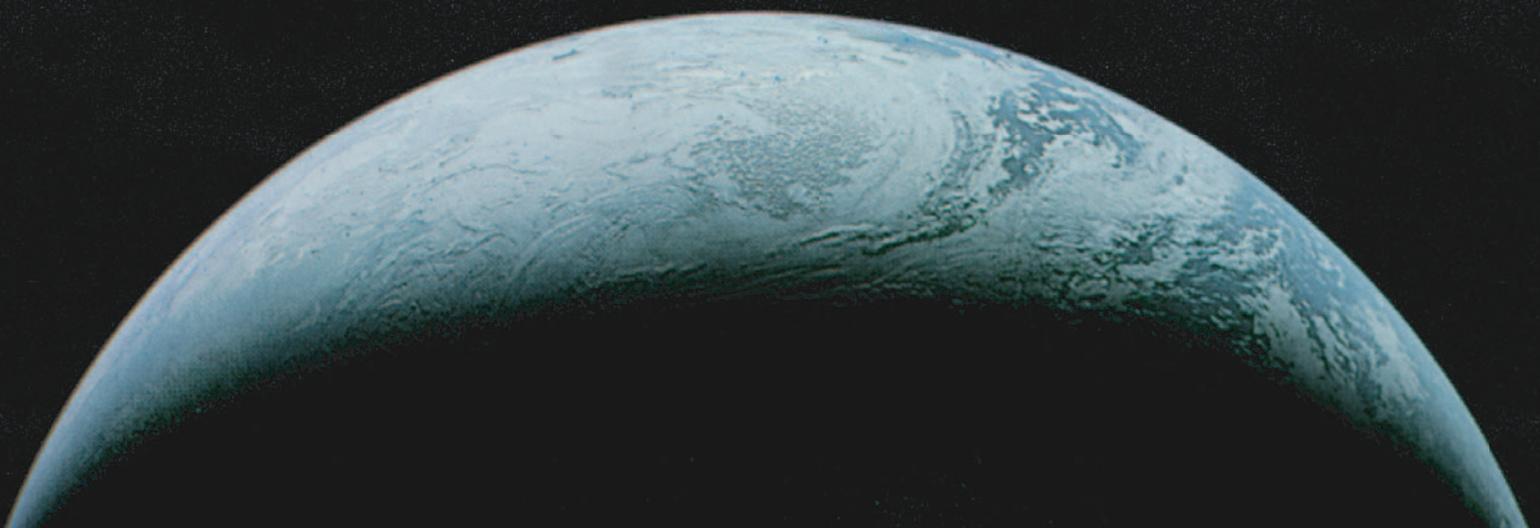


FUSION SCIENCE



HARNESSING
THE ENERGY
OF THE STARS



What Is Fusion?

Fusion is the power source of the sun and other stars. On earth, our challenge is to understand and harness this basic energy process for the benefit of humanity.

The unimaginably large quantities of energy released by the sun and the stars is the result of the conversion of matter into energy. This occurs when forms of the lightest atom (e.g., hydrogen) are combined together under great temperatures and pressures to form a heavier atom (e.g., helium). In this process of combining or fusing, some of the matter involved in the reaction is converted directly into large amounts of energy.

Why fusion?

Two primary reasons exist for pursuing fusion: the creation of a new (to planet earth) energy source, and the furthering of our understanding and

control of plasma, the state of matter which dominates the known universe. This dual nature of fusion research makes it one of the most exciting and promising frontiers in science and technology.

Fusion energy would complement renewable technologies which are also environmentally attractive, but probably do not have the capacity to power large cities and industries. Fusion power will not contribute to global warming, acid rain or other forms of air pollution, nor will it create long-lived radioactive waste.

Even though there is rapid scientific progress in all areas related to fusion, including plasma physics, limited resources available for its development dictate that commercial power plants may not be built until the middle of the next century—a time when new, large sources of clean energy will be needed.

WHAT'S ALL THIS TALK ABOUT PLASMA?

The four principal states of matter are solid, liquid, gas, and plasma.

The key to fusion is to heat hydrogen to extreme temperatures which strip electrons from the nuclei of the atoms. The resultant mix of positive (the nuclei) and negative (the electrons) particles creates an ionized gas called “plasma”. Importantly, the fact that particles in a plasma have these positive and negative charges allows them to be confined by magnetic fields in a fusion machine. Because stars are made of plasma, it is by far the most common state of matter, comprising more than 99% of all the visible matter in the universe. On earth, plasmas are common in nature, in lightning, and in man-made devices like fluorescent lamps and arc welders. Plasma physics, the scientific discipline that has grown primarily out of fusion research, is the quest to fully understand the complex behaviors exhibited by plasmas — a grand challenge of science. Once mature, that understanding will yield the key to practical fusion energy and other applications of plasmas, as well as a greater understanding of the universe itself.

