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INERTIAL CONFINEMENT FUSION: PRESENT STATUS AND FUTURE POTENTIAL

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ABSTRACT

Power from inertial confinement fusion holds much promise for society. This paper points out many of the benefits relative to combustion of hydrocarbon fuels and fission power. Potential problems are also identified and put in perspective.

The progress toward achieving inertial fusion power is described and results of recent work at the Lawrence Livermore National Laboratory are presented. Key phenomenological uncertainties are described and experimental goals for the Nova laser system are given. Several ICF reactor designs are discussed.

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INTRODUCTION

The harnessing of fusion power offers the prospect of producing abundant energy from a virtually limitless fuel source available to all peoples--water. Furthermore, while fusion power reactors must solve their own set of safety and environmental impact problems, these, in many respects appear to be relatively more tractable than those of many other energy sources.

There is inherent safety in the fact that it is so difficult to start and sustain the fusion reaction. It is impossible to put too much fusionable fuel in one place and accidentally start a chain reaction; spontaneous fusion does not exist. There are no accidental sources of ignition, as there are with hydrocarbon fuels, because it takes an enormous concentration of energy to initiate the fusion reaction. In nature, the reaction has been initiated only in stars where the enormous gravitational forces establish the ignition conditions. Core meltdown is not an issue in fusion reactors because fusion stops automatically if the reactor geometry is altered and afterheat from induced radioactivity can be made negligibly small. There will be some combustion hazards due to the use of hydrogen isotopes and materials like liquid lithium. However, the chemical energy in the amounts of such materials present at a fusion plant will be several orders of magnitude smaller than at equivalent hydrocarbon combustion plants. Fusion reactor operators will have to deal with radioactivity in two forms. Tritium is generated inside the breeding blanket and used as a fuel, and some of the reactor vessel materials become radioactive upon bombardment by fusion neutrons. However, since the radioactivity is from a secondary reaction, it can be made very much smaller than it is in fission reactors. It will be lower-level and shorter-lived radioactivity by large factors. Furthermore, the anticipated impact on the environment of the radioactive waste products can be very much smaller than it is for hydrocarbon plants because the volume of such materials is orders of magnitude smaller than those that contribute to chemical air pollution, acid rain, and the greenhouse effect. Even the cost of such a high technology energy source as fusion appears to be reasonable according to most studies (1,2) although this is an area that is sure to receive increasing attention in the future.

To make the fusion reaction produce a net gain in energy one must produce a hot (∿100,000,000 K), dense plasma and confine it long enough that

$$n\tau > 10^{14}\ \mathrm{s/cm^3}$$

where n is the particle density and τ is the confinement time (3). In inertial confinement fusion this is accomplished by concentrating energy from a driver (a laser or particle beam) onto a small pellet of fuel. This pellet reacts to that energy by compressing itself to about 1000 times its normal density and heating a central portion of the fuel to the required ignition temperature. A thermonuclear burn front then propagates through the remainder of the fuel in a few picoseconds (10^{-12} s). This is insufficient time for the fuel to disassemble far enough to quench the reactions; hence, we say it is confined by its own inertia. Energy is released in the form of 14 MeV neutrons, x rays, and target debris kinetic energy. In a reactor, this process will be repeated a few times a second and the resultant energy converted to electricity(4). This report will discuss the progress to date in achieving the goals of inertial confinement fusion and will describe some reactor design studies that are defining the practicality of inertial fusion energy.

PROGRESS TOWARD HIGH PELLET GAIN

Inertial confinement fusion has a very important fact going for it. The basic feasibility of the approach has been experimentally verified numerous times in the many tests of thermonuclear explosives that have occurred since 1952. What remains is to establish that the same approach can be used on a very much smaller scale and that the process can be initiated using a laser or particle beam as a driver.

