The Quest for Fusion Energy

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In recent years, a steady flow of press releases from nuclear fusion research projects has hailed breakthrough advances and new record yields. Despite the relentlessly optimistic tone of these announcements and the repeated claims that the prospects for commercialization have never looked brighter, the stark reality is that practical fusion-based electric power remains a distant prospect. It is likely unachievable anytime in the next half a century.

Even then, it may still remain beyond our grasp.

The most readily accessible nuclear fusion process combines the hydrogenic isotopes deuterium and tritium to release energy in the form of energetic neutrons and helium ions. There are two broad approaches toward achieving terrestrial fusion. In magnetic confinement fusion (MCF), magnetic fields are used to confine the hot fusion fuel in the form of a fully ionized gas or plasma that persists for seconds or longer. In inertial confinement fusion (ICF), laser or particle beams are used to compress and heat a tiny capsule of fusion fuel to generate a micro-explosion of a nanosecond duration.

The most advanced MCF device currently in operation is the Joint European Torus (JET) tokamak located at the Culham Centre for Fusion Energy in the United Kingdom.[1] Commissioned almost 40 years ago, JET is one of the world's two largest tokamaks and the only MCF device presently equipped to use tritium fuel. The ICF approach is exemplified by the laser-induced micro-explosions at the National Ignition Facility (NIF) near Livermore, California.[2] Completed in 2009 at a cost of around US$5 billion, NIF is the world's most powerful laser-driven fusion facility.

This essay is concerned with scientific feasibility, a basic prerequisite that the reacting fusion medium must satisfy before it can be developed as the basis for a commercial fusion power reactor. A demonstration of scientific feasibility is usually taken as the achievement of fusion energy breakeven. This condition is met when the fusion energy produced during a pulse is equal to or greater than the energy applied from external sources to heat the plasma during that pulse.

During the last 12 months, a clear disparity in relative performance between MCF and ICF has emerged. This was evident from the results of the near-simultaneous deuterium-tritium (D-T) experiments that took place at the NIF and JET facilities during 2021. These were the most important ICF and MCF experiments undertaken in the last quarter of a century. Taken together, the two sets of results have arguably the greatest significance for the development of the field since the T-3 tokamak results were presented in the summer of 1968 at an international fusion energy conference in the Soviet Union.[3]

This essay compares the backgrounds and outcomes of the recent D-T campaigns at the JET and NIF facilities, shows why inertial confinement has established a clear lead over magnetic confinement in attaining reactor-relevant fusion conditions, and examines the future directions of both approaches. While there is a strong argument that the scientific feasibility of ICF has been demonstrated in recent experiments, the status and prospects for MCF are far less favorable.

The fusion energy gain, Q, of a reacting plasma configuration is commonly described as the ratio of the fusion energy output released in a pulse, Ef, to the external heating energy deposited in the plasma during that pulse, Eh.

In MCF devices, the dominant heating energy is injected into the plasma by neutral particle beams and radio-frequency waves. In ICF devices with indirect drive, such as the NIF, a D-T fuel capsule is emplaced inside a tiny box, known as a *hohlraum*, from the German for "cavity." The fuel capsule is then imploded and heated by x-rays generated when incident laser beams converge on the hohlraum's interior surface. Here the definition of Eh has been a subject of debate. For the purposes of comparing MCF and ICF, Eh can be taken as the laser-generated x-ray energy incident on the fuel capsule. Around two-thirds of this energy is actually absorbed. For the NIF hohlraums, Eh amounts to around 20% of the total laser energy.

Scientific feasibility, or fusion energy *breakeven*, is most often described as the demonstration of Q = 1 or greater. Net electric power production requires a Q of at least 5.

Four-fifths of the output of the D-T reaction comprises neutrons that escape the reacting plasma. The remainder consists of helium ions, commonly termed alpha particles,

which decelerate in the plasma and help to heat it. In quasi-steady MCF, a *burning plasma* is defined as one where the alpha-particle heating power is equal to or exceeds the external heating power. This condition is met when Q is 5 or greater.

