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The dawn of star power: laser fusion in sight

The science for the "internal combustion engine" of the next century has been experimentally demonstrated in a series of breakthroughs. By Charles B. Stevens.

On July 15, 1985 the National Academy of Sciences' National Research Council submitted an interim report on laser fusion to President Reagan's science adviser, who was then Dr. George A. Keyworth. The Academy report predicted: "It is quite likely that the results of the Nova, PBFA-II and Halite-Centurion programs over the next three to four years will indicate whether a laboratory microexplosion can be achieved as well as the required size of the driver."

Now, researchers at the California-based Lawrence Livermore National Laboratory report that they have experimentally demonstrated the science for harnessing the "internal combustion engine" of the 21st century—the thermonuclear-powered laser fusion reactor. At the same time, a detailed study by Los Alamos National Laboratory has concluded that the KrF excimer laser could be developed into a practical inertial confinement fusion (ICF) laser driver within the coming decade. Thus, fusion can still be realized before the year 2000 to provide a virtually limitless source of cheap and abundant energy and clean hydrogen fuel, and the rocket to conquer the solar system.

Because of this major breakthrough in harnessing the energy source of the stars by Livermore fusion scientists, prototype laser fusion reactors could be producing electricity at half the present cost of fossil and fission power plants within the next decade. Fusion-powered hypervelocity ramjets will reduce travel time between New York and Tokyo to less than two hours. And given a sufficient effort, an interplanetary fusion rocket will carry men and women to Mars before the year 2000—a trip which will take only a few days instead of the year-long transit times projected for chemically powered systems.

On Friday, Aug. 7, 1987 Livermore researchers succeeded in compressing a tiny pellet of fusion 64,000-fold utilizing the 100 terawatt-plus Nova glass laser system. And Dr. Stephen O. Dean, head of Fusion Power Associates, stated the week before that this would be the level of compression needed to ignite high-gain thermonuclear fusion reactions, like those produced in the dense, high-pressure cores of stars, and to therefore realize practical laser fusion reactors.

The initial breakthrough came last May when Livermore scientists compressed fusion fuel pellets 27,000 times in volume. "The first time we did that specific experiment in May, we were so astonished that we did so well so easily," reported Erik Storm, Lawrence Livermore's deputy associate director for laser fusion. "We had expected it would take us many, many months to control the environment around the target and we thought we'd have to go to very carefully shaped laser pulses," Storm said. "We did the experiment more to see how badly it would fail, and it didn't. It just blew us out of the water, quite frankly."

This 27,000-fold compression experiment was repeated in June "to convince researchers that the first successful try wasn't a fluke." "This is like reducing a basketball to the size of a marble," said Dr. Storm. (The 64,000-fold compression is like reducing a basketball to the size of a pea.) Storm reported that his team had previously used the 10-beam Nova laser to reduce the tiny fusion fuel spheres—which are the size of a grain of sand—by between 125 and 2,200-fold in volume. "We had expected that it would take a year-and-a-half of very careful experiments."

"At that time, we couldn't believe the results; they were so good," Storm said. "It took us several weeks to make more fuel capsules to duplicate the experiment. Then last week we decided to push the limits and we got higher convergence. It seems Mother Nature is smiling on us."

According to Sue Stephenson, spokeswoman for Lawrence Livermore, "These experiments confirm the belief that the conditions required to achieve the ignition of small capsules of fusion fuel can be achieved using lasers or similar methods." Dr. Storm reported that this series of experiments, combined with results from the top secret Halite-Centurion program, gives him "very high confidence" that practical laser fusion is possible.

National Academy of Sciences Report

At the time that the National Academy of Sciences issued its report on laser fusion, July 15, 1987, the Reagan administration attempted to suppress the report. (The report was only made public eight months after it was submitted to the White House.) The reason for this was that the report's evaluation and recommendations contradicted the stated administration policy of putting the laser fusion program under wraps. In fact, the Reagan budget request for fiscal year 1987 proposed reducing the laser fusion program to only $23.8 million, a de facto phase-out of the civilian laser fusion program. And in the 1986 budget, Reagan had proposed a cutback from $168 million spent in 1985 to $70 million, but Congress voted to restore the budget to a level of $155 million.

The 1985 National Academy study concluded that the laser fusion "program is today a vigorous and successful research effort which has made striking progress over the past five years." At the time of the report's release, the chairman of the study, Prof. William Happer, Jr. of Princeton University, reported that "we know of no physical reason why the goal of the program cannot be achieved." But as one senior official from the Department of Energy's Inertial Confinement Fusion (ICF) division wryly noted at the Fusion Power Associates seminar held in the last week of August at Princeton Plasma Physics Laboratory, "The more we make progress toward demonstrating the viability of commercial ICF, the more the administration moves to downgrade the program."

Making stars on Earth

Thermonuclear fusion reactions power the stars and provide the means through which the chemical elements, which make up our biosphere, are generated. Deep within the core of stars, such as our Sun, tremendous gravitational forces are generated by their huge mass. This produces the pressures and temperatures needed to ignite thermonuclear fusion reactions. In general, thermonuclear reactions consist of the "fusing" of the nuclei of lighter elements to form the nuclei of heavier chemical elements. (In our Sun, four ordinary hydrogen nuclei are fused to form helium, the next heavier element.)

