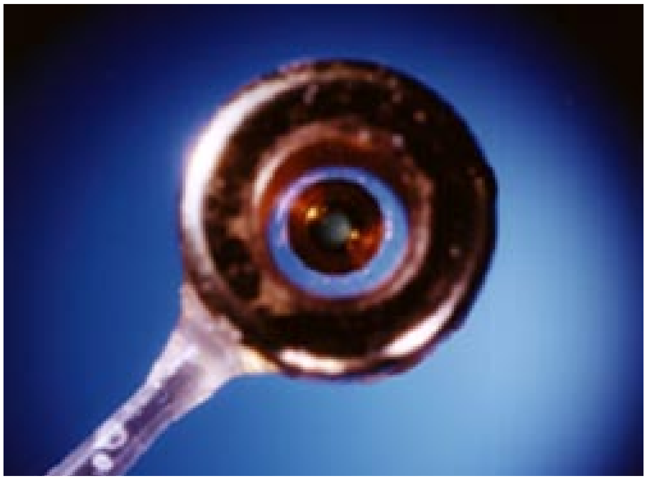
NIF and National Security



Although producing total energies that are minuscule compared to those in a nuclear device, the National Ignition Facility will produce energy densities high enough to duplicate many of the physics phenomena that occur in nuclear weapons and will thus help the U.S. to maintain its enduring stockpile of nuclear weapons.

THE other articles in this issue describe the intended features and capabilities of the National Ignition Facility and the diverse kinds of research that it will support, such as attempts to achieve break-even energy output through inertial confinement fusion (ICF). These other applications are important benefits that derive from the availability of NIF, but here we describe the value of the facility through its key contribution to experimental research in the physics of nuclear weapons. With the moratorium on nuclear testing and the likelihood of a Comprehensive Test-Ban Treaty making such testing permanently unavailable, NIF becomes one of a few means of maintaining and advancing our understanding of the weapons now in the stockpile.

Stockpile Stewardship

Since the Cold War ended with the dissolution of the Soviet Union, the U.S. nuclear weapons program has changed dramatically. The U.S. brought a unilateral halt to the development and production of new nuclear weapon systems. Also, a moratorium on underground nuclear testing was implemented to further negotiations on a Comprehensive Test-Ban Treaty and to encourage the broadest possible participation in the Nuclear Non-Proliferation Treaty.

A major change in the nuclear weapons program has accordingly been a move from nuclear test-based weapon reliability and safety to reliance on a thorough scientific understanding and better predictive models of performance–that is, science-based Stockpile Stewardship. The Stockpile Stewardship Program is based on several assumptions and observations:

- Nuclear weapons cannot be uninvented and will not go away, even if the U.S. were to dismantle its entire nuclear stockpile.
- U.S. defense policy will continue to rely on nuclear deterrence for the foreseeable future. Therefore, maintaining confidence in the stockpile—in its safety, security, and reliability—is essential.
- The moratorium on nuclear testing will likely be followed by a Comprehensive Test-Ban Treaty, which the U.S. must adhere to while retaining confidence in its nuclear arsenal.

- No new weapons are being developed, and currently there is no known need for future weapon development programs; moreover, some essential facilities of the U.S. nuclear weapons production complex no longer exist.
- The U.S. nuclear stockpile will contain fewer weapons, of fewer types, as well as weapons that will become considerably older than their design lifetimes; this stockpile will require enhanced surveillance and maintenance to recognize, evaluate, and correct problems that may arise.
- There may be a growing need to evaluate potential threats from unfriendly foreign powers and terrorist groups.

We must continue to provide the training and required information for a group of scientists and engineers that will be the stewards for this stockpile under these conditions. The remaining tools at their disposal will have to be used to fill the gaps left by the cessation of nuclear testing. (See Figure 1.)

Complexity of Nuclear Weapons

Maintaining confidence in the stockpile under the conditions described above is a challenge because of the complexity of nuclear weapons design and of the phenomena that take place when nuclear weapons are operated—chemical explosion, hydrodynamic implosion, mixing of materials, radiation transport, thermonuclear ignition and burn, etc.

Nuclear testing provided a pragmatic solution—integrated tests of the devices—that is no longer available. With the moratorium on nuclear testing, we must rely on advanced computational modeling and non-nuclear experimental techniques for predictions and data.

