Controlled Thermonuclear Research in the United Kingdom

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HISTORICAL

The possibility of utilising the energy released in nuclear reactions between the light elements was probably first discussed at the Cavendish Laboratory, Cambridge, in 1932. It was at this time that Lord Rutherford and his colleagues demonstrated that artificial nuclear reactions could be produced in the laboratory and that energy was released in each nuclear event. These reactions were produced by accelerating positive ions or nuclei to high velocities, using potential differences of hundreds of kilovolts, and firing them at a target containing the other elements. At low bombarding energies these reactions were found to be most probable with the light elements.

No direct application of their discoveries for power generation was foreseen; in fact, Lord Rutherford described such speculations as "moonshine". At best, only 1 in 10^5 of the bombarding particles reacted with a target nucleus, the remainder being brought to rest by unproductive energy losses to the target atoms.

It is the intention of controlled thermonuclear research to find an efficient way of utilising the energy produced when light elements react together to form heavier ones. Such a process occurs at the centre of the sun and in other stars under conditions of immense pressures and extreme temperatures. It is altogether impossible to reproduce similar conditions in the laboratory. Fortunately, there are nuclear reactions which occur much more easily than those responsible for the sun's energy, but even then extremely high temperatures are believed to be necessary.

The concept of thermonuclear reactions providing the energy radiated by the stars was clearly put forward by Atkinson and Houtermans ¹ in 1928, but no suggestions for achieving a similar energy source on a terrestrial scale were seriously considered in the United Kingdom until 1946.

It was clear that the high temperatures necessary could not be reached unless some means was devised for keeping the hot gas away from the walls of the containing vessel. Experimental investigation of the confinement of a hot, electrically-conducting gas by magnetic fields was started by Sir George Thomson in London in 1947 and by myself in Oxford in 1948. These independent programmes attracted Government support in 1948 and continued in the two Universities until 1951.

Several possible magnetic field configurations were studied in relation to toroidal tubes but confinement by the self-magnetic field of a current flowing in a gas appeared the most promising. Some of the results of this early work were published in 1951.²⁻⁴ Figures 1 and 2 show the type of apparatus employed at that time. In 1951 the London group moved to the Research Laboratory of Associated Electrical Industries, Aldermaston, and the Oxford group to Harwell. A small team at the Atomic Weapons Research Establishment began in 1956 to pay special attention to the interesting features of the dynamic pinch.

It will be appreciated that this subject involves almost the whole range of classical physics included in the electromagnetic spectrum—from steady electrical currents to X-rays. Measurements of ionisation and excitation cross-section of multiply charged ions are now required together with further development in the basic theory of particle transport processes and in the new subject of magnetohydrodynamics. Perhaps it is not surprising that progress is slower than one would wish.

We have now reached the stage of producing deuterium plasmas at temperatures in excess of 10^6 °K for appreciable intervals of time. At these temperatures we can study some of the phenomena which are likely to occur in a fusion reactor. Whilst other approaches to the problem of producing and maintaining a very high temperature gas will undoubtedly be described to this Conference, research in the United Kingdom has been devoted to a study of gas confinement by the "pinch effect"; that is, confinement by the magnetic field which accompanies an axial flow of current through the gas. Many other possible methods have been studied at earlier times but none appeared so promising.

The size of the apparatus employed depends to a large extent on the time for which the electrical currents are required to pass through the gas. Thus the group at the Atomic Weapons Establishment are interested in extremely short times and a rapid increase in discharge current. A recent form of their

apparatus is shown in Fig. 3. The essential feature of the equipment lies in the use of a large number of separate switches (spark gaps), synchronously triggered so as to connect in a parallel arrangement the large number of capacitors that form the total bank. This reduces the inductance of the circuit external to the discharge to a very low value. At the other end of the time scale is the Zeta apparatus at Harwell. The discharge in the gas takes place in a toroidal vessel for longer periods of time and at much lower gas densities. Figure 4 shows a general view of the arrangement. In between these two extremes is the Sceptre device at the Research Laboratory of Associated Electrical Industries which is similar to Zeta but which has a more rapid rate of current rise. This apparatus is shown in Fig. 5.

THE BASIC FUSION PROCESS

I now turn to a short discussion of the basic fusion process. What is fusion and where does the energy come from? In order that a nuclear reaction takes place between two charged nuclei these particles must be brought close together against the Coulomb repulsion of like charges. As an example, consider the fusion of two nuclei of deuterium. When the nuclei approach within the range of the attracting nuclear forces, about $10^{-13}$ cm, we can speak of a compound nucleus of two neutrons and two protons. This nucleus is similar to that of ordinary helium.

