Appendix B

Other Approaches to Fusion

The main body of this report has discussed magnetic confinement fusion, the approach to controlled fusion that the worldwide programs emphasize most heavily. However, two other approaches to fusion are also being investigated. All three approaches are based on the same fundamental physical process, in which the nuclei of light isotopes, typically deuterium and tritium, release energy by fusing together to form heavier isotopes. Some of the technical issues are similar among all the fusion approaches, such as mechanisms for recovering energy and breeding tritium fuel. However, compared to magnetic confinement, the two approaches discussed below create the conditions necessary for fusion to occur in very different ways, and some substantially different science and technology issues emerge in each case.

Inertial Confinement Fusion[1]

The inertial confinement approach to fusion research has been studied for some two decades, and its current budget almost half that of the magnetic confinement program. In inertial confinement fusion, a pellet of fusion fuel is compressed to a density many times that of lead, and then heated and converted to plasma, by bombarding it with laser or particle beams (see figure B-1). At this density, about 10 billion times the density of a magnetically confined plasma, the confinement time needed is so small (less than one-billionth of a second) that it should be possible to generate net fusion power before the pellet blows itself apart. The pellet's own inertia is sufficient to hold it together long enough to generate fusion power,

Inertial confinement already has been demonstrated on a very large scale in the hydrogen bomb, an inertially confined fusion reaction whose input energy is provided by a fission (atomic) weapon. The challenge of laboratory-scale inertial confinement research is to reproduce this process on a much smaller scale, with a source of input energy other than a nuclear weapon. In a hypothetical inertial confinement reactor, micro-explosions with explosive yields equivalent to about one-tenth of a ton of TNT would be generated by irradiating fusion pellets—called targets—with laser or particle beams; these explosions would be repeated several times a second.

[1]The U.S. inertial confinement fusion research program is reviewed in a recent report by the National Research Council: *Review of the Department of Energy's Inertial Confinement Fusion Program* (Washington, DC: National Academy Press, 1986).

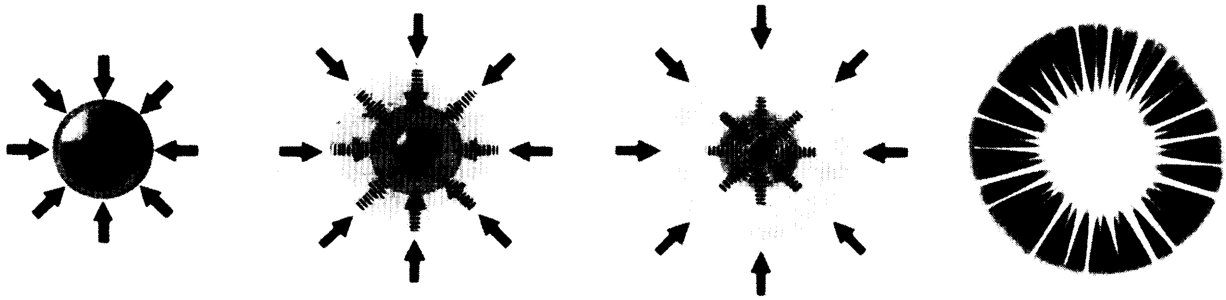
The issues addressed by inertial confinement fusion research in the United States concern the individual targets containing the fusion fuel; the input energy sources, called *drivers,* that heat and compress these targets; and the mechanism by which energy from the driver is delivered–or coupled–into the target. Due to the close relationship between inertial confinement fusion target design and thermonuclear weapon design, inertial confinement fusion research is funded by the nuclear weapons activities portion of the Department of Energy's (DOE's) budget. Inertial confinement research is conducted largely at nuclear weapons laboratories; its near-term goals are dedicated largely to military, rather than energy applications, and a substantial portion of this research is classified.

There are two near-term military applications of inertial confinement fusion—one actual and one not yet realized. First, because the physical processes in a pellet micro-detonation resemble those in a nuclear weapon, inertial confinement experiments now contribute to validating computer models of these processes, to collecting fundamental data on the behavior of materials in nuclear weapons, and to developing diagnostic instruments for actual nuclear weapons tests. These activities can be conducted today with existing high-energy inertial confinement drivers.