Besides generating most of the chemical elements, nuclear fusion also produces net energy. This is the energy source which lights up the stars. Nuclear fusion generates upwards of four times the energy per unit mass of reactants than nuclear fission of uranium or plutonium, and tens of millions of times more than that of fossil and other chemical fuels.

One gallon of seawater contains enough "heavy" hydrogen fusion fuel to produce the equivalent energy of 300 gallons of gasoline. (See box on fusion.) And while the actual fusion fuel is only a minute part of this gallon of seawater, it is cheaply and readily extracted today at a cost of a few pennies.

Fusion energy generation was first demonstrated with the successful detonation of hydrogen bombs in the 1950s. With the advent of the laser in 1961, research efforts were initiated throughout the world to explore the possibilities of generating a "micro"-hydrogen bomb, a laser-produced fusion microexplosion.

A large nuclear fission-powered atomic explosive is utilized to ignite a hydrogen bomb. In the H-bomb, both the fission explosive and hydrogen fusion fuel are placed inside a small chamber called a hohlraum. When the fission explosive is detonated its initial output primarily consists of x-rays. The hohlraum chamber acts to both momentarily contain and transform these atomic bomb-generated x-rays. During the few billionths of a second that the hohlraum does this, the atomic bomb x-rays are absorbed and re-emitted as soft x-rays within the chamber. The geometry of the hohlraum is such that the soft x-rays are then directed onto the fusion fuel.

This intense burst of x-rays then drives the fusion fuel to the pressures and temperatures needed to ignite thermonuclear reactions. This is accomplished through ablative implosion and shock heating of the fusion fuel. The hydrogen fusion fuel literally "burns up" before it blows up. And while it is "burning," that is, undergoing thermonuclear fusion, the only force containing the fuel is that of its own inertia. For this reason, this general approach to fusion, as opposed to magnetic fusion where magnetic fields are used to contain hydrogen plasmas, is called inertial confinement fusion (ICF).

There are two general routes to achieve ICF. The first consists of direct drive, in which lasers or high-energy particle beams are used to compress and heat a small pellet of fusion fuel. The second is that of indirect drive, in which the same lasers or high-energy particle beams are used to generate soft x-rays, which are then used to compress the small fusion fuel pellet. The second indirect drive, or what is termed hohlraum approach, is of the same general characteristics that are used in the design of H-bombs, and most details of this indirect drive approach are therefore kept highly secret.

Since the early 1960s, there has been significant progress in the design and construction of high-energy lasers. Liver-

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What is nuclear fusion

Everything in nature, solid, liquid, or gas, is made up of one or more of some 92 different elements. An atom is the smallest portion of an element that can exist, while retaining the characteristics of that element. The lightest atoms are those of the element hydrogen, and the heaviest atoms occurring naturally in significant quantity are those of uranium.

Atoms, although extremely small, have an internal structure. Every atom consists of a central nucleus, carrying nearly all the mass of the atom, surrounded by a number of negatively charged electrons. The nucleus of an atom has a positive electrical charge which is balanced by the negative charge of the electrons. Consequently, in its normal state, the atom as a whole is electrically neutral.

All atomic nuclei contain even smaller particles, called protons, and all except one form of hydrogen also contain neutrons. The protons have a positive electric charge, and the neutrons have no charge. The protons are thus responsible for the electric charge of the nucleus. Each atomic species is characterized by the number of protons and neutrons in the nucleus.

Fusion reactions

There are many different nuclear fusion reactions which occur in the Sun and other stars, but only a few such reactions are of immediate practical value for energy production on Earth. These primarily involve forms (isotopes) of the element hydrogen. Three isotopes of hydrogen are known; they are hydrogen (H), deuterium (D), and tritium (T). The nuclei of all three isotopes contain one proton, which characterizes them as forms of the element hydrogen; in addition, the deuterium nucleus has one neutron and the tritium nucleus has two neutrons. In each case, the neutral atom has one electron outside the nucleus to balance the charge of the single proton (see **Figure 1**).

To produce net energy, fusion reactions must take place at high temperatures. The power production process which can occur at the lowest temperature and, hence, the most readily attainable fusion process on Earth, is the combination of a deuterium nucleus with one of tritium.

The products are energetic helium-4 (He-4), the common isotope of helium (which is also called an alpha particle), and a more highly energetic free neutron (n). The helium nucleus carries one-fifth of the total energy released and the neutron carries the remaining four-fifths.

This D-T reaction and some other possible candidates are listed below:

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n} + 3.2\ \mathrm{MeV}^{*}$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T} + \mathrm{p} + 4.0\ \mathrm{MeV}$$

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$$

(See **Figure 2** for illustration of D-T reaction)

$$\mathrm{D} + \mathrm{He\text{-}3} \rightarrow \mathrm{He\text{-}4} + \mathrm{p} + 18.5\ \mathrm{MeV}$$

* MeV = million electron volts. An electron volt is a unit of energy equal to the energy acquired by an electron passing through a potential difference of one volt. 1 MeV $= 1.52 \times 10^{-16}$ BTU $= 4.45 \times 10^{-20}$ kilowatt-hours

