Nuclear Weapons Development in a Nuclear Test-Free World

André Gsponer, Jean-Pierre Hurni

The signing of the CTBT has put an end to explosive testing of nuclear weapons. However, since laboratory testing is not covered by the CTBT, the development of nuclear weapons will continue using a number of techniques perfected during the last fourty years and which today can effectively replace field testing.

Laboratory techniques have the potential of orders of magnitude improvement over traditional methods because they enable to study many nuclear weapons processes that are still poorly understood. With a complete description of nuclear weapons physics from first principles, producing a new weapon becomes a pure engineering enterprise — deprived of the kind of scientific uncertainties which made of nuclear weapons's design a kind of a black art.

In fact, the absence of explosive testing combined with vastly enlarged laboratory capabilities creates new opportunities for producing extremely safe and robust new nuclear weapons, whether they are based on old or new principles.

The most significant modern laboratory tool available to weapons designers is inertial confinement fusion (ICF). Various ICF facilities are operating or under construction in several countries. The two largest one currently being built are the "National Ignition Facility (NIF)" at the Lawrence Livermore National Laboratory (LLNL) in California and the "Laser Mégajoule (LMJ)" near Bordeaux in France. These facilities will be about twenty times more powerful than the largest existing one, the NOVA laser of LLNL.

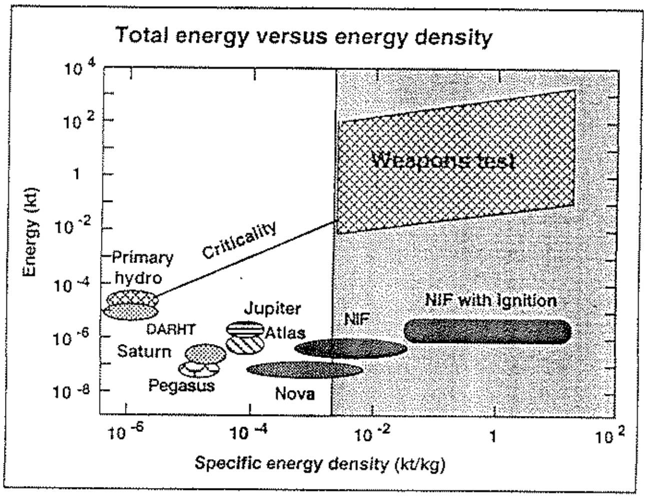
In order to demonstrate the potential of NIF and other above ground experiments (which are mentioned below in this paper), scientists from LLNL prepared a series of impressive graphs comparing the capabilities of NIF with those of explosive testing [1,2,3]. In this paper we reproduce seven of these graphs and explain their significance for nuclear weapons development.

Fig.1. Total energy versus energy density

The two axes of the first graph are the total energy in a test and the specific energy density, i.e. the amount of energy per unit of weight. For both quantities the energy is measured in kilotons (kt) equivalent of TNT (1 kt = 4.16 x 10^6 MJ).

For weapons tests the total energy is of the order of kilotons whereas for experiments on NIF it is equivalent to only a few kg of high explosives. (The baseline NIF laser energy is 1.8 MJ, i.e. equivalent to 0.43 kg of TNT.) However, the specific energy densities achieved in NIF operation show significant overlap with the energy density regime available from weapons tests. NIF can therefore be used to investigate the high-energy-density subprocesses that occur in that regime.

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 type of experiments described in reference [3] and in the first half of this article (Fig.2, 3 and 4). These experiments — which are among the most fundamental in the sense of probing phenomena that are virtually irreducible — do not use thermonuclear-fuel-filled capsules; instead, the targets are samples of materials heated by x-rays to high energy densities.

