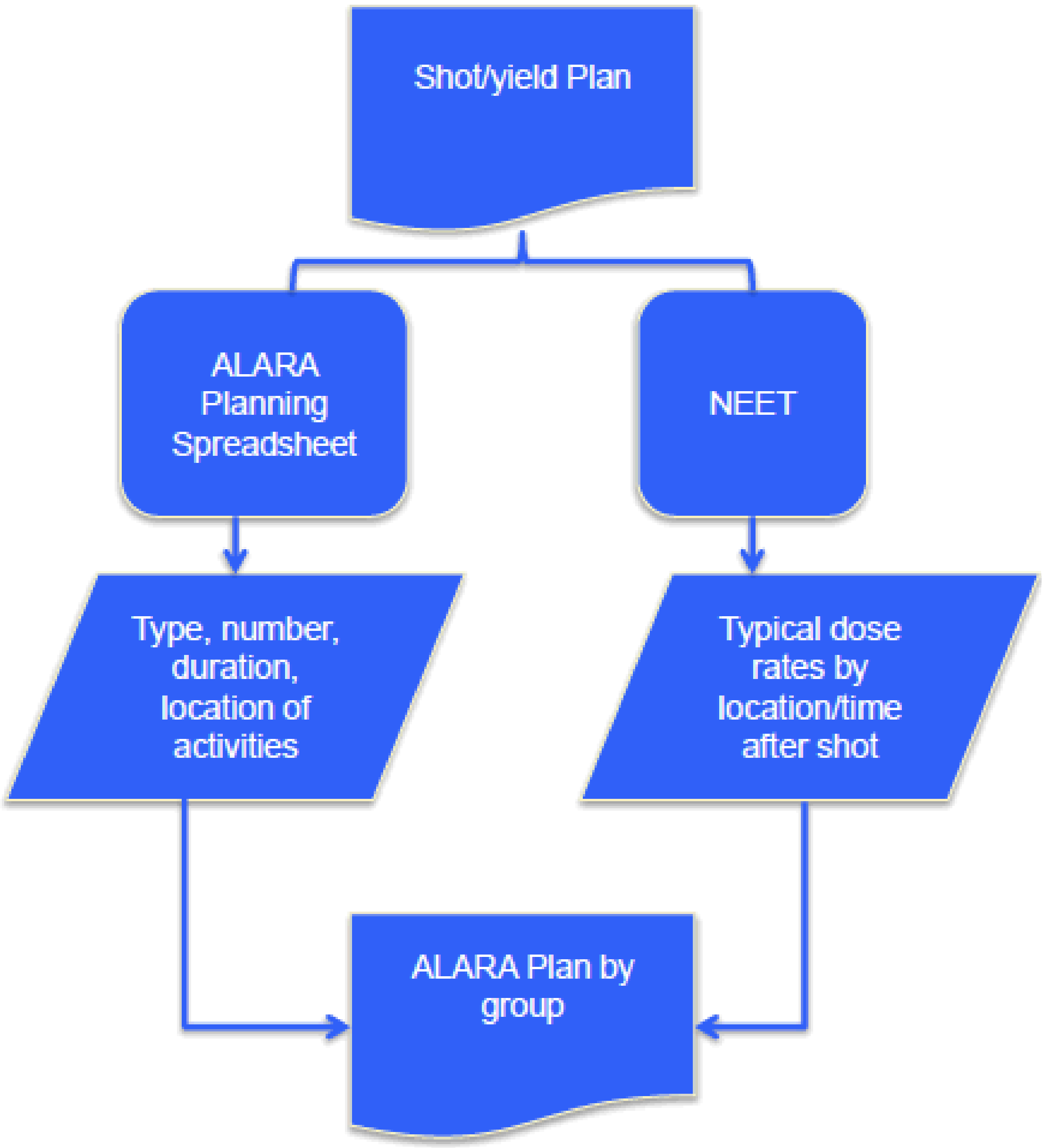

Shot/yield Plan
ALARA Planning Spreadsheet
NEET
Type, number, duration, location of activities
Typical dose rates by location/time after shot
ALARA Plan by group

Figure 13. ALARA planning process.

TABLE I. Dose rates in the vicinity (~30 cm) of the equatorial DIMs following a 10^{16} shot.

Decay Time	Dose Rate (μSv/h)	
	DIM (90, 78.75)	DIM (90, 315)
1 h	31	29
3 h	23	21
6 h	18	16
12 h	13	11
1 d	7	6
3 d	1	1
6 d	< 1	< 1

TABLE II. Dose rates in the vicinity (~30 cm) of the two Target Positioners following a 10^{16} shot.

Decay Time	Dose Rate (μSv/h)	
	CryoTARPOS	TARPOS
1 h	28	26
3 h	19	19
6 h	13	13
12 h	08	8
1 d	4	5
3 d	1	1
6 d	< 1	< 1

TABLE III. Dose rates in the vicinity (~30 cm) of the polar DIM and the L4 floor following a 10^{16} shot.

Decay Time	Dose Rate (μSv/h)	
	Polar DIM	L4 TB floor
1 h	38	5
3 h	27	3
6 h	23	2
12 h	17	1
1 d	9	< 1
3 d	1	< 1
6 d	< 1	< 1

[1] X-5 Monte Carlo Team, "MCNP - A General Monte Carlo N-Particle Transport Code, Version 5," Los Alamos National Laboratory, LA-UR-03-1987 (2005)

2 The TPS oxidizes unburned tritium exhausted from the target chamber and associated volumes, and captures it on a molecular sieve.

3 Supplement Analysis of the 2005 Final Site-wide Environmental Impact Statement for continued Operation of Lawrence Livermore National Laboratory (2011 SWEIS SA), U.S. Department of Energy

(DOE) National Nuclear Securit5y Administration (NNSA), August 2011 (DOE/EIS-0348-SA-03)