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THERMONUCLEAR ENERGY AS A PRACTICAL POWER SOURCE: A SEMITECHNICAL INTRODUCTION

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THERMONUCLEAR ENERGY AS A PRACTICAL POWER SOURCE:
A SEMITECHNICAL INTRODUCTION

W. M. Brobeck
May 4, 1956
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THERMONUCLEAR ENERGY AS A PRACTICAL POWER SOURCE: A SEMITECHNICAL INTRODUCTION

W. M. Brobeck
Radiation Laboratory
University of California
Berkeley, California
May 4, 1956

ABSTRACT

Several possible means of utilizing the energy that could be released by deuteron and triton reactions are considered. Whether the energy would be first converted to heat and then to electricity by conventional means, or directly to electrical energy by "electromagnetic" effects, the principal problem is still how to bring the ions close enough together to react. Any possibilities so far considered would involve temperatures, pressures or fields (electrostatic or magnetic) never yet approached or considered attainable. Yet ways may perhaps be found of approximating conditions known to exist in stars if the action of a magnetic field can be made to "contain" ions somewhat as gravitation concentrates stellar material. Three magnetic field configurations now being studied are discussed. Some advantages of fusion reactors over fission reactors--in cost and in safety--are listed.
By thermonuclear energy is meant the release of nuclear energy through collisions occurring in a gas. The random motion of the molecules of a gas which occurs at all temperatures above absolute zero is referred to as thermal motion. Thermonuclear energy production can be contrasted with the energy production of a directed beam of nuclei such as is produced by a particle accelerator when it strikes a stationary target. Such directed beams are, of course, widely used to study the reactions produced and the energies released, but the energy required to produce the beam (in the form of the kilowatts used by the accelerator) is always far greater than that developed in the reactions. Uncontrolled (comparatively) thermonuclear energy production occurs in the explosion of a hydrogen bomb. In the practical thermonuclear release of energy the energy produced must be sufficient to enable the reaction to proceed, just as the heat released by a bonfire must keep the combustible materials above their ignition temperature.

Reactions

The major part of the energy is expected from the following reactions:

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<th>In charged particles</th>
<th>In neutral particles</th>
<th>Total</th>
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<td>$d + d \rightarrow t + p$</td>
<td>4.0</td>
<td>-</td>
<td>4.0</td>
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<td>$d + d \rightarrow He^3 + n$</td>
<td>0.8</td>
<td>2.5</td>
<td>3.3</td>
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<tr>
<td>$t + d \rightarrow He^4 + n$</td>
<td>3.5</td>
<td>14.1</td>
<td>17.6</td>
</tr>
<tr>
<td>$5d \rightarrow He^3 + He^4 + p + 2n$</td>
<td>8.3</td>
<td>16.6</td>
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$d + d \rightarrow t + p$ means that two deuterons passing near enough to each other at sufficient relative velocity react, producing a tritium nucleus and a proton. The reaction energy of 4 million electron volts from one reaction (two deuterons) appears as kinetic energy of the triton and the proton, divided in this case in inverse proportion to the masses of the particles. The first two reactions are about equally probable, i.e., half the deuterons produce $He^3 + n$ and half $t + p$. The triton formed immediately reacts with another deuteron, owing to the large cross section of the $t-d$ reaction. From the over-all accounting 5 deuterons are consumed and 24.9 Mev released, one-third of which is in the form of kinetic energy of charged particles and two-thirds in the kinetic energy of neutrons.
The above reactions are not the only ones that might be of interest. Additional energy might be obtained by the reaction of the helium-3 with deuterons, or by the neutrons with absorbing material such as lithium. The main features of the process are illustrated by the t-d and d-d reactions, however.

The reaction energy would reach the bus bars either by first being converted into heat, or directly by the reaction of the moving charges on a containing magnetic field. In the first case heat would be developed where the reaction products strike absorbing materials. The neutrons would bury themselves in lithium, water, or other material, where they would give up their kinetic energy to raise the temperature of the absorber. In the case of water, steam would be formed, which would expand through conventional turbines driving electric generators. The charged particles would give up their kinetic energy close to the surface of the first solid that they struck, and the resulting heat would have to be transferred to a fluid—water for instance—from which it would be extracted by expansion in turbines as before. Direct conversion of the energy of the moving charges has the possibility of considerably higher efficiency, with the use of less expensive equipment, than required by the conversion to heat and then to mechanical energy in a steam turbine.

