Research on Controlled Thermonuclear Reactions in the USSR

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The idea of developing controlled thermonuclear reactions for power generation by utilizing the synthesis of light atomic nuclei has been expressed time and again in the past. But it is only after many years of preparatory work, the results of which were not tangible earlier, that justified hopes have arisen as to the possibility of finding a successful solution to this problem. A rapid expansion of the scale of research followed, and now the development of ways of attaining controlled thermonuclear reactions has become the most important problem of atomic engineering.

The trend towards a lessening of the rigid bounds of secrecy that had earlier so fully isolated physicists working on this problem in the different countries from one another was important in speeding up scientific investigation. As long as the dominant doctrine in this field was that the danger of publishing one's scientific results cannot be balanced by the advantage to be gained through scientific information from abroad, research languished. A significant change occurred in 1956, when certain results of work done in the USSR were disclosed for the first time. This was followed by the gradual emergence of publications from England and the USA. It was then possible to begin some sort of an exchange of ideas and experience—a thing of incalculable value in attacking such a scientific and technical enigma as is the problem of controlled thermonuclear reactions.

In spite of the wide range of the investigations for controlled thermonuclear reactions, all of them are still in the stage of exploring various approaches to the problem. Not a single one of these approaches has been explored to such an extent as to permit one to say that success is assured. Apparently there is only one conviction that seems to be generally accepted, and that is that the solution of the problem must follow from a correct choice of the technique of magnetic confinement (thermoinsulation) for practical realization of the general idea of confining hot plasma by strong magnetic fields.

Methods of utilizing a magnetic field for the purpose of thermoinsulation and heating of plasmas may be divided into two basic groups. One group includes methods of accelerating the plasma by electrodynamic forces; the other, methods of obtaining equilibrium plasma configurations, that is, states in which the pressure of the plasma is balanced by magnetic pressure. The difference between these two groups of methods becomes more distinct if we express it in terms of magnetohydrodynamics, which deals with the general laws of behavior of a conducting fluid in a magnetic field. Under certain conditions which we shall assume fulfilled, the plasma may be regarded as analogous to a conducting fluid, macroscopically speaking. The equation describing the behavior of a plasma under the action of electrodynamic forces is

\[
\frac{d\mathbf{v}}{dt} = \frac{1}{e} \mathbf{j} \times \mathbf{H} - \nabla p
\]  

where \(\mathbf{v}\) and \(p\) are respectively the velocity and density of an elementary volume of plasma moving under the action of electrodynamic forces and a pressure difference. The electrodynamic force acting on a unit volume of plasma is represented by the first term on the right-hand side of the equation. It is due to the interaction between the magnetic field and the currents flowing in the plasma (\(\mathbf{H}\) is field strength and \(\mathbf{j}\) is current density).

A glance at this equation is sufficient to see that two extreme cases are possible, each characterizing a large group of confinement methods.

If the gas kinetic pressure is relatively small, the electrodynamic force will be balanced by "inertial forces":

\[
q \frac{d\mathbf{v}}{dt} = \frac{1}{c} \mathbf{j} \times \mathbf{H} .
\]

Under these conditions, the plasma as a whole will acquire under the action of electrodynamic forces a directed velocity which may considerably exceed the random thermal velocity of the ions. The kinetic energy of directed motion due to acceleration of the plasma in the magnetic field may then be utilized for subsequent heating of the substance (in processes...
of the implosive compression type, during impact of accelerated plasmoids on a target, etc.). Some concrete techniques of such utilization will be described below.

Characteristic of this type of plasma–magnetic field interaction is the short duration of the process. In order of magnitude it is equal to \( a/v \), where \( a \) is the distance traversed by the plasma under the action of the accelerating forces, and \( v \) is the velocity attained. In cases of practical interest, the duration of this acceleration process should be of the order of \( 10^{-6} \)–\( 10^{-5} \) sec. Obviously, such momentary pulsed processes will be of considerable interest only if it is possible to utilize them as the first phase in heating the plasma. This phase should result in the transformation of kinetic energy into heat and in the transition to some quasi-stationary state in which the rapid inertial motions remaining after the first phase should damp out within a very short time.

An opposite case will occur if acceleration of the plasma is small and if the “inertial term” on the left-hand side of the equation may be disregarded compared with the pressure gradient. In this case the gas-kinetic and magnetic pressures balance each other for all times:

\[
\nabla p = \frac{1}{c} j \times \mathbf{H}.
\]

One may imagine a multiplicity of ways for attaining such equilibrium plasma configurations characterizing a quasi-stationary state of plasma in a magnetic field. At present the following trends appear to be emerging in more or less clear outline:

(a) Development of methods for confinement and heating of plasma in systems with large closed discharge currents which are maintained by an external voltage and stabilized by an external magnetic field;

(b) Research into magnetic traps in which a high-temperature plasma is produced by accumulation of fast particles injected into the trap.