Fusion: Dual Nature

Plasma Science

Stellar Atmospheres

Semiconductor
Production

Free Electron Lasers

Plasma
Polymerization

Destruction of
Hazardous Materials

Plasma Etching

Fusion Energy

Ion Sources

MHD Thrusters & Ion
Engines for Space
Propulsion

Compact X-Ray
Lasers

Plasma Chemistry

Solitons

Plasma Lighting

Vacuum Electronics

Planetary
Magnetospheres

Thin-Panel Displays

Eyeglass Lens
Hardening

Synthetic Diamond
Film

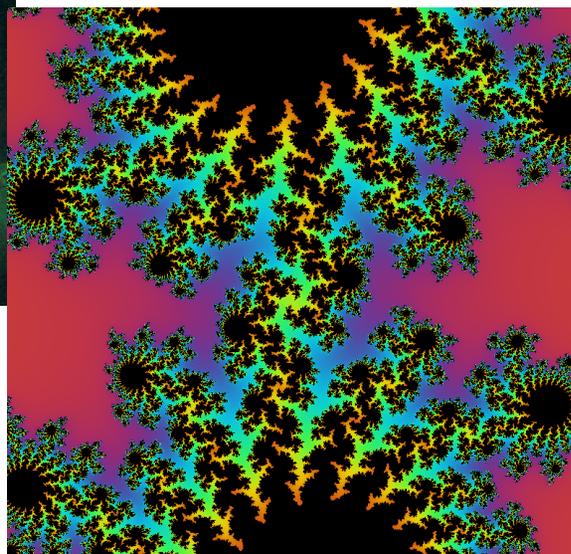
Photo Accelerators

RF Sources

Metal Recovery,
Primary Extraction,
Scrap Melting

Plasma is the name given to an ionized gas interacting through electromagnetic fields. It is the fourth primary state of matter, along with solids, liquids, and gases, and makes up more than 99% of the visible matter in the universe.

Understanding the complex behavior of confined plasmas led researchers to formulate and solve the fundamental equations of plasma, giving rise to a whole new discipline, plasma science. As illustrated in the left and right columns of this page, this fundamental work has subsequently found applications in diverse fields.



Basic plasma science continues to be a vibrant scientific discipline. Recent new discoveries have improved our understanding of: extremely cold plasmas (which condense to crystalline states), high-intensity laser interactions, and the basic physics of plasma surface interactions, as motivated by semiconductor chip manufacturing.

Plasma science has also spawned new avenues of research. Most notably, plasma physicists were among the first to open up and develop the new and profound science of “chaos” and nonlinear dynamics. Plasma physicists have also contributed greatly to the little-understood science of turbulence, which is important in weather prediction, high-speed aircraft design, and numerous other applications.

Self-Focusing Lasers

Aurorae

Ultra-Fast Switches

Laser Ablation
Plasmas

Active Species
Production for
Industry

X-Rays for
Lithography &
Materials Testing

Medical Instrument
Sterilization

Gas Lasers

DC & Pulsed Arcs for
Steel Processing,
Welding, and Toxic
Waste

Ion Implantation

Pulsed Power
Systems

Surface Treatment of
Polymer and Wool
Fabrics for
Printability

Astrophysical Jets
and Shocks

Plasma Cutting,
Drilling, & Welding

Solar Wind

Plasma Armature
Rail Guns

Tool Hardening

Destruction of
Chemical Warfare
Agents

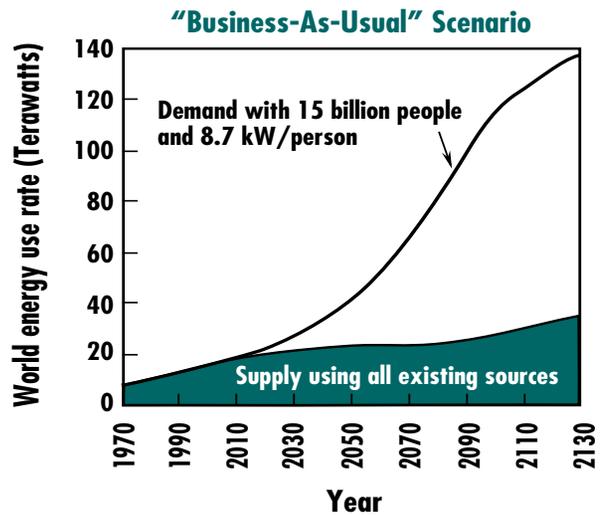
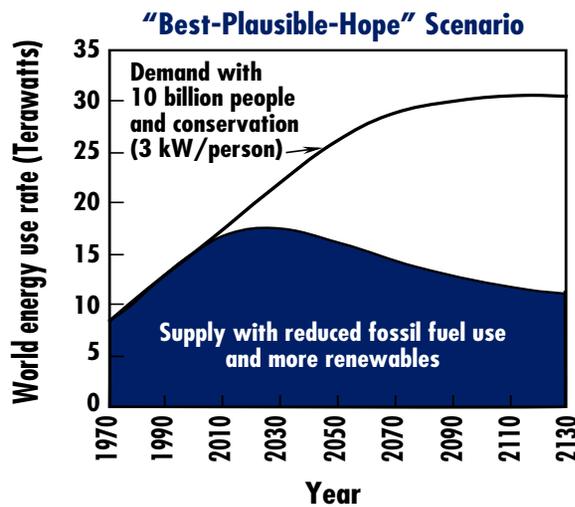
re, Dual Role

