Inertial confinement fusion: the civilian applications

In the second part of our series on the immediate promise of fusion power, we let Dr. Erik Storm's congressional testimony of February 21, 1989 speak for itself.

The author, Deputy Associate Director for Inertial Confinement Fusion at Lawrence Livermore National Laboratory, prepared the statement excerpted below for presentation to the Subcommittee on Energy Research and Development, House Committee on Science, Space, and Technology, on Feb. 21, 1989. The figures have been re-numbered, since not all of Dr. Storm's exhibits are being used here.

Foreword

This is my first opportunity to appear before this Committee to provide my opinions on the promise of fusion—particularly Inertial Confinement Fusion (ICF). I want to express my appreciation to the Committee for this opportunity. There is increasing interest and activity in ICF research and development worldwide, motivated by the long-term civilian energy applications as well as, in some cases, the near-term military and defense missions. I am pleased to report that the United States' ICF Program has made significant technical progress since it was last reviewed for you two years ago. The United States continues to lead the world in ICF research and development, and I am particularly gratified that the Program at the Lawrence Livermore National Laboratory (LLNL) has continued to be at the forefront of that progress.

Introduction

Fusion has the potential to provide an environmentally attractive, inherently safe, and virtually inexhaustible energy source. Our awareness of the need for new energy sources that meet these requirements is becoming more acute because of the diminishing reserves of fossil fuels, rising worldwide energy demand, and increasing concerns about the environmental consequences of continuing with our present fossil fuel based energy technologies. I will summarize the recent technical progress that has given us even greater confidence than we had just two or three years ago that ICF is scientifically feasible. The new data support our projections about the basic feasibility of achieving ignition and high energy gain under the conditions required for electric power production with ICF. The rate of progress has motivated the Department of Energy to begin a planning activity for a Laboratory Microfusion Facility (LMF). That facility would demonstrate the achievement of ignition and high gain in the laboratory, thereby demonstrating the scientific feasibility of ICF while providing the capability for the full spectrum of defense applications of ICF.

There is increasing ICF research and development activity worldwide. None of these activities are yet at the scale of the U.S. Program. The Japanese experimental program at Osaka University is the largest with a civilian (energy production) orientation. This program, which includes collaborations with scientists from other countries, uses a neodymium-doped glass laser that is the most powerful in the world after LLNL's Nova laser; its design is based on pre-Nova LLNL technology. Several other countries have established civilian research programs with smaller lasers. Still other countries are conducting theoretical and computational modeling of various aspects of ICF. Next to the United States, the largest programs for defense purposes are in France and England. Several countries, without U.S. involvement, are now exploring the establishment of multinational laboratories in which to pursue the science and technology of ICF, including the development of driver technologies compatible with power plant requirements. For example, the European scientific community has recently proposed constructing a Nova-class laser facility. Because of the military/civilian nature of the United States' ICF Program, the commitment to the near-term defense mission and the concomitant national security concerns, we do not formally interact with foreign ICF activities with two exceptions, a classified exchange with the United Kingdom and a limited unclassified collaboration with France.

The United States leads the world in ICF research and development. Based on our success, I believe that it is important and not too early to establish a significant civilian increment to the ICF Program that would fund research and development on laser and particle beam driver technologies appropriate to ICF power plant requirements as well as the technologies required for the power plant itself. Because energy is an essential component of national security, and because it can take several decades to put these new technologies on line, it is advisable to begin this development. I believe we can lead the world in developing ICF as an energy technology.

