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MAINTENANCE OF THE NATIONAL IGNITION FACILITY CONTROLS HARDWARE SYSTEM*

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Abstract

At the National Ignition Facility (NIF), achieving fusion ignition for the first time ever in a laboratory required one of the most complex hardware control systems in the world. With approximately 1,200 control racks, 66,000 control points, and 100,000 cables, maintaining the NIF control system requires an exquisite choreography around experimental operations while adhering to NIF's safety, security, quality, and efficiency requirements. To ensure systems operate at peak performance and remain available at all times to avoid costly delays, preventative maintenance activities are performed two days per week as the foundation of our effective maintenance strategy. Reactive maintenance addresses critical path issues that impact experimental operations through a rapid response 24x7 on-call support team. Prioritized work requests are reviewed and approved daily by the facility operations scheduling team. NIF is now in the second decade of operations, and the aging of many control systems is threatening to affect performance and availability, potentially impacting planned progress of the fusion ignition program. The team is embarking on a large-scale refurbishment of systems to mitigate this threat. Our robust maintenance program will ensure NIF can capitalize on ignition and push the facility to even greater achievements. This paper will describe the processes, procedures, and metrics used to plan, coordinate, and perform controls hardware maintenance at NIF.

INTRODUCTION

National Ignition Facility Background

The National Ignition Facility (NIF), currently the world's largest and most energetic laser system, was built by the United States Department of Energy (DOE) National Nuclear Security Administration (NNSA) inside the one square mile boundary of the Lawrence Livermore National Laboratory (LLNL) site in Livermore, California. The purpose of NIF was to execute high-energy-density (HED) laser experiments as a national and international user facility. These HED laser experiments would enable the study of physics for discovery science and inertial confinement fusion (ICF), while serving as a key experimental capability in the NNSA's establishment of a science-based stockpile stewardship program (SSP) in the absence of underground nuclear testing [1].

In 1997, construction started on the NIF building, which stands 10 stories tall and covers an area approximately the size of three football fields (Fig. 1). Construction involved the installation a target chamber weighing 130 metric tons and measuring 10 meters in diameter (Fig. 2), beampath for 192 laser beams, and the largest capacitor bank in the world capable of storing 300-400 megajoules of energy.

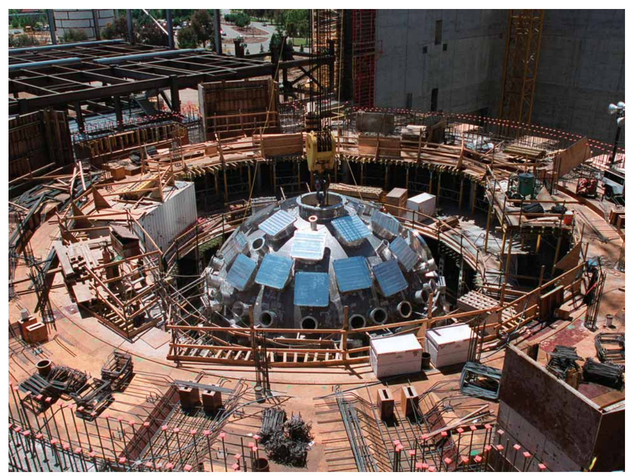

Figure 2: The 1999 installation of the NIF target chamber inside the half-constructed Target Bay. Credit: LLNL.