Energy

Only Three Alternatives for the Future

Most energy experts agree that, as world energy consumption continues to grow, fossil fuels (oil, coal and gas) will either become too scarce or too polluting to rely upon after the next few decades. If this is true, there exist only three alternative sources: solar and renewables, fission, and fusion.

As the graphs below show, even with the most optimistic assumptions about world population, energy conservation and fossil fuel supplies, vast new energy supplies must be created to power the future.



Note that current average energy consumption in the industrial nations per person is 8.7kW. These graphs based on information from *Energy, An Agenda of Science for Environment and Development Into The 21st Century*, chapter 4, page 103, J.P. Holdren and R.K. Pachauri, Cambridge University Press (1992).

CONVERTING MATTER INTO ENERGY

With his famous formula $E=mc^2$ (Energy = Mass x Speed of Light squared), Albert Einstein opened many doors, including the understanding of how the stars work: fusion. In the fusion reaction (which is partially described by Einstein's formula), very small quantities of matter can be converted into tremendous amounts of energy. For example, one quart of fusion fuel contains the same amount of energy as 6600 tons of coal. That is because this type of nuclear reaction is a million times more powerful than a chemical reaction, such as burning coal.

To Achieve Star Power On Earth

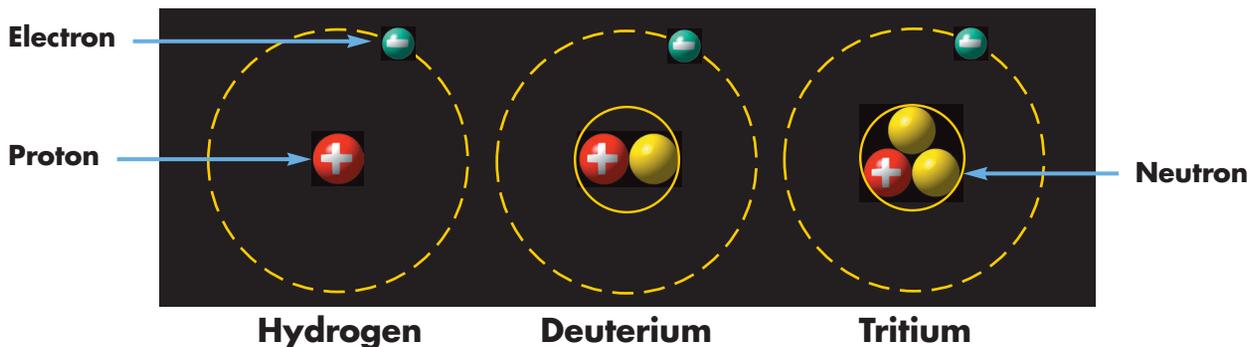
In a star, the large stellar mass has sufficiently high gravitational forces to confine the fusion fuel. This, together with the temperature of the stellar interior, provides the conditions required for fusion energy production. In one approach to fusion on earth, scientists and engineers use magnetic “bottles” to hold the fusion fuel.

Many of the complex issues associated with demonstrating the conditions necessary for a controlled fusion reaction have already been solved and solutions to the rest are close at hand. From the physics point of view three conditions are necessary to achieve controlled magnetic fusion on earth:

- Temperature** The fuel must be heated to energies at which the electrons and nuclei separate (about 10 thousand degrees) resulting in a plasma, and then to temperatures (about 100 million degrees) at which the energies of nuclei overcome their natural repulsive forces and begin to “fuse”.
- Confinement** The collection of high energy particles which compose the plasma must be confined (held together) for a sufficient period of time (a few seconds) to ensure that they fuse.
- Density** The plasma must attain high enough density for the fusion process to become self-sustaining (ignition) and to generate an economically attractive power density. The plasma density in a commercial magnetic fusion power plant will be much less dense than air although, because of the high temperature, its pressure will be several atmospheres.

FUSION FUEL: WHAT IS IT AND HOW LONG WILL IT LAST?

The first generation of fusion power systems will use two forms [isotopes] of hydrogen—deuterium and tritium. Deuterium occurs naturally in the fresh and saltwater. Tritium does not occur naturally but it can be made within the fusion system from the light metal lithium. The world reserve of lithium is sufficient to supply the world’s electricity needs for well over one thousand years at current rates of consumption. More advanced fusion power systems could use only deuterium as fuel. Although this option is more demanding technically, the world’s deuterium supply is essentially unlimited. Once fusion technology is developed we will have an energy source to satisfy the world’s needs for millions of years.