FIGURE 1

Fusion reactions

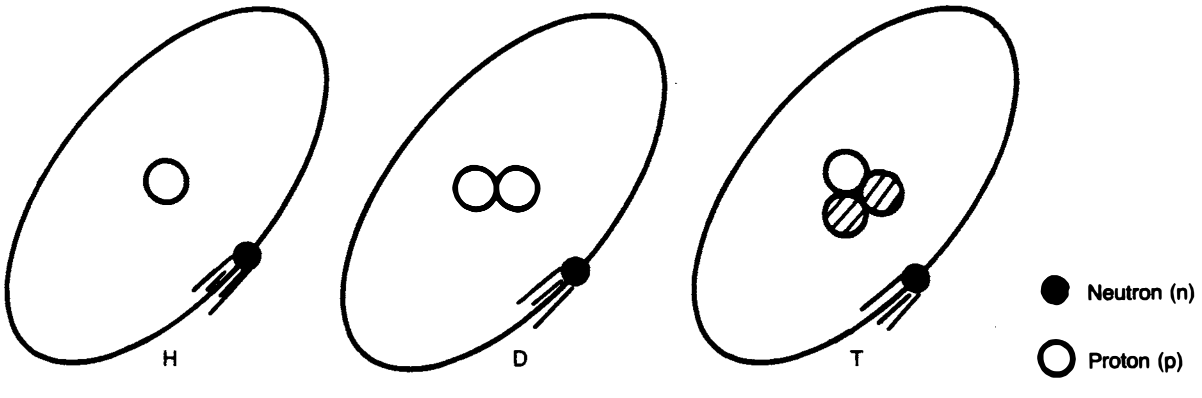
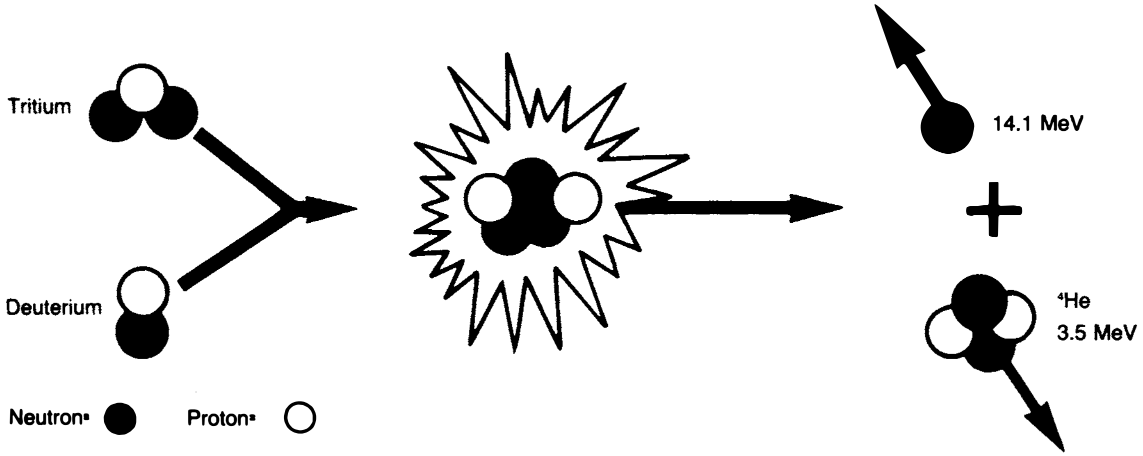


FIGURE 2
Conditions for fusion



= 1.6×10^{-13} joules.

Since nuclei carry positive charges, they normally repel one another. The higher the temperature, the faster the atoms or nuclei move. When they collide at these high speeds, they overcome the force of repulsion of the positive charges, and the nuclei fuse. In such collisions resulting in fusion, energy is released.

The difficulty in producing fusion energy has been to develop a means which can heat the deuterium-tritium fuel to a sufficiently high temperature and then confine the fuel long enough, such that more energy is released through fusion reactions than is consumed in heating and confining the fuel.

Temperature: In order to release energy at a level of practical use for production of electricity, the gaseous deuterium-tritium fuel must be heated to about 100 million degrees Celsius. This temperature is more than six times hotter than the interior of the sun.

Confinement: High as these temperatures are, they are readily attainable; the problem is how to confine the deuterium and tritium under such extreme conditions. One general approach is to deploy magnetic fields to confine the hot fuel, based on the fact that, at multimillion-degree temperatures, hydrogen becomes ionized, i.e., it becomes a plasma in which the electrons are separated from the nuclei. Because of this, the electrically charged electrons and nuclei can become trapped along magnetic "force field" lines. By using the appropriate geometry of magnetic fields, the plasma can be confined and insulated with a "magnetic bottle."

The second major approach to fusion is that of inertial confinement fusion (ICF). In this approach, the fusion fuel is driven to high densities so that it will "burn up" before it blows up. The object here is to generate gigantic pressures, like those found in the center of stars, in order to compress the fuel to high densities.

In both types of fusion, magnetic and inertial confinement, the measure of the net energy output is given by the Lawson product of the fuel density and the energy confinement time—the time during which the temperature of the plasma must be maintained. For D-T magnetic fusion, this product must be about 100 trillion nuclei per cubic centimeter times one second. That is, if the fuel density is 100 trillion nuclei per cc, then it must maintain its 100 million degree Celsius temperature for 1 second on the average. These are parameters characteristic of magnetic fusion.

For inertial fusion, the densities are almost a trillion times greater. But because inertial confinement fusion involves a dynamic burn, it must obtain a higher Lawson product—10 to 100 times greater.

