

ENERGY FROM INERTIAL FUSION

Progress in drivers, reactors and targets has made smaller, more flexible power plants feasible and has reduced the potential costs of developing them.

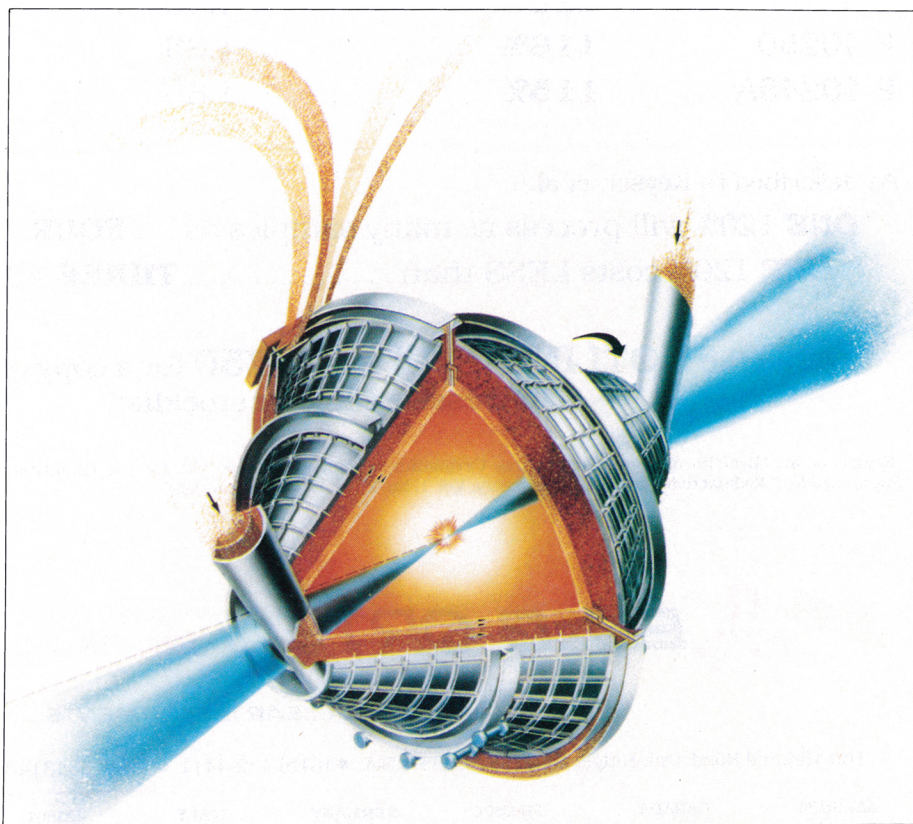
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Fusion is potentially a safe, clean energy source not limited by political boundaries. Magnetic and inertial fusion share this promise, but there are differences between them. An inertial fusion power plant is based on different physics and technology from a magnetic fusion power plant and therefore presents somewhat different benefits and challenges. The facilities required to demonstrate inertial fusion power are potentially much smaller. In this article we describe concepts for such a power plant,

its beneficial features and a low-cost reactor test facility for developing practical fusion power.

Some of the challenges facing inertial confinement fusion as opposed to magnetic fusion include inertial confinement's different ignition and burn method, its pulsed nature, the high rate at which targets must be manufactured and put in place, and the technically difficult driver-reactor interface. Inertial fusion power plants must be designed to handle these technical prob-

The Cascade reactor. A flowing bed of ceramic granules, held against the wall by the rotating chamber, transforms thermonuclear energy into heat, breeds tritium and protects the structure from the effects of the thermonuclear microexplosions. The granules are fed into the ends of the reactor and slide along the wall to the waist, where they exit and are thrown into heat exchangers through tubes (not shown). The reactor wall consists of silicon carbide tiles held in compression with composite tendons. **Figure 1**



lems in a satisfactory manner. Figure 1 shows one design concept, known as Cascade. Here ceramic granules cascade along the walls of the reaction chamber to collect the fusion energy, breed tritium and protect the structure from the short bursts of fusion energy.

Components

An inertial fusion power plant has four major components:

- ▷ The driver, a laser or particle accelerator that delivers energy to the fusion target

- ▷ The target factory, where targets are manufactured, filled with deuterium-tritium fuel and stored

- ▷ The reactor, where targets and driver beams are brought together to produce thermonuclear microexplosions a few times a second

- ▷ The generator, which converts thermal energy to electricity.

Most drivers now envisioned can transport energy pulses large distances—for example, from a separate building. This separability implies that the driver can be maintained easily and can in principle support several reactors. The burning inertial fusion plasma is extremely small—much less than 1 mm in radius—and short lived—lasting from tens to hundreds of picoseconds. (A complete discussion of fusion targets can be found in the article on page 32 by John D. Lindl, Robert L. McCrory and E. Michael Campbell.)

Once the burning begins, performance can be affected only by events within a few centimeters, even if a particular effect travels at the speed of light. Thus one can design the reactor to contain the microexplosions and breed tritium without the designer having to worry about target performance. The reactor vacuum requirement is determined only by the requirements of beam propagation. One can vary the plant's power output by changing the pulse rate or yield of the target. In the development phase, targets with small gain and yield can be used in reduced-scale low-power reactor tests at reduced cost.