HOW DO YOU TURN ON A MAGNETIC FUSION REACTION?

Starting a fusion reaction is basically a simple process — but it presently takes massive equipment to do it.

- First, air is pumped out of the fusion chamber, and the walls are then cleaned by baking (as in an ordinary self-cleaning oven).
- Second, hydrogen gas is puffed into the ring-shaped vacuum vessel and, using an electrical transformer, a ring of plasma is formed much like a neon light. By increasing the current flowing in the plasma ring, the plasma temperature is increased to 10 million degrees Celsius. The plasma current is sustained using radio frequency or microwave power as in a microwave oven. During this process, the plasma must be carefully controlled so that it is centered in the vacuum chamber and isn't cooled by touching the vacuum vessel walls.
- Third, to significantly increase fusion reactions, the temperature must be increased to over 100 million degrees Celsius, which is six times the temperature at the center of the sun. This heating is accomplished by particle beams (injecting energetic ions) or by radio frequency or microwaves (heating ions or electrons).
- As a result, the fusion deuterium-tritium mixture produces neutrons which cross the magnetic field and carry 80% of the fusion energy to the specially designed wall, called the blanket. In a working power plant, the blanket would capture the neutrons, breed the tritium fuel, and collect the heat to drive the electrical generators.

The other 20% of the fusion energy is released in helium ions, which are contained by the magnetic field and which self-heat the plasma. If conditions are right, then the ring of plasma can produce enough fusion power so it heats itself, a so-called “burning plasma”. As the fuel is burned, the deuterium-tritium fuel is replenished, and the helium is continuously exhausted. In a functioning commercial power plant, the fusion reaction will be continuous and will probably not rely at all on outside heating. Instead, it will be hot and stable enough to sustain the fusion reaction as new fuel is injected into the reaction chamber.

What about safety and waste?

Although fusion is a nuclear process, it differs from the fission process in that there is no radioactive by-product from the fusion reaction—only helium gas and a neutron. However, neutrons from the fusion reaction can produce some radioactivity in the surrounding systems, but at a much lower level than in a fission nuclear reactor.

Numerous studies have shown the level of radioactive waste associated with fusion to be substantially less than that associated with fission. For example, the 1995 report of the President's Committee of Advisors on Science and Technology states that “with respect to radioactive waste

hazards, those of fusion (based on the most meaningful indices combining volume, radiotoxicity, and longevity) can be expected to be at least 100 times and perhaps 10,000 or more times smaller than those of fission.”

A fusion power station will be an inherently safe system with no potential for a Chernobyl-type event. The amount of fuel in the vacuum vessel at any given time will be sufficient for only a few tens of seconds' operation. Any malfunction will produce a rapid elimination of the conditions necessary to sustain the fusion reaction and, as a result, a complete and safe shutdown of the fusion process is assured.

The Tokamak & Progress In Fusion Science

One of the greatest innovations for fusion science was the tokamak concept which was invented in the Soviet Union. The tokamak employs magnetic fields in a



Tokamak is an acronym developed from the Russian words TOroidalnaya KAmera ee MAgnitaya Katushka which means "Toroidal Chamber with Magnetic Coil".

doughnut shaped configuration to confine the plasma. It is now the major magnetic confinement approach being pursued throughout

the world. To date the tokamak has brought the best scientific results and has demonstrated the greatest success.

Progress in the development of plasma science has gone in tandem with the improved results in fusion machines. With this progress, our ability to predict and control plasma behavior has increased multifold. The chart below shows progress in understanding tokamak physics with the current generation of machines.

Much of the knowledge of plasma science gained in tokamak experiments is directly applicable to alternate fusion systems. The present generation of these experiments, therefore, are effective tools for advancing the foundation of science and technology required for developing a commercially-viable fusion power plant.

Progress in developing tokamak physics understanding

Issue	Past Progress		
	Early 1970's	Year 1995	Year 2000
Equilibrium	?	✓✓	✓✓
Macroscopic stability	?	✓✓	✓✓
Energy & Particle Transport	?	✓	✓✓
Control of Impurities & Helium	??	✓	✓✓
Plasma Heating	??	✓✓	✓✓
Non-Inductive Current Drive	??	✓✓	✓✓
Self-Heating (α -particles)	??	?	✓
Steady-State Operation	??	?	✓
Low activation structural materials	??	?	✓
Advanced Tokamak Power Plant Optimization	??	?	✓

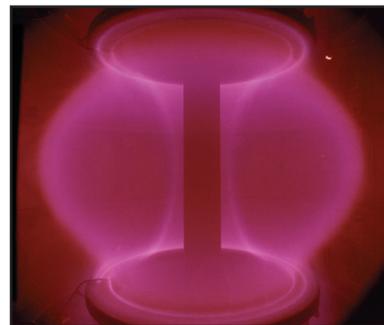
Key: ?? = completely unknown
? = primitive