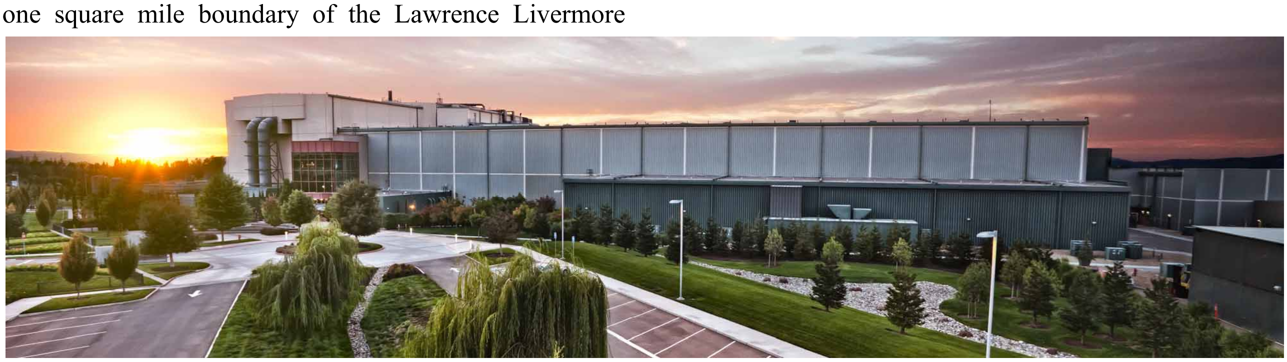

Figure 1: The National Ignition Facility at Lawrence Livermore National Laboratory in Livermore, California. Credit: Jason Laurea/LLNL.

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The first tests began in 2002 with 4 laser beams which generated 43 kilojoules of infrared light. In 2009, 12 years after the NIF groundbreaking ceremony, operations formally commenced with 192-beam experimental shots to Target Chamber Center. Gains in technology have allowed us to increase laser energy to 4.8 megajoules of infrared light and 2 megajoules of ultraviolet laser energy on target, which has an equivalent peak power of 500 terawatts. This laser energy contained within NIF's 192 laser beams can strike and spherically implode a 2 mm target with precision timing and alignment to produce conditions of extreme temperature, pressure, and density found only within stars, giant planets, and exploding nuclear weapons.

The unique nature of these HED experiments has allowed us to explore the science of ICF laser indirect drive and become the first in history to create fusion ignition within a laboratory environment on December 5, 2022. On this occasion, the laser delivered 2.05 megajoules to the target, shown in Fig. 3, and generated 3.15 megajoules of energy output. What remained of the target stalk after the December 5th experiment is shown in Fig. 4.

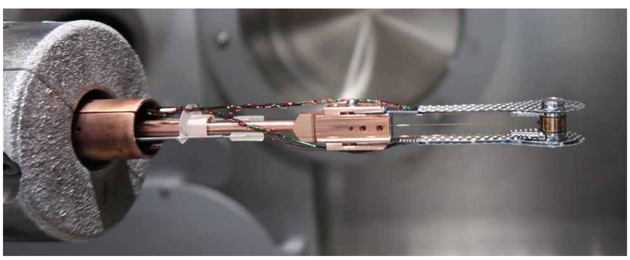

Figure 3: Quality control photo of the holhraum containing the cryogenically layered target capsule used in the historic December 5, 2022 fusion ignition experiment which achieved target gain. Credit: LLNL.

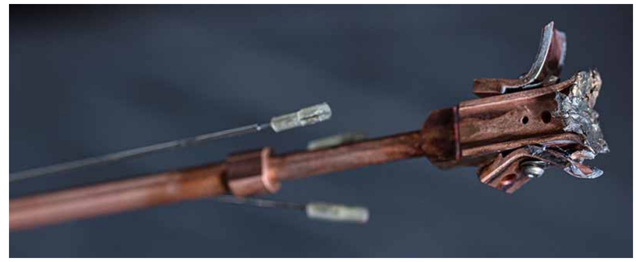

Figure 4: Target stalk remnants after the December 5, 2022 fusion ignition experiment. Credit: Jason Laurea/LLNL.

A CONTROLS HARDWARE SYSTEM FOR FUSION IGNITION

The fusion ignition NIF achieved on December 5, 2022 was repeated on July 30, 2023, delivering 2.04 megajoules of laser energy to the target and generating 3.88 megajoules of energy output. These ground-breaking milestones required one of the largest and most complex control systems of any experimental facility in the world. NIF's vast control system is comprised of 2,300 front end processors (FEPs), embedded controllers, and supervisory servers in over 1,200 controls racks throughout the Facility which support the largely autonomous operation of approximately 66,000 remotely controllable components such as mirrors, lenses, actuators, sensors, triggers, cameras, digitizers, diagnostic instruments, amplifiers, calorimeters, valves, motors, pressure regulators, and temperature controllers.