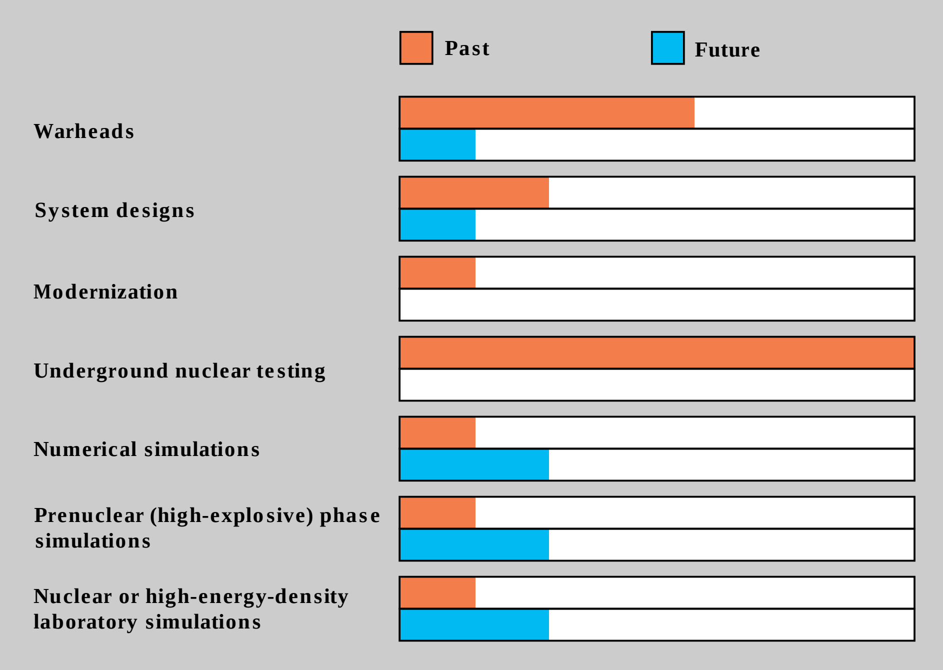


Figure 1. Graphic comparison of the situation of the nuclear-weapons stockpile before and after the enormous changes of recent years. The challenge is to maintain confidence in a much smaller stockpile without nuclear testing and modernization.

We do not completely understand the physical processes involved in the operation of a nuclear weapon. Indeed, a complete, detailed, and mathematically exact description of the physics would exceed the capabilities of today's supercomputers. We must therefore make approximations to the physics in our evaluations of performance, although these approximations introduce uncertainties in our predictions. We must rely on our cumulative knowledge, including past test data, to make valid inferences for physics regimes that are inaccessible with current experimental methods.

This expertise is also the only way we now have for the evaluation of many crucial issues, including:

- The severity of age-related material changes discovered through routine stockpile surveillance.
- The severity of unexpected effects discovered with improved computer models.
- Whether retrofits, such as to improve safety or reliability, will function properly.
- Whether new technologies can or should be incorporated in a stockpiled weapon system.

In a nuclear weapon, the phenomena occur in two very different regimes of energy density. In the early phase of the implosion, before the development of significant nuclear yield, temperatures are relatively low. This is the low-energy-density regime; here there is considerable complexity because the strength of the materials and the chemistry of their composition play a role in how events proceed. Full-scale assemblies using mock nuclear material are used to test experimentally the hydrodynamics of the implosion process at the beginning of a weapon's operation. The study of this subcritical regime is carried out at hydrodynamic test facilities using powerful x-ray machines, high-speed optics, and other methods. Current hydrodynamic test facilities can access the precritical physics regime, although, without complimentary nuclear tests, these facilities must be improved to provide much more spatial and temporal information.

After significant nuclear yield begins in a real device and fissile material is heated, we enter the high-energy-density regime. Although no laboratory experiment can duplicate the amount of energy released by a nuclear weapon, many of the physical conditions relevant to such a weapon can be created in the laboratory.

Improving our predictive capabilities for evaluating these processes will be difficult. Without nuclear tests, we can never directly observe the full operation of this high-energy-density regime. We must therefore improve our understanding of the relevant physics with better computations and new experiments, techniques, and facilities. The National Ignition Facility will allow us—on a microscopic scale—to attain the high-energy-density conditions that exist in weapons.

NIF and Weapons Physics

As a versatile high-energy-density physics machine, the NIF will enable us to gain an improved understanding of the underlying physics and phenomena of nuclear weapons, to acquire and benchmark new data to existing databases, and to test and validate the physics computer codes for ensuring future reliability and performance. The NIF will provide valuable data for predicting the performance of nuclear assemblies and for testing the complex numerical codes used in weapons test calculations.

Creating thermonuclear burn in the laboratory will not only help us to integrate and test all of our physics knowledge but will also help the Department of Energy maintain expertise in weapons design. We envisage training designers both on specific stockpile stewardship issues and on broader NIF ignition questions relevant to inertial confinement fusion.

Weapons research on NIF is driven by a need to acquire a much more detailed understanding of physics processes at high energy densities, as well as by a desire to achieve ignition. We have been studying these processes on Nova and other lasers, but, again, NIF allows us to move our studies into those energy densities that occur in a nuclear weapon.

The maximum total energies available on NIF will be an extremely tiny fraction of the yield of the smallest nuclear weapon (see the box on p. 26); but there are significant benefits to generating so much less energy. The main event of a nuclear test is both extremely brief and extremely violent; it destroys most or all of the diagnostic and measuring instruments. It remains for the researchers afterwards to try to sort out all the physics and phenomena submerged in the event in order to analyze it. By contrast, on the NIF, we can design and perform experiments that isolate whatever physics phenomenon is of interest. We can study the physics at relevant energy densities without having to deal with large total energies. We can thus build an incremental, exact description of the cumulative physics that would make up a nuclear event.

In the high energy densities at which thermonuclear reactions occur, several distinctive phenomena predominate: very high material compressions; unstable, turbulent hydrodynamic motion; highly ionized atoms with high atomic numbers (high-Z atoms); and radiation important in energy transport. These phenomena occur in such astrophysical realms as stellar interiors, accretion disks, and supernovae (and occurred in the Big Bang), but on Earth they occur only in machines such as NIF (and formerly in testing environments created in the areas surrounding nuclear tests).