✓ = significant understanding
✓✓ = predictive ability

Alternative Roads To Fusion

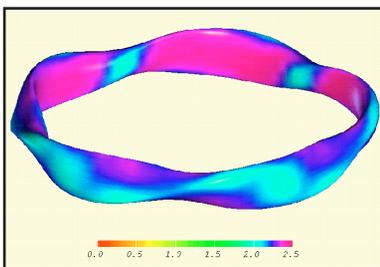
Although the tokamak has yielded the best results to date, it may not ultimately prove to be the best configuration for electric power production. In light of the tremendous strides in fusion science that the tokamak has made possible, fusion researchers worldwide continue to study alternatives to the tokamak. These include the stellarator, the spherical tokamak, the reversed-field pinch, and the spheromak. With the exception of the stellarator, the guiding principle of each of these machines is to make the plasma itself do much of the work of confining and controlling itself in lieu of complex magnet sets. Although these alternate approaches require developing a much more sophisticated understanding of the physics of plasmas and better diagnosis and control mechanisms, they could yield greater economy in constructing and operating a fusion power system.

Spherical Tokamak



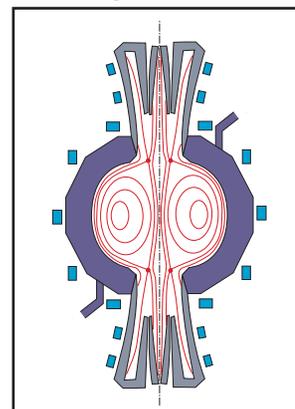
In the spherical tokamak the central conductor has an extremely small radius. The resulting configuration, although still a tokamak, has a more spherical shape which, theoretically, is favorable for holding high plasma pressure.

Computer model of plasma shape in an advanced stellarator



In the stellarator, the role of the current in the plasma is replaced by external magnetic coils, which may make steady-state operation easier.

Spheromak

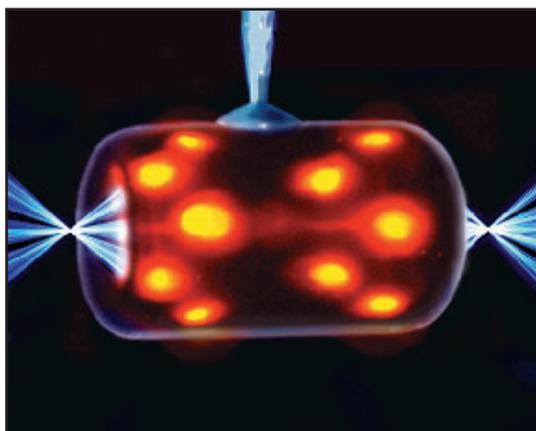


In the spheromak, the central conductor is removed completely and all of the toroidal magnetic field is generated by internal plasma currents. The shape is spherical since the magnetic coils are outside of the plasma – a big engineering and cost advantage.

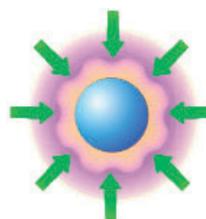
Inertial Confinement Fusion

Inertial Confinement Fusion (ICF) offers a different approach to developing fusion energy. To achieve ICF, powerful lasers or particle beams are focused on a small target of hydrogen fuel for a few billionths of a second. The target is compressed to densities 1000 times the normal density of solid materials and heated to temperatures of about 100 million degrees Celcius such that the hydrogen nuclei fuse to form helium, releasing significant amounts of energy. The process is also the same as in the sun, except that a laser or particle beam heats and compresses the hydrogen fuel, rather than the sun's gravity.

ICF is a research and development program supported by the Department of Energy Defense Program as part of the U.S. "Science Based Stockpile Stewardship" activity. The primary mission of ICF is to carry out experiments on nuclear weapons physics and effects, using the extreme conditions of density and temperature created in inertial fusion. A secondary benefit is the potential for Inertial Fusion Energy applications, which would substitute repetitive energetic ion beams for the laser beams used in today's laser-based experiments.

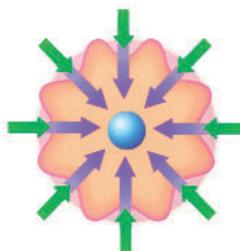


Inertial Confinement Fusion target being struck by laser beams



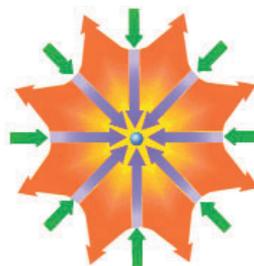
Direct drive illumination

Laser or ion beams rapidly heat the surface of the fuel capsule.



Fuel capsule compression

Fuel is compressed by the rocket-like inward push of the hot surface material.



Fusion ignition

During the final part of the implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000°C.