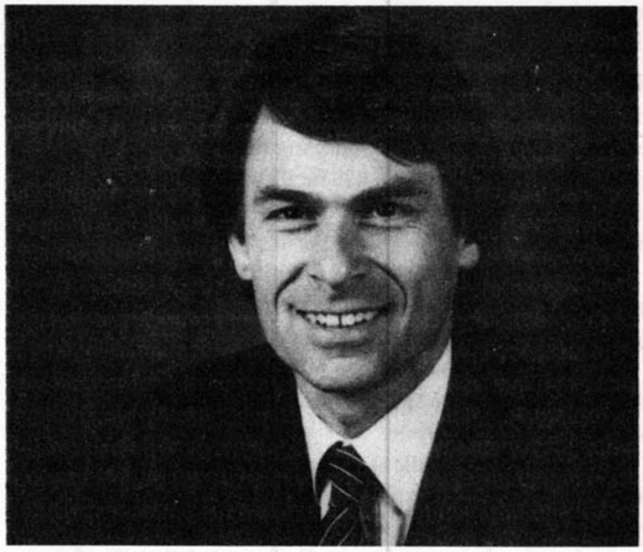
ICF program goals

The goal of the U.S. ICF Program, since its inception in the early 1970s, has been to fully develop inertial confinement fusion technology for both defense and civilian applications. The Livermore ICF Program continues to be fully committed to both objectives. The full realization of these applications requires a fusion output energy of several hundred to 1,000 megajoules, or 50 to 200 times greater than the energy provided by the laser or particle beam driver used to initiate the process; we call this requirement high gain. The achievement of high gain will have payoffs for this country in two areas vital to national security—nuclear defense and energy production.

The principal near-term goal of the Program, after we acquire the necessary additional data in the next few years, is to provide an LMF that will produce yields of about 100 to 1,000 MJ for defense applications. Our current research efforts are therefore focused on acquiring the remaining data that supports achieving high-gain ICF in the laboratory at an acceptable cost. Demonstrating high gain in the laboratory will also establish the scientific feasibility of ICF as a candidate for electrical power production.

. . . High-gain microfusion in the laboratory would also provide a unique means of studying matter under extreme conditions and would provide the U.S. scientific community with an unmatched ability to work in areas that have been identified by the National Academy of Sciences as frontier fields of physics.

The principal long-term goal of the Program is to develop and demonstrate the inertial confinement approach to fusion as a pure or hybrid technology for electric power production. (The "pure" approach is the one already described—the use of thermal energy produced by fusion reactions to generate electricity. In the "hybrid" approach, neutrons released in the fusion process are used to produce fuel for fission reactors.) Both of these ultimate applications of ICF require significantly more technology development than the defense applications. However, the potential national and global payoff is very high. Duplicating on Earth the fusion process that generates the energy of the Sun has the potential to provide a virtually inexhaustible, environmentally attractive, and inherently safe energy option. In the long term, in addition to power generation, ICF reactors and ICF technologies have potential applications for fissile fuel production, isotope production, and space propulsion.


Lawrence Livermore National Laboratory

Dr. Erik Storm: "Fusion works. . . . An aggressive program to develop commercially competitive power plants is scientifically and technologically realistic."

The ICF approach to obtaining a high-gain reaction is to compress and heat fuel composed of isotopes of hydrogen, contained in a small fusion pellet, to a density close to 20 times that of lead and a temperature of about 100,000,000° C. Such conditions exist only two other places in the universe—in hydrogen (thermonuclear) bombs and in stars. By imaging the fusion products emitted from miniature "stars" produced by the Nova laser facility at LLNL, we have demonstrated a fundamental performance requirement for ICF. The photograph on the frontispiece [not shown here] shows the fusion neutrons from a pellet compressed in volume by a factor of nearly 32,000. For a brief instant, the laser drove a microfusion pellet to a temperature and density exceeding those in the Sun. Although it is a long way from this generation of Nova experiments to the ultimate application and full return on the investment in ICF, the recent progress has reinforced our confidence that the goals are attainable. This progress has also supported a decision within the Department of Energy that the time has come to plan for the next step, a Laboratory Microfusion Facility with which to make high-gain ICF a reality.

Major program objectives and milestones

There are three significant milestones on the road to developing ICF for commercial power production. . . .

• The first milestone is to demonstrate scientific feasibility. We must develop the science and technology base for the target and the driver so we can confidently define the technical requirements for obtaining high gain, build a laboratory high-gain experimental facility (LMF), demonstrate high gain in the laboratory, and optimize the driver-target performance.

• The second milestone is to build an "engineering test reactor" to develop and demonstrate solutions to the technology and engineering requirements.

