Centimeter

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 mm |

Inches

| 1.0 | 1.1 | 1.25 |

MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.
Achieving Competitive Excellence in Nuclear Energy:
The Threat of Proliferation;
The Challenge of Inertial Confinement Fusion

John H. Nuckolls

This paper was prepared for presentation at the
American Nuclear Society Annual Meeting
New Orleans, Louisiana
June 20, 1994

June 1994

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
DISCLAIMER

This document was prepared as an account of work sponsored by an agency of
the United States Government. Neither the United States Government nor the
University of California nor any of their employees, makes any warranty, express
or implied, or assumes any legal liability or responsibility for the accuracy,
completeness, or usefulness of any information, apparatus, product, or process
disclosed, or represents that its use would not infringe privately owned rights.
Reference herein to any specific commercial product, process, or service by trade
name, trademark, manufacturer, or otherwise, does not necessarily constitute or
imply its endorsement, recommendation, or favoring by the United States
Government or the University of California. The views and opinions of authors
expressed herein do not necessarily state or reflect those of the United States
Government or the University of California, and shall not be used for advertising
or product endorsement purposes.
Nuclear energy will have an expanding role in meeting the twenty-first-century challenges of population and economic growth, energy demand, and global warming. These great challenges are non-linearly coupled and incompletely understood.

In the complex global system, achieving competitive excellence for nuclear energy is a multi-dimensional challenge. The growth of nuclear energy will be driven by its margin of economic advantage, as well as by threats to energy security and by growing evidence of global warming. At the same time, the deployment of nuclear energy will be inhibited by concerns about nuclear weapons proliferation, nuclear waste and nuclear reactor safety. These drivers and inhibitors are coupled: for example, in the foreseeable future, proliferation in the Middle East may undermine energy security and increase demand for nuclear energy.

The Department of Energy's nuclear weapons laboratories are addressing many of these challenges, including nuclear weapons buildup and nonproliferation, nuclear waste storage and burnup, reactor safety and fuel enrichment, global warming, and the long-range development of fusion energy. Today I will focus on two major program areas at the Lawrence
Livermore National Laboratory (LLNL): the proliferation of nuclear weapons and the development of inertial confinement fusion (ICF) energy.

PROLIFERATION

Throughout the nuclear age, defense and civilian applications of nuclear energy have been strongly coupled: both utilize nuclear fission, and their fissile fuels are generated by nuclear reactors and isotopic enrichment.

Last September, in a speech to the United Nations General Assembly, President Clinton warned of the growing threat of proliferation:

"If we do not stem the proliferation of the world’s deadliest weapons, no democracy can feel secure . . . .

"I have made nonproliferation one of our nation’s highest priorities. We intend to weave it more deeply into the fabric of all of our relationships with the world’s nations and institutions . . . .

"We will pursue new steps to control the materials for nuclear weapons. Growing global stockpiles of plutonium and highly enriched uranium are raising the danger of nuclear terrorism for all nations . . . .

". . . the end of the Cold War did not bring us to the millennium of peace. And, indeed, it simply removed the lid from many cauldrongs of ethnic, religious, and territorial animosity . . . .

"Let us ensure that the world’s most dangerous weapons are safely reduced and denied to dangerous hands."

Recently, the National Academy of Sciences Committee on International Security and Arms Control (CISAC) reported on options for managing the vast quantities of plutonium resulting from the dismantlement of the U.S. and former Soviet Union nuclear arsenals. The CISAC found that

"The existence of this surplus material constitutes a clear and present danger to national and international security. None of the options yet identified for managing this material can eliminate this danger; all they can do is to reduce the risks. Moreover, none of the options . . . can be expected to substantially reduce the inventories of excess plutonium from nuclear weapons for at least a decade."
According to this CISAC study, the world’s plutonium stockpile is approximately 1100 tons—including both weapons and civilian sources. By the turn of the century this stockpile is expected to grow to about 1700 tons. The U.S. has agreed to purchase 500 tons of HEU from Russia. The global stockpile of HEU is more than 1000 tons. Highly enriched uranium and weapons- and reactor-grade plutonium can all be used to make nuclear weapons. The Committee stated:

"Even with relatively simple designs such as that used in the Nagasaki weapon—which are within the capabilities of many nations and possibly some subnational groups—nuclear explosives could be constructed (from reactor grade material) that would be assured of having yields of at least one or two kilotons."

Concerning the disposition of the excess weapons plutonium, the Committee recommended:

"Advanced reactors should not be specifically developed or built for transforming weapons plutonium into spent fuel because that aim can be achieved more rapidly, less expensively, and more surely by using existing or evolutionary reactor types."

