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OPERATIONS ON THE NATIONAL IGNITION FACILITY

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ABSTRACT

The National Ignition Facility (NIF) is a high-energy-density-physics, experimental user facility that focuses up to 1.8 MJ of UV light in 192 laser beams onto a mm-sized target at the center of a target chamber. This paper describes how we conduct experimental shots on the NIF. We review processes and tools used to facilitate experiment planning and operations. Safety and radiological aspects of NIF's operations are discussed. We also describe efforts to continuously improve operational efficiency and further increase shot rate.

Keywords: National Ignition Facility, operations, user facility, laser facility

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I. INTRODUCTION

In this paper, we describe the experimental operations of the National Ignition Facility, including facility preparations for experiments; operations supporting the experiments; and maintenance of the target experimental systems, laser, and support infrastructure. We also discuss how NIF safely deals with the small quantities of hazardous materials used in NIF's targets as well as the levels of x-rays, neutrons, and other radiation generated by some experiments. Lastly, operational improvements to increase the efficiency of operations are discussed. The NIF Shot Operations Plan[1]—in conjunction with the NIF Operations Management Plan[2], the NIF Users' Manual[3], and the NIF Maintenance Plan[4]—describes the overall operations. This paper provides a snapshot of NIF operations at the time of publication, though the facility is transitioning from construction and commissioning to an experimental user facility. Many policies and organizational elements are actively being reworked and will be discussed in future publications.

II. CONDUCTING EXPERIMENTS ON NIF

The NIF—the world's first, operational, megajoule-class laser facility—is a user facility managed by the National Nuclear Security Administration in the Department of Energy. Its major missions are the National Nuclear Security Administration (NNSA) Stockpile Stewardship Program (SSP), national security applications for the Department of Defense (DOD) and other federal offices and agencies, discovery science, and energy missions for the DOE.

II.A Preparation and Execution of Experimental Campaigns on NIF

Operating NIF as a user facility involves two different aspects: (1) definition, review, and planning of the experimental campaigns; (2) detailed facility implementation, including machine

safety review, configuring the facility and diagnostics, fielding the targets, firing the lasers to the target, and archiving the experiment results. Both aspects are described in the sections to follow.

Once an experiment has been accepted by the program following a peer review process and ranking by one of the participating programs, the first step in the process of execution of an approved NIF experiment is an initial strategy meeting involving the principle investigator and key elements of facility leadership. This meeting occurs between 6 and 15 months prior to the planned experiment, depending on the complexity of the experiment, required new capabilities, and other factors. This group identifies the major issues associated with the experiment and, in particular, identifies the NIF Expert Groups whose approval will be required (e.g., relative to issues such as laser and user optics specifications, impacts to the target chamber/target bay equipment, debris and shrapnel, cleanliness, or hazardous materials).

The experiment is then reviewed in further detail by the NIF Expert Groups, target fabrication and target diagnostics specialists, and other key stakeholders, as determined by the strategy meeting. The final target design is released to fabrication within 6–9 months of the experiment date, with all expert group reviews completed no later than two months of the planned shot date. The target design, diagnostic requirements, and other major factors driving the planned experiment are “frozen” three months before the shot date.

A preliminary readiness review is conducted approximately one month before the shot date. This meeting, led by senior NIF staff, is the final check to ensure that all preparations for execution of the experiment are complete. All specifications for the setup of the laser, diagnostics, and user optics are finalized at this time. Following successful completion of the preliminary readiness review, the detailed setup for the experiment will be approved by the expert groups and diagnostic and target reviewers. Once approval is completed, the shot will be

approved for execution by the NIF Operations Manager (NOM). Final readiness checks are conducted one week before the experiment to review details such as personnel availability and any required adjustments to the experiment due to facility changes.

Following shot execution, the experimental team and facility identify any issues that may have arisen with the target, laser, and/or diagnostics during performance of the experiment and that need to be addressed prior to the next shot. The shot data is provided to the investigator for distribution to the campaign team. Shortly after the experiment, the investigator presents a short, post-shot review of experimental results at a weekly NIF update meeting. NIF data is managed using policies similar to that in use at other large user facilities; further details are available from the NIF User Office.

A primary goal of the NIF is to produce high-quality, experimental data to validate theoretical physics models and advance programmatic objectives for a wide range of users and missions.

A software tool suite has been developed to acquire and integrate NIF data from multiple sources, including machine state configurations, calibrations, experimental shot data and pre- and post-shot simulations. During a shot, data from each diagnostic with electronic output is automatically captured and archived into a database, which triggers the Shot Analysis, Visualization, and Infrastructure (SAVI) engine, the first automated analysis system of its kind. The engine manages signal and image processing across a Linux cluster and calibrates and analyzes data from each diagnostic. Results are archived in NIF's data repository for experimentalist approval and display using the web-based tool. Scientists can review data results remotely or locally, download results, and perform and upload their own analysis.

Post-shot data analysis and reporting of laser performance is provided by the Laser Performance Operations Model (LPOM) application. Within minutes of the shot, LPOM provides the NIF Shot Director and user a report of predicted and measured results that summarize how well the shot met the requested goals (see Fig. 1 for an example output). In addition, the LPOM data reporting system can access and display beam energetics, spatial, temporal power and spectral data at critical points in the laser and on target. More detail on this subject can be found in a companion paper in this issue entitled "NIF Controls and Data Systems."

The NIF archive database stores all the relevant experiment information—including target images, diagnostic data, and facility equipment inspections, as well as the post-shot state of the facility using a combination of high-performance databases and archival tapes. A crucial design feature of the database is that it preserves the pedigree of the data—all the linked pieces of information from a particular experiment, such as algorithms, equipment calibrations, configurations, images, and raw and processed data—and thus provides a long-term record of all the linked, versioned shot data. The Archive Viewer application provides researchers secure access to the archive to retroactively analyze and interpret results, or perhaps to build upon experimental data originally produced by other scientists.

The NIF year is divided in 44 shot-weeks, two Holiday weeks and 6 dedicated maintenance weeks. NIF is operated 24 hours a day, 7 days a week. NIF's typical shot week consists of five shot days and two maintenance days. The total shot operations and facility reconfiguration team consists of approximately 160 people covering four, 12-hour shifts. This does not include technical staff and off site facilities for optics processing and target assembly.

II.B. Facility Implementation of Experimental Operations

II.B.1. Laser Operation and Alignment

Details of the laser and facility preparations are specified in the experiment setup. The Integrated Computer Control System (ICCS) configures devices and manages automated setup and alignment of laser components and parameters, such as pulse length and shape, wavelength, bandwidth, timing, beam aim points based upon the beam usage and requirements of the experiment setup. A wide variety of beam configurations, from a single beam to 192, beams is possible. Approximately 60,000 devices must be correctly set and configured for a shot. A detailed description of the laser is provided in the accompanying paper in this issue entitled "Description of the NIF Laser."

The desired laser wavelength and pulse shapes are configured in the Master Oscillator Room (MOR), where the laser pulses are created prior to distribution to the large amplifiers. Each of the 48 quads of four beams are distributed into three groups, each of which may be set to slightly offset wavelengths, depending upon experiment requirements. Each of the 48 quads may also be setup with their own pulse shape and timing delay relative to the reference. Each beam quad shares a common preamplifier (see below).

For each experiment, the laser beams are aligned from the Pre-Amplifier Modules (PAM), through the main laser in the laser bays, and onto the target using the Target Alignment Sensor (TAS). Most of these tasks are highly automated, with operators intervening when there are issues with processes or equipment or when there is a need to perform verifications. Full alignment of all laser systems to the Target Chamber Center (TCC) takes less than an hour. Alignment of the target is manual, using graphical alignment aids and off-line target metrology data. Details of each alignment procedure vary depending on the complexity of the target and experiment configuration. For more information on the alignment process see Reference 5.

Prior to each full system shot, one or more low-energy PAM preamplifier shots are conducted. These shots are fired with the system in the final shot configuration, but only using the PAM rod amplifiers (i.e., the main amplifier capacitor banks/flashlamps do not fire). These so called “rod shots” verify proper operation and configuration of the laser systems, critical laser parameters such as energy splits between quads and beams, pulse shapes, laser beam wavefront, and timing prior to proceeding with the actual shot. The LPOM operations model assists the shot director in this evaluation by analyzing all rod shot results within approximately 10 minutes after the shot. As part of the rod shot, the target diagnostics complete a dry run to verify their setup and operation. These checks are done for equipment protection to verify the system will not be damaged on the full system shot and as a means of ensuring experimental goals will be achieved.

Following the completion of a successful preamplifier rod shot, we start a full-system shot countdown sequence. During this sequence, all devices are armed, power supplies are charged, the target is uncovered, and the laser is fired in a tightly coordinated process (see section II.B.5, NIF Shot Cycle). Following the shot, the main amplifier flashlamps are cooled using clean, dry air to reduce turnaround time to the next shot. We also conduct equipment and optics checks to identify any maintenance items that need to be addressed before subsequent shots.