In an ICF system, the energy confinement time is proportional to the radius of the compressed fusion fuel. The Lawson product can then be given in terms of the product of the fuel density and radius. This is termed the "rho-r" of the fuel. For high-gain ICF, where 100 times more fusion energy is generated than the energy of the laser input, rho-r's of about 3 grams per square centimeter are required. Densities would be several hundred grams per cc—an order of magnitude greater than that of lead. At such densities only a couple of milligrams of fusion fuel would be used, as compared to several hundred thousand grams needed in hydrogen bombs. The compressed radius of the fuel would be about 30 microns.

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more began its laser fusion R&D with a one-joule, billion-watt laser. Today, the 10-beam Nova glass laser system generates up to 100,000 joules at a power level greater than 100 trillion watts. Nova is currently the world's most powerful high-energy laser. Other lasers operating in Japan, the Soviet Union, and France generate tens of thousands of joules at levels of tens of trillions of watts in power levels.

Because of its intrinsic characteristics and the fact that it has been researched intensively for almost four decades, the indirect drive hohlraum approach is currently considered the easiest approach to ICF to demonstrate scientifically. However, for power reactors, the indirect drive approach would necessitate much greater energy levels because of energy losses during the transformation of the laser energy to soft x-rays. It is hoped by many ICF scientists that once high-gain laser fusion has been realized through R&D on hohlraum targets, the knowledge gained can then be utilized to achieve high-energy gains with direct drive targets. And this is indeed what the Livermore results are demonstrating. Direct drive ICF power reactors could operate with lasers 100 times smaller than those required for indirect drive.

The Livermore program

The current objective of the Livermore Nova program is to demonstrate the science of high-gain ICF. The Nova effort incorporates general experiments on the interaction of laser light with matter in order to achieve efficient coupling of the laser energy to the fusion fuel. For indirect drive this means that the efficient production of soft x-rays within a closed chamber—the hohlraum—is the chief objective.

Moreover, Livermore plans to test scale models of high-gain reactor targets which fully integrate all aspects of ICF. For indirect drive, it has been projected that a short-wavelength laser, operating at between one-quarter to one-third micron, would put 3 million joules of laser light with a power level of several hundred trillion watts in order to achieve a fusion energy output of 300 million joules—that is, a gain of 100.

Livermore's Aug. 7 result demonstrates that hohlraum pellets can be stably compressed to the high densities needed for high gain at the projected levels. Also, since this result was achieved so readily, it opens up bright prospects for further developments leading to higher gains for hohlraum targets and the possibility of developing direct-drive, high-gain targets which could be ignited with lasers 100 times smaller.

The key to achieving this will be the mastering of the Rayleigh-Taylor hydrodynamic instability.

One of the major, if not *the* major, aspects of laser fusion target operation is that of hydrodynamic stability. If the target becomes turbulent during the implosion, a spherically convergent compression is not attained and only low fuel densities can be achieved.

Laser fusion

With the realization of the laser in the early 1960s scientists in the United States, the Soviet Union, France, Great Britain, India, and Japan began to explore the possibility of substituting a much smaller pulse of intense laser energy for the rather large pulse of atomic bomb x-rays. And in 1972 much of this research was declassified and presented in published scientific articles.

The basic idea is that coherent laser light or directed particle beams can be focused to extremely high power densities. And through the mediation of ablative implosion of spherical targets of fusion fuel, these power densities can be translated into gigantic pressures, like those found only in the cores of large stars. Furthermore, this opened the prospect of "driving" hydrogen fusion fuel to extremely great densities—orders of magnitude greater than that of lead.

At these superdensities, the fusion fuel burns up much faster so that the minimum size needed for net energy generation becomes much smaller. In particular, the size of an ICF energy-producing system scales inversely with the square of the fuel density. That is, if the fuel density could be increased a thousandfold, then the size of the energy-producing thermonuclear explosion could be decreased a millionfold less than that of the H-bomb. And the necessary radiation input (soft x-rays) could also be decreased a millionfold.

Actually, it is possible to further improve on this miniaturization of the H-bomb through bootstrap heating of the fusion fuel. That is, most of the fusion fuel is only compressed and not heated to fusion temperatures. A small core region of the compressed fuel is heated to the more than 100 million degrees Celsius needed to ignite hydrogen fusion. The fusion output from this "spark plug" core heats the remaining fuel, and is burned up by a thermonuclear burn wave before blowing up.

This means that the necessary preconditions for igniting energy-producing fusion could be reduced more than 100 millionfold. A few tens of thousands of joules of laser light—the energy equivalent of burning a 100 watt light bulb 5 minutes—could ignite enough fusion fuel to generate 100 times more fusion energy—a gain of 100.

But until the recent breakthroughs with the Livermore

Nova Laser and Halite-Centurion, it appeared that this ideal minimum could not be readily attained. It appeared that multi-hundred terawatt (a terawatt is a trillion watts) systems developing millions of joules of laser light would be required. Such lasers are only now being designed and will not be built until the early 1990s.

The recent breakthroughs scientifically demonstrate that such multi-megajoule lasers will indeed be capable of harnessing practical ICF. But they also open the prospects for achieving the originally calculated ideal minimum. This possibility could dramatically increase the economic and technological benefits of ICF.