The energy released per deuteron is seen to be about 5 Mev. At the commercial price of heavy water of 25 cents per gram, assuming a thermal efficiency of 33%, the fuel cost per kilowatt hour comes out to about 0.03 mil compared to about 3 mils for coal.

**Operating Conditions**

In order to approach closely enough to react in spite of their electrostatic repulsion the hydrogen ions (deuterons or tritons) must be moving at high velocity. The velocity required for useful reaction rates corresponds to a kinetic energy per atom of the order of 10,000 electron volts, which is the average energy of the particles of a gas at a temperature of about 100,000,000° C.

Assuming that some means exists for handling such a gas, we can consider the dependence of its power output on pressure and temperature. The cross sections for the reactions increase with the velocity of the particles, as also does the number of particles that cross a given area. The number of collisions also depends on the number of ions in a unit volume—that is, the density of the gas. The power output per unit volume of gas can then be expressed as $P = \overline{\sigma V n^2}$ where $\sigma$ is the cross section, $V$ the velocity, and $n$ the number of particles per unit volume. The bar indicates that $\overline{\sigma V}$ is the average over the distribution of velocities. $\overline{\sigma V}$ increases with temperature above a threshold of around 1000 electron volts. In a given reactor, however, the pressure would undoubtedly be limited, so that increasing the temperature would decrease the density of ions. Therefore, as the temperature is increased the power density would be expected to go through a maximum at about 100,000,000°.

From the density and temperature of the reacting gas the pressure can easily be calculated ($PV = MRT$). It comes out that for reasonable powers, pressures of a few thousand pounds per square inch are desirable. Even with
these pressures the density is very low, owing to the necessarily high temperature. For example, with deuterons at a temperature of 100,000,000° K and a pressure of 1000 psi, the density is $10^{-4}$ that of hydrogen at room temperature and pressure, and the total rate of heat generation 300 kw per cubic foot. Increasing the pressure at a constant temperature would increase the ion density in direct proportion, and the power density would increase as the square of the pressure, without limit.

An equal mixture of deuterium and tritium should give about one hundred times the power density of straight deuterium at the same operating temperature and pressure. The practical difficulties of the high cost and poisonous nature of tritium may not be important compared with the other difficulties in producing the reaction.

The high-temperature gas, even though ideally insulated from its surroundings, can still radiate energy in the form of soft x-rays, called bremsstrahlung. This radiation is well understood and is known to increase according to the square of the density times the square root of the temperature. As this loss occurs at temperatures below the threshold for the thermonuclear reaction, some independent means of heating must be employed to raise the temperature to a point at which the reaction energy exceeds the bremsstrahlung loss. This is in contrast to the production of energy by fission, which can start at room temperature as two blocks of uranium are brought together.

The Design Problem

A practical reactor must then provide a means of containing a gas at a temperature of the order of a billion degrees and a pressure of a few thousand or at least a few hundred pounds per square inch. Obviously any conventional pressure vessel would immediately vaporize if subjected to such temperatures. Reactors actually exist in nature, however, in the form of the stars. In this case the pressure is resisted by gravitation. The stars have enough mass to develop internal pressures of the required amount and by their hanging in space the troublesome problem of their support is solved. This solution is obviously impractical on earth--or even as a satellite--because of the very large size required to provide sufficient mass at the low density.

Schemes for reactors therefore must be based on containing the gas without the use of material walls or gravitational forces. By analogy with the gravitational field used for containment in the stars, one naturally thinks of the use of electric or magnetic fields in some way. Electromagnetic containment is reasonable because any gas at the temperature considered is a good electrical conductor. This is because the electrons are stripped from the nuclei of the atoms at a much lower temperature, owing to the high relative velocities of the particles, and the gas consists of a mixture of electrons and positive ions called a "plasma". A plasma acts very much like a metallic conductor, as, in both, large currents can be carried with low voltage gradients owing to the presence of easily moved electrons.