These applications could be greatly intensified, and a second set of applications would arise, if a laboratory facility producing substantial pulses of inertially confined fusion energy could be developed. No such facility yet exists. Such a facility could simulate the effects, particularly the radiation effects, of nuclear detonations on systems and components. This application might be particularly important if a Comprehensive Test Ban Treaty prohibited underground tests of nuclear weapons.

The near-term, military inertial confinement research effort also contributes information that would be essential to any longer term commercial applications. For example, both military and civilian applications of inertial confinement fusion (other than the computer program and diagnostic development activities that are being conducted today) require that an inertial confinement target generate several times more energy than is input to it. Such an accomplishment, which would show the scientific feasibility of inertial fusion, is beyond the capability of any existing laboratory device. (Of course, thermonuclear weapons have already demonstrated the scientific feasibility of very-large-scale inertial confinement fusion.)

Figure B-1.—Inertial Confinement Fusion Process



Heating
Laser or particle beams rapidly heat the surface of the fusion target, forming a plasma envelope.

Compression
Fuel is compressed by rocket-like blowoff of the surface material

Ignition
The fuel core reaches high density and ignites.

Burn
Thermonuclear burn spreads rapidly through the compressed fuel. yielding many times the input energy.

Laser or particle beam energy

Heat transported inward

SOURCE Lawrence Livermore National Laboratory, "ICF Reaction," *Energy* and Technology Review, April-May 1986

The technical requirements for commercial applications of inertial confinement fusion go considerably beyond the requirements for weapons effect simulation and would require still further scientific and technological development. Due to the relatively low efficiencies (e.g., 10 to 25 percent) at which the drivers operate, each target explosion must generate several times more energy than it is driven with to reach breakeven. An additional factor of 4 to 10 is required beyond breakeven to produce substantial net output. In a commercial reactor, therefore, as much as 100 times as much energy must be released in a pellet explosion as is required to heat and compress the pellet to the point where it can react. Furthermore, commercial energy production requires that pellets be detonated several times a second, far more frequently than needed for military applications. Finally, cost-effectiveness, reliability, and high efficiency are much more important for energy applications than military ones; successful commercialization will depend on how well the technology addresses the commercial requirements discussed in chapter 5.

A significant potential advantage of inertial confinement over magnetic confinement is that the complex and expensive driver system can be located some distance away from the reaction chamber. Because radiation, neutron-induced activation, and thermal stress due to the microexplosions could be largely confined to the reaction chamber, the driver would not have to be designed to withstand this environment. In the core of a magnetic confinement fusion reactor, on the other hand, systems both for supporting and maintaining the plasma and for recovering the energy and breeding tritium fuel are located in high radiation, high neutron-flux environments. A second potential advantage of inertial confinement arises from the relatively relaxed vacuum requirements inside the reaction chamber, which would permit the use of neutron absorbing materials such as liquid lithium inside the first structural wall of the reactor. Use of such neutron absorbers would lessen neutron irradiation levels in the reactor's structural elements, increase the lifetimes of those elements, and lessen induced radioactivity levels.

On the other hand, inertial confinement also has disadvantages compared to magnetic confinement. inertial confinement is inherently pulsed; the systems needed to recover energy and breed fuel in the reaction chamber have to withstand explosions equivalent to a few hundred pounds of TNT several times a second. Inertial confinement reactors must focus high-power driver beams precisely on target in this environment. Furthermore, the energy gains needed for these facilities must be much larger than those of a magnetic confinement device to make up for driver inefficiencies.

Four principal driver candidates are now being studied in the U.S. inertial confinement research program. Two of them —solid-state or glass *lasers* and *light-ion*[2] accelerators—have by far the largest facilities; the other two principal candidates—gas *lasers* and *heavy ion accelerators—are* in lesser stages of development. Major U.S. glass lasers are located at Lawrence Livermore National Laboratory in California and the University of Rochester Laboratory for Laser Energetic in New York. The Livermore facility, the most powerful laser in the world, does both classified and unclassified inertial confinement research; the University of Rochester facility conducts only unclassified research on a laser fusion approach that is not as relevant to weapons applications as is the approach pursued at Livermore. The largest light-ion accelerator in the world is located at Sandia National Laboratory in New Mexico; like the Livermore facility, it conducts both unclassified and classified research. The krypton-fluoride gas laser, the third driver candidate being studied, is being developed at Los Alamos National Laboratory. Other contributors to the laser and light-ion inertial confinement programs are the Naval Research Laboratory and KMS Fusion, Inc., the only private corporation significantly involved.

