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The Basics of Magnetic Fusion

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INTRODUCTION

Most of the world's energy now comes from fossil fuel—oil, coal, and gas. The burning of such fuel with oxygen amounts to chemical reactions in which the fuel molecules are recombined into different molecules and release heat of combustion in the process. The atoms that make up the molecules remain unchanged, and the total weight of the end products (smoke and ashes) equals the total weight of the fuel plus the oxygen. Weight, or mass, is conserved.

In a nuclear reaction the atoms themselves change, and some of the fuel's mass disappears as energy appears. The energy and mass are related by Einstein's famous equation $E = mc^2$, where E is the energy, m is the amount the mass changes, and c is the speed of light (186,000 miles a second).

Magnetic fusion is one approach to harnessing one type of nuclear reaction. To place its concepts in context, we first review some general concepts of nuclear energy.

NUCLEAR REACTIONS

There are two basic types of nuclear reactions: *fission* is the splitting of heavy atoms and *fusion* is the welding together of light atoms. They are illustrated in Fig. 1. Both types convert mass to energy according to $E = mc^2$.

Fission

In the fission reaction, if certain kinds of heavy atoms capture a "stray" neutron, they split into lighter atoms and emit more than one neutron of their own in the process. The emitted neutrons in turn can be captured by other heavy atoms, thus causing additional splits and releasing more and more neutrons. Repeated capturing and splitting is called a *chain reaction.* It is sustained if there are enough heavy atoms close enough together that the emitted neutrons will be recaptured. Having enough such atoms close together is called having a *critical mass.* Assembling a critical mass takes very little energy compared to the energy that is released.

Sometimes, the emitted neutrons are captured by a different kind of heavy atom; these atoms, now

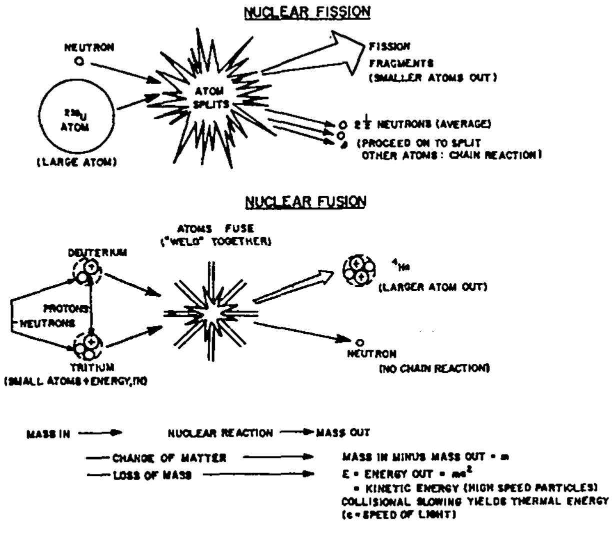

Fig. 1.

altered, can be used as fissile fuel; the process of creating them is called *breeding*.

Fusion

In the fusion reaction, the speeds of light atoms must be increased so that when pairs of them collide, they "weld" or fuse together. Much more energy is released than the amount needed to speed them up. Enough such atoms must be collected and held in one place long enough to obtain net gain in the energy release.

FUSION FUELS AND HEATING

The first fusion reactors will likely employ two hydrogen isotopes, deuterium (D) and tritium (T). Compared with ordinary hydrogen, D has one extra neutron in its nucleus and T has two. Paired as D-T, they are easier to fuse than other fusion fuel pairs such as deuterium-deuterium or deuterium-helium.

Deuterium is easily obtained. It occurs naturally in the oceans as a constituent of heavy water (HDO vs H_2O). Tritium, however, does not occur naturally. Although it is slightly radioactive, with a half-life of about 12 years, it is a biological hazard only if taken into the body. The first charge of T fuel for the first fusion reactor will be bred by bombarding lithium with neutrons in a fission reactor. After that, neutrons from fusion reactions will be used to breed T in a lithium blanket that will surround the fusion reactor core.

Heating the fusion fuel mixture (equal parts of D and T gas) means, on the microscopic scale, raising the random speed of the atoms. As the gas is heated, electrons leave the atoms; the mixture of free electrons and ionized atoms, or *ions*, is called *a plasma*. Each ion then has a positive charge and repels neighboring ions with great force. However, if the ions are heated further, they can gain sufficient energy so that their momentum overcomes the repelling forces and they can fuse. Not all of the heated fuel needs to fuse for a net energy gain.

The fuel must be heated to about 5 million Kelvin (a temperature like that of the sun) for fusion. Such temperatures are now routinely attainable in laboratory experiments. Schemes for heating fusion fuel include: "preheating" with laser or electron beams or radiofrequency excitement, or heating by passing an electrical current through the plasma—so-called *ohmic* heating. Or the fuel can be simultaneously heated and compressed by shock waves, or by some combination of the above.