Central to the economics of any inertial fusion power plant is the fusion cycle gain.¹ The fusion cycle gain is the product of the driver efficiency η (the ratio of the energy delivered to the target and the energy supplied to the driver), the target gain G (the ratio of the thermonuclear yield and the driver energy), the nuclear energy multiplier M (the energy change due to neutron reactions) and the thermal-to-electric energy conversion efficiency ϵ . In any inertial fusion power plant, the net electricity P_n is related to the gross electricity P_g through the power balance equation

$$P_n = P_g - P_a - P_d = P_g(1 - f_a - 1/\eta GM\epsilon)$$

Here P_a , which is equal to $f_a P_g$, is the power used for auxiliary equipment, and P_d is the driver power. The driver's recirculating power fraction P_d/P_g is the inverse of the fusion cycle gain.

The cost of electricity is to a good approximation proportional to the yearly amortized capital cost divided by the net annual energy produced. To a first approximation, the capital cost of the reactor and conventional steam-cycle generator is proportional to $P_t^{0.6-0.8}$, where P_t is the thermal power.¹ Using this simple model, figure 2 shows the relative cost of electricity for a plant producing

1000 MW of electricity as a function of the fusion cycle gain and the total cost of the driver and target factory. A sharp knee defines the minimum acceptable fusion cycle gain, which is about 4 or 5. Further increases in fusion cycle gain do not lower the cost of electricity as rapidly as do driver and target factory cost reductions. Since the nuclear energy multiplier M is typically 1.05–1.15—due primarily to the exothermic reactions in lithium required to produce tritium—and the conversion efficiency ϵ is typically 0.35–0.45, the product ηG must be above about 10. This product determines the minimum gain necessary for any given driver. Since driver cost usually scales as some power (0.4–1.0) of driver energy, it is important to obtain this minimum gain at the lowest possible driver energy.

Note that to reach power break-even for the plant—that is, to produce enough power to operate the driver—requires a fusion cycle gain of only 1, if we ignore f_a , which is usually only a few percent. That reduces the minimum required gain by a factor of 4 or 5. While reaching power break-even will not be an important technical requirement in itself, it is usually considered a noteworthy milestone on the way to economic competitiveness. The fact that break-even can be achieved at reduced gain therefore will help keep early inertial fusion reactor development costs low.

Solid-state lasers

The drive energy can be delivered by lasers or ion beams. The four concepts receiving significant effort in the US are solid-state lasers, KrF lasers, light-ion accelerators and heavy-ion accelerators.

Solid-state lasers, in particular Nd:glass lasers, have dominated inertial confinement fusion research to date. Almost all important target-physics experiments worldwide have been done with these drivers, for a simple reason: Beam irradiances of 10^{14} – 10^{15} W/cm² are required for fusion, as explained in the article by Lindl, McCrory and Campbell. At small drive energies the target mass can be reduced proportionately. However, the necessary beam intensity remains about the same, and lasers, even small ones, can provide the required values easily. Particle beams have much more difficulty providing high irradiance at low energy. Lasers enabled early low-cost target experiments to prove some of the fundamental features of inertial confinement fusion. In particular, Nd:glass lasers, because of their scalability, modularity, energy-storage capability, wavelength-conversion capability and advanced state of development, established their capabilities early on as an inertial confinement fusion research tool.

The most energetic and powerful laser in the world is

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Nova at Lawrence Livermore National Laboratory, described in detail in the article by Lindl, McCrory and Campbell. Other large Nd:glass research lasers are the Gekko XII laser at Osaka University and the Omega laser at the University of Rochester. Numerous laboratories worldwide have smaller Nd:glass lasers.

Solid-state lasers were initially discounted for reactors because of the characteristics of flashlamp-pumped Nd:glass lasers—in particular, their inefficiency and low pulse rate. However, the diode-pumped gas-cooled solid-state laser may overcome these problems.² Its architecture is similar to the proposed Nova Upgrade, but the gas cooling, crystalline disks and diode pumping are different. Glass disks on either side of each crystalline laser disk confine flowing helium gas to remove heat. The crystalline laser disks have suitable thermomechanical characteristics for removing the heat without creating excessive optical distortion. Experiments have confirmed that this design can remove heat in an acceptable manner.²

Laser diodes with an efficiency of about 60% have been demonstrated. Such a diode's emission spectrum is quite narrow, and a second laser with an overlapping narrow absorption band can be designed, resulting in high overall laser efficiency. However, the diode's cost is proportional to the peak wattage required. Therefore, for a laser operating in a pulsed mode, the energy transfer time should be as long as possible. But this time is limited by the emission lifetime τ of the crystalline laser. Thus the cost of the required diode array is proportional to the cost per peak watt of the array divided by the emission lifetime τ . For any diode unit cost there is a required τ for the laser. Diode arrays will probably decrease from \$1–10 per

peak watt to 1–10¢ per peak watt when they are produced in volume. If this cost goal is achieved, emission lifetimes of 1–10 msec will suffice for a driver suitable for a competitive 1000-MW_e power plant. One current candidate is an InGaAs diode array and an ytterbium-doped fluorapatite crystal—Yb:Ca₅(PO₄)₃F. The estimated wall-plug efficiency of such a laser could be 14–16%, but an integrated small-scale demonstration is needed to prove its feasibility. If such a test is successful, researchers must see if these lasers can meet the cost goals, given that the emission lifetime of Yb:Ca₅(PO₄)₃F is about 1.3 msec; find out the long-term durability of optical components; obtain target gains of 60–100; and find a design for the driver-reactor interface that can survive the thermonuclear environment at low cost.