• The final milestone is to build a demonstration power plant and optimize the specific technologies for commercially competitive fusion power.

ICF has made excellent progress on target physics issues in the last few years. Experimental results have significantly increased our confidence about the basic feasibility of achieving high gain. It is now generally accepted that the driver energy required to achieve high gain is between 5 to 20 MJ. Economic considerations make the lower end of that range (5 to 10 MJ) highly desirable—and possibly necessary. It is my belief that the target physics data supports the projection that high gain can be achieved within that lower range of driver energies. The current funding-limited experimental program at LLNL is directed toward answering the remaining questions required to support the construction of an LMF with which to complete the first milestone. If funding were restored to the equivalent of that in fiscal year 1985, we believe that a more comprehensive basis for a decision on the direction of the ICF Program can be available in about four years. The extremely rapid progress over the last two years has demonstrated that experimental capabilities and theoretical modeling tools are in place to justify an accelerated program.

Program status and accomplishments

The national ICF Program is pursuing the demonstration of the scientific feasibility of high-gain ICF with a three-component program. In order to present program status and accomplishments, I will first briefly review the technical components of that program.

• A laboratory component to study driver-target performance with targets up to 1/10 full scale. This effort will provide the physics and technology base to quantify most of the requirements for achieving high gain in the laboratory. The LLNL Nova laser is the primary facility for this component.

• 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.

• The driver development component, aimed at providing the technology base for a low-cost, flexible, high-energy, high-power driver to demonstrate and optimize high gain in the laboratory. A desirable but presently underfunded and underemphasized adjunct would be to identify an associated technology path to a driver with characteristics required for an ICF power plant.

The centers for ICF research in the United States are at the Lawrence Livermore National Laboratory, the Los Alamos National Laboratory, and the Sandia National Laboratory. Supporting activities are carried out by an industrial participant, KMS Fusion, Inc., by the University of Rochester Laboratory for Laser Energetics, and by the Naval Research Laboratory.

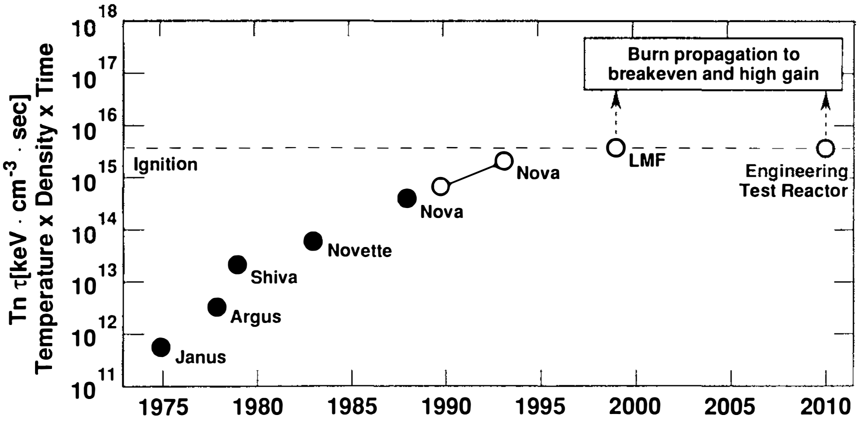
Because of budgetary constraints and technical priorities, the LLNL ICF Program has recently consolidated its efforts into a two-component program: target physics, with Nova, and driver development; the Halite program has been suspended.

Nova experiments at LLNL

The LLNL Nova laser facility . . . is the primary U.S. facility devoted to the study of the indirect (or hohlraum) drive approach to inertial fusion. Nova's principal objective is to demonstrate that laser-driven hohlraums (hollow chambers that trap electromagnetic radiation) meet the conditions of beam/target coupling efficiency, beam irradiation symmetry, beam pulse shaping, target preheat, and hydrodynamic stability required for high gain. In the past two years, rapid progress has been made toward all these objectives. The first of these comprehensive indirect-drive experiments with Nova was conducted in 1986. In less than three years, in various experiments with about 20 kJ of 0.35 micrometer light (less than 50% of Nova's full performance capability), values for the drive temperature and pressure, preheat, and symmetry that meet or exceed those required for high gain have been documented with a properly scaled target geometry.

