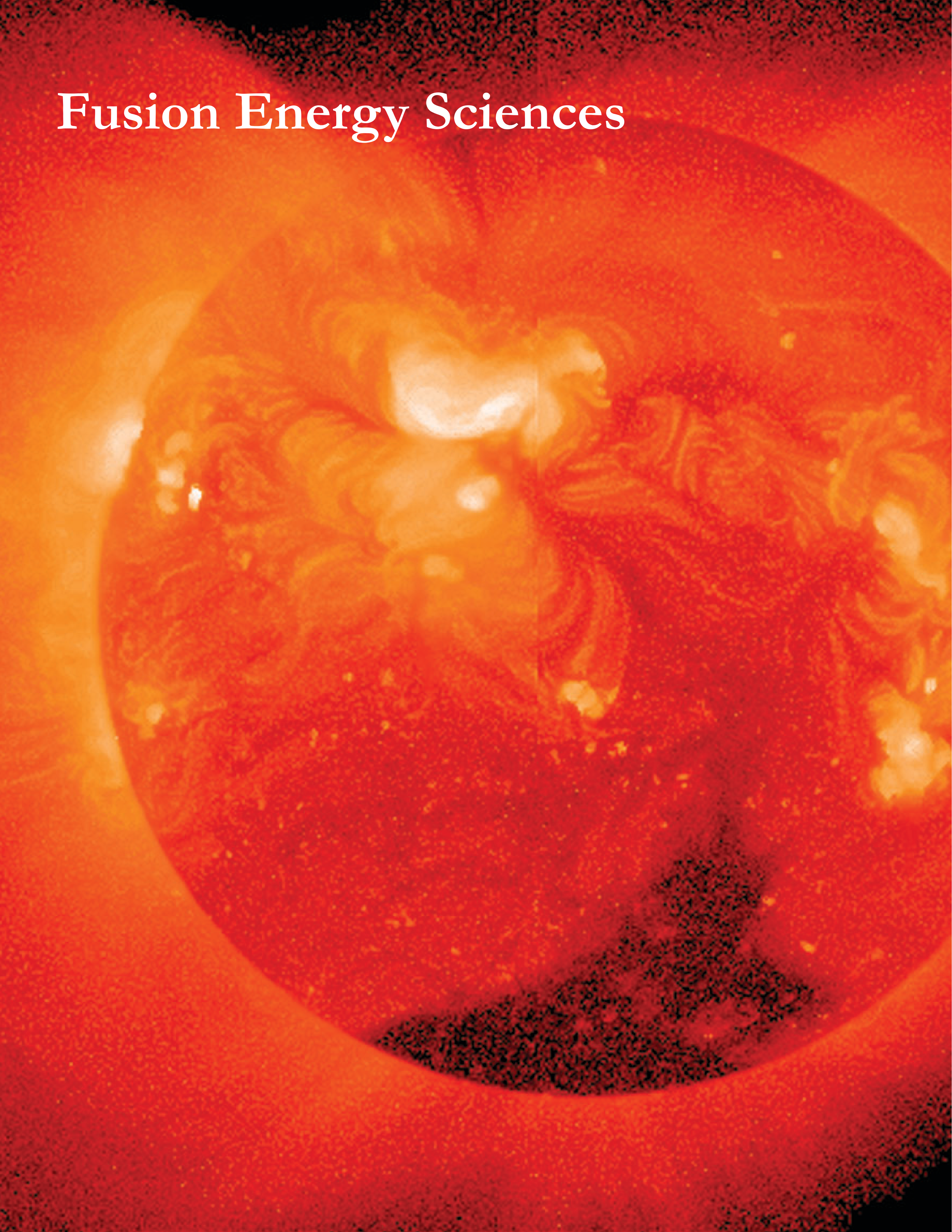
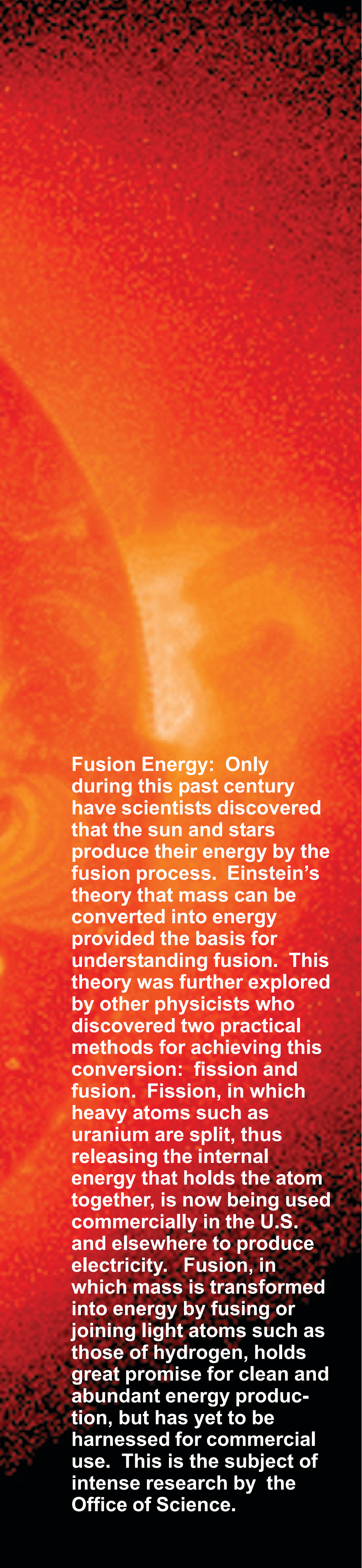
Fusion Energy Sciences