Comparing powers is not meaningful for short-pulse ICF devices because the alpha-particles only begin to appear near the end of the x-ray-induced implosion. A burning plasma in ICF is one in which the total alpha-particle heating of the fuel is at least as large as the energy delivered to the fuel by the implosion.

In MCF, *ignition* occurs when the fusioning plasma is heated entirely by fusion alpha particles, which requires that the energy confinement time be twice that needed for Q = 5. In ICF, ignition has occurred when the core of the compressed fuel capsule continues to rise in temperature after the compression phase is complete, indicating that alpha heating exceeds radiative and kinetic energy losses during expansion cooling. Ignition may instigate a *propagating thermonuclear burn* into the surrounding fuel layers until the capsule disassembles.

A state close to ignition is required for the purposes of substantial net electricity production.

In 1997, the JET project reported record results for its latest D-T campaign. These included a peak fusion output of 16 megawatts (MW) and a transient Q of 0.67. The maximum quasi-steady Q achieved was roughly 0.4.[4] Each successive report from Culham and the JET project has made a point of mentioning that theirs is the only MCF facility equipped for tritium use. This exclusive status is not without disadvantages. In the absence of any equivalent facilities, independent verification becomes impossible. Indeed, more than two decades after they were announced, JET's claimed record results still cannot be replicated elsewhere.

Even the JET project itself has been unable to reproduce these results. The records for peak power and Q achieved in 1997 have never been matched, let alone exceeded. This situation was unchanged after JET's most recent experiments. Although no records were broken, the two campaigns that took place in 1997 and 2021 were still able to provide confirmation for D-T results obtained at an earlier tritium-fueled facility.[5] Located near Princeton, New Jersey, the Tokamak Fusion Test Reactor (TFTR) was the only MCF facility besides JET that has been equipped to use tritium. A lengthy tritium campaign was carried out at the TFTR between 1993 and 1997 when the project was shuttered.

After JET's record-breaking 1997 campaign, a series of performance upgrades were planned with the goal of eventually demonstrating Q = 1. Unexpected obstacles soon emerged. One of the upgrades involved replacing JET's entire carbon plasma-facing wall—along with other materials in the divertor that exhausts outflowing particles and heat—using an array of beryllium tiles and tungsten plating. This configuration is similar to that being designed and fabricated for another much larger project in southeastern France. The International Thermonuclear Experimental Reactor (ITER) facility is a giant tokamak currently being constructed at Cadarache, near Aix-en-Provence.[6] With three dozen countries involved in the project and an estimated cost exceeding 20 billion euros, the ITER consortium thought it important to simulate its operating environment as closely as possible using JET.

Contrary to expectations, the initial JET experiments using the upgraded reactor vessel and divertor system yielded poorer results than those achieved during the 1990s. As it turned out, the shortfall was mainly due to beryllium and tungsten ions invading the plasma. It was only after many years had been spent developing complex mitigation techniques that previous performance levels using deuterium could be achieved. These efforts involved elaborate manipulations of the plasma edge and outflowing plasmas, along with special heating and fueling strategies.

Most tokamak research during the last 25 years has focused on mitigating the interaction of the plasma with the surrounding solid surfaces and finding ways to remove particles and heat. Once the plasma instabilities that have plagued MCF devices are under control, attention will then turn to pacifying these environmental interactions. One source of tokamak instability that appears to be unavoidable is plasma disruption.[7] This is a fairly common event that results in the entire plasma energy striking the wall, causing intense sputtering and melting with a huge influx of impurities for many subsequent discharges.

Preparing for tritium use in an MCF device is a complicated and time-consuming operation. After two decades of preparation, including the aforementioned upgrades, JET restarted tritium operations in late 2020. Essentially pure tritium plasmas with relatively low neutron yields were produced in the months that followed, until D-T operation began in August 2021.

