molten. Eventually the heavier rock formed a core surrounded by the lighter ice. How the heating occurred is still not well understood, but two mechanisms have been proposed. The first relies on the decay of hypothesized short-lived radionuclides. The other mechanism is tidal heating: Proto-Miranda, according to this idea, was held in an elliptical orbit by resonance effects of the outer Uranian moons; as it followed this elliptical orbit it was continually squeezed by tidal forces, heating the moon's interior. At any rate, proto-Miranda now consisted of separate regions of rock and ice.

Then a catastrophe occurred. Something in Uranus's orbit—possibly some of the original material from which the planet itself formed—smashed proto-Miranda to bits. Its orbit became filled with large chunks of ice and of rock. Calculations show that these chunks would, within a few tens of thousands of years, reassemble into Miranda. But the resulting Miranda consisted of lumps of heavy rock randomly mixed with lighter ice. The heavy rock sank toward the center and the ice rose, until at some point the entire conglomerated mess froze and all activity ceased. Features like the ovoids could perhaps be explained as reflecting later subsidence of chunks of proto-Miranda.

Ariel is the next most active of the Uranian moons. It is covered by large fault valleys and smooth areas that are intepreted as evidence for either liquid or glacial flow. Many of the faults are evidently stretch lines, indicating that the smooth areas could have been viscous oozings of material from below the surface.

Umbriel is the picture of what all Uranian moons were supposed to be—dark and pitted with craters, but otherwise geologically uninteresting. It is the darkest of the five moons, with an albedo of only about 19%. Its unusual darkness is thought perhaps to result from a coating of dark dust that was somehow confined to Umbriel's orbit.

Titania, the next moon out, follows Ariel in geological activity. It is covered by a large, planetwide fault system and relatively young craters. The lack of older craters may indicate that Titania's features also were formed by resurfacing.

Oberon is a relatively sedate moon, with one or perhaps two fault systems. The ejecta from its craters are bright, but some of the crater floors are filled with dark material. This might indicate that the dark material bubbled up later, filling the craters, or perhaps the material was light to begin with and was darkened later by radiation or some unknown process.

—BRUCE SCHECHTER

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Committee reviews DOE inertial-confinement fusion program

Inertial-confinement fusion clearly works. It's demonstrated every time a hydrogen bomb is detonated. But is it possible to ignite a small deuterium–tritium pellet under controlled conditions in the laboratory—driving the requisite implosion with anything less drastic than a fission bomb?

The answer is not yet known. In the long run one wants to know whether one can ignite a pellet using an implosion driver frugal enough to yield more energy than it expends—a necessary condition for a commercial inertial-confinement fusion reactor. "But first we have to demonstrate that the thing can be done at all, irrespective of driver efficiency," says William Happer (Princeton), chairman of the National Academy of Sciences committee whose review of the DOE inertial-confinement-fusion program, undertaken early last year, was recently released[1] for publication.

In a December 1984 letter to the academy, George Keyworth II, the President's science adviser, requested that the NAS put together a committee to "review the accomplishments, management, goals and anticipated contributions of the [Department of Energy's] Defense Inertial Confinement Fusion program." Keyworth's charge asks that a committee "of individuals highly qualified in scientific disciplines associated with the development and testing of nuclear weapons . . . review all major areas of the inertial confinement program, . . . prioritize activities within the present and future ICF program, and present an appropriate time scale for attaining the program goals." The establishment of a review group, Keyworth's letter pointed out, had been mandated by Congress.

The relative emphasis on military issues in Keyworth's charge reflects a different environment today from that of the early 1970s, when the ICF program began to grow. Today, as the committee's published review puts it, "the energy crisis is dormant for the time being; the demand for electrical power has been much less than anticipated, and the growth of fission power has essentially stopped. . . . New programs, notably third-generation weapons and the Strategic Defense Initiative, are competing for funds and scientific talent."

With the exception of the heavy-ion-driver program, the entire ICF effort at DOE has, from the beginning, been funded by the department's Defense Program. Thus the review committee's report deals only briefly with the heavy-ion-driver effort. This should not be construed as a judgment on the long-term promise of heavy-ion beams relative to lasers or light-ion beams as ICF implosion drivers, Happer told us. It's just that the requirement for expensive particle accelerators places the heavy-ion ICF effort more properly in other parts of the overall DOE program.

