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ELECTRICAL POWER FROM INERTIAL CONFINEMENT FUSION: ISSUES AND PROSPECTS

Michael T. Tobin
John H. Pitts
Charles D. Orth
Ralph W. Moir
William J. Hogan
Roger O. Bangerter
Lawrence Livermore National Laboratory

Wayne R. Meier
W.J. Schafer Associates

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Lawrence Livermore National Laboratory

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Executive Summary

The goal of the Inertial Confinement Fusion (ICF) Program since its inception in the early 1970's has been to demonstrate a significant fusion capability with a Laboratory Microfusion Facility (LMF) and to fully develop ICF technology for both defense and civilian applications. The applications of ICF are broad and numerous, ranging from basic and applied science to weapons physics and weapons effects to energy production.

Criteria used to assess the desirability of future power plants will include economic competitiveness, availability of fuel and other consumables, reliability, maintainability, safety, waste disposal, and environmental impact. In the near future, the desirability of ICF power plants will probably be evaluated with respect to criteria similar to those used for fission reactors, which emphasize small, inherently safe reactors constructed from factory-built, standardized modules that lower direct capital costs and shorten construction time.

ICF shares many desirable features with magnetic fusion (e.g., essentially unlimited fuel). Unlike magnetic fusion, ICF has the inherent advantages of relaxed vacuum requirements and physical separability of the driver, target, and reaction chamber. ICF is uniquely challenged by the pulsed nature of its energy and in the manufacture of its targets (fuel pellets).

Many inter-relating factors will determine whether ICF electrical power production will be economically competitive. Certain factors that taken alone first appear unfavorable can be offset by greater than predicted performance in other areas. Therefore, it is difficult to assign a particular value to any *one* parameter as being the minimum or maximum value that is acceptable. However, certainly a reasonable set of parameters can be assembled that do indicate, taken together, that ICF power can be economically competitive with future fission and coal plants. Such a list is provided here for a 1 GW_e power plant:

- Driver cost ≤$150/J.
- Driver efficiency ≥10%.
- Target gain of 60–100 at a driver energy of 2–5 MJ.
- Target factory cost ≤$100 million.
- Fusion-to-electric-power conversion efficiency ≥35%.
- Pulse rate ~5–10 Hz.
- Plant availability ≥70%.

For this set of parameters, the cost of electricity will be less than 5¢/kW_e·h. Predicted costs for future power are 3.7¢/kW_e·h for fission and 4.5¢/kW_e·h for coal. If one or more of these ICF goals is exceeded, fusion power will be competitive at even smaller plant sizes than 1 GW_e. ICF is particularly adaptable to the modular construction approach suggested for fission reactors because a single driver can support several reactors.

The separability of the driver and reaction chamber in ICF power plants has led to several conceptual designs that illustrate the ability of ICF technology to address various plant-selection criteria. LLNL has emphasized reactor designs that take advantage of another ICF feature, the option of putting large masses of x-ray-, debris-, and neutron-absorbing material inside the reaction chamber (see Figs. 4–6). In HYLIFE, a thick region of falling liquid lithium jets close to the target reduces neutron damage to the wall enough that the wall can survive for the 30-yr life of the plant. In HYLIFE–II, the lithium is replaced by the molten salt FLiBe. In Cascade, a $LiAlO_2$ ceramic-granule blanket accomplishes the same results, and in addition eliminates the fire hazard of liquid lithium and achieves a higher pulse rate than HYLIFE. The Starlight reactor concept relies on a small mass around the target itself to prevent wall ablation. Further, Starlight uses a solid, stationary breeding region. These "inner-chamber" blankets result in less first wall neutron activation than in PWRs and in some magnetic-fusion reactor designs. We expect Starlight to become only slightly less activated than a magnetic fusion reactor. Cascade operates at high temperatures and therefore achieves a high thermal-to-electric conversion efficiency (55%).

Both HYLIFE and Cascade restrict the target illumination geometry. In these designs, optimum coupling of driver energy to fuel pellets is achieved only with heavy-ion-beam drivers. In contrast, Starlight allows an arbitrary illumination geometry, so that good energy coupling is also possible with laser drivers. Starlight has a solid breeding blanket and nonvaporizing walls that are protected from x rays and ion debris by a sacrificial shield that surrounds each fuel pellet as it is injected into the reactor. Neutron damage will require the first wall of Starlight to be replaced every 6 yr. Wall replacement costs have not yet been assessed and folded into the cost of electricity for Starlight.

Although most ICF reactor issues are adequately addressed analytically, experimental data are needed (and generally unavailable) for some issues. ICF is learning a great deal from the magnetic-fusion energy reactor technology program, but almost no experimental attention has been given to problems specific to ICF reactors; this is primarily because of ICF's near-term defense applications, which have resulted in its near-term funding from the nuclear weapons program in DOE. Areas in which data and studies are needed include neutron damage to reflective optics, disassembly of isochorically heated liquids, condensation times for hot plasmas near cold walls, radiation damage for pulsed sources, fracturing of solids in pulsed-radiation environments, extraction and recycling of target materials, and target manufacture, injection, and tracking. At some point it will be necessary to begin an ICF reactor technology program to address these and other reactor issues through fundamental and systems studies at the national laboratories, at universities, and in industry.

I. Introduction

Among the many applications for inertial-confinement fusion (ICF) technology, its use as a source of commercial power is one of the most promising and challenging goals. ICF shares with magnetic-fusion energy (MFE) the promise of providing virtually unlimited energy from ordinary water and lithium, materials available throughout the world. The safety and environmental issues for fusion appear to be more tractable than those for many other energy sources. ICF has some inherent advantages over MFE. The first structural wall of the reaction chamber can be protected from plasma debris, x rays, and neutrons by thick fluid layers. Vacuum requirements are more relaxed, and the driver, target, and reaction chamber are physically separate, so that the driver can be placed a substantial distance from the reactor. ICF presents additional technological challenges because of the pulsed nature of its energy production and the manufacture and emplacement of its targets (fuel pellets). Thus, although ICF shares many advantages and technological development issues with MFE, it represents a very different approach to commercial fusion energy.