Krypton fluoride gas lasers

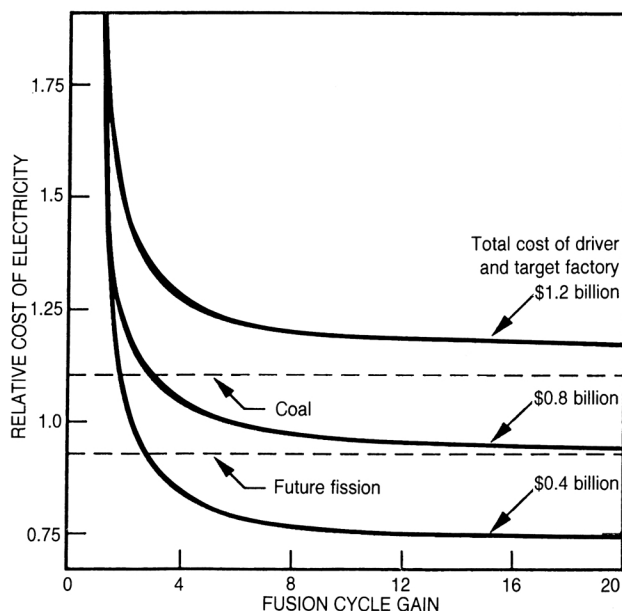
In excimer lasers using gases such as KrF, the gaseous lasing medium is pumped by an electric discharge or an electron beam. The lasing gas flows through heat exchangers to remove waste heat. The 250-nm wavelength and broad bandwidth of KrF lead to good coupling to the target.

The use of the KrF laser is made complicated by its very short spontaneous emission lifetime—that is, it does not store energy in the excited state for lengths of time longer than the desired extraction time. Thus for good efficiency light must be extracted during the entire pumping time. The anticipated pumping time, as dictated by pulsed-power requirements, is several hundred nanoseconds. Therefore the pulse must be shortened by a factor of 100.

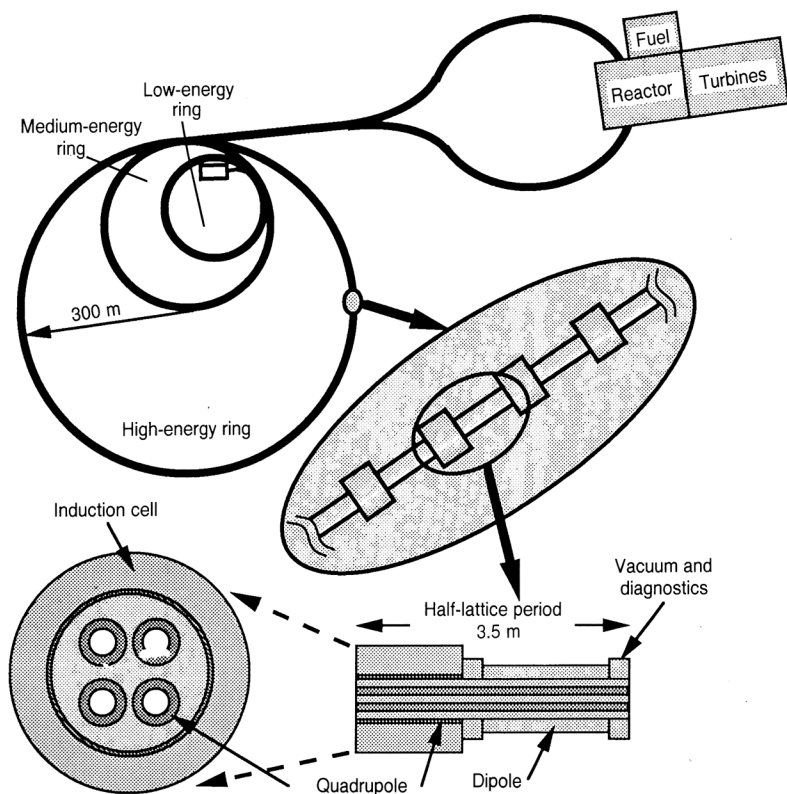
Two methods for doing this have been studied. In the angular multiplexing scheme, short seed pulses pass through the amplifier sequentially for the entire duration of the pumping, each at a different angle. These beams are transported through paths of different lengths so they arrive at the target simultaneously. In the second alternative a long pulse is extracted and then shortened by passing it through a stimulated-Raman-scattering cell, such as a chamber filled with sulfur hexafluoride gas. Through backward Raman scattering the pulse can be efficiently shortened by a factor of 100. The cell must be long, because the returning short pulse must not reach the end of the cell before the long pulse finishes entering. Both pulse-shortening techniques have been demonstrated, but they increase the complexity of the optical system.

Small KrF lasers with energies under 10 kJ have been built at various laboratories around the world. As recommended by a recent National Academy of Sciences panel,³ the Naval Research Laboratory now leads KrF development in the US with its Nike laser, currently under construction. Other examples are the Sprite laser at Rutherford Appleton Laboratory, the Aurora laser at Los Alamos and lasers at several facilities in Japan.

Key issues for KrF reactor drivers are efficiency, cost and reliability. The brightness of the laser beams, which is a measure of their focusability, is also an issue for indirect drive targets. Recent studies of KrF lasers found^{4,5} net wall-plug efficiencies of only 6–8%. This driver efficiency η would require a target gain G of 140–160 to achieve a product ηG of 10—the largest required



Relative cost of electricity as a function of fusion cycle gain $\eta G M \epsilon$ and cost of driver and target factory. **Figure 2**



Recirculating heavy-ion driver with four beam lines accelerated progressively to 0.05 GeV in the low-energy ring, 1 GeV in the medium-energy ring and 10 GeV in the high-energy ring. The total energy put on the target is 4 MJ in a 10-nsec pulse. The direct cost is estimated⁸ to be under \$500 million. **Figure 3**

gain of any candidate driver. The cost of the KrF laser approach is increased by its optical complexity, the susceptibility of its optics to damage by the 250-nm ultraviolet light, and an optical transport problem more complex than that of the solid-state laser.