II.B.2. Target Operations

Two insertable positioners are available to hold and align various target types at the center of the target chamber (TCC) for experiments. Beams can nominally be pointed in a 30 mm cube centered at TCC to enable backlighters and more complex target arrangements. The basic target positioner (TarPos) can hold either room temperature (“warm”) or cryogenic (“cold”) targets (see Fig. 2). Cryogenic targets may be cooled to as low 18 K, as specified by the

experimenter, using an on-board cryocompressor/cryostat system. Cryogenic insulating shrouds are used to maintain target conditions and prevent condensation until a few seconds prior to the shot, when they open to expose the target to the laser beams. Temperatures can be maintained to a precision of a few tens of milli-Kelvin. Target insertion into the target chamber and alignment occur with the shrouds closed. The target positioners provide positioning with 5 degrees of freedom: x, y, z and roll/nod (within a certain range).

Three, individual, gas manifolds provide the capability to fill the targets of each positioner with low-pressure (a few torr up to about 20 psig) condensable gases, or low- or high-pressure (up to approximately 900 psig) non-condensable gases (see Fig. 3). Gases used to-date include helium (He-3 and He-4), hydrogen (including deuterium), argon, krypton, xenon, propane, deuterated-propane, neopentane, and various mixes of the above.

The cryogenic target positioner (cryoTARPOS) can, in addition to the above functions, form and characterize cryogenic crystalline layers of fusion-fueled targets. Layer growth and characterization is performed using an *in situ* x-ray system with three, orthogonal sources/views isolated from the target chamber. Development of high-quality layers typically takes several days. Various mixtures of high-purity, hydrogen isotopes (normal hydrogen (H), deuterium (D), or tritium (T)) can be used. Tritium mixtures are prepared at the LLNL tritium facility per experimenter-specified ratios. Then, the fuel reservoirs are transported to the NIF and installed in the cryoTARPOS system by cryo operations staff. Typical D-T implosion experiments use reservoirs containing about 0.74 TBq (20 Ci) of tritium gas. More detail on this subject can be found in a companion paper in this issue entitled “Cryogenic Target System and DT Layering.”

Target operations personnel assist experimenters with the specifications necessary to achieve the desired target fill purity and density and the correct temperature profiles to meet

experimental needs. The detailed requirements for each experiment are specified in the shot setup report. In addition, operations personnel manage the gas preparations, target transport, installation and checkout, cool down, and operation of the target and supporting systems during the entire shot cycle.

II.B.3. Diagnostic Preparations

Over 60 facility target diagnostics of various types (neutron, gamma, x ray, optical, and others) are available for use depending upon experimental requirements. The configuration and setup parameters for each are specified in the experiment setup.

Some diagnostics require physical reconfiguration in the field to install the correct pinholes, imaging optics or filters, and attenuators or to change out complete diagnostics. Three Diagnostic Instrument Manipulators (DIMs) are used to insert sophisticated diagnostic instruments to within a few cm of the target to acquire close-up, time-resolved images or streaked radiation emission of capsules compressed to less than 100 μm, or to measure shocks propagating inside targets using high speed interferometric laser metrology inside the target. To prevent damage to the instruments, these devices must be equipped with appropriate shields to protect them from target debris, laser light, and the x-ray load of the shot. These insertable diagnostics are normally retracted, isolated from the target chamber, and vented between shots to remove the used front end and to configure for the next shot.

Other diagnostics can be set up remotely (for example, changing optical filters, oscilloscope, camera, or timing settings). Setup for each diagnostic can vary from several hours (e.g., changing out an insertable diagnostic, see Fig. 4) to a few seconds for remotely settable devices. The computer control system and physical configuration database verifies that diagnostics are set up as specified in the experiment setup. Insertable diagnostics must be aligned

to the target during the experiment as part of the overall alignment sequence. Target Diagnostic operation is verified prior to the actual shot during diagnostic dry runs that test timing and operation.

Prior to the shot, the diagnostics are automatically armed and triggered for the shot, and electronic data is archived; that data is available to experimenters within a few minutes. Some data is captured on film, image plates, or other media (such as activation foils), and is retrieved by operations personnel and processed offline. That data is usually available within a few hours to a day after the diagnostics are serviced.

During high neutron yield shots, such as layered DT ignition implosions, we have to remove selected close-up electronic instruments and detectors before the shot to avoid damage by neutrons. Cameras are either removed or replaced by film-based detectors.

Target diagnostics are typically operated and maintained by the NIF Target Diagnostic Operations team and their engineering staff working closely with the shot physics team, including the Shot Principal Investigator and the Shot Responsible Individuals.

The deployment of new Target Diagnostics follows a disciplined process that is managed by the NIF Work Authorization and Design Review process. This ensures that the design, assembly, offline testing, and online testing proceeds safely and efficiently with appropriate review by experts, operators, and management. Target Diagnostics are typically extensively tested and validated off line, before they are integrated in the facility and tested on line with the integrated control software system,

II.B.4. Facility Preparations

For precise operation of the laser system, atmospheric and ambient conditions inside and outside of the laser beam path must be tightly controlled. Most of the laser beam path is either pressurized with low-pressure clean, dry air or humidified argon gas, or maintained at vacuum in those portions of the system where the laser beam comes to a focus, such as the spatial filters or the target chamber. Argon is used to suppress Stimulated Rotational Raman Scattering (SRRS) that can occur when high-power, long-pulse lasers propagate over long distances through atmospheres consisting of multi-atomic gases. Argon fills the beam path from the exit of the main laser in the laser bay to the final optics assemblies in the target bay over a distance of approximately 60 meters. The pressure, temperature, and humidity of these gases is precisely controlled and verified for each shot. Similarly, the temperature and pressure of the entire facility containing the laser system is precisely controlled to maintain beam alignment on the target within the specifications for several hours (typically on the order of 30–100 μm or less). The target chamber is maintained at less than 1E-5 Torr, typically below 1E-6 Torr to prevent High voltage breakdown in the target diagnostics and reduce ice deposition on cryogenic targets.

From a personnel safety perspective, most of the operational laser areas must be cleared of personnel prior to firing the system shot. The capacitor bays, laser bays, switchyards, and target bay must be free of personnel to protect them from potential high voltage, laser hazards, and/or x-ray and neutron exposure. An integrated Safety Interlock System (SIS) is used to ensure that the facility is properly configured for the shot. Personnel are cleared from these areas by a combination of physical sweeps (using “watchman-type” key switches turned by operators), automated announcements, klaxons, and warning indicators. Once personnel are cleared of the various areas, the system monitors the perimeter doors, beam stop configurations, crash buttons, and other safety devices. If any device is not in the required position, the SIS system removes

electronic permissives from the main amplifier power supplies, preventing operation of the amplifiers in the main laser.

For fusion implosion and other experiments that have the potential for producing a significant number of neutrons over 1E14, large concrete shield doors (varying from 0.5 to 2 m thick and weighing several tons) may need to be closed to provide adequate neutron shielding. See Fig. 5 for examples. The required position of these doors depends upon the maximum possible neutron yield from a particular experiment. There are three different configurations of doors possible, depending upon the yield. A total of 48 shield doors are installed. Operators close the specified doors, and the SIS ensures the proper configuration of the doors consistent with the type of shot, as set by the Operations Manager. The yield category is based upon an analysis of the maximum credible yield of the target-laser configuration and reviewed by system experts as part of the Work Authorization Point and approval process of the shot. See Section V for additional discussion of safety controls and management. Following a yield shot, stayout times and reentry processes are being used based on the yield category and gamma ray activation radiation level observed. These protocols are discussed further in Section V.B.1.

II.B.5. NIF Shot Cycle

The shot operations team consists of technicians expert in operations of the various subsystems, field engineers, a Lead Operator, and a Shot Director, who has the overall responsibility for executing the shots.

The ICCS computer control system is used to coordinate the execution of each experiment. The highest level of supervisory software, the “shot director” *application*, is a state machine that coordinates the operations of lower levels of supervisory software, and eventually individual devices (via Front-End Processors (FEPs)). The controls of the 192 laser beams are

broken up into groups of eight beamlines, called bundles, that share a common infrastructure. The bundle-based controls architecture greatly simplified the overall design of the control system.

The shot director sequences the shot through several “shot life cycle states” (Fig. 6) that have different functions. Upon loading the experiment, the experiment high-level goals and configurations—specified in the shot setup—are loaded. In “populate plan,” the system calculates the required device settings and setpoints (e.g., power supply setpoints, shutter positions, timing settings, attenuator, and scope settings, etc.,) necessary to achieve the shot goals. In “implement plan” the system then executes the various tasks to configure the laser, diagnostics and target systems. This includes things such as pulse shaping, laser sub-system alignments, diagnostic setup and dry runs, timing setup, and alignment of target chamber devices. Each bundle of eight laser beams, the common resources (such as the MOR and utilities), and the target area systems are managed by lower level supervisory software, and coordinated where necessary. Operators perform some functions manually, but most are performed automatically by the ICCS. Tasks are logically sequenced by the system, with individual tasks happening in parallel when possible.