The function of the driver is to deliver energy to the target in a form that will produce an efficient pellet implosion. At various laboratories different paths are being pursued. Work is being done on a light ion driver, heavy ion beams, and CO_2, free electron, and KrF lasers, but by far the greatest effort to date has been on the neodymium-glass laser. This laser, radiating at 1.06 μm, has been the overwhelming choice around the world for conducting inertial confinement fusion research and there has been much progress in recent years. In December 1982 the Novette laser (See Fig. 1)

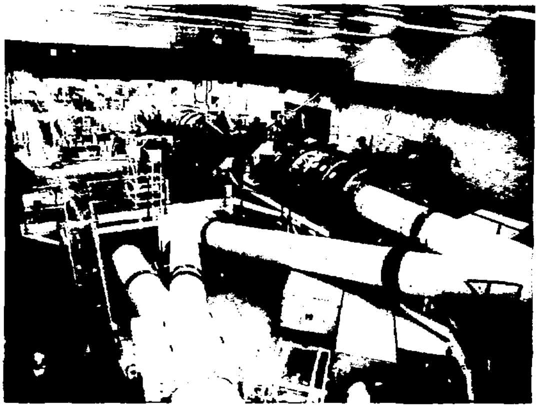

Fig. 1 The Novette 24-TW laser.

went into operation at the Lawrence Livermore National Laboratory and extensive experimentation has occurred since then. One of its two beams is able to put as much 1 μm energy on target as the Shiva laser did using twenty beams. Novette, however, is more flexible than Shiva because it can operate at both 1.06 μm and at 0.53 μm. Since it began operations, Novette has produced > 12 TW/beam at 1.06 μm in 100 ps, and > 6 TW/beam at 0.53 μm. In 1 ns the system has produced 9 kJ/beam at 1.06 μm and 4.5 kJ/beam at 0.53 μm. Operating Novette has allowed us to work out the bugs for the Nova laser which is scheduled to come on line in Fall 1984. Nova (see Fig. 2) is essentially a 10 beam version of Novette, and thus, will have

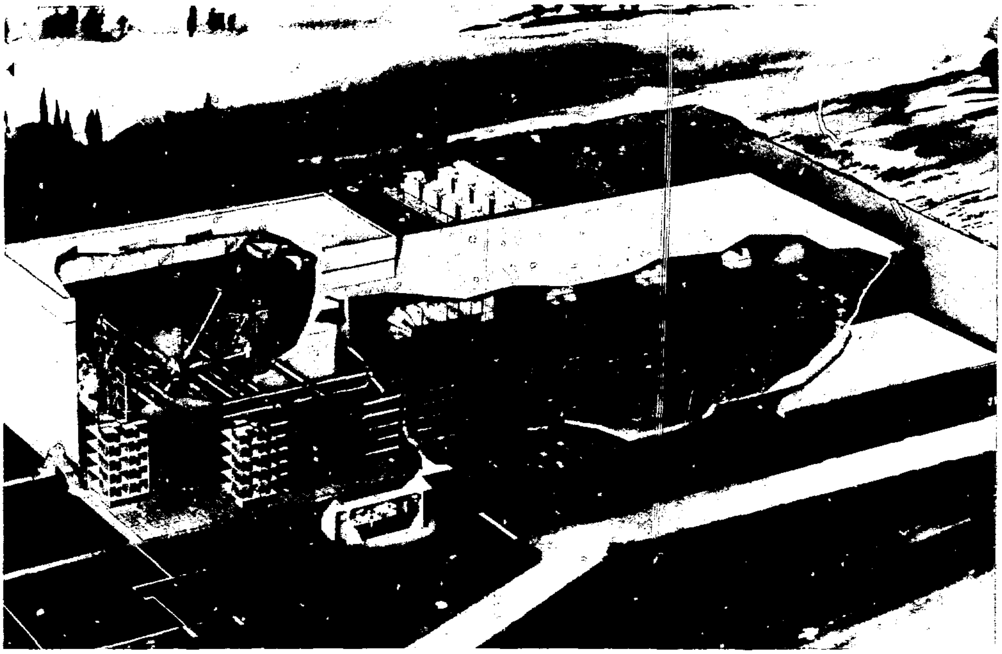

Fig. 2 The Nova 120-TW laser.

five times the power. It will have even greater frequency flexibility, however, since it will also be able to operate at 0.35 μm as well as 0.53 and 1.06 μm.

The experiments on Novette have provided much information on the coupling of high-intensity, coherent light to matter. Understanding the physics of this interaction is critical to finding successful designs for both the driver and the target.