That the latest JET results should be regarded as especially important will come as a surprise to most observers. Prior to a recent press conference, there had been little, if any, news from the project during the previous twelve months. By contrast, countless press releases were issued by other MCF projects during the same period, heralding record pulse lengths, breakthrough magnet designs, and enhanced heat removal as notable advances. On the topic of actual fusion production, the details provided were scarce, or entirely absent.

On February 9, 2022, the JET project finally held a major press conference to announce their latest results.[8] The peak fusion power generated in 2021 was reported as 13MW transiently, while the maximum transient Q was about 0.4—compared with the record figures of 16MW and 0.67 achieved in 1997. The maximum quasi-steady Q value was 0.33, compared with 0.4 in 1997. In fact, JET's latest results were not much of an improvement over the best achieved by the TFTR in the mid-1990s: 10.7MW of fusion power, a transient Q of 0.28, and a quasi-steady Q of 0.18.[9]

Among the 2021 results from JET, a maximum fusion yield per shot of 59 megajoules (MJ) was described as a major advancement. This result was more than double the best yield in 1997: 22MJ. The fact that 40% higher injected heating power was needed to achieve this result received less coverage. But even this apparently favorable result was not as it seemed.

In plasmas heated by neutral particle beams, fusion is generated by beam ions reacting with the thermalized plasma ions, termed beam-thermal reactions, and by reactions among the thermalized ions. The latter process is known as thermonuclear fusion. For a purely beam-thermal system, the maximum theoretical Q is limited to less than 2.[10] To stand any chance of producing Q > 5, the value required for net power output, thermonuclear fusion must predominate over beam-thermal reactions.

In the 2021 JET experiments, most pulses used a 50:50 D-T ratio for both the beams and thermal plasma. By contrast, the 59MJ shot extolled in the most recent press conference used 100% D beams and an overwhelmingly tritium thermal plasma.[11] Although the full details have not yet been released, it appears that at least 75% of the fusion output resulted from D beam ions reacting with thermal tritium ions. No more than 25% of the fusion output, or 15MJ, came from thermonuclear reactions among the thermal deuterons and tritons.

The JET results from its 1997 D-T campaign were one of the most important justifications for proceeding with the ITER project. With a maximum thermonuclear Q around 0.20, the 2021 results give plenty of reason to be apprehensive about ITER's performance, which is supposed to achieve Q ~ 10.

When the NIF first began operating in 2010, its fusion yield was an extremely low 2.5 kilojoule (kJ) per pulse. The Q was similarly underwhelming and no higher than had been achieved years previously by the OMEGA laser facility at the University of Rochester—a system that possessed only a tiny fraction of the laser energy available at NIF.[12] There ensued a nearly decade-long development program that roughly coincided with the efforts at JET to reproduce its 1990s performance levels.

While tokamak R&D has been primarily focused on the interaction between the reacting plasma with its surroundings, laser-induced fuel compression R&D is centered on the design of the hohlraum and its interior fuel capsule. The main objective is to improve the spherical symmetry of the fuel capsule implosion. The vastly expanded implosion diagnostics available at NIF led to manufacturing improvements and innovations such as varying the size and shape of the hohlraum; modifying the size, shell materials, and thickness of the fuel capsule; minimizing micron-sized perturbations of the capsule surface; altering the membrane system that suspends the capsule within the hohlraum; and determining the optimal concentration of the helium gas used to fill the hohlraum. Experiments focused on the time waveforms of the 192 laser power pulses reduced nonuniformities in the beams and helped researchers microtune their wavelengths. This broad development program proved marvelously successful, generating a series of advances in NIF's fusion yield and Q: 25kJ in 2014, 55kJ in 2017–18, and 170kJ in 2020–21, with a maximum laser input of 1.9MJ.[13]

Between November 2020 and February 2021, the NIF produced a number of record shots at the 100kJ level. Four shots producing 98, 106, 160, and 171kJ generated a burning plasma. In each case, the alpha-particle heating of the D-T fuel exceeded the heating provided by the capsule implosion.[14] While that process yielded Q-values of only between 0.25 and 0.45 by our definition, an MCF system would have to reach Q = 5 to achieve the same self-heating effect.