Once the system is prepared for the shot, the system sequences into conducting a PAM “rod shot” sequence, which confirms the system setup and performance is acceptable to proceed to the system shot. The data from the rod shot is analyzed by the Laser Performance Operations Model (LPOM) and presented to the Shot Director, who reviews it and approves proceeding with the system shot. If changes are necessary, “update system” is executed, and the rod shot is repeated.

After completion of a successful rod shot, the last few devices required for the system shot are configured, and an automated countdown (about five minutes) executes the timed activities leading up to firing the laser, including the main amplifiers. Operators monitor the countdown and intervene only if issues occur. Following the shot, laser and target diagnostic data is automatically archived and cooling of amplifiers is initiated. Automated analysis of the diagnostic data is launched, providing most of the initial analysis within minutes. A shot cycle can be abandoned at any point to stop the shot, update the setup, or correct a major issue.

III. OPERATIONAL PROCESSES

A highly qualified and capable staff, along with formal processes for executing work is needed to ensure safe, efficient, and reliable operations, both from equipment and personnel safety standpoints. Plans, procedures, practices, and protocols flowing from regulatory requirements have been put into place to manage hazards, such as tritium, beryllium, depleted uranium, neutrons, and associated activation and fission products. The required administrative controls have been implemented through authorizing documents and safety plans, as well as work permits for specific activities at NIF.

III.A. Work Planning and Execution

As shown in Fig. 7, the work planning and execution process has various time horizons. Planning activities in the six month to two year horizon focus on ensuring readiness for major facility maintenance and improvement periods. These are planned sufficiently far in advance to support shot planning and integration with the facility maintenance and reconfiguration periods (FMRs). A NIF year typically consists of two weeks of Holidays, six weeks of FMRs and 44 shot weeks. The normal NIF work week is organized in five shot days and two maintenance days operating on a 24/7 schedule. Six weeks per year are allocated to dedicated FM&R periods to

deal with extended maintenance (such as venting the target chamber) and installation of new capabilities.

In the 6-month-to-8-week window, the work planning focuses on the next milestone, or maintenance period, while ensuring that less impactful maintenance is appropriately prioritized and coordinated with shot operations.

Near-term (seven days or fewer) work planning and execution rely on the work group planners working with the work center supervisors to allocate resources and coordinate among the work groups and shot operations to de-conflict work. Their roles are described below.

Department Planner: The Department Planner for each area is responsible for understanding the maintenance and other work that needs to be accomplished. The Department Planners gather this information from the system managers, the shot plan and set-ups, and the computerized maintenance management system (see section IV.D), where applicable. They chair the weekly planning meetings and work with the work groups to prepare shot and maintenance window packages and present them for scheduling.

Work Center Supervisors: The work center supervisors know the resources (labor, time, and equipment) required to perform work. They work with department planners to prepare resource-loaded weekly plans and allocate the labor to support the daily work plan. They are responsible for reviewing work permits for scope, hazards, and controls, and for ensuring that work is safe, well-planned, and ready to proceed.

Field Supervisors: The Field Supervisors are in the field supervising the technician teams assigned to their areas. They work with the Work Center Supervisor to develop daily work

plans and make the daily job assignments. They also conduct the shift turnover and shot reconfiguration meetings (prepare reports and distribute).

The Daily Operating Schedule Team is comprised of Work Center Supervisors and Shot Operations. They compile all the activities that are either required for execution of experiments on NIF or that could interfere with the conduct of the experiments. See an example in Fig. 8, which provides both an overview of the week's facility activities and a detailed list of critical path tasks and their contribution to upcoming shot operations.

The Daily Operating schedules are published on the NIF Web site, emailed, and available on a Sharepoint server. Tables with baseline scheduled start and fire times for each shot are published along with the project schedule.

Changes to the shot schedule within two weeks of the shot time are managed by the Shot Change Control Board, which meets daily to discuss readiness issues and disposition issues, and to decide on imminent schedule changes. A computerized Schedule Change Request process is used to expeditiously propose, evaluate, and disposition any change to the NIF shot schedule.

III.B. Work Control

From the operation of the NIF laser to maintenance tasks, every activity at NIF goes through a risk-based graded review and approval process. The work authorizing document, the integration safety management worksheet, and the job hazards analysis all guide the conduct of this process. Work tasks are evaluated, the associated hazards are analyzed, and specific controls for each task are identified, as needed. In some cases, an operational safety plan may also be needed when significant hazards are involved. A tiered approach to hazard mitigation is employed with options that may include engineered controls (e.g., interlocks, alarms, and

shielding), administrative controls (e.g., procedures and signs), and personal protective equipment (e.g., gloves, safety shoes, and respirators). Detailed controls for specific work tasks flow down from the safety documents and are approved through the use of work permits.

Work that is executed on the NIF has to be properly planned and coordinated. The NIF has a challenging set of work activities and operations requiring a higher level of coordination than traditional, smaller laser facilities. Work is fully evaluated for its impact on other scheduled activities—including target shot operations—to avoid delays and conflicts in the field.

III.C. Cleanliness Protocol

Cleanliness of optics inside the NIF beam path is critical to maintaining laser performance and availability, as significant optic damage can occur due to the high laser fluences in a NIF beam line (see the companion paper in this issue entitled "Cleanliness Strategy and Its Implementation"). Both a high level of particulate cleanliness and low non-volatile residues are important to maintaining the NIF optics' lifespans. Materials used in the beam path must pass out-gassing as well as particulate cleanliness tests.

When the beam path must be opened for maintenance, local cleanroom conditions are established. This includes use of only approved materials, cleanroom garb, cleaning of the area, either positive clean air purge from the beam path or local HEPA ventilation, and air sampling. In addition, the amount of time that the beam path is opened is minimized using a maximum "class-hour" protocol. These measures have been found to be very effective in meeting the NIF optics' performance goals.

While the target chamber environment is, by necessity, not as clean (due to target debris), controls are still in place to ensure that anything exposed to the TC environment is at least gross

cleaned, and materials must be on the approved NIF materials list for this application. This process ensures that deleterious materials are not present that could be damaging to the final optics.

III.D. Training

A detailed training and qualification program has been developed and implemented to ensure that all NIF workers understand the hazards and controls associated with their work and are qualified to work safely and efficiently in the NIF environment.

The NIF Operations training philosophy is to maintain a standardized, proactive training posture to develop and expand the level of expertise of the workforce and to establish uniform standards of safe operation while ensuring that workers are competent to perform all assigned task

Training may consist of web-based classes, instructor-led classes, or on-the-job training, often referred to as Qualification Cards. All training course completions are tracked in the LLNL training database (LTRAIN).

III.E. Configuration Management

Configuration Management is an integrated management system to maintain the relationship between design requirements, the physical/functional configurations, work execution and experimental data integrity. This is critical for the continued operation of a system with hundreds of thousands of components. It involves the systematic identification of NIF hardware configurations and the systematic management of changes to those configurations. The term “configuration” encompasses not only the physical items delivered but also the controlled safety and performance requirements and criteria that those items have been verified to satisfy.

NIF uses a number of computer tools to assist in the implementation of configuration management; these are the Enterprise Configuration Management System (ECMS) for documents and drawings, the Locations, Components, and States tracking system (LoCoS) for physical hardware, and the Campaign Management Tool (CMT) for experiment definitions and configuration. See the following section for more information regarding these tools.

The NIF configuration management process is applied in a graded manner. Those elements related to public safety, worker safety, the environment, significant programmatic impact, and safety basis administrative controls are “special” configuration items (CIs) and undergo more rigorous review than those that support functional requirements and routine facility functions.

III.F. Tools

Several software tools are used routinely by NIF personnel and are critical to successful day-to-day operations of the facility. These fall into several categories: production, assembly, test and inventory control of parts and Line Replaceable Units (LRUs); installation/removal and condition, status and configuration of installed parts and LRUs; work management, such as Work Permits, task scheduling, and problem identification, tracking, and disposition; optics damage monitoring and management; verification that facility configuration matches that requested for a specific experiment; shot specification; and scheduling.

A combination of commercial software and in-house developed tools are required to meet these varied needs. Some of the key tools used at the NIF are summarized in this section.

Approval Manager: A tool that manages the detailed review and approval of all aspects of experiments in a parallel, independent fashion. It provides reports and resources to enable

expert groups and subject matter experts to review and decide when their section of an experiment is properly configured. This includes target, diagnostics, laser, backscatter, debris and shrapnel, alignment, materials, safety, and security. Workflow rules determine when the experiment, as a whole, is ready to be approved by the Principal Investigator, and finally by the NIF Operations Manager before being release to the facility for execution.

Campaign Management Tool: NIF experimenters use the CMT to generate the laser, target, and diagnostic configuration required for an experiment. CMT is a suite of software applications designed to translate experimental plans and specifications into actions required by the control system and the target area operations team to execute the shot.