PPPL

Fusion Energy: Only during this past century have scientists discovered that the sun and stars produce their energy by the fusion process. Einstein's theory that mass can be converted into energy provided the basis for understanding fusion. This theory was further explored by other physicists who discovered two practical methods for achieving this conversion: fission and fusion. Fission, in which heavy atoms such as uranium are split, thus releasing the internal energy that holds the atom together, is now being used commercially in the U.S. and elsewhere to produce electricity. Fusion, in which mass is transformed into energy by fusing or joining light atoms such as those of hydrogen, holds great promise for clean and abundant energy production, but has yet to be harnessed for commercial use. This is the subject of intense research by the Office of Science.

Bringing the Power of the Stars to Earth

Answer the key scientific questions and overcome enormous technical challenges to harness the power that fuels a star, realizing by the middle of this century a landmark scientific achievement by bringing fusion power to the U.S. electric grid.

When fusion power becomes a commercial reality, current national concerns over imported oil, rising gasoline prices, smokestack pollution, and other problems associated with our dependence on oil and other fossil fuels will largely disappear. We will have achieved energy independence. Fusion power plants will provide economical and abundant energy without greenhouse gas emissions, while creating manageable waste and little risk to public safety and health.

Making fusion energy a part of our national energy solution is among the most ambitious scientific and engineering challenges of our era. The following are some of the major scientific questions we will answer:

- Can we successfully control a burning plasma that shares the characteristic intensity and power of the sun?
- How can we use nanoscale science to construct radically new materials that will withstand the temperatures and forces needed for commercial fusion power?
- To what extent can we use scientific simulation to model the behavior of the fusion fuel that is found at the center of the sun—or in the confines of a functioning commercial prototype?

Our ultimate success in answering these questions requires that we understand and control remarkably complex and dynamic phenomena occurring across a broad range of temporal and spatial scales. We must also develop materials, components, and systems that can withstand temperatures exceeding those that are typical of a star. The experiments required for a commercially viable fusion power technology constitute a complex scientific and engineering enterprise that must be sustained over several decades. We can now define the specific challenges that must be overcome, see promising approaches to addressing those challenges, and confidently anticipate the availability of even more powerful computational and experimental measurement capabilities.

