Laser fusion can meet defense and energy needs

Charles B. Stevens, in the first part of a two-part report, shows that this unlimited source of cheap energy is on the immediate horizon. Now Congress must act.

In recent congressional testimony Dr. Erik Storm, director of the Lawrence Livermore National Laboratory laser fusion program, documented that the laser approach to generating the virtually unlimited energy potentials of thermonuclear fusion reactions is ready to be developed. But, as Dr. Storm also detailed, the current policy is to cut back funding, even below minimal levels required to maintain existing research capabilities.

The irrationality of this do-nothing policy with regard to fusion energy is further demonstrated by the fact that the U.S. government is about to spend tens of billions of dollars over the coming decade to solve a problem which development of laser fusion reactors could solve much more effectively and probably at less cost. The problem is the current dilapidated condition of U.S. nuclear weapons production facilities. It is currently proposed to build six new nuclear fission production reactors to meet defense requirements into the first decades of the 21st century.

The fact is that one laser fusion reactor, operating at the energy output level of one of the proposed six fission reactors, could generate the same output of tritium—the primary weapon material required—as the six fission reactors combined. And it is probably the case that the total R&D cost for developing laser fusion and building such a prototype laser fusion reactor for tritium production would be about the same.

But the benefits would be immense. First, existing engineering studies show that laser fusion "would be cost-competitive with coal and with advanced fission reactors," according to Dr. Storm. Second, given the inherent scientific potentials of the fusion process, such as its high energy density, high quality of energy output, etc., the fusion process could be further perfected to provide even greater economies. Third, fusion provides a unique window on the frontiers of science and technology. Research utilizing fusion as a scientific tool will unlock entirely new possibilities, including that of the matter-antimatter reaction.

In this first part of a two-part report, *Executive Intelligence Review* presents a review of the status of laser fusion and its potential for meeting the existing requirements for tritium production. The second part will present extensive excerpts from the testimony of Dr. Erik Storm, Deputy Associate Director for Inertial Confinement Fusion at Lawrence Livermore National Laboratory, before the House Committee on Science, Space, and Technology's Subcommittee on Energy Research and Development.

Nuclear fusion

Nuclear fusion is the primary source for the energy output of the stars, including our Sun. In this case, the gigantic pressures and temperatures generated in the core of these massive bodies lead to the fusion of the nuclei of lighter chemical elements, such as hydrogen, to produce the nuclei of heavier chemical elements, such as helium. In this way, nuclear fusion is also responsible for the creation of the predominant elements which make up our Earth.

The easiest fusion reactions to ignite involve what are called the heavy isotopes of hydrogen, deuterium, and tritium. The ordinary isotope of hydrogen has a nucleus consisting of one proton. The deuterium nucleus consists of one proton and one neutron. The radioactive tritium isotope has one proton and two neutrons.

When a tritium nucleus and a deuterium nucleus are fused, they constitute the nucleus of a helium atom (two neutrons plus two protons) together with the release of one free neutron. The energy released during the reaction is extremely large, about 100 million times greater than that released by chemical reactions.

The energy from the fusion of one deuterium (D) and one tritium (T) is 17.6 MeV, where one MeV is equal to 1.6×10^{-13} joules and is roughly equivalent to a temperature of 110 billion degrees Celsius. (A 100-watt light bulb consumes 100 joules every second.)

The primary reaction energy is contained in the velocity of the reaction products. The helium nucleus having an energy of 3.5 MeV and the free neutron an energy of 14.1 MeV. From this it follows that over 80% of the primary fusion energy output is taken up by free neutrons, that is, 14.1/17.6 is about 0.8.

Fusion is extremely neutron rich compared to nuclear fission. And, unlike nuclear fission, maintaining the fusion reaction does not require the use of these free neutrons or the energy they contain. (The nuclear fission chain reaction is maintained by the neutrons generated during nuclear fission.)

This means that fusion's prolific neutron output can be utilized in many applications other than simply converting the neutron energy to heat. In fact, the fusion neutron can be used to either create fission in materials that ordinarily do not support a chain reaction, or to breed fissile fuel for nuclear fission reactors. This application of the fusion neutron can multiply the total energy output from tens to hundreds of times. And this energy multiplication can either take place immediately in a blanket surrounding the fusion chamber or over a much longer period through the extraction of fissile fuel from a breeding blanket and then later burning this fuel in a fission reactor.