The weapon physics research program at the NIF will stress investigations of these phenomena, including:

- Material equation-of-state properties.
- Unstable hydrodynamics.
- Radiation flow, including the opacity of ionized elements and x-ray production.
- Nonequilibrium plasma physics, including short-wavelength lasing.
- Thermonuclear burn in the laboratory.

The NIF will have the capacity for doing systematic, well-characterized experiments because of the flexibility of its multiple beam configuration. Considerable experience in doing such experiments very successfully on Nova and other lasers will carry over to the NIF. Laser experiments on the NIF, like those on Nova, can be directly or indirectly driven. In direct drive, multiple beams are directed at the target. In indirect drive, a set of laser beams is directed into a hohlraum, which is a tiny, hollow cylinder (see Figure 2) made of a high-Z material such as gold. The beams enter through the open ends and strike the inner walls, where they are absorbed and generate x rays that heat the interior of the hohlraum. The target is then bathed in this relatively uniform radiation field that heats it to the desired temperature.

In either direct- or indirect-drive experiments, a second set of laser beams prepares a backlighter that produces x rays that probe the target

NIF: High Energy Density at Low Total Energy

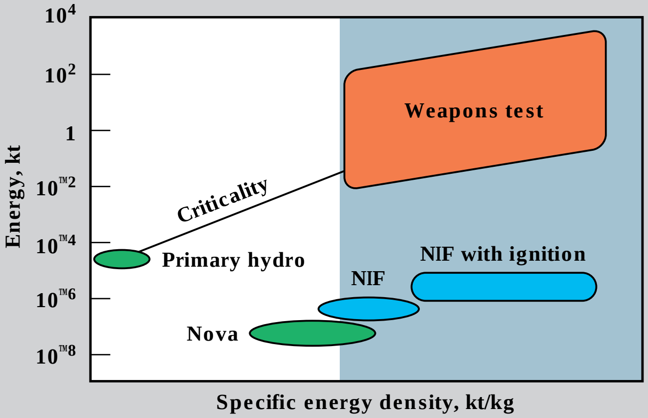
The NIF will provide the high energy densities that are needed for thermonuclear reactions to occur. High energy density, however, should not be confused with high total energy. The two measures are independent: there can be high total energy with low energy density, and high energy density with low total energy. Energy density is the amount of energy per particle, or per unit of volume.

The NIF will operate at low total energies. High energy densities can be produced on a small scale, and in the case of the NIF, the scale is about a millimeter. This fact is vividly evident in Figure 2, which shows a Nova hohlraum compared to a human hair; the large hohlraum used on NIF will be no larger than a dime. A DT-filled capsule of the sort used for ignition studies on the NIF is very small—some 2 to 5 mm in diameter, a tiny fraction the size of a thermonuclear secondary. Thus, although the energy density—the energy per particle—in such a capsule is comparable to that in a thermonuclear secondary, the total energy is minuscule. Ignition on the NIF will have roughly the same explosive force—that is, total energy—as a gallon of gasoline.

The accompanying figure shows the importance of the difference between the two measures of energy. The figure plots energy density versus total energy for laser facilities, such as Nova and NIF, as well as that achieved in a weapon test. Two regions are shown for NIF—without ignition and with ignition. This distinction reflects the two alternative modes in which NIF will be used for experiments in physics related to weapons. NIF without ignition is characterized by the types of experiment described in this article. These experiments do not use fuel-filled capsules; instead, the targets are foils and other materials that enable us to study the behavior of materials and media in the extreme conditions heated by x rays to high energy densities.

NIF with ignition characterizes experiments in which the target is indeed a DT- or fuel-filled capsule, and the calculated energy densities are those predicted to be achievable in the different regions of a burning DT capsule.[1] Because the energy densities achieved in both modes of NIF operation—with and without ignition—show significant overlap with the energy density regime available from weapons tests, NIF can be used to investigate the high-energy-density physics subprocesses that occur in that regime.

Nevertheless, physics investigations on NIF rely only on high energy density (i.e., how dense and hot we can make a relevant target), not on total energy. (The total energy is only high enough to heat or drive a target that is big enough to yield measurable results.) The second, related, point is that the NIF or any other AGEX (above-ground experiment) facility cannot conduct integrative weapon tests because its total energy falls many orders of magnitude short of that regime. NIF cannot be used as a testbed for weapon development. Our analysis of stockpile questions will therefore rely on computer calculations to put together different parts of the physics that we study on NIF.



NIF energy densities will overlap those of nuclear weapons; the shaded area represents the region of high energy density. Note, however, that in measures of total energy, NIF energy regimes are well below the weapons test regime.

and go to the detector. The measured absorption of this well-characterized and well-controlled x-ray source provides insight into the characteristics of the target material. The timing of the heating beams and backlighter beams can be independently controlled to probe the targets under a wide variety of conditions.

Although the experimental program at NIF evolves from techniques developed on Nova, NIF experiments will probe the qualitatively different regime of plasmas characterized by radiation dominance at high-energy densities. The three examples of laser-driven experiments described here figure prominently in weapons research on the NIF: opacity, equation-of-state, and hydrodynamic instability experiments. Each of these explores a different set of fundamental phenomena characteristic of the extreme conditions within a nuclear weapon. In all three experiments, we can analyze how far the 1.8-megajoule drive of NIF can push the energy density.