As an integral part of this Strategic Plan, we have identified the need for four future facilities to realize our Fusion Energy Sciences vision and to meet the science challenges described in the following pages. One of the facilities, ITER, is a near-term priority. ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma." It is the next essential and critical step on the path toward demonstrating the scientific and technological feasibility of fusion energy. All four facilities are included in our Fusion Energy Sciences Strategic Timeline at the end of this plan. They are also discussed in detail in the DOE Office of Science report, *Facilities for the Future of Science: A Twenty-Year Outlook* (November 2003).

Our Strategies

Given the substantial scientific and technological uncertainties that we know exist, we will employ a portfolio strategy that explores a variety of magnetic and inertial confinement approaches and leads to the most promising commercial fusion concept. Advanced computational modeling will be central to guiding and designing experiments that cannot be readily investigated in the laboratory, such as testing the agreement between theory and experiment and exploring innovative designs for fusion plants.

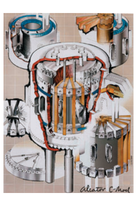
To ensure the highest possible scientific return on limited resources, we will extensively engage with and leverage other DOE programs and the investments of other agencies in such areas as materials science, ion beam physics, and laser physics. Large-scale experimental facilities will be necessary to test approaches for self-heated (burning) fusion plasmas, for inertial fusion experiments, and for testing materials and components under extreme conditions. Where appropriate, the

"Everytime you look up at the sky, every one of those points of light is a reminder that fusion power is extractable from hydrogen and other light elements, and it is an everyday reality throughout the Milky Way Galaxy."

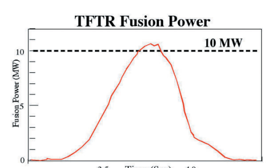
—Carl Sagan, Spitzer Lecture, October 1991

Our History of Discovery…Select Examples

1978
Achieved ion temperatures in excess of 58,000,000½C—the minimum required for a self-sustaining fusion reaction.



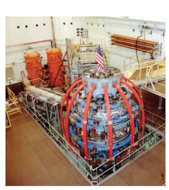
1983
Exceeded the Lawson criterion—the product of the plasma density and energy confinement time required for fusion energy breakeven—on MIT's Alcator-C device.



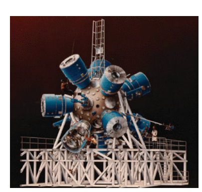
1994
TFTR achieves 10.7 million watts of power.

1970 1980

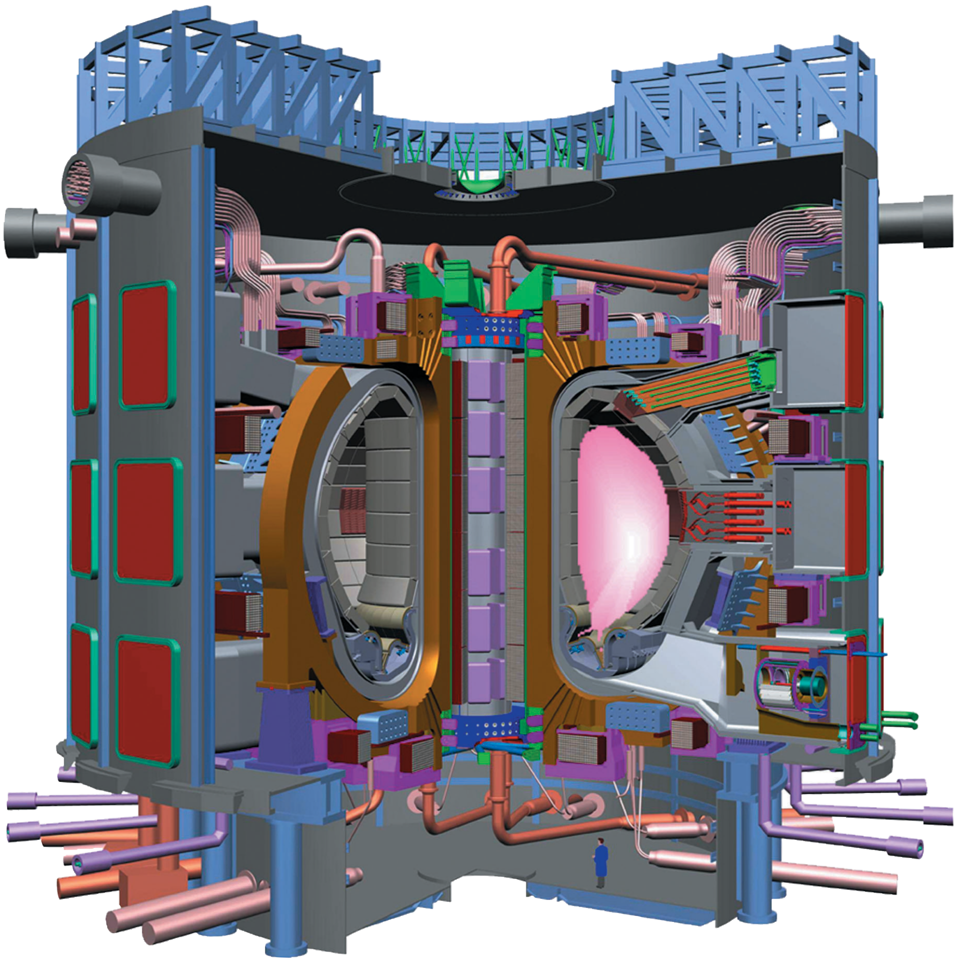
1982
Started the Tokamak Fusion Test Reactor (TFTR).