Light-ion accelerators

Pulse power technology can compress large quantities of electricity into reasonably short pulses efficiently and at relatively low cost. In a light-ion accelerator, an electrical pulse of the required energy is progressively shortened by a variety of pulsed power techniques, and the resulting pulse of a few tens of megavolts is applied to a diode whose anode emits the desired ion such as Li^{+1} . The ions are generally accelerated in a single step; although multigap light-ion accelerators have been proposed as fusion drivers, most ongoing studies have concentrated on diode accelerators. Estimates of net driver efficiencies are 20–25%.

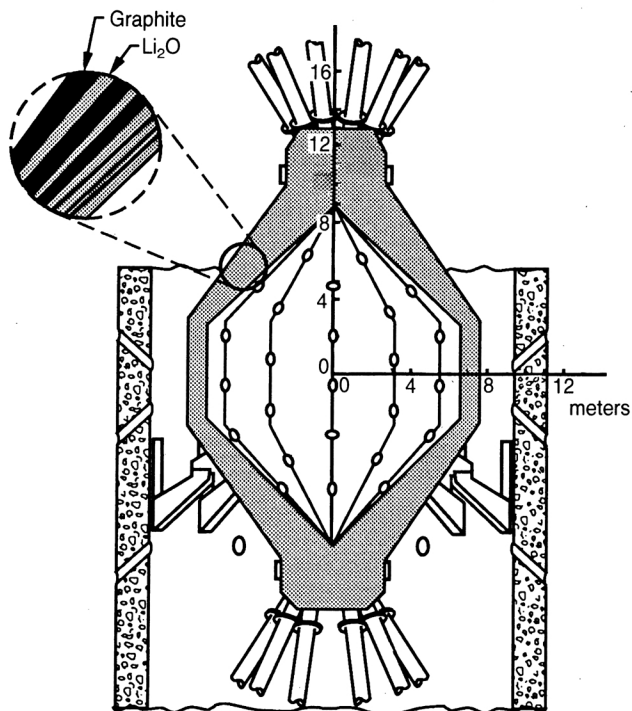
Several laboratories around the world are studying pulsed-power technology and light-ion diodes. The Angara V machine at Troitsk, Russia, is the largest pulsed-power machine, but light-ion diode studies are not being pursued there. The Particle Beam Fusion Accelerator II at Sandia National Laboratory is the most energetic inertial confinement fusion driver in existence, with the potential to put about 1 MJ on target. At its maximum voltage of 10–30 MV, it requires a few megamperes to achieve the required power. However, it has not yet obtained the intensities required for significant fusion implosion experiments. Obtaining the required beam divergence is extremely difficult. Present Li^{+} ion intensities at the target are in the range of 1 terawatt/cm², although 5-MeV protons have been focused to 5 TW/cm². The recent NAS review³ of the inertial confinement fusion program established a 10-TW/cm² Li^{+} goal for PBFA II for fiscal year 1992.

Light-ion-driven fusion power plant designs have been studied.⁶ Driving high-gain targets requires intensities greater than 100 TW/cm². To survive the effects of the target explosion, the diode must be several meters away, and the beams must be transported to the target. The diode on PBFA II is only about 15 cm away from the target. We must develop reliable, long-lifetime diodes that can be pulsed at 1–10 Hz and from which appropriate beams can be extracted.

Heavy-ion accelerators

The Department of Energy's Fusion Policy Advisory Committee judged heavy-ion accelerators the leading candidate for a reactor driver because of their durability, reliability, high-pulse-rate capability and potential for high efficiency.⁷ Heavy ions such as xenon, cesium or bismuth with kinetic energies of 2–10 GeV have the correct stopping range to drive targets. To obtain the 4×10^{14} W, which is the power needed to drive the target, requires a current on the order of 100 kA, assuming singly charged ions are used. This current is large compared with the currents that are common in conventional high-energy accelerators. Beams with these characteristics have not yet demonstrated the required brightness.

There are two main approaches to heavy-ion drivers: radiofrequency accelerators and induction accelerators. Physicists in Europe and Japan are studying the rf accelerator because of their large body of experience with the many existing high-energy physics accelerators. Physicists in the US are examining the induction accelerator because of its simplicity and ability to handle high-current beams. In such accelerators space-charge-dominated beams are periodically accelerated by induction cells and transported by a sequence of alternating-gradient quadrupoles. At any beam velocity there is a maximum current that can be successfully transported in an alternating-gradient lattice. The current limit is reached when the



The Sombbrero reactor protects the graphite first wall from target x rays with xenon gas that allows the laser beams to reach the target. Li_2O granules fall through channels in the carbon-carbon-composite wall. The small circles are openings for 60 uniformly spaced laser beams that illuminate the direct-drive target. **Figure 4**

space-charge forces of the beam become equal to the applied focusing forces. For a properly designed system this current, in mks units, is given by

$$I_{\max} \approx 4 \times 10^{-12} a B v^2$$

where a is the beam aperture radius, B is the pole-tip magnetic field of the quadrupoles, and v is the ion velocity. For electrostatic quadrupoles, B is replaced with E/v . The current limit is often referred to as the Maschke limit after Alfred W. Maschke, who proposed heavy-ion accelerators as inertial fusion drivers.