Fusion burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

History Of Fusion R & D

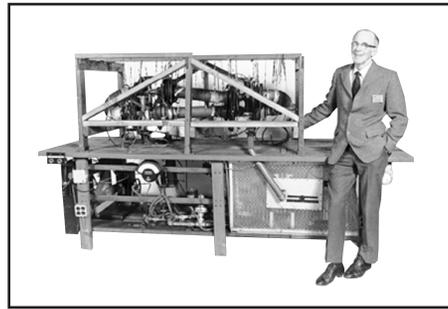
Since 1951, the United States has been conducting fusion research. There was early optimism that harnessing fusion would prove as easy as controlling a fission reaction. However, there have been many technological hurdles on the path to fusion energy.

The Truman Administration committed the first major funding for fusion research. At that time, fusion research was a classified program known as Project Sherwood. The original objective of the project was the development of neutron sources for nuclear weapons applications. However, many scientists joined because they believed in its potential as an environmentally attractive and virtually inexhaustible fuel supply.

In 1958, fusion research was declassified worldwide, and scientists around the world began to collaborate in the development of fusion for peaceful purposes.

In the mid-1960s, the Russians announced breakthrough results with their magnetic confinement concept called the tokamak. After British scientists verified the Russian results, fusion research in Europe and the U.S. followed the Russian lead with numerous tokamak fusion experiments. During this same period, much of the intellectual foundation was established for the new discipline of plasma science.

In the 1970s, uncertainty over the long-range energy supply, coupled with the



Lyman Spitzer, Jr., recognized by many as the father of U.S. fusion research, posing with an early fusion experiment.

growing environmental movement, combined to create tremendous enthusiasm for fusion research. Funding for fusion continued to increase until it peaked at \$468 million appropriated in Fiscal Year 1984.

In 1986, President Reagan and Soviet President Gorbachev discussed the joint design, development, and construction of a magnetic fusion experiment that would, for the first time ever, demonstrate sustained, controlled fusion power. In 1987, President Reagan invited Japan and Europe to join in this process, the International Thermonuclear Experimental Reactor, which is now commonly referred to as ITER.

The declassification of fusion research provided a vehicle for communication among scientists. More than 40 countries are now conducting research in fusion, and sharing in the vision of harnessing fusion to provide for civilization's long-term energy demands. This climate of cooperation in fusion research has strengthened the development of the underlying science and reduced costs globally.

The Technological Challenge

By the year 2040, the world population is expected to double to approximately eleven billion. New large-scale energy sources will be required to meet the increased demand of a growing population and to improve the quality of life in the developing nations. Even if energy efficiency can be doubled, the combined effects of rising population and rising global average per capita energy usage means that tens of thousands of large power plants will be needed. As a potential abundant energy source for the 21st Century, magnetic fusion could be a safe source of the needed large amounts of electricity.

Over the past 20 years a 1,000,000 fold increase has been achieved in the overall performance of experimental fusion devices. This record surpasses the often heralded rate of progress in computer chip density and power. This rapid progress has put us very

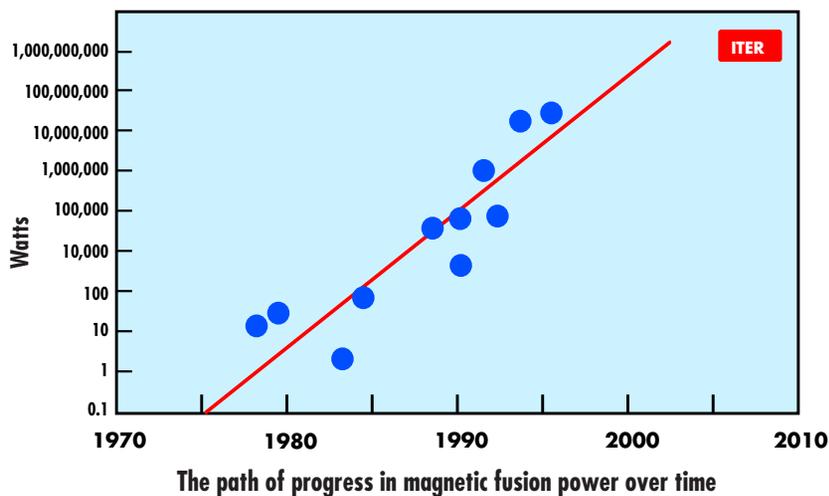
close to the conditions required for a fusion power plant.

Advancing fusion research requires the development of new technologies and materials. The new leading-edge technologies that will be required, include:

- **Very large-scale superconducting magnets;**
- **Cryogenic engineering;**
- **High heat and radiation flux elements within the vacuum vessel in the presence of electromagnetic forces;**
- **Remote handling and maintenance;**
- **Tritium handling; and**
- **Minimizing environmental impact.**

Materials will have to be chosen which can withstand temperatures on the order of 1,000 degrees centigrade, while exhibiting very low induced radioactivity by fusion neutrons. In

addition, other components of a fusion power station will be composed of state-of-the-art metal alloys, ceramics and composites, many of which are now in the early stages of development and testing.