This classification of different approaches to the problem of obtaining and maintaining high temperatures in plasmas is of course very incomplete, but within the scope of this paper it is quite natural, since it corresponds to the principal directions of research on controlled thermonuclear reactions in the USSR.

Before describing some concrete results obtained in the theoretical and experimental studies carried out along the lines mentioned above, I should like to touch on some questions relating to the general properties of future thermonuclear reactors. Of course I fully realize that at the present stage of our knowledge any discussion of such questions can only rest on our faith in the ultimate triumph of human ingenuity.

First it is necessary to note that, irrespective of which concrete variant of magnetic system is proposed as a technical solution of the thermonuclear energy problem, the system must satisfy one fundamental condition: the energy released in nuclear fusion must cover by a wide margin the energy consumed from other sources for maintenance of the high temperature in the plasma.

A simple analysis shows that this condition may be written in the form of the following relationship between the principal parameters determining the performance of a thermonuclear generator:

\[
H^2 \tau > A(1 - \eta).
\]

In this formula, \( H \) is the intensity of the plasma-confining magnetic field and \( \tau \) is the time the high temperature is maintained in the plasma. The quantity \( \eta \) denotes that fraction of the thermal energy of the plasma which is converted into electrical energy at the end of the operation cycle. The constant \( A \) depends on the nuclear fuel selected. Under the most optimistic assumptions concerning the character of the processes occurring in a thermonuclear generator, this constant may be taken as equal to \( 10^6 \) for pure deuterium and \( 10^7 \) for a mixture of D and T in equal proportion. These values of the constant are based on the supposition that thermonuclear reactions in the plasma proceed at an “optimum” temperature, which for deuterium amounts to \( 50 \) kev \((5 \times 10^8 \, ^\circ \text{K})\) and for the D–T mixture to \( 15 \) kev \((1.5 \times 10^8 \, ^\circ \text{K})\).

When applying the inequality (2) with the indicated values of the constant \( A \) one must bear in mind that strictly speaking it refers to the ideal case, where there is no escape of particles from the plasma in the high-temperature regime. This implies that the particle lifetime coincides with the time the high temperature is maintained in the plasma.

From condition (2) it follows that the shorter the time interval during which a high temperature is maintained, the higher the intensity of the magnetic field must be. In order to satisfy these requirements by means of present-day electrical facilities, one must have some method for confinement of the fast particles of the plasma during periods of time of the order of seconds or even tens of seconds. To illustrate, if \( \tau \) is put equal to \( 10 \) seconds then the field strength in a generator with pure deuterium must be of the order of \( 30,000 \) gauss. This value is within limits technically feasible for stationary apparatus. However, it should be pointed out that in this case the power released per unit volume of the generator would be small, and for such a complex machine to be workable it would have to be of an enormous size.

We shall now examine the problem of direct conversion of thermonuclear energy into electric power. The energy released in a fusion reaction consists of two different parts that play quite unequal roles in the operation of a thermonuclear generator. The energy carried away by neutrons produces no effect on the processes occurring in a plasma. In the balance of electric energy produced by a generator, this part can participate with an efficiency that does not exceed 0.3 (which is the same as for the energy released in conventional nuclear power stations using the fission of heavy nuclei). The other part of the nuclear fusion energy is related to the charged particles produced in the high-energy reaction; it is
released directly in the plasma, producing the temperature rise and it may be converted into electrical energy with an efficiency $\eta$ close to unity.

The possibility of a transformation of this nature stems from the fact that during magnetic thermonuclear reaction, the high-temperature nuclear fuel is surrounded by a strong magnetic field which is similar to an elastic shell compressing the plasma. Upon expansion a plasma heated to a high temperature does work against the magnetic pressure at the expense of thermal energy which is thus converted into electromagnetic energy. If the maximum temperature of the plasma at the onset of expansion is equal to $T_1$ and the minimum temperature to which the plasma cools at the end of each work cycle of the thermonuclear generator is $T_2$, the maximum value of $\eta$ will be given by the familiar formula

$$\eta = 1 - \frac{T_2}{T_1}.$$

From the foregoing it follows that at least in principle it is possible to make $\eta$ very close to unity, inasmuch as the upper temperature in the thermal cycle of the generator is very high and therefore the ratio $T_2/T_1$ can be made sufficiently small.