It has long been known that at the intensities necessary to produce a strong enough implosion (10^{14} to 10^{15} W/cm^2) a hot, dense plasma would form around the target soon after the first photons arrived at its surface. In such a plasma, the light is absorbed or scattered through a variety of mechanisms including inverse Bremsstrahlung, Brillouin scattering, Raman scattering, and the two plasmon decay instability. Earlier work on Shiva and Argus had established that some of these mechanisms were beneficial, while others[5] were detrimental to establishing proper conditions for a satisfactory implosion. Those that resulted in large amounts of scattering were bad because the scattered light was lost and its energy could not help compress the fuel. Even some of the absorbing mechanisms were found to be undesirable. The most efficient implosion is created by ablating target material from the outside in and keeping the fuel inside cold during the compression. Some of the coupling mechanisms, however, put too much of the energy into very fast or "suprathermal" electrons that have very long ranges. These hot electrons not only reduce the effective coupling to the ablator by carrying energy away, but worse yet, they preheat the fuel inside the target thus making it harder to compress.

Experiments in Shiva, Argus and, now, Novette have led to increased understanding of these effects and to their control. Fig. 3 shows that switching to shorter wavelength light has produced greatly increased absorption at the intensities of interest to ICF (10^{14} to 10^{15} W/cm^2). Novette experiments have demonstrated that these greater absorption efficiencies are obtainable even with plasma scale lengths 5 times larger than those obtainable in earlier experiments(5). Fig. 4 is a plot of the x-ray spectra observed from experiments at different laser wavelengths. These spectra reflect the fraction of energy that is being deflected into suprathermal electrons. The greater the fraction, the hotter the x-ray spectrum. It is seen that as wavelength is reduced, so is the fraction of hot electrons. Both these facts lend support to our models that now predict successful coupling and target compression using wavelengths less than 0.5 µm. The bottom line is shown in Fig. 5. Target compressions and peak fuel temperatures that have been obtained in experiments to date are shown(2). Novette has achieved fuel densities over 100 times liquid density.

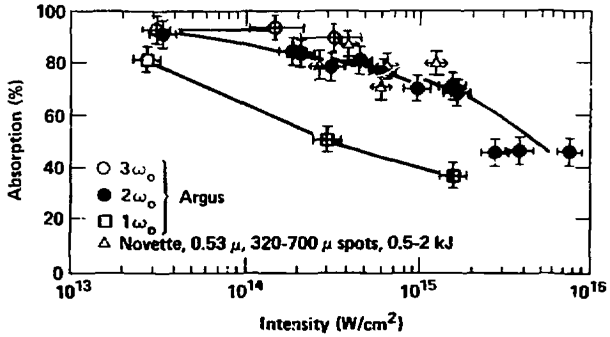

Fig. 3 Absorption of laser light as a function of intensity and wavelength.

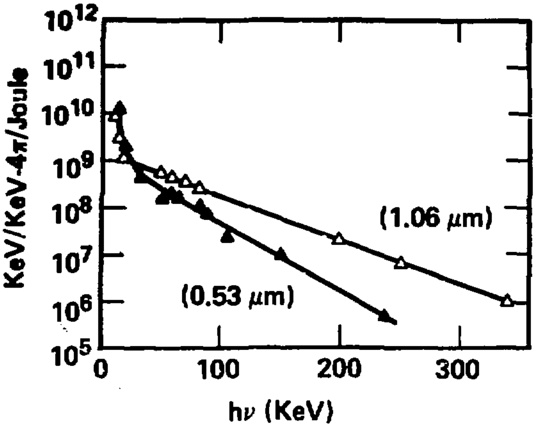

Fig. 4 X-ray spectra from targets irradiated at various wavelengths.

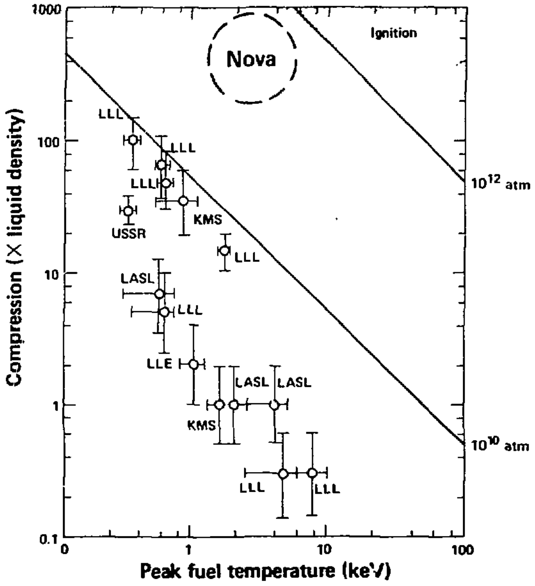

Fig. 5 Fuel compressions and temperatures obtained in various ICF experiments. Estimated values for Nova and those required for self sustaining D-T ignition are also shown.