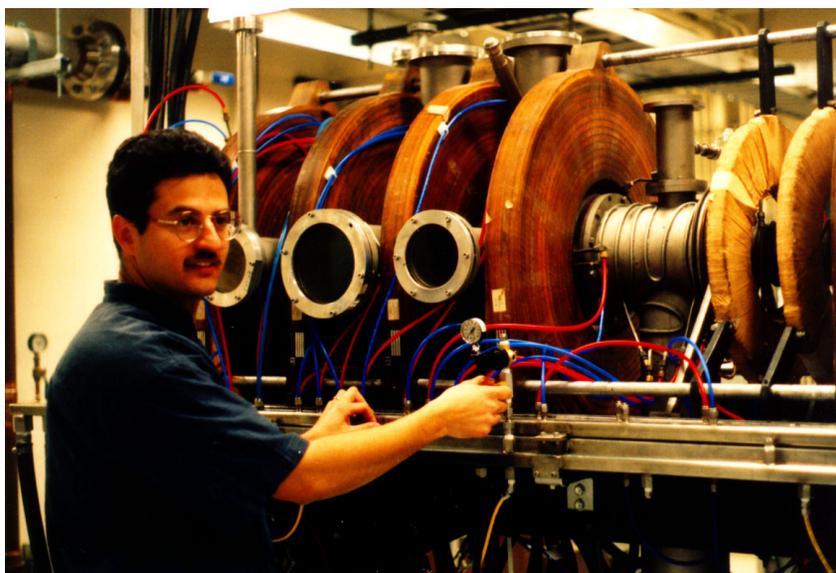
Fusion Research & Development: A Close Melding Of Science & Technology

The history and the future of fusion development is a textbook example of the close interrelationship between scientific and technological advances. Theoretical research and calculations performed in universities and fusion laboratories suggest new experimental designs and approaches, as well as providing interpretations of ongoing experimental explorations. In parallel, technological innovations, driven by fusion research itself, provide the ability to implement and test theoretical science. The experimental results on machines and equipment using these new technologies then provide a base for further advances in theory.

Fusion science research stimulates the development of new technologies. For example, to create the conditions for a controlled fusion reaction in a laboratory required the development of:

- **superconducting magnet technology;**
- **plasma heating techniques, including microwaves and neutral beams;**
- **large-scale high-vacuum technology; and**
- **advanced materials.**

Fusion science was a driving force in the development of high-performance computing, as well as a full range of specialized diagnostic instruments.



Students work side-by-side with faculty and researchers at universities to develop an understanding of fusion plasmas.

Fusion R & D Yields Excellent Returns On Investment

While most people view the ultimate “payoff” of fusion research as clean, unlimited energy, U.S. taxpayers have already realized a substantial return on their dollars invested in fusion and plasma R&D. Fusion

technology development and advances in plasma physics have a rich and growing history of economically significant spinoffs. These include major advances in microelectronics, medicine, computers, space science, and materials coatings.



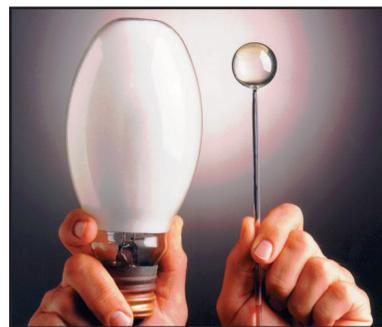
Plasma Processing of Semiconductor Electronics

Plasma etching, a major process in the semi-conductor industry for producing high density microcircuits and integrated circuits, evolved in part from studying the plasma/vessel wall interaction.



Materials Coatings

Plasmas are a particularly effective way of introducing better, longer-lasting coatings onto medical implants, machine tools, recording media, and other items.



Plasma Lighting

High-efficiency ultraviolet light sources emitted from plasmas have many industrial applications, e.g., drying special inks, coatings, and adhesives; as well as lighting large areas with reduced energy consumption.



Plasma Electronics

Applications include plasma displays for video displays; plasma switching devices are key components of a major new industry.



Superconducting Magnets

Progress in magnetic confinement fusion has been a driving force behind magnet research and development. Large volume superconducting magnets are now used in modern Magnetic Resonant Imaging (MRI) systems.

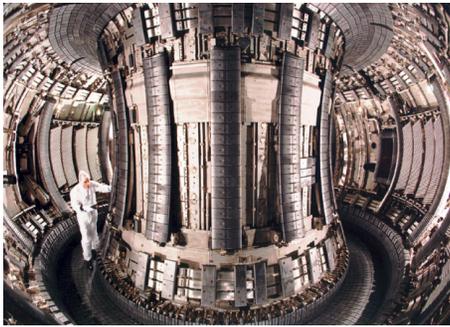


Space Science

Fusion research helps us to understand plasmas in stars and interstellar space, and may provide the basis for a new generation of space propulsion systems.