Criteria for determining desirable future power plant characteristics are unclear. Any new power source will have to be economically competitive, however. Even this fundamental objective is difficult to use quantitatively because its definition is subject to considerable disagreement and because any given figure of merit is subject to large spatial, temporal, and sociological fluctuations. The history of the fission power industry over the last twenty years provides ample evidence that perceived economic competitiveness is a necessary but not a sufficient condition for a decision to deploy a power source. Other criteria often used explicitly (besides being folded into the economic evaluation) are availability and reliability of the sources of consumables (e.g., fuel); reliability and maintainability of equipment; construction variables such as modularity, expandibility, construction time, and technical risk; disposal of wastes; environmental impact; safety; and public acceptability. We choose to avoid placing too much emphasis on any one criterion because its relative importance is likely to change. The separability of the issues relevant to drivers, targets, and reaction chambers provides ICF with a design flexibility that is important when selection criteria change.

Still, it is useful to examine the criteria likely to be used for near-term, first-generation plants, because people's willingness to consider fusion as a future source will be colored by those considerations. Recent experience in the fission power industry suggests that considerable emphasis will be placed on small, inherently safe reactors made from factory-constructed, standardized modules with as little nuclear-grade field construction as possible. Fusion plant design studies are likely to be evaluated by the same standards in the near term.

II. General Economic Issues

We have developed a technique for general economic analysis of ICF reactors and have proposed a standard method for comparing ICF power plant designs. This method can be used to compare these designs with future coal and fission plants. We use standard fission and coal cost data bases[1,2] and financial models and set a standard model for an ICF plant.[3] Using this method, we find that future 1-GW_e fission and coal plants would produce power at a cost of electricity (COE) of 3.7 and 4.5¢/kW_e·h, respectively. Figure 1 shows the variation of COE with fusion-cycle gain for three driver and target factory combined costs. The fusion-cycle gain (the reciprocal of the recirculating power fraction) is the product of driver efficiency η, target gain G, overall energy multiplier M, and thermal-to-electric conversion efficiency ε. The sharp knee in the curves implies that once the fusion cycle gain is above 4 (recirculating power fraction is below 25%), reducing the driver/target factory cost is far more important in controlling costs than further improvement in fusion-cycle gain. For the Cascade reactor, with M = 1.1 and ε = 0.54, a laser target gain of 80 is sufficient for economic competitiveness with a driver efficiency of 10% if the driver can be built for about \$0.3 billion (fission) to \$0.7 billion (coal). If the driver cost rises slightly, however, the required gain rises rapidly.

All the fundamental target physics of inertial fusion is contained in gain curves such as those shown in Fig.2 and Figs. 3a and 3b. (Fig. 3a shows a family of laser gain curves and Fig. 3b shows a pair of heavy-ion gain curves.) These indicate the range of gains expected for a given laser or heavy-ion driver energy. Figure 2 shows the required gain for a given laser driver energy to achieve 3.7, 4.0, and 4.5 ¢/kW_e·h cost of electricity. The comparison of the required gains with the range of gains indicated by laser gain curves B and C (shaded) indicate, that for current reasonable estimates of driver and target performance, ICF can be competitive with future coal for a 1-GW_e power plant operating at 5 Hz. The gain curve labeled A is our most optimistic estimate of target performance using current designs and would result in a COE that would be competitive with future fission as well. A further two-fold improvement in gain is anticipated for laser target advanced concepts. The gain curves in Fig. 3a and 3b were used to calculate the more complete economic and power plant data in Table 1a and 1b which show the COE's for various gain curves. The heavy-ion driver costs in Table 1b are taken from the HIPSA study.[12] More recent analysis indicates that a reduction of 1.25 in the costs of a linear accelerator are possible. We therefore show the effect on the COE for such a savings. A ring-like accelerator has the potential for further cost reductions of 2 or even 3. The effects on the COE of these savings (provided in Table 1b) show that heavy-ion fusion may also be competitive with future coal and fission.

Analysis of the sensitivity of the COE to changes in other factors (other than gain) leads to further important conclusions:

- Improvements in target gain at low driver energy are more valuable than improvements at high driver energy but are more difficult to achieve.
- The optimal driver energy and the sensitivity of the COE to variations in cost and performance parameters decrease with the improved target gain anticipated for complex target technology.
- Raising the chamber pulse rate lowers the gain required for a given COE. But the COE is relatively insensitive to pulse-rate changes between 5 and 10 Hz. If these pulse rates are achievable, gains of 80 to 100 will be enough to yield a competitive COE for a driver with $\eta = 10\%$. Drivers with higher efficiency (such as heavy-ion accelerators) may achieve competitive COEs at even lower gains.
- Lowering the cost of the balance of plant has the greatest leverage in reducing the relative COE for driver costs of $0.4 billion to 0.6 billion.
- As the plant size decreases, a competitive COE becomes harder to achieve.

One method being considered to make fission power more attractive is building the plant in modules. Given the usual economies of scale, one might think that this would always result in a higher COE, but several factors may mitigate (or even reverse) this effect. First, costs can be reduced if the modules are small enough that more of the work can be done in factories than in the field, and/or if the construction time can be shortened. On the other hand, even if the COE is increased, modular construction may offer added decision-making flexibility. It might not be necessary to make projections of demand so far into the future, and it might be possible to derive revenue from the first module while the next is still under construction.

ICF is particularly adaptable to modular construction because an ICF driver can serve more than one reaction chamber. We have analyzed the effect on the COE of using multiple reactor modules of a fixed size, such as 0.5 GW_e, to construct the fusion power plant. For a target gain of 100 with a 3-MJ laser driver (this is slightly below gain curve A in Fig. 3a), and a pulse rate corresponding to the lowest COE, the cost is 5.5¢/kW_e·h for a single 0.5-GW_e plant, but the COE drops significantly as additional plants are added to the same driver (to 3.3¢/kW_e·h for four units, 2 GW_e total). When credit for reduced construction time and factory construction is included in the COE, we expect an even more favorable scaling for modularization.

III. Design of the Reactor

A reaction chamber must perform the following functions:

- Contain the energy and debris from the fusion pulses.
- Convert the *pulsed* energy into a *steady* flow of energy in a form that can be efficiently converted to electricity (or convert the ICF energy directly to electricity).
- Breed tritium to replace that consumed by the reactor.

