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THE PATH TOWARD FUSION ENERGY

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The Path Toward Fusion Energy

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The world economy has three long-term energy options: fission, fusion, and solar. Some potential advantages of fusion relative to fission are that the basic fuel, deuterium, is abundant and cheap, that there is no long-term nuclear waste-disposal problem, that fusion reactors are physically incapable of nuclear excursions, and that there is no need for proliferation-sensitive fuel-reprocessing plants. The use of either fission or fusion would have the advantage, relative to solar power, of minimizing demands on land area and structural materials.

While fusion is relatively free of fundamental drawbacks, in the near term it must overcome a set of extremely difficult technical challenges: (1) to make a "burning plasma" in the laboratory; (2) to develop practical power-handling technology; (3) to produce a commercially competitive power source.

International fusion research was undertaken during the 1950's with a good deal of intuitive optimism, but with no real technical basis for the belief that even the first of these challenges could be overcome. In recent years, the scientific outlook has improved greatly, and reactor plasma conditions are expected to be reached by existing experimental devices during the 1980's. The prospects for achieving commercial attractiveness are still controversial, but once more there is intuitive optimism that new ideas and technologies will be found as they are needed. In particular, there is an expectation that scientific expertise in the handling of hot plasmas will continue to evolve rapidly, and will facilitate the solution of the engineering and economic problems of fusion power.

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History

Nineteenth-century astronomers were able to estimate the cooling-off rate of the sun; the surprising conclusion was that it should have turned dark long ago. During the 1920's, a plausible explanation emerged. The nuclei of light atoms, such as hydrogen, were found to contain a slight excess of mass per nucleon, which might be converted into free energy by fusing them into heavier elements, such as helium. The sun and the stars were rightly suspected to be natural fusion reactors.

In 1934, Lord Rutherford's laboratory at Cambridge University used a 100-kilovolt (kV) accelerator to fuse deuterium nuclei into two types of and product: helium 3 plus a free neutron, and tritium plus a free proton. The possibility of releasing practical nuclear energy on earth then began to be mentioned -- but mainly in a negative sense. Fusion reactions are less probable than ordinary non-energy-producing collisions, and so a simple accelerator approach does not lend itself to net power production. In order to imitate the sun's fusion furnace, it is necessary to create and confine a similarly hot body of fuel in our cold terrestrial environment. From the point of view of the technology of the 1930's, this looked like an altogether hopeless enterprise.

The reality of nuclear energy became evident during the 1940's through the explosion of fission bombs and the construction of net-power-producing fission reactors. In the case of fission energy, the fuel consists of very heavy nuclei, such as uranium. Like hydrogen, these nuclei have an excess of mass per particle, which can be turned into free energy by splitting them into lighter elements. (The lowest energy state, towards which fusion and fission reactions ultimately tend, is the nucleus of iron.)

Large-scale release of terrestrial fusion energy was demonstrated in 1952 by the explosion of a hydrogen bomb -- basically a fission bomb that heats fusion fuel to stellar conditions. At about the same time, secret national programs in controlled fusion research were undertaken by the US, the UK, and the USSR. When these programs were declassified in 1958, the paths to fusion that had been discovered turned out to be remarkably similar. The basic invention was the "magnetic bottle," and bottles came in two logical shapes -- tori with closed magnetic field lines, and open-ended linear "mirror machines." Other nations took note, and the present pattern of cooperative world fusion research soon established itself.

During the next decade, major scientific progress was made, but in light of developing theoretical insights, the prospect for early success seemed to recede rather than advance. A decisive upturn took place in the late 1960's with the experimental breakthrough of the T-3 tokamak device, a toroidal magnetic bottle developed at the Kurchatov Institute in Moscow. During the subsequent years, the tokamak has become the main vehicle for high-temperature research in the world fusion program.