Pressure can be associated with either an electric or a magnetic field by defining it as energy density. This may seem an abstract relationship, but in any practical device in which electric or magnetic fields exert
forces the force per unit area—i.e., the pressure—is limited to the energy per unit volume of the field. This pressure can therefore be expressed as

\[ P = \frac{E^2}{1.5 \times 10^9} \quad \text{or} \quad \frac{B^2}{1.7 \times 10^6}, \]

where \( P \) is in lbs/in\(^2\), \( E \) in volts/cm, and \( B \) in gauss. It can be seen that for a pressure of 1000 psi an electric field of 1.2 million volts per centimeter or a magnetic field of 40,000 gauss is involved. The high electric field makes an electrostatic type of containment appear impractical for this reason alone. The use of a magnetic field, however, still seems reasonable from this standpoint.

The trick then is to arrange a magnetic field to push on the reacting gas in all directions. To anyone familiar with magnets this seems a formidable if not an insoluble problem. However, there seem to be possibilities. These arise from the fact that the confinement need not be perfect. It is only necessary to confine the hydrogen ions until a sufficient fraction have reacted. After this the reaction products can be allowed to escape. Going a little further, it is clear that the life of the deuterons will have a wide range of values depending on how soon after it is ionized a deuteron hits another deuteron approaching at sufficiently high speed. It is not necessary to hold every deuteron until it has reacted. If the number lost because they haven't had a successful collision in the available time is small enough, operation may still be possible. The confining magnetic "tank" then can leak, provided the rate of leakage is not too great. In fact, such leakage may be necessary to get rid of the energy that appears in the charged particles.

That there will be a force on the plasma exerted by the magnetic field can be seen by the following argument. The force exerted on an ordinary low-temperature gas by a tank wall can be described by saying that the molecules striking the wall bounce off and are returned to the body of the gas. Now consider a conducting gas made up of charged particles all moving at high speeds. If a magnetic field is applied these particles start to move in circles. This motion of charges in circles is the same as a current in a circular loop of wire. The magnetic field produced by this current is in the direction to reduce the original field. This is the case for either positive or negative charges. The total field then is weaker near the center of the plasma, so that an ion moving out necessarily enters a stronger field. The stronger field tends to turn the particle back, just as the walls of a tank return the molecules that strike them.

In the direct conversion of the ion energy to electrical power, the circulating ion current would be made to generate a voltage in the field coils in the direction required to send power into the external circuit. This could be done by causing the field to move (through three-phase excitation, for example) so as to slow the ions down. Thus kinetic energy would be extracted electrically directly from the plasma. This conversion would be subject, of course, to the laws of thermodynamics, but in this case the maximum temperature would be millions of degrees and no material would have to withstand it. The Carnot efficiency could in principle approach close to 100%, compared with 40% or so for a present-day steam plant. The reaction of the ion current on the moving field would be closely analogous to the reaction of a jet on the blades of a turbine, but in an entirely different physical situation. A particularly attractive feature of this scheme is that the coils producing the traveling
field might be connected directly to the outgoing electrical circuit and the ma-
chine operated in the same manner as an induction generator.

We can now see some of the qualitative requirements of a thermonuclear
reactor. It must:

(a) confine the reacting gas.
(b) heat the gas to the reacting temperature.
(c) remove the reacting energy in a practically useful form.

In addition, to be of practical value it must be economically compet-
tive with other methods of power generation available at the time.

Cost Considerations

A list of the items going into a cost comparison may be instructive
here, even though a quantitative discussion is not now possible.

Income

1. Sale of power. The price of power at a time at which thermonuclear energy
might become competitive may be higher than at present.

2. Irradiated products. A large neutron flux will be produced in operation
which can be used to produce valuable isotopes. Tritium, plutonium, and ura-
nium-233 are obvious examples. Others might be salable at the time operation
becomes feasible.

Expense

1. Fuel. The cost of deuterium as a fuel would be only about 0.03 mil/kw-hr
at today’s commercial price.

2. Investment charges. Reduction of the capital investment per kw of output
will be a major problem. Little can be said today about what figure might be
reached. A large inventory of lithium and tritium might be required.