None of present generation of ICF lasers, led by the ten-armed, 100-kilojoule Nova laser at Livermore, can deliver sufficient pulse energy to drive a deuterium–tritium pellet to ignition. Building a suitable laser with present-day Nova technology would be a very expensive proposition. "I think it would be a great mistake to stop the program now to try and design such a laser," Happer asserts. "It's clear that a laser-driven power reactor is an issue for the next century. The real question *now* is whether any laser, no matter how efficient, can implode these pellets to ignition." The review committee concludes that the laser ICF program at Livermore, Los Alamos, KMS Fusion, the University of Rochester and the Naval Research Laboratory should continue the study of pellet-implosion physics with its existing lasers, to determine the parameters necessary for an ignition laser. Given the expense of such a laser, one cannot afford the luxury of overbuilding it by a factor of two.

The new PBFA-II light-ion-beam accelerator just now beginning operation at Sandia is described by the committee as "the only laboratory-scale facility with the potential capability of delivering a megajoule in the next few years." This is very likely to be adequate energy for pellet ignition. The principal problems with light-ion beams lie elsewhere. Laser pulses are much more easily shaped in space and time than are pulses of light (lithium) ions. Driving a pea-sized D–T pellet to ignition will require a power density of about 10^{14} W/cm^2 on target. This is a hundred times the power density thus far achieved at PBFA-II. The limited focusing capability of light-ion accelerators at present requires that the beam travel no more than a few centimeters from the accelerating diode to the target, raising the problem that the diode would have to be replaced after each successful ignition shot. Furthermore, one will have to learn how to shape the time profile of the 70-nanosecond PBFA-II pulse. The pulse must start off very gently, lest shock waves generated in the pellet keep the plasma from reaching a sufficiently high density. Whether one can achieve adequate focusing and pulse shaping with a light-ion-beam accelerator will remain an open question for several more years at Sandia.

Much is at stake in this quest, because light-ion drivers can, in principle, deliver energy at perhaps one-tenth the capital cost ($25 per joule) of lasers. "If PBFA-II works, that will be the way to go for ignition, because it's the cheapest," Happer told us. "People have their fingers crossed. But at this point it's a riskier technology than lasers."

Quite apart from the question of energy efficiency—whether one can ultimately recover more fusion energy from an ignited pellet than one spent in driving the implosion—"it's a tremendous challenge just to drive a D–T pellet to ignition in the lab," Happer told us. "In effect you're seeking a laboratory instrument that can light a mini H-bomb. The majority of the committee feel that during the next five years all the resources of the program should be put into determining whether, and by what means, this is feasible. The computer simulations suggest that it is, but it's certainly not yet proven."

The density required for ICF ignition—in excess of 10^{25} particles per cm^3—is very similar to that found in the center of an ordinary star, Happer reminds us. At these densities the pressure (at the initial low temperatures) is dominated by electron-gas degeneracy. "This would be our first controlled laboratory encounter with the phenomena of the astrophysics texts," says Happer. Tokamaks, by contrast, involve plasmas 11 orders of magnitude less dense, essentially because their confining magnetic fields permit the D–T plasma to burn on a leisurely scale of minutes rather than the fraction of a nanosecond that must suffice in inertial confinement.

Then there are of course the weapons applications, which are, after all, paying the bills. "ICF could be especially important in the event of a comprehensive test ban," the committee's report points out. The fusion burn of a pea-sized deuterium–tritium pellet would only put out as much energy as a jerry can of gasoline—or olive oil. But its spectrum of high-energy neutrons and photons would be comparable to that of a thermonuclear bomb, making it possible to do weapons-effects studies easily in the laboratory. Underground bomb tests are very expensive, requiring very long lead times—and the diagnostic equipment suffers promptly and catastrophically. John Nuckolls, head of the Livermore physics department, points out that the enormous difference of scale between bombs and pellets means that laboratory implosion will never really be a substitute for underground tests, "but it's certainly better than nothing."

The committee also points out that "the challenges of ICF are providing unique new tools . . . for other programs of national importance like SDI. Some examples are large lasers and intense particle beams, diagnostics for microimplosions, sophisticated computer codes [and] x-ray lasers."

The last general review of the DOE fusion program, conducted in 1979 by a committee headed by John Foster of TRW, had given the ICF program rather high technical marks. The Foster review suggested that several areas would be "important milestones for the future": going to shorter laser wavelengths, understanding the coupling of laser energy to target pellets, investigating the design and fabrication of efficient targets, and research into ion-beam drivers. Seven years having passed, the Happer review tells us, "the committee found that the ICF program has made substantial progress in response to all these recommendations."