Since the leadership of the tokamak in approaching the reactor regime does not automatically establish its credentials as the best ultimate solution, a number of other magnetic fusion reactor concepts are being pursued in parallel: tori of different design, as well as open-ended mirror machines. The development of high-powered lasers during the 1970's served to open up a radically different approach to fusion power: the heating and compression of small fuel pellets, from which fusion energy is to be released in the form of repetitive microexplosions. The burning fuel is held together by its own inertia, and this approach is therefore called inertial confinement fusion (ICF). Because of the relevance of ICF subject matter to hydrogen bomb

development, much of the US work in this field is still classified. Some potential drivers for the inertial fusion process, aside from various types of lasers, are high-powered electron and ion beams, including multi-GeV nuclei. Finally, there are yet other fundamentally different approaches to fusion, such as the use of exotic elementary particles to catalyze fusion reactions in cold fuel, but their practical potential is still uncertain.

Plasmas and Fusion Reactions

When matter is heated, it first turns into a liquid, then into a gas, and finally into a plasma. The first two transitions relate to the relaxation of interatomic bonds. The gas-to-plasma transition, which typically begins at temperatures somewhat below $10,000^{\circ}\text{C}$, consists of stripping electrons from their atoms -- mainly by particle collisions. The positively charged atomic residue is called an ion. The hydrogen atom has only one electron, and therefore only a single ionization state. Heavier elements pass through a sequence of ionization states, with increasing numbers of electrons stripped from the nuclei as the temperature rises.

When two charged particles meet, they tend to deflect each other's paths, a phenomenon that is known as Coulomb scattering. Only when two nuclei approach to within distances of 10^{-11} - 10^{-12} cm do they begin to notice a strong nonelectrical force that may cause them to fuse. The energy required to bring them that close, in the face of electrostatic repulsion, is typically in the range 10-100 kiloelectron volts (keV). A plasma where the kinetic energy of random thermal motion of the nuclei is sufficient to produce frequent fusion reactions -- a so-called "thermonuclear" plasma -- should have a temperature at least in the 10-keV range, corresponding to about 10^8°C . (One electron volt corresponds to about $12,000^{\circ}\text{C}$.)

Because of its huge mass and high-quality thermal insulation, the sun is able to operate at a somewhat lower temperature (about $1.4 \cdot 10^7$ °C) and can burn ordinary hydrogen as its input fuel. Terrestrial fusion reactors, for which the quality of heat insulation is a serious problem, must use faster burning fuels, such as deuterium, as well as operate in the higher temperature range, where fusion events occur more frequently. Fortunately, the deuterium isotope of hydrogen is sufficiently abundant on earth so that natural water contains about 300 times the energy equivalent of gasoline.

The fastest burning fuel is a 50-50 mixture of deuterium and tritium. The D-T reaction (Fig. 1) produces a helium 4 nucleus plus a free neutron, and releases 17.6 MeV of nuclear energy. The neutron escapes readily from the plasma region, carrying off 80% of the energy release. In a D-T reactor, the fusion neutrons will be stopped in a 60-80 cm thick fusion reactor "blanket," (Fig. 2) made largely of natural lithium. While depositing its energy in the lithium blanket, the neutron ideally produces 1.5 new tritium atoms, so that the tritium fuel component can be self-regenerating. The problem that is solved here is that tritium is not naturally abundant on earth: it decays to helium 3 with a half-life of 12 years.

The helium nucleus of the D-T reaction (also called an alpha particle) receives 20% of the fusion energy release. Since it is electrically charged, the alpha can deposit its energy inside the fuel volume by colliding with other particles. If the heat insulation of the plasma is good enough, the fuel can therefore maintain its high-temperature state by means of its own fusion reactions -- just like the sun. Entry into this desirable reactor regime is called ignition.

The required quality of thermal insulation is typically measured by the product of the plasma density n and the energy confinement time τ_E (the time

it would take for the plasma to cool off by various processes of heat leakage). The product $n\tau_E$ is called the Lawson parameter (Fig. 3). Ignition of a D-T plasma at a 10-keV temperature calls for a Lawson parameter of about $2 \cdot 10^{14} \text{ cm}^{-3} \text{ sec}$. Net reactor output power could, of course, be generated even when the quality of insulation is not quite that good. The Lawson break-even point (where the ratio Q of total fusion power produced to required plasma heating power is at least unity) occurs already at a Lawson parameter of $6 \cdot 10^{13} \text{ cm}^{-3} \text{ sec}$. Non-Maxwellian plasma regimes with enhanced energetic-ion tails are expected to reach break-even conditions at $n\tau_E$ -values as low as $10^{13} \text{ cm}^{-3} \text{ sec}$. For economically attractive electric power generation, a Q -value of 10 or more is desired, and ignition ($Q = \infty$) is preferred.