For example, detailed engineering designs for ICF power reactors based on multi-megajoule lasers show that laser fusion could produce electricity for half the cost of present fossil and fission systems. The chief factor in this computed cost is that of the reactor's capital cost, and, in the advanced cycle systems reviewed in a 1983 Livermore study it was the laser that constituted the chief expense in this regard. Reducing the laser by a hundredfold would substantially reduce the capital cost. (This is particularly true for the case of utilizing multiple chains of fusion targets, where the initially small, laser-ignited fusion microexplosion is used to ignite a second, much larger fusion microexplosion.) Electric power cost reductions of an order of magnitude are not inconceivable. And for fusion rocket propulsion the potentials are far greater.

Laser fusion requirements

There are two basic approaches to laser fusion.

I. Direct drive: This approach consists of directly irradiating a small spherical pellet of fusion fuel with short, powerful pulses of laser light. The laser light burns off a thin surface layer of the pellet and heats it to form a plasma—an ionized gas. Thus, a very fast jet of ionized gas streams outward from the pellet surface at a velocity of about 1,000 kilometers per second. The fast jets of plasma rising from the surface cause the remaining surface to be accelerated inwardly. This is exactly the same dynamic that propels rockets.

If the resulting inward acceleration of the spherical pellet surface is symmetric, then the result will be a spherically convergent implosion of the remaining material of the pellet. (If the acceleration of the surface is not symmetric around the entire surface of the pellet—such as could occur if the laser light were not symmetrically deposited, or, if the surface became turbulent, that is, hydrodynamically unstable—then the implosion would be divergent and not achieve the maximum compression—the smallest possible implosion volume.)

II. Indirect (hohlraum) drive: In this approach the intense laser pulses are not directly deposited onto the fuel pellet. Instead, the laser pulses are directed into and trapped in a chamber called the hohlraum. In the process of passing into and being trapped within the hohlraum, the laser light is absorbed and re-emitted as soft x-rays. The soft x-rays then irradiate and drive the implosion of the spherical fuel pellet. In this case, the laser light "indirectly" drives the implosion of the spherical fuel target.

The indirect drive is much easier to achieve scientifically, both because the hohlraum approach has been extensively researched as an essential part of the H-bomb design, and, because the transformation of the laser light into soft x-rays leads to intrinsically symmetric energy deposition on the fusion fuel pellet, it, therefore, produces a highly symmetric, convergent implosion. But, indirect drive necessitates utilizing a larger input energy, since a large fraction of the input laser energy is lost in the transformation process and in heating the hohlraum. It is possible that the direct drive approach could unlock significant outputs of fusion energy—high gain—with laser energy inputs 100 times smaller than that of the hohlraum.

The major issues which face both the direct and indirect drive approaches to ICF are: 1) efficient coupling of the laser energy: a) efficient generation of soft x-rays for indirect drive; and b) efficient and symmetric ablation of the pellet surface for direct drive; 2) efficient conversion of pellet rocket ablation into a spherically symmetric and stable hydrodynamic implosion; 3) tailoring of the hydrodynamic implosion to achieve an "isentropic" (zero entropy change) and adiabatic shockwave-driven compression of the fusion fuel in order to attain superdensities; 4) the generation of the temperature spark to 100 million degrees Celsius within the compressed core, which is most easily achieved through the convergence of a series of weak compression shockwaves at the center of the pellet.

The first and third processes are intimately related. If, during the deposition of the radiation to generate rocket ablation, the remaining, interior portions of the pellet are heated, then efficient compression to superdensities cannot be achieved. The remaining fuel to be compressed must be kept relatively "cold" during the compression process. This can be achieved if the deposition of the radiation on the ablation surface only produces heat at that surface and if the hydrodynamic implosion unfolds as a temporal series of "weak" shockwaves. The sparking to fusion temperatures in the core can still be achieved if each of the successive weak compression shocks is made slightly faster in speed, such that they all converge simultaneously on the pellet core.

The use of hollow spherical shells for fusion fuel pellet configurations is key to lowering the laser energy and power inputs necessary to achieving high gain. Utilizing hollow spheres increases the time over which the laser energy can drive the pellet to higher velocities before compression begins. And this is particularly key in allowing the pellet to achieve high hydrodynamic efficiencies.

In moving between two fixed points, rockets are most efficient when rocket velocity approaches that of exhaust velocity. By increasing the time during which the fusion fuel can be accelerated to higher and higher velocities at a low power level, the rocket efficiency of the pellet implosion during the high-power, final implosion stage can be greatly increased. It is through this velocity-matching that the required laser energy input can be decreased 100-fold.

Hollow pellets are more susceptible to the Rayleigh-Taylor hydrodynamic instability.

The Livermore results

The Livermore results are most spectacular with regard to the Rayleigh-Taylor instability. The originally projected year-and-a-half of experimentation was to have been chiefly concerned with developing procedures to reduce the expected Rayleigh-Taylor instability. But the Rayleigh-Taylor instability only began to emerge once the Nova was taken to its highest energy level. And even then, only a mild form of instability arose.

This means that the same techniques that had previously been thought requisite for any significant compression can now be utilized to significantly improve the performance of laser fusion targets, which thereby significantly relaxes the requirements for laser fusion reactors. Before exploring these prospects in greater detail, I will review some of the as-yet-unutilized methods of suppressing the Rayleigh-Taylor instability.

