Laser Fusion: One Milepost Passed—Millions More to Go

The controversial company that challenged the research might of the U.S. government in a race to develop laser-induced fusion has demonstrated that it is at least temporarily leading. KMS Fusion, Inc., which invested $18 million in a program to demonstrate that a high-powered laser could implode a pellet of fusion fuel and produce thermonuclear energy, seems to have shown that the implosion approach to laser fusion is conceptually sound—although not necessarily an imminent source of energy.

Before last fall, most federal and private research programs for laser fusion were heavily classified, so experiments were described to the public only in the most guarded way. But when the curtain of classification was lifted, just before a meeting of the American Physical Society in Albuquerque, New Mexico, 28 October 1974, it became clear that the $185 million program of the Atomic Energy Commission (AEC) had not yet demonstrated that a pellet would implode when it was evenly illuminated with laser light, but the KMS program apparently had. At the Albuquerque meeting, KMS researchers presented their data in an open scientific forum for the first time and convinced many of the 1200 physicists attending that they were conducting careful, well-designed experiments in more than 1500 tests.

The occasion was a landmark for laser fusion—an idea whose appeal had previously been based more on computer simulations than on experimental results. Many investigators had produced energetic neutrons characteristic of a thermonuclear reaction by irradiating a slab or a solid pellet of fusion fuel, but the feasibility of producing net energy depends on being able to compress the pellet. In their implosions, the KMS researchers were able to compact the fusion fuel, which is a mixture of deuterium and tritium, to ten times its normal density as a solid.

The KMS experiments also produced a significant number of neutrons, as many as 7×10^6 from a single laser shot, but still far too few to replenish the energy in the laser beam that caused the implosion. To reach that milestone, called scientific "breakeven," much more powerful lasers will be required. At the present time, the energy released in the form of neutrons falls short of the laser beam energy in the KMS experiments by a factor of 10^7.

Past KMS claims of progress in laser fusion have been met by considerable skepticism, both from scientists and the press. After a KMS announcement of a "definitive step" taken last spring, *Time* reported growing doubt among scientists that KMS "had done anything more than Soviet and U.S. researchers had previously announced." At that time many details of the KMS experiments were still classified. But the impression that KMS too often cried wolf persisted after classification ceased, and the *Wall Street Journal* headlined a story about a subsequent announcement as "KMS again claims gains in developing new energy source."

It still appears that KMS—as well as everyone else—is light-years away from energy production, but the notion that the company was based on scientific amateurism at best, or quackery at worst, seems to have been dispelled. Physicists at the Albuquerque meeting jammed into crowded rooms to hear from KMS scientists and commented that the company had a very ingenious optical system, had many more diagnostic instruments than had been supposed, and seemed to have very fine facilities for making pellets. Perhaps the greatest compliment to the KMS experiments was that scientists from the AEC laboratories rushed to simulate the results in order to test their computer programs. At the same meeting, scientists from the AEC's Los Alamos Scientific Laboratory reported that they had achieved some compression of a deuterium-tritium pellet in July 1973, in an experiment with a single laser beam illuminating a target of the type shown (Fig. 1), but had observed no neutrons.

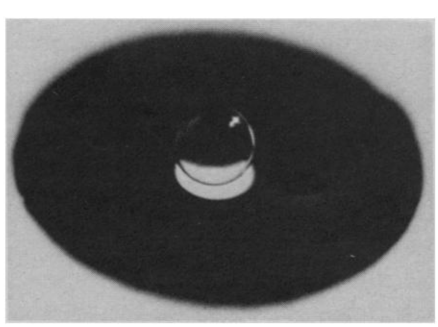

Fig. 1. A hollow glass microballoon of the sort used as a target in laser fusion research. [Source: Los Alamos Scientific Laboratory]

At the heart of the KMS system is the target pellet, a tiny, hollow glass sphere with gaseous deuterium and tritium inside. Most laser fusion researchers have experimented with the glass microballoons (*Science*, 8 November 1974) which provide a convenient way to mold fusion fuel into a spherical shape without having to freeze it. The microballoons used at KMS were typically 70 micrometers in diameter, with walls about 1 micrometer thick. Two beams of light from a neodymium glass laser were focused onto the target with specially designed elliptical mirrors, which ensure that the light is spread uniformly over the fuel pellet. In order to make the pellet implode, the light had to be delivered in a very fast pulse, lasting only about 300 picoseconds (10^{-12} sec). The total energy in the laser pulse was typically 100 joules.

