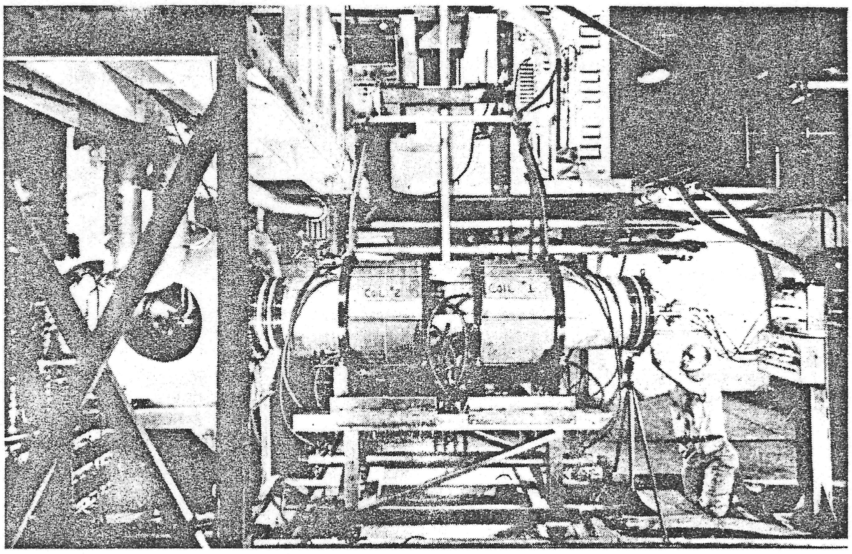

Experimental mirror machine designed for experiments in trapping injected high energy particles by a time using magnetic field. The magnetic field is generated by a 10^6 joule condenser bank which is discharged through the coils. University of California Radiation Laboratory, Livermore and Berkeley, U.S.A.

November, 1958

THE FUNDAMENTALS OF FUSION

By ELIZABETH A. RAUSCHER

Fusion/thermonuclear energy when released from Hydrogen creates heat and light. Fusion is thus one of the principal sources of energy of the universe.

American, British and Soviet scientists are exploring various ways of utilizing thermonuclear fusion for peaceful purposes. The reason: the need to compensate for diminishing fossil fuel resources.

Peaceful Use—Project Sherwood

Development has recently been accelerated in the peaceful application of the hydrogen fusion reaction. The race is on in this field. The Atomic Energy Commission's Project Sherwood, directed by Dr. A. E. Raurks, is investigating the production of low-cost energy from the fusion of hydrogen nuclei. Research is proceeding energetically also at two University of California laboratories, Los Alamos and Livermore, at Princeton and New York universities, and at Oak Ridge.

Fusion in Nature

The sun's brilliance—and that of billions of other stars—is provided by the fusion of nuclei at a temperature of several hundred million degrees centigrade or at energies of 10,000 electron volts. In order to utilize the energy released by fusion, one must attain the temperature at which the reaction will occur, 350 million degrees centigrade.

He from H_2

The fusion reaction that is activated at such a high "kindling" temperature occurs in the deep interior of the sun where the nuclei of ordinary hydrogen are fused to form helium. On earth we have deuterium and tritium; the latter does not occur naturally, but deuterium is available from the sea in virtually unlimited amounts.

Helium is produced from hydrogen in four main steps:

(1) Deuterons merge to form a triton (tritum nucleus).
$2\,{}_1D^2 \longrightarrow {}_1H^3 + {}_1H^1 + 4$ mev.

(2) An equally possible reaction may produce He^3 and a neutron.
$2\,{}_1D^2 \longrightarrow {}_2He^3 + {}_0N^1 + 3.25$ mev.

(3) Next a deuteron combine with a triton to form He^4 and a neutron.
${}_1D^2 + {}_1H^3 \longrightarrow {}_2He^4 + {}_0N^1 + 17.6$ mev.

(4) Then a deuteron fuses with helium producing He^4 and a proton.
${}_1D^2 + {}_2He^3 \longrightarrow {}_2He^4 + {}_1H^1 + 18.3$ mev.

The Plasma

At the temperatures necessary for the above reactions, the reactants and their products will be a completely ionized hot gas called a "plasma."

In an idealized experiment in which deuterium gas is heated in a container, the following steps can be observed:

(1) At room temperatures we would have diatomic molecules at 14.7 lbs./in^2.

(2) At about 5,000°C we would have monatomic atoms, i.e., split diatomic molecules.

(3) At 100,000°C the heat energy would ionize the atoms and form a plasma of positive ions and electrons which are electrically neutral as an over-all quantity. The pressure would read 20,000

pounds per square inch.