PROSPECTS FOR FUTURE DEVELOPMENT

The experiments to be performed on Nova will provide important milestones in the development of inertial confinement fusion. We should be able to simulate conditions in scaled targets that would occur in a full sized ICF reactor. We should reach fuel compression several times those obtained in Novette. However, it is our current estimate that we will not be able to obtain high gain (target yield/energy in laser beams) with the Nova facility.

Studies of ICF reactor economics have suggested that to be competitive, an ICF reactor should have a product of driver efficiency (η) and target gain (G) of 15 to 40 (in order to keep the fraction of recirculating power low). Fig. 6 is our current estimate of the achievable target gain as a function of driver energy. For laser efficiencies of 5 to 10% the above criterion implies a required driver energy of 1 to 10 MJ (using the

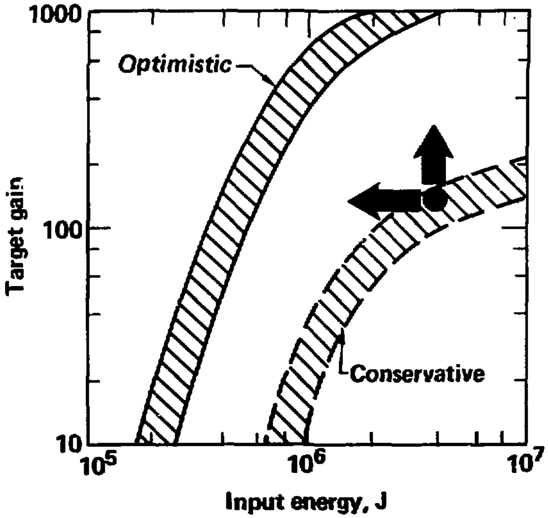

Fig. 6 Conservative and optimistic estimates of achievable target gain vs driver energy.

conservative curve). Thus, a driver ten to a hundred times the energy of Nova is needed to thoroughly explore the high gain regime and provide the information necessary to design an efficient reactor. Note that this does not necessarily imply that future commercial reactors will require drivers this large. Once driver/target interactions and target performance are thoroughly understood in this high gain regime, it is quite possible that we will be able to design a reactor using a more optimistic curve. For example, it has been suggested that the use of polarized DT fuel in the pellet should significantly increase the target gain achievable with a given driver energy (1).

It has long been assumed that a solid state laser would not be a good choice as a driver for a full scale ICF reactor because of limitations in efficiency, wavelength, pulse rate, average power capability, complexity and cost. Hence, there are a number of programs to examine light and heavy ion accelerators, and CO_2, free electron, and KrF lasers. However, a study about 1-1/2 years ago(6) concluded that present solid state lasers were far from their fundamental limits and suggested re-examining their prospects for the future.

Significant progress can be reported. Measurements have been made of coating damage thresholds of up to 40 J/cm^2 compared with our current operating level of 5 J/cm^2, and of laser glass that can absorb twice as much pump light as present glass and still maintain a long fluorescence time. Efficient harmonic conversion with large beams and large arrays has been demonstrated. These and other developments on solid state lasers are providing a conceptual basis for building a 1 to 10 MJ driver. With such a driver, a facility could not only investigate the high-gain target physics, but could also provide an intense source of fusion neutrons and x rays for reactor engineering studies. If a decision is made soon after experiments confirming the target physics are done on Nova, such a fusion studies facility could be available early in the next decade.

REACTOR STUDIES

Assuming all these developments occur as planned, what would a fusion reactor look like? ICF reactor studies have benefited a great deal from studies of magnetic fusion reactors because many of the same problems exist. However, there are important differences that give an ICF reactor a somewhat greater flexibility and potentially lower costs. First, the high technology (and therefore high cost) equipment consists primarily of the driver which can be located at some distance from the reaction chamber. This means it will not suffer damage from the fusion reactions (thus, it will last longer), and that it will not be in a radioactive area (thus, hands on maintenance can be used). Second, the volume in which fusion reactions occur is very much smaller for ICF than for magnetic fusion and therefore, the necessary shielding and containment building might be significantly smaller. Third, the vacuum requirements for propagating laser beams are not as stringent as they are for magnetic fusion and, in fact, are low enough that high temperature liquid metals can be used inside the reaction chamber walls. This has the effect of reducing the blanket mass needed and lowering the induced radioactivity.

