ELECTRIC POWER RESEARCH INSTITUTE

Program on Technology Innovation: Assessment of Fusion Energy Options for Commercial Electricity Production

2012 TECHNICAL REPORT

Program on Technology Innovation: Assessment of Fusion Energy Options for Commercial Electricity Production

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Abstract

Fusion energy options were reviewed to assess technical readiness levels for commercial electricity production for the power industry. Magnetic and inertial confinement systems, in addition to nontraditional fusion concepts, were reviewed by a technical panel of experts, based on workshop presentations by the proponents of each technology. The results are summarized in this report. The conclusion of the review is that, although significant progress is being made in many areas, commercial application is not likely for at least 30 years—if the concepts prove feasible. Recommendations are provided to focus more of this research on engineering and power applications and to engage the power industry in monitoring progress.

Keywords
Energy
Fusion
Hybrid fusion
Inertial confinement
Magnetic confinement
Technical readiness levels

Executive Summary

The electric power generation industry today is focused on nuclear power from fission energy as a power generation source. However, energy from fusion has been a long-term vision for many decades. Some notable recent accomplishments are worthy of review with regard to fusion energy's potential to become a practical source of power. This report summarizes an industry effort to assess the state of the art of fusion energy, through a review of seven proposals for near-term applications.

Technical Conclusion Summary

Several innovative fusion technologies were reviewed and assessed from the standpoint of a technical readiness level (TRL) analysis; the TRL analysis showed the technologies to be at an early stage of readiness. The conclusion of this review is that no near-term (less than 30 years) fusion options are available to the power industry. However, global commitments to fusion technologies in excess of $23 billion (USD) are now under way, which might lead to breakthroughs. Ultimately, demonstration facilities sponsored by the U.S. Department of Energy will be required, just as was the case in the early days of water reactor technologies.

The three inertial confinement approaches are based on lasers, heavy-ion beams, and pulsed-power system drivers. The committee heard about two laser-drive options. The greatest financial support is being directed to the laser inertial fusion energy (LIFE) concept for the National Ignition Facility. The Naval Research Laboratory's direct-drive laser program is less well funded, but it is steadily meeting its technical challenges and might have the more useful technological approach in the longer term.

The international thermonuclear experimental reactor (ITER) tokamak is the largest magnetic confinement facility in the program, and it will address many of the physics and engineering challenges for magnetic fusion power facilities during its construction and operation in the next 20 years.

Alternative magnetic fusion energy approaches are also being pursued by private venture capital–funded companies that are making progress in the development of fusion energy on a smaller scale. These initiatives are less well funded, but they have the potential for smaller fusion devices with possible earlier deployment, should they reach demonstration stages.

Recommendations for Future Actions

From the utility perspective, the production of electricity should be the main objective of a fusion development program. At present, electricity generation appears to be an add-on and not a primary objective to the basic science of the fusion development program, largely due to the challenges of developing a fusion device that produces more energy than it consumes. The following actions are recommended:

- Direct more fusion research on the engineering and operational challenges of a power plant, including how to maximize the value of the fusion power produced. More consideration should be given to the conversion of the heat of fusion to power production and the reliability of any fusion device. Consider developing more advanced and perhaps direct power conversion systems to enhance the overall efficiency of energy-to-electricity conversion.
- Identify common materials and technology needs (such as tritium production) that a fusion test facility could address to meet most of the needs for both magnetic and inertial confinement systems.
- Monitor and periodically re-evaluate the fusion programs to assess the potential for electric power production in the nearer term to identify which concepts are likely to produce tangible fusion power. At the appropriate time, do the following:
  - Create a utility advisory group to focus fusion energy research and development projects to address more utility needs, particularly in the area of operations and maintenance, and to provide input into the design of the fusion power plants.
  - Begin to consider the regulatory requirements for commercial fusion power plants in terms of establishing safety and licensing standards.

Table of Contents

List of Figures

List of Tables

Section 1: Overview of Fusion Study Program

1.1 Background

The vision of fusion energy as a sustainable component of a global power generation future has been in place for decades. More than 60 years have passed since the first fusion reaction took place in the laboratory. A variety of fusion power system designs have been studied across the world. Although the initial forecasts for success proved to be wildly optimistic in the face of many technological challenges, substantial progress has been made.

In the last 10 years, some important commitments have been made to advance the state of the art. In the field of magnetic confinement systems, which use a magnetic field to confine the hot fusion fuel in the form of plasma, the international thermonuclear experimental reactor (ITER) is under construction. It is supported by 34 nations, has a budget of about US$22 billion, and is scheduled to begin operation in France in 2019. Another magnetic confinement system, the stellarator fusion experiment, Wendelstein 7-X, is under construction in Germany, with a budget of US$500 million.

In the field of inertial confinement systems, in which fusion reactions are initiated by compressing and then shock heating a small spherical, cryogenic fuel target, the U.S. Department of Energy (DOE) National Nuclear Security Administration (NNSA) supports the National Ignition Facility (NIF), which was built at a cost of US$3.5 billion. It is an inertial fusion confinement power testing program that uses laser beams to drive the target. In addition to advanced nuclear weapons research, it has a goal of producing substantial energy gain for inertial fusion energy.

Following a request from DOE in 2010, the National Research Council undertook a study to assess the prospects for inertial fusion energy. In its interim report, the committee presented the following preliminary conclusion [1]:

> The scientific and technological progress in inertial confinement fusion has been substantial during the past decade, particularly in areas pertaining to the achievement and understanding of high-energy-density conditions in the compressed fuel . . .

Indeed, the entire field of high-temperature plasma is much better understood now, and there is optimism that ITER and NIF will ultimately meet their design goals. In addition, these advances in the state-of-the-art knowledge gained over the years have stimulated innovative new approaches to fusion power generation, and a number of venture startups are proceeding in the United States and Canada. A broad review of the potential marketplace indicates that at least six fusion power initiatives are substantive enough to warrant more detailed evaluations by the U.S. power industry.

1.2 Project Objectives

In 2010, the Electric Power Research Institute (EPRI) Technology Innovation (TI) program initiated a project to assess the more notable fusion initiatives for their potential relevance to future commercial power generation. For each of the most significant fusion power initiatives, the objectives were to: (1) identify the major obstacles and technical challenges to overcome and (2) develop a timeline for an electric power production facility. Six to seven fusion power initiatives were selected for evaluation based on existing public information.

1.3 Organization and Roles of Involved Groups

The following two committees were organized to support the project:

- **Technical Advisory Committee.** This committee consisted of recognized, North American fusion power experts from national laboratories and universities. The committee was tasked with providing a technical assessment of the chosen fusion initiatives and with interacting with the sponsors of those initiatives to identify key technological challenges and timelines.
- **Program Advisory Committee.** This committee of EPRI and industry executives was responsible for providing the overall coordination of the study, including the communications between the Technical Advisory Committee and the organizations developing the various fusion concepts..

1.4 Abbreviations and Acronyms

The following abbreviations and acronyms are used in this report:

DOE	Department of Energy
EPRI	Electric Power Research Institute
FNF	fusion nuclear facility
IFE	inertial fusion energy
IFMIF	International Fusion Materials Irradiation Facility
ITER	international thermonuclear experimental reactor
JET	Joint European Torus
LIFE	laser inertial fusion energy
LLNL	Lawrence Livermore National Laboratory
MFE	magnetic fusion energy
NIC	National Ignition Campaign
NIF	National Ignition Facility

NNSA	National Nuclear Security Administration
NRL	Naval Research Laboratory
SABR	subcritical advanced burner reactor
TFTR	tokamak fusion test reactor

Section 2: Fusion Technology Options

2.1 Main Approaches to Fusion Energy

In the simplest terms, there are two main approaches to fusion energy—magnetic fusion and inertial fusion—each of which has two subcategories (see Figure 2-1). In all cases, the task is to achieve sufficient confinement of high-energy fuel particles (typically deuterium and tritium) to achieve net power output.

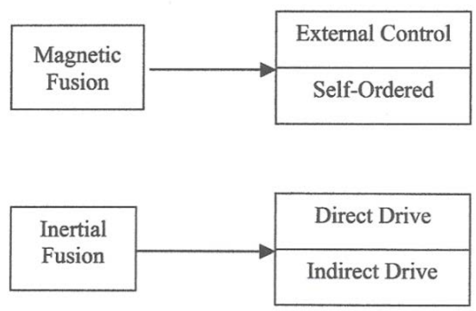
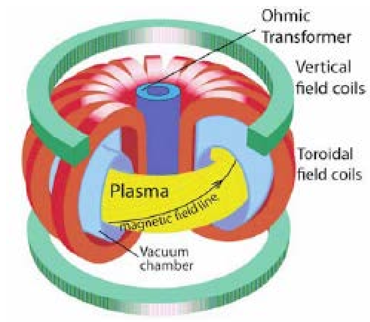


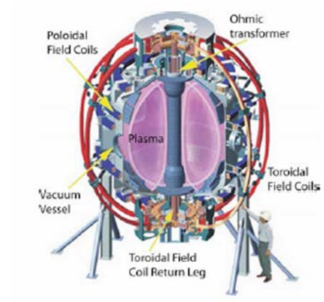
Figure 2-1
Main approaches to fusion energy [2]

2.1.1 Magnetic Fusion Energy

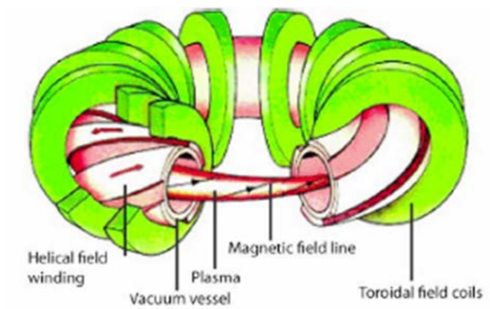
Magnetic fusion energy (MFE) takes advantage of the fact that charged particles spiral tightly around magnetic field lines. A collection of magnetic field lines that form a ring, or *torus*, if cleverly arranged, can confine the charged particles of the plasma well. These closed field lines can be generated by both external magnetic coils and internal currents. In externally controlled systems (see Figure 2-2), the fields are totally or mainly provided by external coils.



(a) Tokamak



(b) Spherical torus



(c) Stellarator

Figure 2-2
Externally controlled configurations [3]

In self-ordered systems (see Figure 2-3), the fields are generated largely by internal currents.

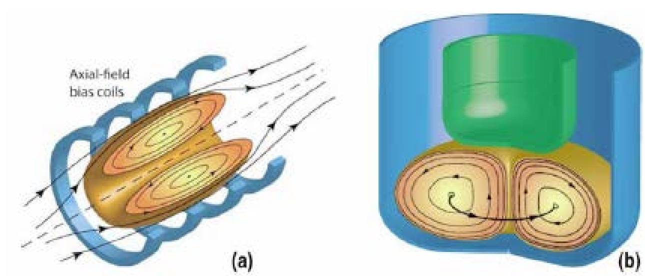


Figure 2-3
Self-ordered configurations: (a) field-reversed configuration and (b) spheromak [3]

2.1.2 Inertial Fusion Energy

Inertial fusion energy (IFE), rather than having a steady-state reactor, adopts the approach of a repetitively pulsed engine in which successive capsules of fusion fuel are imploded rapidly to extremely high density. A small central hotspot then begins to fuse, igniting the remaining fuel so quickly that its inertia prevents it from escaping the burn wave. In direct-drive systems, laser beams are proposed to cause the capsule compression and ignition. For indirect-drive systems, lasers or ion beams are to be used to create a sea of x-rays in a small cylinder that surrounds the capsule, with a temperature great enough to lead to capsule compression and ignition. Figure 2-4 illustrates direct-drive and indirect-drive concepts.

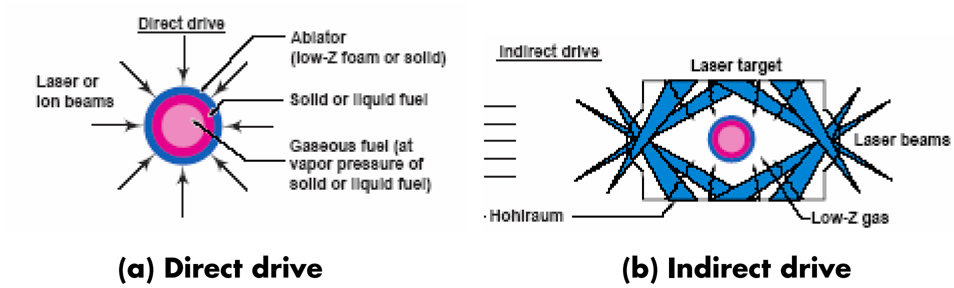


Figure 2-4
Direct and indirect drive with lasers [4]

2.1.3 Fusion–Fission Hybrids

A fusion–fission hybrid uses fusion neutrons from burning deuterium-tritium (D-T) not only to produce the required tritium to continue the fusion process but also to deal with the needs of fission plants. The primary reason for considering fusion–fission hybrids to support fission reactors is for their nuclear waste transmutation and fuel breeding potential. A byproduct could be the production of electricity, using extracted heat from the fusion reaction.