Aside from D-D and D-T, some other fusion reactions, such as $\text{D-}^3\text{He}$, are of potential long-term interest, because they release most of their energy in charged particles. In that case, direct conversion of fusion energy to electric power can be considered. Another interesting possibility is to polarize the nuclei and align them so as to enhance their fusion cross section. The conventional expectation is, however, that first-generation fusion reactors will be burning ordinary D-T fuel. Most of the heat will be deposited by neutrons in the reactor blanket (Fig. 2) and will be used to generate steam and electricity in conventional ways. In this context, the high energy and penetrating power of the fusion neutrons is actually convenient, since it helps distribute the energy release over a thick volume of coolant.

Fusion Systems and Their Special Problems

Charged particles moving in a magnetic field have helical orbits (Fig. 4). If the magnetic field lines close on themselves in toroidal geometry, and if the details of the magnetic field structure are properly

designed, a single particle cannot escape from such a bottle; however, Coulomb collisions between charged particles may allow them to hop randomly from orbit to orbit. This irreducible form of plasma leakage, known as classical diffusion, is sufficiently slow so as not to create a serious obstacle to the achievement of the nT_E -value required for ignition.

The real problem for the toroidal approach to a fusion reactor has been the transport of plasma particles and heat due to cooperative phenomena involving large numbers of particles. When the local densities of ions and electrons do not quite coincide, strong macroscopic electric fields can appear inside the plasma. Similarly, when there are net relative motions between ions and electrons, macroscopic currents and magnetic fields are generated. The interaction of these macroscopic electric and magnetic fields with the plasma can give rise to exponentially growing instability modes, turbulence, and "anomalous" transport coefficients greatly exceeding classical prediction.

In the case of open-ended magnetic bottles (Fig. 5), the highest priority problem has been to stop the leakage of plasma out the ends. A gyrating charged particle constitutes a magnetic dipole that opposes the ambient magnetic fields; it is therefore decelerated when entering regions of stronger magnetic field -- so-called magnetic mirrors -- at the ends of the plasma-confinement region. Mirror confinement depends on the ratio of the velocity of gyration relative to the velocity along magnetic field. In an ordinary mirror machine (Fig. 5), a single Coulomb scattering event can cause two gyrating particles to acquire predominantly axial velocities and thus escape from mirror confinement. Even at optimally high plasma temperatures and with D-T fuel, the probability of fusion is sufficiently smaller than the probability of loss by Coulomb scattering so that the Lawson criterion for breakeven can barely be met, and ignition is unattainable. An additional

problem of the simple mirror machine is that the prerequisite non-Maxwellian energy distribution lends itself to the excitation of high-frequency instabilities and anomalous transport in velocity space, so that the plasma is lost on a time scale even faster than that of classical Coulomb scattering.

In magnetic confinement systems, the ratio of the plasma pressure nT (product of density and temperature) to the Maxwell stress $B^2/8\pi$ is called the beta value. If the plasma pressure is to be held in equilibrium, the maximum possible value of beta is unity. In general, however, the upper limit must be set at a much lower level of beta, in order to avoid a type of gross anomalous transport where the plasma escapes from confinement by bending the field lines of the magnetic bottle. For example, in a conventional tokamak, the limiting beta value is expected to be in the range 5-10%.

Combining these plasma physics considerations with the constraints of present-day magnetics and materials technology, one can deduce the main characteristics of a magnetic fusion reactor. First of all, the use of superconducting magnet coils is found to be advantageous, since the resistive power dissipation in an ordinary magnet system tends to consume an excessive fraction of the total electrical power output, unless the plasma beta value is very large. Assuming the use of present-day superconductor technology, the magnetic field strength is limited to about 50 kilogauss (kG) at the plasma, corresponding to a Maxwell stress of about one hundred atmospheres (atm) and a typical plasma pressure of order ten atm.