Configuration Checker: A tool used by NIF shot operations to ensure that the hardware configuration of the NIF laser and target area systems meets the specified experimental configuration. This includes verifying that the specified target, diagnostic filters and components, and user optics are installed.

Enterprise Configuration Management System (ECMS): ECMS provides industry standard best practices for managing engineering change requests, engineering orders, work flows for review and release of drawings and documents, and a document vault. Disposition of hardware is part of the Engineering Change Request (ECR) process; material in process, inventory, and/or installed are all addressed.

Locations, Components, and States Tracking System (LoCoS): As discussed above, LoCoS is a custom application built to support the work activity of all parts of the NIF organization, including work authorization, problem and non-conformance reporting, laser system and diagnostics status for operational readiness, LRU installation transactions and inspection/metrology data sets. The web-based LoCoS is used to track installed parts from the

facility level down to individual parts. With more than 6,000 LRUs, knowing exactly what parts are installed and keeping track of their history and configuration data is critical. LoCoS also captures and manages calibration data for target diagnostics and targets. A screen shot of LoCoS is provided in Fig. 9.

Production Optics Reporting and Tracking (PORT): PORT provides specialized data aggregation, reporting, and selection functions for the optics and target production processes. PORT also includes functions to manage tasks for work teams, as well as high level reports on shot metrics.

Glovia Enterprise Resource Planning: A commercial product configured and customized as the system of record for parts, serial numbers, bills of material, and assembly/installation/removal transactions, Glovia Enterprise Resource Planning provides visibility into the location and status of key optical, target and diagnostic components. It tracks work orders for all configuration changes. This tool also allows retrieval of full histories on serialized parts and LRUs, from vendor inspection reports, through to warehousing, processing, assembly, installations, and removals.

IV. MAINTENANCE

The reliability of the NIF, including its facility support systems and utilities, is essential to ensuring that NIF is available to conduct experimental operations. The NIF maintenance strategy has been to perform preventative, corrective, and reactive maintenance on all systems as appropriate to best maximize facility availability in the most cost effective way. Each system is evaluated to ensure the best combination of these types of maintenance is applied to maximize facility productivity. This maintenance strategy has worked well because predictive and condition-based (vibration monitoring, thermal imaging, oil sampling, etc.) maintenance

strategies have been added for many systems. Routine preventive maintenance is scheduled during 2–2.5 days of the week, with FM&R periods included in NIF schedules for more extensive maintenance operations (e.g target chamber venting and entry). Reactive maintenance is scheduled and executed when needed to support the facility and shot schedule. Each shot has a specified number of beams and diagnostics (called “rules of engagement”) that could be dropped when random failures occur during the shot cycle. If the configuration is not within these rules of engagement, immediate repair is required or the shot may be rescheduled if a significant impact is expected.

The goal of the NIF Maintenance program is to achieve a reliable, available, and maintainable facility. A reliability-centered maintenance (RCM) program was recently deployed to reduce failure rates and the time require to repair equipment, to anticipate and mitigate problems before they occur, to respond faster to failures (by having parts, permits, and procedures ready), and to plan maintenance during windows of opportunity.[6] Using the RCM process to decide where to focus maintenance resources has allowed NIF to identify and focus on shot-critical functions, determine critical failure modes and impacts, strategically apply health monitoring tools to anticipate problems, evaluate the most cost effective mitigation to preserve functions, and tailor maintenance tasks based on impact to shots.

System-level maintenance plans (SLMP) detail the approach and methods designed specifically for each of NIF’s approximately 160 systems. The SLMPs are developed based upon RCM principles, with a focus on maintaining functional requirements for each system. The RCM process begins with a system functions determination and then proceeds with a Failure Modes and Effects Analysis to determine critical failure modes and their impact on shots; it concludes with a determination of the most cost-effective mitigation to preserve functions.

Periodic maintenance is tracked through the Systems Maintenance and Reliability Tracking tool (SMaRT), a computerized maintenance management system based on the INFOR product that manages the information and processes necessary to perform maintenance on NIF subsystems. SMaRT tracks work that is performed and retains the records of work performed.

For conventional facility and utility systems, each maintenance activity is described by a work order. Each work order proceeds through a review and approval process prior to being executed in the field. Typically each work order contains a maintenance procedure detailing the work activity. In addition, when material is required to perform the activities, the work order contains a material list. Each work order undergoes a close-out review where data from the field and booked hours are captured. In addition, various data fields are set or completed during the close-out process to enable sorting of data for reliability and availability analysis. SMaRT provides a means of tracking hours between failures and repair times to provide mean time between failures and mean time to repair. In addition, by using failure codes at the equipment level, one can track common failure modes and identify common quality issues.

Maintenance for each system is the responsibility of the system manager. A system manager typically is responsible for several like-systems. He/she is responsible for understanding performance requirements for their system, including all safety aspects; creating the SLMP that defines the maintenance required for that system; and directing and defining the work through maintenance procedures and work orders. The facility maintenance organization is also responsible for logistics, transport and handling, and calibration services.

V. SAFETY AND RADIOLOGICAL ASPECTS

The hazards associated with NIF and its operation have been identified and evaluated since the earliest stages of design, and safety features have been incorporated into the design to

mitigate these hazards. The bounds of NIF operations are described in the National Environmental Policy Act (NEPA) documentation.[7, 8] This NEPA documentation ensures that a thorough evaluation of the impacts of NIF operations has been completed, that these impacts are part of any decision making, and that the risks to the public and the environment are understood and communicated.

The limits specified in the NEPA documentation have been synthesized into NIF's Safety Basis Document (SBD). The SBD provides a more detailed identification and assessment of hazards, resulting in additional controls to ensure that risks to co-located workers and the public are low. In addition to flowing down fusion yield and inventory limits, the safety basis document has identified a set of credited safety systems (e.g., radiation shielding) and other credited administrative controls that govern NIF operations. NIF also utilizes an integrated safety management system (see Section III.B) that evaluates the safety of operations at the worker level, identifying specific controls associated with facility hazards.

V.A. General Safety Issues

A variety of safety issues exist at the National Ignition Facility. These have been evaluated in detail, and mitigations have been put in place to control the hazards. A summary of the key hazards at the NIF, their sources, and the typical mitigations is provided in Table I.

The goal of the safety program is to provide a safe and healthy work environment for employees and visitors. A full-time staff of highly skilled environmental, safety, and health (ES&H) professionals (health physicists, environmental analyst, safety engineers, industrial hygienist, health and safety technicians, and administrators), led by an ES&H Manager, is available at NIF. This team's role is to develop, monitor, and ensure safety and regulatory

compliance of NIF operations. The importance of safety is embraced at all levels of NIF and ranks above all other aspects of our operations, including schedule and production.

By embracing safety as a key value, the NIF organization has achieved an excellent safety performance record. The Total Recordable Case (TRC) rate[a] has been maintained well below 1 for years. NIF has been recognized for its excellent safety performance by the National Safety Council.

V.B. Radiological Operations

NIF safety documentation describes the hazards and provides controls for managing radiation hazards and radioactive material used in NIF targets during operations. Radiological hazards include radiation generated during shots and radioactive contamination from tritium in fuel, as well as radioactive by-products from shots. The radioactive environment can also impact equipment, limiting its performance or lifespan. This section summarizes some of the key aspects of NIF radiological operations.

V.B.1. Radiological Safety

Shots on the NIF laser system may generate prompt radiation. This can range from x-rays only—if the lasers impinge on a metal target—to a burst of prompt neutrons and gamma rays for deuterium-tritium fueled capsules. For the highest yield shots anticipated on NIF, about 7.1×10^{18} neutrons will be produced, corresponding to 20 MJ of total fusion energy. This energy is released over times much less than 1 ns, so the power level is extremely high. The fusion energy is primarily (80%) carried by energetic neutrons (around 14 MeV). These energetic neutrons interact with materials in the target and in and around the target chamber. Some of the

interactions lead to activation of these materials, producing radioactive species that subsequently emit ionizing radiation (primarily beta particles and gamma rays) as they decay.

Anticipated radiation levels in and around the facility have been studied in detail.[9, 10] Fig. 11 presents a prompt dose map of the anticipated radiation levels (neutron and gamma) within the NIF for a 20 MJ yield shot (note that this level of yield has yet to be achieved on the NIF). 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 dose values at the ground level of the facility. There is significant shielding around the facility that mitigates the dose from a shot in occupied spaces—both inside and outside the facility—to less than 50 μSv.

