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FACTSHEET

Office of Education,
Business & Labor Affairs

Assistant Secretary for Intergovernmental
and Institutional Relations

United States
Department of Energy

14. NUCLEAR FUSION

INTRODUCTION

Most of the energy we use on this planet is converted from its stored (potential) form by the combustion reaction - by "burning" fuels. The important feature of this combustion reaction is that it is, in scientific language, "exothermic." It releases more energy than is required to start or keep it going.

In the search for ways to replace the primary energy of fossil fuels, we have turned to different kinds of "exothermic" reactions, nuclear ones. Fission, which is the energy source for nuclear power plants, is one such reaction. In this Fact Sheet we describe another, the fusion reaction, one of the most promising exothermic reactions - from the point of view of energy released per pound of fuel - that science has yet discovered.

It is not enough, however, for a reaction to be exothermic. To be a large scale source of energy, a reaction must be self-sustaining or, to use fission terminology, something like a "chain reaction" must occur. It must be arranged so that some of the energy released in each event is absorbed by the surrounding fuel material causing further reactions to occur. Only under this condition do we get more energy out than we put in. We light a fire, for instance, supplying energy with a match, and unless we have arranged our fire so that small sticks catch fire and heat larger sticks to their kindling point, the fire does not burn. It is toward the achievement of this second condition that fusion scientists are currently struggling.

The fusion reaction was first scientifically demonstrated and studied 45 or so years ago. It has glimmered brightly before us for almost 30 years, giving hope for a return to the Eden of abundant energy. But to date, the only man-made, self-sustaining fusion reaction has been the explosion of a "hydrogen bomb" - and that has nothing to do with Eden.

Fusion uses "fuels" which are essentially inexhaustible. It appears to be relatively benign environmentally and safe. It does not (unless it is designed to do so) produce materials which can be side-tracked for bomb making. Only solar energy, in fact, can compete with its promise. But the achievement of this promise, on a commercial scale, is surely the most difficult technical task that our species has yet undertaken. We describe this task and the progress towards its accomplishment in the sections which follow.

RESOURCES

The resources for the fusion reactions are deuterium, an isotope* of

* Isotopes of elements differ only in the number of uncharged neutrons in the nucleus. They are chemically identical. See Glossary, Fact Sheet #18.

hydrogen, and the light metal lithium. Lithium is an indirect resource since the other important fusion fuel, tritium, a radioactive isotope of hydrogen, will be "bred" from it in the fusion reactor.

Deuterium is rare. It combines with oxygen to make the laboratory curiosity "heavy water." In a natural sample of water, only one molecule in 6500 is of that variety. In other words, in 60,000 pounds of water, there is only about 1 pound of deuterium. But water is enormously abundant and the Earth's oceans, rivers, and lakes contain ten trillion tons of deuterium. The world's total "recoverable" resources of coal are estimated to be only 6 to 8 trillion tons. In a fusion reaction between deuterium nuclei, the total amount of energy released is 340 million Btu per gram of deuterium or about 1.5 quadrillion (1.5×10^{15}) Btu per ton. In contrast, coal releases at most 25 million (25×10^6) Btu per ton when burned. Thus each ton of deuterium could produce 60 million times more energy than a ton of coal.

The energy content of all this deuterium is difficult to comprehend. The total energy the world uses in one year could be obtained from 200 tons of it. Even if the world consumed twice the annual amount of energy it now does, the deuterium supply would last about 50 billion years - which is longer than we can be sure the world will last. The use of deuterium as a fuel is the most attractive fusion possibility.

The easier reaction to achieve experimentally, and therefore, the one presently emphasized, uses the even rarer isotope of hydrogen, tritium. Lithium, from which tritium could be made, is less abundant than deuterium, but from its known reserves alone (and there has been little exploration for lithium) we could fuel the world at twice its present level for almost 50,000 years.