It should be noted that a D-T fueled fusion reactor would require that tritium be bred from lithium because tritium does not occur in large quantities in nature. Tritium is also radioactive and has a half-life of 12.6 years, and must be replaced over a period of time in nuclear weapons. But existing designs show that a D-T fusion reactor would be quite prolific at breeding tritium, and only a portion of the fusion neutron output is needed to readily breed more tritium than is consumed in the reactor.

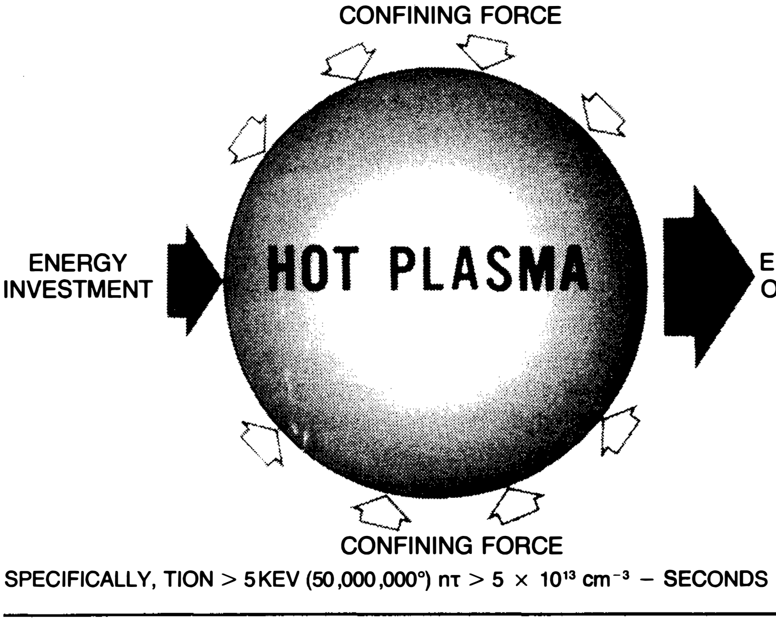
Fusion reaction conditions

The mutual electrical replusion of two positively charged nuclei is so great that it is difficult to get nuclei to come close to one another. Yet, when the right nuclei do, they will link up together to form one nucleus—nuclear fusion. A useful analogy is to think of the problem of rolling a ball up the slope of a volcano and into its mouth. If the ball does not have sufficient velocity, it will not make it up the slope to the crater. On the other hand, if it goes too fast, it can simply jump over.

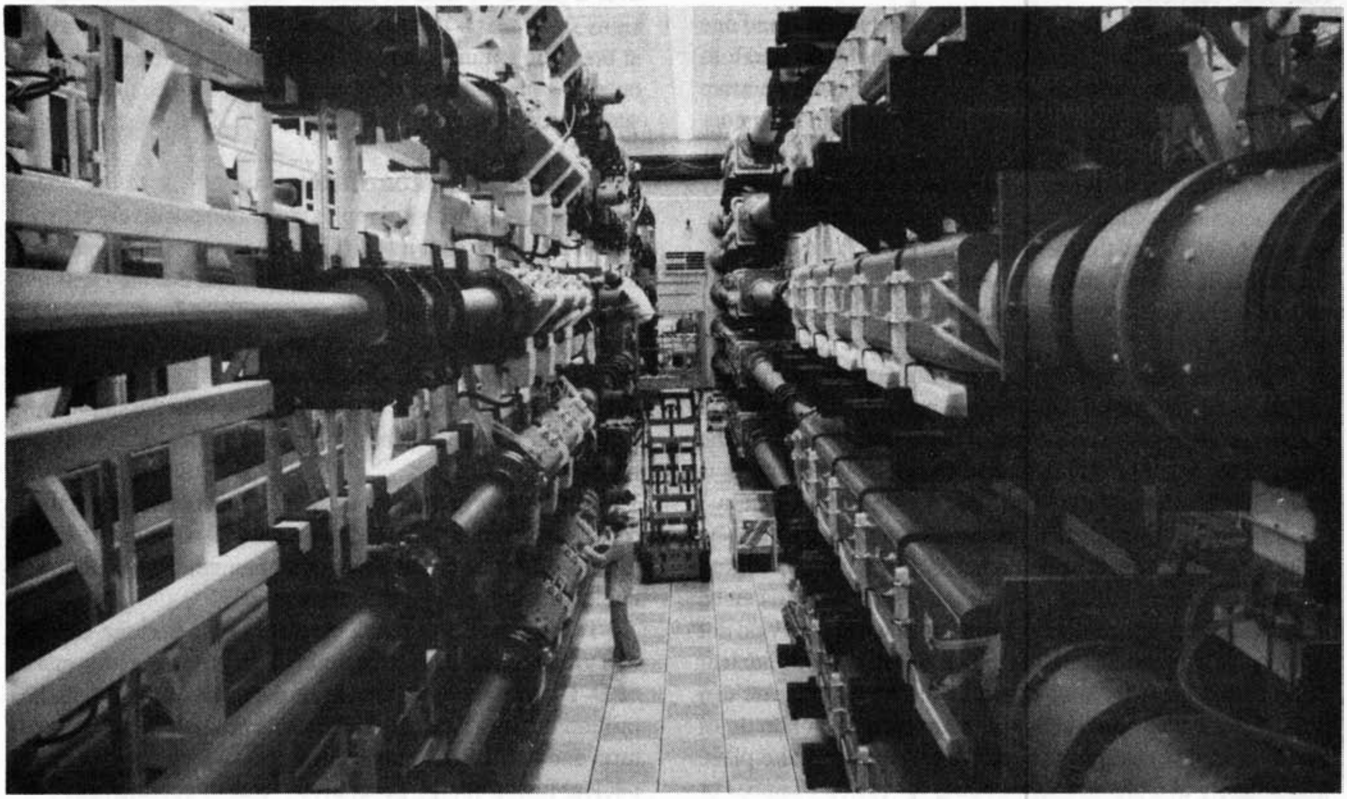
In the case of nuclear fusion, there is also an optimal relative velocity at which the two nuclei will join. At velocities less or greater than this optimal range, the likelihood of nuclear fusion taking place decreases.