Material in the TB is subject to neutron activation, and there will be a decay radiation field that persists for some time after a shot, depending on the shot yield. Although the Target Bay air becomes activated (e.g., Ar-41), the post-shot decay radiation environment is dominated by activation of structural components. Many components within the facility were fabricated using 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 with a 14.97 hour half-life. Several days after a 20 MJ shot, the dose rate in most spaces within the TB is expected to fall below 50 μSv/h, the level of a radiation area. Fig. 12 is an example of a decay radiation dose map.[10] A few localized hot spots are evident. These are tips of entrant devices that were in close proximity to the target 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. Workers would be exposed to low levels of radiation while performing these tasks. The goal for worker doses is to maintain them “As Low As Reasonably Achievable” (ALARA). This is accomplished by

mandating a stayout time after high yield shots, gamma monitors, controlled reentry procedures by RadCon staff using prescribed dose surveys before opening the areas to the qualified workers, tightly controlling access to the TB after reentry, 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 using personal electronic dosimeters.

Another radiological issue to manage is the dispersion of radioactive material within the target chamber and associated systems. This contamination derives from unburned tritium, 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 Depleted Uranium (~40 mg) in the target's hohlraum. The NIF confinement envelope and contamination control systems work to confine the contamination created from the NIF shots. One of the challenges for the NIF is that regular access to 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, Personnel Protective Equipment (PPE), draping, defining contamination areas, and monitoring. More detail on NIF Radiological operations can be found in References 11, 12, and 13.

V.B.2. Target Hazard Management

Any experiment and target proposed by Principal Investigator is reviewed by a Hazards Review Committee to ensure all materials are on the approved materials list. Any new materials, hazards, radiation, and contamination hazards require approval by the NIF Operations Manager (NOM) following a Work Authorization Point (WAP). For significant new hazards, the NOM may invoke a Management Prestart Review by an independent committee of experts. All reviews

and approvals are tracked by the Shot Approval Manager tool. Once all reviews have been completed, the shot can be approved for export to the facility by the NOM. At that point the shot set-up information becomes available to the Shot Director to load and execute**.**

Separate processes are in place to ensure the physical target for the shot conforms to the target specified in the shot set up, and all required controls have been put in place to ensure safe handling prior to and after the shot and materials are tracked against our inventory limits. The RadCon team logs inventory for radiological materials and Be. The shot director physically validates the target package, serial number, and target traveller against the shot set-up. Safety controls are listed in the shot permit for the experiment and tracked by the Shot Director. Radiological and contamination control processes are implemented by the RadCon team through specific procedures.

V.B.3. Fuel Gas Management

An isotopic mixture of hydrogen is the basic fuel for fusion/ignition targets. The physical form of the hydrogen fuel prior to the shot is a <100 μm thin hydrogen “ice” layer within the precision target capsule. The quality and safety of the shot 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 NIF, isotopic mixtures of hydrogen gas are prepared and analyzed at the LLNL Tritium Facility and subsequently transported in fuel reservoirs to the NIF.

The capsule is nominally 2 mm in diameter and contains a hydrogen ice layer of 60 μm. Once installed and connected, fuel is admitted to the capsule from the reservoir through a 5-μm glass fill tube. At fill time, the capsule is cooled to the 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 a maximum deuterium/tritium (DT) fusion yield, a 50/50 mix, or a mixture of normal hydrogen and tritium with a small amount of deuterium (THD) to suppress the neutron yield. As the formation of a single crystal of hydrogen ice is required for a smooth, highly spherical hydrogen ice layer, the fuel gas must be free of contaminant gases. A three-axis, x-ray imaging system is used to monitor and control the formation of the ice layer. An example of an image of an ice layer is shown in Fig. 13. More detail on this subject can be found in a companion paper in this issue entitled "Cryogenic Target System and DT Layering."

High levels of contaminant gases—such as nitrogen, argon, water, and methane—can lead to defects in the ice layer as it forms. In addition, ingrowth of ^{3}He, the decay product from tritium, must be managed. More details on the fuel gas management process can be found in Reference 14.

V.B.4. Radiation Damage

A deuterium-tritium (DT) target shot will generate primarily 14 MeV neutrons that propagate outward from the center of the target chamber. The neutrons pass through the chamber wall and into the TB with multiple scattering events, resulting in a high-fluence, broad energy band of neutrons and gamma rays. When the scattering process results in energy deposition into materials, the deposited energy can lead to permanent changes and damage to the material structure. Several infrastructure support systems will be exposed to the high-yield shots over the NIF's 30-year lifespan. During the shot, the scattering neutrons will interact with various

electronic components located in the TB and will potentially cause operational concerns, including “upsets” (memory corruption in electronics, communication errors, and false alarms), and/or permanent damage.

The TB contains many systems that require some sort of mitigation to address the radiation environment. Examples of equipment that are exposed to neutrons include the positioners, diagnostics, alignment instruments, monitoring systems, seals and o-rings, optical fibers, optics, motors, air handling systems, and safety systems.

In response to this potential radiation exposure, analysis and testing of several facility safety systems have been conducted to establish management guidelines. The guidelines include operational risk based on location, sensor longevity, and conduct of respective operations for each. The major goals of the mitigation strategy are to increase the longevity of the system, allow for the system to be operational during a shot (if appropriate), and to allow for easy replacement of the subsystem, if damaged. The mitigation plan establishes “upset” and “damage” levels, and requires that action be taken before the “upset” level is reached to assure continued reliable operation.

Monte Carlo radiation transport calculations were performed to establish the expected radiation field in the TB. Then, based on instrument locations within the TB, an estimate of the local dose levels in which the system would be expected to operate could be determined. The shot history of a system is tracked and the cumulative dose levels are monitored and compared to the expected levels for upset and damage. Based upon this comparison, a system can be managed though an operational plan. Examples of mitigation strategies that could be included in an operational plan are provided in Table II. More details on management of NIF equipment in a radiation environment can be found in Reference 15.

VI. CONTINUOUS IMPROVEMENT EFFORTS

The most important challenge for NIF as a User Facility is to increase the number of user shots while simultaneously maintaining the safety and quality of the operations, reducing the operating cost, and improving efficiency.

The number of shots that can be executed is the product of time available for shots divided by the average duration of a NIF shot, and we need to both increase the time available for shots and reduce the shot-cycle time. We are increasing the time available for shots on NIF by optimizing the maintenance process and reducing the time needed to shut down operations to commission new capabilities for the facility. We also have an active effort to measure the shot cycle, implement engineered shot-cycle reduction and reliability-improvement projects, and facilitate staffing optimization and process improvements.

Early on we operated on a commissioning and construction schedule that only used to fire the facility at night; this timeline allowed daytime to be allocated to construction, installation, and maintenance. We are now moving to a five day shot period per week dedicated to back-to-back shot operations with a fixed, two day maintenance period. Facility maintenance is being optimized using the Reliability Centered Maintenance approach,[6] focusing the overall preventive maintenance effort and thereby adding redundancy for critical systems, such as the cooling system for NIF's 1000 electronic equipment racks. Working with field supervisors and technicians to acquire and incorporate feedback and recommendations on maintenance cycles has saved hundreds of hours a year, eliminating unnecessary maintenance.

We are reducing the shot-to-shot cycle time by evaluating and optimizing each shot task and sequence and by improving activity planning by developing an integrated shot and facility planning schedule that maximizes facility availability and minimizes diagnostic and optics reconfiguration. A new shot-cycle-metrics process for control room activities has been implemented to collect data on each shot step—including delays and problems—to make additional improvements to shot-cycle efficiency.

We have established a four-pronged approach to improving the shot rate on NIF: consolidate facility staffing so we can swarm reconfiguration activities in between shots; implement a series of engineering projects to speed up the shot cycle by hardware and software changes; reduce the impact of equipment failures by targeted equipment reliability improvement efforts that include improving redundancy, spares, and training; increase the time allocated to shot operations by planning maintenance during two days of the week, with 6 weeks annually allocated for larger projects and upgrades.

Now on the path to mature operations, NIF continues to evaluate and improve processes and capabilities, with the goal of maximizing availability, efficiency, and facility access while preserving personnel and machine safety. Initial facility controls were deliberately very conservative, but with a trained and stable workforce and roles, procedures, and protocols in place, controls are now being revised to be commensurate with our current understanding of the impact of hazards and to reduce unnecessary overhead burden. Examples of recent efforts to revise facility controls include automated facility sweeps prior to firing a laser shot, optimized radiation and contamination controls, and the use of simplified equipment safety procedures (Lock-Out/Tag-Out).