The following features are desirable:

- Structural elements (expensive to replace) last the lifetime of the plant.
- Inventory and routine leakage of radioactive material (tritium and neutron-induced activity) are minimized.
- Flammable materials are avoided.
- Melting of structural elements by heat from radioactive decay after shutdown is avoided without an active emergency cooling system (inherent safety).
- Site-boundary dose (related to biological hazard potential) for a worst-case accident is <25 rem, in accordance with Chapter 10, Section 100, of the Code of Federal Regulations (CFR) of the Nuclear Regulatory Commission (NRC).

- Radioactive wastes qualify for shallow burial under Chapter 10, Section 61, of the CFR under the NRC.
- Dose rates from activated materials are low enough to allow "hands-on" rather than remote handling during maintenance.

These goals are the same as those for a magnetic fusion reactor. ICF has greater design and engineering flexibility in achieving these goals, however, because the physics of beam-energy absorption, implosion, ignition, and burn of the fusion plasma are almost completely separate from the environmental and structural requirements of the chamber. Events occur in sequence, albeit on short time scales; interfacing between systems is constraining only at certain times in a fusion pulse cycle. An important example of this flexibility in ICF reactors is the ability to put flowing materials (solid granules, liquids, or gases) inside the reaction chamber to protect the structural elements and to take greater advantage of the high density of fusion energy.

This design flexibility is apparent in the forty ICF reactor studies that have been carried out in the last 18 yr.[4] Interfaces between various types of drivers (light ions, heavy ions, and several types of lasers) and the reaction chamber have been studied. Reactor implications of using directly or indirectly driven targets have been investigated. Reaction-chamber concepts studied can be grouped into those that protect the first wall only from x rays and debris and those that also protect the first wall from neutrons. In the first category, concepts have included the following:

1. Dry wall—requires low target yields and structural elements protected principally by distance; sometimes an inner high-temperature layer provides thermal inertia.
2. Gas-filled cavity—protects walls from low-energy x rays and debris, minimizing vaporization of wall material.
3. Magnetic-field protection—diverts charged debris from walls and may provide some direct energy conversion.
4. Thin liquid films—provides self-renewing layer to prevent wall vaporization by x rays and debris.
5. Liquid sprays—similar to item 4, but also reduces effect of ablation-generated shocks.
6. X-ray and debris shield—not actually a chamber concept, but an improvement to the dry-wall concept in which a small mass at a small radius around the capsule, injected with the capsule, prevents wall ablation by x rays and debris.

Two concepts provide additional protection against neutron damage:

7. Thick liquid falls and sprays—protects against neutrons as well as x rays and debris; tritium is bred inside the chamber.
8. Thick, flowing granular blanket—similar to item 6 but can operate at higher temperatures.

At LLNL, we have concentrated our studies on thick liquid or granular blankets (items 7 and 8) because of their advantages in increasing structural-wall lifetime and reducing neutron activation. We are also pursuing a solid-breeding-blanket concept and a HYLIFE design that uses FLiBe, a molten salt, instead of Li for first-wall protection and tritium breeding. These designs are most suitable for laser or heavy-ion-beam drivers and indirectly driven targets. We describe four designs in detail.

A. Cascade: A Centrifugal-Action, Ceramic-Lithium-Granule Reactor

Structural elements of the Cascade reactor (Fig. 4) are protected by a flowing, 1-m-thick blanket of solid $LiAlO_2$ ceramic granules about the size of grains of sand.[5] These granules, injected into the two ends of the 4.5-m-radius chamber, are held against the chamber wall by centrifugal force. The entire chamber rotates at about 0.8 Hz. The kinetic energy acquired by the granules as a result of the chamber rotation is also used to throw them into the vacuum heat exchanger. They are returned to the chamber by gravity. Use of $LiAlO_2$ ceramic granules allows operation at high temperatures and therefore at a high (55%).thermal-to-electric conversion efficiency. The wall consists of tiles of SiC , a particularly abrasion-resistant material, held in compression with a network of Al/SiC-composite tendons. Like any ceramic, SiC is weak in tension, so the tiles are held in compression even during the fusion pulse.

The blanket has three layers, which remain separate because of differing granule densities and sizes. The 84-cm-thick outer layer is composed of $LiAlO_2$ granules, which breed tritium. The 15-cm-thick middle layer is BeO, which is used for neutron multiplication. The 1-cm-thick inner layer is pyrolytic graphite, which absorbs about one-third of the fuel pellet yield in the form of x-ray and ion-debris energy. The inner-layer granules move with a speed about ten times greater than that of the middle-layer granules, so that the exit temperature only reaches 1600 K. Energy is transferred from the granules to 5-MPa helium gas in heat exchangers. The gas exit temperature is 1300 K, which allows a 55% power conversion efficiency to be obtained in a Brayton helium-gas-turbine cycle. This design produces a net power of 800 MW_e with a thermal power of only 1670 MW_t.

Cascade's advantages are inherent safety, high energy-conversion efficiency, high pulse rate, and low activation. $LiAlO_2$ and BeO do not burn, and the carbon does not produce temperatures or overpressures high enough to release activated aluminum from the $LiAlO_2$ under even a worst-case accident scenario. Although vacuum heat exchangers are used, the high temperatures result in good heat-transfer efficiency and a small required heat transfer area. The Cascade pulse rate is determined by the condensation of vaporized material, which amounts to about 1 kg per pulse. Although there is uncertainty about the phenomenology of energy and mass transfer between the hot, ionized plasma and a cold wall, the large surface area represented by the granule blanket makes it likely that the condensation will occur in less than 100 ms. The use of high-purity, low-activation materials such as SiC for the reactor wall reduces activation and disposal problems. Additionally, the use of Li_2O rather than $LiAlO_2$/BeO for the granule material layers reduces the long term activity (100 years) by two orders of magnitude due to the reduction in ^{14}C production. Lithium oxide is not the granule material of choice because of the 300°C lower operating temperature compared to lithium aluminate.

Several issues are of concern for Cascade. The inner layer of granules may break up because of x-ray and debris spall or thermal stress. The condensing vapor may cause some granules to aggregate. Remanufacturing this layer after each pulse may be too expensive. The practicality of operating at such high temperatures must also be considered. We are examining the possibility of using an x-ray and debris shield around the target to prevent the ablation of blanket materials, which would mitigate some of these issues.