(4) At 100 million degrees Centigrade and a pressure of 22 million pounds per square inch, some deuterons would fuse but would not yet be self-sustaining. The gas would glow due to electrons colliding with one another and with the deuterons, generating radiant energy and making the vapor glow with increasing brilliance as the temperature increases.

In order to obtain a large scale substained reaction, sufficient fusion must occur to release the energy needed to maintain the gas at its kindling temperature—350 x 10^6° C.

While the plasma is being heated, the relatively light electrons gain kinetic energy faster than the heavier particles of the plasma. Collisions cause the electrons to impart energy to the positive ions or deuterons tending to equalize the energy level throughout. For this reason, higher densities of the gas make for a faster and more effective warm-up.

An equilibrium is established when all the particles of the plasma have the same kinetic energy. Until this equilibrium is attained, the temperature is not a good indication of the heat content since the electrons have greater kinetic energy. The kinetic energy of the electrons can be expressed in terms of the temperature; i.e., 1 ev = 10^4° C.

The Magnetic Bottle

To contain the plasma at ignition temperatures for an appreciable time requires an unusual concept of a container since no known material could hold such an ultra-hot gas. We know that the solar gravitational field contains the solar plasma, but this is hardly a "container" to be reproduced in the laboratory.

The most successful solution proposed thus far is the "magnetic bottle" which is based upon a rather simple theory. A strong magnetic field will deflect the charged particles in the plasma from a straight path and force them to spiral around the lines of magnetic force in a helical path, thus confining them within an applied or induced magnetic field which functions as a wall. This field would isolate the plasma from the walls of the container preventing a kinetic energy loss which would stop the fusion reaction for lack of heat. The magnetic lines of force can be supplied by external coils around a cylindrical tube. The magnetic field is produced by the solenoidal coils with the lines of force extending lengthwise, parallel to the axis of the cylinder in accordance with electromagnetic principles. Fields of around 50,000 gauss are produced and can contain a gas at 100 atmospheres.

Another method of producing the magnetic bottle is to send a powerful electric current containing deuterium gas of the order of magnitude of 2 x 10^6 amperes through a cylinder by electrodes.

Michael Faraday showed more than a century ago that two parallel conductors carrying a current in the same direction will attract each other by their self-induced magnetic fields. This phenomenon is applied to the control of thermonuclear reactions. With a heavy discharge of electricity, the gas is "pinched" into a thin column away from the walls of the cylinder by its own circular magnetic field.

The "pinch" may also be produced by a transformer core placed around a torus shaped tube. The torus tube, having its ends joined together, eliminates the consequences of the magnetic lines of force emerging from the tube. The hot gas comes in contact with solid matter and is thus able to give up its kinetic energy. The primary current in the transformer coil produces a secondary current in the deuterium gas and creates the "pinch."

The gas compressed by the pinch effect is heated to about one million degrees centigrade and becomes a completely ionized plasma. At the same time electrical resistance to current flow causes a temperature increase.

Heating to the 100 million degrees centigrade level can be brought about by "magnetic pumping." An oscillating electric current will expand and contract the lines of force, thereby heating the plasma.

Complications have not been elimi-

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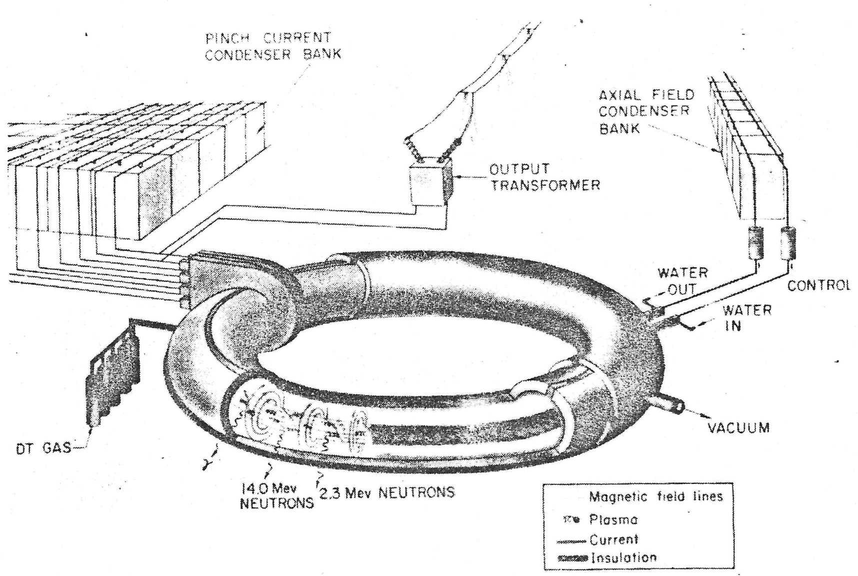