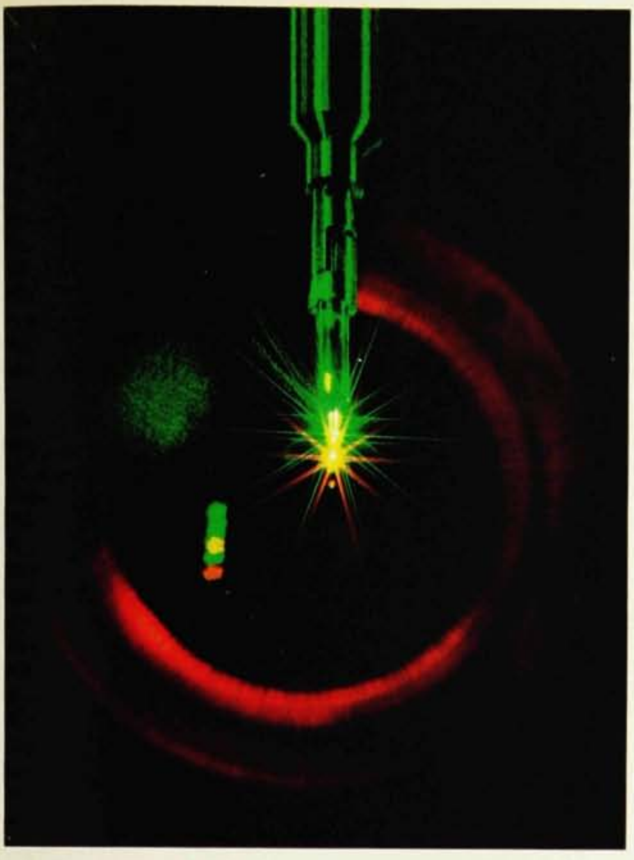
In the past few years, the need to go to shorter-wavelength laser light has been underscored by the Los Alamos experience with CO_2 lasers, emitting at a wavelength of 10 microns. As the committee summarizes it, "Unfortunately, nature proved to be unkind in that it was found, both theoretically and experimentally, that . . . the long-wavelength light favored the production of supra-thermal electrons. Although a valiant effort was made by the laboratory . . . it was ultimately accepted that a successful [CO_2 laser driver] design would be extremely difficult if not impossible." The 40-kilojoule Antares CO_2 laser, which began operation at Los Alamos late in 1983, has now been shut down.

Supra-thermal electrons pose the problem of premature pellet heating. To drive a small D–T pellet to the ultrahigh density required for fusion in the absence of magnetic confinement, one needs to avoid heating the pellet too soon. The hotter the D–T plasma, the more difficult it is to compress. The longer the wavelength of the laser driver, the harder it is to keep the pellet cool enough long enough. When laser light penetrates the pellet to a critical density such that the plasma's natural oscillation frequency equals the laser frequency, the incident photon energy is converted almost entirely to plasma waves. Electrons in the plasma are then accelerated to very high energies as they ride these waves like surfers, penetrating further into the interior of the plasma and heating it prematurely. Because the plasma's natural frequency increases with its density, shorter-wavelength laser photons can penetrate more deeply into the pellet before plasma waves are excited. Having traveled farther to reach the critical-density surface, more of the light will have been absorbed, so that less is available to excite the troublesome plasma waves. Furthermore, at these higher densities, the plasma waves are effectively damped by internal collisions.

"**One of the great** success stories of the ICF laser program," Happer told us, "has been the realization that one can get around these hot electrons by going to much shorter wavelengths." Nova and the smaller Omega laser at the University of Rochester are both neodymium-glass lasers, with the fundamental lasing wavelength at 1.06 microns. But the emphasis at these facilities is now on frequency multiplication of the fundamental laser output to the third (0.35 micron) and fourth (0.25 micron) harmonics. These experiments, the committee reports, "have confirmed the hope that target coupling would be improved at shorter laser wavelengths. . . . The plasma physics is now understood quantitatively. . . ."

One can carry the virtues of shorter wavelengths still further by going to x rays. In the absence of a suitable x-ray laser, one needs to use "indirect drive" laser implosion to exploit x rays. Livermore and Los Alamos have led the way in this direction. The details of the target geometry are classified, presumably because of weapons applications. The deuterium–tritium pellet, one gathers, is housed inside a blackbody "hohlraum"—the German for "cavity"—whose function is to absorb the incident laser light and reradiate its energy at x-ray wavelengths to the D–T pellet inside. The overall coupling efficiency of such an indirect laser-drive scheme is a tradeoff between the enhanced efficiency of coupling to the D–T pellet at x-ray wavelengths and the less than perfect efficiency of conversion of the incident laser light to x rays. Indirect drive would in fact require an order of magnitude more laser energy to achieve ignition, but it is regarded as a more technologically conservative approach than direct laser illumination of the pellet.