Further shots with a substantial yield were generated at NIF in the months that followed. But it was a shot generated on August 8, 2021, that convulsed the fusion world.[15] The yield was 1.3MJ, eight times the previous record with Q > 3, corresponding to a fractional burnup of more than 1% of the total tritium charge. Most of the core D-T gas underwent fusion, and the fusion burn was on the threshold of propagating into the surrounding frozen D-T shell before expansion cooling killed the fusion reaction. This phenomenon was the beginning of the long-sought propagating burn.

The peak ion temperature of approximately 10 kilo-electron volts (kev) observed in this supershot was twice that of the previous record shots. The NIF project estimates that the alpha heating alone was at least twice that imparted by the implosion, corresponding roughly to Q = 10 in an MCF system.

While the supershot has not yet been replicated, four subsequent shots in 2021 produced yields of 200, 430, 460, and 700kJ—well above the most productive shots of the previous winter.[16] Three of these shots comfortably demonstrated scientific feasibility, or Q > 1, when defined with respect to the total x-ray energy deposited on the fuel capsule, even if not entirely absorbed.

These high-performing shots suggest that the supershot will be eventually reproduced. This will likely occur when higher laser energy is available for the NIF. In common with the 1997 record results from JET, independent replication of the NIF results is problematic. High-intensity laser facilities almost as large as the NIF have been constructed in France, China, and Russia, but few results of any kind have been reported from those installations.

On average, tokamak experiments use 1,000 times as much tritium per pulse as ICF experiments. This huge disparity is due to the large plasma volumes, pulse lengths of at least several confinement times, and inefficiency of fueling the core reacting region. A large

tokamak such as JET requires at least 100 milligrams (mg) for each shot. Extensive plasma tune-ups must be done without tritium due to its high cost, radioactivity, and the excessive activation of structural materials by the D-T neutron output. Deuterium is generally used because it is the closest to a D-T mixture, and because the neutrons produced in D-D reactions provide unparalleled diagnostic benefits. Tritium can be introduced only after a multiyear campaign of optimizing plasma conditions in deuterium, as in JET's campaign to recover from its wall conversion.

As part of the experiments, some tritium usually becomes embedded in the chamber structure and other components. A safety limit sets the maximum tritium use in any campaign. Many of the limited number of tokamak shots with tritium are effectively wasted, used only to load the plasma-facing walls with tritium to ensure the proper fuel mix in the plasma. Injected tritium must be recovered by processing the outgoing plasma and scouring the vessel walls.[17] No MCF device other than TFTR and JET has even dared to use tritium because of its cost and safety issues.

By contrast, experimental ICF systems, such as the NIF, require less than ¼mg of tritium per shot. The tritium is preinstalled in the fuel pellet and can be abandoned after the shot. D-T neutron output is the best measure of performance; it also provides vital diagnostic information concerning plasma properties. The low fuel load per capsule makes it practical to use tritium on every shot, a procedure that is impractical in MCF. Using tritium ab initio, the NIF project circa 2010 found that fusion results were far worse than expected in comparison to computer simulations. The NIF took almost a decade of experimentation and hundreds of D-T shots, each with different parameters, before researchers were finally able to improve the fusion yield by almost three orders of magnitude.

Even if plasma stability issues can be resolved, MCF systems still possess an inherent weakness: the fusioning plasma must interact with its physical environment, commonly referred to as the plasma-facing walls. Over the last 25 years, tokamak researchers have succeeded in making plasma pulses progressively longer—with no attempt at fusion production. This accomplishment amounts to little more than a heat-removal and plumbing exercise that has no impact on scientific feasibility. Any claim that these incremental improvements contribute to commercial viability is dubious, at best.