A representative fusion reactor plasma is thus seen to have a thermal pressure nT and energy density $(3/2) nT$ no greater than that of ordinary steam -- the high plasma temperature T being offset by the low plasma density n , which is typically a few times 10^{14} particles per cubic centimeter. From the magnitude of n , it follows that the energy confinement time τ_E in an

ignited D-T plasma must be at least of the order of one second. The allowed plasma pressure also limits the fusion power density to about 5 megawatts (MW) per cubic meter (MW/m^3).

These numbers indicate the general range of "conventional" present-day fusion reactor design. They reflect certain technological prejudices that could change in the future. For example, if more advanced superconducting coils were to provide a field strength of 100 kG at the plasma, then the containable plasma pressure would increase fourfold, and the resultant fusion power density would increase sixteenfold. Similar increases may be achievable, even at a given magnetic field strength, in tori of advanced design, with greater rigidity against pressure-driven magnetic-field perturbations and therefore higher allowable beta values. To realize this potential in the form of higher powered reactors, however, will call for matching advances in the technology of wall materials.

In current reactor design studies, the vacuum chamber, inside of which low-density plasmas are produced and heated, is generally assumed to be made of stainless steel. The passage of energetic fusion neutrons tends to displace the atoms of the steel wall, thus reducing its mechanical strength. In a fusion reactor with a neutron flux of $3\text{-}5 \text{ MW}/\text{m}^2$ of wall surface, the expected lifetime of the wall is about 4-6 years. If the fusion power density were to be successfully increased, the lifetime of the wall material would have to be improved correspondingly.

Since the "ash" of the fusion process (i.e., helium) is not radioactive, the replacement of first-wall materials gives rise to the main problem of radioactive waste disposal. By proper choice of materials, radioactivity could be minimized so that long-term burial of wastes will not be required in the case of a fusion power economy. A second basic advantage, that the

nuclear reaction can never "run away" or fail to shut down, follows simply from the smallness of the total fuel energy that is present at any one time in a fusion reactor.

A new set of plasma physics topics and technological constraints is encountered by the inertial confinement approach to fusion. In an ICF reactor, the surface of a small fuel pellet (typically a frozen D-T pellet a few millimeters in diameter) is to be heated by means of some 10^{14} watts (W) of instantaneous power in the form of laser light or charged-particle beams. The ablation of the heated pellet surface exerts a recoil force that compresses the pellet core one-thousandfold while also generating ignition-level temperatures. The ignited core then burns outward, releasing additional fusion energy before the pellet re-expands and cools.

The condition for achieving ignition is essentially the same as in the case of magnetic fusion, but the individual elements of the $n\tau_E$ -product are quite different: The typical density n of the compressed pellet core is some $3 \cdot 10^{25}$ particles per cubic centimeter (cm^3), instead of $2 \cdot 10^{14}$, and the minimum confinement time τ_E is of the order of ten picoseconds (psec), instead of one second. Correspondingly, the plasma pressure is 10^{12} atm instead of ten.

Even a well-optimized ICF compression process will be only about 10% efficient in terms of delivering energy from the driver to the hot pellet core. To achieve an overall power gain of $Q \sim 10$, the burn time must be long enough to permit a roughly 100-fold gain in the pellet itself. The required $n\tau_E$ -value turns out to be about ten times greater than the Lawson parameter for single ignition. By specifying very large pellet compressions and final densities, one can satisfy this severe $n\tau_E$ -constraint while keeping the pellet size relatively small. In this way, the total pulsed energy required to ignite an ICF pellet is minimized.