Opacity Experiments

Loosely defined, opacity is the degree to which a medium absorbs radiation of a given wavelength. Knowledge of the opacity of a medium is crucial to understanding how the medium absorbs energy and transmits it from one place to another. This knowledge is important in nuclear weapons, where we care specifically about opacities at x-ray wavelengths, because this is the manner in which much of the energy in a weapon is transported.

If we are analyzing radiant energy transfer in a medium that is locally in thermodynamic equilibrium (LTE), we need know only an appropriate average of the mean distances that a photon can travel before it is absorbed—that is, its Rosseland mean free path between emission and absorption. (To analyze radiant energy transfer in a medium that is not in thermal equilibrium, we would have to retain detailed transmission information for every wavelength.) To achieve LTE for opacity experiments, we use the indirect method described above, creating a bath of x rays inside of a hohlraum. We thus make a diagnosable plasma in equilibrium and then determine its x-ray transmission at the appropriate wavelength.

To make a good plasma, the sample must be carefully tamped so that it retains uniform density under heating while hydrodynamically expanding to the desired density during measurement. The measurement is performed by passing backlighter x rays through the hohlraum to probe the tamped target. The target may have sections of different thickness so that, when analyzing the film image, we can separate the actual sample opacity from the absorption of radiation by other parts of the experiment. Figure 3 shows a typical transmission experiment in local thermal equilibrium.[2] Generally, as the atomic number is increased, we need to either increase the temperature of the tamped target, or lower its density, or both, in order to strip off enough electrons from the atoms in the target to ionize the plasmas to the desired level. Reaching such ionizations in the materials relevant to weapons requires a much more powerful laser than Nova, as Figure 4 shows.

Opacity research on the NIF will be conducted to evaluate new methods for predicting opacities. Such predictions are difficult, because there are many transitions and competing ionization stages that can contribute to the opacity of a given element. The electrons in atoms are arranged in shell structures of increasing complexity (from innermost outward), and the shells are conventionally labeled K, L, M, N, etc. M-shell-dominated opacities occur when an atom has been stripped of enough electrons to open the M shell. Complicated configurations of

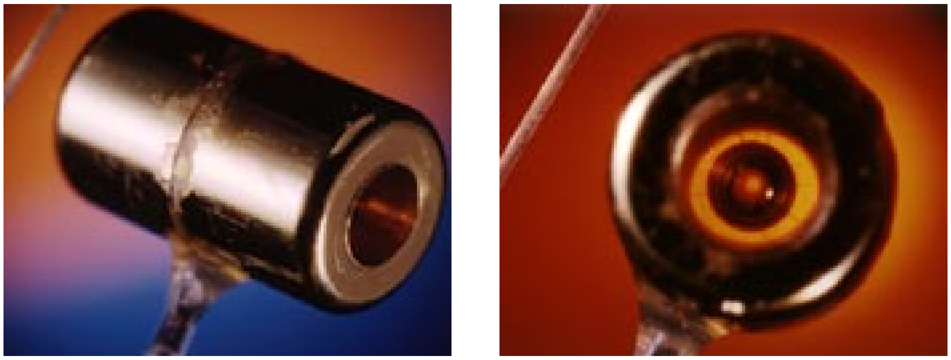


Figure 2. Two views of a typical Nova hohlraum shown next to a human hair. The end-on view shows a target within the hohlraum. Hohlraums for NIF will have linear dimensions about five times greater than those shown.

this sort play an important role in determining opacity; for example, the M-band opacity of materials involves computing features of 10^8 ionic configurations. Clearly this is impossible in any direct way; present ideas necessarily involve predicting key features with approximate statistical methods.[3] Experiments are crucial in checking that these models and predictions are correct.