The multi-minute discharges that have been reported in the last 12 months were mostly made using hydrogen or helium plasmas with no mention of fusion neutron production.[18] It remains an open question whether fusion output would have been maintained during those pulses if deuterium were used. In JET's shorter 59MJ pulse using D-T, the fusion output decreased by one-third over 5 seconds and would likely have fallen almost to zero if the pulse had been maintained for 20 seconds.

In tokamaks, physical size and magnetic field strength can be traded off, more or less, for comparable plasma performance. The most cost-effective tokamak is often thought to be as physically compact as possible, thereby requiring a much higher magnetic field. For this reason, superconducting magnetic coils are currently being developed with extremely high field strength. These will be piloted in the privately funded SPARC tokamak currently under development near Boston, Massachusetts.[19] Although its diameter will be only around one-third the size of ITER, its promoters contend that SPARC will still obtain essentially the same level of fusion performance due to its magnetic field strength, which is planned to be at least twice that of ITER.

It is unclear whether extreme magnetic field strength can be utilized in a tight toroidal configuration. An isolated magnetic coil has been demonstrated to produce 20 tesla on a test stand,[20] but there are daunting engineering challenges involved in stabilizing a torus where the inboard legs of the magnet coils are subjected to extraordinarily high electromechanical stresses and overturning moments. In any case, improving cost-effectiveness is surely a distraction for MCF research when there have been no advances in Q and fusion neutron power in recent decades and attaining thermonuclear fusion energy breakeven remains in doubt.

SPARC and ITER are the only future tritium-burning MCF facilities for which full funding is currently in hand. Both are scheduled to achieve their first plasmas in the mid-2020s, but these milestones will likely be delayed. Although computer simulations have indicated that both facilities will readily attain Q = 10, the development histories of MCF and ICF suggest otherwise. The predictions of computer models extrapolated to regimes that have not been entered experimentally should be treated with great caution.

Assuming that these new facilities are completed, both will face the same environmental problems that initially plagued JET and all other tokamak experiments. Unlike ICF experiments, any roadblocks that arise for MCF devices cannot be readily investigated and cured in D-T operation due to the forbidding amounts of tritium needed. SPARC and ITER will be ready for tritium use only after much experimentation using deuterium alone, a process that will likely drag on into the 2030s. The next challenge will be to achieve energy breakeven, Q = 1, with thermonuclear reactions alone. There is also no guarantee that either facility will subsequently achieve a burning plasma—a milestone already demonstrated by the NIF.

Fusion plasma configurations other than the tokamak, the closely related stellarator and laser-compressed pellets, are generally termed alternative fusion concepts.[21] The promoters of these concepts, mainly private fusion startups, have claimed that the latest supercomputers will enable them to develop new devices

much faster than their predecessors. Despite the availability of supercomputers, the vast majority of these projects are yet to produce any fusion neutrons at all. A half-dozen, at most, have produced only token amounts.[22] A common refrain among all these endeavors is that fusion energy breakeven will be achieved by the mid-2020s and a commercial solution will be in place by the early 2030s. As I have explained in a pair of articles published by the American Physical Society, these claims cannot be taken seriously.[23]

The most promising tokamak alternatives are several magneto-inertial fusion, short-pulse, high-density plasma concepts that make use of a magnetic field, often internally generated, that slows the plasma's disassembly. Numerous models of the venerable dense plasma focus systems first developed in the 1960s have produced up to 1 trillion neutrons per pulse in deuterium,[24] but seem unable to reach higher levels. The Magnetized Liner Inertial Fusion imploding liner device at Sandia National Laboratories in Albuquerque, New Mexico, has produced about 10 trillion neutrons per pulse, which is still 1,000 times smaller than the highest yields of tokamaks in deuterium operation.[25]