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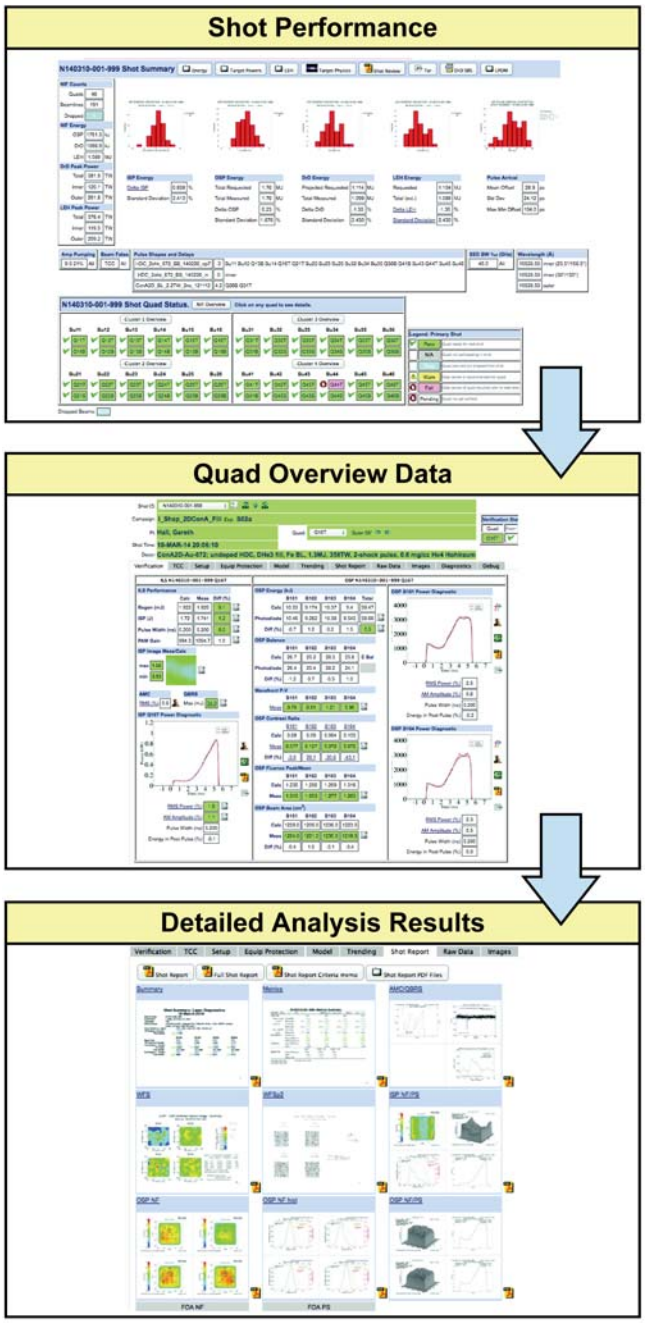

Fig. 1: Within minutes of each shot, the detailed performance of every participating beam line is analyzed and evaluated. A high-level overview and detailed reports are available.

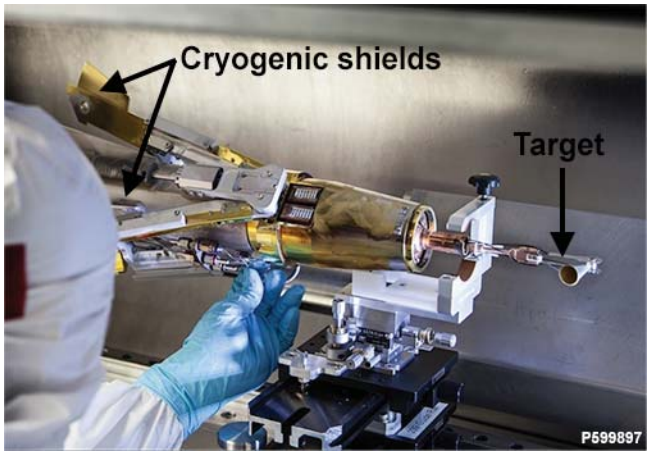

Fig. 2: Installation of a cryogenic target on the TARPOS. Note that the cryogenic shields (shrouds) are retracted in this view. These will close around the target once the installation is complete, to maintain target conditions until just prior to the shot. At that time, the cryogenic shields will swing open, exposing the target to the laser beams.

Fig. 3: Target Gas Manifold Operations. The gas manifolds provide a variety of gases that can be used in the targets.

Fig. 4: Worker installing a diagnostic snout onto a DIM diagnostic. This operation is performed while the DIM vessel is vented to air. After installation, the vessel is evaluated, and the cart holding the diagnostic snout positions it to within a few cm of the target at target chamber center.

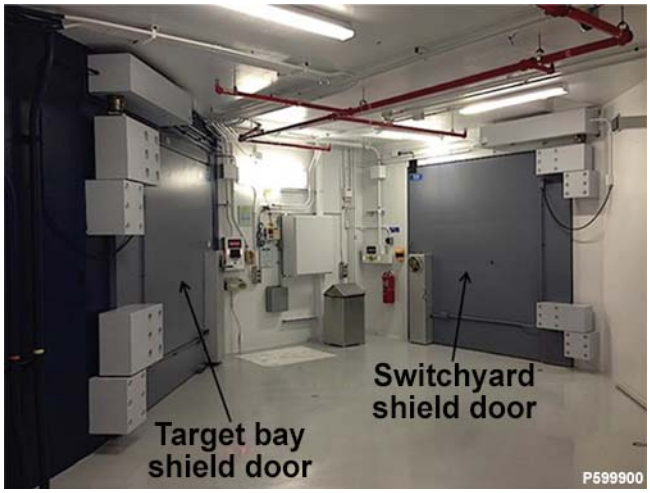

Fig. 5: Examples of primary (Target bay) and secondary (Switchyard) shield doors. This view is taken in the Switchyard, with the door on the left closed at the entrance to the Target bay, and the door on the right closed at the exit from the Switchyard to the core of the NIF building. Depending on the anticipated neutron yield of the shot, some or all of the shield doors will be closed.

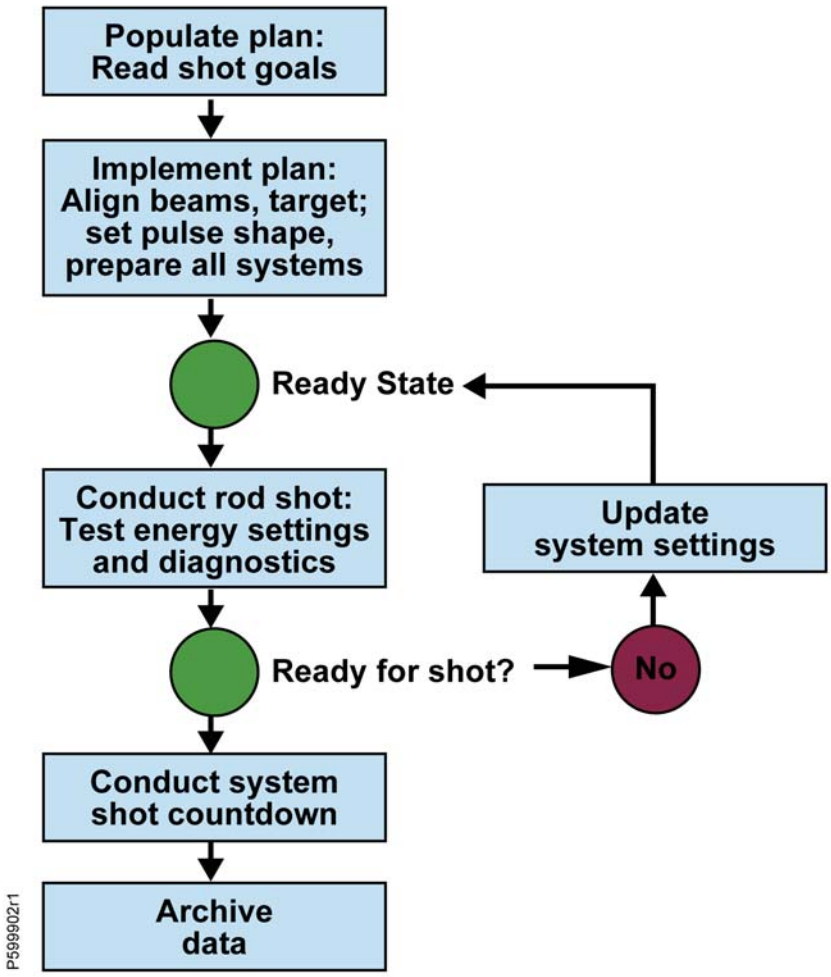

Fig. 6: The NIF Shot Cycle. The primary path of the shot cycle follows the solid arrows. If conditions are not met, the shot cycle can be abandoned, as indicated by the dashed arrows. The dotted arrows show alternate paths, such as “Update Desired.” This would occur if the Shot Director was not satisfied with the performance of the PAM preamplifier shot, and adjustments are necessary.