The Rayleigh-Taylor instability can be greatly enhanced during the early stages of the pellet implosion. When the initial radiation pulse strikes the surface of the fuel pellet, the pellet shell is immediately compressed. This means that the imploding shell will initially have a higher aspect ratio than the unradiated pellet. The higher aspect ratio leads to a greater tendency toward the Rayleigh-Taylor instability. This problem is referred to as the "inflight" aspect ratio.

A second problem is that the hollow pellet is much more susceptible to Rayleigh-Taylor during the initial stage of implosion. This is particularly true if the imploding shell experiences a large initial acceleration. Acceleration drives the Rayleigh-Taylor instability, in general, and the pellet is particularly vulnerable during the initial implosion phase when it has a high inflight aspect ratio.

Two methods of overcoming these dangers are laser pulse shaping and pellet engineering. It is most significant that neither was utilized in achieving the Livermore success. Nova will shortly have incorporated laser pulse shaping capabilities. The incident laser pulse can then be shaped to produce minimal inflight increases in aspect ratio and acceleration during the initial stages of implosion. This should further significantly suppress whatever Rayleigh-Taylor instability that has arisen. The result will be that higher aspect ratio pellets can be symmetrically imploded.

Pellet engineering can also significantly reduce Rayleigh-Taylor, through the introduction of various layers of material other than the fuel itself to the pellet. These additional layers can have various densities and other properties that suppress or break up the Rayleigh-Taylor instability. A possible example is to utilize several different wavelengths of radiation to implode the pellet. The differing wavelengths deposit their energies at differing depths in the ablating surface of the pellet, which can suppress or stabilize the Rayleigh-Taylor instability. Other methods such as pellet rotation are conceivable.

The existing Livermore results are sufficient for assuring high-gain (100 times) pellets for practical laser fusion. New experiments using the above and other techniques should substantially improve the performance of laser fusion pellets. It is generally thought that Livermore is currently using hohlraum pellets with an aspect ratio on the order of 40. Further research should improve this by as much as an order of magnitude. But a fivefold increase, to, say, an aspect ratio of 200, could revolutionize prospects for direct-drive laser fusion.

The reason is that exploring the Rayleigh-Taylor with hohlraum indirect drive provides the experimental basis for mastering the implosion process in general. Hohlraum targets operate with the ideal wavelength of radiation, about one-hundredth of a micron—the wavelength of soft x-rays, and with an ideal spherically symmetric deposition of driver energy. But hohlraum targets necessarily involve larger energy inputs and intrinsic inefficiencies due to the transformation of laser light into soft x-rays. Given that the full parameters for Rayleigh-Taylor are experimentally established, direct drive target and laser researchers will have the essential parameters needed to design high-aspect ratio targets. An aspect ratio of 200 would permit high gain to be reached with a mere 30,000 joules of direct-drive laser energy. This is 100 times less than currently projected for hohlraum targets.

This would substantially reduce the capital cost and size of laser fusion reactors. And capital cost is the primary cost for producing electricity from laser fusion. Fuel costs are virtually negligible. Existing Livermore reactor design studies have shown that hohlraum-type systems could generate electricity at half the cost of existing types of nuclear fission and fossil fuel power plants. Decreasing the required laser input 100-fold could further decrease the cost of electricity generation by an order of magnitude. We could achieve this by both increasing the repetition rate—the number of fusion microexplosions per second—and by utilizing the initial fusion pellet output to implode a second, larger pellet.

Halite-Centurion

As quoted above, the National Academy of Sciences prediction for success in ICF rested on both the Livermore Nova and the Los Alamos-Livermore joint project, Halite-Centurion. In announcing the Livermore breakthrough, both Dr. Storm and Department of Energy officials have reported that Halite-Centurion has also achieved success. In reality the Halite-Centurion results are far more significant than those of Nova.

According to the National Academy of Sciences 1985 result, Halite-Centurion is a top secret project that would demonstrate full-scale reactor-grade ICF targets within "five years." In 1986, *Science* magazine reported top secret congressional testimony that was inadvertently released, which showed that Halite-Centurion consisted of a special underground nuclear weapons test facility. During the early 1970s, R&D Associates, a West Coast defense company, developed detailed designs for harnessing, in a practical fashion, the energy output of hydrogen bomb explosions. The system was called Project Pacer. The basic idea was to create large chambers in geological salt-dome deposits. The salt-dome chamber could contain and withstand many large H-bomb detonations. Water would be injected into the chamber and steam would be extracted for electricity generation. Breeding of fuel for fission reactors was also included in the design.

In the late 1970s, R&D Associates began designing smaller metal chambers for containing much smaller nuclear weapons explosions than those envisioned by Project Pacer. This has evidently led to the successful Halite-Centurion facility.

The successful containment of nuclear weapons explosions has many defense, scientific, and technological applications. Previously, the most important and expensive nuclear weapons underground tests were carried out for x-ray lasers and electromagnetic pulse (EMP) testing of various defense systems, such as satellites, aircraft, and land vehicles. The tests consisted of constructing a one-time, kilometer-long vacuum chamber. Heavy doors would be used to siphon off x-rays and gamma rays from nuclear explosions in order to carry out these tests. A single test could cost upward of tens of millions of dollars.

By fully containing a nuclear explosion in a reusable facility, the same EMP tests, and even more advanced scientific studies, could be carried out at costs many times lower than the old, single-shot vacuum tunnel. The containment of nuclear weapon-scale outputs also makes any type of verification for a test-ban treaty virtually impossible.