It will require energy, of course, to separate that one deuterium atom from its 6500 or so chemically identical brothers (or is it sisters?). We do that now; heavy water is produced routinely, with the energy cost of providing a gram of deuterium substantially less than 1 per cent of the fusion energy available from that gram. Clearly, fusion energy will not be limited by fuel resources. Limits may be set, as we shall see, by other resources - capital, for instance, or the materials needed to build the complicated plant and its machinery.

TECHNOLOGY

The fuel picture for fusion has a rosey hue. We can give almost the same tint to the evaluation of environmental effects. In the discussion of technology, however, a different

color - the gray haze of uncertainty, shall we say - intrudes. In spite of more than 2 decades of determined effort by scientists and engineers of several countries, the demonstration of a controlled, self-sustaining fusion reaction has not been achieved and beyond that achievement lie many known and many more unknown technical challenges.

Fusion is a nuclear reaction. It is, in a sense, the opposite of fission. The release of energy in fission occurs because a large nucleus (uranium, for instance) is split into two smaller ones. In the fusion reaction two very small nuclei combine to form a larger one. In both cases, the mass of the end product(s) is less than the mass of the original reacting nuclei and this lost mass is converted into energy.

The four fusion reactions which are the most interesting as future energy sources are the two reactions between deuterium particles, (D in the equation below):

1. $D + D \longrightarrow T + p + 3.3 \text{ Mev}$ (75 M Btu/gm)
2. $D + D \longrightarrow {}^3\text{He} + n + 4.0 \text{ Mev}$ (92 M Btu/gm)

and the two reactions of deuterium with the products of those reactions, (T) tritium and ${}^3\text{He}$ (helium e, a rare isotope of helium).

3. $D + T \longrightarrow {}^4\text{He} + n + 17.6 \text{ Mev}$ (313 M Btu/gm)
4. $D + {}^3\text{He} \longrightarrow {}^4\text{He} + p + 18.3 \text{ Mev}$ (334 M Btu/gm)

The promising resource picture that we have already anticipated is contained in these four nuclear equations. The energy released is given both in the units of nuclear physics (Mev - defined in the Glossary, Fact Sheet #18) and in millions of Btu's per gram. The hope for low environmental impact is also contained in them. Of all the participating reaction components, deuterium (D), tritium (T), helium 3 (${}^3\text{He}$), the proton (p) and neutron (n) and finally, common helium (${}^4\text{He}$), only tritium is radioactive. It is short lived (with a half-life of 12 years) and its biological - radiological hazard is, at least thousands of times less than that of the fission products.

These equations also suggest difficulties to the experienced eye. The reaction products, in particular, the neutrons (n) and protons (p) which carry away most of the energy can create radioactivity in the materials they strike. This "experienced eye" will also note that the particles, D, T, or ${}^3\text{He}$ which must react, which must get close enough together to each other to allow the short range nuclear force to take over, are electrically charged. They will repel one another. Our "experienced eye" will ask "How do you bring them together?"

The problem is fairly simple to state. The reacting particles must be given enough energy that they will collide in spite of the electrical force trying to shove them apart. In a simple analogy, they must roll up over a hill before they crash down together into the deep valley and give up energy.

The early study of fusion reactions was accomplished with "particle accelerators" - cyclotrons, Van De Graff generators, etc. In these experiments a deuterium particle was hurled against a stationary target of deuterium or tritium. Created in this fashion, however, the reactions are not self-sustaining. Even though net energy is released in each successful reaction, most of the incoming particles miss and the emerging particles do not hit others and cause a chain reaction. Much more energy is used overall to cause reactions in these experiments than is released by them.

There are, however, other examples to guide us. Fusion reactions do occur in the sun and in hydrogen bombs. In those cases, energy is supplied in the form of heat. If a mixture of deuterium and tritium (D and T) can be held together and brought to a temperature of 50 to 100 million degrees Celsius (C), the fusion reaction will take place. The ignition temperature - as this reacting temperature is called - is about 500 million °C for a D + D mixture. Since the ignition temperature for D + T mixtures is lower, the experiments now underway, concentrate on this reaction (reaction 3 of the above list).