2.2 Commercialization Process

Naturally, there are also variants around these main themes. Within the fusion portfolio, the technological development of concepts advances through a series of stages of experimental development (see Figure 2-5). These stages are concept exploration and proof of principle, followed by performance extension. Success in these stages should lead to fusion energy development and demonstration, and finally, to delivery of commercial plants. When a project is sufficiently mature, many other development considerations arise—such as optimization for economic performance, operational and maintenance attractiveness, supply chain readiness, licensing compatibility, and so on.

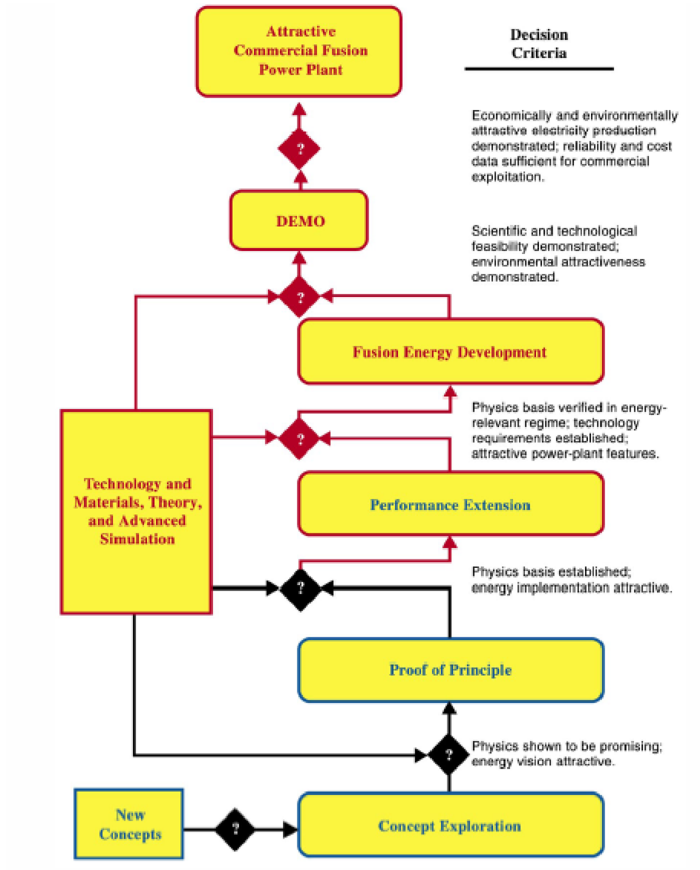


Figure 2-5
Roadmap for fusion energy [4]

Each stage of development brings increased opportunities for developing the building blocks successively, a greater range and capability (dimensional and dimensionless parameters) for exploring plasma conditions, and more demanding technology requirements. The steps are as follows:

- **Concept exploration** typically costs less than US$10 million per year and involves the investigation of basic characteristics. Experiments cover a small range of plasma parameters (such as at <1 keV) and have few controls and diagnostics.
- **Proof of principle** is the lowest cost program (US$5 million to US$40 million per year) to develop an integrated understanding of the basic science of a concept. Well-diagnosed and controlled experiments are large enough to cover a fairly wide range of plasma parameters, with temperatures of a few kilo electron volts, and some dimensionless parameters in the power plant range.
- **Performance extension** programs explore the physics of the concept at or near fusion-relevant regimes. Experiments have a large range of parameters and temperatures (>5 keV), with most dimensionless parameters in the power plant range. Diagnostics and controls are extensive.

- **Fusion energy development** develops the technical basis for advancing the concept to the power plant level in the full fusion environment. It includes ignition devices, integrated fusion test systems, and neutron sources.
- **A demonstration power plant** is constructed and operated to convince electric power producers, industry, and the public that fusion is ready for commercialization.

2.3 Review of Fusion Options Presented

This section summarizes information gathered during a workshop and documented by the Technical Advisory Committee. The objective of the workshop was to better understand the potential for fusion to produce electricity and the cost and timelines to develop this energy source for commercial application. In addition, for each of the most significant fusion power initiatives, the goal was to develop a timeline to achieve an electric power production facility and identify the major obstacles and challenges to overcome to achieve that goal. The following fusion concepts were presented, covering a range of technical, organizational, and philosophical approaches:

Table 2-1
Fusion concepts presented

Presentation Title	Presenters
Magnetic Fusion Energy: from physics to DEMO	Princeton Plasma Physics Laboratory General Atomics University of Wisconsin University of California–San Diego Concordia Power
Fusion–Fission Hybrids – Fusion Augmenting Fission	University of Texas Oak Ridge National Laboratory Princeton Plasma Physics Laboratory National Instruments
Magnetized Target Fusion	General Fusion
LIFE – A Diode-Pumped, Solid-State Laser/ Indirect Drive–Based Approach to Inertial Fusion Energy	Lawrence Livermore National Laboratory Team
Fusion Energy with Krypton Fluoride Lasers and Direct Drive Targets	Naval Research Laboratory
The Fusion Engine – A Pulsed Field-Reversed Configuration Fusion Reactor	Helion, Inc.
A Supplemental Fusion–Fission Hybrid Path to Fusion Power Development	Georgia Institute of Technology

2.3.1 Spherical Torus—Princeton Plasma Physics Laboratory

The Princeton Plasma Physics Laboratory (PPPL) is developing a spherical torus (also called a *spherical tokamak*), using magnetic confinement, to be used as a research tool. Researchers have not yet focused on power conversion, but they hope to improve the understanding of plasma control and materials issues to allow spherical tori to be considered for future power production applications. Figure 2-6 illustrates the spherical torus concept.

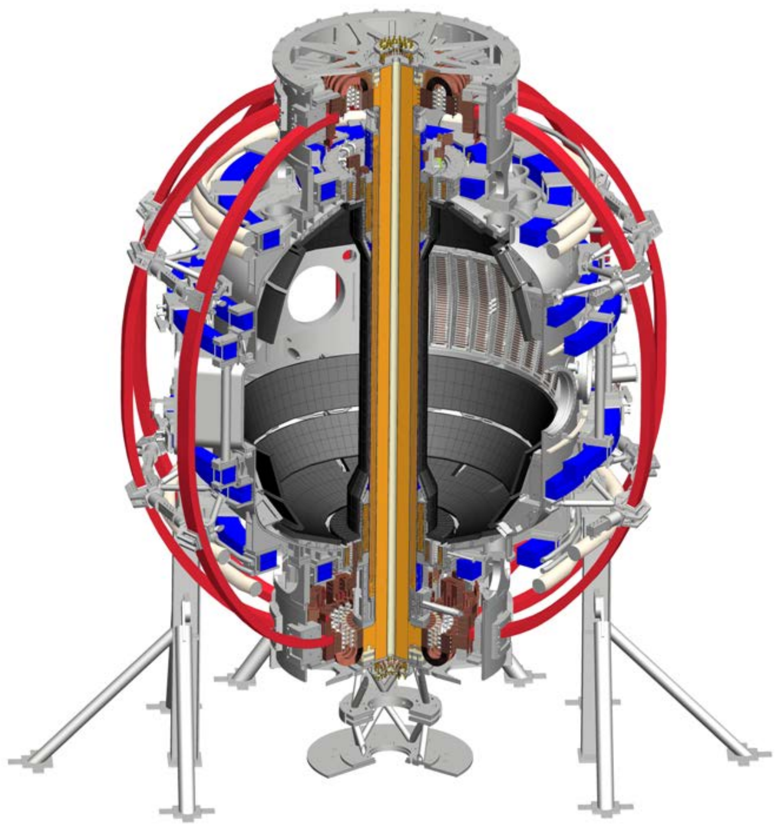


Figure 2-6
Spherical torus experiment [5]

The stated advantages of this magnetic confinement system are that it is radially compact, it provides a more stable plasma with lower magnetic fields and higher plasma pressure, and it is more amenable to modular operation and maintenance. Researchers are configuring this device to be a volume neutron source for possible hybrid fusion–fission applications. A spherical torus has a very high *beta* (the ratio of plasma pressure to magnetic pressure) that can allow the use of demountable, water-cooled coils. With a low aspect ratio ($R/a < 2$), there is no need for a breeding blanket on the inner side of the plasma. The fission blanket can be placed outside the fusion blanket in a readily accessible position. The compact size of the device would allow the entire core (300–1000 tons)—which includes the inner legs of the toroidal field coils, fusion blanket, and vacuum vessel—to be removed vertically when the outer limbs of the toroidal coils are demounted (see Figure 2-7).

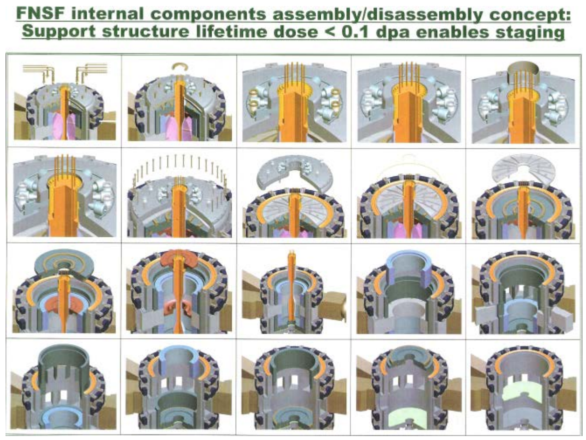


Figure 2-7
The compact size of the device would allow the entire core to be removed vertically when the outer limbs of the toroidal coils are demounted [6].

At present, it is still a research tool that the PPPL team is proposing as the Fusion Nuclear Science Facility to test materials, plasma-facing components, and confinement physics in parallel with ITER and beyond. Eventually, the team would like to develop the spherical torus as a fusion energy system, but they have not yet reached that step.

2.3.2 Compact Fusion Neutron Source Hybrid—University of Texas, Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory

The compact fusion neutron source hybrid uses the Princeton Plasma Physics Laboratory spherical torus as a source of neutrons to produce power through transmutation of nuclear wastes, as part of a potential U.S. waste management strategy, or through breeding fuel for light water reactors.

Researchers are scaling the fusion system—which is less than half the weight of conventional, advanced tokamak systems—to 400 MWth. Figure 2-8 shows an artist's rendering of the compact fusion neutron source hybrid with the breeding or transmutation blanket.

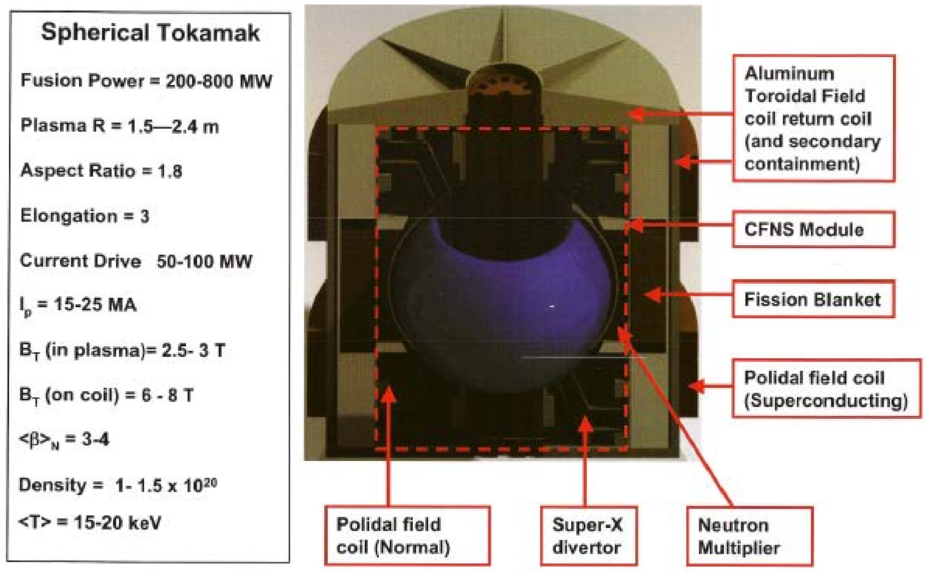


Figure 2-8
Compact fusion neutron source hybrid [6]

The goal of this hybrid is to use subcritical blankets consisting of either transuranic wastes or uranium-238 to breed fuel for light water reactors. The fission blanket is outside the fusion core, which allows for separate removal and maintenance. Researchers claim that one hybrid can support the waste of 20 light water reactors and provide fuel for four to five light water reactors without the need to reprocess. Should this technology be successful in the breeding mode, the use of light water reactors could be extended, avoiding the need to build fast breeder reactors. The technical challenges of a fusion–fission hybrid are less severe than those for direct fusion electric plants—the Q multiplication factor need not be as high because the purpose of the fusion core is to produce neutrons, not power, which is done in the multiplication system of the blanket. The technical challenges of the spherical torus core and the engineering of the hybrid plant must still be addressed. The developers estimate the timeline for deployment to be in the mid to late 2020s.