For a specific example of the current limit, consider the case of 10-GeV ions, a beam aperture of 5 cm and a magnetic field of 2 T. At 10 GeV the velocity of a heavy ion is about 10^8 m/sec, so that $I_{\max} \approx 4$ kA. To achieve 4×10^{14} W per pulse requires a total current of 40 kA, so multiple beams—more than ten—are necessary. To focus each beam also requires multiple beams because of the space-charge limits. Fortunately multiple beams can be accelerated simultaneously through the same induction cells, which are very efficient at high beam current. This technique, combined with the use of superconducting quadrupoles for transport, can produce overall accelerator efficiencies of 20–30%.

Several linear and recirculating architectures that are being considered try to minimize cost. In the linear versions the beams are accelerated in a single pass. In the recirculating versions the beams pass through the same induction cells many times, as shown in figure 3. Preliminary studies show that the recirculating systems may be less expensive than the linear systems.⁸ Recent

studies of fusion power plants with heavy-ion drivers have shown that several accelerator designs can obtain driver efficiencies of 20–30%, requiring target gains of about 30–40, much lower than those required by lasers.^{4,5} Such drivers are sufficiently inexpensive that power plants will be economically competitive at the 1000-MW_e level.

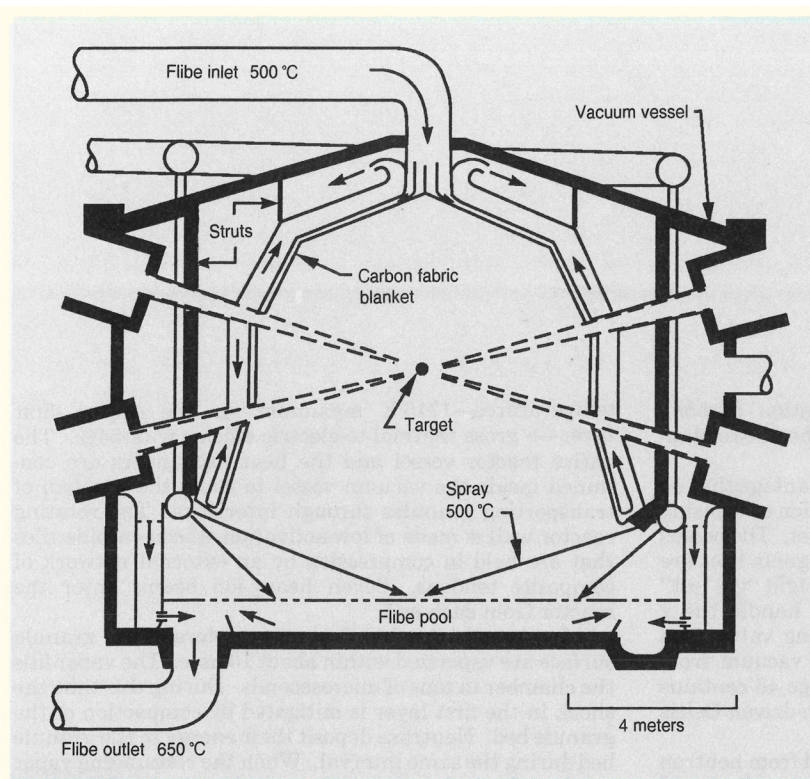
The principal scientific challenge for heavy-ion drivers is to obtain the beam intensity required to drive a fusion target. Converting the energy to x rays in indirect-drive targets with good efficiency requires an intensity of about 10^{15} W/cm², as Lindl, McCrory and Campbell explain in their article. This implies a required focal-spot radius of less than about 3 mm. To survive the effects of each microexplosion, the final focusing magnets must stand off at a distance of a few meters. Obtaining the required spot size requires that the transverse emittance and longitudinal-momentum spread of the beams at the final focusing magnets be sufficiently small. The emittance ϵ is given by $\beta\gamma qr$, where β is the particle velocity in units of the speed of light, γ is $(1 - \beta^2)^{-1/2}$, and r and q are the beam radius and the angular spread among the beam rays, respectively. At the final focusing magnets the emittance must be less than about 10^{-5} meter-radians, and the final longitudinal momentum spread must be less than 1%.

Heavy-ion sources have produced beams with emittances about 100 times better than required, but the question remains whether space-charge-dominated multiple beams can survive all the beam manipulations with acceptably low growth in their emittance and momentum spread. Previous small-scale experiments have had encouraging results, but experiments are needed at larger scales.⁹ A proposed accelerator at Lawrence Berkeley Laboratory, known as Induction Linac Systems Experiments, may answer the question. ILSE will be much shorter than a power-plant driver, but it will carry the same charge density and be able to test emittance growth at the appropriate scale.

A megajoule-class driver must be built before high-gain fusion target implosions driven by heavy ions can be tested. There are many similarities between laser and heavy-ion hohlraum (radiation containing) targets, and much of the target physics research for heavy-ion targets can be done with laser targets on the Nova Upgrade. Nevertheless we will eventually need experimental confirmation that heavy-ion drivers can drive fusion targets.