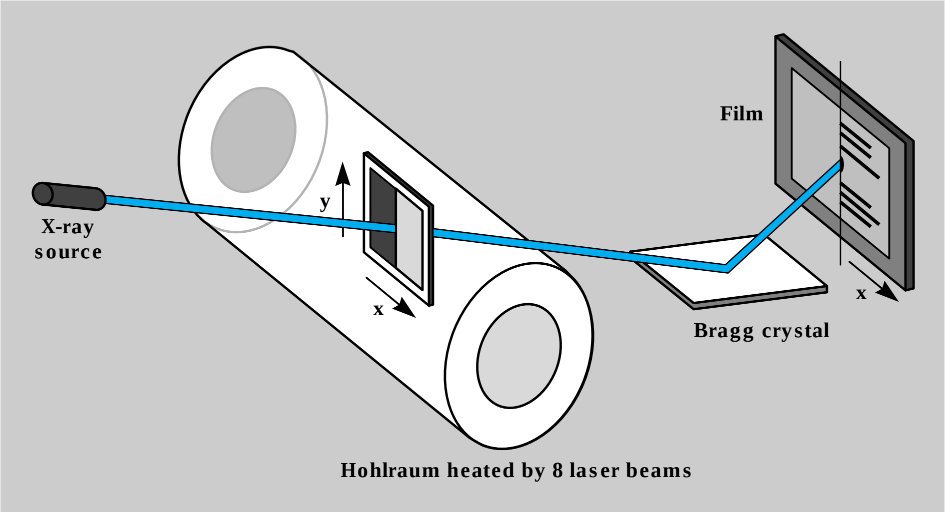
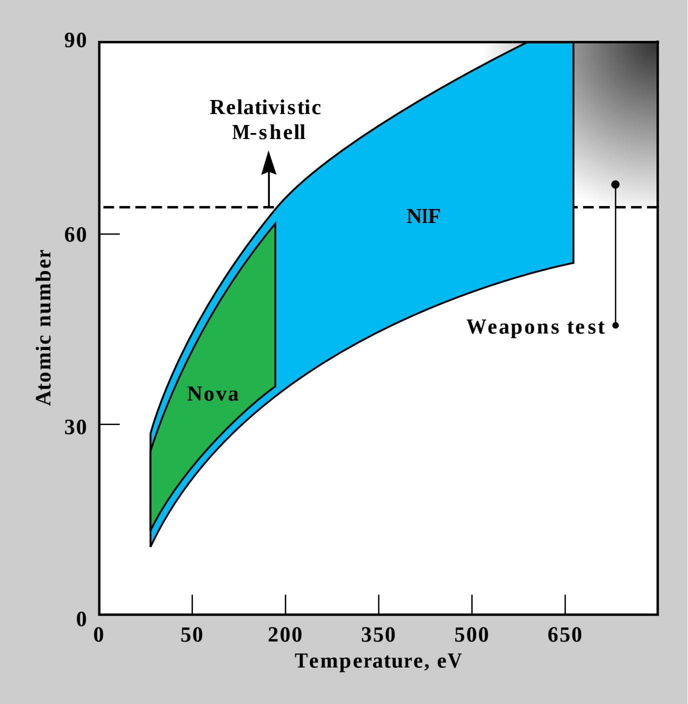


Figure 3. Schematic of a setup for absorption opacity experiments. The tamped target has two thicknesses. Laser beams entering the hohlraum generate an x-ray bath to heat the target. Backlighter x rays have significantly higher energies than the driver x rays.

Figure 4. Comparison of opacity regimes achievable on Nova and NIF and in weapons tests.



Equation-of-State Experiments

Understanding the physics of nuclear weapons requires that we answer the practical question of how much pressure is developed in a given material when a given amount of energy has been added. That is, we must determine the material's equation of state: the thermodynamic relationship between the energy content of a given mass of the material and its pressure, temperature, and volume.

Figure 5a shows a setup for a shock breakout experiment—an experiment for determining the thermodynamic states created by the passage of a single shock wave through the subject material. By striking a material at standard temperature and pressure with single shocks of different strengths, we obtain a set of states that lie on the principal Hugoniot. Hugoniots not only describe how materials behave when shocked; they also serve as baselines for models of much of the thermodynamic space covered by the full equation of state. Hugoniot experiments present a rare case in which thermodynamic quantities such as pressure can be determined from the measurement of material velocities alone.

In a shock breakout experiment,[4] lasers create an x-ray bath inside a hohlraum. The x rays heat an absorbing material that ablates, or rockets off, and sends a shock wave into a flyer plate. The flyer plate then hits a target that has two precisely measured thicknesses or "steps." The stepped target is observed end on by diagnostics that record the shock breakout. By measuring the difference in the timing of the shock breakout from the two sides of the step (Figure 5b), we can determine the speed at which the shock passed through the stepped material. However, shock breakout experiments are difficult to interpret. For example, we must determine whether the shock was planar: Did it strike the surface of the stepped plate with uniform force, or did the flyer plate undergo "preheat" and disassemble before it shocked the step? Like opacity studies, equation-of-state studies of these microscopic quantities are not only crucial to understanding the effects of high-energy densities in weapons, but they are crucial to understanding laser-based experiments themselves. Nova allowed us to study equations of state in the multimegabar pressure regions, but scaling equation-of-state experiments to pressures in the important gigabar region require a more powerful laser such as the NIF. This comparison is detailed in Figure 6.

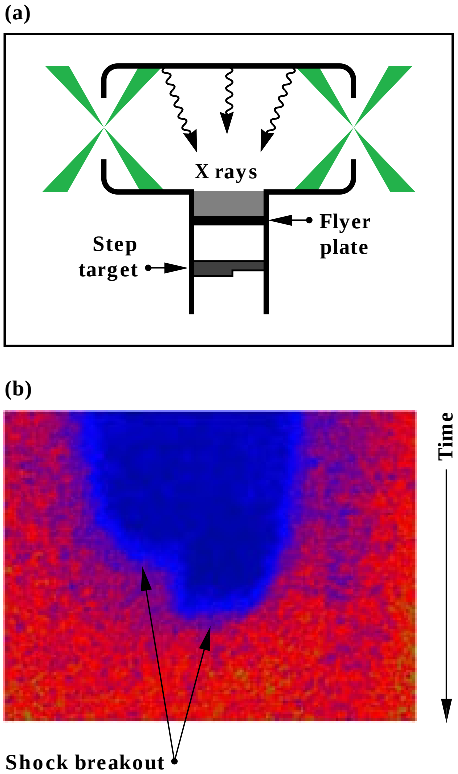


Figure 5. (a) Schematic of an x-ray-driven shock breakout experiment in colliding foils (the flyer plate and the step target are gold foil); (b) shows the breakout timing difference between the two sides of the step, as captured on film.