2.3.3 Magnetized Target Fusion—General Fusion

General Fusion, a small startup company based in Canada, is developing magnetized target fusion. General Fusion is collaborating with Los Alamos National Laboratory to develop a pulsed plasma device, using acoustic mechanical drivers to send the plasmas into a magnetic confinement and creating a fusion reaction based on the pressure pulse created. They are targeting the commercial electricity market with a 100 MWe power plant, with a demonstration plant to be built by 2020.

In the General Fusion version of magnetized target fusion, compact D-T plasma tori will be formed and translated to collide into a chamber with a thick wall of rotating liquid lithium. The liquid lithium will be compressed by pistons, adiabatically compressing the plasma to fusion temperature (see Figure 2-9).

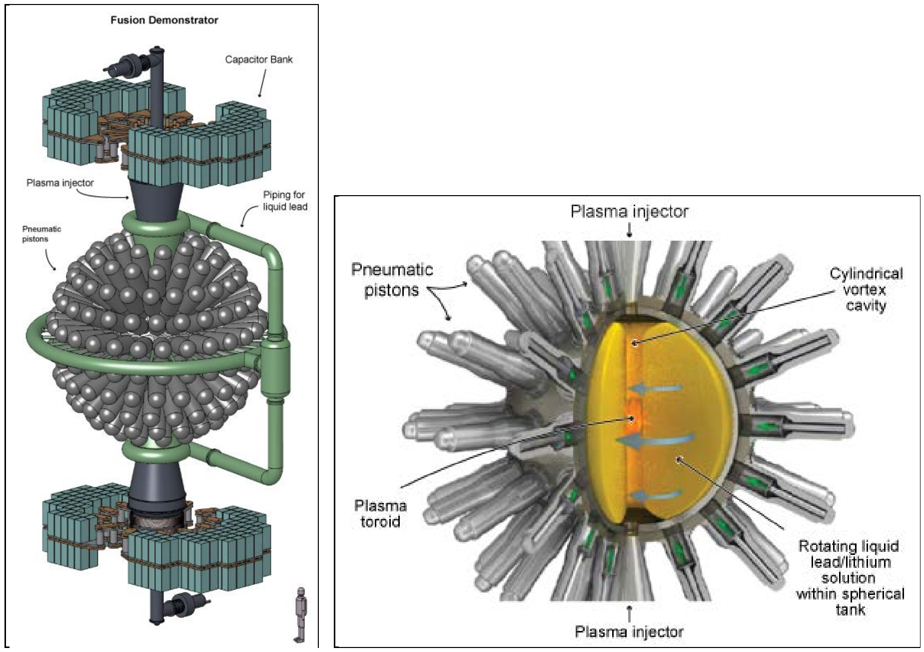


Figure 2-9
General Fusion version of magnetized target fusion [7]

The basic design is based on magnetized target fusion projects in Russia, as well as the Atlas and Linus projects. Each of the protrusions is an acoustic accelerator of a piston. They extract the heat from a lead lithium blanket to a conventional steam turbine power plant (see Figure 2-10).

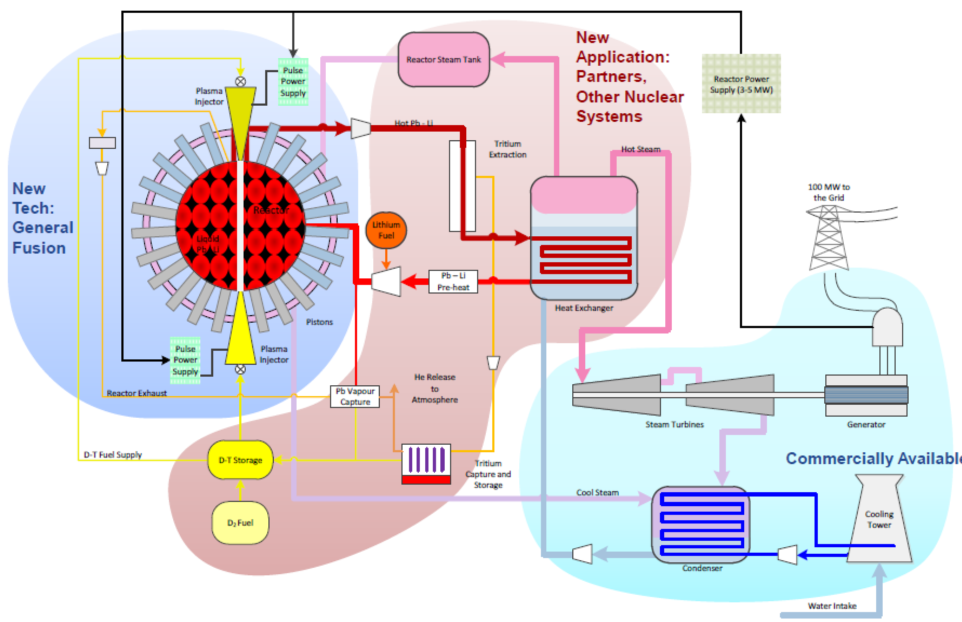


Figure 2-10
General Fusion magnetized target fusion power plant [8]

General Fusion is in early feasibility testing of the concept, but they have an ambitious US$1 billion demonstration project that includes building a demonstration plant by 2020. They hope to build a full-scale reactor by 2015, with a budget of US$50 million. General Fusion estimates that the levelized cost of power from their 100 MWe fusion reactor system would be in the range of US$0.07 to US$0.08 per kWh.

General Fusion is testing subcomponents to qualify equipment and fundamental physics. The hardware that they have built on their US$40 million development budget is impressive.

2.3.4 Laser Inertial Fusion Energy—Lawrence Livermore National Laboratory

The laser inertial fusion energy (LIFE) project is funded by Lawrence Livermore National Laboratory (LLNL) director's funds. It derives from work funded by the NNSA to support the NIF, aimed at the nation's security to avoid the need to test nuclear weapons. Construction of the NIF was completed in 2009 at LLNL. It is currently undergoing testing to achieve ignition, which is needed to prove its viability as an energy production source. Ignition signifies the ability to produce a propagating fusion burn in the target. In NIF, 192 laser beams are focused on a tiny, 1-mg fuel target of D-T to create the densities and temperatures needed for fusion. The LIFE system also uses an indirect-drive target in which up to 384 diode-pumped, solid-state lasers are directed at tiny canisters (*hohlraums*) that absorb the energy, creating the pressure and temperatures needed for fusion. Today, these holraums are generally made of gold, but LIFE is shifting to lower-cost lead.

The NIF uses neodymium glass. It is designed to deliver, in a few nanoseconds, 1.8 MJ of laser light from 192 beamlets at the third harmonic in the ultraviolet. The present ignition program is using indirect drive. Modifications to allow polar direct drive are possible.

The NIF architecture, with large slabs of laser glass driven by flash lamps, is an inefficient, low-repetition-rate system. More efficient, repetitively pulsed, diode-pumped, solid-state lasers at 351 nm are being developed for use in LIFE. (The Mercury laser operated at 60 J, 1054 nm, at up to 10 pulses per second, for ~10^5-shot, continuous operation.)

The diode-pumped, solid-state lasers have an operating lifetime of 1500 hours. This limited lifetime requires that the design allow for line-replaceable units, to enable replacement during operation. Figure 2-11 shows a top view of the NIF's laser bays.

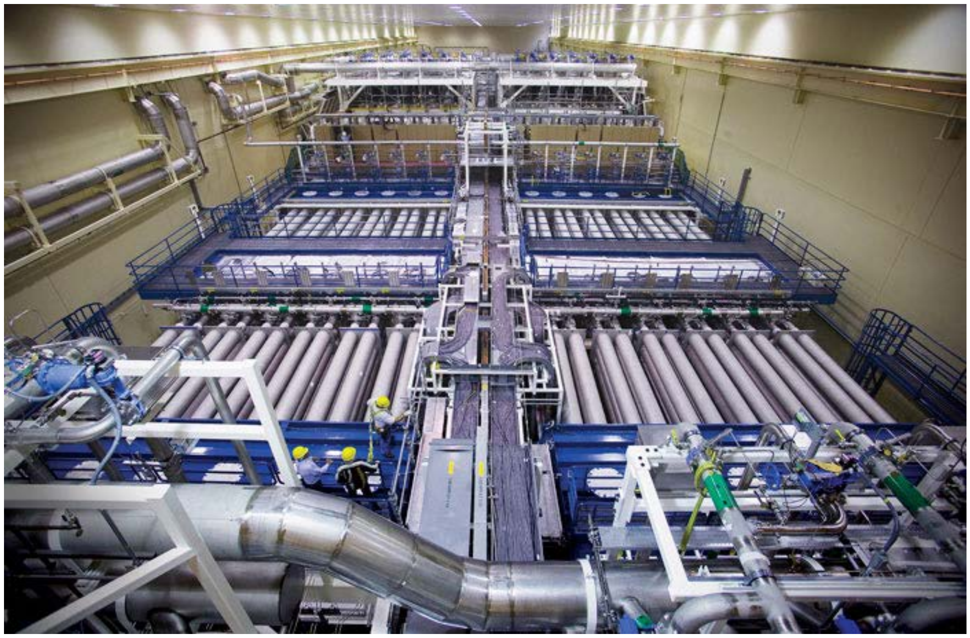


Figure 2-11
Each of the National Ignition Facility's two identical laser bays has two clusters of 48 beamlines, one on either side of the utility spine running down the middle of the bay [9].

Figure 2-12 shows a typical configuration of the proposed power plant, sized to produce 2000–3000 MW of thermal power, which translates to a 1000-MWe power plant. The diameter of the proposed fusion chamber is 12 m, making the facility size—including the lasers and all processing equipment—approximately 12 acres for a 1000-MWe power station.

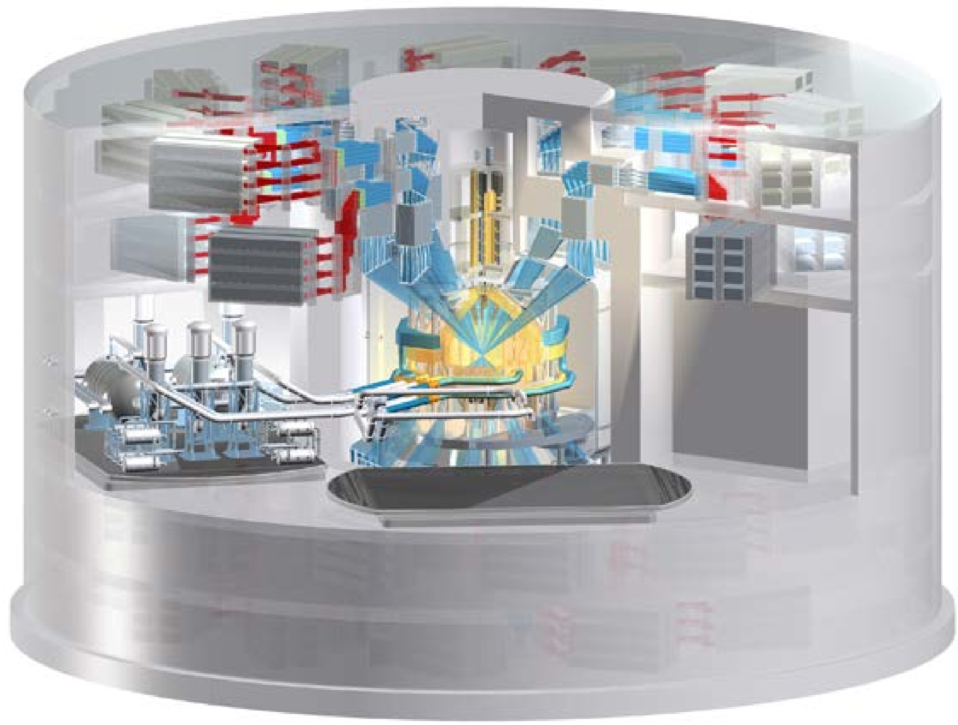


Figure 2-12
Typical configuration of the proposed power plant [10]

The power conversion system presently relies on a molten salt in the blanket for cooling, which will then be converted to a steam cycle for power production. Current claims are that the cost of power would be from US$0.05 to US$0.08 per kWh for a 1000-MWe plant, assuming a US$5.9 billion overnight capital cost. The schedule for deployment calls for a demonstration plant in the early 2020s, with a full commercial plant rollout in the 2030s. The detailed delivery plan calls for plant operations to begin 10 years after ignition is achieved.