Reactors

A fusion target burns to completion in a few tens of picoseconds to 100 psec. Interaction with material surrounding the fuel capsule can lengthen the duration of the pulse of x rays and target debris to about a nanosecond. Typical target yields in a reactor will be a few hundred megajoules. The reactor must contain the effects of this microexplosion, capture the thermonuclear energy and breed tritium. A variety of structural walls and a



The Osiris reactor. The carbon-composite structure is protected by a thick blanket of molten flibe—a mixture of LiF and BeF₂—guided by a carbon fabric “tent.” **Figure 5**

breeding and thermal transport “blanket” thick enough to stop 14-MeV neutrons perform these functions. Neutrons carry away about two-thirds of the thermonuclear energy. The rest is in the form of x rays and target debris. One can vary the x-ray and debris spectra and pulse lengths considerably, depending on how much material one places around and near the target.¹⁰ Nevertheless the deposition range of this nanosecond-long pulse of energy is small. Therefore the first wall will be subjected to very high instantaneous power loads. Over 50 imaginative designs can plausibly handle this problem.¹¹ We will describe three recent representative examples: Sombraero,⁴ Osiris⁴ and Cascade.¹²

Sombraero. The simplest way to handle the high peak power load is to protect the wall with a buffer gas so that no material is vaporized—a dry-wall reactor. In the Sombraero design (shown in figure 4), a wall made of carbon composite at a radius of 6.5 m is protected from the effects of the 400-MJ targets by 0.5 torr of xenon gas. The laser beams penetrate the gas, but the xenon absorbs the x rays from the target and reradiates their energy to the wall on a longer time scale, thereby reducing the wall loading. Without the gas, the wall would have to be over 12 m away. Within the 1-m-thick first-wall structure are channels through which flow gravity-fed solid Li₂O ceramic granules. The neutrons deposit their energy in the granule bed and create tritium through exothermic (n,Li) reactions. Most of the x-ray and debris energy is conducted through the first wall to the flowing bed. After exiting the reactor, the granule bed is fluidized with helium and transported around a loop, where heat and tritium are extracted. In this direct-drive design, 60 uniformly spaced laser beam lines penetrate the reactor wall and blanket.

The final optical element in each beam line is a grazing-incidence metal mirror that reduces neutron effects by presenting a large surface area to the incident beam. It is about 25 m from the center. The next-to-last

optical element must be a sizable distance from the grazing-incidence mirror to be out of the target’s line of sight. As a result, the building housing the reactor must be very large—about 100 m in diameter and 100 m tall. With a rearrangement of the laser illumination angles, the Sombraero design could also be used with indirect-drive laser targets. The table on page 48 shows typical operating parameters for a Sombraero direct-drive power plant with a KrF laser driver.

The first structural wall in this type of reactor will be exposed to direct neutron bombardment by 14-MeV neutrons and, as a result, will in time lose its structural properties. It is estimated that the inner wall of such reactors will have to be replaced every few years.

Osiris. Figure 5 shows the Osiris reactor, in which hohlraum targets are indirectly driven by six heavy-ion beams entering from each of two principal directions.⁴ The reactor is small to reduce capital costs. To handle the large power density, a self-renewing liquid first wall flows at a radius of about 4 m. The working fluid is a eutectic mixture called “flibe,” which is two-thirds LiF and one-third BeF₂. It enters the reactor at 500 °C and flows through a woven carbon fabric tent-like structure. The porous material allows flibe to weep through, wetting the entire inside surface with a film about 2 mm thick. When the target explodes, the x rays vaporize a layer of flibe a few micrometers thick—a few kilograms’ worth—within about 10 nsec. The vapor fills the chamber and reaches a steady pressure in a time on the order of tens of microseconds. The neutrons deposit their energy in the 0.5-m-thick flibe layer, causing it to expand and force more flibe through the pores of the carbon cloth to replace the fluid that vaporized. The flibe vapor is directed toward cold flibe sprays near the bottom in a few milliseconds, and the cold flibe droplets condense the vapor. Calculations predict that the low pressure—less than 10^{−3} torr—required for propagation of the heavy-ion beams is

restored within 100 msec. A low-activation carbon-carbon-composite vacuum vessel contains the entire blanket.

Heavy-ion-driven reactors have the advantage that no material object important to beam propagation or focusing need be in a direct line of sight with the target. The beams can be bent out of the direct path with magnets that are themselves out of the line of sight. Line-of-sight "get lost" (non-reflective and non-scattering) dumps handle the x rays, neutrons and debris, while fast-closing valves and differential pumps isolate the accelerator vacuum from the vapors in the reactor. The table on page 48 contains typical operating parameters of a heavy-ion-driven Osiris power plant.

In Osiris the structural wall is protected from neutron damage by the thick blanket of flibe, so the wall should last the 30-year lifetime of the plant without replacement. The reactor's top can be removed, and the entire carbon cloth structure, which is exposed to higher fluences, can be lifted out for replacement every few years.

Cascade. Cascade¹² uses a flowing blanket of ceramic granules, as does Sombrero, but in this design they are inside the structural wall, as seen in figure 1. The granules flow by force of gravity into the ends of a rotating, cement-mixer-like structure about 5 m in radius. The chamber's rotation keeps the 1-m-thick granule bed against the wall, flowing toward the largest radius. The reactor cone angle is set at the angle of repose (the angle of a freely formed sand cone) to maintain a uniform blanket thickness. At the waist the granules fall out of slots and are thrown through tubes (not shown) into a heat exchanger, where they transfer their heat to helium gas, which in turn generates electricity through a closed Brayton cycle. The granules can operate at very high

temperatures—1715 K maximum for the carbon first layer—a gross thermal-to-electric efficiency of 54%. The entire reactor vessel and the heat exchangers are contained inside the vacuum vessel to avoid the problem of transporting granules through interlocks. The rotating reactor wall is made of low-activation silicon carbide tiles that are held in compression by an external network of composite tendons. Seven heavy-ion beams enter the reactor from each end.