The enormous temperatures which are needed greatly limit confinement techniques. Ordinary vessels - bottles, cans, and tanks - cannot be used. The reacting particles must be suspended in a vacuum, free of any matter which could conduct their heat away. We know of two ways to accomplish this, magnetic confinement and inertial confinement.

In magnetic confinement, the deuterium-tritium mixture is given enough energy so that the electrons are stripped from the nuclei, forming a "plasma" of charged electrons and nuclei. This plasma can be controlled by a magnetic field much in the same way that a beam of electrons is controlled in a television tube. Several different experimental approaches using magnetic confinement are described below.

In inertial confinement, a solid target (a droplet or sphere) of deuterium and tritium is heated extremely rapidly so that it reaches the ignition temperature for fusion before it can expand and reduce its density. Bombardment of a small sphere of deuterium from all sides with a high powered laser is one method which may achieve this.

Magnetic Confinement: There are three basic magnetic confinement systems under development.

1. Toroidal-shaped chambers ("doughnuts"), in which the plasma travels around inside an evacuated chamber: The Russian-invented Tokamak is the most successful of these and about 70 percent of the U.S. effort is going into similar devices; examples are the PLT (Princeton Large Torus), ORMAC (Oak Ridge Tokamak), Alcator at MIT, Doublet IIA at the General Atomic Company in LaJolla, California, and the much larger TFTR (Tokamak Fusion Test Reactor) under construction at Princeton University.

2. Magnetic mirrors: These are linear tubes in which the magnetic field which confines the plasma is so shaped that it turns the particles around at each end, as a mirror does light beams. The most successful of these devices is the 2X-IIB at the Lawrence Livermore Laboratory of the University of California. Mirrors are now the principle alternative to Tokamaks.

3. The magnetic pinch device: In these the interior space is filled with plasma and then the plasma is "pinched" by a rapid compression of the magnetic field. This is accomplished by increasing the strength of the field and forcing the plasma toward the center of the tube. The Scyllac at Los Alamos is an example of a pinch device.

Heating: In addition to the proper confinement conditions, the plasma must be heated to 50-100 million °C. Heating can be accomplished in three ways.

1. The plasma may be heated by induced electric currents. The plasma heats up like a resistive wire does when current flows through it. The toroidal machines rely, in part, on this type of heating.

2. A plasma can be heated by injecting an energetic beam of nuclear particles into it. Techniques of firing beams of uncharged deuterium atoms into the plasma are used in the toroidal and the mirror machines.

3. The plasma acts in some respects like a gas (a gas of charged particles). Therefore, like a gas, it can be heated by compression. The magnetic pinch devices not only confine their plasmas, but heat them.

Inertial Confinement

The confinement problems can also be solved by freezing the mixture of deuterium and tritium to form a solid. The major problem left is that of heating and compressing the solid to the temperature and density needed for the reaction to occur.

Experiments with inertial confinement have proceeded along the following lines. A small frozen droplet of the fusion fuel, preferably spherical in shape and of very small diameter

(less than a millimeter) is placed in the center of an evacuated chamber and bombarded from all sides by an energy source - a laser, or a beam of charged particles (ions or electrons).

Lasers are powerful sources of light that can be accurately focused to a very small spot. In order to bombard the pellet symmetrically, from all sides, the main beam is usually broken up into several smaller beams by a system of mirrors and these beams are then all brought to bear on the target sphere. The burst of energy must be very short, lasting only about 10^{-9} seconds in order that the deuterium-tritium mixture is heated rapidly, without expanding. As the energy hits the outside layer the material essentially vaporizes and in rushing outward exerts a reaction force back against the sphere (this is the principle of a rocket) which "implodes" the sphere, crushing it inward and greatly increasing its density. The high temperature and high density allow ignition of the fusion reaction and the pellet explodes. Most of the energy is carried out by neutrons released in the fusion reaction.

Nuclear Fusion in Practice

For self-sustaining fusion to occur, the plasma density, confinement time, and temperature must all be above certain values. Satisfactory values of each of these parameters have already been achieved separately, but not in the same machine at the same time.