The project has developed detailed work breakdown structures and cost estimates, but they were not available to the committee for review. The LIFE presentations were also not available, making it difficult to report more details than those that are contained in this document.

2.3.5 Krypton–Fluoride Lasers and Direct-Drive Targets—Naval Research Laboratory

The Naval Research Laboratory (NRL), with its consortium of government laboratories, universities, and industries, has been researching laser fusion as part of the Department of Defense program to explore alternative energy sources because the Department of Defense is the largest single-source energy consumer in the United States. The focus of the research is the development of krypton–fluoride lasers, which NRL researchers believe will benefit among lasers from their shorter wavelength and ability to readily vary the focal point spot size as the target is compressed. They operate at shorter wavelength (248 nm) than the NIF and LIFE lasers. The repetitively pulsed Electra laser (see Figure 2-13) has operated at 300–700 J, up to five pulses per second, for ~10^5-shot continuous operation. This system has run 11.5 million shots at 10 Hz over 319 hours. During the 2000s, NRL managed the high-average-power laser program. Under this program, considerable progress was made in laser IFE at a number of laboratories and universities, including the krypton–fluoride lasers at NRL and the diode-pumped, solid-state lasers at LLNL.

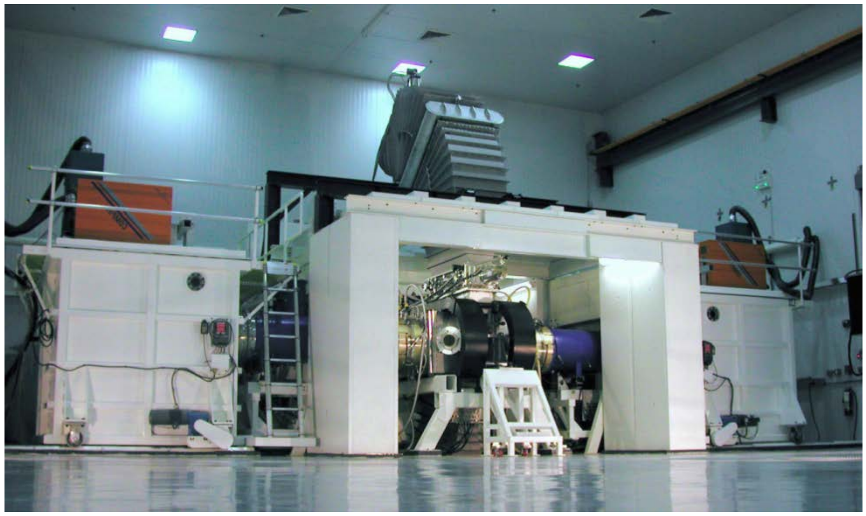


Figure 2-13
Electra laser [11]

NRL researchers are also focused on direct-drive systems, in which the target is symmetrically struck by 40 to 60 laser beams with up to 6000 beamlets. The target is a spherical D-T frozen shell, surrounded by an ablative foam outer shell, that when struck by the lasers, creates a shock wave to support ignition. In principle, direct drive can be more efficient than indirect drive, particularly if shock ignition is used. Although Figure 2-14 shows gain curves for krypton–fluoride lasers, they are a possibility for both krypton–fluoride and diode-pumped, solid-state lasers [12].

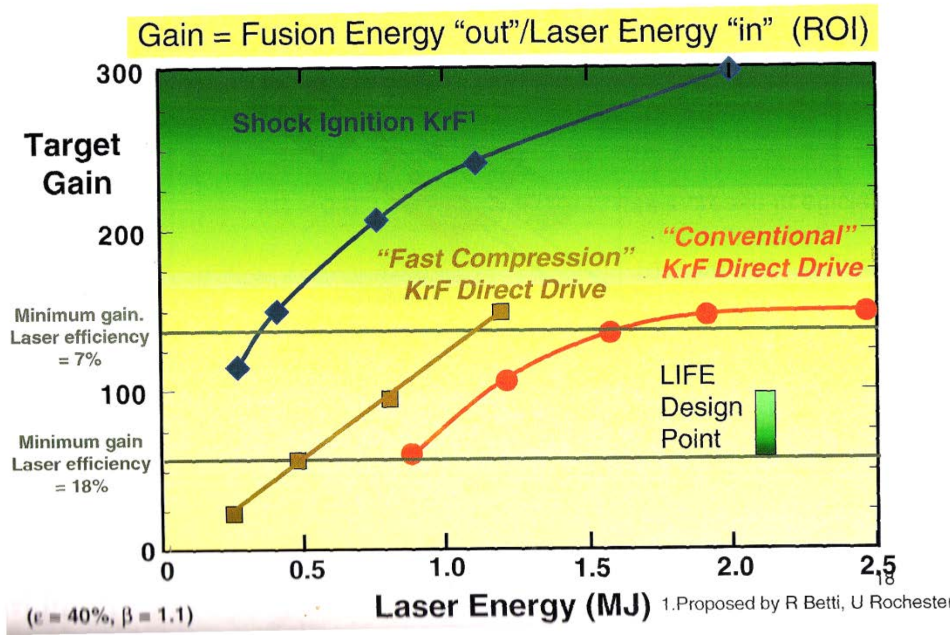


Figure 2-14
One-dimensional gain curves for direct drive [12]

NRL has developed a conceptual design of a fusion power plant, as shown in Figure 2-15.

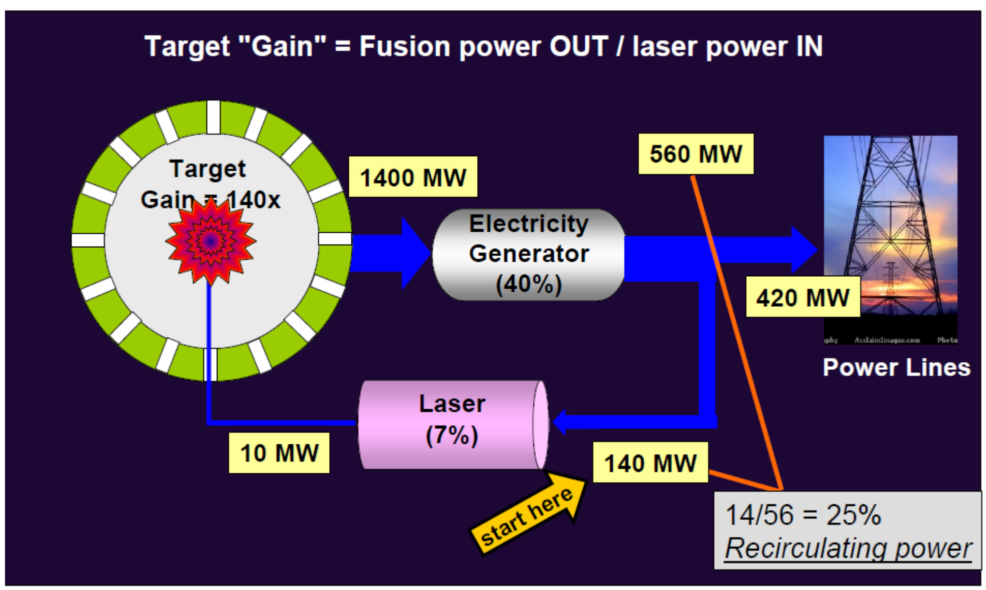


Figure 2-15
Conceptual layout of the Naval Research Laboratory fusion power plant [11]

NRL has a steady research and development program with assigned technology readiness levels for the key challenges in developing a power station. They expect to have a prototype facility available in the 2030 time frame.

2.3.6 Pulsed Field-Reversed Configuration Reactor—Helion Energy

Helion Energy is designing a fusion engine aimed at producing a modular linear reactor capable of producing 40–50 MWth of fusion power. The design calls for the creation of two plasmoids at opposite ends of a linear accelerator to launch the plasmas into a central, high-magnetic-field compression section, creating the temperatures and pressures needed for a fusion reaction. With repetitive firings, such as a diesel engine, a sustainable source of heat and power can be achieved.

The fusion central section is surrounded by a lithium and beryllium fluoride blanket to trap the neutrons and helium particles to capture the heat, which is then transferred to a conventional steam cycle. The collaborators on this project include universities, the National Aeronautics and Space Administration, the U.S. Air Force, and the Defense Advanced Research Projects Agency. The effort has relatively low funding and is aimed at technology development.

The concept of field-reversed configuration plasmoid formation is based on sequential reversal of axial magnetic fields, which are then accelerated to high velocities and adiabatically compressed into smaller coils using pulsed magnetic fields. This compression is sufficient to initiate a D-T fusion reaction. Figure 2-16 is a schematic of the proposed fusion engine (the blanket surrounding the central compression zone and power conversion system is not shown). The present experimental setup is shown in Figure 2-17.

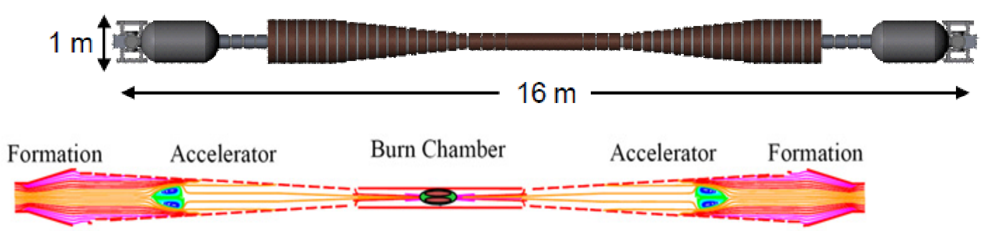


Figure 2-16
Helion version of magnetized target fusion [13]

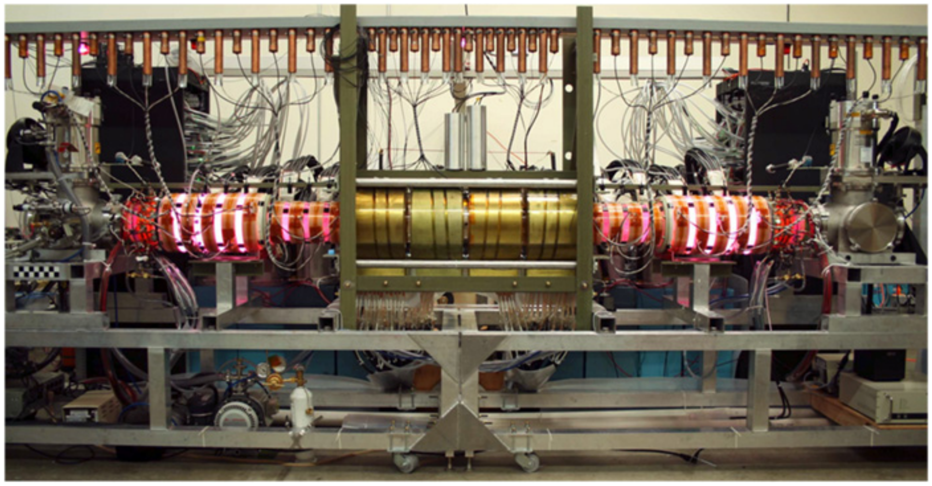


Figure 2-17
Schematic of proposed system and present experiment [8]

The proponents of this technology are targeting small, modular units using what they claim are commercial off-the-shelf technologies. Their goal is to build a prototype by 2020, at a cost of about US$18 million after component testing and development. At present, the average technology readiness level ranges from 3 to 4, which is at the proof-of-concept and laboratory testing stage of components and systems.

The proponents suggest that this technology reduces the scale and order of magnitude of challenges faced by initial laser and magnetic confinement fusion, that it is closer to deployment at lower cost, and that it is a nearer-term solution to commercialization of fusion.

2.3.7 Subcritical Advanced Burner Reactor—Georgia Institute of Technology

The Georgia Institute of Technology is working to capture the developments in magnetic confinement based on the ITER concept and sodium-cooled fast reactors to create a fusion–fission hybrid reactor that they believe can lead to an earlier fusion reactor. This belief is based on a less demanding multiplication factor (Q of 3–5 compared to >30) than that needed for pure fusion electric production because the sodium-cooled breeder blanket provides a neutron multiplication factor in addition to that created by the fusion reaction. The goal of the combination of technologies is to make electricity while either making fuel for light water reactors (breeding) or transmuting nuclear wastes and, in the process, making electricity.

A subcritical advanced burner reactor (SABR) transuranic waste burner reactor would be able to fission all the transuranic waste from three light water reactors of the same power. A nuclear fleet of 75% light water reactors (75% of nuclear electricity) and 25% SABRs would reduce high-level waste repository requirements by a factor of >10 relative to direct burial of spent fuel from a nuclear fleet of 100% light water reactors.

A SABR minor actinide burner reactor would be able to burn all the minor actinide from 25 light water reactors of the same power, while setting aside plutonium for future fast reactor fuel. A nuclear fleet of 96% light water reactors and 4% SABRs would reduce needed high-level waste repositories by a factor of 10.