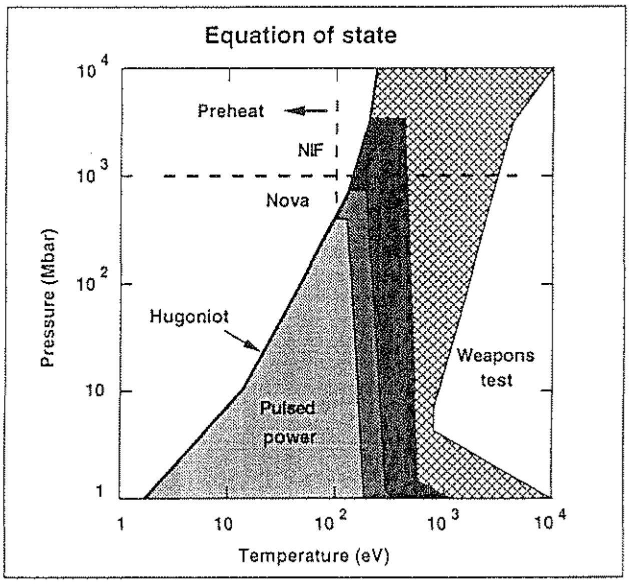


NIF with ignition characterizes experiments in which the target is indeed a capsule filled with deuterium-tritium (DT). In Fig.1 the calculated energy densities are those predicted to be achievable in the different regions of a burning capsule. It can be seen that with ignition the maximum achievable energy density is the same for NIF as for weapons test: about 20 kt/kg, slighly more than the fission energy content of plutonium, and about a quarter of the theoretical maximum yield-to-weight ratio of a thermonuclear weapon, the energy released in the total fusion of a DT mixture.

The lower limit of the energy density scale is 1 kg/kg, the energy content of high explosives. It corresponds to "hydrodynamic experiments" for which new powerful X-ray machines, such as DARHT in the USA and AIRIX in France, are under construction. Other facilities indicated on Fig.1 are pulsed power machines based on electromagnetic energy cumulation (Pegasus, Atlas, Saturne and Jupiter). Compared to laser pulsed power systems, electrical pulsed power technology has the advantage of having target volumes that approach sizes larger than a cubic centimeter whereas NIF target volume is only millimeter in size. However, as will be seen in the following graphs, "it is evident that NIF will be dominant in all the parameter spaces shown when it comes to reproduce bomb conditions" [1,p.80].

Fig. 2. Eqation of state

A material's equation of state is the thermodynamic relationship between the energy content of a given mass

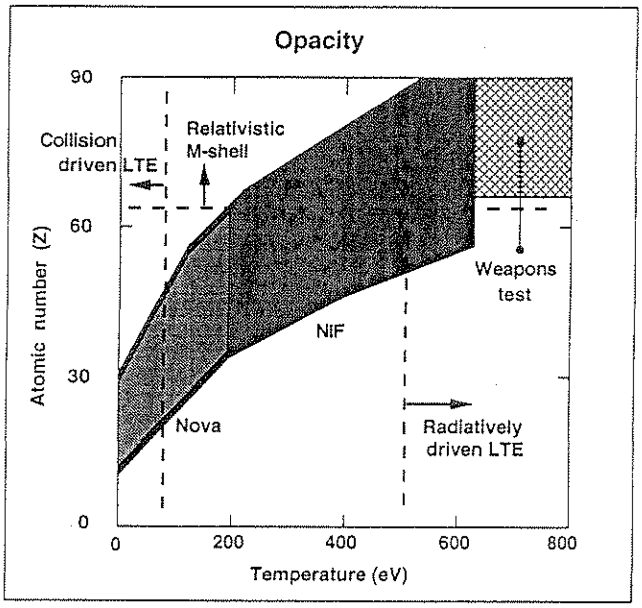


of the material and its pressure, temperature and volume.

In an operating weapon, pressures may reach hundreds of Gigabar (Gbar) and temperatures several tens of keV in LiD. As can be seen in Fig.2, equation of state experiments on NIF do not extend to this regime. They are limited to a few Gbar and to less than one keV. But this is not really a problem: in the very-high-pressure/temperature limit there are good theories based on the Thomas-Fermi model. In fact, it is in the Gbar regime were NIF is operating that precise data are most necessary. In this region, NIF has the advantage of enabling very clean measurements. In contrast to lower energy laser systems, it can produce planar shocks that are much easier to analyse than spherical shocks,[4] and it avoids the "preheat" problem which tends to destroy the sample before it is shocked.