Temperature provides a measure of the average velocity of a group of particles. The optimal velocity range for fusion of D-T corresponds to temperatures in the range of 50-100 million degrees Celsius. This is an extremely high temperature, and immediately raises a second major precondition for nuclear fusion energy generation—that of confinement.

At high temperatures, matter tends to rapidly diffuse, unless it is contained in some manner. One approach to fusion makes use of the fact that at these high temperatures matter becomes electrified—ionized plasma. And plasmas can be contained by magnetic fields. The use of "magnetic bottles" to contain and insulate fusion fuel is termed magnetic confinement fusion.



Confinement for fusion. Significant amounts of the nuclear fusion reaction occur at temperatures above 5 keV—a temperature above 50,000,000 degrees Celsius. At this temperature all matter becomes ionized gas, the so-called "plasma" state of matter. Also, the fuel would rapidly diffuse and thereby rapidly dissipate the fusion reactions at these temperatures unless something acts on the fuel to confine it. In one approach to fusion, magnetic fields are used to confine and insulate the fuel. In the ICF approach, the fuel is first driven to high densities at which the reaction becomes extremely rapid. If the density is high enough, the fuel will burn up before it blows up. In both the magnetic and inertial confinement fusion (ICF) approaches, some energy must be initially invested in confining and heating the fuel to fusion conditions. Energy gain is defined as the fusion energy output divided by this required energy input (investment).



The Livermore Nova Laser System. This photo shows technicians making the final adjustments on the 46 centimeter diameter amplifiers on the Nova Laser System. The amplifiers, the box-shaped device the technician is standing in front of, are composed of various optical parts including glass laser disks and energy pump flashlamps. These parts amplify a pulse of laser light so that it is powerful enough to impode a fuel pellet to fusion conditions. The Nova laser has more than 1,000 optical parts comprising more than 300 square meters of optical surfaces. This makes Nova the world's largest optical instrument, in addition to being the world's most powerful laser.

The second major approach to fusion is that of inertial confinement fusion (ICF). In this case, the fuel is brought to a sufficient density, and is suddenly ignited so that it will burn up before blowing up. That is, only the inertia of the fuel mass confines it.

How laser fusion works

ICF was first demonstrated with the successful detonation of the hydrogen bomb in the early 1950s. In the H-bomb, the intense x-ray radiation from an atomic bomb fireball is used to compress and shock ignite fusion fuel. This is done by placing the fusion fuel target and the atom bomb inside a chamber called a hohlraum, which derives from the German name used by Max Planck to describe blackbody radiation—*Hohlraumsstrahlung*.