A basic plasma physics issue of ICF is whether the driver power can be absorbed efficiently at the surface of the pellet -- as distinct from being lost by reflection or transported from the surface to the plasma interior, which would interfere with the compression process. A second critical issue is the ability to achieve high compression ratios in the face of imperfectly symmetric surface illumination. Any initial asymmetries in the compression process tend to be amplified by a Rayleigh-Taylor instability mechanism that is quite similar to ordinary gravitational instability (i.e., the unstable mixing mode of a heavy fluid supported by a light fluid). One way to minimize the problem of uniform illumination has been the "hohlraum" approach, where the fuel pellet is placed within a cavity, the primary driver system is used to heat up the cavity walls, and the thermal X-ray emission from the walls then acts as a very uniform secondary driver.

Current estimates for the minimum energy input requirement of an ICF reactor are in the range of about 5 megajoules (MJ) so that the output per pulse amounts to some 500 MJ. The pulse repetition rate is envisaged to be several per second. A promising way to capture this power would be by means of a liquid-metal curtain surrounding the pellet (Fig. 6). The curtain would typically be composed of lithium or lithium-lead eutectic, in order to meet the tritium-breeding requirement, and would serve to cushion the reactor first wall against the microexplosions, as well as protect it against neutron-irradiation damage.

Progress in Magnetic Confinement

During most of the 1950's and 1960's, progress towards a hot, magnetically confined plasma was impeded by various instabilities and the resultant anomalous transport. Typical plasma parameters in this period were n_T -values below 10^{11} cm^{-3} sec and plasma temperatures below a few hundred

eV. Substantial progress has been made meanwhile, particularly by means of the tokamak confinement device (Fig. 7).

The main magnetic field component of the tokamak is a strong toroidal magnetic field (typically 50 kG), which is generated by an array of external magnet coils. In addition, a poloidal magnetic field component is produced by inducing a toroidal plasma current with an air-core transformer. The two field components form helical magnetic field lines, lying in nested toroidal magnetic surfaces. The orbit of each plasma particle is restricted to the vicinity of such a surface, except in the presence of classical collisional diffusion -- or anomalous transport. The outstanding experimental success of the tokamak approach has consisted in confining the plasma ion heat content about as well as the classical theory would predict. Electron heat transport in tokamaks is still anomalous, but since its magnitude is comparable to that of the classical ion heat transport, the experimentally achievable temperatures and $n\tau_E$ -values are not very far below classical expectation.

An experimental tokamak plasma is produced by puffing low-density neutral gas into the toroidal vacuum chamber and then inducing a toroidal plasma current -- typically 1 MA in present-day experiments. The electrical conductivity of the plasma improves with rising temperatures, and so the ohmic heating power associated with the plasma current tends to diminish. Typically, plasma temperatures up to 2 keV can be reached in the ohmic heating phase. For this type of heating, small-sized tokamaks with exceptionally high magnetic fields are most effective. During the past year, the Alcator C device at MIT, which operates at 100 kG, achieved an $n\tau_E$ -value close to $10^{14} \text{ cm}^{-3} \text{ sec}$ (cf. Fig. 3).

To advance to still higher temperatures, various forms of auxiliary heating have been developed. During the late 1970's the injection of energetic beams of neutral atoms proved effective in raising the plasma ion temperature to the 7-keV range. Recent experiments with deuterium plasma on the D-III tokamak at GA Technologies, Inc. have achieved $n\tau_E$ -values above $10^{13} \text{ cm}^{-3} \text{ sec}$ at temperatures of 6 keV. If these experiments had been carried out with D-T plasmas, the ratio Q of fusion power relative to input heating power would have been above 0.1.

The largest US fusion research device at present is the Tokamak Fusion Test Reactor (TFTR) at Princeton (Fig. 8), which will be capable of operating with D-T fuel. The plasma current will range up to 3 MA in a 52-kG magnetic field, and the plasma will be heated with 25-30 MW of neutral beams of 120-keV energy for times of the order of one second. These experiments are expected to reach 10-keV D-T plasmas with enlarged high-energy tails and $n\tau_E$ -values well above $10^{13} \text{ cm}^{-3} \text{ sec}$ -- sufficient to produce a Q-value around unity (i.e., breakeven). The present TFTR schedule calls for the demonstration of $Q \sim 1$ plasma conditions in a deuterium plasma during 1986, followed by the D-T demonstration in 1988.