When the laser heats the glass shell, the outer surface is rapidly ejected, driving the shell inward and compressing the deuterium and tritium inside. As the shell implodes, the core is heated and fusion reactions produce neutrons. The shell generates x-rays when it is first heated, and again when it reaches its greatest compression, so that two rings can be seen in pictures of implosions made with an x-ray pinhole camera (Fig. 2). Measurements of the picture with a densitometer indicate that the pellet in the figure was compressed by a factor of 210 in volume. The temperature of the deuterium-tritium core could not be measured directly, but various considerations suggest it was about 10 million degrees.

A criticism of the KMS experiments often raised is that there is no evidence that the temperature in the core of the pellet, at its greatest compression, is high enough or uniform enough to give a true "thermonuclear burn." The neutrons observed are undoubtedly produced by the fusion of deuterium

Economic Breakeven May Be the Problem for Laser Fusion

Edward Teller, who has observed thermonuclear science closely since the development of the first hydrogen bomb, does not believe that laser fusion will produce any energy in this generation, or the next. In a speech at Stanford University on 31 October 1974, Teller said, "It won't help us with this energy crisis or the next one. Maybe it will help us with the one after that."

Several years ago many scientists were optimistic that laser fusion could be developed rapidly, and that it might surpass the progress of magnetic containment fusion as a potential energy source. Such optimism was at least partly responsible for the exponential growth of the Atomic Energy Commission budget for laser fusion in the last 4 years. But it is worth noting that no one has yet demonstrated that a true thermonuclear burn occurs with laser-induced fusion (see accompanying story), although physicists studying magnetic fusion produced a thermonuclear burn in 1957 with the Scylla I device at Los Alamos, New Mexico. A number of scientists now seem to be more cautious about predicting early success for laser fusion, and a few, such as Teller, express doubt whether research on laser-induced compression and heating of pellets should be categorized as energy research at the present time. One critic commented, "To say that fusion has anything to do with energy right now is like saying Evel Knievel was trying to develop a new method of family transportation."

Neither Teller nor the other critics question the scientific merit of laser fusion research. "It should be sold as a research project," Teller said in an interview with *Science*. "You will be able to compress all kinds of materials to great densities, and do it out in the open where they can be seen," he said. "If you want to know the equation of state of something at high pressure, this is a way you can study it." Such an application of laser fusion research is foreseen because calculations suggest that laser implosion techniques are capable of compressing solids a thousandfold or more; thus laser experiments could possibly simulate conditions in the centers of planets or stars. But, "The laser fusion program was oversold as an energy solution," Teller says, "and I think many of the excellent researchers working on it realize that now."

Teller will not guess when the goal of energy breakeven may be achieved, saying he would not be surprised if it were done in 2 years or 10 years; but he thinks the more important question is "when economic breakeven will occur." An industrial scientist who has studied the prospects for economical power from laser fusion, Henry Hurwitz at General Electric Co., also thinks laser fusion research is scientifically valuable. But when Hurwitz and his colleagues at General Electric started investigating laser fusion, they based their hopes for economic feasibility on the chance that the energy gain would be as high as 10^5. But the energy gain predicted by U.S. scientists is typically 10^2, which Hurwitz thinks is marginal at best.

Among the problems that could make a laser fusion reactor economically unfeasible, even if it did produce net energy, are the costs of producing billions of fuel pellets and the short life expectancy of high-powered lasers. The recent disclosure of the miniscule size of the present pellets has served as a reminder that very little energy will be produced with each laser shot. If a 1-million-joule laser pulse initiated a fusion reaction with an energy gain of 100, the value of the energy produced would be no more than 10 cents, assuming 100 percent efficiency for all systems. But it now appears that the pellets will have to be multiple shell structures, and some researchers think they will have to be polished to a smoothness that is state-of-the-art for optical technology. To produce power at the rate of a large generating station would require hundreds or thousands of shots per minute, but the materials used in the present lasers fail frequently with far less usage.