The Committee also recommended:

"...that the United States pursue new international arrangements to improve safeguards and physical security over all forms of plutonium and highly enriched uranium... This global effort should include continued consideration of more proliferation resistant nuclear fuel cycles including concepts that might offer a long term option for nearly complete elimination of the world’s plutonium stocks."

The major forces which have inhibited nuclear weapons proliferation during the past half century are gradually decaying or have been eliminated:

- Nuclear weapons secrets cannot be protected indefinitely.
- Science and technology diffuses, and the revolution in science and technology continues.
- Gross domestic products increase.
• Iraq and North Korea have demonstrated weaknesses in IAEA inspections and in export controls.

• Thousands of personnel have nuclear weapons experience.

• Thousands of tons of plutonium and highly enriched uranium have been created—and control of this material is not assured.

• Tens of thousands of nuclear weapons exist. Former Secretary of Defense Les Aspin warned of the potential for loss of control of some of these weapons— the threat of "loose nukes."

As a result of these changes, more and more nations and subnational groups will become capable of developing or acquiring nuclear weapons as we proceed into the twenty-first century.

In May 1994 at a conference on proliferation held at the Los Alamos National Laboratory, Senator Sam Nunn, chair of the Senate Armed Services Committee, summarized\(^3\) the global challenge posed by nuclear and other weapons of mass destruction:

"Proliferation [of weapons of mass destruction (WMD)] is likely to be our top continuous national security priority for the next 10-20 years.

"The major sources of fissile materials and of advanced chemical and biological weapons are in some twenty countries, including the countries of the former Soviet Union, China, North Korea, Iran and Iraq. Of these, Russia is the major challenge because of its vast array of weapons and its political and economic turmoil ... This is the first time in history that literally thousands of scientists who know how to make nuclear weapons, ballistic missiles, chemical and biological weapons, don't know where their next paycheck is coming from or how their families are going to be fed .... I think the Russian organized criminal elements, now joining with other organized crime elements in the rest of the world, is a part of the overall proliferation challenge.

"Who are the developers and purchasers and users of these weapons? Who will they be in the future? The list is likely to grow very rapidly. Let's take a look at those who already are in this category.

"• First of all, those who use terrorism as a tool of national policy, countries like Libya and Iran.

"• Second, those who harbor expansionist ambitions like Iraq.
"• Third, those who both fear an invasion and threaten an invasion of others, like North Korea.

• Fourth, those who are armed to the teeth because they fear their neighbors, like India and Pakistan.

"This is a very large threat . . . . The whole array of our governmental capability is going to have to be brought to bear. Like the Cold War, this effort is long term. It could be as long as the Cold War, it could be longer. Like the Cold War, it is going to require an all out, consistent, dedicated, persistent effort by our government."

In May 1994, the Office of the Secretary of Defense issued a report to Congress on U.S. government nonproliferation and counterproliferation activities and programs.4 This report summarizes the policy considerations and the approach to address the threat posed by weapons of mass destruction.

"Several broad policy considerations are shaping the U.S. approach to the proliferation problem:

• Nonproliferation and counterproliferation initiatives have a high priority on the U.S. national security agenda.

• The U.S. will implement domestic export controls that recognize both our nonproliferation objectives and the commercial needs of U.S. exporters.

• The U.S. cannot rely on technology denial alone.

• The U.S. will devote special attention to regions and countries where the dangers of proliferation are particularly acute.

• The U.S. will lead global efforts to reduce reliance on missiles and weapons of mass destruction.

"To this end, the U.S. is pursuing a broad-based approach to address the threat posed by weapons of mass destruction:

• Strengthening international nonproliferation norms, including indefinite extension of the nuclear nonproliferation treaty.

• Limiting the production of fissile materials.

• Strengthening multilateral export controls on WMD and ballistic missile technologies.

• Reforming U.S. export control implementation.

• Pursuing an activist regional nonproliferation policy.

• Integrating commercial space and nonproliferation policy.

• Supporting the Chemical Weapons Convention."
The U.S. Government is approaching the problem posed by the proliferation of WMD and missiles through a balanced program of prevention, reversal, and protection (from reference 4):

"Prevention/Reversal

"Detection/Identification"—detection and identification of proliferation activities . . .

"Dissuasion"—convincing non-WMD states that their security interests are best served through not acquiring WMD . . .