1985
Conceived the Spherical Torus—a plasma confinement device that can confine a higher plasma pressure for a given magnetic field strength.



1987
Achieved 100x compression on Nova laser-fusion facility.



ITER: The U.S. is engaging in negotiations with international partners aimed at constructing the world's first sustained burning plasma experiment, capable of producing 500 million watts of fusion power for periods of five minutes or more. The Office of Science will be a primary participant in the ITER experiment.

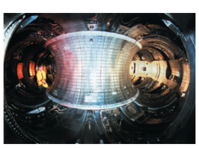
rewards, risks, and costs of major facilities will be shared through international collaborations.

The overall Fusion Energy Sciences effort will be organized around a set of four broad goals.

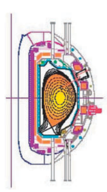
1. Demonstrate with burning plasmas the scientific and technological feasibility of fusion energy.

Our goal is to demonstrate a sustained, self-heated fusion plasma, in which the plasma is maintained at fusion temperatures by the heat generated by the fusion reaction itself, a critical step to practical fusion power. Our strategy includes the following emphases:

- As decided by the President, we will participate in negotiations that could lead to participation in the international magnetic fusion experiment, ITER project, with the European Union, Japan, Russia, China, South Korea, and perhaps others, as partners.
- For inertial fusion, we depend on DOE's National Nuclear Security Administration's (NNSA's) National Ignition

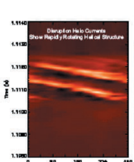


1995
TFTR sets the record for highest temperature achieved in a laboratory plasma, more than thirty times hotter than the center of the sun.

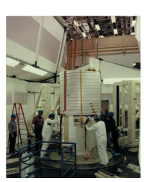


2001
Theory and experiment on DIII-D show that through plasma rotation and active control of plasma stability using specialized coils you can increase the plasma pressure limit above conventional limits.

1990 2000



1995
Measurements of disruption halo currents in Alcator C-Mod tokamak determine their predictive scalings, asymmetric structure, and toroidal rotation, information necessary for establishing engineering loads.



2000
Successfully completed testing of the world's largest pulsed superconducting magnet—Central Solenoid Model Coil—which is the prototype for the solenoid coil to be used in ITER.

2002
The Madison Symmetric Torus at U.Wisconsin reduced magnetic fluctuations in the plasma resulting in a 10-fold improvement in energy confinement.

Facility, which is expected to complete construction within five years, demonstrate target ignition by about 2010, and, combined with other experiments, lead to a future inertial fusion Engineering Test Facility.