The x-ray radiation from the atomic bomb fireball is absorbed by the inner chamber wall and reemitted as blackbody x-rays. The geometry of the chamber is arranged so that the reemitted x-ray blackbody radiation impinges from all sides on a spherical target of fusion fuel. The incident x-rays are absorbed in a surface layer of this target. This causes this surface layer to rapidly ablate outwardly. And like the exhaust from a rocket, this outward ablation causes an inward force on the remaining portion of the target. This inward force is actually a shock wave, and when done properly it takes the form of a spherically imploding shock front proceeding from the outer surface of the spherical target to its core.

When the imploding shock front converges on the center of the fuel, it will cause the fuel to be heated to extremely high temperatures. The passage of the compression shock wave can also cause the remaining fuel to be compressed to high density, if done in the proper fashion—that is, isentropic compression.

Once the imploding shock converges, it heats the core fuel to fusion temperatures. The hot helium reaction products will deposit their energy in the outer fuel regions, and in this way will heat the remaining fuel to fusion temperatures. That is, the hot core will generate a burn wave which passes through the outer fuel faster than it takes for the fuel target to blow up.

The realization of high-power lasers and particle beam accelerators opened up the prospect of miniaturizing the ICF process. In the H-bomb, billions of joules of radiation are used to drive hundreds of pounds of fuel to fusion conditions. With the prospect of higher power densities, through focusing of laser or high-energy particle beams, and much greater precision and versatility of laser beams, it was projected that energy-generating ICF could be carried out at energy outputs 1 million times smaller than in the case of the H-bomb. This level of energy output could be readily contained in a reaction chamber and thus converted to electricity and other useful forms.

The laser or particle beam driver used to accomplish this would operate with an output in the megajoule—millions of joules—range and a power level in the range of 500-1,000 trillion watts. The driver would ignite a pellet containing less than one one-hundredth of a gram of fusion fuel. The ignited pellet would generate over 100 times more energy than that of the driver laser. This ratio of fusion energy output to driver energy input is termed "pellet gain," or simply gain.

The key to miniaturizing ICF is the ability to drive the pellet fuel to super-high densities. At these higher densities, the fuel burns much more rapidly, so the required inertial confinement time is much less. The required density increase is about a thousandfold to 20 times that of lead.

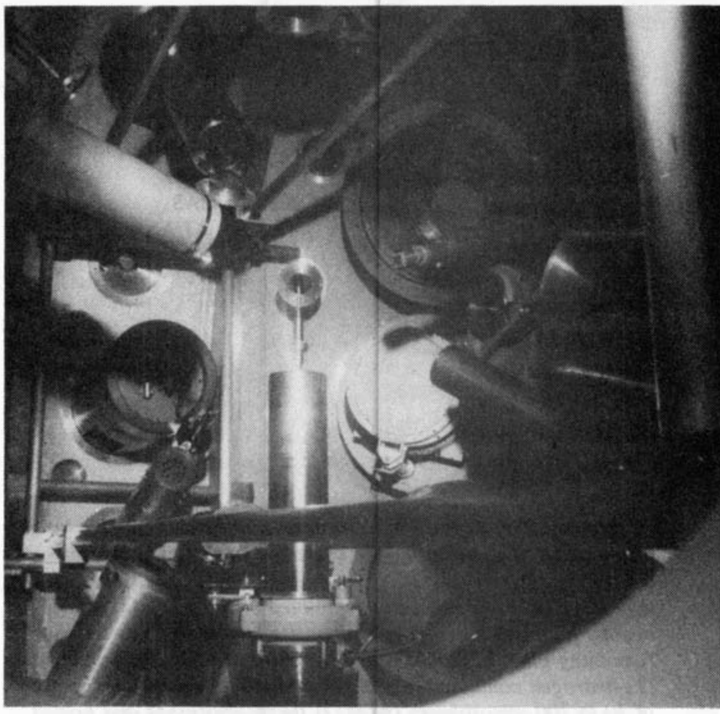
Such high densities are difficult to achieve and represent an entirely new frontier of science. First of all, in order to achieve such super-high densities, the compression process must be isentropic. That is, the fuel cannot be heated to too high a temperature during the time that it is being ablatively compressed. But it is still required that the converging shock wave be sufficiently intense to ignite the fuel core. Furthermore, the compression process must be extremely uniform; if not, there will be no significant overall compression.