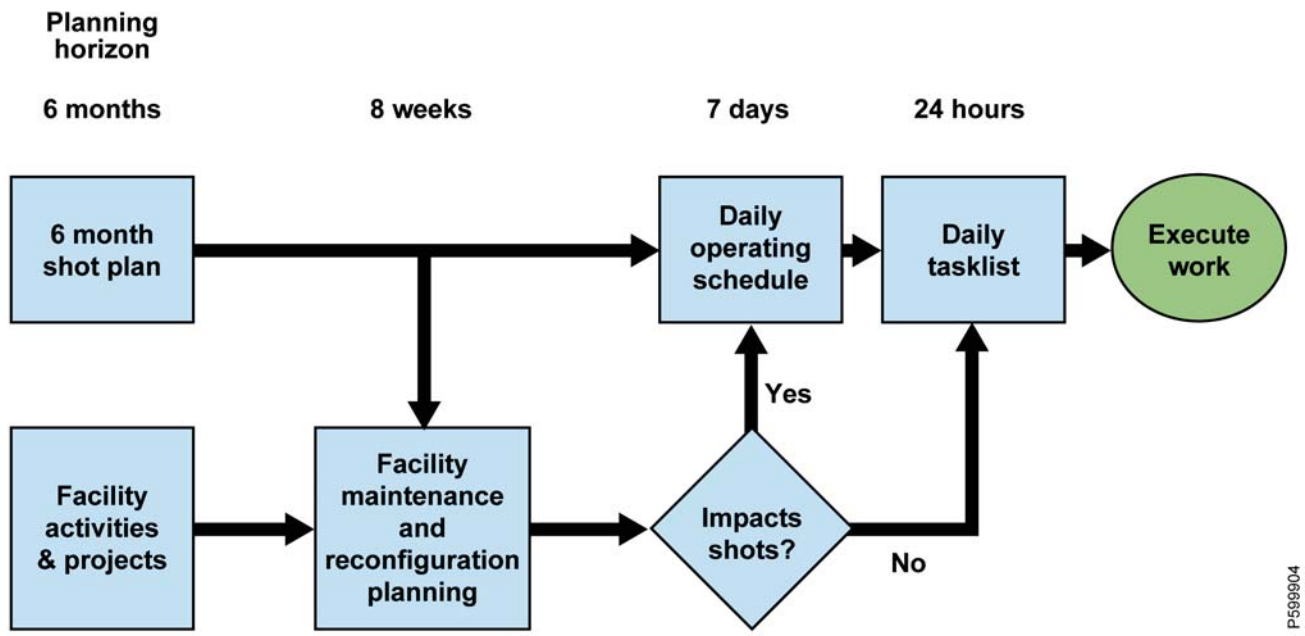

Fig. 7: The NIF maintenance planning process is integrated with the shot scheduling. This flow chart shows the planning horizons for facility maintenance and improvement activities. If done sufficiently in advance, maintenance can be effectively coordinated with shot operations.

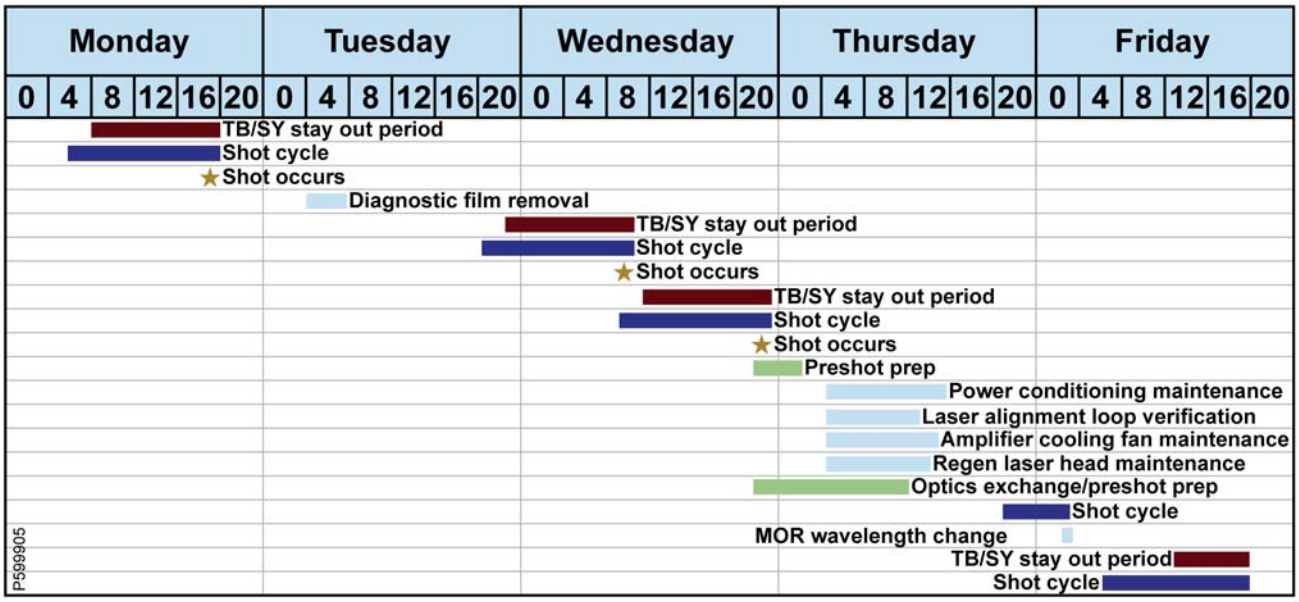

Fig. 8: Example of a Daily Operating Schedule. Red bars identify stay out times for a shot. Purple bars identify the shot cycle. Green bars identify pre-shot preparation activities, and blue bars identify maintenance activities.

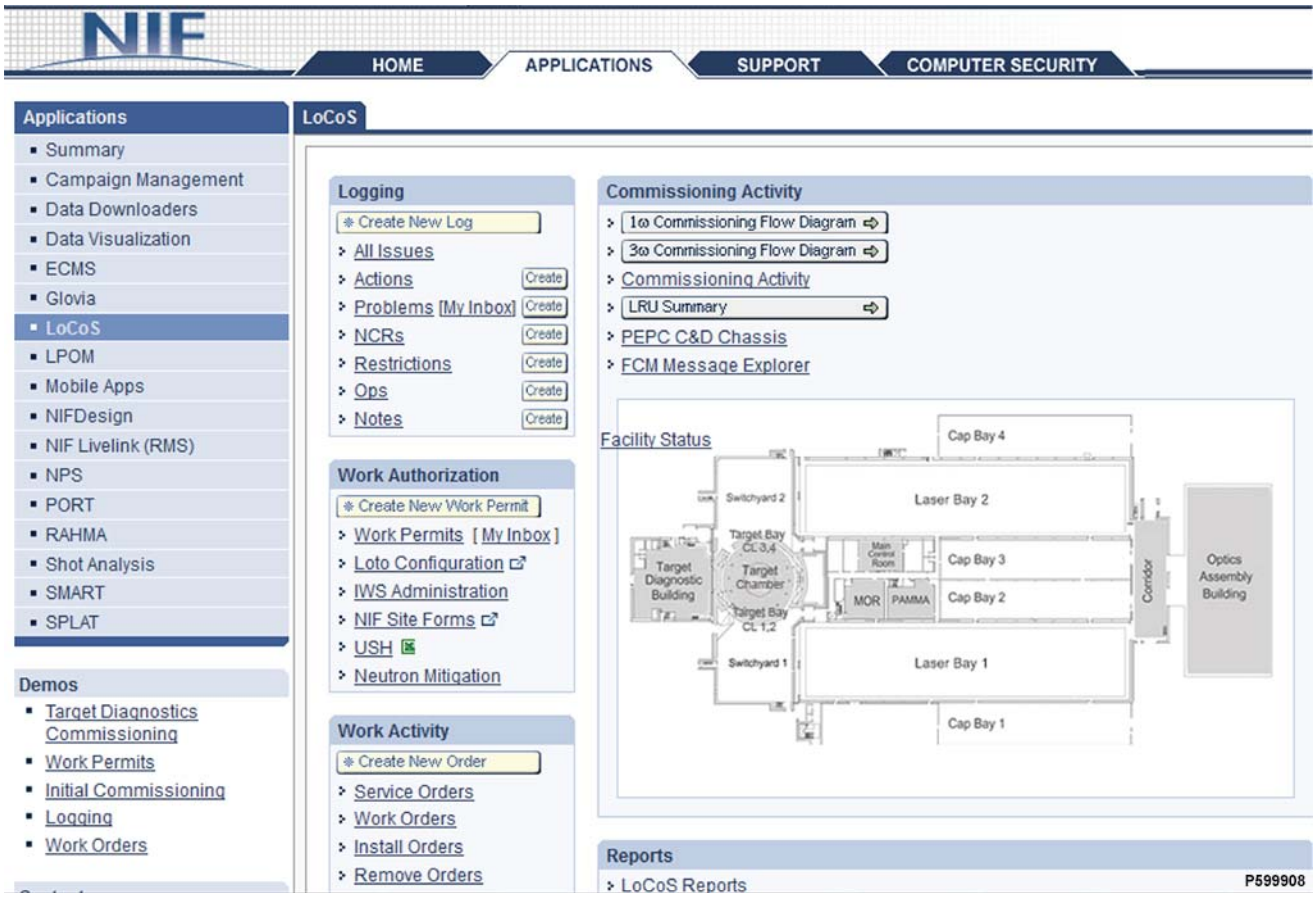

Fig. 9: Screen shot of the web-based Location and Component System (LoCoS). Key applications/tools supporting NIF operations can be selected on the left. The work permit module, discussed in Sections III.B, is found near the center of the screen shot, under “Work Authorization.”