The compound nucleus can break up in the three ways described by the following equations

$$ H^2 + H^2 \rightarrow (He^4) \xrightarrow{\ast} H^3 + n + 3.25 \text{ Mev} $$
$$ H^3 + H^1 \rightarrow H^2 + H^2 + 4.03 \text{ Mev} $$
$$ H^2 + H^1 \rightarrow 3.25 \text{ Mev}. $$

In the first two cases, the new nuclei Helium 3 and Tritium are formed. The third case corresponds to simple elastic scattering and no energy is released.

Because three of the attracting nuclear particles come much closer together, forming a new stable configuration, the fourth is ejected with the energy difference. This energy difference $\Delta E$ may be calculated from the mass difference $\Delta M$ between the initial and final nuclei taking part, according to the well-known equation $\Delta E = \Delta M c^2$.

At the particle energies of interest in thermonuclear research the probability of elastic nuclear scattering is much greater than the probability of a nuclear reaction. On the average, therefore, a fuel nucleus will make many elastic collisions with other nuclei before a reaction occurs and any ordered motion initially present will be completely disorganised before appreciable energy is released. For this reason, a fusion power source will almost inevitably be a thermonuclear process since nuclear reactions take place as a result of impacts between particles with thermal or random motion.

To calculate the minimum temperatures required for a net energy gain, the conditions under which a high temperature gas can be confined must be discussed in more detail. It is essential that there be an equal concentration of negative and positive charges, otherwise the resultant electric fields would be so enormous that confinement would be impossible. The presence of electrons leads to electromagnetic radiation due to the acceleration of electrons as they are deflected by the positive nuclei. This radiation escapes without absorption in the tenuous gas and no radiative equilibrium is possible. The energy radiated is many orders of magnitude less than that from a black body at the same temperature.

Consider a cycle in which electrical energy is used to heat the gas and maintain it at a high temperature. Energy must be supplied continuously to make up the radiation loss. This energy can be recovered only as heat, some 70% of which is lost in its conversion back to electrical energy. To make up the deficit, the energy released by nuclear fusion must be at least twice the energy radiated. Both the energy radiated and the nuclear energy released can be calculated. The minimum temperature turns out to be about $3 \times 10^7 \, ^\circ \text{K}$ for a deuterium–tritium mixture and $3 \times 10^8 \, ^\circ \text{K}$ for pure deuterium fuel. At these temperatures the fuel nuclei have energies corresponding to about 3 kev and 30 kev. This is small compared to that attainable in modern particle accelerators. The difference lies in the much higher particle densities needed.
necessary and the requirement of confining the particles in spite of repeated collision.

The margin between success and failure is narrow. Under the best conditions, the rate at which deuterium gas produces nuclear energy is only about ten times the rate of radiation from the same gas. For a tritium-deuterium mixture the factor is a hundred and it is likely that the first successful fusion reactor will employ this fuel. At the present time the use of fuels other than the hydrogen isotopes appears to be excluded, first by the enhanced radiation due to the higher nuclear charge and secondly by the slower reaction rates.

The previous discussion has assumed that the charged particles, nuclei of deuterium and electrons, are perfectly confined and only electromagnetic radiation reaches the walls of the surrounding vessel. It is the problem of particle containment which is the principal stumbling block at the present time. Gravitational fields are not available and the next best thing is a magnetic field. Whilst it is possible, in principle, to confine a high temperature plasma by rapidly oscillating electric fields, all methods studied experimentally in the United Kingdom have employed strong magnetic fields.

A high temperature gas is a good electrical conductor because of the free electrons. The force acting on an element of the gas, carrying an electric current normal to a magnetic field, can be used to balance the kinetic pressure of the gas, \( \mathbf{p} = n\mathbf{k}T \). A static balance of pressure is ensured if \( \nabla \cdot \mathbf{p} = \mathbf{J} \times \mathbf{B} \) where \( \mathbf{J} \) is the current density and \( \mathbf{B} \) the magnetic field.

The current density \( \mathbf{J} \) in the plasma may be produced by an external emf or it may result from the slow expansion or diffusion of the charged particles across the magnetic lines of force. In the latter case, new energetic particles must be introduced to maintain a steady state. There are several possible solutions to this equation, but all must satisfy two conditions. First, the net force acting on the gas as a whole is zero, and second, any displacement of the gas from a position of equilibrium must lead to a restoring force.

This restoring force must be produced by the interaction of electrical currents in the plasma and currents in external conductors, because any force due to particles striking the walls is to be made zero. The first condition is satisfied by the magnetic field associated with the flow of current in a cylindrical conductor and gives rise to confinement of the plasma by the pinch effect. The second condition is satisfied by enclosing the current channel in a cylindrical conductor. Any displacement of the current channel away from the axis of the cylinder results in currents in the outer conductor which, by Lenz's law, oppose the motion. Both the Zeta and Sceptre experiments have employed this principle.