Over the last year these tests have culminated in precision experiments . . . that have demonstrated the successful implosions of capsules with a uniform volume compression exceeding the value of 30,000 required for the success of ICF. The photograph on the frontispiece of this testimony [not shown here] is an image produced by the fusion products emitted from a pellet compressed by nearly a factor of 32,000 in volume. In other experiments, volume compressions exceeding 50,000 were measured. This performance is a critical requirement for ICF, and its achievement meets a major program objective. The fuel pellet performance essentially matched optimal, one-dimensional computer predictions of implosion values. The experiments also demonstrated control of the hohlraum environment—in particular, the achievement of the radiation flux uniformity required for high gain. This is the first time that ICF theory and experiments have agreed so closely, and it indicates that our ability to predict and understand results has greatly improved. The

FIGURE 1
Inertial Confinement Fusion (ICF) progress in achieving conditions required for fusion power



This graph shows past achievements (solid bullets) and projected results from crucial Livermore laser fusion experiments. Janus was the first Lawrence Livermore National Lab laser fusion research facility. Argus, Shiva, Novette and Nova are larger and more powerful follow-on laser systems. The product of temperature, fuel density, and the time during which the fuel is confined in ICF experiments provides a rough measure of the fusion potential. When the temperature is measured in keV (thousands of electron volts, 1 keV = 11 million degrees Celsius), the density in nuclei per cubic centimeter, and the confinement time in seconds, a product of several times 10^{15}, in other words 1,000,000,000,000,000, is required for igniting the core of a compressed fusion fuel pellet. To obtain burn propagation throughout all of the fuel, even higher levels are required.

Source: Lawrence Livermore National Laboratories

experimental results were achieved both through improved theoretical understanding and computational modeling and through the use of ultraviolet (0.35 micrometer) light from the Nova laser. The physical conditions in these experiments were chosen to match those of appropriately scaled high-gain targets, and we achieved a combination of confinement time and fuel temperatures that was less than a factor of 10 away from the value needed to meet the criterion for fusion ignition and high gain, as shown by the solid Nova point in **Figure 1.** This result is comparable to the best conditions obtained in magnetic confinement fusion experiments.

We have just completed improvements to Nova that will allow us to operate it routinely at its full design energy. With the benefit of experiments at these higher drive energies, and using the sophisticated temporal pulse shaping capability of Nova and the advances in diagnostic capability we have added to the facility, we will refine target designs and expect improvements in our results to the regimes indicated as open circles in Figure 1. The successful execution of these physics and implosion experiments will confirm that fuel pellets indirectly driven with a 5 to 10 MJ driver will achieve the conditions required for high gain.

Halite/Centurion

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 considerably 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. I believe that this accomplishment will reduce the uncertainty in the drive energy required for high gain from the current 5 to 20 MJ to the anticipated 5 to 10 MJ.