These control points are connected by thousands of kilometers of cabling, 300 kilometers of which are high voltage cables alone, and are distributed throughout the laser bays, switchyards, and the target bay. The controls perform a myriad of critical functions such as moving debris shields into place at the Final Optic Assemblies, shown in Fig. 5,

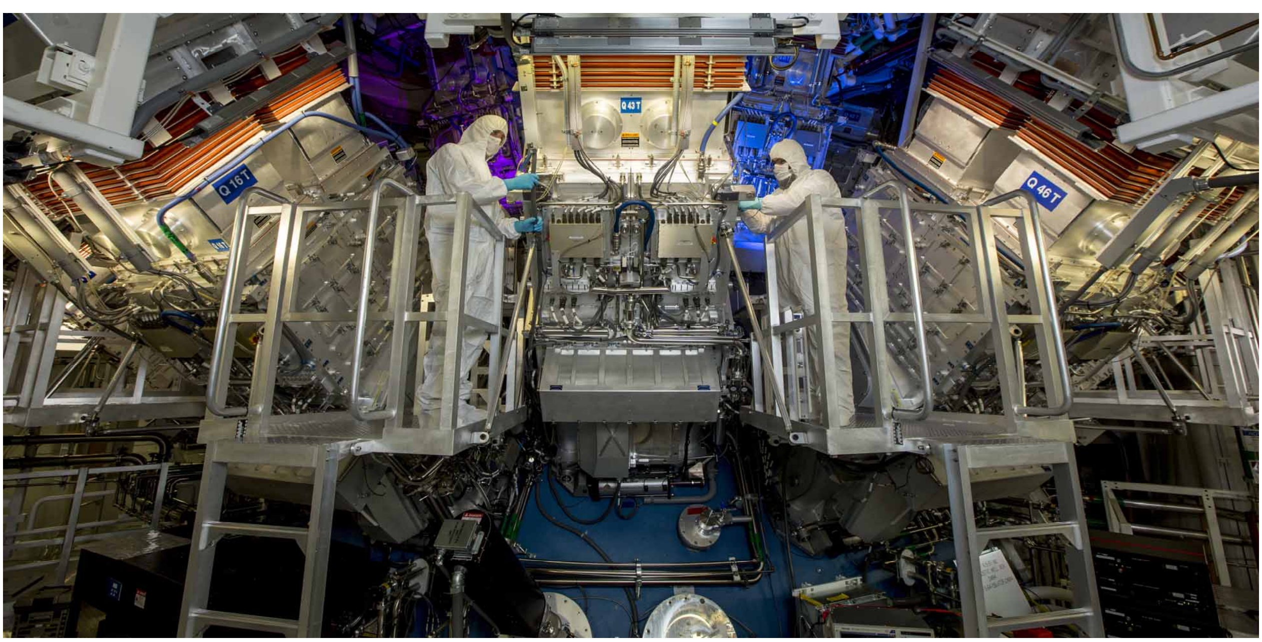

Figure 5: Final Optics Assemblies (FOAs) where control cables and junction boxes are mounted to the exterior of the beamline enclosures. Through these points, the control system moves automated disposable debris shields inside the beampath to protect the FOAs' internal optics against damage from experiments. The FOA optics convert 1w infrared light to shorter wavelength, 3w ultraviolet light which can more efficiently drive ICF targets. Credit: Jason Laurea/LLNL.

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Figure 6: The NIF Controls team gathered outside NIF in August 2023 after participating in an all-hands SuperClean day, a day set aside to restore efficient and organized workspaces throughout NIF. Credit: Mark Meamber/LLNL.

maintaining argon and stable pressures within the beampath, keeping the target chamber under vacuum, cryogenically freezing micron thick target layers, producing 30 billionth-of-a-second pulses with a specific shape, amplifying the laser beams 20,000 billion times, guiding all 192 laser beams to converge on target within 30 trillionths of a second and within 50 microns of beam alignment tolerance, then capturing images and measuring results on over 120 diagnostics, all within the boundary of an overarching Safety Interlock System (SIS).