In Cascade the first few micrometers of the granule surface are vaporized within about 10 nsec. The vapor fills the chamber in tens of microseconds. During this time the shock in the first layer is mitigated by compaction of the granule bed. Neutrons deposit their energy in the granule bed during the same interval. When the rebounding vapor reaches the bed again, it flows in hundreds of microseconds into the porous bed of relatively cool granules. The enormous surface area recondenses the vaporized material to restore pressures of 1–10 pascals in less than 100 msec. The granule bed then relaxes to its original density.

Some granules may break apart due to the shock. Outside the reactor fine particles are removed and recompact into granules of the proper size. Target debris and tritium bred in the granules are removed through the vacuum system. All structural parts in Cascade are protected by a blanket that is thick to neutrons and should not fail from neutron damage during the lifetime of the plant. The table shows characteristic operating parameters of a heavy-ion-driven Cascade power plant. The main issues to study in the development of Cascade are the integrity and lifetime of the granules and the effects of abrasion on the reactor structure.

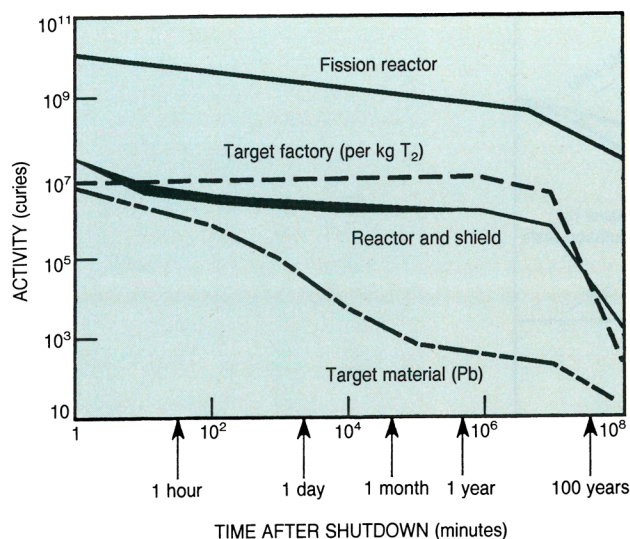
Target factory

The fusion targets, which must be manufactured at rates of up to ten per second, have a simple structure. The fuel capsule is a spherical shell that contains the D-T fuel and that doubles as an ablator and pusher for the implosion process. In indirect-drive targets this fuel capsule is surrounded by a high-atomic-number hohlraum wall to contain the x rays. The gain at low drive energy depends upon the surface finish of the capsule. Surface finishes with no features larger than 1000 Å are required for high gain. However, the hohlraum shell does not have high-precision requirements and can simply be stamped out.

Several techniques have been proposed for making the high-precision capsules. Drop towers are used to make today's targets at rates of several hundred per second, although only for very short times, because we do not need many targets today. In drop towers, the shell material is forced through a collection of small openings. A succession of droplets falls through the heated tower, and the droplets cure into nearly perfectly spherical shells of a predetermined size as they fall. The yield of this technique for thin targets has been 10–25% with surface

Power plant operating parameters

	Sombrero	Osiris	Cascade
Driver energy (MJ)	3.4	5.0	5.0
Gain	118	87	75
Yield (MJ)	400	432	375
Pulse rate (Hz)	6.7	4.6	5.0
Driver efficiency (%)	7.5	28	20
Fusion power (MW)	2680	1987	1875
Thermal power (MW)	2849	2504	1890
Thermal efficiency (%)	47	45	54
Gross electric power (MW _e)	1359	1127	1030
Driver power (MW _e)	304	82	125
Auxiliary power (MW _e)	55	45	15
Net electric power (MW _e)	1000	1000	890
Cost of electricity (1992 cents/kWh)	6.7	5.6	5.0–6.2



Radioactivity in the Cascade reactor as a function of time after shutdown. The activity is much smaller than that in a fission reactor. **Figure 6**

finishes better than 1000 Å. In current research only the best targets are used. Microencapsulation is an emulsion technique that may be better for the larger and thicker capsules needed in the future. This technique has been used in the batch mode to date but appears adaptable to continuous operation. Machinery costs for a full-sized target factory, with redundancy, are estimated at only a few million dollars.

A power plant using several 400-MJ targets per second requires a tritium throughput of 1–2 kg per day. The fuel can be loaded into the capsule by diffusion through the capsule wall or through small holes that are later sealed. Diffusion filling requires a high-pressure chamber containing many times the target-fuel mass. A uniform layer of fuel can be made in several ways. For example, if liquid D–T in a spherical container is allowed to sit, then heating from beta decay of the tritium is greater in the thicker regions than in the thinner ones, and the D–T sublimates and migrates to make the shell uniform—the so-called beta-layering technique. Alternately the fuel can be frozen in a tailored thermal environment, or liquid fuel can be supported by a low-density, low-atomic-number foam shell.

The total amount of tritium contained in the target factory depends upon the methods of filling and of establishing a uniform spherical shell of fuel. If diffusion filling and beta layering are used, then the tritium inventory in the target factory may be as much as 8 kg. For some alternative methods the inventory could be less than 1 kg. The cost of handling the 1–8 kg of tritium may be significantly higher than the cost of the machinery to manufacture the targets themselves. However, research is needed on a variety of specific fabrication techniques before we can choose the best ones for a reactor.

Environmental, safety and health issues

Credible fusion power-plant studies consider environmental, safety and health issues as the design is conceived. All the studies cited here employ low-activation structural materials and blankets. All minimize the tritium inventory and the sources of chemical energy—for example, by using flibe or Li_2O instead of liquid Li. When all these

steps have been taken into account, the activation is calculated, and its impact on maintenance, routine off-site dose rates, accidental doses, waste disposal and the need for costly nuclear-grade construction is assessed.