Driving matter to such super-high densities also requires much higher power drivers and power densities. The coupling of the radiation to the pellet also becomes much more important. If the coupling is not efficiently converted to the hydrodynamic implosion of the pellet, the energy gain will be greatly reduced. The coupling must also not generate byproducts, such as "hot electrons," which would preheat the fuel and thus prevent isentropic compression to super-high densities.

Direct drive versus indirect drive

There are two different types of pellet target configurations in ICF. The first consists of a bare pellet upon which many beams are evenly directed. The incident laser light directly burns off the surface layer which drives the implosion. This approach requires extreme precision and uniformity in deposition of the laser energy. The longer wavelength of optical lasers is much more difficult to couple efficiently and without preheating effects than with blackbody x-rays.

The second approach is that of indirect drive targets, and is based on the basic physics of H-bomb design. In this case, the laser light is introduced into a hohlraum chamber. In the process, the laser light is absorbed and reemitted as soft x-rays—"blackbody" x-rays. The x-rays then impinge on a pellet target, also contained within the chamber. The shorter wavelength of the x-rays leads to more efficient, high quality coupling to the fuel pellet. Also, the geometry of the chamber and absorption/reemission process lead to a higher uniformity of irradiation of the fuel pellet. And this can be achieved even though the input laser light may be highly asymmetrical and non-uniform. That is, a much lower quality laser can be utilized.



Nova target chamber. This photo shows the Nova laser system target chamber. At the center of the vast array of diagnostics and alignment systems is a minute, one-millimeter glass capsule filled with deuterium and tritium fusion fuel. The glass target is at the center of the 15-foot diameter chamber. In one billionth of a second the ten beams of the Nova will implode this target to star-like fusion conditions. Mirrors are used to focus and direct the 10 laser beams of nova onto the minute glass capsule. The laser is housed in a separate building which has nearly the length of a football field and is five stories high.

But indirect drive hohlraums necessarily require much higher driver energies. This can be seen from the fact that a large fraction of the input energy is simply absorbed by the hohlraum without ever impinging on the fuel pellet. It is sort of like burning down the house to heat a pot of coffee.

Historically, though, mainline ICF efforts in the United States, Japan, France, and the U.S.S.R. have pursued indirect drive targets. This is due both to the fact that there is a much greater depth of knowledge about indirect drive, given the many decades of research into hydrogen weapon development, and that the lasers required for indirect drive are more readily built and have much greater versatility in terms of experimental applications.

The fact remains that even though indirect drive config-

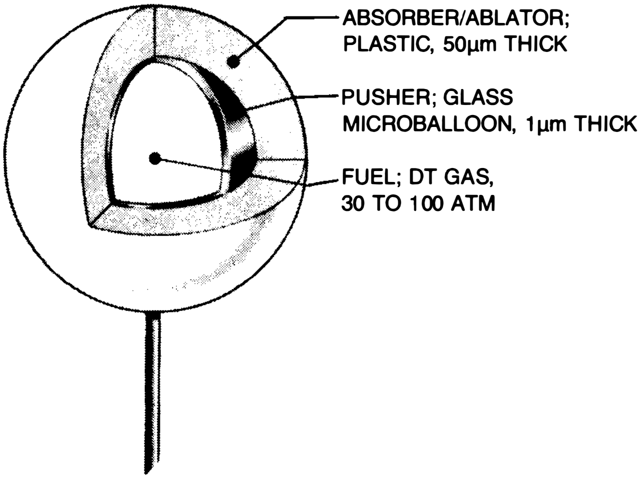


Diagram of ICF target. This is a diagram of a direct drive laser fusion pellet. The pellet has an overall diameter of .4 millimeters (400 microns). The outer layer is designed to absorb incident laser light. As this layer is ablated off by powerful laser beams, it causes an equal and opposite imploding force on the remaining glass microballoon. The deuterium (D) and tritium (T) hydrogen contained in this glass microballoon at a pressure of 30 to 100 atmospheres (ATM) is then compressed and heated to fusion conditions.

urations will be the first to demonstrate high gain, the scientific knowledge gained from this research will immediately benefit direct drive ICF research. Eventually, direct drive high-gain configurations will be achieved.

Research background

Laser fusion research has been carried out for about two decades in the United States. Despite continuing progress, the program was significantly cut back during the Carter administration. And efforts begun in late 1970s, were implemented during the Reagan administration to almost completely end the civilian ICF program and completely convert it to military research.