The remaining problem is to maintain a sufficient density of fuel atoms, n (number per cubic centimeter), for a long enough time, τ (seconds), for enough reactions to occur to obtain a net energy gain. The product of n times τ is the important parameter. The smaller the n, the larger the needed τ, and vice versa. A general target for $n \times \tau$ for a D-T plasma is $n\tau = 10^{14}$ (100 million million). To date, scientists have been able to come within a factor of 10 of that target.

MAGNETIC FIELDS AND GEOMETRIES

At such high temperatures, the plasma cannot be contained by material walls. If it touches a wall, "impurities" from the wall enter the plasma, cool it, and quench the reaction. Thus, the plasma must be inertially confined in "free space" by mass, or must be confined by some other means. Because the plasma is a collection of charged particles, it can be pushed and confined by magnetic fields, since such fields exert force on the charged particles of the plasma. This approach—*Magnetic Fusion*—has been studied in the United States and abroad for over two decades.

The plasma pressure, enormous because of the plasma's high temperature, pushes back against the pressure of the magnetic field. The ratio of the plasma pressure to the magnetic field pressure is a number called β (beta), necessarily less than or equal to 1.

If we think of the invisible lines of a magnetic field as rubber bands surrounding and squeezing Jell-O (the plasma), we begin to understand the difficulty of confining a hot plasma in a magnetic "bottle." In all magnetic fusion approaches studied thus far, the plasma finds a way to wriggle out of the field and contact the walls, quenching the reaction before it reaches the needed confinement time τ. The plasma's wriggling out is called *instability*.

Four basic magnetic field configurations under study are summarized in Fig. 2. Two categories are the theta pinch and the z pinch. In the theta pinch, the magnetic field lines are parallel to the plasma axis; in the Z pinch they are perpendicular. *Some concepts use a mixture of z and theta fields for added plasma stability.* Devices are also categorized as "open" or "closed." In an open device, even though the magnetic field or "bottle" can be made to pinch at the ends by so-called magnetic mirrors that "reflect" charged particles, plasma will eventually leak out. In a closed device, there are no ends, but the bending of the magnetic field lines to close the bottle results in a slightly nonuniform field, whence the plasmas tend to drift to the walls prematurely. In all cases, instabilities have been a problem.

All magnetic fusion experiments are pulsed. A pulse of electrical energy momentarily powers magnets whose fields squeeze the plasma. During