With Livermore concentrating on laser-driven hohlraum targets, Rochester and the Naval Research Lab have become the primary foci of direct-drive laser ICF work. It was the Rochester group that pioneered the high-efficiency frequency-multiplication technique for glass lasers. Although the



The ten-armed Nova inertial-confinement-fusion laser at Livermore created this "artificial star" by firing 18 kJ of third-harmonic (blue) light at a 1-mm-diameter deuterium–tritium pellet. This nanosecond laser pulse, coming from ten different directions, heated the D–T mixture to 10^8 K, generating a record 10^{13} fusion neutrons.

Omega laser is an order of magnitude less powerful than Nova, its 24-arm configuration seeks to provide the implosion symmetry that is crucial for direct-drive ICF ignition. For hohlraum targets, on the other hand, drive symmetry is a less serious issue. A detriment to symmetrical, uniform target implosion is the shimmery "speckle" that characterizes laser illumination. The Happer review describes as "ingenious" the "induced spatial incoherence" technique recently developed[2] at the Naval Research Lab to improve the uniformity of illumination by smearing out broadband laser beams spatially and temporally. "We do it with mirrors," explains Stephen Bodner, head of the NRL group, "splitting an imperfect laser beam into hundreds of components, and then recombining them into a perfect laser beam." The committee urges that the Rochester and NRL groups undertake a collaboration for the purpose of incorporating the ISI concept in future Omega experiments. If the Rochester group achieves its goal of improving drive symmetry sufficiently to allow pellet compression to 100 times liquid density, the committee suggests, "it would be necessary to take the potential of direct drive very seriously, and to consider a 30-kJ upgrade of Omega."

Priorities. "It is important to recognize that the present state of knowledge does not permit a narrow focusing of the ICF program," the Happer committee's report tells us. "At the same time, budget limitations require a prioritization of activities.... The Committee believes that the current program has the essential structure and capabilities to permit a fairly reliable ... specification of the required driver and targets, if the program is funded at about current levels." Happer decries the roller-coaster rides to which ICF funding has been subjected in recent budget proceedings. "We'd very much like to see sensible, regular funding of this program at the level of the last two or three years [155 million fiscal 1986 dollars]."

"To reach the five-year decision point ... the Committee is unanimous that Centurion–Halite and the efforts to exploit ... the major facilities, Nova and PBFA-II, and maintenance of a vigorous program of smaller-scale research ... are the top priority elements.... We prefer to view them as a single priority ... [but] if ranking must be entertained," the report lists the components of the continuing ICF program in the following order:

▶ Centurion–Halite, which is given highest priority by most of the committee members, is a classified program involving collaboration of weapons and ICF groups at Livermore and Los Alamos. The nature of the implosion driver has not been made public. Centurion–Halite is a theoretical and experimental effort to investigate design characteristics of efficient ICF targets. The hope is that the completion of this program "within the next five years ... [will] give us critical information on the feasibility of ICF."

▶ Exploitation of Nova and PBFA-II, the two new major ICF facilities, is given second priority. "In the forthcoming period, Nova should be capable of producing 100 kJ [pulses] of blue light. This should be the most capable laser source for indirect drive in the forthcoming period.... [It] should be able to implode well-diagnosed, hydrodynamically equivalent, scaled-down targets, but it is unlikely to produce ignition." As for PBFA-II, "development of an efficient diode and focusing and pulse shaping of the ion beam require critical investigation over the next few years. If this can be accomplished, PBFA-II will provide a high-energy, low-cost [ignition] driver. We believe that supporting target-design efforts at Los Alamos and Livermore should begin immediately, so that if PBFA-II successfully delivers its focused ion beams it can be used effectively for target implosion within the five-year period."

▶ The smaller-scale ICF programs are also accorded high priority by the committee. [Committee member Marshall Rosenbluth (University of Texas) would place them second, ahead of Centurion–Halite.] KMS Fusion of Ann Arbor, Michigan, the only private company in the ICF program, "has made, and continues to make, important contributions to target fabrication and [related] plasma physics." Happer reminds us that "in many ways KMS started it all—in the early 1970s. They convinced people that laser implosion might be a quick way to get to fusion." As to NRL and the university groups, the report argues that though they account for less than 10% of the ICF budget, they "constitute a very important component, providing ... innovative ideas, major technical advances, training of personnel, ... knowledgeable advice and criticism." Rochester and NRL, the principal proponents of direct drive, believe that it will ultimately prove more effective than the Livermore hohlraum approach.

