# NATIONAL IGNITION FACILITY PROJECT COMPLETION AND CONTROL SYSTEM STATUS

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*Abstract*

The National Ignition Facility (NIF) is the world's largest and most energetic laser experimental system providing a scientific center to study inertial confinement fusion (ICF) and matter at extreme energy densities and pressures. Completed in 2009, NIF is a stadium-sized facility containing a 1.8-MJ, 500-TW 192-beam ultraviolet laser and target chamber. A cryogenic tritium target system and suite of optical, X-ray and nuclear diagnostics will support experiments in a strategy to achieve fusion ignition starting in 2010. Automatic control of NIF is performed by the large-scale Integrated Computer Control System (ICCS), which is implemented by 2 MSLOC of Java and Ada running on 1300 front-end processors and servers. The ICCS framework uses CORBA distribution for interoperation between heterogeneous languages and computers. Laser setup is guided by a physics model and shots are coordinated by data-driven distributed workflow engines. The NIF information system includes operational tools and a peta-scale repository for provisioning experimental results. This paper discusses results achieved and the effort now underway to conduct full-scale operations and prepare for ignition.

## NIF BACKGROUND

Completed on schedule in March 2009, and within its budgeted cost of $3.54B, the National Ignition Facility (NIF) is the world's largest laser system, housed in a ten-story building with the footprint of three football fields at the Lawrence Livermore National Laboratory (LLNL). Experiments using NIF's 192 laser beams will make significant contributions to national and global security, could lead to practical fusion energy, and will drive many advances in basic science and technology. The initial goal is to achieve fusion ignition, a thermonuclear event where more energy is created than consumed during the few billionths of a second of inertial confinement. For these ignition experiments, NIF will focus up to 1.8 million Joules of ultraviolet laser energy on a mm-sized target centered in the ten-meter-diameter target chamber, creating conditions similar to the core of a star.

## NIF OPERATIONS

After 12 years of construction, NIF was declared operational by the DOE with its dedication in May 2009. All 192 beams have been commissioned, and target shots using up to 20ns pulses of laser energy are being conducted to tune various laser operating parameters, commission new diagnostic systems, and carefully increase the total energy delivered to the target. Currently, a detailed set of experiments are being performed as part of the National Ignition Campaign (NIC)—an overall strategy for making a credible attempt for achieving ignition in 2010. Many novel results were presented in September 2009 at the IFSA (International Fusion Sciences and Applications) Conference in San Francisco [1, 2].

Between August 16 and September 5, 2009, NIC scientists completed eleven 192-beam experimental shots, each with about 500 kJ of ultraviolet energy. The last four shots were fired into cryogenically-cooled target capsules (~20 degrees-K) providing data on nearly 200 diagnostic channels. The data demonstrated excellent scientific results—high compression of the target capsule and high temperatures in the hohlraum (the gold can that holds the capsule). The target implosions were very symmetrical, so the final two capsules were filled with 10% deuterium to produce fusion neutrons in an implosion experiment. Those final two shots generated the first neutrons on NIF and showed excellent repeatability [1]. Neutron yield from deuterium fusion (designed to be purposely low) was successfully diagnosed by three different types of detectors. All of these results were in line with predictions, showing that many of the elements for ignition are nearly in place.

## SOFTWARE CONTROL OF NIF

Laser alignment, shot timing and data management during experiments in a facility the size of NIF can only be done with an automated and scalable control system. The facility's Integrated Computer Control System (ICCS) makes this possible. With about two million lines of code (2 MSLOC) running on more than 1,300 front-end processors, embedded controllers and supervisory servers, ICCS operates laser hardware containing 60,000 control and diagnostic points to ensure that all of NIF's laser beams arrive at the target within a few tens of picoseconds of each other and that a host of diagnostic instruments record data in a few billionths of a second. Twenty-four hours a day, ICCS supervises shot setup and countdown; oversees machine interlocks to protect hardware, data, and personnel; provides operators with graphical interfaces for control and status; performs automatic beam alignment; controls power conditioning and electro-optic subsystems; operates target diagnostics for recording X-ray, optical and nuclear phenomena; and monitors the health of all subsystems and components [3].

### Project Management

Early adoption of software project management and engineering methodologies, such as an incremental development lifecycle, an architecture that reduced complexity, and code frameworks to realize recurring design patterns, led to early success [4]. From the project outset in 1996, ICCS reliability has been enhanced under the guidance of a software quality assurance plan (SQAP). Using a graded approach, the SQAP maintains quality over the long planned lifecycle by emphasizing the importance of requirements management, change control, source code configuration, unit testing, offline product integration and independent verification testing.

### Current Software Status

During the past year, in preparation for project completion, the control system was expanded to include automation of target area systems including final optics, target positioners and diagnostics. Additional capabilities to support fusion ignition shots in the NIC are being developed and commissioned. These include a cryogenic target system, over 20 target diagnostics systems, a tritium processing and monitoring system, personnel and environmental protection systems and integrated experimental shot data analysis with tools for data visualization and archiving.