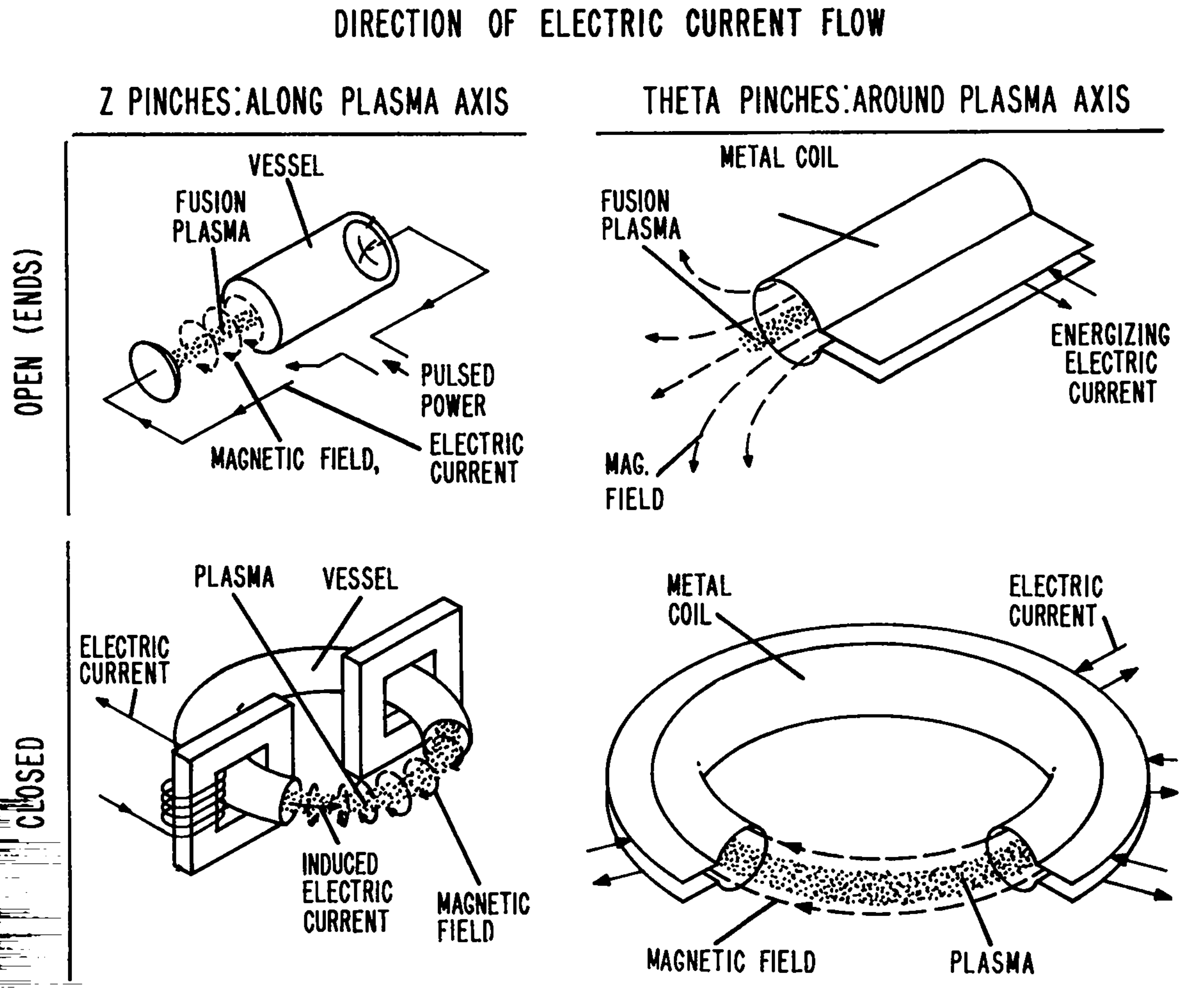

Fig. 2.

the magnetic field's rise it squeezes the plasma away from the walls and heats it, alone or with other heating mechanisms.

Another concept is to implode a metal liner onto the plasma, cushioned from the plasma by a magnetic field, to provide a form of *inertial* (heavy mass) confinement that we hope will achieve the needed τ.

ENERGY CAPTURE

When fusion of a D ion and a T ion does occur, they form a helium ion (^{4}He) and eject a neutron (Fig. 1). About 80% of the energy released appears as the neutron's energy of motion (kinetic energy), and about 20% of the energy appears as the helium ion's energy of motion.

It is beyond the scope of this article to discuss reactor concepts fully. Briefly, however, in most concepts using D and T as fuel, the ^{4}He energy is given to "unburned" D and T ions through particle collisions or is captured on the inside walls of the reactor when the particle hits a wall and converts its kinetic energy to heat. The energetic neutrons pass through the wall, but then give up their energy to a liquid lithium blanket that surrounds the wall. When they collide with the lithium atoms, they heat the lithium. During this process, T fuel is also bred. The heated lithium can be circulated through a heat exchanger to make steam from water; the steam, in turn, can be used to drive a turbine to make electricity. The concepts are summarized schematically in Fig. 3.

Other reactor concepts, such as using direct conversion from the kinetic energy of charged particles to electrical energy, are possible when other fuels are used.

HYBRIDS

In fusion-fission hybrid concepts, a *sub*critical array of fissile material is located in a blanket surrounding the fusion core. Neutrons from the fusion reactions bombard the blanket, to produce additional energy by fission reactions or to breed fissile fuel. Because this additional energy can be produced in the fissile material blanket, the performance requirements for the fusion core can be reduced and still leave the entire system a net energy producer.

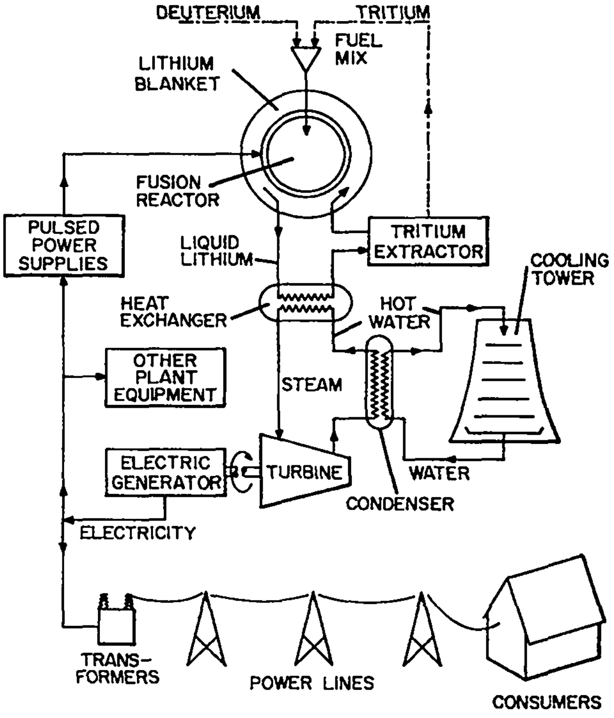

Fig. 3.

THE POTENTIAL

If the natural D in only one gallon of sea water (one part in 30,000 by weight) were burned completely in a fusion reactor, it would release an amount of energy equivalent to the energy in 300 gallons of gasoline. Thus, fusion's potential for filling our energy needs is enormous. Scientists hope to have the first demonstration fusion reactor working by the year 2000. If this goal is achieved, then a few decades later enough additional reactors can be built to have a significant impact on energy supplies.

Mini-Review readers are encouraged to correspond directly with the author.