Figure 2-18 shows the basic configuration of the SABR, and Figure 2-19 illustrates the transuranic waste incineration process.

ANNULAR FAST REACTOR (3000 MWth)
- Fuel—TRU from spent nuclear fuel. TRU-Zr metal being developed by ANL.
- Sodium cooled, loop-type fast reactor.
- Based on fast reactor designs being developed by ANL in Nuclear Program.

TOKAMAK D-T FUSION NEUTRON SOURCE (200-500 MWth)
- Based on ITER plasma physics and fusion technology.
- Tritium self-sufficient (Li_4SiO_4).
- Sodium cooled.

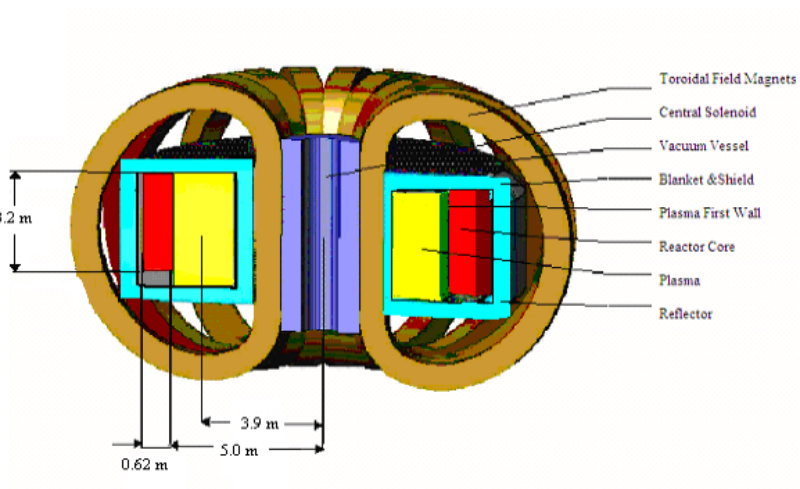


Figure 2-18
Schematic of the subcritical advanced burner reactor hybrid plant [14]

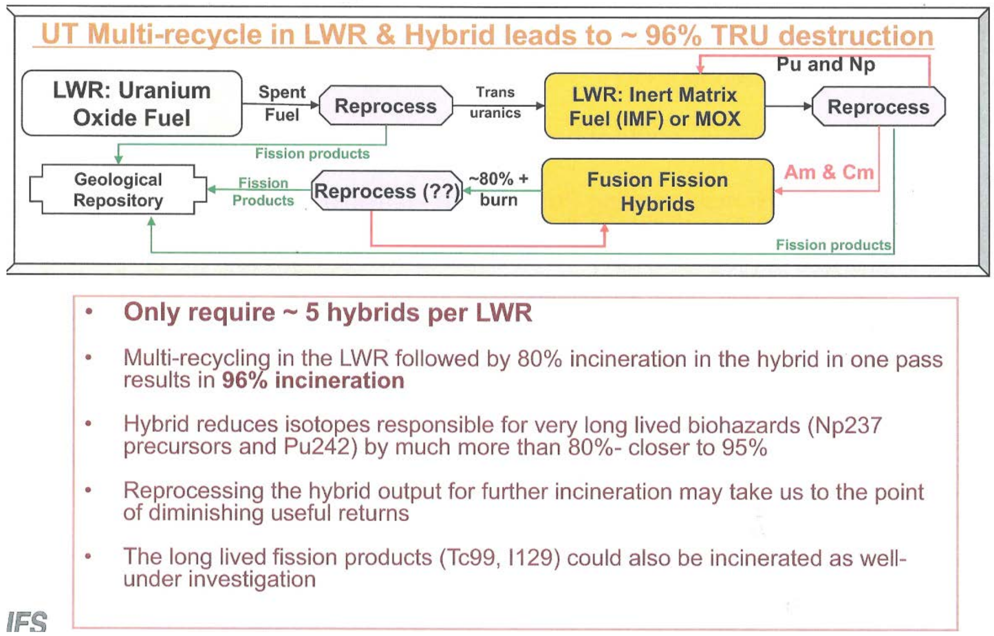


Figure 2-19
The transuranic waste incineration process [6]

Researchers will rely on a basic tokamak design and lessons learned from both the ITER program and the integral fast reactor development work that was started at the Idaho National Laboratory but cancelled by Congress in the 1990s.

The deployment schedule for this hybrid fusion–fission reactor is realistically set at 2050 because many of the technology developments depend on successful ITER demonstration and continued development of sodium-cooled, fast reactor technology. The SABR team has focused on both aspects of the needed technology development, including fission fuel and traditional fast reactor accident analysis.

Section 3: Expert Panel Assessments

3.1 Assessments by the Technical Advisory Committee

3.1.1 Magnetic Fusion Energy

The physics of tokamaks and stellarators is mature, although understanding is not yet complete. There is little doubt among practitioners about the basic performance extrapolations—that is, that a machine like ITER, when it reaches the fusion energy development stage, will achieve plasma conditions required to produce massive quantities of fusion power. However, until the ITER operates and demonstrates certain key principles, absolute assurance of performance cannot be made. Although a great deal of work continues on the basic predictability of plasma performance, the focus of current research has shifted into areas related to the interplay among plasma physics, technology, and engineering—such as steady-state operation, plasma-wall interactions, control in high-Q (fusion gain) operation, off-normal events, and so on. All of these touch directly on the ultimate reliability, availability, and economics of a fusion reactor. Much of the complementary engineering and materials research, however, remains to be done.

To that end, the MFE community has carried out extensive gap analyses and identified program elements required to fill these gaps. A development pathways study from 2003 is currently being updated. The aim is not only to lay out a long-term strategy for fusion development but also to inform short-term decisions on required R&D. The most important gaps concern materials for structural and plasma-facing components. In addition to a great deal of laboratory R&D, materials testing facilities, and advances in computational modeling, these questions will require a burning plasma experiment dedicated to fusion nuclear technology. A number of preconceptual designs have been prepared for a machine to complement ITER and fill that mission. They range from a fusion nuclear facility (FNF) to provide the additional basic research needed to enable fusion power to the more ambitious pilot plant that would produce net electrical power. There is an ongoing debate within the community about how soon such a machine could be built. The target of all this research is to provide the component data for a demonstration power plant—that is, a machine that produces fusion power, available on the grid at commercial scale. Improvements in other areas of technology are also required, including systems for heating, current drive, fueling, and improved superconducting magnets.

3.1.1.1 The International Thermonuclear Experimental Reactor and the Fusion Nuclear Facility

In experiments on the Joint European Torus (JET) conducted in 1998, a peak fusion power of 16 MW was achieved at a gain in the range of 0.6 to 0.9—good enough to claim *scientific breakeven* (fusion power equal to the plasma heating power). The JET facility is unique in the world due to its tritium systems and its extensive remote handling capabilities for installation and removal of contaminated and beryllium in-vessel components. Following on the achievements of the JET and those of the tokamak fusion test reactor (TFTR) in the United States, ITER aspires to demonstrate the scientific and technological feasibility of fusion energy at scale. One of ITER's primary goals is to achieve a fusion gain of 10 (fusion power/plasma heating power) at a fusion power level of 500 MW with 50 MW of plasma heating power. At Q = 10, two-thirds of the thermal power required to maintain the plasma at its operating point comes from the reaction products. Producing and controlling these predominantly self-heated plasmas will be the primary objective of the ITER science mission. The ITER Q = 10 plasma design point (plasma pressure of 0.3 MPa) is based on conservative physics. Because the fusion power scales as the square of the pressure, a factor of two improvement would make an ITER-size reactor (incorporating a blanket energy multiplication factor of 1.17) capable of generating ~2400 MWth.

ITER will be equipped with first-wall materials that are similar to those currently installed on JET and will be capable of injecting 73 MWth of heating power into the plasma, using radio frequency and neutral beam injection heating systems proven on JET and numerous other experiments around the world. Its vacuum vessel, superconducting magnets, fueling and tritium systems, heat rejection system, remote handling and maintenance systems (hundred-ton class), and hot cells all could be typical of or similar to those deployed in a first-generation demonstration reactor, although some technologies such as the heating systems will require factor of two improvements to more efficiently deliver power to the plasma. An extensive R&D program in the late 1990s qualified manufacturing processes and successfully tested reduced or full-scale mockups of a vacuum vessel sector, toroidal field coil, in-vessel components (blanket and divertor modules), remote manipulators, a central solenoid (magnet) module, and torus exhaust cryopumps. Additional development and testing as part of the construction project is being performed in the areas of heating and current drive, fueling, vacuum and pumping, high-heat-flux first-wall and divertor components, tritium processing, superconductor qualification, and so on.

The ITER blanket and shield will be made of stainless steel, which is not suitable for operating at high temperature and is limited by radiation hardening to a neutron fluence of <1 MW-yr/m^2. ITER will, however, perform the first tests of reactor-relevant structural materials and tritium breeding blanket components in six dedicated ports that make up a total of 9 m^2 of the first-wall area. The structural material for the six tritium test blanket modules to be deployed will be the high-temperature (550°C), low-activation, radiation-resistant steel that has been under development in the United States and Japan (F82H) and Europe (Eurofer). This is the consensus material for the demonstration project, having an extensive materials property database at a neutron fluence up to 3 MW-yr/m^2. The combination of coolant schemes (water, helium, and lead–lithium) and breeding materials (ceramic pebbles and static and flowing lead–lithium) for these tests will cover a wide range of breeding blanket concepts, at an average neutron wall loading of 0.5 MW/m^2 and nuclear heating levels approaching 8 MW/m^3 on the front end of the modules and 13 MW/m^3 in the breeding zone 4 cm beyond that. The corresponding test program will evaluate thermomechanical and thermofluid effects, tritium breeding, and technologies for tritium extraction and processing over a range of concept-specific temperatures (and resulting plant efficiencies) corresponding approximately to conditions in a PWR at the low end to an advanced high-temperature reactor (and above) at the high end. The ITER parties are in the process of conducting R&D, qualifying fabrication processes, and developing structural design rules for these components.

3.1.1.2 Fusion Nuclear Facility

Several presentations were made regarding the FNF. The presenters summarized the status of their research, along with short- and long-term visions for fusion energy development. A centerpiece of MFE research is the ITER device that is currently being constructed in France by an international team, including representatives from the United States. ITER is scheduled to begin operations in 2019 and to achieve significant fusion power in 2029. Nearly half of the multibillion-dollar cost will be provided by the European Union, with China, India, Japan, Korea, Russia, and the United States splitting the remainder.

ITER's ultimate goal is to produce ~500 MW of fusion power with 20% to 25% availability over extended periods of two to four weeks. Although it is not a functioning reactor, ITER would be within small factors in most parameters of reactor requirements. The exceptions concern parameters connected to the device lifetime—a commercial reactor will require perhaps 100 times as long a period in integrated operation. Fusion reactors arising from this line of research are all assumed to be steady-state reactors.

To support the next step beyond ITER, an FNF is being proposed to operate as a complement to ITER. The goals of the FNF are the following:

- Operate for 10^7 seconds (2780 hours) per year; that is, a duty factor of 0.3.
- Run for two straight weeks without a disruption and experience only one unmitigated disruption per year.
- Produce significant fusion power in true steady state with tritium breeding.
- Demonstrate chambers and blankets that can survive high plasma and neutron fluences.
- Demonstrate diagnostics that can survive a high neutron flux and fluence.
- Produce high-grade heat from fusion and making electricity.

Figure 3-7 shows examples of possible FNFs based on a tokamak, a spherical torus, and a stellarator.

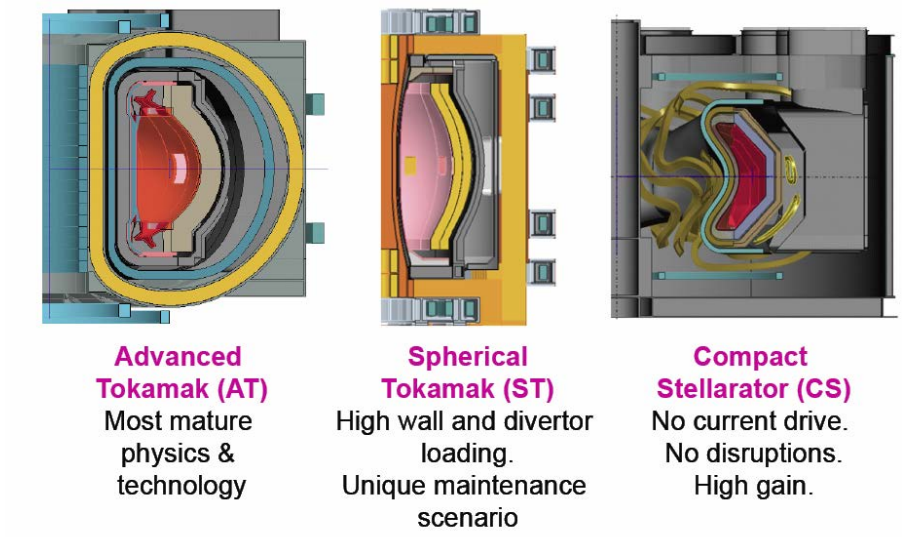


Figure 3-1
Examples of possible fusion nuclear facilities [15]

The MFE team described a range of devices and missions for FNF. On one end is a compact, low-gain (Q = 1.7 to 2.5) spherical torus version that complements the ITER burning plasma mission by concentrating solely on the development of high-temperature fusion blankets and other in-vessel components that are exposed to a fusion environment. Because of its significantly smaller size, it would require only ~30% of ITER's fusion power to create four times the average neutron wall loading (and more realistic environmental conditions in the first-wall/blanket).