Given the lack of funds, sufficiently high-energy and high-power drivers have not yet been built to fully test high-gain pellets. To achieve the high gains required for energy production (gains greater than 100), a laser operating at almost 1,000 terawatt power levels with an energy output of between 5-20 megajoules would be needed. The currently largest facility is that of the Lawrence Livermore National Laboratory (LLNL) Nova laser system in California. This laser has a power level over 100 trillion watts and an energy output up to 100,000 joules. This is thus a factor of 10 too low in power, and 10-20 times too low in energy output to ignite high-gain pellets. The lasers that exist have been able to examine such questions as laser light coupling and absorption and x-ray generation. Innovative experiments have permitted the simulation of high-gain pellets with laboratory lasers. Driving matter to high densities and generating large-scale uniform compressions of spherical pellets have also been demonstrated.

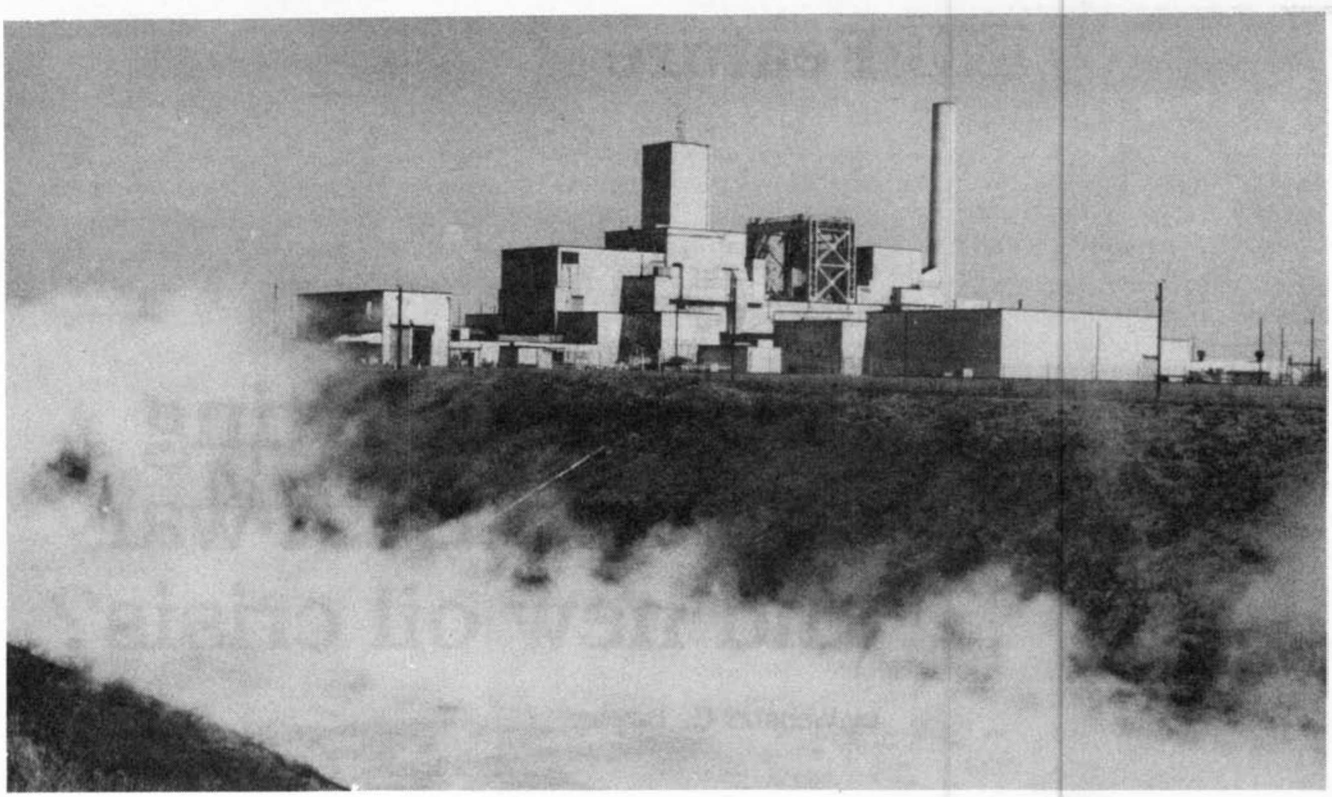
Halite/Centurion

While Dr. Erik Storm of Livermore details the achievement of major milestones in laboratory experiments, his congressional testimony revealed also that there has also been major progress in top secret experiments carried out in the Nevada nuclear weapons testing site under the codename Halite/Centurion:

"A classified component, Halite (at LLNL) and Centurion (at Los Alamos National Laboratory), utilizing underground nuclear tests at the Nevada Test Site. The purpose of this component is to study the design characteristics of efficient ICF targets. Halite and Centurion have played a vital role in establishing our confidence in the scientific feasibility of ICF. . . . As discussed above, the principal approach to inertial fusion in the United States involves the use of indirectly driven targets. In this concept, energy from a laboratory driver is converted to x-rays that are used to implode and heat the fusion fuel in an inertial fusion capsule. The ability to study and understand the performance of such capsules in the laboratory has been limited by the energy and power that can be provided with presently available lasers. In Halite/Centurion, a portion of the much greater energy from a nuclear device in underground explosions at the Nevada Test Site has been used to implode inertial fusion capsules, thereby extending the range of inertial fusion research. These experiments have produced excellent results, contributing to our increased confidence in the basic feasibility of achieving high-gain ICF. The combination of Nova and Halite/Centurion data and the recent development of cryogenic high-gain target fabrication technologies makes us sure that in the next three to five years we can obtain the data and demonstrate the technology necessary to resolve the remaining target issues."

Given the limitations of classification, this means that the essential scientific questions concerning whether super-high-density, high-gain pellets will work has been, or is shortly about to be, experimentally resolved. The only real barriers to realization of commerical laser fusion is the lack of the political will to do so.

But Dr. Storm also reveals that the existing budget levels and cuts that are being proposed "has had a serious impact on our program." He points out: "This year we have had to impose a drastic curtailment in Nova experiments, severely reduce technology development efforts for advanced drivers, eliminate technology development for reactor drivers, and reduce work on power-plant concepts to paper studies. This has resulted in a recent staff reduction of 60 more people. With continued funding at this level, the LLNL ICF Program would of necessity become a one-component program within about three years, comprising Nova experiments only; we would probably have to abandon attempts to develop a low-cost, high-energy laser driver by the early 1990s, and all



Weapons Materials Production Reactor. This is a photo of the Savannah River Plant production reactors. These nuclear fission reactors generate tritium fuel used in nuclear weapons. It is currently proposed to build six production reactors to replace ones currently becoming obsolescent. One ICF fusion reactor could produce the equivalent output of tritium.

work on ICF energy-production technologies."

Most ominously, Dr. Storm was able to report that "the Halite program has been suspended."

Getting back on track

In this context, the requirement to rebuild and modernize the nuclear weapons production infrastructure provides a unique opportunity. As Dr. Storm notes in his testimony, fusion will probably be used first as a hybrid system. That is, the prolific neutrons from fusion will be used to generate fuel for nuclear fission reactors. But even before this sort of application of fusion could be realized, it is quite possible to use a fusion reactor for the production of tritium needed for nuclear weapons.

An ICF reactor for tritium production would require the minimum in terms of technology and science. Unlike an electric power plant, which must operate most of the time in order to be economical, the tritium production facility could be operated quite economically with frequent and long duration interruptions.

It is currently proposed to build six fission reactors to meet defense needs after the year 2000. One laser fusion reactor, operating at the same power level as just one of these fission reactors, could produce the same output of tritium. As noted previously, this is because of the prolific neutron output of fusion.

Therefore, the crisis facing the nuclear weapons materials production infrastructure provides the United States with the opportunity to turn around today's irrational energy policies and get America back on the road to scientific progress. Even from a cost standpoint, accelerating the fusion program is an ideal answer to meeting this essential defense need. With a crash effort, a laser fusion reactor for tritium production could be brought online before the year 2000.

This step would be quite logical even without considerations of national security. The tritium production facility would actually constitute an engineering test reactor to test more advanced technologies required for fissile fuel breeding and pure fusion electric power reactors. The tritium production facility could also be used to test various methods of burning up fission reactor radioactive wastes.

Most significantly, a program to develop these advanced technologies would revive the U.S. nuclear industry and put America first, again, in these fields which comprise the largest portion of the frontiers of science and industry. And given the overall spin-off benefits of developing fusion, this advanced-track program would pay for itself many times over before it were completed. Such a course of action makes far more sense than simply turning the clock back 35 years to build an improved fission reactor.