An ICF reactor, then, will look significantly different than a magnetic fusion reactor. There will be a building to house the driver and its associated power conditioning equipment. The driver beam will be transported to the reactor building and split into as many components as are necessary to provide a symmetric driving force on the target. This could be several tens of beams for symmetric illumination or it could be as few as two if so-called hohlraum targets are used. (In hohlraum targets the incident laser energy is converted to x rays which then symmetrically drive the target implosion.) An automated target factory outside the reactor would produce 1 to 10 targets per second and an injector would shoot them into the center of the reaction chamber at that rate.

The design of the reaction chamber has received a fair amount of attention because it must contain the microexplosions, convert the neutron and x-ray energy into more usable forms, and breed the tritium necessary to use for fuel. Three different reaction chamber concepts are shown in Fig. 7.

Use of liquid lithium inside such a chamber is illustrated in Fig. 7a in an artist's concept of the HYLIFE ICF reactor. In this concept, the reactor walls and other structural elements are protected from the effects of the fusion microexplosions by a 1-m thick curtain of liquid lithium that is allowed to fall through the chamber. This lithium fall not only protects the structure, but also acts as the tritium breeder and heat exchange medium.

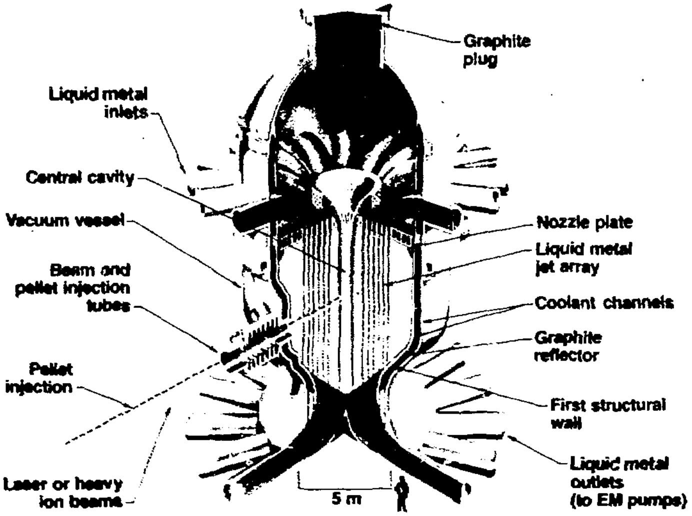

Fig. 7 Three designs for ICF reaction chambers: a) the HYLIFE liquid-lithium fall.

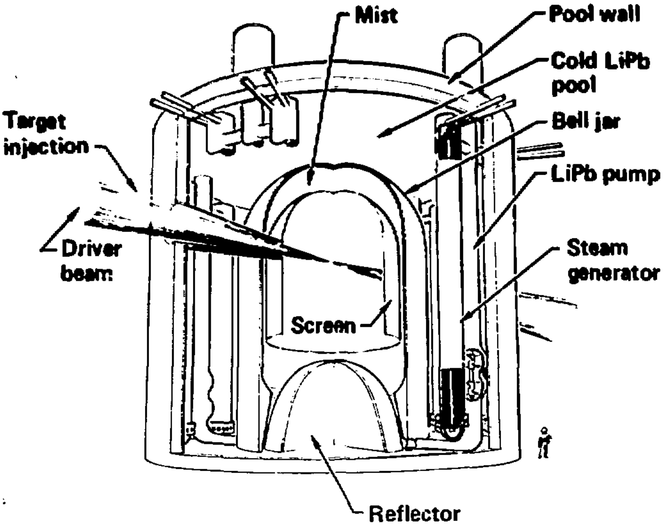

Fig. 7 Three designs for ICF reaction chambers: b) the Pulse*Star pool-type reactor.