That requirements for density and confinement time are related can be seen from the following simple argument. What we are seeking is a chain reaction, of sorts, in which the energy released by one fusion event causes another one. To occur, either the particles must be very close together (have a high density) or there must be sufficient time for the energetic particles to wander around until they hit other ones (a large confinement time).

The "yardstick" for fusion reactor performances is the so-called "Lawson criterion" which says, that for a self-sustaining, energy producing $D + T$ fusion reaction to be possible, the product of the particle density and the confinement time must be about 10^{14} . In the best performance of a Tokamak-type machine, so far, that of MIT's Alcator, a product of density and confinement of 2×10^{13} (a factor of about 5 below that breakeven point) was reached. A magnetic pinch machine (the Scyllac) recorded a product of 2×10^{12} , while the best that a mirror machine has done so far (the 2X-II) is 10^{11} .

The record on ignition temperature has also improved. The Tokamak devices are still operating at factors of 5 to 10 below ignition.

The PLT and the Soviet Tokamak (T-10) have produced temperatures of 20 million $^{\circ}\text{C}$ and 10 million $^{\circ}\text{C}$ respectively. The 2X-II mirror machine has produced a record temperature of 230 million $^{\circ}\text{C}$, getting closer to a demonstration of energy breakeven and ignition.

Laser fusion in practice: The principal problem for laser fusion is to heat the fuel pellet efficiently and evenly so that it will be compressed symmetrically. The best achievement to date has been a temperature of 90 million $^{\circ}\text{C}$ at a density-confinement time number of 10^{12} . Some fusion-produced neutrons were observed. Further improvement is occurring as the construction of new, more powerful lasers is completed. There are still many problems to be solved, however, before this technique can be called a success.

Fusion Reactors

Given the current status of fusion and the scientific and engineering problems which must be solved before the "scientific feasibility" of fusion can be demonstrated, it may seem premature to spend time considering what a commercial power producing plant would look like. It is important, however, to anticipate some of the problems which will remain after the scientific success is achieved. There are a few general points worth making.

The magnetic confinement machines will all be large, it appears, with generating capacities in the thousands of megawatts range. The major components will be the chamber itself and a surrounding thick blanket of lithium - probably in a molten form which will absorb the neutrons and convert their energy to heat. The lithium will also be the source of the tritium and ^3He which will be created by reactions between the neutrons and the lithium nuclei and then separated from the blanket and used as fuel. Heat extracted from the hot lithium will be used to create steam to turn a steam turbine. It is expected that high temperatures will be achieved and that efficiencies will approach 40 percent.

There is some hope for even greater efficiencies. In fusion reaction 4 (above list), the end products are charged. It may be possible to collect these particles, and the electrons accompanying them, separately, and directly convert some of the kinetic energy into electrical energy. Efficiencies in the 80 percent range may be feasible.

Unless some unforeseen breakthrough is accomplished, however, the first fusion reactors will be huge machines, practical only as sources of large amounts of electrical energy. They could also be used for chemical processing or to breed fissionable fuel. They will

certainly increase the already important centralization of energy production.

Laser fusion may depart from this trend. The energy released in each explosion will be relatively small. They will be pulsed, one small explosion following another. It may be that generators with capacities as low as 100 Mw will be feasible.

A laser fusion generator will be quite different than the magnetic machines. The reactor vessel will be a fairly large sphere strong enough to withstand the repeated small explosions as the pellets are bombarded. Lithium will be introduced in some manner around the inside surface of this vessel. It will perform the same function as in the magnetic devices, creating new fuel, absorbing the energy from the neutrons, and converting it to heat. Ample challenge still remains, for example, in the search for means to make inexpensive little target pellets (the electricity generated from each explosion is worth only a few cents) and in constructing a vessel that is not weakened by the neutron bombardment and/or damaged by the explosions.

Environmental Effects, Safety, Etc.

We have described the major advantages of fusion reactors in the section on Resources. They also seem to offer significant advantages over fission reactors in their possible effects on the environment and on the society which uses them.