The application to inertial confinement fusion would consist of siphoning off x-rays from the nuclear weapon plasma and utilizing them to implode laser fusion pellets. Apparently, this facility has permitted the testing of full-scale ICF targets before the construction of a full-scale laser or particle beam driver.

High gain fusion and the Rayleigh-Taylor

Among the most important determining parameters in ICF is the Rayleigh-Taylor hydrodynamic instability. The Livermore breakthrough demonstrates that the Rayleigh-Taylor instability is far less severe than previously projected; and that major new gains could be achieved in future experiments.

The simple hydrodynamic analogue of the Rayleigh-Taylor instability can be readily produced with a table-top experiment. Place oil in a clean glass. Carefully place a layer of water on top of the oil. Now lightly tap the glass. If properly done, the interface between the water and oil will begin to oscillate. These oscillations will grow until a turbulent mixing of the water and oil takes place. Eventually the denser water will "move through" the lighter oil to take its place at the bottom of the glass. Gravity is the force driving the instability.

One of the chief techniques for lowering both the power and energy required for achieving laser fusion is to utilize hollow spherical shell fuel pellets. The "hollowness" of a fuel pellet is measured by its aspect ratio, which is simply the overall radius of the hollow pellet divided by the thickness of the shell. In fact, both the laser power and energy required to drive high-gain fusion pellets are inversely proportional to the square root of the aspect ratio. But hollow shells are subject to the Rayleigh-Taylor instability.

In the case of hollow shells, the fuel takes the place of the water, the gas in the hollow interior takes the place of the oil, and the acceleration during the compression takes the place of the force of gravity. The Rayleigh-Taylor instability can therefore produce turbulence along the surfaces of the hollow pellet during the compression process. This can, in itself, simply prevent a symmetric compression, or it can also produce mixing between the fuel inside the pellet and non-fuel elements utilized in the outer portions of the pellet, such as metal tampers used to prevent preheating of the fuel and the special ablation materials placed on the surface of the pellet.

The hollower the pellet—that is, the greater its aspect ratio—the greater the danger of the Rayleigh-Taylor instability. On the other hand, the higher the aspect ratio that can be utilized with a stable symmetric compression, the lower the laser power and energy requirements.

The laser is ready: KrF progress

While ICF can utilize a large variety of drivers—various lasers, charged particle beams, and even hypervelocity projectiles, one particular technology has already been essentially demonstrated: the krypton fluoride (KrF) excimer gas laser system. The recent Livermore and Halite-Centurion results have demonstrated that with a 3 million joule output laser, operating at a power level of several hundred terawatts and a wavelength of about one-quarter micron—that is, ultraviolet wavelength light—the laser would trigger a fusion burn that produces 300 million joules of fusion energy. Los Alamos National Laboratory has recently completed a detailed review of the status of the KrF excimer gas laser as an inertial fusion driver. (See *Fusion Technology,* Vol. II, May 1987.)

Table 1 gives a summary of the technology issues that determine the present status of the KrF technology's ability to meet the requirements of efficiency, scalability, and cost for providing the driver of an ICF electric power reactor. Table 1 shows that almost every category has already been achieved or favorable resolution is emerging from current experiments. Only two small areas require technology improvement.

Rare-gas-halide excimer lasers, such as KrF, have properties that make them highly promising candidates for inertial fusion drivers. One particularly advantageous property is that KrF lasers produce a short wavelength that couples more efficiently to both direct drive and hohlraum-type fusion targets. Recent theoretical and experimental work on inertial fusion laser-target interactions has shown that the efficiency of coupling the laser energy into the fusion targets increases as the laser driver wavelength decreases. The KrF is nearly optimum for a fusion driver because its wavelength is short enough to ensure efficient laser-target coupling, yet long enough to make use of practical materials such as mirrors and other optical transmission elements.

TABLE 1

KrF base case issues for construction of power plant system

KrF issues	LANL assessment
Front end	
Attain contrast ratio>10^7	A
Pulse-shape versatility	A
Amplifiers and amplifer scaling	
Diode pinch	B
Diode closure rate	B
High-voltage bushings	C
High-voltage switches	B
Pulse-propagation/energy extraction	B
Beam-quality degradation	B
Efficiency	B
Amplified spontaneous emission: transverse/longitudinal	B
Electron optics	B
Parasitic oscillations	C
Reliability	B
System issues	
Channel-to-channel cross talk	B
Saturable absorbers	B
Retropulse phenomena	A
Amplifier coupling	B
Flexibility in pulse shaping	A
Propagation (Raman scattering)	A
Propagation (turbulence scattering)	B
Repetition rate	A
Optical engineering	
Damage from synthetic long pulses	B
Short-pulse damage on large optics	B
Fluorine-resistant coatings	B[a]
Damage from scattered electrons	B
Optical scattering from coatings	B
Other damage effects	B
Alignment systems	
Cost	A
Reliability	A
Operability	A
Kinetics	
Gain/absorption in krypton-rich mixtures	B
Rate of formation of Kr_2F^*	B
Magnetic splitting of KrF^*	A
Beam quality	
B-integral effects	A
Spatial filters	A
Intensity profile at target	B
Target coupling	
Absorption	A
Hot-electron production	A
Filamentation	B