"Denial"—curtailing access to technology and materials for weapons of mass destruction through export controls or other tools. It is particularly important to strengthen multilateral export control regimes, as this enhances the effectiveness of the controls while reducing the economic costs to US suppliers. Other, more direct techniques could include the disruption of black markets.

"Arms Control"—reinforcing the Nuclear Non-Proliferation Treaty, the Biological and Chemical Weapons Conventions, a Comprehensive Test Ban Treaty, nuclear-free zones, conventional arms treaties that stabilize regional arms races, and confidence- and security-building measures . . .

"International Pressure"—punishing violators with trade sanctions, publicizing and exposing companies and countries that assist proliferators, and sharing the intelligence to heighten awareness of the proliferation problem.

"Protection

"Defusing"—undertaking actions to reduce the threat from WMD already in the hands of selected countries—for example, agreements to destroy, inspect, convert, monitor, or even reverse their capabilities.

"Deterrence"—bringing to bear military, political, economic, and commercial tools by the United States, its allies, and friends in an effort to persuade even the most ardent proliferator that the risks of the acquisition, threat, or use of WMD are not acceptable.

"Offense"—protecting US forces and responding to allied requests for assistance to meet legitimate security needs, by being prepared to seize, disable, or destroy WMD in time of conflict, if necessary. It is also important to monitor, track and interdict shipments of WMD or their precursors.

"Defense"—responding to a potential adversary armed with WMD or missiles to deliver them by employing active and passive defenses that will mitigate the effects of these agents and enable US forces to fight effectively even on a contaminated battlefield. It also includes border control against unconventional delivery and terrorists."
Based on our experience in Iraq, North Korea, Pakistan, and elsewhere, the containment of proliferation will require greatly strengthened international controls.

Proliferation is a major challenge which will inevitably impact the deployment and success of civilian nuclear energy in the twenty-first century. Nuclear power plants with inherent proliferation resistance may have an important advantage if they can be made economically competitive.

INERTIAL CONFINEMENT FUSION

Since fusion is neutron rich, fusion reactors could also be used to breed fissile materials. Consequently, international inspection will be required.

Fusion has major advantages as an energy source. Fusion power plants would generate many orders of magnitude less radioactive waste than fission reactors. A virtually unlimited supply of fusion fuel is available to all nations. The deuterium in every gallon of ordinary water has a fusion energy potential equal to that of 30 gallons of gasoline. However, the scientific and commercial feasibility of fusion as an energy source has not yet been demonstrated. Only in hydrogen bombs have we succeeded in utilizing fusion energy.

The quest to harness fusion energy for civil power production began in the late 1940s and early 1950s. It is one of the most difficult scientific and technological challenges ever undertaken. None of the fusion pioneers are likely to live to see the success of fusion power plants. After 40 years of research and development by many nations, giant tokamak magnetic confinement machines can now briefly produce almost as much energy as they consume. Joint plans are being developed by European, Russian, Japanese, and U.S. collaborators to build the International Tokamak Thermonuclear Reactor (ITER), estimated to cost $10 billion. Beyond ITER, the challenge will be to build a practical power plant which is economically competitive with other energy sources. Power plants based on ITER technology may be available in the second quarter of the twenty-first century.

In a magnetic fusion power plant, overall costs are significantly increased by the costs of the giant magnetic confinement system and the large scale size set by the relatively low-density fusion plasma and by neutron damage to the first wall. It has been suggested that lower costs may be achieved by utilizing inertial confinement of the fusion plasma. Then the magnetic confinement
system would be eliminated, the first wall could be shielded from neutron damage by fluid layers, and the scale size could be reduced. However, for ICF a low-cost driver technology must be developed to ignite small-scale fusion explosions.

In the late 1950s and early 1960s an inertial confinement approach to controlled fusion energy was explored at LLNL. In 1957 I was assigned the task of designing a fusion power plant driven by the explosion of a series of hydrogen bombs in a giant steam-filled hole in granite. Although this approach would eliminate the magnetic confinement system, the scale is very large, and the hydrogen bomb is initiated by a fission explosive. To eliminate the use of fission explosives and to greatly reduce the scale, I addressed two key questions:

- What is the smallest possible fusion explosion?
- How can such a small fusion explosion be ignited without a fission explosion?

The feasibility of very small fusion explosions follows from the fact that the thermonuclear burn rate is proportional to the density of the fusion fuel, and the fact that fusion fuels can be imploded to at least 1000 times normal density. The inertial confinement time is proportional to the characteristic dimension of the exploding system. Therefore, for a sphere, a thousand-fold increase in the density (and burn rate) makes possible a thousand-fold reduction in the radius and a $10^6$-fold reduction in the mass and fusion yield. Minimum-size fusion explosions can be achieved by imploding DT, the fastest-burning fuel, to very high densities.