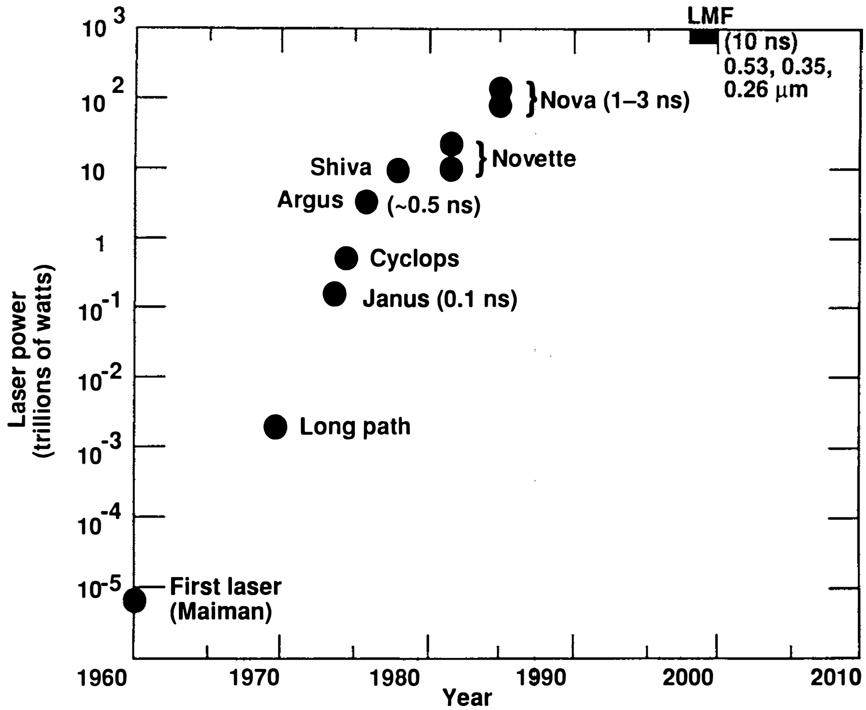
Driver development

There are two essential aspects of ICF research and development for driver technology. The first of these is directed at the driver requirements for the high-gain LMF and is discussed below. The second addresses the development of a power plant driver optimized for efficiency and cost-effectiveness and designed to repetitively drive optimized fusion targets. This second effort will be briefly discussed in the following section on ICF power plants.

The driver issues associated with high-energy, high-gain experiments that would be conducted at the rate of a few per week in an LMF are associated almost exclusively with cost. Our experience and analysis supports the opinion that the extension of present short-wavelength solid state lasers to the

FIGURE 2

LLNL solid state lasers are very close to the power needed for an LMF



It is technically assured that a multimegajoule, ~1000 TW solid state laser can be built

This graph shows the historical power levels of past and present LLNL laser facilities. The power level is given in trillions of watts. Beside the name of the laser system (Long Path, Janus, Cyclops, Argus, Shiva, Novette, Nova and LMF) are figures for the pulse length and wavelength of the laser system output. The pulse length times the power level gives the total energy of the laser beam output.

Source: Lawrence Livermore National Laboratories

energy and power regime required to achieve high gain is technically straightforward. The 100-kJ, 100-TW class Nova laser has proven to be an extremely successful and flexible experimental facility. The design and construction of the 10-beam Nova alser required the development of numerous capabilities and technologies in which more than 1,200 U.S. companies participated. The result, in addition to producing the most powerful and versatile laser research facility in the world, was to provide new capabilities and products for a number of U.S. companies. This gave them expanded markets and increased competitiveness. Nova required, for example, over one hundred very high quality mirrors and lenses up to 3½ feet in diameter. At the time, low-cost production quantities of such optics were not available. Working with several U.S. manufacturers, we developed the techniques and helped provide the facilities to allow manufacture of the required components. As a result, these companies now have the world's leading capabilities to produce large, high-precision optical components, and in many cases the technologies have been significantly advanced and extended into new fields. . . .

Drawing on this body of scientific, engineering, and industrial expertise and experience, we have refined an LLNL point design for a 10-MJ, 1,000-TW solid state laser driver for an LMF. The design uses compact, modular units to increase laser efficiency and reduce assembly time and manufacturing costs. The design parameters and component costs are based on our experience with Nova together with engineering estimates based on present production techniques and demonstrated laser technology improvements. As a result of this study we are confident, that using technology we have at hand, a high-gain fusion laboratory facility (LMF), including experimental capability, could be completed before 1998 and at a cost of approximately $800 million in fiscal year 1989 dollars. The tenfold increase in power required beyond Nova, as shown in **Figure 2,** is a small extension of the more than 100,000-fold improvement in high-energy laser performance that we have already achieved at LLNL.