Another problem is that the sort of short-pulsed, very intense laser needed for laser fusion has not been developed, and efforts to scale up present generation of lasers are not proceeding as rapidly as government planners had hoped. While testing prototype modules for the 20-beam neodymium glass laser to be built at Livermore, scientists found that the glass disks were becoming so badly pitted that the modules had to be dismantled and overhauled every 30 shots. With a NASA clean-room proceure to keep dust out, the reliability of the modules is improving but still marginal. Los Alamos researchers are now having difficulty with the optical quality of their neodymium laser, which was originally designed to produce 1000 joules, but they now hope to generate only 400 joules with it. KMS Fusion typically gets about 100 joules from its laser system, which was initially rated at 1000 joules, and apparently has fewer problems with reliability and optical quality because the system has been derated.

According to Hurwitz, the possibility of laser fusion as an energy source is very interesting to investigate, "but to be successful will require a miracle of the same order of magnitude as the development of solid state microcircuitry."

An alternative to a pure laser fusion plant is the laser fusion hybrid reactor, which some planners think would become economical at much lower laser energies. Such a reactor would breed plutonium with the neutrons from laser fusion, and then produce energy by fission of the plutonium. It could be an easier technical goal for researchers to achieve, but would negate—because plutonium would be used—many of the advantages that seem to make fusion more attractive than fission.

Few people expect the laser fusion program to keep growing as rapidly as it has in the past, unless some completely unexpected breakthrough occurs. At the same time, research on laser isotope separation that could produce cheap enriched uranium for light water reactors is developing rapidly and could pay off sooner. The isotope separation effort is carried out in the same divisions of the AEC laboratories as laser fusion work. According to one scientist at Livermore, "The isotope separation effort got started, to some extent, on laser fusion money. And I wouldn't be surprised, if isotope separation becomes the bigger sister, who knows, all the money might go the other way."—W.D.M.

and tritium, but it is not yet clear whether the entire core reached equilibrium at a temperature high enough to cause fusion, or whether only a few fast-moving ions underwent fusion. Scientists at the Livermore and Los Alamos laboratories, who have computer codes generally recognized to be more powerful than those of KMS, suggest that an equilibrium situation was not achieved. The best way to determine if a true thermonuclear burn has occurred is by experiment, if thermal broadening of the neutron energy spectrum can be observed. But that will not be possible until many more neutrons are produced—probably 10^{10}.

Dim Prospects for Breakeven

No one knows exactly how much laser energy will be required to achieve breakeven, but it will certainly be much more than is now available with the KMS laser system. Henry Gomberg, president of KMS Fusion, says that the company still believes that breakeven will occur at a laser energy in the neighborhood of 1 kilojoule. KMS is planning to upgrade its laser system with additional amplifying modules, and Gomberg predicts, with the tone of extreme optimism by which the company has become known, that they will achieve breakeven in the first half of 1975. Others predict breakeven will require between 5 and 100 kilojoules.

Scientists in the AEC program, such as Richard Morse at Los Alamos and John Nuckolls at Livermore, believe the KMS experiments may never reach breakeven because they operate in a mode that uses laser energy inefficiently. The KMS implosions occur in what Nuckolls and Morse call the exploding pusher mode, which is wasteful of energy because too much of the glass in the microballoon explodes outward. Nuckolls and Morse prefer a gentler form of implosion, in which a much smaller amount of material evaporates from the surface, called the ablation driven model. With a different sort of pellet, perhaps coated with plastic or possibly made of special glass, they believe that the target can be compressed much more effectively than by the exploding pusher method. But the ablation driven mode may have its problems too. A phenomenon called the Rayleigh-Taylor instability may allow the fuel to squirt through a thin spot on the shell just as the compression builds up. Many other sorts of pellets, which give still different im-

