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PEACEFUL USES OF FUSION

Edward Teller

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PEACEFUL USES OF FUSION

by

Edward Teller*

The problem of how to release fusion energy in an explosion process has been solved several years ago. How to release this energy in a slow and controlled manner has proved to be a much harder question. This situation is in sharp contrast with the history of energy release from fission. One year of intensive work had sufficed to produce the first nuclear reactor in the early winter of 1942, while several more years were needed to perform the first successful nuclear detonation.

Among the reasons for this difference I should like to mention two which are simple and important:

FUSION AND FISSION

Fission energy is released by the mechanism of a chain reaction. The chain-carrying neutrons can be slowed easily. This facilitates a controlled reaction not only because the time that the process takes becomes longer but also because slow neutrons are more easily controlled by specific absorbers and other means. On the other hand, release of fusion energy is accomplished by a heat explosion, or to use the technical term, a thermonuclear reaction. The particles carrying that explosion will necessarily move with high velocity.

The second and more important difference is the following: The fission chain reaction is regulated by assembling the correct amounts of active materials and absorbers. If the correct amount is exceeded the energy release rises in a rather slow manner due to the role of delayed neutrons. In contrast, the main regulating feature in a fusion reaction is the temperature. When a certain ignition temperature has been exceeded, the reaction itself raises the temperature and leads to an exceedingly rapid acceleration of further energy release.

Slow energy release is possible only at low densities; but this raises further problems.

HISTORY

The problem of controlled fusion is difficult but not necessarily insoluble. Some of us have discussed it in a rather detailed manner during the war, in Los Alamos. This group included Enrico Fermi, John von Neumann, James Tuck, and Luis Alvarez.

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Some elementary general facts were recognized at that time: That deuterium gas could react¹ above an ignition point of approximately 35 kilovolts; that deuterium-tritium mixtures could react² at a considerably lower temperature of a few kilovolts; that the gas should be introduced at an exceedingly low density of approximately 10^{14} to 10^{15} particles/cubic centimeter in order to make the reaction rates sufficiently slow and in order to avoid excessively high pressures; that at these high temperatures the gas will be completely ionized (such an ionized gas is called plasma); that with the help of magnetic fields the ions in this plasma can be forced onto spiral paths and that by appropriate arrangement of the magnetic fields the losses to the walls can be reduced; that the pressure of the plasma on the field leads to a thermal expansion of the plasma which tends to stabilize the reaction; that equilibrium with radiation is not established and that the energy emitted as bremsstrahlung should be treated as a loss; that for this reason atoms other than hydrogen isotopes must be eliminated as completely as possible; and that even the equilibrium between electron and positive ion energies will not be complete at the highest temperatures. Very particularly it was also noticed that in a simple closed field distribution along a torus the particles will not continue indefinitely to spiral around the same magnetic line of force but that they will drift in a direction perpendicular to the magnetic lines and to the gradient of the magnetic lines. This leads to smaller but nevertheless prohibitive wall losses. For the time being, no experimental work was undertaken for the specific purpose of carrying the theoretical considerations into practice.

In 1952 and 1953 under the stimulus of a successful man-made release of thermonuclear energy such an experimental approach was started. To a very great extent this was due to the initiative and confidence of the chairman of the Atomic Energy Commission, Lewis L. Strauss. It was recognized that the problems of heating and containing the plasma would be extremely difficult. For this reason several parallel approaches were undertaken which between them amounted to an attack on plasma research on a broad front.

THE PRESENT APPROACHES

Two of these approaches, the pinch and the stellarator, were based on the idea of containing the plasma in an annular region. The main difference between these two approaches is that in the pinch an axial current is established with magnetic lines of force encircling the current while in the stellarator the roles of current and magnetic lines are reversed with the principal currents established outside the reacting region. In the United States the work on the pinch effect has been started by James Tuck in Los Alamos. Later, similar work was undertaken in the University of California Radiation Laboratory by Baker and Colgate, and still later at other sites. Nicholas C. Christofilos proposed an ingenious steady-state arrangement, the Astron, which bears some similarity to the pinch effect.

At the very beginning of the thermonuclear program, the stellarator was proposed by Lyman Spitzer and work on it was carried out in Princeton.

Taking an entirely different approach, the advantages of a confinement geometry based on externally generated, cylindrically symmetric magnetic fields were recognized by Richard Post and Herbert York. Starting with these

concepts, Post evolved an approach which has come to be called the "Mirror Machine" which uses various applications of the magnetic mirror principle in its operation. In this magnetic mirror machine the ions are spiraling along magnetic lines between two regions in which the magnetic field is more intense and where the ions are reflected. This kind of machine is now under study at the Radiation Laboratory, at Oak Ridge National Laboratory, and at Los Alamos.