Three other major tokamak devices will be in operation during the 1980's in Europe (JET), Japan (JT-60), and the USSR (T-15). The largest of these is the JET device, which has a vacuum vessel with interior dimensions comparable to those expected for a practical tokamak reactor (Fig. 9). At present, TFTR and JET are in the ohmic heating phase. An energy confinement time of 0.6 sec has already been reached by JET at its full magnetic field strength of 35 kG, and is expected for TFTR at its maximum field strength of 52 kG.

A principal objective of these large tokamak experiments is to create the scientific and technological data base for an ignited long-pulse tokamak reactor. The European, Japanese, and Soviet fusion programs have specific plans for such a facility, with construction to start around the year 1990 and operation to begin in the late 1990's. Current US planning is oriented towards international collaboration on such an undertaking.

As tokamak experiments enter the reactor regime, increasing effort is being devoted to improving the practical engineering potential of both the tokamak and the competing approaches to a magnetic fusion reactor. In the tokamak area, the somewhat cumbersome, though effective, neutral-beam-heating method is being replaced successfully by various forms of rf-heating, where plasma waves are excited by external antennas or waveguides, and damped in the plasma. The same methods have also lent themselves to driving the tokamak plasma current, thus creating the possibility of maintaining the tokamak reactor burn in steady state, or at least during very long pulses (many hours). The latter feature is important in order to minimize thermal and mechanical fatigue problems that might arise from shorter pulsed operation with purely transformer-driven tokamak currents.

Major efforts are also being devoted to maximizing the beta value of the tokamak by appropriate shaping of the minor plasma cross section. The D-shaped vacuum vessel of the JET machine (Fig. 9) should lend itself to beta values above 5%. Theory predicts that a bean-shaped tokamak cross section should permit even higher beta values, and the initial experiments along this line have been encouraging.

In the case of the mirror machine approach, the problem of gross anomalous transport across magnetic field was solved in the early 1960's at the Kurchatov Institute, by means of the minimum-B configuration (Fig. 10),

where the magnetic field strength increases away from the confined plasma, not only in the direction towards the mirrors but in the cross-field direction as well. Since the plasma is diamagnetic, this geometry is energetically favorable to a stable equilibrium at the bottom of the "magnetic well."

During the following decades, the critical issue for mirror confinement was anomalous end-loss caused by various high-frequency instabilities. This problem was solved in the late 1970's, along with the more fundamental problem of excessively large classical end-loss, by the invention of the tandem mirror concept (Fig. 11) at the Lawrence Livermore National Laboratory and the Nuclear Physics Institute in Novosibirsk.

The basic idea of the tandem mirror is to confine most of the reacting plasma in a long, straight central cell, and to plug up the ends of this cell by means of a system of electrostatic potentials, generated by smaller, higher energy plasmas confined in special end-plug cells. The success of this technique in stopping both classical and anomalous end-losses has been documented by recent experiments at Livermore as well as in the USSR and Japan. The main problems at present are the control of fine-scaled anomalous cross-field transport and the minimization of the fraction of electric power that would have to be recirculated in a reactor to maintain the end-plugs. A large tandem mirror experiment, the MFTF-B, is scheduled to begin operation in Livermore in the late 1980's. A principal attraction of the mirror approach is that the plasma will be maintained in true steady state.

The toroidal approach to magnetic fusion contains a number of other interesting options, aside from the development of advanced tokamak designs. The stellarator is a similar device, but with the plasma current replaced by currents in external helical multipole windings. This configuration was invented at Princeton in 1951 but at first appeared to give unfavorable

confinement. Recent experiments in Japan (Heliotron E) and Germany (Wendelstein VII A) have shown that the confinement quality of stellarators can be at least comparable to that of tokamaks of the same size. The stellarator has the potential advantage of steady-state operation, but the drawback of somewhat greater geometric complexity.