Hydrodynamic Instability Experiments

The third experimental example uses indirect drive to create hydrodynamically unstable flows at high compressions and Reynolds numbers. Unstable flows in highly compressed materials are ubiquitous in weapon physics. We typically must determine the thickness of the mixing layer between two materials caused by the passage of a strong shock wave. Much research on turbulent flows relies on the assumption that the flow is incompressible (like water in an ocean). However, here we are interested in the situation where considerable compression and ionization can occur at the same time as turbulent, mixing motion.

Figure 7 shows the experimental setup for studying the instability growth at an interface caused by the passage of a controlled, planar shock. As before, the lasers heat the hohlraum to create the x-ray heat bath that drives the experimental package. Here, the x rays ablate a carefully designed sleeve that drives a shock into the instability experiment. Another laser beam makes an x-ray backlighter that allows us to "photograph" the growing instability. We must carefully check the equation of state of the subject materials, the planarity of the shocks, etc., before we can compare the experiment with a detailed simulation. Figure 8 shows a comparison between a preliminary instability experiment done on Nova and an arbitrary Lagrange-Eulerian hydrodynamics calculation of the same setup done to test the ability of the code to probe large-scale sliding motions and deformations.

The program of work in instability research involves the study of shocked mixing layer growth, and the evolution of compressible turbulence from the small-amplitude, linear

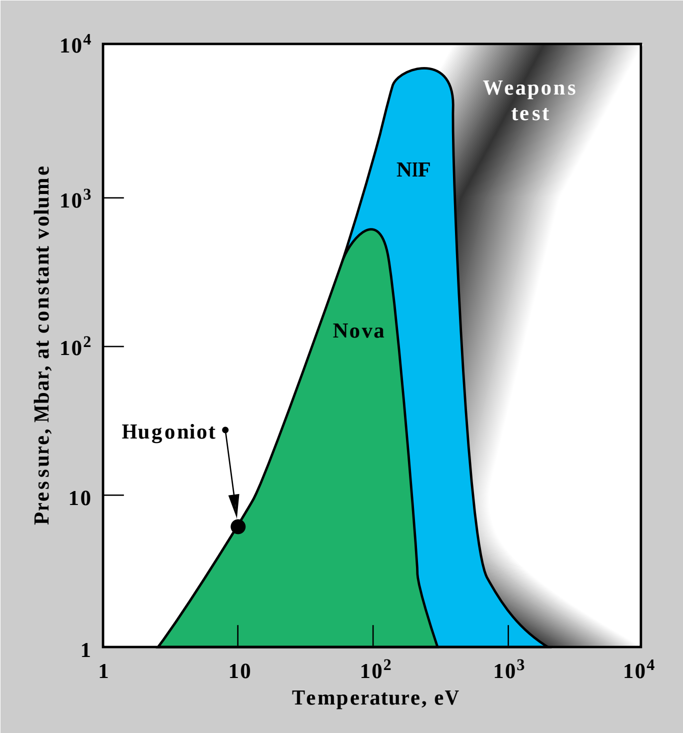


Figure 6. Comparison of equation-of-state regimes in flyer-plate experiments achievable on Nova and NIF; also roughly indicated is the weapons-test regime.

growth regime (which is pertinent to ICF implosions) to the full nonlinear evolution of turbulence. In the case of the mixing layers, there are suggestions for universal rules that control the width of such mixing layers as a function of time.[5] It would be of great importance to weapons designers to pin down these rules.

To explore the full evolution to turbulence from the simpler linear growth to the highly compressed turbulent regime, the experiments naturally scale to a higher-energy laser, as Figure 9 shows.[1]

Other Weapons Experimental Realms

The three types of experiments just described are among the most fundamental that will be performed on NIF—fundamental in the sense of probing phenomena that are virtually irreducible. Several areas of investigation are more integrative, probing phenomena arising from combinations or interactions of several different processes. These areas, described below, will also receive intensive investigation on NIF. These investigations and those already enumerated will contribute to further refinement of our weapons codes.

Radiation Transport. We do not understand nuclear weapon processes well enough to calculate precisely the transfer of energy within a weapon.[6] This transfer is crucial, since inadequate energy coupling can degrade yield or cause failure. In the era of nuclear testing, this incomplete