B. Starlight: A Solid-Breeder Reactor with Nonvaporizing Walls

The Starlight reactor concept[6] has the potential advantages of arbitrary illumination geometry, inherent safety, flexibility, simplicity, and no moving parts. The first structural wall is protected by a sacrificial, softball-sized x-ray and debris shield that surrounds each pellet as it is injected into the reactor. High-energy neutrons get through the shield and will eventually damage the first wall. The economic effect of wall replacement has not yet been folded into the COE for this reactor. Present designs call for cryogenic fuel pellets, and the shield offers thermal protection from the higher-temperature environment in the reactor. The fuel pellets may be fragile, and the shield could add vital support during injection. Holes in the shield allow driver beam penetration to the fuel pellet.

Figure 5 shows an option for Starlight for a laser-driven reactor design. The first wall is cooled by 4-MPa helium gas flowing in cooling channels. The calculated lifetime of the wall, which is made of 2-1/4 Cr–1 Mo steel (a common low-alloy ferritic steel) is greater than 6 yr. With a 10-cm thickness, the wall allows an acceptable tritium breeding ratio with a solid Li_2O granular blanket (at 50% effective density). A reactor radius of 6 m results in a helium exit temperature of over 700 K and a first-wall bulk temperature of only 760 K. Power conversion efficiency is expected to reach 35%. The temperature of the first wall inner surface reaches 1900 K for an instant after each fusion pulse, and thermal stresses near that surface exceed the yield strength of the material. The thickness of this region is a small fraction of the wall thickness and therefore has a minimal effect on structural calculations.

C. HYLIFE: A Liquid-Lithium Reactor

In the HYLIFE chamber (Fig. 6), 20-cm-diam jets of liquid lithium fall in a cylindrical array between the target and the first structural wall.[7] The array is 1.5 to 2.0 m thick and has an average density about half that of liquid lithium. The lithium fall protects the structure from the effects of the fusion pulse, breeds tritium, and acts as the primary heat-exchange medium. The pool of lithium at the bottom and a stream across the top protect structures in these areas.

The HYLIFE system was designed when we were less informed about target performance than we are today. In HYLIFE, targets are injected at 1.5 Hz, imploded by a 4.5-MJ driver, and yield 1800 MJ of energy. This assumes a target gain of 400. We now predict gains of 70 to 100 for the most thoroughly studied target designs, but gains of ≥400 for advanced design concepts. The lithium exit temperature is 770 K. The plant fusion power is 3170 MW_t, which produces 1010 MW_e net power.

The flowing-lithium-jet system is simple and effective. The 0.75- to 1.0-m (effective thickness) layer of liquid lithium reduces the 14-MeV neutron flux on the wall by a factor of 200. The wall (2-1/4 Cr–1 Mo steel) can last the lifetime of the plant if a lithium fall thickness greater than 0.75 m is used. Arranging the falling lithium in an array of 20-cm-diam jets, rather than in a continuous fall, provides effective shock isolation from the fusion pulse. Because the hot, vaporized lithium simply blows through the array of jets, this configuration minimizes the wall stress resulting from the impact of lithium accelerated by high-pressure blowoff gas, caused by the deposition of x-ray and debris energy. Much of the kinetic energy of expansion of the fluid, which results from the neutron absorption, is dissipated in the liquid—liquid interactions among colliding jets. The large surface area of the disassembled fluid acts as an effective condensation pump for the lithium vapor.

We have raised some issues with the HYLIFE design. The lithium jets must rapidly reestablish themselves between pulses. Without experimental data, we are uncertain how quickly this can be reliably done. At 1.5 Hz, the pumping power is high. At higher rates, the pumping power becomes excessive and degrades economic performance. At this pulse rate (and lithium flow rate), the lithium temperature rise per pulse is only 18 K. The flow rate required to obtain the 1.5-Hz pulse rate is many times that needed for heat transfer. Liquid lithium is flammable and reacts with water. The chemical energy stored in the lithium inventory is about 10^{13} J (about the same as that stored in the sodium in an LMFBR). For comparison, the chemical energy in a railcar of propane is about 10^{12} J. An intermediate heat-exchange loop using liquid sodium must be used to separate the tritium-bearing lithium from the water in the steam cycle. All concrete must be lined with steel and the reactor room segmented to minimize reactions of lithium with concrete. These factors combine to make the HYLIFE design about a factor of 2 more expensive than a LWR.

D. HYLIFE-II: A FLiBe Reactor

We are investigating a new version of HYLIFE, called HYLIFE-II,[8] which uses a lithium salt (LiF + BeF_2) to avoid the high stored chemical energy of liquid lithium. We reduce the effective thickness of the fall to 0.4 m and use a high-nickel alloy for the structure. The intermediate coolant is $NaBF_4$. The main features of the reactor are essentially unchanged, but safety is increased. In addition to the change of fluid, we are trying to adapt the HYLIFE reactor to simple targets having a gain of 70 at a driver energy of 5 MJ.

Reducing the gain from 400 to 70 requires that the repetition rate increase by a factor of 5.7. The time for the fall to reestablish itself depends on flow speed and dimensions. We can increase the repetition rate by introducing the flowing liquid at a significantly higher rate or by using multiple chambers. We assume three chambers and a repetition rate about twice that of the original HYLIFE design, with a similar flow speed of about 10 m/s and a yield reduced from 1800 to 350 MJ. The chamber radius will be reduced from 5 to about 3.5 m. All these changes preserve the HYLIFE design principles, resulting in the need for three chambers to get 3 GW of thermal power. Of course, we would like to get this power from one chamber for design simplicity—for example, by increasing the flow speed and further reducing the chamber size. The high total flow rate is another reason we would like to find ways to reduce the number of chambers. If the flow rate is increased substantially (e.g., from about 10 to about 30 m/s), we would consider pulsing the flow, which would present a significant engineering challenge.

Along with the predicted lower gain, another change is the need (with lasers) to illuminate the target more symmetrically, or the need (with heavy ions) for multiple beams to deliver enough total intensity. These and other aspects of HYLIFE-II are discussed in Ref. 8.