With up to 400 shots conducted per year [2] and 2 million operations per shot, Controls hardware is continuously exercised and therefore must be meticulously maintained and continuously replaced/updated. Minor degradations in these systems, many of which are exercised to their performance limits, can have a significant impact on the laser due precision requirements. Over the last 14 years of exceptionally successful 24x7 operations, the NIF control system has and will continue to require comprehensive and robust processes, procedures, and a highly dedicated team to ensure the high reliability, availability, and maintainability of the laser system. The recent fusion ignition achievements were only made possible with the NIF Control team's focus on maintenance of the system to ensure the laser repeatably operates with the extreme precision and accuracy necessary to achieve these world-first results.

A TEAM TO MAINTAIN CONTROLS

The NIF Controls team, shown in Fig. 6, is part of a technical support group that works with NIF Operations and experimental groups to maintain NIF as a world-class, high-energy-density research facility. The NIF Controls team is comprised of software engineers, designers, electronic engineers, PLC developers, electronic technologists, and fabrication technologists. Of this group, approximately 24 electronic engineers, PLC developers, electronic technologists, and fabrication technologists are assigned to addresses controls hardware preventative and reactive maintenance within three main systems:

- Integrated Computer Control System (ICCS), an in-house developed software and hardware system.
- Industrial Control System (ICS), an Allen-Bradley PLC-based control system.
- Safety Interlock System (SIS), an Allen-Bradley PLC based control system.

MAINTENANCE WINDOWS

Scheduled Maintenance

With such a complex control system, setting aside regularly scheduled blocks of time for preventative maintenance is essential to ensure high system reliability and to sustain the pace of experiments. Preventative maintenance for controls hardware is ongoing and includes testing each of the 7 SIS PLC systems every 6 months. Periodically, we refresh legacy timing hardware, power supplies, VME single board computers, instrument-based controllers, and network switches. Recently, we replaced Uninterruptible Power Supplies (UPS) and their I/O interface cards (Fig. 7) for critical NIF systems: SIS, Hazardous Material Management, Tritium Processing, and Target Chamber Vacuum.

Figure 7: New UPS units and I/O cards in the Target Chamber Vacuum and SIS PLC racks/enclosures. Credit: LLNL.

We are also in the process of replacing digital video servers which boot Windows from internal hard disk drives with diskless servers which boot Linux off the network. Aging oscilloscopes with LCD displays are being replaced by streamlined digitizers without physical displays. Mechanical limit switches with soldered terminals within assemblies and nearing end-of-life, are being replaced by limit switches with quick connect terminals that will speed up future limit switch replacements.

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Every week, after 5 days of round-the-clock experimental operations, 2 days are set aside for the maintenance of all systems. The Controls team utilizes this time for proactive preventative maintenance, replacing failed hardware, and troubleshooting device control and signal feedback issues. In addition to the weekly maintenance days, a lengthier facility maintenance and reconfiguration period, approximately 1 to 3 weeks, is planned into the operations schedule 3 times per year, as shown in Table 1.

Table 1: Maintenance Windows

Frequency	Duration	Timeframe
Weekly	2 days	Friday, Saturday
Yearly	1-3 weeks	April
Yearly	1-3 weeks	August
Yearly	1-3 weeks	December

This provides approximately 6 weeks of downtime per year to perform tasks which have wide-reaching impacts throughout NIF, such as replacing SIS oxygen deficiency sensors. The longer maintenance periods also provide an opportunity to implement new laser and diagnostic capabilities to the continually evolving NIF that would otherwise be impossible to complete within the weekly 2-day maintenance windows.