Another instance where an old and formerly unsuccessful approach has recently begun to yield encouraging experimental results is the "reversed-field pinch" or RFP -- a kind of tokamak where the toroidal field is weaker than the poloidal field and reverses its direction at the plasma edge. The RFP may be capable of reaching very high plasma beta values and fusion power densities. Finally, there is a new generation of "compact toroid" experiments (Fig. 12) which differ from conventional tori in that the plasma is not linked by toroidal field coils. As a result, the reactor topology is simplified, and potential problems of first-wall replacement and maintenance are greatly eased.

Progress in Inertial Confinement

The possibility of using laser light to make an inertial fusion reactor was pointed out by a number of authors in the early 1960's. Ten years later, substantial experimental programs were underway in the US, France, the USSR, and Japan.

The initial expectation was that an ICF reactor could operate efficiently with pellet-input energies of 100 kilojoules (kJ) or less. In the course of ICF research, these numbers have risen by about a factor of 50. Concurrently, the most serious physical problems have been understood and solved, so that the successful ignition of D-T pellets by laser beams has become a realistic prospect (Fig. 13).

One element of recent experimental progress has been the development of shorter wavelength laser capabilities and the associated demonstration that the main plasma physics limitations of ICF can be overcome by proceeding in that direction. At the natural 1-micron wavelength of a neodymium-glass laser, the fraction of usefully absorbed power falls to about 30% in the range of incident power fluxes of practical interest ($10^{14} - 10^{15}$ W/cm²). When the 1-micron output is converted to a 1/3-micron wavelength by a frequency-multiplying technique developed at the University of Rochester, the power absorption rises to about 90%. The physical reason is that collective plasma effects are less easily excited when there is a larger difference between the natural frequency of plasma oscillations and the frequency of the light waves. As a result, the shorter wavelengths can penetrate to regions of high plasma density, where their energy is absorbed by ordinary collisional processes.

The same considerations explain why the acceleration of superthermal electrons decreases by orders of magnitude in the case of shorter wavelength light. In order to maximize the compression ratio of the pellet, one wishes to avoid preheating its core by these penetrating fast electrons. Using shorter wavelength light, the Novette laser at LLNL (Fig. 13) has already reached density factors of 120 relative to liquid hydrogen at temperatures up to 700 eV and pressures above 10^{10} atm (Fig. 14). Compression factors up to 1000 are expected to be achieved in the recently completed NOVA facility at LLNL, which will have a 100-kJ, 1 nsec output. There are similar plans for the Gekko XII laser at the Institute of Laser Engineering in Osaka, Japan.

While neodymium-glass lasers with short-wavelength convertors have proved to be particularly effective in achieving reactorlike pellet implosions, the efficiency and pulse repetition rate of the existing laser systems is too low for reactor purposes. A large CO₂ laser, such as the Antares at Los Alamos

National Laboratory, would have much more desirable driver characteristics, but since its wavelength is ten microns, the plasma interaction problems are severe. The use of laser beams for an ICF reactor will depend on the development of more advanced technologies -- possibly free-electron lasers.

Higher driver efficiencies appear to be readily achievable with particle-beam drivers. Electron beams would be particularly straightforward from the point of view of source technology, but they are too penetrating to lend themselves to pellet compression. The use of light ion beams in the energy range of a 3-30 MeV is being pursued at the Sandia National Laboratory and at Osaka. Heavy ion beams in the multi-GeV range would be advantageous for minimizing plasma effects and facilitating a sharp focus at a distance, but the magnitude of the required investment has thus far inhibited this approach.

Practical Utilization of Fusion Energy

While fusion fuel is an inexpensive and abundant terrestrial energy resource, the path to practical fusion power has been blocked by a series of formidable barriers. Fifty years ago, the generation of terrestrial fusion energy seemed physically impossible. Twenty years ago, it was believed to be possible in principle, but no specific reactor solution was known that had any real claim to engineering feasibility. The anomalously poor energy confinement observed in fusion experiments of that time extrapolated to power plants with unacceptably huge minimum size.

During the past decade, both magnetic and inertial fusion research have made major progress. Reactor plasma regimes will be in to be reached with existing facilities in the latter part of the 1980's, and experimental fusion reactors could then be operating around the year 2000.