Fig.3. Opacity

Opacity is the degree to which a medium absorbes radiation of a given wavelength. This fundamental quantity is very difficult to calculate because there are many transitions and competing ionization stages that can contribute to the opacity of a given element. Knowledge of the opacity of a medium is crucial to understanding how the medium absorbs energy and transmits it from one place to another. In a nuclear weapon, opacities at X-ray wavelengths are particularly important, because this is the energy range in which much of the energy is transported.



In Fig.3 the abscissa is the temperature of the material. A sample is placed in a hohlraum heated by the NIF laser, creating a bath of X-rays which uniformly drives it to the desired temperature and density. The measurement is performed by passing X-rays generated by a backlighter laser through the hohlraum to probe the sample. Backlighter X-ray may have energies from a few tens of eV to a few keV (the maximum X-ray energy produced by a fission primary). NIF hohlraum temperature of 600-700 eV should be accessible, which will enable opacity measurements to be performed under close-to-secondary conditions.

The ordinate in Fig.3 is the atomic number of the sample. The lower and upper boundaries of the shaded area correspond to the minimum hohlraum temperature necessary to open the L or M shell of the atom under investigation. As can be seen, NIF enables to reach ionization levels sufficient to measure M-shell-dominated opacities in materials as heavy as uranium (Z=92).

In modeling radiant energy transfer a considerable simplification occurs when the material is sufficiently opaque to radiation that the medium is locally in thermodynamic equilibrium (LTE). In this limit the so-called

Rosseland approximation (or radiative conductivity model) is valid. Radiation transfer is governed by a non-linear diffusion equation and the medium is characterized by a single parameter: the Rosseland mean free path λ, which is related to the Rosseland average opacity σ by the equation $\lambda \sigma \rho = 1$ where ρ is the density. In Fig.3, it can be seen that with NOVA LTE is driven by collisions between the electrons and the ions of the plasma, whereas with NIF it is possible to reach the radiatively driven LTE which is characteristic of nuclear weapons.

Fig.4. Compressible turbulence

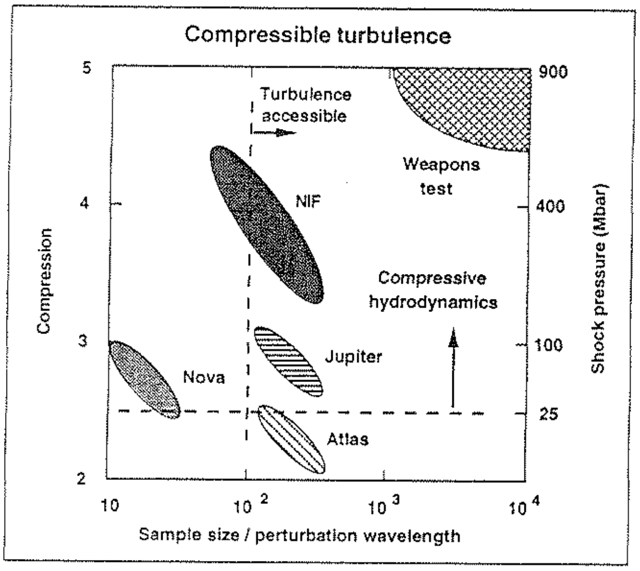
A major issue in the operation of nuclear weapons is the question of stability of implosion in both the primary and the secondary. In inertial confinement fusion the fuel must be compressed to densities of the order of 1000 to 10000 times of solid density. Success in achieving such high compression implies very symmetrical energy deposition as well as the avoidance of the well-known hydrodynamic instabilities (Rayleigh-Taylor, Kelvin-Helmholtz, and Richtmyer-Meshkov) whose understanding is also critical to weapons design [1, p.39].