Reactive Maintenance

Even with regularly scheduled preventative maintenance, reactive maintenance is inevitable. The Controls team is on-site Monday through Friday as part of their regular work week and are available to address controls related issues which need to be resolved for an imminent experiment. A subset of the Controls team, approximately 4 developers/engineers for SIS/ICS PLC systems and 4 electronic technologists for hardware controls system, are on-call and available to troubleshoot and resolve urgent issues impacting shot experiments outside of normal business hours, 7 days a week. In these situations, the Shot Director in the Control Room (Fig. 8) will notify on-call personnel, who will then call back to troubleshoot over the phone, if possible, or respond on-site within the hour.

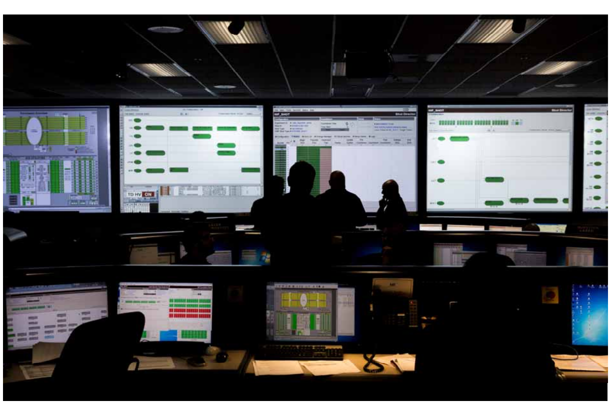

Figure 8: The NIF Control Room during shot operations. Credit: Damien Jemison/LLNL.

MAINTENANCE PLANNING

Work Control

The NIF is an extremely complex scientific instrument that has a full spectrum of hazards in addition to laser light, such as radiation, beryllium, and high voltage just to name a few. These hazards pose a danger to both the laser system, the personnel that operate the facility, and the environment. In the 14 years of NIF operations, no major incident has occurred, and this is entirely attributable to robust engineered controls and the exceptional Integrated Safety Management (ISM) processes and procedures established during the project execution and operation. These processes and procedures require a comprehensive work control program which implements, reinforces, and validates work coordination and authorization, as well as best work practices. This work control program, in turn, sustains the high standards the Integrated Safety Management system was founded upon, and has remained critical to the operational success of NIF since its inception.

Work Coordination

Work requests for both planned and reactive maintenance are submitted, reviewed, prioritized, and coordinated daily. Planned work requests, such as new installations and installation qualifications, are submitted through Atlassian Jira tickets. Reactive maintenance requests, such as troubleshooting or repairs, are submitted via Problem Logs by Control Room Operators and System Managers through an in-house developed application called Location, Component and State (LoCoS). Daily meetings are held with the Shot Director, Lead Operator, and Facility Work Integration team to review current experiments in the Daily Operations Support (DOS) schedule shown in Fig. 9, discuss priorities, and add any necessary maintenance tasks.

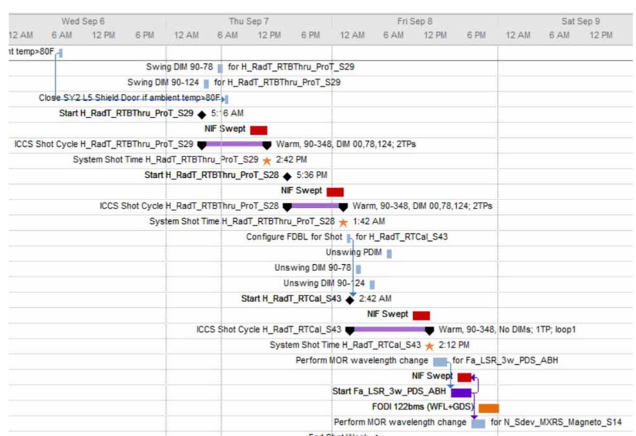

Figure 9: NIF's Daily Operations Support schedule showing preparations for upcoming experiments. Credit: LLNL.

To minimize disruption to experimental operations or disturbance to neighbouring systems, authorized work and the impacts of that work must be carefully planned and coordinated with other potentially impacted work teams in the NIF Operations Organization: Shot Operations, Laser

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Operations, Facility and Infrastructure Systems, Target Area Science and Engineering, Target Experimental Operations, and Data Systems.