3. Transmission costs. To reduce the capital cost per kw an extremely large
plant might be required. At present-day load densities this might require
transmission of the power an appreciable distance. However, continuing in-
crease in load with time may make this factor less important.

4. Maintenance and depreciation. Radiation damage might account for consid-
erable maintenance work, which would have to be done under radioactive con-
ditions.

Schemes Under Development

Three configurations of magnetic fields are being studied as possible
containing means. One, called the Stellarator, can be compared to a long
solenoid containing a vacuum tube. Such an arrangement should work well
except for losses at the ends. The first thought would be to eliminate the ends
by changing to a doughnut form. Even this, however, can be shown to lose
particles, owing to a drift at right angles to the axis of the tube. This drift
can be greatly reduced by twisting the doughnut into a figure eight. The Stellarator, therefore, has a centerline in the shape of a figure eight. The centerline length is something like 150 times the tube diameter, and a strong magnetic field parallel to the centerline is provided over most of the length. Special arrangements are to be made for removing the charged reaction products by devices called "diverters," for reducing the drift still further by "scallops" in the centerline at the turns, and for heating the gas to the reacting temperature by "magnetic pumps." Put together this becomes a formidable aggregation of engineering problems, but might be the only way of producing a reactor with a practical output.

The second device to be described is called the magnetic mirror machine. It relies on an increased magnetic field at the ends of the solenoid to reflect enough of the particles. This effect exists, but calculation of its magnitude expressed as a "containment time" is difficult and uncertain. Whereas the Stellerator is looked on as a dc machine, the mirror machine magnet would be pulsed or operated on alternating current. Heating would occur as the field rises, and there is a hope that the reaction energy of the charged products might be removed electrically by the effect of their circulating current on the electrical circuit of the solenoid coils. The machine would be analogous to a transformer whose secondary winding was the magnet coils and whose primary current was the circulating ions.

The third line of effort is to use the magnetic field produced by a current flowing through a gas to compress the current itself. This phenomenon, called the "pinch effect," has been known for some time and is only now beginning to be understood. Heating would be produced by pulsing the current.

In the two devices first described the confining magnetic field must be provided by an electromagnet, which is bound to absorb a large amount of power. The power required per unit length for geometrically similar coils is independent of the diameter, whereas the power generated in the thermonuclear reaction varies with the reacting volume or the square of the diameter. There should, therefore, be some diameter above which a useful output can be obtained. The fact that this critical diameter is rather large—in the Stellerator apparently around three feet—accounts for the large size (by present standards) of the machines considered. A study of the Stellerator as a producing reactor indicates an electrical power output of 5000 Mw, about 10% of the generating capacity of the nation, as an economical size. It seems possible that the economical size might be much smaller with the mirror principle.

All these methods and some others have been subjected to intensive mathematical analysis. Answers are sought to the two questions, (a) how long does the average deuteron spend in the plasma before being lost (i.e., the confinement time), and (b) is the configuration of the plasma pushing against the field stable? If not, how rapidly does instability develop?

Most of these ideas may seem quite visionary in terms of the machines and processes with which we are familiar. However, their relation to the practical generation of power is probably as close as the relation of the experiments with lodestones and frog legs to the present electrical industry.
Comparison with Fission Energy

It is interesting to compare the so-far-hypothetical controlled thermonuclear release of energy with the release of fission energy in a pile. The following differences can be noted.

1. The raw material, deuterium, is practically inexhaustible and is cheaper per unit of energy than uranium. The energy release per gram is four times as great, and per dollar probably 100 times as great.

2. The fuel can be used over and over without reprocessing.

3. There appears no danger of the thermonuclear reaction's running away. This hazard is a predominating factor in fission reactor design.

4. As the reaction is expected to occur in a gas, deterioration of the fuel, at least, will not occur. However, radiation damage to the rest of the machine is probably no less a problem than with uranium.

5. No highly radioactive waste products would have to be disposed of.

6. A controlled thermonuclear reaction on any scale is yet to be demonstrated, whereas production of power by fission has already been shown to be practical.
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