E. The Driver-Reaction Chamber Interface

HYLIFE and Cascade were designed for two-sided illumination by lasers or heavy-ion beams. (Unfortunately, the target coupling efficiency of a laser is low with two-sided illumination.) From the standpoint of reactor design, it would be desirable to have as few chamber penetrations with as small a solid angle as possible. Present designs assume that the final laser mirrors are several tens of meters away from the fusion pulse (60 m for HYLIFE). The mirrors are protected from the effects of soft x rays and debris by a few torr-meters of a high-Z gas in part of the beam pipe. Neutrons streaming up the beam lines will limit the lifetime of dielectric mirrors to <1 yr. If grazing-incidence metal mirrors have reflectances high enough and lifetimes long enough, they might permit frequency converters and dielectric mirrors to be out of the line of sight of neutrons. The beams would enter the containment building through a large window (with a backup shuttering system) upstream from the final mirrors and out of the line of sight of the fusion pulse. For heavy ions the final focusing magnets are just outside the chamber. Although we have yet to determine magnet lifetimes for the HYLIFE or Cascade concepts, detailed neutronics calculations in the HIBALL-II study[9] indicate that the magnets will survive an entire power plant lifetime.

For laser propagation through the chamber to the target, the nominal atom density should be $<10^{15}$ to 10^{16} cm^{-3} (two to three orders of magnitude below the peak density). All of the designs considered appear capable of condensing the vaporized material to this atom density in tens of milliseconds. On the other hand, heavy-ion-beam propagation may require an atom density $<3 \times 10^{14}$ cm^{-3}, unless one of the high-pressure transmission "windows" is usable.[10] For this great a density change, the uncertainties in condensation phenomena are more important. Furthermore, use of some blanket materials is difficult. For example, the vapor pressure of lithium at 770 K is ~2.5×10^{-3} Torr, corresponding to an atom density of about 3×10^{13} cm^{-3}. Options for reducing the atom density, should they be needed, include lowering the lithium temperature to 720 K or injecting cooler lithium near the beam lines to reduce the atom density locally. The atom density set by the vapor pressure of FLiBe at the chosen HYLIFE-II operating point is 5×10^{12} cm^{-3}.

While narrow, two-sided illumination is good for ion targets, it is not optimal for laser targets (even indirect-drive targets). Substantially higher driver energy is required if all beams approach the target from only two directions. This was a prime motivation for developing HYLIFE-II and an especially important reason for developing Starlight, which allows much more favorable laser beam configurations. In Cascade, a more optimal laser illumination geometry is difficult to achieve because of the chamber rotation. If there were eight beam ports in the sides of the Cascade chamber (four on each side of the midplane), the granules could conceivably flow around them. The timing of the chamber rotation would have to be such that the ports lined up with the beam lines each time the laser was fired. The rotation rate best for granular flow is near the value necessary for port alignment.

F. Safety and Environmental Issues

Table 2 shows the neutron-induced activities of four reactors at shutdown and at various times thereafter. The PWR data are based on the assumption that each batch of fuel (ten batches) has been in the core for 3 years with an 80% availability. The Starfire data represent the activity at the time the first wall is replaced after 20 MW·yr/m^2. The induced activity of the two ICF reactors is after 30 yr operation at 70% availability. HYLIFE has the lowest activity at shutdown and at 100 yr; Cascade has the lowest from 1 day to 30 yr. If Li_2O is used for the breeding material, then Cascade has the lowest activity at 100 years as well. There are, of course, many other MFE reactor concepts in addition to Starfire, with varying activities. (Starfire is one of the most complete and recent MFE reactor studies, however.) The average activity at shutdown for the six reactors in the ESECOM study[11] is 4×10^3 MCi.

Table 3 shows decay afterheat, which is an indicator of the need for active cooling to prevent the melting of structural components and possible release of activation products after a planned or unscheduled shutdown. For afterheats lower than a few megawatts, it is likely that radiative cooling would be sufficient, and no active cooling system would be required. HYLIFE satisfies this criterion at shutdown. Cascade's afterheat is also low enough to prevent damage because it is constructed mainly with ceramics.

Table 4 shows the inhalation biological hazard potential (bhp), an indicator of the potential risk due to the release of activation products to the air. The bhp is the volume of air that must be mixed with the radioactive material to allow it to be continually inhaled without any detectable medical effects from irradiation. Of course, any given accident would release only a small fraction of the material, but the total amount is used as a relative indicator of the hazard. The data for the PWR include the actinides and fission products present after a 3-yr fuel burnup. The Starfire data again reflect the value after 20 MW·yr/m^2. The ICF reactor data are at the end of life, 30 years. HYLIFE appears to have the lowest risk.

One fact stands out in all these safety comparisons: for these figures of merit, ICF reactors appear to have a significant advantage over a PWR and a modest advantage over the Starfire MFE reactor design.

IV. Development Issues

Many ICF reactor concepts have been proposed, and many studies of ICF reactor issues have been conducted. The small community of reactor designers is still defining the ICF design and operating space. It is too early to select a "best" design. All reactor design studies could be improved by the acquisition of data that address the most fundamental and generic issues. The ICF reactor design effort has benefitted from the MFE technology program. For example, some of the fundamental issues concerning the use of Li, FLiBe, and Li ceramics as blanket materials have been addressed in that program, and the results are usually applicable to ICF reactors. On the other hand, data concerning issues specific to ICF are lacking.

Areas in which data and/or development would be helpful include the following:

- Neutron, x-ray, and gamma-ray damage to reflective optics and polymers (plastics, polyimides, etc.) over time.
- Disassembly of liquids isochorically heated by neutrons.
- First-wall vaporization and condensation phenomenology.
- Neutron and gamma-ray damage from pulsed irradiation sources.
- Cracking and fracturing of solids as a result of cyclic temperature and pressure changes in the pulsed radiation environment.
- Maximum target-chamber particle densities at which satisfactory driver-beam propagation is possible.
- Viability of concepts for protection of optical systems (if needed).

In addition to the data, system concepts and studies are needed on automated production of targets (10^6 per day); target injection, pointing and tracking; reprocessing of target materials; and reactor safety systems. Finally, ICF must create an affordable development scenario. Again, ICF may have an advantage here because the intense, pulsed emissions from a target allow a simple and perhaps inexpensive development path. For example, once high gain is achieved, we would begin design of an inexpensive engineering test facility, inexpensive because it would operate at low power (low gain and/or low pulse rate). ICF engineering tests can be done at low powers by moving the test wall close to the fusion pulses to obtain the desired reactor-like flux.