Based on concerns that a cost in the range of $800 million for an LMF is unacceptably high, barring a significant change in national priority, we have begun to reassess higher-technical-risk approaches to solid state laser designs that offer promise for significant cost reductions. Utilizing our experience with laser technology development, we believe that a substantial reduction in the cost of a high-energy solid state laser for an LMF is possible given an appropriate R&D program to support this activity. We have recently completed the preliminary assessment of materials and technologies for a laser-pumped solid state laser. This is a departure in laser architecture and technologies from conventional flashlamp-pumped neodymium-doped glass lasers such as Nova. We have just initiated a four to five year R&D program to assess this option; if successful, it has the potential to reduce the cost of LMF by a factor of two, to a total cost of about $400 million in fiscal year 1989 dollars.

ICF power plants

Working with the nuclear reactor design community, we have studied the details of producing electrical power using pure ICF (the technique already described) and using the "hybrid" concept, in which fusion neutrons are used to produce fuel for conventional fission reactors. These studies indicate that the inertial confinement approach to electric power production has a number of attractive features that offer the potential for high efficiency and excellent safety.

The power plant driver (the laser or particle-beam accelerator) can be physically separated from the fusion reaction chamber. The driver and chamber can therefore be optimized individually, and most of the high-technology, high-maintenance equipment can be far from the environment of the reaction chamber. A single driver could, in principle, serve several chambers if the beam were switched from one chamber to another.

An additional feature possible with an ICF reaction chamber is that the so-called first wall, which is directly exposed to the extreme environment produced by the fusion reaction, can have the form of a flowing, renewable material. This replenished first wall protects the chamber's structural materials from much of the shock and radiation associated with the fusion reactions, acts as the heat transfer fluid, allows for easier maintenance, and reduces external shielding requirements. If the material contains lithium, the fusion neutrons interacting with the lithium-bearing material breed tritium to fuel subsequent fusion targets. This design approach greatly reduces the quantity of long-lived activation products and makes it possible to design a system in which the structural wall lasts for the 30 year lifetime of the plant.

We are continuing to refine our analyses of our Cascade reactor concept . . . which incorporates the features just described. Cascade has received the most detailed engineering and cost analyses of any proposed ICF reactor design. Earlier designs utilized liquid lithium, which presents a fire hazard. In Cascade, the lithium is contained in ceramic granules that cannot burn. A layer about one meter thick composed of these one millimeter diameter granules, flows along the wall of the reaction chamber as the entire chamber rotates. The granules can withstand high temperatures, so Cascade can achieve a power conversion efficiency of 55%, and an overall plant efficiency of 49%. The first structural wall consists of silicon carbide panels, which will have low residual activation.

Further studies must be conducted before Cascade's potential can be fully determined. For example, experiments must be conducted to ascertain the lifetime and manufacturing cost of the ceramic granules, which will affect the viability and economic competitiveness of Cascade. If such matters prove to have slight cost impact, Cascade would be cost-competitive with coal and with advanced fission reactors. Given the amount of study already devoted to Cascade, and the promise that this design appears to hold for a viable ICF power plant, it seems appropriate now to enhance studies of power-plant technologies, particularly studies of materials and of reaction-chamber design.

It is also appropriate to give considerably more emphasis to identifying an appropriate ICF power plant driver. Besides delivering a high-energy, high-power beam, such a driver must of course be efficient, must be capable of reliable operation over extended periods at a few pulses per second, and must cost less than 25% of the total power plant cost. No candidate driver has been developed far enough that its capabilities can be extrapolated to meet all these requirements.

Flashlamp-pumped neodymium-doped glass laser amplifiers, such as those used in the Nova laser, can deliver the necessary peak energy and power, but not the required efficiency or repetition rate. It appears that the use of a flow-cooled crystalline amplifier medium, instead of glass, would permit us to meet both of these criteria as well. However, technical and economic challenges must be addressed and solved before this technology can be extrapolated to the required conditions.

Multistage linear-induction accelerators for heavy ions (such as lead) appear to be capable of the efficiency, repetition rate, and durability required in a power plant. Although technologically promising, work on the heavy-ion drivers, principally being conducted at Lawrence Berkeley Laboratory, has been funded at a relatively low level, and therefore they are not as far along the development path as that for other drivers.