[a] Design response available

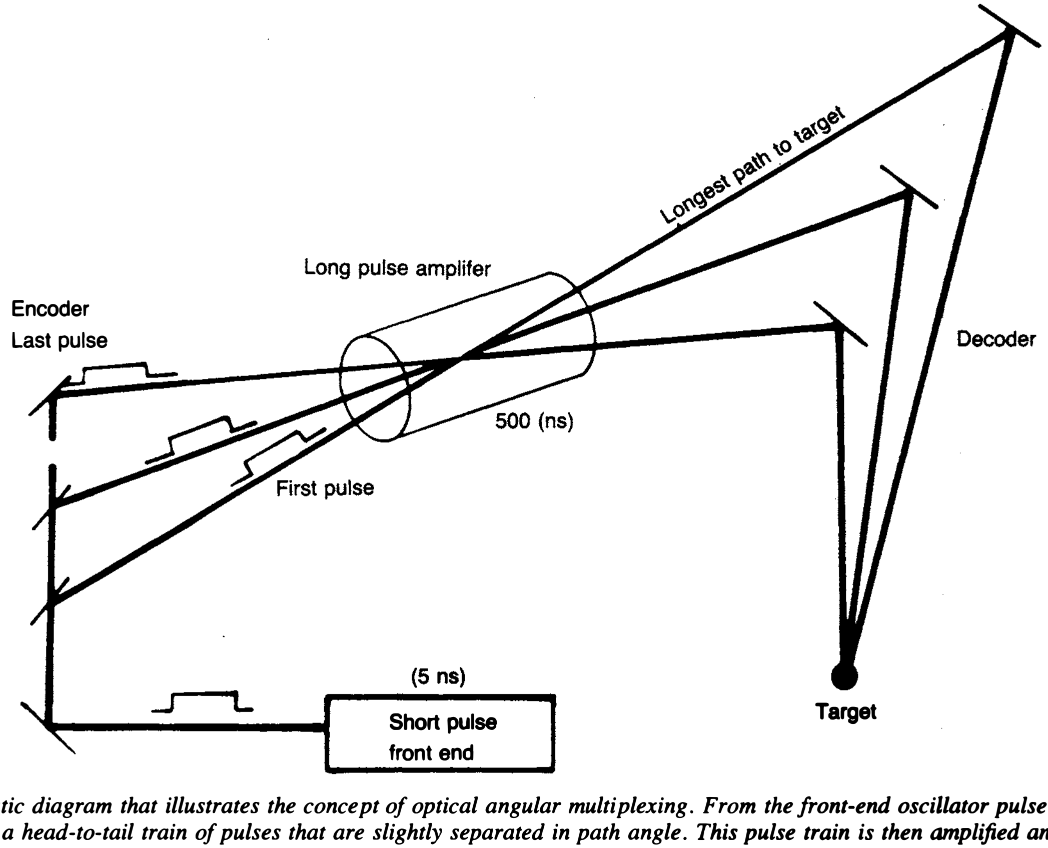
Status of issues
A = Achieved or technology is in hand B = Favorable resolution emerging from current experiments C = Technology improvement required

The KrF consists of a chamber through which krypton and fluorine gas flow, and powerful electron beam guns. When the krypton and fluorine gas is irradiated by the electron beam, the krypton and fluorine combine to form the excimer molecule, KrF. This molecule will then lase to produce the 0.248 micron ultraviolet light output.

Because 0.248 micron light penetrates the target plasma to regions of high density, KrF laser drivers can provide the high ablation pressures needed to generate supercompression of matter. Also, the hot electron production typical of longer wavelength lasers is drastically reduced. The KrF laser has a broad bandwidth, which provides further assurance that hot electron production will not occur. Also, the KrF is powered by electron beams; and electron beam accelerators represent a mature technology which is intrinsically efficient, has scalability to high-energy output, is relatively economical to build, and is capable of high-repetition-rate operation—shooting many shots per second.

In spite of these many advantages, the KrF primary output is limited to fairly long pulse outputs of about 100 nanoseconds, when less than 5 nanosecond pulses are required for ICF, because the electron beam powering the KrF must operate with long pulses in order to achieve high efficiencies and high-energy outputs. But two different methods have been developed for compressing the primary KrF pulse output to the 5 nanosecond width required for ICF. These are: 1) optical multiplexing, and 2) nonlinear optical techniques, such as Raman and Brillouin compression. The optical multiplexing technique creates a synthetic long pulse from a sequence of shorter pulses. This long pulse is more efficiently amplified by the "long pulse" electron beam gun. After amplification, the shorter pulses that comprise the long-pulse train are then appropriately delayed in time to arrive simultaneously (stacked into a single short pulse) at the fusion target. **Figure 3** shows this concept of multiplexing. Researchers on the Los Alamos AURORA KrF laser have essentially demonstrated the optical multiplexing technique for pulse compression.

FIGURE 3
Optical angular multiplexing



A schematic diagram that illustrates the concept of optical angular multiplexing. From the front-end oscillator pulse, an encoder produces a head-to-tail train of pulses that are slightly separated in path angle. This pulse train is then amplified and the individual pulses are sent along appropriate flight paths such that all the pulses arrive at the target simultaneously. The use of multiplexing enables the short-pulse target requirement to be matched to long-pulse KrF lasers.