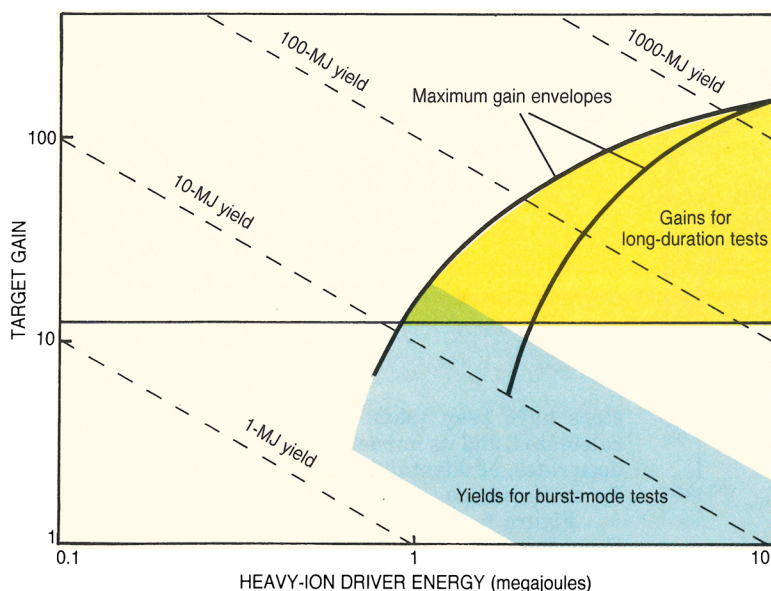
Figure 6 shows the calculated radioactivity of the Cascade reactor as a function of time after a 30-year lifetime. Shown are the activities of the reactor and shield, the target material (assuming a lead hohlraum) and the tritium per kilogram in the inventory. For comparison the inventory of a typical fission plant with the same power is shown. An hour or so after shutdown, tritium is clearly the main radiation source for fusion plants. Other sources of activity will be two or three orders of magnitude smaller than that in a fission plant. Calculations indicate that a fusion plant such as Cascade can meet all safety requirements without any nuclear-grade construction and that all waste produced will be amenable to shallow burial. The waste can thus be disposed of by processes less expensive than those used for fission waste. Note also that the radioactive lifetime of the fusion waste is orders of magnitude shorter than that of fission waste.

Reducing development costs

The Fusion Policy Advisory Committee recommended development plans for both inertial fusion energy and magnetic fusion energy that have since been adopted into the National Energy Strategy.^{7,13} To keep development costs low, it is critical that each facility be as small as possible. Here we discuss one concept for a low-cost reactor test facility.¹⁴

For a reactor test facility a single upgradable reactor driver can be built at the smallest energy at which it is thought possible to achieve ignition and some gain. Such a driver, appropriately upgraded, should be able to support all inertial fusion energy reactor development facilities beyond those needed for ignition, including the demonstration power plant.

Initial reactor test facility experiments would be of two types. Further target development to increase the gain at low drive energy would be done in a single-shot chamber capable of handling yields of a few hundred megajoules. The first integrated reactor tests would be done in parallel with the single-shot experiments. Small-yield burst-mode tests would be done for each candidate reactor. A sequence of a few to perhaps 100 microexplosions would be done to determine the maximum pulse rate. These tests would be carried out at the minimum yield that reproduces the proper chamber phenomenology. A recent study¹⁴ found that for dry-wall, wet-wall and granular-bed reactors the necessary yield range is 2–20 MJ. Thus the initial burst-mode reactor tests can be done with no improvement in target performance over that expected in the Nova Upgrade. Furthermore the scaled reactors would have an internal radius of only about 1 m.



Gain curves for heavy-ion-driven targets. In the blue region, yields required for burst-mode tests in the reactor test facility are possible. In the yellow region, gains needed to produce enough energy to run the driver are possible, resulting in 0.5–50 MW_e test reactors. In the overlapping region (green), both types of tests are possible. Thus a driver of 1–2 MJ should be able to accomplish both types of tests. **Figure 7**

Eventually long-duration tests will be needed to measure power balance, thermomechanical performance and chemical compatibility in steady-state conditions. The small reactors described above will probably be adequate for long-duration testing as well. No specific target gain is required, but it is interesting to note the minimum gain necessary to reach plant break-even—the point where enough power is produced to run the driver. Figure 7 shows the calculated gain for heavy-ion targets. The lower curve assumes a heavy-ion range of 0.1 g/cm² and a spot radius of 2 mm; the upper curve assumes a 0.05-g/cm² range and a 1-mm spot radius. Assuming a 25% efficient heavy-ion driver, the minimum gain necessary for plant break-even is just 12—again consistent with upgraded Nova's target expectations. The blue area in figure 7 shows the operating regime for burst-mode tests, and the line at gain equal to 12 shows the minimum gain necessary for break-even tests of plants. A driver of 1–2 MJ should be sufficient to carry out both types of tests. Such a scaled reactor would test all reactor performance parameters at a power level of 0.5–50 MW_e. Such small reactors should not be expensive to construct or operate. The cost of a reactor test facility will be driven by the cost of the driver, so it is critical to obtain ignition at small drive energy. Following the long-duration tests, one or more of the reactor concepts could be built at a larger scale as a demonstration power plant, using the same driver.

Inertial fusion energy's potential for low-cost development makes it an attractive fusion option. The inertial fusion energy community is prepared to take the next steps—demonstrating ignition and gain, developing a reactor driver and choosing a reactor technology—when the country determines it can afford to do so.

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