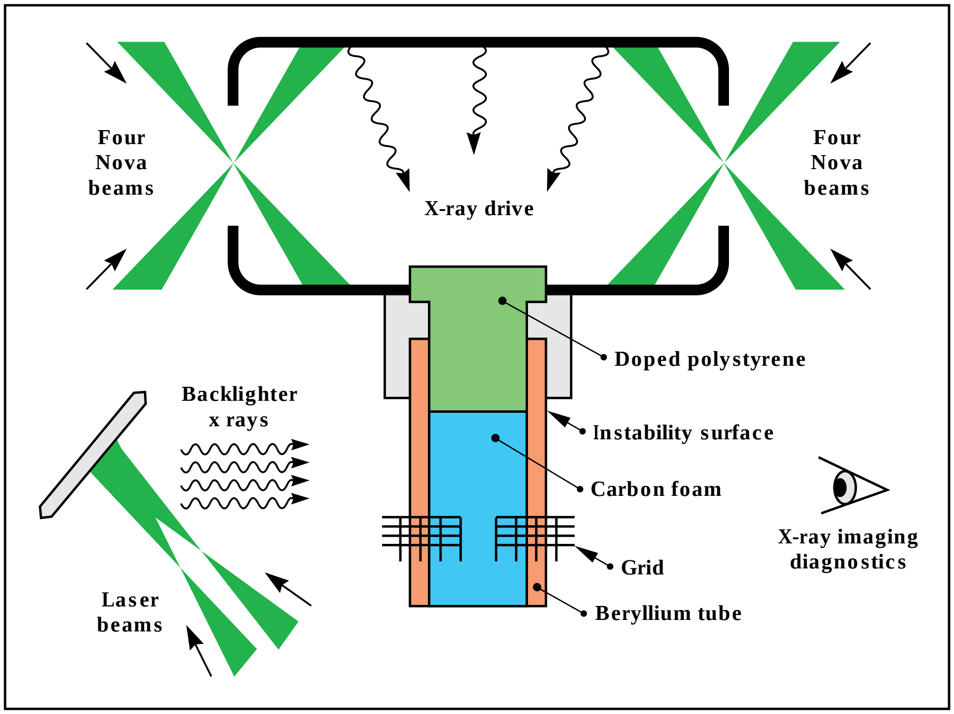
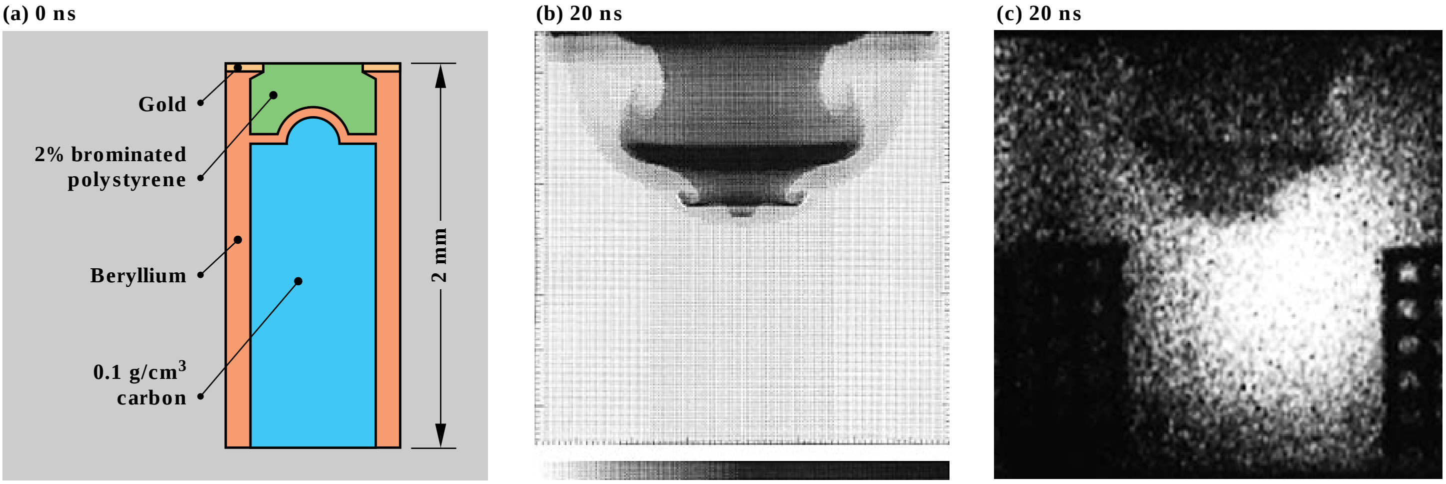


Figure 7. Schematic of a shock-driven hydrodynamic instability experiment. Changes in the transmission profile of the backlighter x rays reaching the diagnostics allow the mixing at the shocked interface to be measured.


(a) 0 ns

(b) 20 ns

(c) 20 ns

Figure 8. Calculated development of an axial jet compared with experimental data. (a) The experimental setup in initial conditions (0 nanoseconds). Center and right are the event after 20 nanoseconds: (b) is the calculation of instability evolution by arbitrary Lagrange-Eulerian code; (c) shows the data from an instability experiment on Nova.

understanding was not a problem because the radiative energy transfer could be determined specifically.

Weapon Output. The output of a nuclear weapon includes neutrons, gamma rays, x rays, fission products, activated elements, and exploding debris as kinetic energy. The ability to calculate the total spectral output of a weapon is an ultimate measure of our understanding of weapon performance.

Role of Ignition. Ignition encompasses two distinct weapons physics issues: weapons physics measurements and maintenance of critical skills. Several broad areas appear uniquely accessible to an ignition capsule:

- The possible use to study onset of DT ignition in the presence of impurities, which can occur from a mix of intentional contaminants placed in the gas. The NIF will provide the only place where DT burn will be studied in detail.
- The generation of x rays from the capsules. This will challenge our ability to model and understand burn, energy balance, and transport processes in a highly transient system having large gradients.
- The NIF capsules will also provide an intense source of 14-MeV neutrons. These neutrons could be used to heat material instantaneously to temperatures more than 50 eV without changing the material’s volume. This unique capability may prove useful for other weapons physics studies such as equation-of-state experiments.

Designing NIF fuel capsules to tailor output and explore efficient operation is a challenge to designers, computational physicists, and engineers. Such modeling will challenge our understanding of many fundamental processes associated with weapon design and will help keep us intelligent in this critical technology.