International Collaboration On Fusion Research

Magnetic fusion research has been carried out with unprecedented international cooperation since the late '50's. This collaboration expanded in 1969 when a British team brought a laser



The Joint European Torus in the United Kingdom is the world's largest operating tokamak

system to Moscow to measure plasma temperatures. In later projects the Japanese and the Russian Federation supplied equipment to American tokamaks, and American equipment has been sent to the European Union (EU), Japan, and Russia. Consequently, collaborative experiments and joint R & D have come to be the hallmark of fusion research.

One key research project is the Joint European Torus (JET) in the United Kingdom, which was built and is operated by fourteen European countries as the world's premier tokamak facility.

The Large Coil Project was a four-party project (EU, Japan, Russian Federation, and the U.S.) in which multiple parties manufactured superconducting tokamak magnet coils which were then successfully assembled and tested in the U.S.

Now several international partners are designing a large tokamak, which should produce as much fusion power as a typical generating station, about 1000 megawatts. The name of this program is the International Thermonuclear Experimental Reactor (ITER).

International collaborations stimulate broader implementation of scientific and technological breakthroughs, and thereby enable world-wide progress in fusion research.



Fusion:

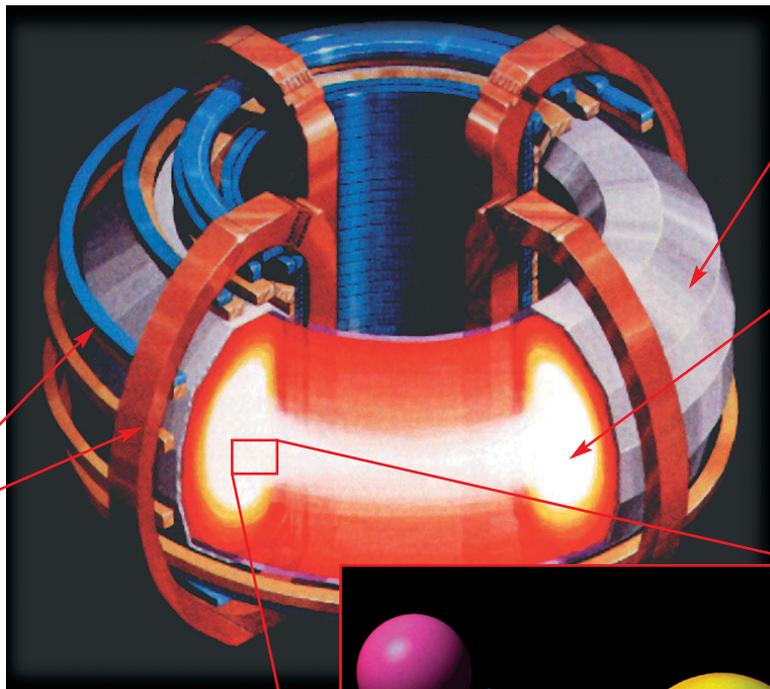
Science For Our Energy Future

Among the world's long-term energy sources—fusion, fission, and renewables—fusion offers a significant mix of potential advantages: abundant fuel available to all nations, environmentally benign, safe, and without atmospheric pollutants or long-term radioactive waste. Steady progress in fusion science and technology strengthens the vision of

fusion as an ultimate energy source for future electrical power plants.

The quest for fusion has spawned the new discipline of *plasma science*, which has subsequently found many valuable and diverse applications, ranging from the understanding of astrophysical phenomena to the processing of semiconductor materials.

Simplified diagram of a magnetic fusion device



VACUUM VESSEL to isolate the hot plasma from atmospheric gases

HOT GAS or "PLASMA"—The study of plasma in experimental devices such as this has spawned an important scientific discipline: *plasma science*

MAGNETIC COILS to confine and stabilize hot plasma

The essence of the fusion reaction is to combine or "fuse" two small atoms together to create a larger atom plus a large quantity of energy.

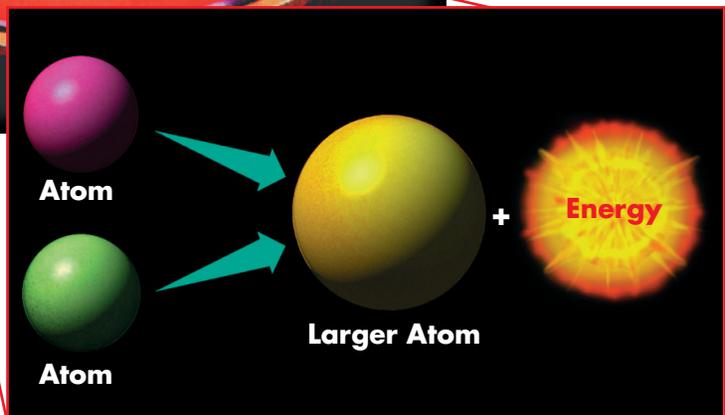


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