A milligram of DT imploded to a thousand times normal density ($200 \text{ g/cm}^3$) and ignited will achieve a 25% burn efficiency and a yield of about $10^8 \text{ J}$.

Only $10^4 \text{ J}$ is required to compress 1 mg of DT to $200 \text{ g/cm}^3$, provided the DT is isentropically compressed to a Fermi degenerate state (this means that the thermal energy of the compressed DT must be a small fraction of the Fermi energy, which is several hundred electron volts at $200 \text{ g/cm}^3$). The fusion energy release from this milligram of DT is almost 10,000 times larger than $10^4 \text{ J}$, so that the compression is energetically "free." ($<<$ the fusion energy)

The minimum ignition energy is also much smaller than the fusion energy. If the entire milligram-mass pellet at $200 \text{ g/cm}^3$ is heated to a 10 KeV ignition temperature, then the resulting fusion energy would be about 100 times larger than the ignition energy. However, less than 1% of the pellet needs to be ignited, since the radius of the compressed pellet is six times
larger than the range of the 3.5-MeV α particle arising from the DT reaction. If \((1/6)^3 \approx 0.5\%\) of the pellet mass is heated to ignition, this critical-size hot spot will then initiate a burn wave which ignites the remainder of the pellet. For this pellet, the minimum required ignition energy is about \(5 \times 10^3\) J. After compression, the ignition is also energetically "free."

The sum of the minimum energies required to compress and ignite the 1-mg pellet is \(15 \times 10^3\) J, almost \(10^{-4}\) of the roughly \(10^8\)-J fusion energy release.

Because the fusion energy is so much larger than the minimum energy required for compression and ignition, an ablative implosion (which is typically 10% efficient) may be used to achieve both compression and ignition. However, because the velocity required for ignition (of a milligram) is roughly three times the velocity required to compress 1000-fold, the overall efficiency is reduced to 1%. Then the energy source must deliver \(10^6\) J to the target, and the efficiency of the energy source must be more than 10% for civil power applications.

A major challenge is to achieve the required power. The \(10^6\) J of energy must be applied to the milligram in a few nanoseconds—corresponding to a multi-hundred terawatt power.

For a power plant, the \(10^6\) J must be projected in a beam across a distance of more than a meter from the wall of the explosion chamber to implode and ignite the subcentimeter-scale pellet. This standoff distance is necessary to avoid the destructive effects of the fusion explosions on the chamber wall. These destructive effects are from the 14-MeV neutrons, the soft x-rays, and the hot plasma. The explosive impulse is relatively small because the pellet mass is so small.

The 14-MeV neutrons may be absorbed in several tens of \(g/cm^2\) of lithium-rich material. Lithium fission and \((n,2n)\) reactions may then be used to regenerate the tritium consumed by the DT burn. The soft x-rays and hot plasma are readily absorbed in the lithium-rich material. Flowing fluid (liquid or granular) lithium compounds can be used to create a continuously renewable curtain which protects the solid chamber wall, and thereby extends the first-wall lifetime to that of the power plant. This fusion-heated fluid is then circulated to a heat exchanger.

To generate average powers of hundreds of megawatts, several pellets per second would be projected into the chamber and ignited.

The fusion pellet and the "driver" (source of the ultrahigh-power energy beam) are a system and must be designed to couple efficiently. In addition to
the energy, power, standoff, repetition rate and other requirements described above, the driver must satisfy several other conditions:

• The driver energy must be absorbed by the pellet in an amount of matter small enough that the required pressures and temperatures are achieved, while the DT fuel is not internally preheated.

• The target implosion must be driven isentropically—this means that the driver pulse must be varied ("shaped") in time as required by the implosion dynamics.

• The surface of the imploding DT sphere must be heated symmetrically—asymmetries greater than a few percent are not tolerable—and growth of fluid instabilities must be minimized.

To meet these coupling requirements with the as yet unknown driver, I proposed in the late 1950s to adapt a powerful thermonuclear weapon concept invented by Edward Teller in the early 1950s. I proposed to “indirectly drive” the ablativ implosion with thermal x-rays generated by rapidly injecting energy from the driver beam into a cavity which has high-Z walls and contains a DT pellet coated with a low-Z ablator. Re-radiation of thermal x-rays back and forth across the cavity rapidly reduces temperature gradients, and rapid ablation of the pellet surface by the x-rays generates the required implosion pressures while reducing the rate of growth of fluid instabilities. To prevent excessive thermal losses into the cavity wall due to the adverse scaling of the surface to volume ratio as the cavity is made smaller, I decreased the cavity temperature and the average initial density of the imploding capsule.