### Architecture

ICCS uses an innovative architecture that allows each of the 24 bundles of eight laser beams to be aligned and prepared for a shot independently. With this modular approach, scientists can design experiments so individual bundles have different energy and waveform characteristics. ICCS fires the laser and conducts these experiments automatically by directing the actions of hundreds of computers controlling NIF through a complex script using an automated shot control framework [5] that calculates the required configuration of the laser beams, aligns them on target [6], fires the laser and collects the data. NIF is thus an unusually flexible user facility that will provide scientists with the wide experimental regime they need in the decades ahead.

The automated control subsystems are built from a common object-oriented software framework based on CORBA distribution that deploys the software across the computer network and achieves interoperation between different languages and target architectures. An experimental database, or shot repository [7], and an automated shot analysis infrastructure [8] have also been developed and is being used for conducting experiments.

### Software Reliability

Reliability of the control system software is essential to NIF's operation. Rigorous software engineering practices helped deliver the NIF project on time while assuring high reliability. A distributed architecture was chosen to reduce complexity and risk, which had the added benefits of lower cost, consistent performance and improved maintainability. Quality assurance initiated early in the project emphasized configuration management (CM), offline integration testing, and independent verification to successfully meet customer expectations. A dedicated CM team maintains the configuration and installs all releases, thereby assuring integrity of the code while coordinating simultaneous releases across multiple target environments for development, offline quality control testing, or online deployment.

At the end of each coding cycle, and after unit testing is complete, software components are integrated and undergo two more levels of offline testing. In integrated test facility, many control points are modeled by software emulators to allow testing at a large scale that closely mimics actual device behavior. A second, more formal offline test is designed and conducted by the Test Team, whose personnel are independent of development. The formal test verifies functional, interface and performance requirements. Both normal and off-normal test cases are conducted. After completing offline tests, the software is scheduled for online deployment. Operations personnel who are qualified to run laser shots conduct the online test with Test Team support. Throughout the project, about 30% of the total software effort was assigned to perform independent quality control and assurance activities.

Metrics gathered during the software lifecycle continue to help assess quality and guide improvements. With over 31,000 change requests processed to-date, software quality assurance at NIF is very effective, consistently finding major defects and better than 90% of all software defects before deployment.

### Data Stewardship

All data from NIF shot campaigns, laser and target alignment, diagnostics (raw and processed), operations, inventory, calibration, and optics inspections are maintained in a federated database described in detail in [7]. Unlike real-time experimental systems where the data streams are continuously acquired, NIF data arrives in discrete bursts at, for example, shot time or following an automated inspection of critical optics. The overall throughput is manageable—on the order of 10 tera-bytes a month—but the number of different types of data (tables in the schema) is large and complex (>6 million parts).

Data integrity and validation is paramount to the scientific users of NIF results. For this reason, each data set (image, waveform or scalar) is uniquely defined by shot number, part number or serial number, data taxonomy or position in the chain, etc. Change management requires custom work processes and procedures during installation, calibration, and operational qualification. The lineage of the data (or pedigree) as it passes through analysis to final result is maintained.

Automated messaging through message queues is used to notify experiment analysis and visualization systems of experiment completion events and availability of raw and processed experiment results. The information system messaging architecture provides for construction and automated delivery of messages between different NIF information systems. The messaging architecture is based upon Oracle Advanced Queuing and messages are defined as XML documents. This architecture provides guaranteed message delivery, priority, retries, message history, scheduling, tracking and event journals, and internet integration.

## SUMMARY

The National Ignition Facility is a unique experimental physics tool that is now operational and is performing experiments. It has entered the NIC phase of operations during which the first ignition tuning shots are being fired, and additional capabilities are being incorporated for target diagnostics, experiment analyses, tritium fuel and cryogenic layered targets. The distributed control system continues to be updated, using rigorous software engineering practices, to provide reliable access to these new capabilities. Quality assurance will continue to play a critical role as NIF performs its scientific research mission and is enhanced with new capabilities over its planned 30-year lifetime. As NIF transitions to a user facility, it will be available as a shared international resource to researchers from around the world. These users will obtain scientific understanding and achieve breakthroughs in a wide variety of scientific disciplines, including astrophysics, materials science, optics and laser physics, medicine, radioactive and hazardous waste treatment, particle physics and X-ray and neutron science. Current experiments are directed toward laboratory demonstration of inertial-confinement fusion ignition beginning in 2010. Fusion ignition may lead the way to a safe and virtually unlimited, carbon-free energy source.

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Figure 1: The National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL) in Livermore California is the world’s first megaJoule laser facility now conducting experiments for the National Ignition Campaign.