**INSTABILITY**

The greatest difficulties we have experienced in reaching high temperatures is the instability of a magnetically-confined plasma. Satisfying the above conditions only ensures that the plasma as a whole is in stable equilibrium but tells us nothing about the behaviour of a local deformation. Trying to stabilise a plasma against these deformations is rather like trying to balance a ball on the end of a stick. To be successful, you have to be either very experienced or very clever. The lowest state of "stored energy" is undoubtedly on the ground or, in the case of a plasma, at the walls. The best that can be done is to delay the transition for as long as possible.
Charged particles moving in a static magnetic field can only cross lines of force between regions of different magnetic fields strength as a result of collision or longer range electric fields. Collision with other particles are unavoidable and the rate of diffusion to the tube walls is not prohibitive in most cases of practical interest. The effect of longer range electric fields is much more serious. I do not refer to those electric fields which are responsible for ordered current flow in the plasma but to local electric fields arising from charge separation or by magnetic induction. If an electric field exists normal to the confining magnetic field, plasma may flow across the lines of force at a velocity given by $v = Ec/B$. Thus, a random fluctuating electric field will allow a plasma element to make a random walk with the above speed and it will drift steadily away from its starting point across the lines of force.

Many magnetic field configurations for achieving stability have been suggested and the search is still in progress. The theoretical work of Shafranov, Tayler, Bickerton and Rosenbluth on the pinched discharge stabilised by an axial magnetic field has guided the experiments in the United Kingdom but I cannot say that we have achieved the configuration demanded by the theoreticians nor can they say they understand the stability achieved in the Zeta and Sceptre experiments.

THE UK CONTRIBUTION

The principal UK contributions to this Conference are concerned with the results of the Zeta and Sceptre experiments and the fast pinch experiments in straight tubes at the Atomic Weapons Research Establishment. Preliminary results obtained at Harwell and the Laboratories of the AEI have already been reported. Both experiments are essentially high current discharges in toroidal metal vacuum vessels in which an axial magnetic field is used to provide stability. Since the earlier reports, efforts have been made to understand the manner in which the current channel is formed and to explain the stability. Measurement of ion energies, X rays and neutron intensities have been extended, and the role played by impurities investigated. These results, together with details of the construction, will be reported in later sessions. A full account of the experimental methods used to obtain these results will also be given.

The AWRE group has studied the effect of the rate of current rise on the discharge properties as well as the effect of an axial magnetic field and impurities. They have observed some new phenomena which will be reported in detail in a technical session.

The theoretical investigations to be reported are concerned, firstly, with the structure of hydro-magnetic shock waves in a fully ionised gas and, secondly, with the stability of a magnetically-confined plasma. The first subject is of importance in fusion research because shock waves provide a powerful mechanism for communicating energy to positive ions, even when collisions are rare. It is very likely that the transfer of energy by binary collisions between electrons and positive ions will be too slow to reach fusion temperatures in the times required. The importance of the second object has already been pointed out. The principal theoretical objective is to devise an ideal model in which particles cannot reach the vessel walls because of instabilities. This does not mean that instabilities should be completely suppressed but that their amplitude must be limited. Further details along these lines will be presented, together with a discussion of the relevance of the results to the performance of Zeta and Sceptre.

The emission of impurities from the walls of the containing vessel plays an important role, both in the amount of energy radiated by the gas and in determining the magnetic field configuration. When the walls are conducting, the formation of arc spots and vapourisation of wall material is a potent source of impurities. The mechanism of arc formation has been studied as well as the motion of arc spots in magnetic fields. Investigations on both these aspects will be reported.

FUTURE TRENDS

I now turn to the future of research in the controlled fusion field. To my mind, the problem of stability is of paramount importance. Unless the rate at which charged particles cross magnetic lines of force can be reduced to that given by classical diffusion theory, the loss of energy to the walls will prevent fusion reactions from becoming a practical power source. A decrease in the energy flux to the walls by
particle bombardment also reduces the amount of impurities thrown into the plasma and this in turn reduces the energy loss by radiation.

Assuming that the stability problem is solved, it is estimated that currents of about 10 million amperes will be required in a tritium-deuterium mixture before a net balance of power is achieved using self-magnetic confinement. In a tube of reasonable dimensions, these currents must continue for at least one-tenth of a second. Achieving such current amplitudes clearly presents difficult technological problems. I think that the papers to be presented at this Conference, and the discussions which follow them, will show that it is still impossible to answer the question, "Can electrical power be generated using the light elements as fuel by themselves?" I believe that this question will be answered in the next decade. If the answer is yes, a further ten years will be required to answer the next question, "Is such a power source economically valuable?"

REFERENCES