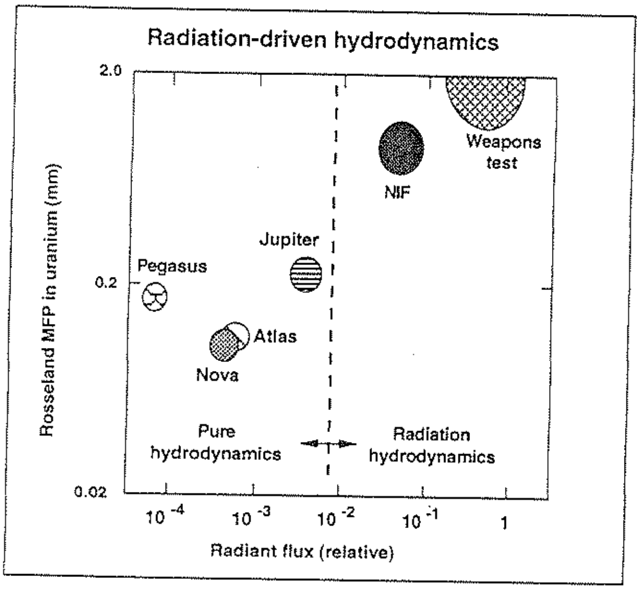
The program of work in instability research on NIF involves the study of shocked mixing layer growth, and the evolution of compressible turbulence from the small-amplitude, linear growth regime to the full evolution of turbulence (which is pertinent to weapons). In Fig.4 it is clear that this regime is acessible on NIF because its smaller sample size makes it more sensitive to perturbations.

On the right hand side of the graph, the ordinate gives the shock pressure on a quadratic scale. On the left hand side, the approximate value of the corresponding compression factor is given. Theoretically, for an infinitely strong single shock, the compression is equal to $\gamma + 1/\gamma - 1$. This gives a maximum compression of 4 for a matter dominated plasma (γ=5/3) and of 7 for a radiation dominated plasma (γ=4/3).

Fig.5. Radiation-driven hydrodynamics

An essential feature of nuclear weapons physics, which has no analogy within other realms of science except some parts of astrophysics, is the importance of radiation-dominated plasma effects.





Rayleigh-Taylor instabilities develop when the interface between two fluids of different density is accelerated, and Kelvin-Helmholtz instabilities occur when one fluid acquires a tangential velocity relative to the other. Both types can lead to laminar or turbulent mixing of the materials, for example depleted uranium and LiD in the implosion of a thermonuclear secondary. While Rayleigh-Taylor and Kelvin-Helmoltz instabilities can to a large extent be controlled by careful design, Richtmyer-Meshkov induced compressible turbulence is more difficult to avoid. This instability produces a mixing layer when a strong shock passes through the interface between two materials.

In Fig.5 the parameter space of radiation-driven hydrodynamics is illustrated in terms of the relative radiant flux and the Rosseland mean free path λ in uranium at normal density. (about 2 mm at 10 keV, and about 0.1 mm at 2 keV [5]) gives a measure of the thickness to X-rays of a fission bomb, or of the penetration depth of X-rays into the surface of the radiation case of an H-bomb.

From the value of their respective , one can infer that the typical radiative temperatures of NOVA, NIF and weapons-tests are about 1.8, 5 and 10 keV. If we take the T^4 temperature dependence of the Planck law, the corresponding radiant energy fluxes have the relative values indicated on the horizontal axis, with NIF relatively close to weapons-tests and NOVA about a factor 1000 below.

Fig.6. Pure hydrodynamics

Shock compression and heating of imploding materials is described by scalable hydrodynamics, provided radiation effects are negligible (pure hydrodynamics) and the various ionic components of the plasma are in local thermal equilibrium (two-fluids hydrodynamics). Such conditions are likely to prevail within a secondary during the implosion before ignition of thermonuclear reactions.