Having listed these principal components of the ICF program, the committee stresses that it is unanimous in "regarding all three ... as areas of high priority. The termination of any one of these three key elements would lessen prospects for success, and it is hard to guess now which will turn out to yield the most essential information."

In assessing priorities, the committee writes, it was guided by the principle that the most urgent task is the study of the physics of pellet compression and

The light-ion-beam fusion accelerator facility PBFA-II, which began operation last December at Sandia, is the only existing inertial-confinement driver with sufficient energy to implode a D–T pellet to ignition—if major hurdles of pulse shaping and focusing can be overcome. Thirty-six pulse-power modules, radiating inward from a surrounding array of capacitor banks, will deliver 10-nanosecond voltage pulses to a small central diode, enabling it to accelerate 2-megajoule converging disk-shaped beam bursts of lithium ions toward the implosion pellet at its center.

ignition. Thus it accords only secondary priority "in present circumstances" to developing an affordable driver. "Hence we recommend only a modest exploratory effort in KrF and advanced glass laser development at this time." Krypton fluoride has the advantage over glass that it lases at shorter wavelengths, making frequency multiplication unnecessary. But it is a relative unknown. The committee recommends that exploratory work on KrF lasers continue at Los Alamos and begin at NRL. Because "KrF lasers are uniquely suited to implement induced-spatial-incoherence concepts," the committee believes that "a small KrF facility at NRL would be a worthwhile use of limited ICF funds." But, it cautions, "it should be clearly understood that the aim of work on KrF and advanced glass lasers is to test concepts. We do not recommend the construction of any large new laser now." One of the more painful tasks of the committee, Happer told us, was to recommend against the proposed upgrading of the 0.8-kJ Chroma laser, with which KMS Fusion "has done some very nice diagnostic work."

With the termination of Antares, Los Alamos is left without a major laser driver. The work at this major ICF laboratory concentrates at present on the design of complex, multiple-shell D–T pellets. The idea is that massive outer shells impart very high velocities to lighter inner shells. This facilitates efficient implosion, but it raises the long-run concern that such complex pellets would be difficult to fabricate in the context of a commercial power reactor.

The Livermore group, by contrast, is examining simpler pellet designs. Livermore has also been concerning itself with threats to the stability of the pellet implosion. Trying to push a denser plasma with a lighter plasma is a bit like trying to make the oil stay below the vinegar in an unmixed salad dressing, as Happer explains it. Livermore has been working on special tricks for suppressing Rayleigh–Taylor instability—the tendency of the lighter plasma to rush through the pellet center, just as the oil wants to get to the top of the dressing—by minimizing density differences in the target. The NRL group, on the other hand, has made an experimental and theoretical case for believing that the stabilizing effect of target-shell ablation will render the Rayleigh–Taylor instability harmless. This stabilizing effect, they argue, works only at very short laser wavelengths, which burn off the shell faster—all the more reason for building a small KrF laser at NRL.

Classification of some parts of ICF is a difficult problem," the committee writes. "It hurts the morale of imaginative scientists who are unable to take credit for their creative work, and often must endure the vexation of seeing nearly identical work published in the open literature, usually some years later, by [foreign] workers." The committee recommends a fresh look at classification, with the goal of keeping secret only those aspects of the program that are closely related to weapons and "not already common knowledge in the international ICF community."

A final recommendation by the committee, this time not unanimous, is that ICF should continue to enjoy separate "line-item status" in the DOE nuclear-weapons-research budget. The report summarizes the arguments pro and con. The majority felt that without the visibility conferred by a separate line item, ICF would be vulnerable to "raids" aimed at satisfying the more immediate needs of the weapons program. "These raids would add another level of instability to budget instability, leading to further erosion of morale and productivity of the capable ICF teams at the laboratories."

The majority argued also that line-item status would enhance the likelihood of achieving within five years the stated goals of getting definitive results from Centurion–Halite, Nova and PBFA-II; establishing the potential of direct drive and induced spatial incoherence; and learning more about the feasibility of advanced drivers. At the end of this five-year period, the committee believes, it should be possible to make a decision "on whether to continue ICF as a line item, to abandon it or to absorb it into the nuclear weapons . . . program."

Dissenting from the majority view, some committee members argued that "since the ICF program was justified by DOE as contributing to the weapons program, it should compete with other parts of that program, and the best forum for decision in such a competition [is] within the weapons laboratories."

The committee was, however, unanimous in recommending that the ICF budget should be stable over the next five years "at a level adequate to achieve the highest-priority objectives, which we believe is approximately at the current level—$155 million/year."

—Bertram Schwarzschild

Reference

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