A COMPARISON OF THE APPROACHES

Each of these proposals have their peculiar advantages and their peculiar difficulties. The pinch effect is based on an earlier idea of Willard Bennett³ who derived the relations according to which a violent gas discharge will contract to a narrow filament under the influence of its own magnetic field. The great virtue of this scheme lies in the fact that starting from a rather moderate plasma density one can push the system to very much higher densities and pressures and at the same time expose the containing system to much more moderate pressures. One price that one has to pay is that the high densities are obtained only for short periods. In other words, we are dealing with a pulsed machine. In order to avoid instability and breakup of the pinch, the original simplicity of the concept had to be compromised by introducing magnetic fields parallel to the direction of the plasma current. The detailed theory of the pinch contraction as well as the theory of pinch stabilization was worked out by M. Rosenbluth in Los Alamos.

Rather early in the game it was noticed that the pinch effect in deuterium gives rise to copious neutron emission. The first public announcement of this fact was made by I. V. Kurchatov.⁴ Unfortunately these neutrons do not appear to be of thermonuclear origin. Considerable progress has been made by S. Colgate in explaining the mechanism by which these neutrons are produced. A general difficulty in the pinch effect seems to arise from the circumstances that during the formation of the high current filament most of the original energy output is lost to the walls. It seems of the greatest importance to understand and prevent these losses.

The Astron is based on the following observations: In contrast to the instability of the pinch current it is expected that a current of relativistic electrons will be stable. If this proves to be correct one can confine a plasma in the field which encircles this relativistic current for a longer period. This arrangement is under development in Livermore.

The thorough theoretical studies of the stellarator, carried out by Spitzer, Kruskal, Frieman, and others, led to the recognition that the simplest arrangements of magnetic lines are unstable in this case also. In order to prevent these instabilities, additional magnetic fields are being introduced in a direction perpendicular to the original fields. Thus the present pinch and stellarator designs are no longer as sharply different as they used to be. However, the stellarator continues to be a device in which steady-state operation will be attempted and in which the main magnetic fields will originate in a region outside the plasma. The problem of heating the plasma in the stellarator has turned out to be a rather difficult one. The first step in the heating process is by ohmic current, but soon the conductivity of the

plasma becomes high and instead of uniform heating, runaway electrons are produced. From this point on, heating is accomplished by transferring energy from magnetohydrodynamic motions to the particles in the plasma. This so-called magnetic pumping process bears a similarity to the acceleration of cosmic rays as described by Fermi. Unfortunately, in the stellarator as in the pinch a very considerable fraction of the energy is lost during the heating process. The heating derived from hydromagnetic shocks has been investigated by H. Grad at New York University, M. Rosenbluth at Los Alamos, and others.

In the evolution of the mirror machine the basic simplicity of the original design has been maintained. In addition to this advantage, the straight geometry makes it possible to operate in a relatively small volume.

An obvious disadvantage of the magnetic mirror machine is the loss of particles through the mirrors. In fact, all particles get lost whose motion includes a sufficiently small angle with the magnetic lines. In the course of time more and more particles will be scattered into these orbits and eventually all of the plasma escapes. Detailed calculations have shown that escape through the mirrors is a serious consideration but that it does not rule out the mirror machine as an effective thermonuclear energy generator. Furthermore, the end losses can in principle be reduced by inducing a rapid rotation of the plasma. The open ends of the machine also lead to an advantage: a simple possibility of injection. One can introduce a sufficient quantity of high-velocity ionized material through these ends and thus, in contrast with the other machines, circumvent the problem of heating a plasma which is already present. In injecting fast ion beams difficulties have appeared due to space-charge limitation in the injection mechanism.

A radically different system of injection is being tried at Oak Ridge National Laboratory. This system consists in bombarding the interior of the mirror machine with D_2^+ ions. Inside the mirror machine the molecular ions get disassociated and the more strongly curved D^+ ions are caught. This procedure has made considerable progress. It may lead to the establishment of a steady-state plasma which is suitable for detailed experimental investigation. In any case a completely satisfactory density and temperature need not at once be obtained by the injection in the mirror machine because simple strengthening of the magnetic fields will lead to an adiabatic compression of the plasma which will increase both the density and the temperature.

The homopolar, conceived by William Baker at Berkeley, is another machine based upon mirror containment — but an enhanced containment, due to the large induced rotation of the plasma. Similar work on rotating plasmas (Ixion) is being done by Keith Boyer at Los Alamos.