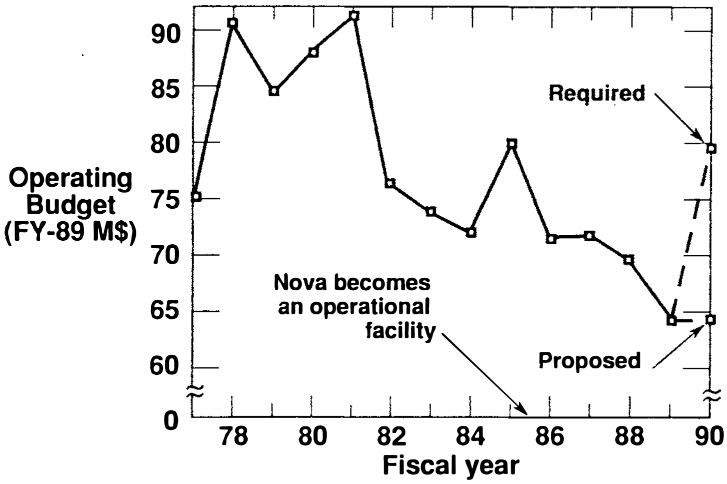
The future of ICF

We think that we have made impressive technical progress in ICF in the last two to three years, with results and accomplishments that, less than a decade ago, some thought could not be achieved. The most difficult problems we now face if we are to move ahead vigorously appear to be not scientific or technical, but financial. Results obtained over the last three years with the Nova laser and in the Halite/Centurion program provide my confidence that the ICF technique is scientifically feasible.

Figure 3 shows (in fiscal year 1989 dollars) the funding history of the LLNL ICF Program. For some time the program operated at the equivalent of $80 million per year in today's dollars; today our operating budget is $64.3 million. This budget erosion has had a serious impact on our program. 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

FIGURE 3

ICF operation funding continues to be well below the critical level for maintaining a balanced program



In this time frame, we have:

- Verified scientific feasibility of the ICF concept using Halite/Centurion and Nova
- Upgraded Nova to provide full design capability

- The Required case productively exploits the progress made to date
- The Proposed case perpetuates a sub-critical program

$80M is the minimum recommended level of operational funding

Source: Lawrence Livermore National Laboratories

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 work on ICF energy-production technologies. Funding of the LLNL ICF Program at its historic level of $80 million (fiscal year 1989 dollars) appears to me to be the minimum consistent with restoring a balanced program.

Further, our technical accomplishments lead me to believe that it is appropriate to introduce new funds to support more vigorous development of the civilian applications of ICF—in particular, ICF power plant drivers and other power plant technologies.

Both the inertial and magnetic confinement fusion programs continue to demonstrate technical progress toward achieving the conditions they require for electrical power production. The magnetic fusion program is constituted as an energy program. It has invested significant resources over the years in sciences and technologies required for the production of electrical power from fusion. By contrast, the ICF Program is funded principally as a defense program and has not had a comparable effort focused on the civilian energy requirements. Additional funding designated for the civilian aspects of ICF would allow these technologies to be studied and developed without diluting the ICF Program's focus and commitment to its defense mission.

I believe strongly that energy science and technology is one of the most important areas for the United States in the long term. The signs of serious energy and environmental problems are becoming more visible at an increasing rate. We should move aggressively toward developing alternative sources that can begin to provide a significant fraction of our energy in 30 to 50 years. I believe that ICF should be one of them. During the last few years there has developed broad based concern over the degree to which the United States is in danger of losing its lead in many high technology areas. Advanced energy technologies is an area in which I strongly believe the United States must be second to none.

Fusion works; the stars are our natural fusion power plants. An aggressive program to develop commercially competitive power plants is scientifically and technologically realistic. The question left for ICF is exactly what driver energy is required for an efficient system. With a national commitment I believe that the technology solutions for a prototype ICF power plant could be in hand by the first decade of the next century. I am convinced that the goal of fusion as a commercial energy source is one of unprecedented importance for humankind. I hope we have the vision and the will to accept the challenge of fusion.

Your Committee has understood the challenge and has supported the vision. We of the fusion community profoundly appreciate that understanding and support.