The threat of an accident is greatly reduced. Fusion reactors will not contain the huge amounts of radioactive material characteristic of fission reactors. Tritium will be produced, but the entire system will be designed to recapture and consume this material and its stockpile, even if released, presents much less of a threat than the fission products. Radioactivity will be produced in the reactor materials by the neutrons and, while this may be a problem, it probably can be reduced by proper choice of construction materials.

Also, importantly, there is no "critical mass" involved in fusion. Any malfunction would destroy the plasma and stop the reaction. Although there will be some "after heat" remaining in the reactor structure, it will be much less than that in a hot fission reactor core and it will not pose the melt-down problem.

The radioactive waste problem would be ameliorated. Some storage of discarded materials may be necessary, but the long term, large volume storage problem facing us in a fission future would be avoided.

Perhaps the greatest relief that successful fusion power generation could offer us would be

from the plutonium nuclear bomb threat. Unless neutrons from fusion reactions were deliberately used to breed plutonium from uranium 238 (as has been proposed), no potential bomb making materials would be produced, transported, etc., a very significant advantage.

The production of fusion fuels, because of the enormous amounts of energy they contain, should cause little disruption of the environment. Removing one hydrogen atom in 6500 from the ocean will have no measurable effect on it and the amount of lithium needed is equally miniscule when compared to projected needs of coal or even uranium.

The fusion reaction would be, it appears, as environmentally benign as any technology except solar energy.

SUMMARY

The fusion reaction, relying on abundant deuterium for fuel, could provide humankind with energy for millions, perhaps billions, of years and at modest cost to the environment. Unfortunately, in spite of almost 30 years of scientific and engineering labor, and a billion or so dollars spent in the U.S., we have not yet produced a self-sustaining, controlled reaction.

The present challenge of fusion is to confine the D-T mixture at sufficient density, hold it together long enough, and get it hot enough to cause the reaction to occur. This accomplishment will demonstrate the "scientific feasibility" of a self-sustaining fusion reaction. Even after this is achieved, however, a host of problems will remain. A very complicated piece of machinery will have been constructed: large vacuum chambers, huge magnets (which may be "superconducting" magnets cooled by liquid helium) and tanks and pipes of extremely hot lithium. There will not only be enormous differences in temperature to sustain, but all of this equipment will be bombarded by an enormous flux of neutrons which will not only create radioactivity but may weaken the metallic structures. These engineering challenges may be as great as the scientific ones. Beyond them remain the economic challenges. Can all this be constructed cheaply enough and operated long enough before breakdown to produce electricity at a competitive price?

As we have said, laser fusion is particularly questionable economically. Lasers themselves are inefficient, converting only about one percent of the input of electrical energy into an output of light. More efficient lasers and very inexpensive target fabrication techniques are among the developments which are necessary to make laser fusion a competitive source of electricity.

A timetable for this "uncertain certainty," as it has been called, is thus not very reliable. The one put forward by DOE anticipates the production of ignition temperatures in plasmas in the 1978-1980 period, releases of thermal energy from fusion in the new Tokamak facility of 1982, production of electrical power by the late 1980's, and the operation of a commercial scale demonstration reactor by the late 1990's. Fusion can not contribute importantly to our energy supplies until the next century.

DOE support for fusion (and the previous support from the former AEC) reached the \$30 million level at about 1960 and remained at about that level for the next decade. It had grown to about \$180 million by 1975 and is estimated to be \$390 million in 1977.

It does appear that the support and manpower commitments to the program are finally approaching a level that augurs well for success. Success, however, is never guaranteed and, even after the achievement of a scientific demonstration of feasibility, there will remain a staggering number of engineering problems to be solved.

The environmental problems and social hazards which accompany fusion also seem of less concern than with fission. It will, however, continue one trend which itself may pose a social problem - the increasing size, complexity, and centralization of our energy production industry. There are questions that need to be asked in this area - but there is time to ask them.

The entire fusion research effort is different from any we have yet undertaken, not only because of the difficulties we have emphasized, but also because of its long range nature. It is an energy source, which if it succeeds, is not for this generation, but for those which follow. It could be a much appreciated inheritance.

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