In the early 1980s, the U.S. declassified the use of this "indirect-drive" approach in ICF—and the fact that this approach was used in thermonuclear weapons driven by fission explosions.

In the late 1950s, shortly after I completed the first supercomputer calculations of the compression and ignition of a milligram of DT by thermal x-rays in a cavity, the laser was invented—and was recognized as a prime candidate for the driver for such implosions. The laser would focus a high-power beam of energy through a hole in the cavity wall. Charged particle beam machines were also recognized as a possible driver.

A program was conducted by LLNL and LANL to implode ICF capsules in underground nuclear experiments driven by underground nuclear explosions. These experiments have been named "Halite-Centurion."
In 1962, LLNL began a laboratory laser fusion experimental program, led by Ray Kidder, to develop high-power lasers capable of igniting a small fusion explosion. Kidder also proposed a directly driven target design, in which many laser beams strike the pellet in a spherically symmetric pattern to implode it.

In the early 1970s, advances in high-power lasers and supercomputer calculations of laser driven implosions led to the initiation of a national ICF program by the Atomic Energy Commission. Subsequently, ICF programs were initiated by several other nations, including the USSR, Japan, France, and Germany.

In the 1970s and 1980s, fusion lasers or charged particle beam machines were developed at many laboratories including LLNL, LANL, SANL, NRL, KMSF, and the University of Rochester in the U.S. Under the leadership of John Emmett a succession of the world’s largest fusion lasers were constructed at LLNL utilizing solid state technology, and used for plasma and implosion experiments. Nova, still the world’s most powerful fusion laser, was completed at LLNL in the mid-1980s, and has been used to conduct highly diagnosed indirect-drive experiments. Similar direct-drive experiments have been conducted at the University of Rochester, at the major Japanese ICF facility in Osaka, and elsewhere.

Laser fusion experiments established a solid understanding and database from which to design and construct the lasers and targets which will achieve ignition of DT in the laboratory. Recently, there has been a major declassification of ICF.

A 2-MJ, $800 million National Ignition Facility (NIF) laser has been proposed as the next step in the U.S. ICF program. The NIF is a major component of President Clinton’s stockpile stewardship without nuclear testing program. The achievement of ignition with the NIF will also be an important step toward an inertial fusion power plant.

For a power plant, an indirect-drive target similar to that to be tested on NIF would be driven by a high-efficiency, high-average-power heavy-ion accelerator such as that now being developed at the Lawrence Berkeley Laboratory.
ICF power plants are being designed with explosion chambers in which the first wall is shielded from heat and neutrons by lithium-rich fluid curtains. Engineers estimate that heavy ion-driven ICF power plants with shielded walls will be economically competitive. The DOE's long-range plan for development of ICF would lead to a power plant early in the second quarter of the twenty-first century.

Beyond the current mainline approach to ICF, there is enormous potential for improvement: it is theoretically possible to reduce the driver energy required to initiate the fusion pellet by a factor of 10 to 100.

Up to ten-fold reduction in the driver energy might be achieved by decoupling the ignition from the compression. In the "fast ignitor" approach now in the early stages of development at LLNL, when the DT reaches maximum compression via ablative implosion, a second, very high-power laser beam initiates thermonuclear burn by suddenly heating a critical-size hot spot on the pellet surface to ignition temperatures.

A second tenfold improvement would require the development of an efficient alternative to the ablative implosion. Such schemes are conceivable.
The achievement of a single tenfold improvement could give ICF significant competitive advantages:

- The driver cost would be negligible.
- Relatively small power plants would be economically attractive.
- Advanced fusion fuels such as DD and D³He could be used, leading to elimination of tritium breeding, substantial reduction in neutrons, and the enhanced production of charged particles, which could make possible significant improvements in the reactor thermal efficiency.

Realizing the highest potential of ICF is a magnificent challenge for future generations of fusion scientists and engineers. As with all approaches to nuclear energy, the highest potential must include meeting the threat of proliferation by technological and political means.

Many of ICF's leaders and major contributors are making presentations at this meeting. I hope this very brief summary of history and concepts has stimulated your interest.
References

1. President Clinton’s address to the United Nations, September 27, 1993.