In contrast to ITER, which will expose test blankets to 14 MeV neutrons for a few thousand seconds at a time, it would operate for pulse durations of up to two weeks at temperature to ensure that a balance is achieved between tritium production, diffusion through materials, and extraction from the breeding material. Having a higher fusion power density than ITER, a 10% duty factor, and greater blanket coverage, the spherical torus version of FNF will be capable of addressing blanket failure mechanisms and failure rates and will implement design improvements to increase reliability. The full-coverage blanket will be constructed of F82H, which, by the time this facility becomes operational, will be qualified for neutron fluences approaching a reactor-relevant 15 MW-yr/m^2. More advanced (higher-temperature) materials such as oxide dispersion strengthened steels (for improved high-temperature creep resistance) and silicon carbide composites (for service around 1000°C) would also be ready for initial testing. In the higher fusion power operational phase (150 MW), it will need to breed 90% to 100% of the 800 grams of tritium burned annually, but it need not demonstrate tritium self-sufficiency in the earlier, low-power phases of operation. A device that is similar in characteristics and mission to this, namely the Component Test Facility, is listed on the Office of Science Future Facilities Plan with a projected 2025 start of operations. The spherical torus FNF is also the concept adopted by the University of Texas for their hybrid.

Next up is a normal-aspect-ratio tokamak version of the FNF, which would be larger and more powerful than the spherical torus version. This device would do all of the above, as well as adding an advanced tokamak mission element (hence the name *advanced tokamak FNF*) to develop the higher plasma performance regimes (higher pressure) for the demonstration plant. In the course of its operation, it would explore a range of fusion powers from 125 MW to 400 MW, corresponding to a gain of 3 to 10, respectively. The duty factor would be increased progressively from 10% to 30%, which would likely require that it eventually be tritium self-sufficient (a tritium breeding ratio of 1.2 is specified). The higher duty factor and neutron wall loading (up to 3.2 MW/m^2) would accelerate blanket development and, with higher available neutron fluence, the advanced tokamak FNF might suffice as a materials irradiation facility. Both the spherical torus and advanced tokamak versions of FNF would use normal conducting magnets for ease of maintenance.

The pilot plant version of FNF adds net electric power to the mission (engineering gain ~1). Fusion power levels in the range of 400 to 550 MW (ITER-like) corresponding to fusion gains in the 4 to 7 range are required, along with a tritium breeding ratio ≥1. The energy mission requires superconducting magnets to keep the power required to operate the plant at reasonable levels and high-temperature materials and coolants to achieve plant efficiencies of 0.3 to 0.45.

Coming back to ITER, its 500 MW of fusion power at Q = 10 would correspond to 635 MWth if it were equipped with a blanket with an energy multiplier of 1.17. With a dual-cooled lead–lithium blanket system (outlet temperature approaching 700°C) coupled to an advanced high-temperature reactor–like energy conversion system, ITER would be capable of generating 280 MWe. The exact power requirements for running the plant have not yet been determined, but if we add up all the maximum power specifications for the various clients for steady-state and pulsed-power, it comes in at 295 MWe. So an ITER-sized device operating at a fusion gain of 10 could realistically generate net electricity. For a smaller-size and lower-cost device to fulfill this mission, higher performance plasma regimes such as those proposed for the advanced tokamak FNF would be necessary.

3.1.2 Pulsed Magnetic Fusion Energy Approaches

Two proposals by private companies were presented. Both are based on underlying concepts—the spheromak and the field-reversed configuration. The companies are attempting proof-of-principle experiments. They have the following inherent advantages:

- The device topology is simply connected; therefore, engineering systems can be cylindrical rather than toroidal, easing construction and maintenance (the plasmas and internal magnetic fields themselves are still toroidal, which is required for magnetic confinement). The device topology simplifies schemes for plasma translation and compression.
- High normalized pressure ($\beta = P_{Plasma}/P_{Magnetic}$).

However these concepts have been studied for many years and have the following recognized shortcomings, as well:

- They achieve high beta at the cost of stability. This can be remedied only by incorporating close-fitting conductive walls and, in the case of the field-reversed configuration, by limiting the plasma size to only a few ion gyro-radii.
- Experiments to date have produced these configurations only for very short pulses (~1 msec). Attempts to extend the lifetime have not met with much success. The proposals try to finesse the sustainment problem through development of pulsed reactors. Neither group has, so far, carried out serious engineering analysis or R&D into the issues presented by repetitive mechanical and thermal stresses (~3×10^7 cycles per year).

General Fusion proposes magnetic target fusion, which would function by strong adiabatic compression of spheromak targets. A version of this scheme proposed by Los Alamos National Laboratory uses solid metallic cylinders for the compression, which would result in a large mass flow in a reactor and a concomitant materials recovery, separation, and refabrication challenge. The General Fusion approach substitutes a liquid metal liner and shock compression. The team recognizes that the first-order challenge involves the creation of the basic configuration, sufficient compression, and achievement of fusion-relevant plasma parameters. They have laid out a systematic development plan based on first addressing this question using high-explosive-driven compression. Although it is not testing reactor-relevant technologies, this approach would provide an early go/no-go checkpoint. They characterize the approach as high-risk, high-payoff and assert an overall chance of success at about 10%. The mechanical systems proposed for a reactor have their own set of challenges; some of these can be studied off-line (that is, without burning plasma), although, in the end, a fully integrated nuclear system would need to be demonstrated.

Helion proposed a system based on pulsed compression of a field-reversed configuration. The field-reversed configuration is unstable to ideal magnetohydrodynamics, even at zero plasma pressure. Experiments take advantage of finite Larmor radius stabilization—that is, the plasmas studied are only the size of a few gyro-orbits. This presents the basic problem that the fusion cross sections, even for the optimal fuel (D-T) at the optimal energies (20–40 keV) are considerably smaller than the cross section for elastic scattering. Thus, even with classical collisional diffusion (no turbulence), ions on their own in a field-reversed configuration will scatter and lose their energy before they fuse. This is similar to the problem presented by open magnetic confinement systems, such as magnetic mirrors, which also lose their confinement on the order of a few ion collision times. The question, then, is how long the electrons will sustain the ion temperature after compression. The company did not present a physical picture or compelling data that their systems could overcome this difficulty, even in a pulsed mode. It is proposed to accomplish plasma compression using a high-field magnetic coil embedded in the fluorine-lithium-beryllium blanket. It was not clear how such a coil could be insulated and handle the fluorine-lithium-beryllium, heat, and 14-MeV neutrons.

In the case of both proposals, more experimental data are required to support their assumptions.

3.1.3 Fusion–Fission Hybrids

Fusion–fission hybrids aim to use neutrons from the fusion reaction to create fuel for fission reactors and/or to destroy unwanted fission products. The desirability of these approaches is based on two assertions:

- The hybrid approach has significant value-added for fission energy systems
- The requirements for a fusion–fission hybrid are considerably easier—notably in availability and gain—and the time for deployment is significantly faster than for a pure fusion system.

A recent assessment can be found in "Research Needs for Fusion-Fission Hybrids" [16].

The two presentations made in this area were aimed at supporting these assertions. It is probably too early to judge the merits. More detailed engineering is required and especially expert analysis from both domains. Advocates argue that the hybrid provides the best of both fission and fusion approaches, whereas skeptics argue the opposite. Fission–fusion hybrid advocates will need to seriously address questions of safety and proliferation.

A related question is whether the possibility of a hybrid approach changes the direction of fusion research in the short term. The committee's guess is no, because a point of divergence is still some years in the future. That is, there is time to conduct a fair comparison among the options. It would be useful to compare respective paths for the three alternate technologies (pure fission breeders, hybrids, and pure fusion power plants) and to identify critical decision points.

The Georgia Institute of Technology proposal is based on conventional tokamak physics and would follow on directly from the ITER technical basis. There would be relatively little extrapolation in the physics, although the standard set of technology issues would still require solution—structural and first-wall materials, tritium breeding and separation, and so on. The proponents seemed to have made a serious attempt to address the nuclear engineering issues associated with the fission blanket.

The University of Texas proposal is based on the small-aspect-ratio tokamak (spherical torus). This could lead to a smaller unit size with more tractable maintenance regimes, but the physics basis is considerably less certain. Issues particularly critical for the spherical torus include electron transport, plasma sustainment, plasma–wall interactions, and magnet engineering. The average magnetic field in a spherical torus is lower than in conventional-aspect-ratio devices, but the field at the coil and the resulting mechanical and thermal stresses are comparable to those for standard geometry.

In both cases, setting aside the choice and performance of the fusion device (which could also be an IFE device), substantial R&D would have to be undertaken on the fusion–fission components.

3.1.4 Inertial Fusion Energy

In general, IFE presents the following potential advantages as a fusion power source:

- The potential for decoupling the driver (laser) from the nuclear-grade nuclear power system could significantly simplify maintenance and operation of IFE reactors compared to other approaches.
- The potential to multiplex reactor chambers or replace them relatively easily (as in the LIFE design) can significantly reduce operational and maintenance issues.
- The tritium inventory in proposed IFE and MFE power plants of the same fusion power is dependent on details of the design—wall materials, breeding material composition, and fractional tritium burn-up. With regard to burn-up, IFE has an advantage.
- The potential to use a variety of reactor wall configurations, including liquid walls for some MFE and IFE approaches.

IFE faces some of the same issues as MFE and some different ones. Many of the unique challenges are associated with the massive scale-up in repetition rate required to go from current experiments, which fire about once per hour, to reactors that require up to 10^6 pulses per day for months or years at a time. In all cases, costs per cycle from all causes must be well below the value of electricity produced. The IFE-specific challenges include the following:

- Laser or optics damage from repetitive operation. Some work has been done in this area, but more work will be needed for the new laser systems.
- Final optics damage from the fusion reaction.
- Target production rates, costs, and quality—although innovative concepts for mass production of cryogenic target have been devised. Costs must come down from the present ~US$10,000 for an especially tailored target to around $0.50 for a power plant.
- Target acceleration and transport, along with driver engagement (current experiments use static targets; however, surrogate systems have been demonstrated). The low-power laser light glint system proposed for LIFE would not require extra, sensitive systems in the radiation zone.
- Prompt first-wall or structural damage from the fusion neutrons.
- Chamber clearing.

The IFE approaches also share certain technological challenges with MFE; in particular, the useful lifetimes of structural materials exposed to nuclear and/or thermal loading, tritium breeding and separation, safety, licensing, and so on.

Two IFE approaches were presented—one from LLNL (LIFE) based on a diode-pumped glass laser and indirect drive and the second from NRL based on a krypton–fluoride gas laser and direct drive. The LLNL program derives from the National Ignition Campaign (NIC) and leverages the large NNSA investment for the nuclear weapons stockpile stewardship program, in which demonstration of net fusion gain is expected in the next few years. As part of the NIC, a robust ignition platform based on indirect drive will be demonstrated for national security objectives. The development of advanced ignition concepts that produce even higher gains than the NIC baseline approach concept are required for IFE. The NIF is presently configured to test indirect drive. It might be configured in a way that will permit the demonstration of ignition with several direct-drive concepts, including central hot-spot ignition and shock ignition using a polar drive configuration. These concepts are under development at the LLE Omega Laser Facility. An NIF polar drive ignition campaign is currently planned to take place before 2020. From a target physics point of view, when NIF achieves gain, the physics will be in the fusion energy development phase.

The NRL presentation featured a step-by-step plan, with a schedule stretching out several decades. The team has identified critical issues and outlined an R&D plan to address them. Theoretically, the shorter krypton–fluoride laser wavelength would be more robust to laser plasma instabilities than the diode-pumped, solid-state laser wavelength; therefore, success with direct drive on Omega and NIF would support the krypton–fluoride approach. Nevertheless, a major gap is the need to demonstrate high gain for direct drive for a krypton–fluoride facility that would require a larger facility.

In contrast to a multidecade program proposed by NRL due to funding limitations, the proposed LLNL LIFE program is a fast-track program. The R&D program is highly compressed and success oriented. That is, it is assumed that a series of critical issues will be solved in a year or two each. The program depends on the maximum use of existing laser, optical, and to-be-tested target technologies.