Efficient Sources of X-Rays

Any practical application for thermonuclear micro-explosions in power generation cannot use a NIF-like laser driver because its electrical efficiency is less than 1% and it can pulse only once or twice a day at the highest energy outputs. A consequential aspect of NIF operations is that fuel implosion is achieved not by laser photons, but by x-ray photons that could in principle be generated by other sources. Candidate fusion drivers include gaseous lasers,[26] high-energy heavy-ion beams,[27] light-ion beams, and relativistic electron beams. These energy sources can have electrical efficiencies amounting to several tens of percent and are capable of repetition rates up to 1 pulse per second. All can utilize hohlraums for conversion of the beam energy to x-rays with sufficient intensity to implode fusion fuel capsules. Thus their feasibility has been established to a limited extent by the 2021 NIF results.

Pulsed electric power can also be used as a suitable x-ray generator, without laser or particle beams. In the Z Facility at Sandia, for example, intense x-ray fluxes were produced from a cylindrical array of wires vaporized by a huge current pulse from a Marx generator and used to compress D-T fuel capsules.[28]

Obviating External Tritium Production

Almost all tritium available for civilian use is currently sourced from Canada Deuterium Uranium (CANDU) fission reactors in Canada, where it is formed by neutron capture in the heavy-water (D_2O) moderator, then extracted and stored. The current tritium inventory is about 30kg, but this figure will decrease drastically as reactors complete their useful life, the tritium decays, and many kilograms are consigned to ITER.[29] Other CANDU reactors are found in South Korea, China, Romania, Pakistan, and Argentina, but tritium is only being extracted in South Korea. The cost of tritium is between US$30,000 and US$100,000 per gram.

A single fusion reactor producing 2 gigawatts of fusion power, converted to about 800MW of gross electrical power, would require around 100kg of tritium per year. Theoretically speaking, this enormous amount could be provided by breeding tritium in the reactor itself, whereby the fusion neutrons are absorbed in a lithium blanket surrounding the reacting plasma. But in practical terms, it will never be possible to replenish all the tritium burned and lost.[30] For purely practical reasons, reactors must be fueled by deuterium alone. Igniting D-D reactions requires extremely high temperatures, density, and energy confinement time—conditions that are unlikely to be achieved in MCF systems with their synchrotron radiation loss and impurity influx.

Deuterium-based operation using tritium generated entirely within the fuel capsule appears to be feasible in advanced ICF systems with sufficiently large fusion drivers.[31] The density-radius product of the compressed fuel capsule must be at least 10 times higher than for D-T,[32] and the diameter of the precompression fuel pellet must be several times larger. Because of the much greater mass that must be imploded and heated, the driver energy must be as large as 100MJ, which is feasible with several of the drivers listed previously.

The capsule core and a thin inner shell would contain the usual 50:50 D-T mixture, which is ignited by compression to generate a propagating burn into the thick outer layers of the shell that contain only frozen deuterium. The much longer disassembly time of the larger capsule permits the temperature to rise high enough—50keV—that D-D fusion reactions can be ignited. These reactions produce high-energy tritons, protons, and helium-3 nuclides that maintain the plasma temperature, while subsequent reactions of those tritons and helium-3 with deuterons produce additional energetic alphas and protons that are vital to maintaining the temperature.[33] Thus the reaction catalyst, tritium, is simultaneously generated and burned within the fuel capsule. While most of the tritium produced would react immediately, a tiny but sufficient amount will remain unburned for fueling the 50:50 D-T core of subsequent capsules.