There is one additional design which has received serious consideration but on which no actual experimental work has proceeded. The name of this design is the picket fence or cusp geometry considered by J. Tuck and H. Grad. It consists of a series of magnetic field systems so arranged that the magnetic fields curve at each point away from the space which is enclosed and which contains the plasma. At the juncture of any two of these systems the magnetic fields have a cusp through which the plasma can escape. The difficulties

connected with the rate of this escape has been the reason for not pursuing this particular design any further. It is by no means clear, however, that such a design could not be successful.

In later sessions a more detailed discussion will be given of the several designs. Here I should like to mention a few general difficulties and to discuss the way and extent to which these difficulties have been overcome.

SINGLE PARTICLE CONFINEMENT

One may consider the plasma from the point of view of the individual charged particles in a fixed field. The first and simplest question is whether or not a field of magnetic lines can retain ions on their orbits for a sufficiently long time. Since the ions slowly drift in a direction perpendicular to the magnetic lines of force and to the gradient of these magnetic lines, it is not clear that an effective confinement is actually possible. In a simple torus with longitudinal magnetic field, the charged particles spiral around closed magnetic lines of force. The inhomogeneity of the field causes them to wander off steadily to the walls.

In the stellarator the lines get twisted, with the result that a line no longer closes but instead returns, after a circuit, into the neighborhood of its starting point. If many circuits are executed, a single magnetic line will have closely covered a toroidal surface. Now an ionized particle in following this more complicated line of force will be subject to displacements due to the inhomogeneity of the magnetic field. One can show, however, that these displacements will average to zero in good approximation.

In the mirror machine an ion spiraling around a magnetic line of force performs a quasi-periodic motion due to oscillations between reflecting points. The periodicity of the orbit is not strict because it drifts to neighboring lines of force, as has been mentioned above. In a cylindrically symmetric case it is evident that the drift perpendicular to the line of force will map out a surface of cylindrical symmetry. But it is not evident where the particles will drift if there exists a nonsymmetric perturbation. The following consideration shows, however, that despite such a perturbation the particles do return to their original line of force with a high degree of precision.

During the periodic motion in a static magnetic field, the energy will be strictly conserved. Two "adiabatic invariants" are also very accurately preserved, even through they vary to a small extent. These are the magnetic moment of the spiraling particle in a direction along the magnetic line and the action $\int p_{\parallel} dq$. Here p_{\parallel} is the momentum of the ion (or the electron) along the magnetic line of force and dq is an element along the magnetic line on which the guiding center of the spiraling particle happens to move. The essential character of the orbit of a particle is determined if its energy and magnetic moment are known. From this the action $\int p_{\parallel} dq$ follows uniquely. If now the particle were to shift to an arbitrary neighboring line of force, conserving its energy and magnetic moment, the action $\int p_{\parallel} dq$ would in general be different. However, the action $\int p_{\parallel} dq$ must be conserved also. Therefore, a shift is not possible to an arbitrary neighboring line, but the guiding center of the particle must remain on a sheet consisting of a single continuous set of

magnetic lines of force. In this way the particle will shift around within the machine, remaining always on a surface on which the $\int p_{\parallel} dq$ is conserved. When the particle arrives back in the original neighborhood, it will as a general rule actually embrace the same magnetic line from which it had started. While this statement is not absolutely correct, it holds with a very high precision for small Larmor radii. Unfortunately, the conservation of the adiabatic invariants is not valid if the field varies with a sufficiently high frequency. Under those conditions, of course, the energy is not conserved either.

INSTABILITIES

Let us consider a time-independent distribution of magnetic lines of force in space, and let us also consider a static distribution of a plasma of vanishing electric resistivity. The magnetic lines need not be curl-free because we may assume electric currents in the plasma to account for the curl. No electric fields will be present: if they were parallel to the magnetic fields, they would give rise to a change in the electric current; while if they were perpendicular to the magnetic lines, they would cause the plasma to move, which is contrary to our assumption of a static situation.

Now the stability of this situation may be decided by investigating infinitesimal virtual displacements. In such a displacement the material of the plasma may slide along magnetic lines of force, but, in any motion transverse to the lines, the plasma and the lines must move together. Furthermore, any expansion or compression of the plasma accompanying the displacement must be considered as adiabatic. If some of these displacements lead to a linear change of the energy of the plasma, then the system is not in equilibrium. If all changes depend quadratically on the displacement, and if all infinitesimal displacements are connected with positive energy changes, then the plasma is stable. If some displacements are connected with negative quadratic terms we expect an unstable equilibrium. Many such instabilities have been discussed and the discussion has been carried to a detailed consideration of the way the particle distribution, magnetic fields and currents change during the displacement. The hydromagnetic consideration given above appears to be, however, a simple and general description which in many cases is satisfactory.