2. Develop a fundamental understanding of plasma behavior sufficient to provide a reliable predictive capability for fusion energy systems.

Basic research is required in turbulence and transport, nonlinear behavior and overall stability of confined plasmas, interactions of waves and particles in plasmas, the physics occurring at the wall-plasma interface, and the physics of intense ion beam plasmas. Our strategy includes the following emphases:

- Conduct basic research through individual-investigator and research-team experimental, computational, and theoretical investigations.
- Launch a major effort to advance state-of-the-art computational modeling and simulation of plasma behavior in partnership with the Office of Science's Advanced Scientific Computing Research program.
- Support basic plasma science, partly with the National Science Foundation, connecting both experiments and theory with related disciplines such as astrophysics.

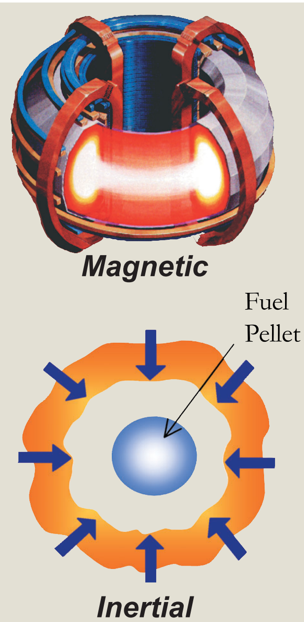
3. Determine the most promising approaches and configurations to confining hot plasmas for practical fusion energy systems.

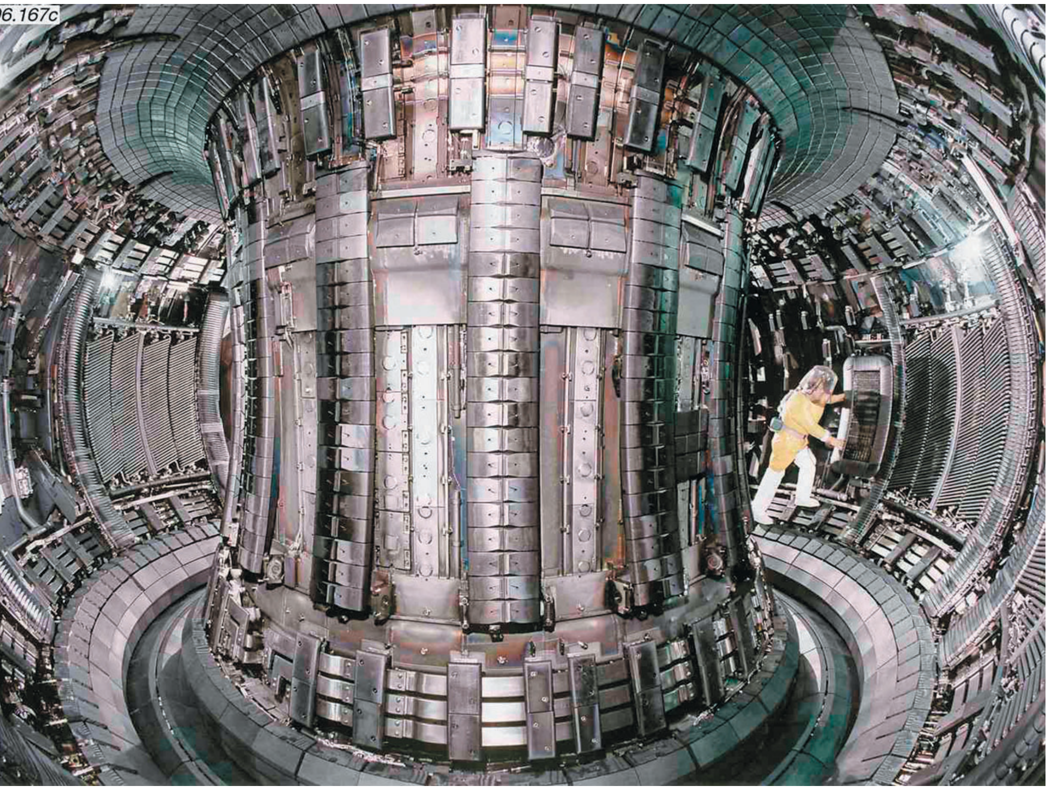
Both magnetic and inertial confinement approaches to fusion have potential for practical fusion-energy-producing systems. Within each of these two broad approaches, there are many possible configurations and designs for practical fusion systems, almost certainly including some yet to be conceived. Our strategy includes the following emphases:

"The results of ITER will produce clean, safe, renewable, and commercially available fusion energy by the middle of this century."

—President George W. Bush, January 2003

Magnetic and Inertial Confinement: The two principal approaches for confining fusion fuel on Earth are magnetic and inertial. Magnetic fusion relies on magnetic forces to confine the charged particles of the hot plasma fuel for sustained periods of fusion energy production. Inertial fusion relies on intense lasers or particle beams to rapidly compress a pellet of fuel to the point where fusion occurs, yielding a burst of energy that would be repeated to produce sustained energy production.





EFDA-JET

Joint European Torus (JET): Predecessor to ITER, the JET Joint Undertaking was established in June 1978 to construct and operate the largest (of its time) single project within the European nuclear fusion program. JET began operating in 1983 and was the first fusion facility in the world to achieve a significant production of controlled fusion power (nearly 2 MW) with a deuterium-tritium experiment in 1991. After 1991, JET was enhanced by the installation of a divertor to handle higher levels of exhaust power. Deuterium experiments in the ITER geometry have made essential contributions to the ITER divertor design, and to the definition of the size, heating requirements, and operating conditions of ITER. The Office of Science continues to collaborate in JET research to help build diagnostics, participate in experiments, and conduct joint research.

- In line with the recommendations of the Fusion Energy Sciences Advisory Council, we will continue vigorous investigation of both magnetic and inertial confinement approaches.
- Innovative magnetic confinement configurations will be explored through experiments, such as the National Spherical Torus Experiment at Princeton Plasma Physics Laboratory and a planned compact stellarator experiment, as well as smaller experiments at multiple sites, and through advanced simulation and modeling.
- Heavy ion beams, dense plasma beams, lasers, or other innovative approaches (e.g., fast ignition) to produce high-energy density plasmas will be explored for potential applications to inertial fusion energy.
- Research in high-energy density physics will be supported in coordination with other Federal agencies.
- The NNSA's National Ignition Facility, along with other experiments and simulations in the U.S., will provide definitive data on inertial fusion target physics.

4. Develop the new materials, components, and technologies necessary to make fusion energy a reality.

The environment created in a fusion reactor poses great challenges to materials and components. Materials must be able to withstand high fluxes of hot neutrons and endure high temperatures and high thermal gradients, with minimal degradation. Our strategy includes the following emphases:

- Design materials at the molecular scale to create novel materials that possess the necessary high-performance properties, leveraging investments through our Fusion Energy Sciences program with the materials research of our Basic Energy Sciences program.
- Create additional facilities, as may be needed, as a follow-on to the ITER project, for testing materials and components for high duty-factor operation in a fusion power plant environment.
- Explore "liquid first-wall" materials to ameliorate first-wall requirements for both inertial fusion energy (IFE) and advanced magnetic fusion energy (MFE) concepts.

Our Timeline and Indicators of Success

Our commitment to the future, and to the realization of **Fusion Energy Sciences: Bringing the Power of the Stars to Earth**, is not only reflected in our strategies, but also in our Key Indicators of Success, below, and our Strategic Timeline for Fusion Energy Sciences (FES) at the end of this chapter.

Our FES Strategic Timeline charts a collection of important, illustrative milestones, representing planned progress within each strategy. These milestones, while subject to the rapid pace of change and uncertainties that beset all science programs, reflect our latest perspectives on the future—what we hope to accomplish and when we hope to accomplish it—over the next 20 years and beyond. Following the science milestones, toward the bottom of the timeline, we have identified the required major new facilities. These facilities, described in greater detail in the DOE Office of Science companion report, Facilities for the Future of Science: A Twenty-Year Outlook, reflect time-sequencing that is based on the general priority of the facility, as well as critical-path relationships to research and corresponding science milestones.