V. Conclusions

Concurrent with the rapid progress in driver and target physics, there has been equally rapid progress in the study of ICF reactor concepts. Studies show that ICF reactors can be practical, clean, and safe. Future studies are likely to emphasize inherent safety and economic competitiveness at the smallest possible size. Most studies have assumed use of the steam cycle for generating electricity. We expect that there may be more emphasis in the future on advanced concepts that convert fusion power into electric power directly or at least more efficiently than the steam cycle.

Viable scenarios exist for economic power production from ICF. The accomplishment of high gain appears to be close enough that it is time to expand the ICF reactor technology program and to increase industry involvement. Obtaining data on issues specific to ICF through fundamental and systems studies at universities and in industry should be part of this expansion. The national laboratories should be intimately involved in these studies.

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Table 1a. System parameters and costs for a 1-GWe power plant with a 5-Hz pulse rate and a laser driver efficiency of 10%. (Reactor performance and cost are based on the Cascade reactor.)

	Laser Target Gain Curve[a]		
	A	B	C
Driver energy (MJ)	3.2	5.2	8.2
Target gain	122	82	58
Target yield (MJ)	391	425	476
Thermal power (MW_t)	2177	2365	2646
Gross electricity (MW_e)	1180	1282	1434
Driver power (MW_e)	160	260	410
Auxiliary power (MW_e)	20	22	24
Direct costs ($ billion)			
Reactor	0.80	0.85	0.93
Driver	0.23	0.32	0.44
Target factory	0.10	0.10	0.10
Total direct costs	1.13	1.27	1.46
Total cost ($ billion)	2.07	2.33	2.68
Cost of electricity (¢/kW_e·h)	3.81	4.29	4.94

[a] See Fig. 3a.

Table 1b. System parameters and costs for a 1-GWe power plant with a 10-Hz pulse rate and a heavy-ion driver efficiency of 25%. (Reactor performance and cost are based on the Cascade reactor.)

	Heavy-ion Target Gain Curve[a]	
	A	B
Driver energy (MJ)	3.3	2.8
Target gain	58	67
Target yield (MJ)	191	188
Thermal power (MW_t)	2125	2087
Gross electricity (MW_e)	1152	1131
Driver power (MW_e)	132	112
Auxiliary power (MW_e)	20	19
Direct costs ($ billion)		
Reactor	0.79	0.78
Driver	1.00	1.16
Target factory	0.10	0.10
Total direct costs	1.89	2.04
Total cost ($ billion)	3.47	3.73
Cost of electricity (¢/$kW_e \cdot h$)	6.36	6.87
COE for 1.25 x reduction in driver costs	5.69	6.09
COE for 2 x reduction in driver costs	4.68	4.92
COE for 3 x reduction in driver costs	4.12	4.27

[a] See Fig. 3b.

Table 2. Neutron-induced activity (MCi) for a 1-GW_e reactor.

	Time after shutdown				
Reactor Type	0	1 d	1 m	30 yr	100 yr
PWR	1.2×10^4	2700	600	21	4.1
Starfire	6000	—[a]	—[a]	2.4	0.3
HYLIFE	300	200	150	0.9	0.3
Cascade	1400	110	5.7	0.7	0.7

[a] Not available.

Table 3. Decay heat (MW) of induced activity for a 1-GW_e reactor.

Reactor type	Time after shutdown 0	1 d
PWR	180	23.0
Starfire	70	—[a]
HYLIFE	2	0.2
Cascade	27	2.6

[a] Not available.

Table 4. Inhalation biological hazard potential (km^3) for a 1-GW_e reactor.

Reactor type	Time after shutdown 0	1 d
PWR	1.2×10^{10}	1.2×10^{10}
Starfire	1.7×10^{10}	—[a]
HYLIFE	5.0×10^{7}	3.0×10^{7}
Cascade	1.7×10^{8}	3.5×10^{7}

[a] Not available.