The first models that have been considered for the pinch machine and for the stellarator turned out to be unstable. Appropriate modifications of the field distribution have given rise to reasonable hopes for circumventing various troubles, but experience connected with the rather well-explored pinch effect seems to show that hydromagnetic instabilities continue to represent a considerable difficulty.

The general question whether a moving steady-state hydromagnetic system is stable or not has been discussed in some interesting special cases but has not been treated along similarly simple lines as has the corresponding static problem. These dynamic effects probably play a very important role during the constriction of the electric current in the pinch process and during the heating of the plasma in the stellarator. At the same time, runaway electrons (with velocities greatly exceeding the Maxwellian values) are produced. These probably give rise to plasma vibrations which also might arise by

coupling with the hydromagnetic motions. All these motions can generate enough disorder to destroy conservation of energy and conservation of the adiabatic invariants for the single particles which are supposed to be confined in the system. As a result both plasma and energy can be lost to the wall.

We see therefore that heating, plasma injection, and plasma compression do represent sizeable additional problems. These problems are, however, closely connected with the more general question of confinement. If the latter were solved completely, then we could take time with the other processes and probably execute them sufficiently carefully so that the plasma could be brought to the appropriate conditions. The actual fact is, however, that the problem of plasma confinement is solved only very partially and therefore this problem and that of the establishment of the right temperatures and densities have to be handled together.

EFFECTS OF IMPURITIES

Another difficulty that is quite generally encountered is connected with impurities. The presence of impurities leads to increased bremsstrahlung and consequent rapid loss of energy from the plasma. At temperatures low compared to the ignition point, these losses are often aggravated by radiation from incompletely ionized atoms. These partially ionized systems are usually not in Saha equilibrium, since of the four possible processes — collisional ionization, radiative electron capture, recombination by triple collisions, and ionization by photons — only the first two occur. This somewhat involved problem has been thoroughly investigated by Post and has led to the recognition that heating must be made to occur rapidly, particularly in the lower temperature regions.

If neutral atoms are knocked off the walls, these cause an energy loss by an additional mechanism: They can neutralize fast plasma ions by charge exchange and these fast neutral particles can cross the magnetic barrier and get to the wall. Here they can knock out more neutral particles and a loss mechanism can be built up.

EXPERIMENTAL DEVELOPMENT

The above enumeration of difficulties and problems is by no means complete. Neither does this theoretical discussion do justice to the experimental problems of machine design and to the diagnostic work which has been carried out. The development of extremely large pulsed condenser banks for creating the large volume, high magnetic fields required, and the operation of large "baked out" vacuum systems for high plasma purity at pressures as low as 10^{-10} mm Hg, are major achievements of the experimentalists. The observation of gross current and electric field behavior and the determination of magnetic field and plasma pressure by means of probes introduced into a system, have given valuable data. Plasma densities have been measured by experiments involving absorption and transmission of electromagnetic waves in the radar range. Spectroscopic observations have been carried out and the appearance and behavior of neutrons have led to additional knowledge about the state of the plasma. Thus our knowledge of plasma physics is increasing considerably with each passing year.

In this way important features of plasma theory have been experimentally verified. The interaction between magnetic pressure and hydrodynamic motions have been observed. Transport phenomena in the plasma have been investigated. These are greatly complicated by the effects of collective motions but when properly attacked have yielded satisfactory verification of our expectations.

Hydromagnetic motions have been extensively studied, most particularly in observing how a pinch is formed. In connection with the same experiment the evolution of instabilities has been studied.

In the stellarator, the mirror machine, and the pinch effect, the importance of impurities has been proved by studies of the influence that the wall materials have on the observed phenomena. In the case of the stellarator a very ingenious device, the divertor, has been developed which harmlessly dumps that part of the plasma which otherwise would get in touch with the wall and would give rise to the emission of disturbing atomic species. The use of this divertor has greatly improved the operation of the machine.

After proper precautions, temperatures of 100 electron volts or more have been reached in the various machines. This should be compared with a few thousand electron volts needed for the effective burning of a deuterium-tritium mixture. More than a hundred electron volts have been reached in the stellarator and still higher temperatures in the mirror machine. Proved temperatures in the pinch effect are a little lower but, on the other hand, greater densities have been obtained.