Additionally, the Office of Science has identified Key Indicators of Success, designed to gauge our overall progress toward achieving fusion energy. These select indicators, identified below, are representative long-term measures against which progress can be evaluated over time. The specific features and parameters of these indicators, as well as definitions of success, can be found on the web at **www.science.doe.gov/measures**.

Key Indicators of Success:

- Progress in developing a predictive capability for key aspects of burning plasmas, using advances in theory and simulation benchmarked against a comprehensive experimental database of stability, transport, wave-particle interaction, and edge effects.
- Progress in demonstrating enhanced fundamental understanding of magnetic confinement and in improving the basis for future burning plasma experiments through research on magnetic confinement configuration optimization.
- Progress in developing the fundamental understanding and predictability of high-energy density plasma physics, including potential energy-producing applications.

Strategic Timeline for Fusion Energy Sciences

Strategic Timeline —

2003 2005 2007 2009 2011 2013

The Science

Burning Plasma Demonstration

- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation in IFE-relevant fuel pellets (2010)

Fundamentals of Plasma Behavior

- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)

Plasma Confinement

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)
- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to design and build fusion-power-producing Next-Step Spherical Torus (2008)
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER (2008)
- Evaluate the feasibility/attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and lasers for fusion approaches involving high-energy density (2009)

Materials, Components, and Technologies

- Start production of superconducting wire needed for ITER magnets (2006)
- Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle (2013)

Future Facilities**

ITER: ITER is an international collaboration to build the first fusion science experiment capable of producing a self-sustaining fusion reaction, called a "burning plasma."

Next-Step Spherical Torus (NSST) Experiment: The NSST will be designed to test the spherical torus, an innovative concept for magnetically confining a fusion reaction.

***These strategic milestones are illustrative and depend on funds made available through the Federal budget process.**

****For more detail on these facilities and the overall prioritization process, see the companion document, Facilities for the Future of Science: A Twenty-Year Outlook.**

Fusion Energy Sciences*

2015 2017 2019 2021 2023 2025

- Complete ITER experiments to determine plasma confinement in parameter range required for an energy-producing plasma (2017)
- Complete experiments on NIF to advance the science of ignition and burn propagation needed to design optimized fuel pellets for an Inertial Fusion Energy plant (2020)
- Complete experiments on ITER to determine the impact of the fusion process on the stability of energy-producing plasmas (2020)
- Achieve high fusion power for long durations on ITER to define engineering requirements for fusion power plants (2025)

- Major aspects relevant to burning plasma behavior observed in experiments prior to full operation of ITER are predicted with high accuracy and are understood (2015)
- Determine the physics limits that constrain the use of inertial fusion energy drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high-energy density physics (2015)
- Deliver a complete integrated simulation of a power-producing plasma, validated with ITER results, that enables the design of fusion power plants (2020)

- Determine the potential of one or more of the promising plasma configurations (for example a spherical torus) for use as a component test facility or a fusion power source (2020)
- Resolve key scientific issues and determine the confinement characteristics of a range of attractive confinement configurations (2015)

- Complete first phase of testing in ITER of blanket technologies needed in power-producing fusion plants capable of extracting high-temperature heat from burning plasmas and having a self-sufficient fuel cycle (2024)
- Complete first round of testing in a component test facility to validate the performance of chamber technologies needed for a power-producing fusion plant (2025)

Fusion Energy Contingency: If ITER construction and operation goes forward as planned, additional facilities to develop and test power plant components and materials will be needed to complete the process of making fusion energy a viable commercial energy resource by mid-century.

Integrated Beam Experiment (IBX): The IBX will be an intermediate-scale experiment to understand how to generate and transmit the focused, high-energy ion beam needed to power an IFE reaction.