The reacting hot Plasma (balls) and axial magnetic field (Horizontal Lines) is contained by the circumferential H magnetic field (circular lines) in the stabilized pinch geometry. The helical pitch is the current flowing on the surface of the Plasma separating the fields. An opposite current flows on the inside surface of the metal torus. The initial axial field H_z before the start of the pinch is created by the axial field condenser bank discharging through a toroidal winding (squares and insulation). A split in the metal toroidal shell (the short way) permits the penetration of the H_z field. The pinch field is created by the main pinch current condenser bank inducing a voltage—and current—the long way around the torus. If a fraction of the Plasma reacts during the pinch, then more magnetic field energy is forced back into the condensers by the Plasma pressure than was initially supplied by the condensers. The stabilized pinch therefore lends itself to the forced oscillations of a resonant system, thereby allowing useful power to be directly coupled out to a load.

FUSION *(Continued from page 21)*

nated by any means. Sufficiently high temperatures have been produced for only microseconds, since the pinch effect is not completely stable. After a millionth of a second or so, the pinch column throws itself violently against the wall, due to magneto-hydrodynamic effects.

This lack of stability takes several forms. A kink occurs where the magnetic lines of force crowd on the concave side of the bent column as it becomes unstable. A constriction forms as the field is crowded into a wasp waist in the column. It is hoped that the kinks and constrictions can be restricted by applying a magnetic field longitudinally through the plasma. Mutual repulsion will hamper the constrictions and the tension will straighten the kinks. This idea was proposed by investigators in the United States, Britain, and the Soviet Union.

Thermonuclear Experimental Devices

Britain, the United States and the Soviet Union have developed a variety of test devices which attempt to contain the fusion reaction. Technical difficulties of confining and heating the gas have been attacked from several directions. Essentially, all of the devices utilize some form of the "magnetic bottle." Experiments concerning heating and confining the gas have employed:

1. Pinch effect
2. The E-layer electrons
3. Magnetic mirror machine
4. Ohmic heating
5. Magnetic pumping

Devices range in size from miniatures with the axial length of the tube measured in inches to projected giants utilizing a tube several feet in diameter and an axial length of several hundred feet. To function as a pilot plant, the Model C Stellerator with a doughnut tube eight inches in diameter and four feet in axial length is being completed at the James Forrestal Research Center at Princeton University. Research is also being carried out with the Zeta machine at Harwall, England, and work with the Astron reactor is underway at the UC Livermore Radiation Laboratory. The Soviet Union is also deeply involved in research in this field.

Evidence of Fusion

The production of n^o was at first considered to be an indication of success. The n^o was observed in both Britain and the United States in experimental devices and attributed to successful sustained fusion. But it was later discovered that these n^o were due only to the constriction instability that caused a few deuterons to fuse. As yet no definite reports of successful *sustained* fusion have been made.

Extracting the Power

Eighty per cent of the energy from fusion of D^2 and H^3 is carried off as kinetic energy of the electrons. If a jacket of water were circulated in tubes around the reactor, the hydrogen in the water would absorb the energy of the neutrons by elastic collisions. The water could then be carried to external turbogenerators and produce electricity in the usual manner. Some of this electricity could be fed back to maintain the magnetic bottle. A full-scale reactor would, therefore, constitute a large hydroelectric plant.

Why Control Sun Power?

The advantages of fusion power over other power sources can be briefly stated as follows:

1. Fusion fuel may be extracted at one per cent of the cost of coal, and can produce power for centuries because of its "limitless" source—the sea. Uranium, on the other hand, is available in limited quantity.
2. The potential power output is tremendous. The complete fusion of one kilogram of deuterium would yield energy of around 10^8 kilowatt hours.
3. Fusion reactors would be relatively safe. They could be fed only enough fuel for a minute of reaction, and this limitation would preclude an out-of-control reaction.
4. The most convincing argument in favor of the effort being made to solve the problems in this field is the fact that with all other forms of fuel, energy is converted from one form into another, such as in the steam engine where there is a conversion of heat to work. But in nuclear power, mass is converted into energy, and a great deal of energy can be extracted from a small amount of mass. If one kilogram of mass was completely transformed into energy, it would produce 9×10^{16} joules or 3.6×10^{14} kilocalories, based on Einstein's famous equation, $E = MC^2$.

When Will Fusion Power Be Perfected?