The barrier of scientific feasibility now seems to be fading away, and the barrier of engineering feasibility is likely to be breached by the end of the century. There remains the most formidable and debatable issue of all: can the promise of cheap, inexhaustible fuel be matched by a low-cost fusion burner? In other words, can the capital investment and the associated interest payments be kept small enough, so that the cost of a kilowatt-hour of electricity will remain close to present-day prices?

A characteristic feature of fusion power is a very marked "economy of scale": that is, a fusion reactor driving a 3,000-MW electric power plant is typically estimated to cost only a few times more than a reactor driving a 300-MW plant. The desire to reduce the ideal cost per kilowatt hour strongly favors large fusion reactor units. On the other hand, there are many practical considerations relating to construction time, reactor maintenance, and system availability that strongly favor minimizing the unit size. A promising solution consists in designing multiunit fusion plants, with moderate-sized reactor units sharing conventional facilities and common auxiliary systems.

Long-range forecasts concerning the economics of high technology are inherently difficult to make. In order to produce "objective" estimates -- as distinct from science fiction -- the experts must carry out their cost analyses in terms of existing materials and designs. On the other hand, the historical record shows that such analyses tend to become outdated in a decade or two. Given past performance in fusion research, there is some basis to expect that continuing scientific advances, together with the rise of high-technology capabilities in general, will make fusion economically attractive at just about the time when it will be most needed. Fusion power could come into initial commercial use around the year 2020 and should be able to supply a major share of the world's energy requirements by mid-century.

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Figure Captions

- Fig. 1 D-T (deuterium-tritium) fusion reaction. Payback (ratio of energy returned to energy invested) is about 450:1.
- Fig. 2 Basic geometry of a magnetic fusion reactor.
- Fig. 3 Lawson diagram, comparing temperatures and Lawson parameters of current machines with conditions required for breakeven and ignition. Data points for TFTR and JET represent initial values.
- Fig. 4 Particle orbits in a magnetic field and cross-field diffusion by Coulomb collisions. (a) View across field. (b) View along field.
- Fig. 5 Particle confinement by magnetic mirrors and escape by Coulomb scattering.
- Fig. 6 Inertial confinement fusion reactor with liquid-metal blanket.
- Fig. 7 Configuration of coils and fields in the tokamak magnetic bottle.
- Fig. 8 Tokamak Fusion Test Reactor. (a) Cutaway view of components. (b) Fully constructed device.
- Fig. 9 Interior of vacuum vessel of the JET.
- Fig. 10 Configuration of coils and fields in the minimum-B mirror machine.
- Fig. 11 Tandem mirror system. (a) Coils. (b) Plasma.
- Fig. 12 Magnetic field configurations in compact tori. (a) Field-reversed θ -pinch. (b) Spheromak.
- Fig. 13 The Novette laser installation for inertial confinement fusion at the Lawrence Livermore National Laboratory.
- Fig. 14 Compression and temperature achieved in inertial confinement fusion devices. $1 \text{ atm} = 14.7 \text{ lbf/in.}^2 = 10^5 \text{ Pa}$.

THE D-T FUSION REACTION

(1 eV = 12,000 Degrees K)

Figure 1

Figure 2

Figure 3

CLASSICAL LOSS PROCESS OF "STRAIGHT" CLOSED SYSTEM

Classical Diffusion: $D = \delta_{\text{orbit}}^2 / \tau_{\text{collision}}$

Diffusion Time $\sim (\text{Radius})^2 / D$

$\sim \tau_{\text{collision}} (\text{Radius} / \delta_{\text{orbit}})^2$

Figure 4

SIMPLE MIRROR MACHINE

$$Q = \frac{\sigma_{\text{FUSION}} W_{\text{FUSION}}}{\sigma_{\text{SCATTERING}} W_0} < 1$$

Figure 5

Figure 6

Figure 7

Figure 8a

Figure 8b

Figure 9

Figure 10

TANDEM MIRROR MACHINE

figure 11

(a) FIELD-REVERSED θ -PINCH

(b) SPHEROMAK

Figure 12

Figure 13

Figure 14

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