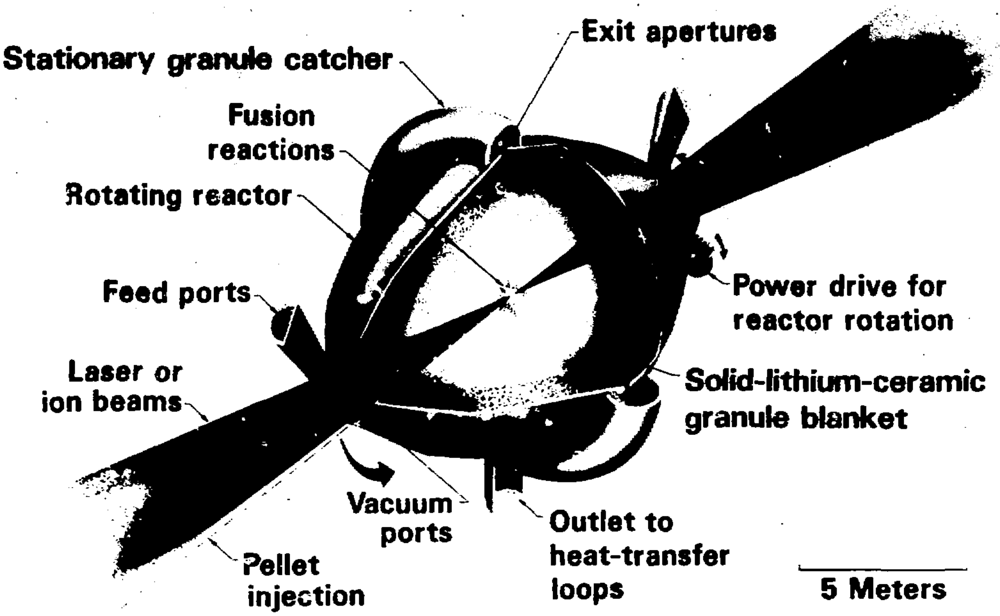

Fig. 7 Three designs for ICF reaction chambers: c) the Cascade ceramic-granule wall.

Engineering studies on this 1 MWe design have indicated that it can be built with existing technology for materials, pumps, heat exchangers, turbines etc., and that the structure is expected to survive a 30-year lifetime using ASME standards and the experience of the fission reactor industry. Furthermore, at the end of its thirty year lifetime, the radioactivity is less than 3% of that of a comparable pressurized water reactor (PWR) and less than 10% of that of a "bare" fusion reactor (one without the protective lithium fall). HYLIFE's biological hazard potential is less than 0.4% and its afterheat less than 2% of a PWR's.

In the interest of reducing the fire hazard of liquid lithium and reducing the cost per unit of electricity produced, two other design concepts have recently been investigated. Fig. 7b is an artist's concept of the Pulse*Star design. In this pool-type reactor, a bell-jar-shaped reaction chamber is submerged in a pool of $Li_{17}Pb_{83}$. LiPb sprays through openings in the bell-jar and impinges on a few-cm-thick metal screen, wetting both sides of the screen and creating a 1-m-thick region of droplets at half density that absorb the effects of the microexplosion. Pumps and heat exchangers are submerged in the LiPb pool. This concept operates at 5 Hz and has a power density inside the pool that is 29 times that inside the containment building of a comparable light water reactor.

Finally, Fig. 7c shows the Cascade reactor concept. Structural elements in this design are protected from the effects of the microexplosions by a 1-m-thick layer of solid Li_2O granules flowing through and held against the wall by the centrifugal action of the slowly rotating 9-m-diameter chamber. Use of the granules not only allows a 5 Hz repetition rate, but also allows operation at a temperature of 1200 K which should increase the thermal/electric conversion efficiency of the plant.

All of these designs depend on converting the fusion energy into heat and then using conventional technology to produce electricity. They also use existing materials technology. These constraints were intentionally applied to demonstrate the basic practicality of fusion energy. However, it has been pointed out(1,2) that once the first fusion reactors are operating, the high quality of fusion energy may allow further improvements. With D-T fuel pellets, about 80% of the fusion energy emerges as outward kinetic energy of neutrons. If we can be innovative about utilizing that energy more directly than going through the steam cycle, we have the potential of obtaining very high efficiencies. Using more advanced fusion fuels than D-T, the number of neutrons can be reduced to a small value (reducing induced radioactivity) and most of the energy might be obtained in the form of moving charged particles. Obviously, there are many ideas for direct conversion of charged particle kinetic energy into electricity.

With such advantages, the main issue for fusion may be its cost. It is high technology at its grandest. However, first reactor studies have concluded that even with all the present uncertainties, a conservative cost of electricity from first plants will be comparable to that from present fission reactors. A recent study(1) has, in fact, looked beyond that and concluded that with only a few reasonable gains in our understanding of the fusion process, electric power from an ICF reactor could very well be much cheaper even than power from coal plants. In this event, our society can have not only the benefits of the safety and cleanliness of fusion power, but can also obtain economic benefits as well.

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