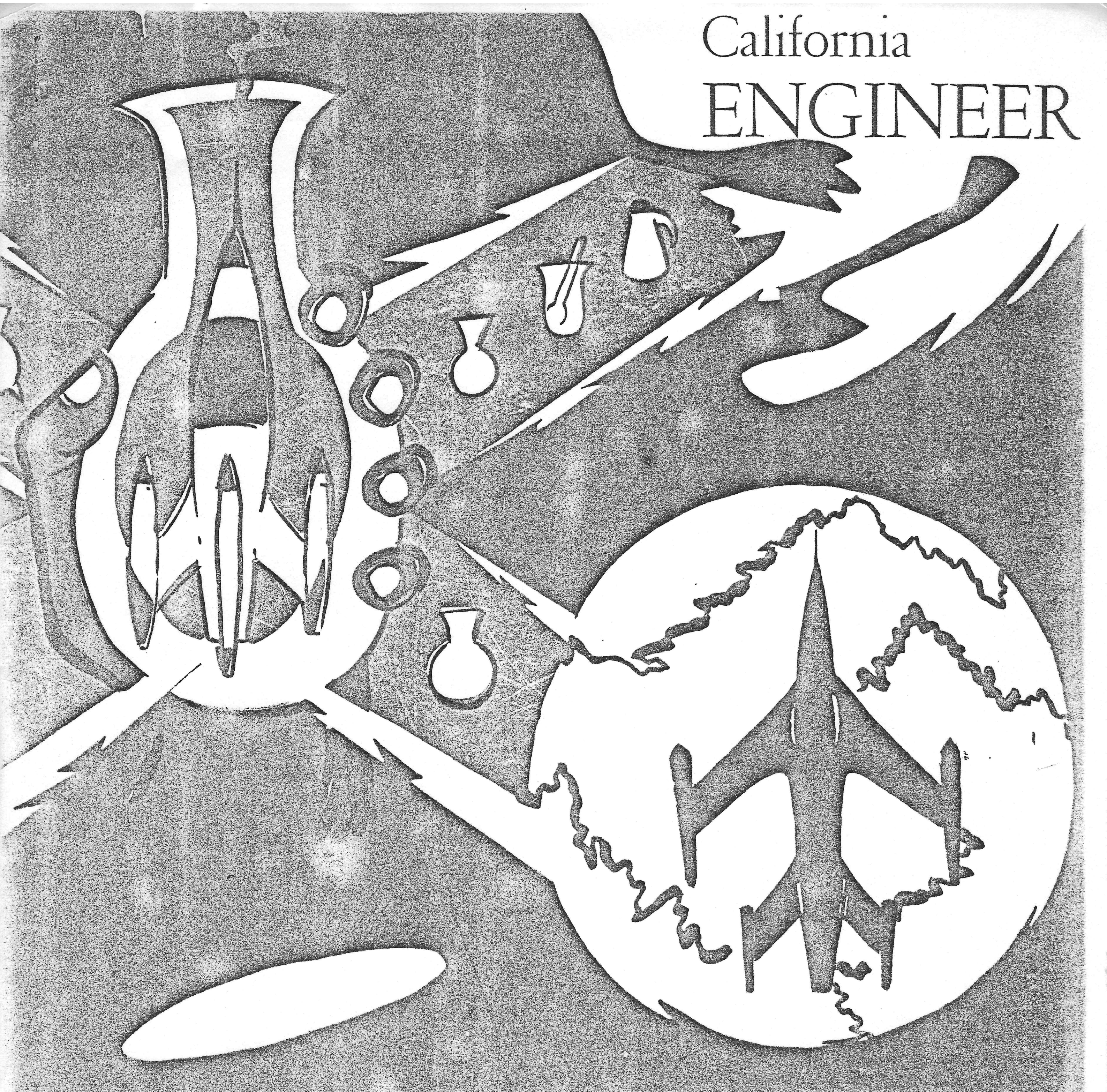
As mentioned previously, many technical problems have not been solved, and as yet no self-sustained reaction has been achieved. On the other hand, no insurmountable obstacles have been uncovered by the research technicians in this field. This suggests that power production by the "tamed" H-Bomb will be a thing of the not too distant future. However, significant problems must still be overcome and it is estimated that fusion power will not be an accomplished fact for thirty years.

Looking to the Future

Due to the increasing importance attached to this field, considerable progress has been made. For example, in 1933 only twenty scientists and engineers were working on the Sherwood project, whereas today there are several thousand involved on this program. Much more money is now being spent to solve the problems involved. The Model C. Stellerator mentioned previously is to be completed by early 1960 at a cost of $23 million.

Harnessing the sun's power for peaceful use is one of the most challenging and important current research problems. If this tremendous goal can be achieved, a great step forward will have been taken. When the fusion reaction is utilized to serve man, a new source of power and energy will be available for generations to come. And this will surely effect greatly the future economic status of present underdeveloped areas of the world. From fusion then comes peace as well as power.

California ENGINEER



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