Perhaps the most important observable variable is the time of containment. In the pinch effect the time during which a high density prevails is only a few tens of microseconds. On the other hand, the working of this machine is in least need of protracted confinement times. In the stellarator, confinement times of a millisecond or more have been established. In the mirror machine, confinement times of several milliseconds are not unusual. This is particularly pleasing because of the small size (a few cm) and high electron temperature (more than 10 kev) of the plasma. Furthermore, in this machine no difficulties have arisen in connection with instability or disorderly motion. These times have to be compared with a period of approximately one second in which a successful thermonuclear reaction would double the original input energy.

NEUTRONS

Throughout the development it has been believed that production of true thermonuclear neutrons would be a milestone in the development toward controlled thermonuclear reactions. Such neutrons would not be merely encouraging but would at the same time give us a sensitive method of measuring temperature distributions within the machine.

In thermonuclear machines neutrons have been repeatedly observed. Unfortunately these neutrons may be due to some form of organized motion rather than to the random agitation of temperature. This shows in a most direct manner that we are still very far from a successful thermonuclear

machine. Furthermore, even where true thermonuclear neutrons will be obtained their effects could be at first obscured by the presence of the neutrons due to collective neutrons.

THE FUTURE OF THERMONUCLEAR POWER

The remaining difficulties appear, therefore, great enough so that it will take several more years before a machine can be constructed that produces more electric energy than it actually consumes. If that goal is reached the feasibility of controlled thermonuclear energy release will have been proven.

In a practical sense, however, the difficulties arising at that stage may be even greater than those with which we are struggling right now. It is likely that we shall be dealing with an intricate machine which is inaccessible to human hands because of radiation and on which all control and maintenance must proceed by remote control. The irradiation of materials by neutrons and gamma rays will cause the properties of these materials to change. Surfaces bombarded by the bremsstrahlung will get heated more fiercely than is the case in any portion of our present nuclear reactors. These and other difficulties are likely to make the released energy so costly that an economic exploitation of controlled thermonuclear reactions may not turn out to be possible before the end of the 20th century.

Nevertheless the ultimate goals toward which we are working are apt to be highly rewarding. Production of energy may not be the earliest practical fruit of the present extensive plasma research. Furthermore, when economic thermonuclear energy production becomes feasible we shall reap a number of important benefits.

The fuel of the thermonuclear reactors is cheap and practically inexhaustible. Thermonuclear reactors produce less dangerous radioactive materials and when once brought under control are not likely to be subject to dangerous excursions. Therefore, they can be operated more safely than fission reactors. Finally, the interaction of the hot plasma with magnetic fields opens up the way of direct production of electric energy. This may be of great practical advantage since high-temperature heat exchangers and many moving parts could be eliminated.

PLOWSHARE

This survey should not be concluded without mentioning another way in which thermonuclear energy can be made to serve peaceful and constructive purposes. Our recent investigations have led increasingly to the expectation that thermonuclear explosions can be brought sufficiently under control to be of help in earth-moving jobs, in mining, and conceivably even in the production of energy.

Recently an underground detonation of a fission device in Nevada has demonstrated the feasibility of the confinement of the energy of the bomb. Furthermore, this experiment has shown that the bulk of the radioactive fission products was entrapped in the glass from the molten rock. The energy in this case was primarily dissipated at low temperature in vaporizing the

relatively large water content of the rock, but in addition a very vast quantity of rock was crushed. This could be useful in mining and for the enhancement of the oil flow in large low-specific-yield formations.

In the peaceful use of nuclear explosives the fusion reaction is likely to play a prominent role for two reasons. One is that the fusion fuel is exceedingly cheap.

The other reason is that fusion reactions give rise to lesser radioactive contaminations. In fact, a careful planning of the fusion explosion can reduce the activity to a point where its effects are quite small compared to the effects from an equivalent fission reaction. This is particularly important in the earth-moving jobs designed to build harbors, canals, change the distribution of water, or lay bare mineral deposits.

It will be noticed that both the cheapness of the fuel and the reduction of radioactive contamination are the same factors which also play an important role in our future expectations concerning controlled fusion reactions.

There is no difficulty of principle in the release of large amounts of fusion energy underground; in the conversion of this energy into high pressure steam and in the use of this steam for the production of electricity. It is, however, important to find a cheap way of confining the explosion in order that the economical exploitation of explosive fusion energy for the production of electricity may become possible. It is not unreasonable to expect that explosive fusion energy can be harnessed for the production of electricity before the same feat can be accomplished in the controlled fusion process.

Even though the first application of thermonuclear power may be by using controlled explosions — and this would be a very great achievement indeed — in the long run the inherent advantages of controlled fusion in a steady-state system will probably dominate our planning for the far future.

In any case, I am convinced that the extraordinary and abundant power of fusion energy can be used in peaceful pursuits for the benefit of mankind. When this will be accomplished, it may well turn out to be one of the most important advances of our age.

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