Work Authorization

Before work can be performed in the Facility, it must go through the ISM work authorization process. The NIF Operations Manager is responsible for implementing the ISM as delegated by the NIF Director. Work Permits are the conduit for that authorization process. First, a Work Permit is created by the Team Lead or Work Permit Responsible Individual (WPRI) to define the scope of work (Fig. 10), identify controls for the associated hazards, specify the required retest, and list technically qualified Daily Work Team Leaders (DWTLs) to lead the work activity.

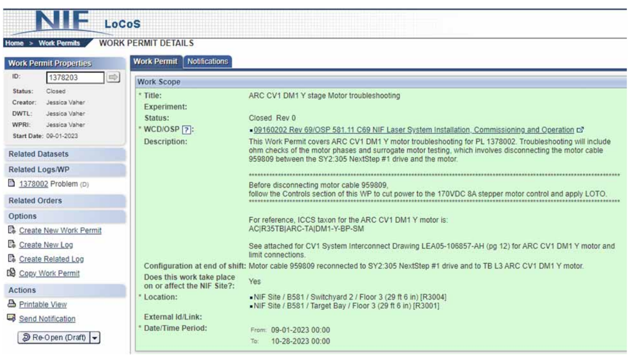

Figure 10: Snapshot from a released NIF Work Permit showing the authorized scope of work. Credit: LLNL.

The Work Permit is then reviewed and approved by the ISM line management chain, from top down: the delegated Authorizing Individual, the Responsible Individual, then the Work Permit Responsible Individual. If applicable, additional reviewers may need to approve, as well, such as the:

- Operation Safety Plan Responsible Individual for beampath access/entry.
- Functional Safety Expert if modifying a Configured Item which performs a specific critical function (or when applying standard/non-standard impairment controls).
- Impairment Control Adjudicator when applying any non-standard impairment controls (whether a Configured Item is being modified or not).
- Radiation Safety Officer if radiological or beryllium hazards are involved.

Only when the Work Permit is approved by these individuals can the Work Permit be released by the Work Permit Authorizer and used by qualified DWTLs for work in NIF.

Work Process

After a Work Permit is released, the authorized work is led by the DWTL following the Safety, Security, Quality, and Efficiency (SSQE) work practices that NIF and LLNL value and rigorously uphold. Each of these four areas are to be considered with equal weight for balance in the workplace and should be continuously assessed to ensure they do not become imbalanced from influencing pressures, as can happen in any long-lived, large operational organization.

To prepare for work, the DWTL creates a Safe Plan of Action (SPA). The SPA is prepared for every job in the facility and lists what tasks are involved, what the hazards are, and what the mitigations for those hazards will be. The tasks involved must stay within the associated Work Permit's defined scope of work and all controls listed in the Controls section of the Work Permit must be followed. The DWTL then reviews the SPA with the work team, adds any feedback from the team members or observations from the job site that could affect the work, and obtains final approval from the Shot Director or Lead Operator to verify the shot schedule (Fig. 11) will not be impacted by any of the planned work.

Figure 11: The status board, which is available to view on the NIF open network, shows the progress of experiments as the week progresses. Credit: LLNL.

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Management periodically observes ongoing work in the Facility. These observations help reinforce expectations and generate constructive feedback, while serving as a method to recognize individuals demonstrating exemplary SSQE practices (Fig. 12). Information gathered from the observations is used to identify process improvements or generate new methods from the lessons learned.

Figure 12: Safety, Security, Quality, and Efficiency are key elements that have become NIF's motto. Credit: LLNL.

As part of SSQE process, any individual can pause or stop work at any time if a situation is deemed potentially unsafe. A "pause work" can be called to clarify questions regarding work scope, procedures, or controls. Work is not to proceed if safety is a concern, regardless of any real or perceived schedule pressure. A "stop work" can be called if an individual believes the safety of personnel, property, or the environment is at risk. Management supports these decisions, which empowers workers to adhere to NIF's high safety standards.