Non-LTE Physics and X-Ray Lasers. The NIF will allow us to address important physics issues in situations in which plasmas are not in thermodynamic equilibrium (called nonlocal thermodynamic equilibrium, or non-LTE, physics). Understanding non-LTE effects plays an important role in determining x-ray outputs and in developing temperature, ionization balance, and kinetics diagnostics. It is also essential in the development of laser-driven x-ray lasers. In the specific area of x-ray lasers, NIF will allow us to explore x-ray laser pumping schemes with various materials and conditions.

An important benefit of the x-ray laser research is its use as an imaging system for ICF, weapons physics, and biology experiments. High brightness, narrow bandwidth, small source size, and short pulse duration give the x-ray laser many advantages over conventional x-ray illumination sources.[7]

Future imaging applications will include the study of laser-driven mass ablation on the interior walls of hohlraums, equation of state, and perhaps the ICF implosions themselves. As the NIF program for high-energy-density physics evolves, we expect these results to influence the development of further advanced diagnostics.

Code Development. To a large extent, our weapons computer codes embody the cumulative knowledge of weapons design. NIF data will help to improve and refine these codes to enable more accurate modeling of results from previous weapons tests and from weapons physics experiments past and future. Code development for ICF research has focused on the need to calculate many coupled physical processes in nonequilibrium conditions and to simulate all resulting experimental diagnostics within a single computational model. The future need for higher accuracy and increased engineering detail will require better numerical methods, three-dimensional simulations, and massively parallel computers. These growing ICF code capabilities will be very important to weapons researchers for

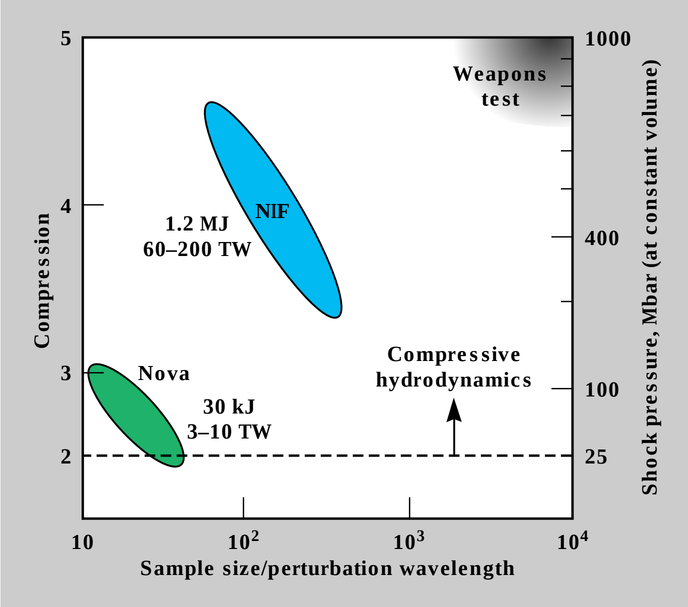


Figure 9. Whereas the moderate compressions on Nova allow us to follow the transition from linear instability to weak turbulence, the high compressions and larger scale volumes on NIF allow us to follow this all the way to turbulent mix.

understanding the results of NIF weapons physics experiments.

Summary

Underground nuclear tests played an important role in advancing knowledge of the physics of nuclear weapons. This knowledge led to progressively safer and more effective performance and to retrofits for older designs that improved their safety as well. Results from tests also enabled us to build and refine our weapons computer codes. The unilateral moratorium that the United States imposed on underground nuclear testing is likely to be followed by a Comprehensive Test-Ban Treaty. The United States must therefore have an alternative means of safely and securely maintaining its stockpile of nuclear weapons and ensuring their reliability. Stockpile stewardship is one of the functions to which the National Ignition Facility will contribute by virtue of experimental work in the physics of nuclear weapons.

The total energy output from thermonuclear ignition on NIF will be an extremely tiny fraction of the energy from even the smallest nuclear weapon—indeed it will be roughly equivalent to the output of a gallon of gasoline. Nevertheless, experiments will generate the same energy densities—energies per particle—that occur in nuclear weapons. This combination of low total energy with weapons-regime energy density will allow us to pursue, besides ignition experiments, many nonignition experiments. These will allow us to improve our understanding of materials and processes in extreme conditions by isolating various fundamental physics processes and phenomena for separate investigation. Such studies will include opacity to radiation, equations of state, and hydrodynamic instability. In addition to these, we will study processes in which two or more such phenomena come into play, such as in radiation transport and in ignition itself.

Weapons physics research on NIF offers a considerable benefit to stockpile stewardship not only in enabling us to keep abreast of issues associated with an aging stockpile, but also in offering a major resource for attracting and training the next generation of scientists with nuclear stockpile expertise. According to the recent JASON report on stockpile stewardship, the NIF "will promote the goal of sustaining a high-quality group of scientists with expertise related to the nuclear weapons program."[8]

Key Words: inertial confinement fusion; National Ignition Facility; Stockpile Stewardship Program.

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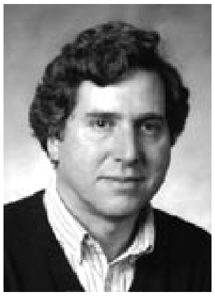

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