Mitigation of Neutron Effects

The problems faced by MCF systems involving reactor structures made radioactive and physically weakened by neutron bombardment can be almost eliminated in ICF systems where the fusion fuel capsule must be enclosed in a one-meter-thick flowing liquid metal sphere or cylinder to accommodate the gigajoule-level impulse loading.[34] This containment approach can take the form of liquid falls com-

prising jets of molten metal.[35] The incoming fusion neutrons sustain the temperature of the circulating liquid metal, whose heat would be extracted to drive a turbine. Relatively few neutrons would strike the solid outer chamber.

If tritium must be produced externally to the reactant assembly, the molten falls must either be lithium, which presents a fire and explosion hazard, or a relatively inert material, such as lithium-lead or a molten salt. But when tritium fuel is produced entirely in the fuel capsule, as described previously, the flowing liquid wall can be an inert metal such as lead. The radioactive tritium inventory of such an ICF power plant would be a small fraction in comparison to that of an MCF power plant, thereby affording a strong safety advantage.

Twenty-five years ago, MCF was thought to be on the verge of achieving fusion energy breakeven, Q = 1, perhaps even in the JET tokamak. At that time, ICF languished at Q < 0.01. This situation has now been reversed. ICF is performing at breakeven or better, and investigating burning plasmas. By contrast, MCF performance has not advanced in a quarter century.

The NIF can now produce shots yielding at least 100kJ, the equivalent of Q = 0.3. In 2021, NIF produced four shots with Q of at least 1.0. More than two decades after its first D-T campaign, the highest quasi-steady Q that JET can produce is Q ≈ ⅓. Indeed, JET still cannot achieve fusion neutron power or Q even a factor of two beyond the best results achieved by the TFTR between 1993 and 1995. Clearly, the scientific feasibility of MCF remains in question.

For typical pulses in JET and other existing large tokamaks, at least half the fusion production results from beam ions reacting with the plasma thermal ions, rather than the thermonuclear reactions that proposed future tokamak reactors will entirely depend on. The thermonuclear Q achieved by JET in 2021—that is, excluding beam-thermal reactions—was no more than 0.2. To conclusively demonstrate scientific feasibility, future large-scale MCF projects, such as ITER or SPARC, must determine whether Q can be increased by a factor of five with thermonuclear reactions alone. If this cannot be achieved, the Q of tokamaks must be seen as fundamentally limited, regardless of what any computer predictions might suggest. This limitation is partly due to the irreducible adverse interaction of the plasma with its physical environment—the plasma-facing components.

Even if thermonuclear Q = 1 can be demonstrated, there is no guarantee that a tokamak can achieve a burning plasma, Q = 5, much less the Q = 10 that some proponents treat as a foregone conclusion. The NIF has already demonstrated burning plasmas, and ITER's attempt is more than a dozen years away, assuming the project remains on schedule.

Based on actual performance, ICF appears to be a far more likely candidate than MCF as the basis for a power plant. MCF may survive as little more than a low-Q neutron source with a dubious tritium supply. ICF also has substantial prospects for eliminating the tritium replenishment issues and adverse neutron effects on reactor structures that plague D-T operation and are unavoidable in MCF systems.[36] Given sufficiently powerful drivers, ICF systems can generate tritium from D-D reactions in very large fuel capsules during the propagating burn. The need to accommodate the impact from repetitive gigajoule-sized blasts also necessitates thick liquid metal blankets to absorb the fusion neutrons, an arrangement that will mitigate, or even eliminate, adverse neutron effects on the outer reaction chamber.

The practical application of ICF requires the development of more efficient lasers or particle beams that can deliver at least 5MJ of short-pulse energy at high rates of repetition to the hohlraum containing the fuel capsule, and at least 100MJ to ignite the very large capsules that will obviate external tritium breeding. There are also many technological issues to address before thermonuclear plasmas can be used in electrical energy production,[37] including the development and manufacture of inexpensive but highly sophisticated fuel capsules and molten metal falls for energy conversion.

The technological hurdles for implementing an ICF-based power system are so numerous and formidable that many decades will be required to resolve them—if they can indeed be overcome.

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