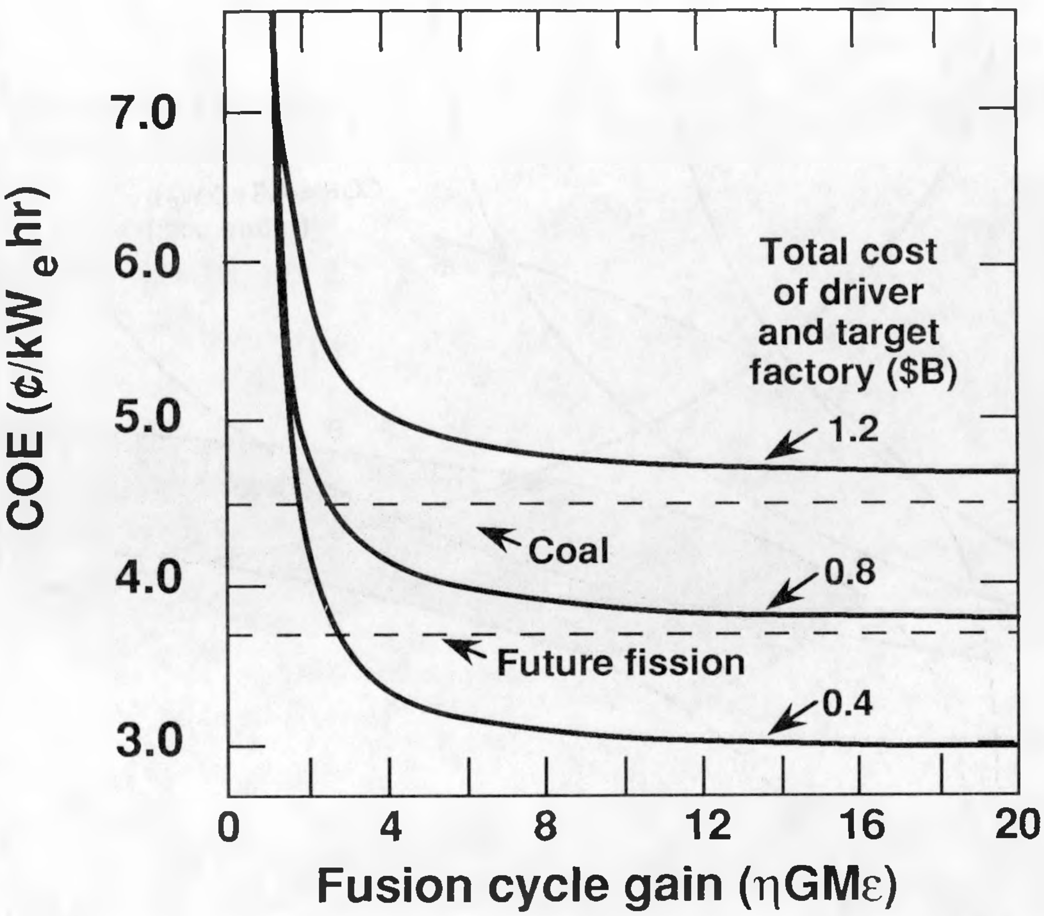

Fig. 1

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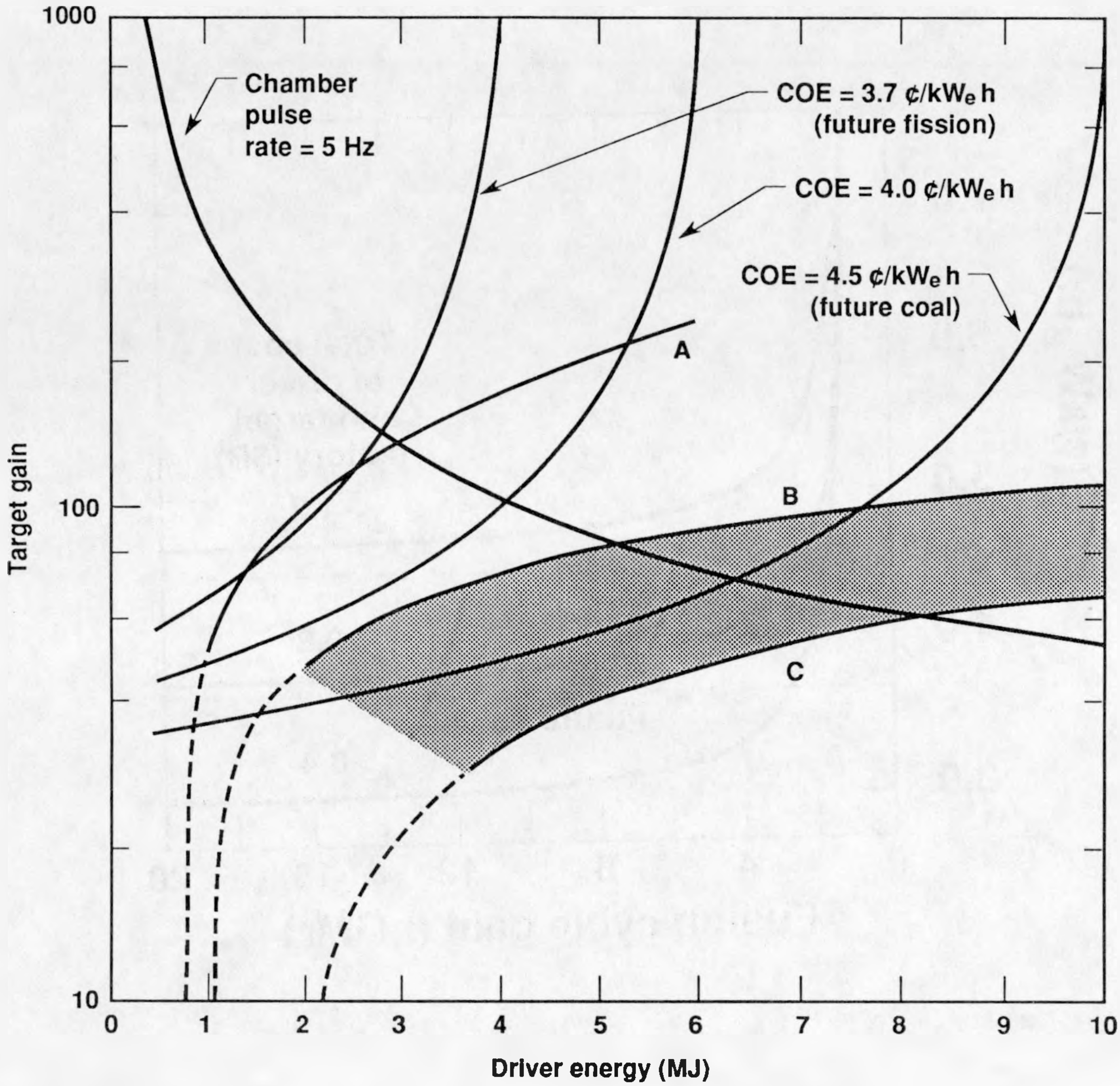

Fig. 2 The ICF reactor Cascade, operating at 5Hz is competitive with future coal and fission power with current estimates of target and driver performance.