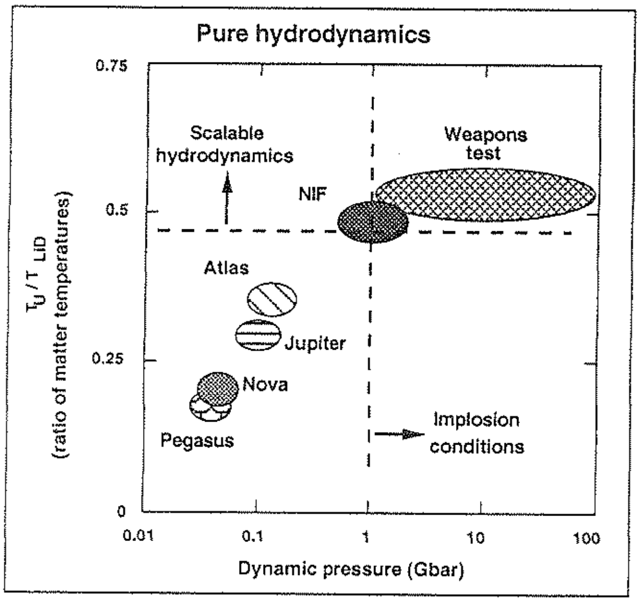
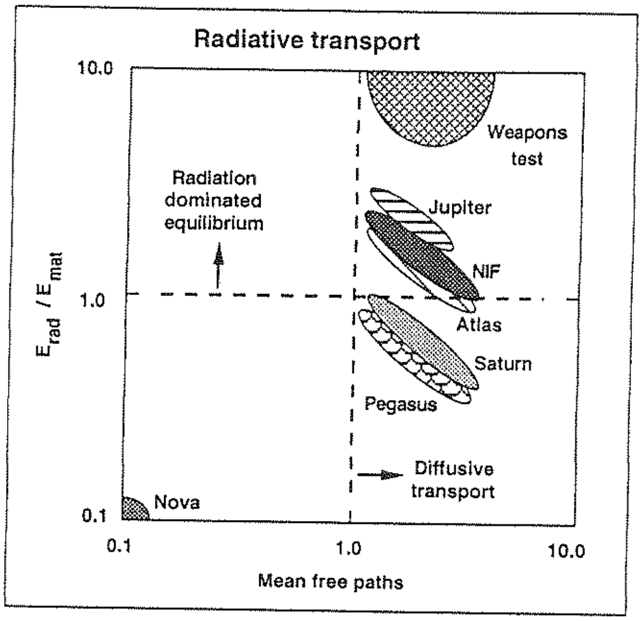


Figure 6 shows the corresponding parameter space. Consistent with Fig.2, it can be seen that NIF is capable of producing single shock dynamic pressures of several Gbar. This allows to simulate implosion conditions equivalent to those of nuclear weapons operation.

In a plasma, the temperatures of the different species of particles are set by energy transfer processes which depend on their respective electric charges and relative masses. Electrons and ions of various kind may thus have quite different temperatures. As can be seen on Fig.6, the LTE conditions reached on NIF are similar to those of weapons tests, with a ratio of heavy to light ion temperatures of about 0.5.

Fig.7. Radiative transport

Figure 7 illustrates the similarities of radiative transport conditions in NIF and weapons tests. $E_{rad} \sim T^4$ and $E_{mat} \sim T$ are the radiation and matter energy densities. Consistent with Fig.5, there is a ratio of about 20 in mean free path between NOVA and weapons test or NIF, and a factor of about 100-200 in Erad/Emat. NIF operation is



clearly in the radiation dominated domain and the diffusive approximation is applicable since NIF targets are larger than the radiation mean free path.

References

[1] S. Drell et al., Science based stockpile stewardship, JASON report JSR-94-345, The MITRE corporation, McLean, VA 22102 (November 1994) 108 pp.

[2] H. Zerriffi, A. Makhijani, The nuclear safety smokescreen - Warhead safety and reliability and the science based stockpile stewardship program, Institute for Energy and Environmental Research, Takoma Park, MD 20912, (May 1996) 49pp.

[3] S.B. Libby, NIF and national security, Energy and Technology Review, Lawrence Livermore National Laboratory, (December 1994) 23-32.

[4] R. Cauble et al., X-ray driven flyer foil experiment near 1.0 Gbar, J. Quant. Spectro. Radiat. Transfer /51/ (1994) 23-32

[5] A. Pritzger et al., Multigroup radiation cross sections of high temperature uranium plasmas, J. Quant. Spectr. Radiat. Transfer, /16/ (1976) 629-635

(9 December 1996)

Andre Gsponer is Director of the Independent Scientific Research Institute (ISRI), Jean-Pierre Hurni is senior researcher at ISRI. Both authors are physicists. Address: Box 30, 1211 Geneva 12, Switzerland; tel: +41-22 346 1810. From the authors the following report is available: A. Gsponer, J.-P. Hurni, ISRINEX: a thermonuclear explosion simulation program for independent disarmament experts, Geneva: ISRI-96-07, 18 October 1996; full-length version of a paper presented at the 1996 INESAP Conference, Gothenburg, Sweden, May 30 to June 2, 1996.