FACILITATING MAINTENANCE

Documentation

With sound work practices in place, mechanical and electrical drawings, engineering design data, and procedures are available to facilitate maintenance. These documents are vital to support NIF long term. NIF uses an institutional configuration control system called Enterprise Lifecycle Management (ELM) to store and manage document revisions. The ELM Change Management process tracks the review and approval of documents, including those that manage Configured Systems and the Configured Items (Fig. 13) within those systems. Configured Items are elements that perform a specific safety function.

Figure 13: Controls team performing the Target Positioner SIS Periodic Test Procedure, which is a Configured Item and performed every 6 months for worker safety. Credit: Tom Kohut/LLNL.

The Controls team also utilizes an in-house developed, quick-lookup tool called the Controls Information Retrieval System (CIRS), shown in Fig. 14 below. This tool cross references processor names, rack locations, control system interconnect diagrams, schematic drawings, and rack layouts to facilitate troubleshooting.

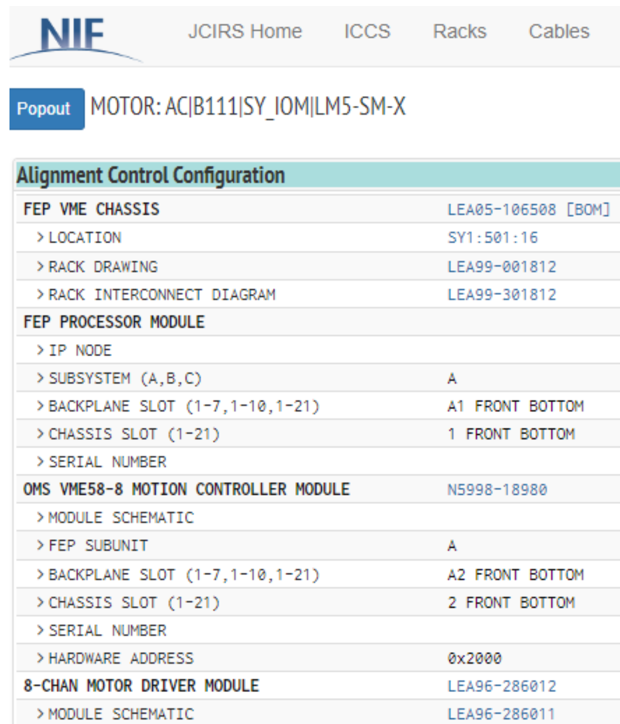

Figure 14: Snapshot from CIRS showing a motor identifier, AC|B111|SY_IOM|LM5-SM-X, along with associated chassis/slot locations, drawing numbers, and configuration data. Credit: LLNL.

Spares Inventory

To reduce downtime when controls hardware fails, the Controls team stocks a local inventory of spare parts, electronic components, and cabling in the NIF Controls Maintenance and Engineering (CME) Facility, which is in a building adjacent to NIF. In addition, surplus spares are stored in a nearby, on-site warehouse. Part numbers and their locations are tracked and managed utilizing Glovia, an enterprise resource planning system. These part numbers can also be used in ELM-U to look up the associated data sheet and the assembly build or system where the part is used.

The spares inventory kept on-hand covers most of the control hardware installed in NIF, both custom and commercial off-the-shelf assemblies. Spares inventory includes binary and motion controllers, motor driver boards, single board computers, laser diode drivers, power supply assemblies, signal converters and generators, VME crates, oscilloscopes, electronic interface boards, time servers, beacons, and convectron gauge controllers, just to name a few.

Failed units removed from NIF are either disposed of, repaired onsite, or returned to an offsite vendor for repair. When a new purchase or repaired unit is delivered to the

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Controls team, an electronic technologist will run the hardware through an acceptance test at one of the many test stations that simulate main subsystems in the CME Facility (Fig. 15). If the hardware passes, it is green-tagged and added to spares inventory.

Figure 15: Motor driver and motion control board tests at an Alignment Control test station. Credit: LLNL.