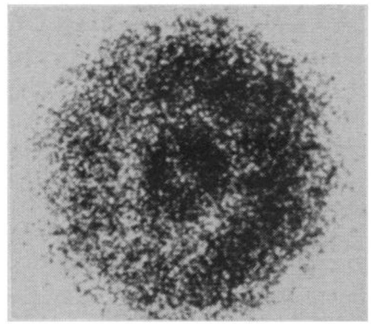

Fig. 2. An x-ray picture of a laser fusion pellet undergoing compression. The outer ring indicates the initial size, and the inner ring indicates the size at maximum compression. In this particular implosion, the deuterium-tritium gas in the pellet was compressed 210 times, and 7×10^5 thermonuclear neutrons were released. [Source: KMS Fusion, Inc.]

plosion modes, have also been tested in computer simulations.

Calculations of the breakeven energy depend critically on the wavelength of the laser light. Almost everyone agrees that laser fusion would work much better if a high-powered blue or ultraviolet laser, capable of delivering short pulses of light, were available. At very short wavelengths, less than about 1 micrometer, breakeven would occur between 5 and 10 kilojoules, according to Nuckolls. But the wavelength of the neodymium glass lasers used now in almost all laser fusion experiments is 1 micrometer, so breakeven would probably occur at higher energies—from 5 to 50 kilojoules Nuckolls estimates. The Livermore laboratory is building a 20-beam neodymium glass laser, designed to produce 10 kilojoules, but Nuckolls is no longer sure it will achieve breakeven. "The question is not whether KMS has a large enough laser," he says, "but whether we will have a large enough laser."

Scientists at Los Alamos are not willing to bet on any particular laser yet but think that the hydrogen fluoride chemical laser, with a wavelength of about 3 micrometers, may offer the best hope of reaching breakeven, probably at 50 to 100 kilojoules. Breakeven could require even more energy with the other high-powered laser Los Alamos is developing, a carbon dioxide laser that emits radiation at 10 micrometers. The advantage of the hydrogen fluoride or carbon dioxide lasers, for a system that generates energy, is that they convert electrical energy to laser light much more efficiently than do the neodymium glass lasers.

Because breakeven is defined in such a way that the inefficiencies of the laser are not counted, laser fusion researchers will still have a long way to go after breakeven before they can produce net energy. Even with a very energetic pulse of blue or ultraviolet laser light, U.S. researchers have calculated the energy gain from the implosion would typically be no more than a factor of 100, which may be uncomfortably small for covering the inefficiencies of both the laser and the thermal cycle of a power plant. For that reason, a new Russian pellet design, which offers the hope of a thousand-fold energy gain when illuminated with a 1 megajoule laser pulse, generated much excitement at a recent conference on controlled thermonuclear fusion in Tokyo.

The success of the KMS program in producing implosions and observing thermonuclear neutrons seems to have stimulated an acceleration of the activities of most other researchers. As one physicist put it, "Now we are all in the neutron derby." Livermore scientists are considering buying a pair of KMS elliptical mirrors to do some small-scale implosion experiments before their big laser is ready in 1977, and since the Albuquerque meeting they have tested the largest module that will go into that laser. Soon after the Albuquerque meeting, Los Alamos scientists began firing at pellets with a 2-beam neodymium laser system. Both AEC labs hope to quickly demonstrate that they can deliver more energy to a pellet than KMS presently can with its commercially built lasers.

The scientific success of the KMS research is bound to be embarrassing for the AEC program. At the Albuquerque meeting it became clear that KMS has a very large fraction of the world's data on laser fusion, and "That's not the way it should be," said one AEC official privately. In its program, the AEC invested most of its money and effort in developing new types of lasers and very large lasers, since its official position has always been that at least 10 kilojoules would be needed for breakeven. As a relatively small company with limited resources, KMS had everything at stake from the beginning, so it could lose nothing more by hoping for breakeven at a lower energy and perfecting a smaller laser system. KMS went for the short gain, and, scientifically speaking, it seems to have paid off.—WILLIAM D. METZ