A fourth driver candidate—the heavy-ion accelerator —is much less developed than the laser or light-ion drivers. Unlike light-ion and laser research, heavy-ion accelerator research is a non-military program funded by the Office of Energy Research, the same DOE office that funds the magnetic confinement fusion program.[3] Heavy-ion experimental work is limited to accelerator technology, and in the United States it is concentrated at Lawrence Berkeley Laboratory in California.

Other national fusion programs conduct inertial confinement research, but at a significantly lower level of effort than their magnetic fusion programs. International collaboration is much more restricted in inertial fusion than it is in magnetic fusion due to U.S. national security constraints. On **balance, the inertial confinement program involves scientific and technological issues that are quite distinct from those relevant to magnetic fusion. A detailed comparison of the relative status and prospects of inertial confinement and magnetic confinement fusion is beyond the scope of this assessment.**

[2]Light ions are ions of light elements such as lithium

[3]The heavy-ion research program is far smaller than the magnetic confinement program and is managed by a different part of the DOE Office of Energy Research

Cold Fusion

Another approach to fusion, presently at an embryonic stage of development, is fundamentally different from either the magnetic or inertial confinement concepts. This approach, called ''cold fusion" or "muon-catalyzed fusion, " might make it possible to bypass the requirement for extremely high temperatures that make the magnetic and inertial approaches so difficult.[4]

If it were possible to "shield" the electric charge of one of the nuclei in a fusion reaction, one nucleus could get very close to another nucleus without being repelled. In this case, fusion reactions could occur at far lower temperatures than would otherwise be required, since the extreme temperatures needed to overcome the mutual repulsion of two electrically charged nuclei would be unnecessary. Such shielding can in fact be provided by a subatomic particle called the *muon.* The muon—like the electron—has a charge that cancels out the charge of a hydrogen nucleus. But unlike the electron, the muon binds so tightly to the nucleus that the nuclear charge is shielded even down to the distances where fusion reactions can take place. Therefore, once a muon becomes bound to a nucleus, the combination can approach a second nucleus closely enough to fuse without the need for extreme temperature.

If the muon is freed in the subsequent fusion reaction, it can become captured by another hydrogen nucleus to repeat the process. In this way it serves as a *catalyst,* enabling fusion energy to be released without itself being consumed. However, since the muon is unstable, muon catalysis can be practical only *if* each muon generates more than enough energy during its 2.2-microsecond lifetime to make its own replacement.

Muon-catalyzed fusion reactions were actually observed in high-energy physics experiments in the 1950s. However, the muons were rarely observed to induce more than one fusion reaction each before decaying, compared to the hundreds of reactions per muon that would be necessary to make the process worthwhile. More recent experimental and theoretical work has shown that the number of fusion reactions that can be catalyzed by a single muon depends on parameters such as the density and temperature of the deuterium-tritium mixture into which the muon is injected. Experiments have shown that muons are capable of catalyzing many more reactions during their lifetime than had been thought many years ago.

[4]A discussion of recent muon-catalyzed fusion research is given in 'Cold Nuclear Fusion, " by Johann Rafelski and Steven E Jones in the July 1987 issue of *Scientific American* pp 84-89

Whether this process can ever yield net energy production depends on increasing the number of fusion reactions per muon, The number is not yet high enough for the process to be scientifically feasible, and fundamental limits may prevent it from ever being so. Muon-catalysis research, currently at a very preliminary stage, focuses primarily on understanding the limits to how many fusion reactions can be induced by a single muon. If muon-catalysis proves to be feasible in principle, a substantially increased level of effort and a more detailed comparison of its potential benefits and liabilities to those of the other fusion approaches may be warranted.