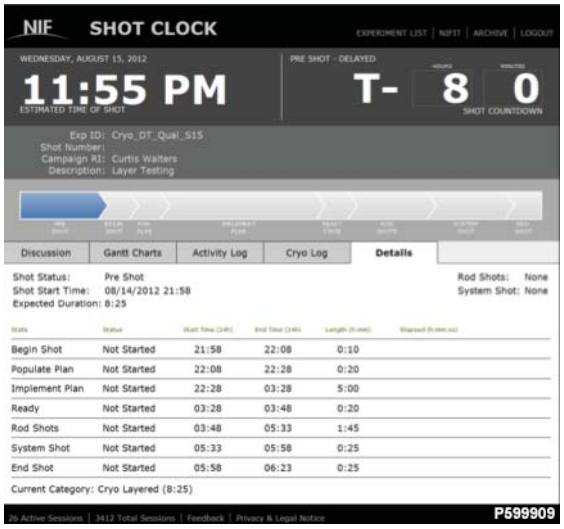

Fig. 10: The NIF Shot Clock screen shows progress in the shot cycle. See Figure 8 for details of the shot cycle.

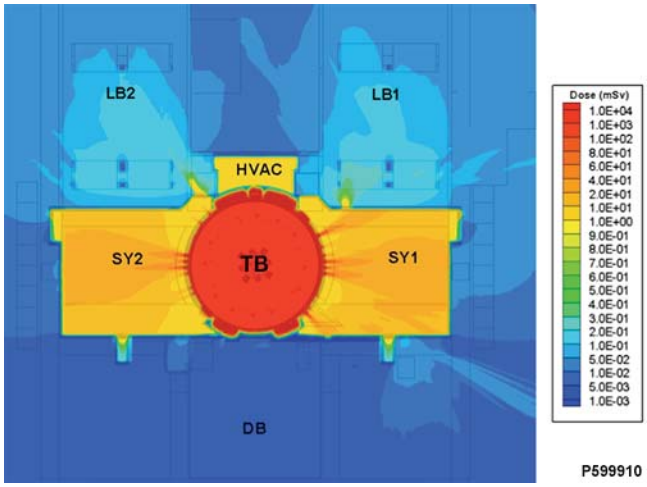

Fig. 11: Prompt radiation dose map showing estimated radiation levels within the facility at ground level during a 20 MJ shot.[10] The shielding around the facility mitigates the dose in occupied spaces both inside and outside the facility to levels < 50 μSv.

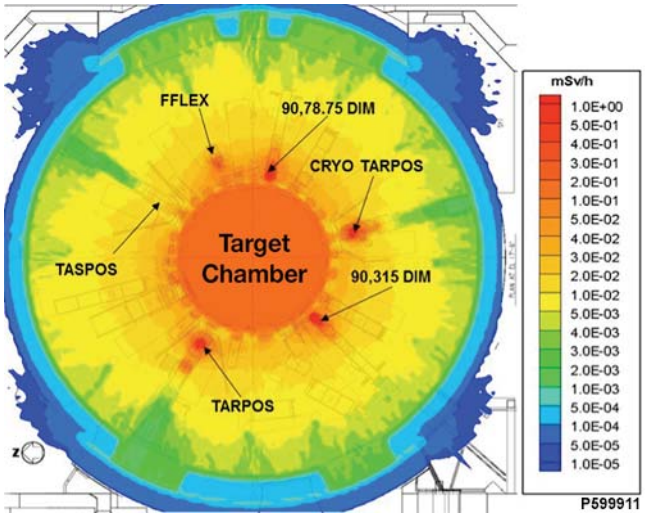

Fig. 12: Decay radiation dose map showing estimated radiation levels within the Target bay (TB, at the mid-plane) five days after a 20 MJ shot. [11] By this time, the dose rate in most spaces within the TB has fallen below 50 μSv/h.

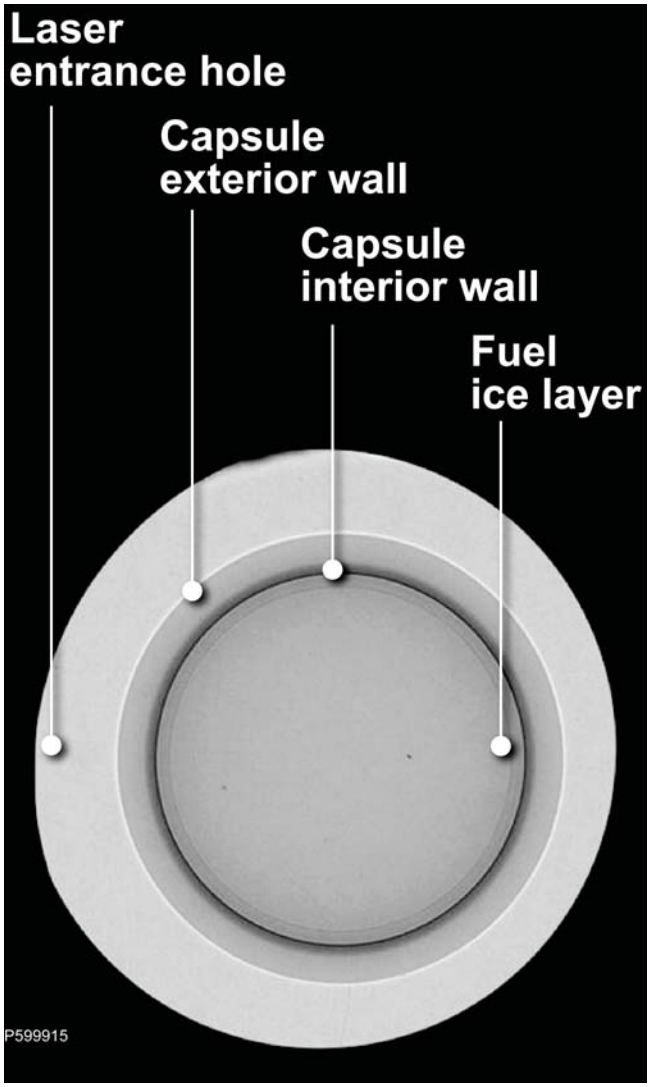

Fig. 13: Phase contrast x-ray image of a fully formed DT ice layer within the target capsule. This view is through the laser entrance hole. The thin, uniform ice layer can be distinguished from the capsule. The darkening along the radius of the capsule moving inwards shows the varying dopant composition in the plastic.

TABLE I: Summary of Key Hazards at the National Ignition Facility*

Hazard	Source	Typical Mitigation
Hazardous Energy Sources	• Electrical equipment • Large volumes at vacuum • Pressure systems • Mechanical equipment	• Lockout/tagout • Venting systems
Oxygen Deficiency	• Argon used in beamtubes • Nitrogen used for cryopumps	• Containment of gases (tanks, piping) • Oxygen deficiency monitoring system and alarms • Pressure relief devices
Fire	• Electrical equipment • Combustible material	• Fire detection and suppression system • Fire barriers
Shrapnel	• Off-normal electrical events (e.g., Power Conditioning System, PCS)	• PCS module design to vent overpressure and trap shrapnel • Reinforced Capacitor Bay walls
Shrapnel and Pressure hazard	• Vacuum-loaded optic failure	• Optics designed to crack not shatter • Optics inspection system to monitor crack growth • Rupture panels on beamtubes
Laser light	• Main laser • Alignment and diagnostic lasers	• Barriers: beam blocks, shutters, laser curtains, enclosures, walls and doors • Lockout/tagout • Permissive keys
Hazardous Materials (e.g., Be)	• Target materials • Diagnostic materials	• Confinement and contamination control systems (see next section) • Contamination control practices, work permits, training, PPE
Radiation	• Target materials • Prompt and decay radiation from shots • Activation and fission products resulting from shots	• See Section V.B

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*The paper focuses on the more unique hazards associated with operation of the National Ignition Facility. Typical industrial hazards, such as working at elevation, dropped tools, slips/trips/falls, mechanical equipment, noise, etc., also exist at the NIF, but they are not the focus of this paper.

TABLE II: List of possible Neutron Mitigation Actions for Systems in the NIF Target Bay

Remove sensitive components, incorporate quick disconnects for easy removal before shots
Administratively gate the alarm signal during a shot
Replace digital sensors with an analog type
Relocate to take advantage of the natural shielding of the building
Replace Liquid Crystal Display (LCD) panels with Light Emitting Diodes (LED) backlit panels
Replace solid state electrical ballast with a transformer type electrical ballast
Separate the battery and control circuit from the load
Use analog tube camera systems and some sacrificial higher resolution Charge Coupled Devices (CCD) cameras

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FOOTNOTES

[a] Total Recordable Case Rate is a measure of the recordable workplace injuries (more serious than First Aid), normalized per 100 workers per year, or per 200,000 worker-hrs.