The proposed LIFE configuration is designed as a modular, parallel-architecture system. The use of line-replaceable units for the laser portion of the system would allow maintenance and replacement during full-scale operations.

Although proponents are optimistic about both approaches, neither has built the multiple kilojoule, repetitively pulsed laser systems required for a fusion test facility. Tests to date have demonstrated up to 10^5 pulses compared to the ~10^9 pulses per year required by a power plant. In addition, it is not yet clear whether indirect or direct drive will be the best approach for laser IFE (see LIFE concerns in the next subsection); therefore, it seems premature to evaluate the relative merits of these divergent laser approaches for energy production until gain is demonstrated and the lasers are proven to work as expected.

Both approaches benefit from the broad-based research undertaken through the high-average-power laser program that was managed for a number of years by NRL. Significant advances were made in repetitively pulsed laser development, target launching, and acquisition in the chamber; final optics, plasma wall, x-ray, and neutron interactions; and the use of magnetic diverters.

3.1.4.1 LIFE Proposal

The LLNL program derives from the NIF and the NIC and leverages the large DOE/NNSA investment for the nuclear weapons stockpile stewardship program. Demonstration of net fusion gain on NIF is hoped for in the next 1 to 2 years (see comments in Section 3.1.4.4). As part of the NIC, a robust ignition platform based on indirect drive will be demonstrated for national security objectives, basic science applications, and the IFE mission. The development of advanced ignition concepts that produce even higher gains than the NIC baseline approach concept are required for IFE and form a central plank of the post-NIC activity on the NIF for all the above missions.

The construction and demonstrated performance of the NIF was a magnificent achievement. The NIF facility is presently configured and optimized for indirect drive, as are the equivalent facilities being designed and constructed in France, China, and Russia. In principle, NIF should be able to be reconfigured (in the medium term, with suitable investment) to address several direct-drive concepts, including central hot-spot ignition and shock ignition, using a polar drive configuration. These concepts are under development at the LLE Omega Laser Facility, similar in scale to the LLNL Nova facility that preceded NIF. A NIF polar drive ignition campaign could potentially take place before 2020, although no decision on this has yet been made by the DOE. From a target physics point of view, when NIF achieves gain, the physics will be in the fusion energy development phase.

The LIFE program has been developed to take advantage of the upcoming demonstration of fusion burn on the NIF, which has not occurred yet.

The team has developed nontechnical aspects of program delivery. Examples are integration into a full-scale power plant, a detailed work breakdown structure for the plant, consideration of the licensing pathway, and a detailed delivery plan and cost estimate that makes use of a wide range of industrial vendors. Because of proprietary constraints, this information was made available only in summary form to the committee but in more detail to EPRI staff.

The LIFE R&D program is highly compressed and success oriented, following the same methodology that was used for NIF. A historical perspective is worthwhile. It is well known that NIF suffered from early delivery problems, which led to a substantial underestimate in cost and project duration. Top management was changed, the project was assigned a new baseline in 2000, and NIF was subsequently delivered according to the revised cost and schedule. This led to the recent award of Project of the Year by the international Project Management Institute. The program depends on the maximum use of existing laser, optical, and to-be-tested target technologies.

The proposed LIFE configuration is designed as a modular, parallel-architecture system. The use of line-replaceable units for the laser portion of the system would allow maintenance and replacement during full-scale operations.

3.1.4.2 Krypton–Fluoride System

The krypton–fluoride approach is less aggressive and differs from other proposed systems in using a lower repetition rate, considering the possibility of using a magnetic divertor to alleviate wall interaction problems, and being based on direct drive, likely with shock ignition, to permit the use of a smaller driver and smaller power plant size.

3.1.4.3 General Comments

Although proponents are optimistic about both approaches, neither has built the multiple kilojoule, repetitively pulsed laser systems required for a fusion test facility. However, a large body of evidence in industry and academia supports the ability of the community to build high-average-power lasers. The state of the art in industry is 100–150 kW average power (from a continuous-output, diode-pumped, solid-state laser). From a power management perspective, this is at the required level for IFE. For the specific laser architecture required for IFE, prototype beamlines have been demonstrated for both krypton–fluoride and diode-pumped options, but not yet at the cost or lifetime required for IFE. Both NRL and LLNL have detailed plans to achieve this step in time frames consistent with their plans.

A great benefit of IFE is its modularity. The options of using krypton–fluoride lasers (as advocated by NRL) or diode-pumped, solid-state lasers (as used in the LIFE project) can be preserved. Construction of a plant using one laser type does not preclude future optimization using the other. Readiness to proceed is thus determined largely by other issues, such as plant integration, vendor readiness, and so on.

Some of the unique challenges with IFE are associated with the massive scale-up in repetition rate required in going from current experiments, which fire about once per hour, to reactors that require more than 10^6 pulses per day for months or years at a time. In all cases, costs per cycle from all causes must be well below the value of electricity produced. The IFE-specific challenges include the following:

- Laser or optics damage from repetitive operation. This area has been addressed as part of the high-average-power laser program and the NIF project, but more work will be needed on the new systems.
- Final optics damage from the output of the fuel pellet, although this can be effectively mitigated by suitable system design.
- Target (fuel) production rates, costs, and quality, although innovative concepts for mass production have been devised, borrowing largely from the existing manufacturing industry.

- Target acceleration and transport, along with driver engagement (current experiments use static targets; however, surrogate systems have been demonstrated).
- Prompt first-wall or structural damage from the x-rays, ions, and neutrons emitted by the burning fuel, although this can be effectively mitigated by suitable system design and adoption of replaceable components.
- Chamber clearing, although this might not be as large an issue for some schemes (such as indirect drive, in which the target is protected by a hohlraum).

3.1.4.4 Inertial Fusion Energy Community Concerns Regarding the Laser Inertial Fusion Energy Proposal

The majority of the Technical Advisory Committee did not agree on the readiness of the LIFE proposal for a moonshot-type effort. This section presents the reasons that the majority of the committee members believe that the LIFE is an interesting proposal but still faces considerable physics and technology challenges.

The three main approaches to IFE involve the following drivers: lasers, heavy-ion accelerators, and pulsed power. Our committee heard only about laser approaches (from LLNL and NRL) and therefore will not comment on the other two approaches.

The recently released interim report from the Committee on the Prospects for Inertial Confinement Fusion Energy Systems states the following conclusions [1]:

> Conclusion 1: The scientific and technological progress in inertial confinement fusion has been substantial during the past decade, particularly in areas pertaining to the achievement and understanding of high-energy-density conditions in the compressed fuel, in numerical simulations of inertial confinement fusion processes, and in exploring several of the critical technologies required for inertial fusion energy applications (e.g., high-repetition-rate lasers and heavy-ion-beam systems, pulsed-power systems, and cryogenic target fabrication techniques).
>
> Despite these advances, however, many of the technologies needed for an integrated inertial fusion energy system are still at an early stage of technological maturity. For all approaches to inertial fusion energy examined by the committee (diode-pumped lasers, krypton fluoride lasers, heavy-ion accelerators, pulsed power; indirect drive and direct drive), there remain critical scientific and engineering challenges associated with establishing the technical basis for an inertial fusion energy demonstration plant.

> Conclusion 2: It would be premature at the present time to choose a particular driver approach as the preferred option for an inertial fusion energy demonstration plant.

There has been a longstanding debate within the IFE community about the relative merits of using lasers with either an indirect-drive target—the present approach on NIF—and a direct-drive target—an approach favored by NRL and others at the Laboratory for Laser Energetics of the University of Rochester.

The problems encountered with NIF in its attempts to achieve ignition are seen in recent discussions of the so-called "plan B," which is a potential new program if the NIC fails to produce in 2012. The requirement for DOE/NNSA to produce such a plan appears in Congressional language and is discussed openly by the NNSA staff responsible for NIF and NIC [17, 18].

Concerns about the NIC are reinforced by a more recent report from DOE, which states, in part, the following [19]:

> All observers note that the functionality of the laser; the quality of the diagnostics, optics and targets; and the operations of the NIC and NIF teams have all been outstanding. By comparison with the startup of other large science facilities, the commissioning and startup of experimental operation on NIF has demonstrated an "unprecedented level of quality and accomplishment" according to one reviewer. Experiments on capsule compression, with improved diagnostic detail and exquisite laser pulse shape and energy control, have provided important insights into the details of ignition capsule compression.
>
> The integrated conclusion based on this extensive period of experimentation, however, is that considerable hurdles must be overcome to reach ignition or the goal of observing unequivocal alpha heating. Indeed the reviewers note that given unknowns with the present "semi-empirical" approach, the probability of ignition before the end of December is extremely low and even the goal of demonstrating unambiguous alpha heating is challenging.

On the positive side, NIF recently achieved record laser power and energy levels [20]. It is possible that the NIC might eventually achieve ignition (gain of 1), but the present uncertainties make it less clear that it could achieve the gain of 10, which is the ultimate goal. The issue for LIFE, then, is whether what is happening is well enough understood to provide convincing evidence that the proposed LIFE target would achieve the hoped-for gain of around 60. Of course, if ignition fails, they could to turn to direct drive. Either way, it seems that the program will take much longer than the original estimates.

The time frame for direct drive, as stated in the NRL presentations, would be longer because it waits for modifications to NIF to allow polar drive and test it—probably 2017 or later.

With regard to laser fusion, an important parameter is the product of the laser efficiency and the target gain. This parameter needs to be around 10 to have acceptably low recirculating power. Table 3-3 compares the LIFE diode-pumped, solid-state laser/indirect drive and the krypton–fluoride laser/direct-drive approach of NRL.

Table 3-1
Comparison of indirect and direct drive

Laser	Efficiency %	Target	Gain	Efficiency % × Gain
Diode-pumped, solid-state	15	Indirect	60+	9+
Krypton–fluoride	7	Direct	140	10

Although there is good evidence that the two lasers will achieve the expected efficiencies, neither has yet demonstrated it. Neither is there experimental evidence for the required gain. Although laser fusion energy looks promising, it is not likely to be a near-term energy option; however, an inertial fusion R&D program should be supported to resolve the issues.

3.2 Technical Readiness Levels

This section describes the technical readiness levels of the various technologies. Table 3-4 provides the U.S. DOE's definitions of technology readiness levels [21].

Table 3-2
Department of Energy definitions of technology readiness levels

Technology Readiness Level	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard in laboratory environment
5	Component and/or breadboard in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
9	Actual system "flight proven" through successful mission operations

Tables 3-1 and 3-2 provide the committee's understanding of the time frames and technical readiness levels for the various approaches, based on the presentations and published material.

Table 3-3
Time frames presented to the committee

Technology	Presenter	Time Frame
Fusion Nuclear Science Facility	Princeton Plasma Physics Laboratory, et al.	2025 (note 1)
Spherical torus hybrid	University of Texas, et al.	Early 2030s
Magnetized torus fusion	General Fusion	Early 2020s
Laser inertial fusion energy (LIFE)	LLNL, et al.	2020–2025 (note 2)
Krypton–fluoride direct-drive laser	NRL	2015 (note 3)
Pulsed field-reversed configuration	Helion	Early 2020s
Tokamak hybrid	Georgia Institute of Technology	Early 2030s

Notes:

1. This is not a proposal to deploy fusion energy plant but to conduct research.
2. Development time frame to have 10 GW on line after NIF ignition.
3. Time frame to build a fusion test facility.

Table 3-4
Technical readiness levels (L, low; M, medium; H, high)

Technology	Cost/ Time Frame	Economics Maturity	Detail/ Rigor	Investments	Licensing	Industrial Readiness	Operations/ Maintenance	Vendor Engagement
Fusion Nuclear Science Facility (note 1)	H/M	–	L	H	M/H	M	M	H
Spherical torus hybrid (note 2)	L/L	L	L	L	L	L	L/M	L
Magnetized torus fusion (note 3)	L/L	L	L	L	M	L	L	H
LIFE (note 4)	M/L	L	L	M	M	L/M	M	H
Krypton–fluoride direct-drive laser (note 5)	M/M	L	L	M	L	L	L/M	M
Pulsed field-reversed configuration (note 6)	L/L	L	L	L	L	L	L	L
Tokamak hybrid (note 7)	M/L	L	L	L	L	L	L/M	L

Notes:

1. This proposal is not for a power plant but for a step along the way to a demonstration power plant. It is backed by decades of tokamak R&D, including the only significant use of remote handling on the JET tokamak, and preparation for ITER, which includes numerous reactor technologies and requires licensing. There is substantial vendor involvement in this area.
2. Essentially no R&D has been done on the fusion–fission interface issues. This proposal uses a spherical torus, for which there is much less data than for the related tokamak.
3. This private venture is developing the necessary technologies, but these are early days for industry involvement as a whole. Moreover, because of relatively limited funding, the plasma physics basis is less well developed compared to the tokamak and spherical torus.
4. The driver technology has been demonstrated at a small scale, but the nuclear technologies are at an early stage of development. Physics issues remain in demonstrating the viability of laser indirect drive. Solid-state lasers are widely used, but those required for LIFE remain to be demonstrated. Consequently, the costing has uncertainties. The proposed time frame to deploy fusion power plants is quite aggressive, given the amount of R&D that must be done.
5. The driver technology has been demonstrated at a small scale, but the nuclear technologies are at an early stage of development. Physics issues remain in demonstrating the viability of laser direct drive. Consequently, the costing has

uncertainties. The proposed time frame to build a fusion test facility is reasonable, given the amount of R&D that must be done.