ENSURING MAINTAINABILITY

NIF Sustainment Plan

Up to this point, NIF has been successfully operating for over 14 years now without any major downtime. However, no operations plan would succeed long term without looking to the future to anticipate upcoming needs. Many systems original to NIF construction over 20 years ago are beginning to age. The facility is due for a mid-life major refurbishment to extend the operating lifetime through the 2030s. With the support of DOE and NNSA, NIF has embarked on a 5-year sustainment program which spans 30 large scale projects to refurbish critical systems which pose the highest risk of impacting the rate of ongoing operations within the next 5 years (Fig. 16).

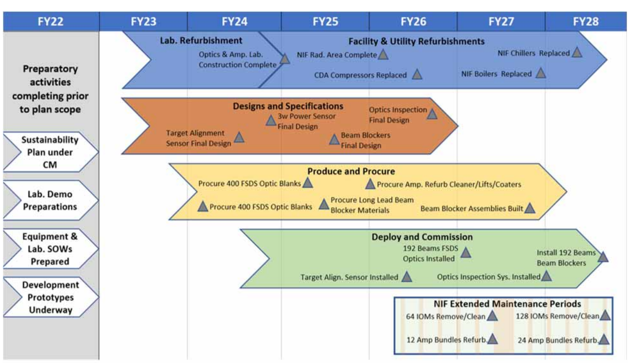

Figure 16: NNSA 5-year NIF Sustainability Plan summary from the June 2023 Congressional Committee Briefing.

The Controls team is a significant part of NIF's 5-year sustainment program to replace or recapitalize priority systems that are degrading, some of which have increased failure rates due to operating in the higher laser energy and neutron yield conditions that NIF is now routinely capable of. This sustainment plan is in addition to the Control team's current efforts to purchase and replace continuously aging hardware, which involves:

- Buying as much new old stock hardware as possible which, in turn, provides additional time to select alternative solutions.
- Working with vendors to develop fit/form/function replacements for legacy hardware.
- Re-designing hardware in-house.

Upcoming plans to combat obsolescence include replacing discontinued encoder electronics with a re-designed encoder interface board and a modern encoder board. FactoryTalk ViewSE GUI software will soon replace legacy servers that hold operationally critical software for ICS, SIS, and the Access Control System. Updated PLC controls will replace the DOS booting system that moves the access lift (Fig 17) used for inspection and maintenance of the Target Chamber interior.

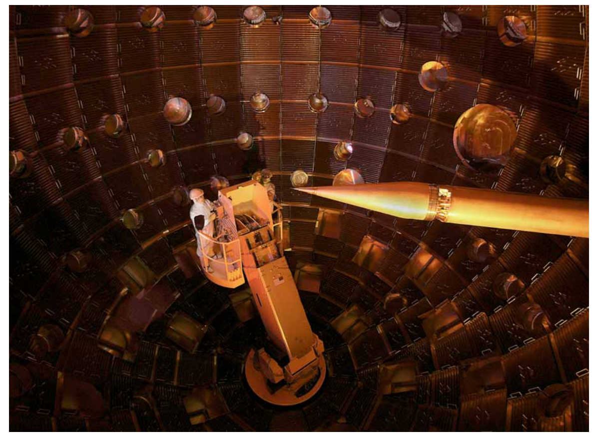

Figure 17: Technicians in the Target Chamber access lift. Target positioner is on the right. Credit: LLNL.

CONCLUSION

Maintaining the multifaceted control system in NIF, a world-class facility producing world-firsts, is a challenging responsibility, but the rewards have been beyond measure. The level of system complexity matches the level of rigor with which the maintenance program must be implemented, while adhering to the high safety standards NIF values for work processes and procedures. Our goal is to keep equipment, personnel, and the environment safe, as we continue to lead groundbreaking scientific discoveries and contribute to national and global security. Our comprehensive maintenance program has served NIF well and will continue to do so as we embark on the NNSA 5-Year NIF Sustainability Plan to continue progress.

ACKNOWLEDGEMENTS

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