BOB-S121-Fig2

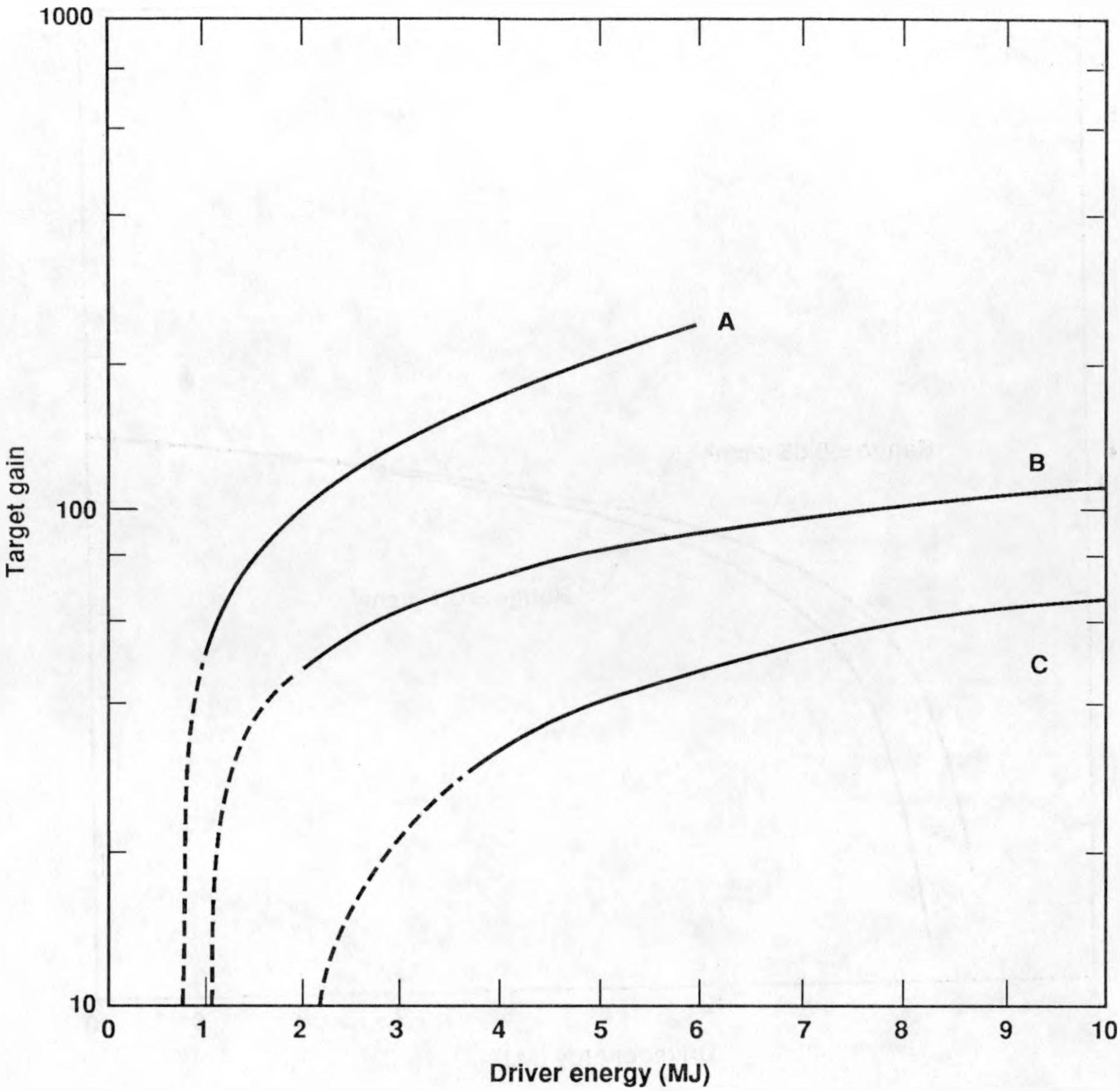

Fig. 3a Three postulated laser gain curves.

Figure 3a
LW-S121-U-2

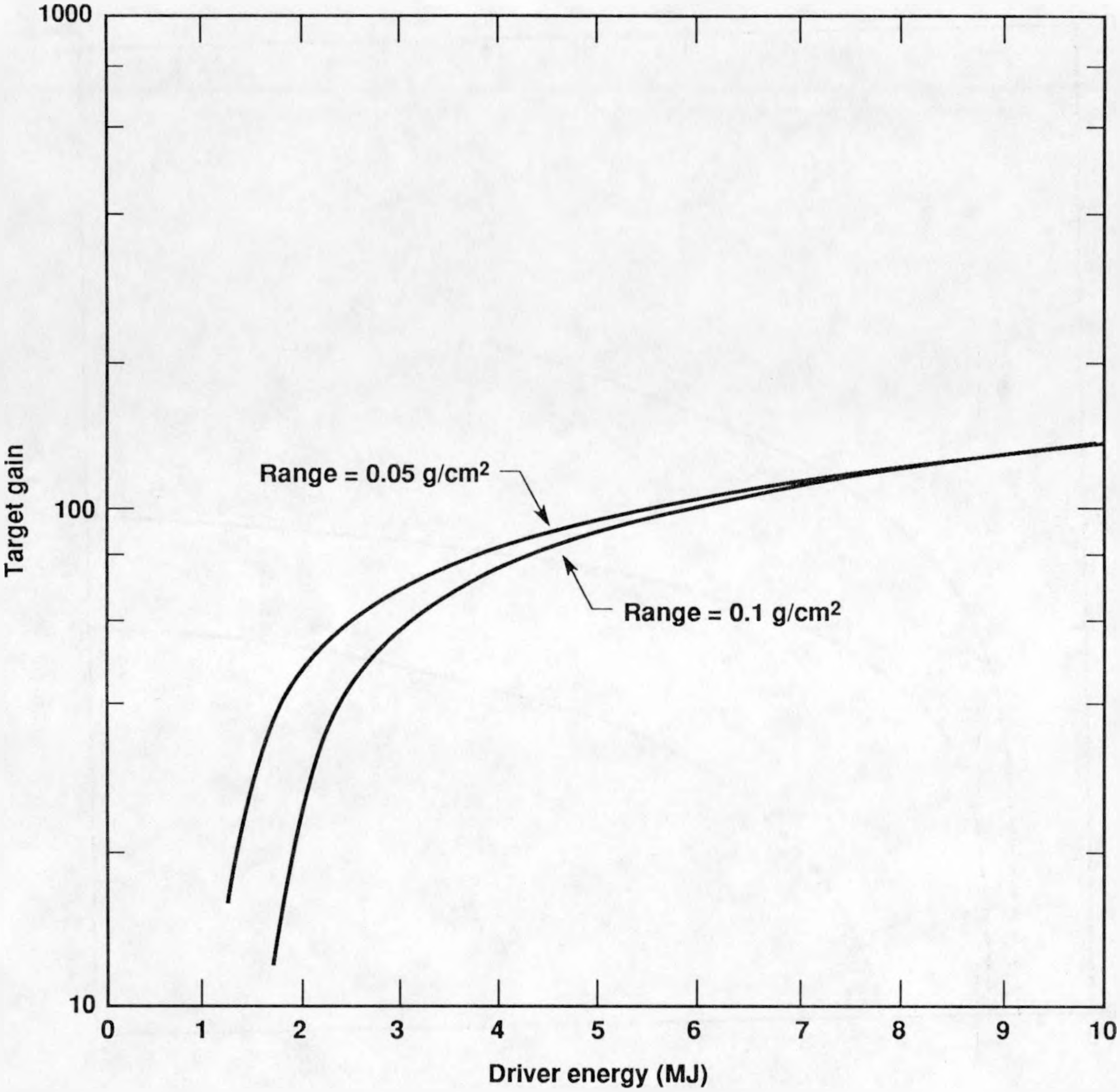

Fig. 3b Two postulated heavy-ion gain curves for a 2mm deposition radius.

Figure 1
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