6. This private venture is developing some of the necessary technologies, but these are early days for industry involvement as a whole, and the technology basis is less mature than the General Fusion work. Moreover, because of relatively limited funding, the plasma physics basis is less well developed than the tokamak and spherical torus.
7. Essentially no R&D has been done on the fusion–fission interface issues. This proposal uses a tokamak and is designed to be based on ITER, benefiting from ITER's massive technology R&D program.

The Technical Advisory Committee independently assessed the technical readiness levels for the fusion energy systems presented. Table 3-5 lists the technical readiness levels of MFE systems as viewed by the Technical Advisory Committee.

Table 3-5
Technical readiness levels for magnetic fusion energy tokamak systems

Area/Level	1	2	3	4	5	6	7	8	9
Plasma physics	Existing experiments			ITER			Demo		
Impurity control	Existing		New experiments		ITER, FNF			Demo	
Heating	Existing			ITER			Demo		
D-T operations	JET, TFTR			ITER, FNF			Demo		
Steady state	Existing		New experiments		ITER, FNF				

Although spherical tori are simply low-aspect-ratio tokamaks, they have been tested only at modest scale, and there is no work with D-T. In addition, they require noninductive current drive to achieve a long pulse, whereas a repetitively pulsed tokamak without current drive is a possibility for a demonstration system.

The new experiments include EAST (China), K-STAR (Korea), and JT-60SA (Japan). EAST and K-STAR are operational, and JT-60SA is under construction. Significant amounts of data should be available by 2020.

Figure 3-2 indicates the importance of an FNF for component and other nuclear testing as a complement to ITER [22].

How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

Figure 3-2
How initiatives could address gaps [22]

Table 3-6 shows the technical readiness levels of fusion–fission hybrid systems as viewed by the Technical Advisory Committee.

Table 3-6
Technical readiness levels for tokamak and spherical torus fusion–fission hybrids

Area/Level	1	2	3	4	5	6	7	8	9
Actinide destruction	Calculations								
Plutonium production	Calculations								
Interface tests	None								

Table 3-7 shows the technical readiness levels for laser-based IFE systems as viewed by the Technical Advisory Committee.

Table 3-7
Technical readiness levels for laser-based inertial fusion energy systems

Area/Level	1	2	3	4	5	6	7	8	9
Target physics (note 1)	Weaps Omega and so on Halite-Centurion		NIF		NIF →Fusion test facility (FTF)			Demo	
Target manufacturer	GA work High-average-power laser		NIF		FTF			Demo	
Drivers (note 2)	Depends on system			FTF			Demo		
Control (note 3)	High-average-power laser NIF		R&D needed		FTF			Demo	

Notes:

1. NIF is presently testing indirect drive. If this is successful, it would move this target physics to technical readiness level 3 or 4, but the environment with repetitive high-gain shots would not have been done. A time frame of 2012 to 2013 might be possible. If this is not successful, tests of direct drive might occur around 2015.
2. Diode-pumped, solid-state and krypton–fluoride lasers have been tested at 100J to ~1 kJ, respectively, for ~100,000 pulses. A module at ~10s kJ and ~ 10^9 pulses is required.
3. Present targets are fixed. Hitting repetitive targets "on the fly" is being tested in terms of following their paths. Complete tests with zapping by powerful lasers await the production laser modules and FTF.
4. Because the formal process to build an FNF has not started yet, it seems unlikely that one could exist until at least 2020.

Table 3-8 shows the technical readiness levels for technologies that are important for both MFE and IFE.

Table 3-8
Technical readiness levels for nuclear technologies important for both magnetic and inertial fusion energy

Area/Level	1	2	3	4	5	6	7	8	9
Materials	MFE			International Fusion Materials Irradiation Facility (IFMIF)*	ITER, FNF				Demo
Tritium breed	MFE lab tests			ITER	FNF				Demo
Tritium systems	JET TFTR TSTA			ITER	FNF				Demo
Power handling	Quite limited because, in MFE, little work in high-power long pulse; in IFE, no repetitively pulsed system				ITER, FNF				Demo
Remote handling	JET preparation for ITER				ITER, FNF				Demo
Waste handling	TFTR, JET, fission facilities → ITER, FNF								Demo

Notes:

- Essentially all the information to date comes from the MFE program and fission. Little progress beyond the present technical readiness levels can be expected before 2020, except in materials if other solutions than IFMIF are used to test with 14-MeV neutrons. Because the formal process to build an FTF has not started yet, it seems unlikely that one could exist until at least 2020.
- The IFMIF is the proposed 14-MeV fusion materials test facility. It is unlikely that it will exist before 2020. Other accelerator-based tests might be done earlier (for example, at the Los Alamos Neutron Science Center or the Spallation Neutron Source at Oak Ridge National Laboratory).
- ITER is the international tokamak 400+ MW of fusion. It will not operate before 2019.
- TFTR and JET are tokamaks that have operated with D-T, producing up to 15 MW of fusion power.
- JET has done extensive remote handling of great relevance to fusion systems.
- TSTA was a tritium test facility at Los Alamos National Laboratory that successfully processed large flow-through of tritium.

Figure 3-3 summarizes fusion energy R&D gaps, using technical readiness levels [23].

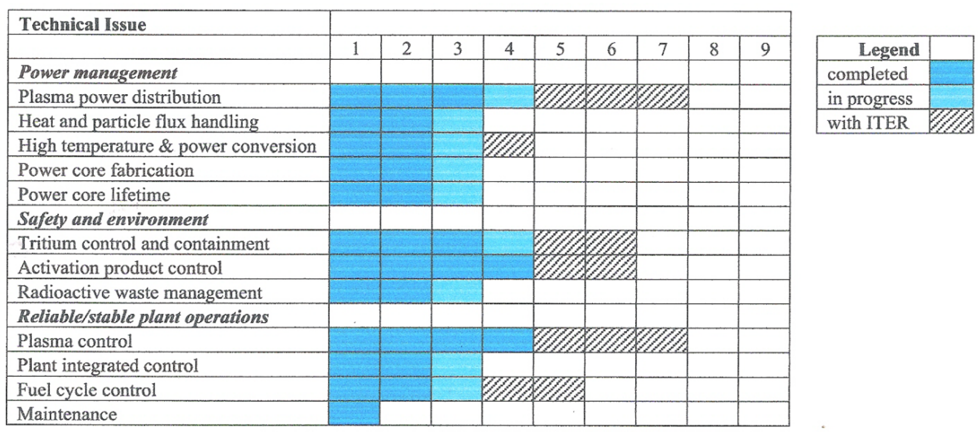


Figure 3-3
An evaluation of fusion energy R&D gaps using technology readiness levels [23]

These estimates are for a different tokamak maintenance approach than that used in ITER. In terms of remote handling, ITER will tackle areas at up to technical readiness level 8, of relevance to both MFE and IFE.

Table 3-9 shows technical readiness levels for compact tori as viewed by the Technical Advisory Committee for this assessment.

Table 3-9
Technical readiness levels for compact tori

Area/Level	1	2	3	4	5	6	7	8	9
Plasma physics	Existing experiments		Ongoing experiments						
Impurity control	Very little	Ongoing experiments							
Additional heating	Very little	Ongoing experiments							
D-T operations	None	?	?	?					
Repetitive pulsed operations	None	Ongoing experiments							

These options, although interesting, have had relatively little funding and are at early stages of development. There is no reason that they could not be repetitively pulsed, but it would have to be done with the proposed repetitive compression and chamber clearing. Presumably, tests at General Fusion and Helion would move the knowledge base to higher technical readiness levels.

3.3 Concluding Observations—The State of the Art

Two major fusion alternatives exist—inertial confinement and magnetic confinement. Within these two domains, inertial confinement has two fundamental alternatives in terms of laser technologies and whether the concept uses direct or indirect drives. The concept with the greatest financial support is the LIFE concept, largely driven by DOE support for the NIF. The NRL's direct-drive, krypton-fluoride laser program is a less-funded program that is steadily meeting the technical challenges in a planned development program that may be more successful based on the technology choice.

Other, nontraditional fusion development programs, on a much smaller scale, such as the General Fusion and Helion programs, have the potential to provide fusion power without large capital investments, but they need financial support to prove the concepts they are developing.

The fusion–fission hybrid concepts of the University of Texas and Georgia Institute of Technology depend on successful ITER operation because the physics and engineering problems of magnetic fusion will be dealt with during construction and operation of ITER. Each has its own unique design advantages and challenges.

An observation about all fusion concepts reviewed is the lack of engineering and materials focus that is necessary for implementation of a successful fusion power reactor. Up to this point, most fusion research has focused on the plasma science programs, leaving the engineering challenges of building a power plant for the future.

From the utility perspective, the production of electricity should be the main objective of a fusion development program. At present, it appears to be an add-on and not a primary objective to the basic science of the fusion development program, largely due to the challenges of developing a fusion device that produces more energy than it consumes. More consideration should be given to the conversion of the heat of fusion to power production and the reliability of any fusion device.

Many presenters proposed the construction of a fusion test facility to address the materials and engineering challenges that could be common to many fusion alternatives. The design of such a facility will be critical to progress in the overall fusion program.

To date, the fusion program has been undertaken one step at a time. There has been no Manhattan or Apollo program in which multiple paths are followed in parallel, with massive budgets and an acceptance that some paths or component options may fail, and in which failure of the entire effort is not precluded. That type of program would undoubtedly accelerate the schedule, but there has been no serious consideration of such a program, so it is not possible to reliably estimate by how much.

The only proposals presented to the Technical Advisory Committee that had truly aggressive time frames were those from Lawrence Livermore National Laboratories, General Fusion, and Helion. Each of these proposals assumes a high rate of success. However, a number of challenges remain that might not be overcome easily or at all, which makes the assumed time frames improbable.

Five years from now, the knowledge base for all of the seven approaches should be much better developed, assuming that the necessary R&D funding is provided. For example, it should be clear whether indirect drive (as proposed in the LIFE project) works well enough or whether direct drive, as proposed by NRL, will be more successful. Advances will have been made in developing the laser modules for the two IFE approaches. Many questions about steady-state operation in tokamaks and spherical tori will have been answered, and the physics performance of compact tori will be much better understood. Ten years from now, more of these issues, as well as direct-drive ignition, should be understood, and ITER will have operated.

Given this situation, the Technical Advisory Committee concluded that all seven proposals were interesting and worthy of continuing R&D funding but that none were ready to be exploited as near-term power sources.

A final observation about all fusion energy systems is that the facilities to produce a fusion reaction are relatively large and the power density of the overall electric generating plant is relatively small, given that the heat generated by the fusion is ultimately converted to steam to produce electricity. This will be a limitation of all fusion energy systems for the production of electricity compared to conventional nuclear fission systems.

Section 4: Recommendations

Several innovative fusion technologies were reviewed and assessed from the standpoint of a technical readiness level (TRL) analysis. From the utility perspective, the production of electricity should be the main objective of a fusion development program. At present, electricity generation appears to be an add-on and not a primary objective to the basic science of the fusion development program, largely due to the challenges of developing a fusion device that produces more energy than it consumes. The conclusion of this review is that no near-term (less than 30 years) fusion options are available to the power industry.

The following actions are recommended:

- Direct more fusion research on the engineering and operational challenges of a power plant, including how to maximize the value of the fusion power produced. More consideration should be given to the conversion of the heat of fusion to power production and the reliability of any fusion device. Consider developing more advanced and perhaps direct power conversion systems to enhance the overall efficiency of energy-to-electricity conversion.
- Identify common materials and technology needs (such as tritium production) that a fusion test facility could address to meet most of the needs for both magnetic and inertial confinement systems.
- Monitor and periodically re-evaluate the fusion programs to assess the potential for electric power production in the nearer term to identify which concepts are likely to produce tangible fusion power. At the appropriate time:
  - Create a utility advisory group to focus fusion energy research and development projects to address more utility needs, particularly in the area of operations and maintenance, and to provide input into the design of the fusion power plants.
  - Begin to consider the regulatory requirements for commercial fusion power plants in terms of establishing safety and licensing standards.

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