However, it should be borne in mind that a very considerable reduction of the temperature during expansion can be accomplished only at the expense of a large increase in the plasma volume. In the case of adiabatic expansion, the temperature is inversely proportional to $V^{2/3}$, where $V$ is the plasma volume. For this reason, the volume the plasma occupies should be increased many-fold in order to convert a large part of the thermal energy of the plasma into electric power. This implies that, during the period of time the plasma is at maximum temperature and is a source of thermonuclear energy, it should occupy only a very insignificant part of volume of the vacuum chamber in the thermonuclear generator, the remaining volume being filled solely by the strong magnetic field. Since only a small part of the generator volume is utilized at $\eta$ close to unity, some compromise value of $\eta$, probably not exceeding 0.75, must be chosen.

The principal advantage of direct conversion of thermal energy of the plasma into electrical energy consists in the fact that in this method utilization of thermal energy of the plasma is attended by much smaller irreversible thermal losses (the magnitude of which is proportional to $1-\eta$). Moreover, the thermal conditions in the system are also more favorable since the thermal load on the plasma chamber walls is lower.

The total amount of energy produced by a thermonuclear generator should not depend to any large extent on whether the thermal energy of the plasma is converted directly into electric energy or an intermediate heat-transfer agent is required. This can readily be seen if we recall that a large part of the energy released in nuclear synthesis is carried away by neutrons and cannot therefore be directly transformed into electric energy.

In most methods of exciting controlled thermonuclear reactions the energy source is either deuterium or a mixture of deuterium and tritium. Of these two types of nuclear fuel, the future will, apparently, belong to the D-T mixture. Its chief merit is the large value of the reaction cross section. In the temperature interval of practical interest the yield of a mixture with equal parts of D and T exceeds that of pure D by two orders of magnitude. Though the tritium obtained from conventional atomic reactors is at present a very expensive nuclear fuel, this can only be a temporary barrier to its use, for there exist methods that can easily compensate the tritium used up in a thermonuclear generator.

In each elementary D-T reaction event, a nucleus of tritium disappears and a fast 14.1 Mev neutron is produced that subsequently leaves the plasma. If a thermonuclear generator is surrounded with a sufficiently thick layer of a substance in which fast neutrons induce $(n, 2n)$ reactions, it should be possible to increase substantially the initial neutron flux. For neutron multiplication via $(n, 2n)$ reactions we may use either beryllium or such heavy elements as lead or bismuth. In these substances, the effective cross section of the $(n, 2n)$ reaction for 14.1 Mev neutrons exceeds that of other competing nuclear processes. If any one of these substances is used as the shell of the thermonuclear reactor the number of neutrons should increase roughly 1.5- to 2-fold. This enhanced neutron flux may be utilized for breeding tritium by disintegration of Li$^6$. An analysis of data relating to $(n, 2n)$ reactions and tritium-producing reactions shows that even in very conservative estimates the breeding ratio of tritium in a thermonuclear reactor should easily be made to exceed 1.

Thus, the use of a D-T mixture should enable us to provide conditions for constant enhancement of the supply of tritium. Therefore, as long as there is no danger that the accessible supplies of Li$^6$ on the earth will be exhausted, thermonuclear reactors can be operated on a D-T mixture with regeneration of tritium. To this we may add that even if for some reason we are forced to give up regeneration of tritium and begin to use deuterium, the principal energy effect will nevertheless be obtained from tritium produced in the D-D reaction.

Now let us examine the theoretical and experimental material on controlled thermonuclear reactions amassed during the past few years in the USSR. Our attention will be directed chiefly to the results of recent work that have not yet been extensively discussed. I shall present the material in accordance with the earlier mentioned classification of research trends.

**FAST PULSED PROCESSES**

In studies of pulsed processes of short duration, the main efforts thus far have been concentrated on powerful pulsed discharges in deuterium at low pressure. The principal idea here is to obtain a high temperature and a high density in a compressed...
plasma column over a short period of time. An investigation of pulsed discharges with a very high rate of current build-up (from $10^6$ to $10^8$ amp/sec) has shown that irrespective of whether such discharges occur in linear tubes or in toroidal chambers, the main role is played by acceleration of the plasma by electrodynamic forces. In the initial phase of the pulsed discharge the plasma is pinched to the axis of the discharge tube. This compression is the first stage of rapid oscillation of the plasma column. Maximum temperature and density is reached when the column radius is a minimum.

**Theoretical**

Two stages can be discerned in the theoretical analysis of phenomena occurring in plasma during pulsed discharges. At first a very simple model was used for a qualitative description of the dynamics of the plasma column. The motion of the ionized gas as a whole under the action of given electrodynamic forces was examined. At the next stage an attempt was made to carry out a more rigorous quantitative calculation of the contraction and pulsation of the plasma column that would take into account the formation and implosion of shock waves in the plasma and the time variation of the mass of the moving gas. This calculation was performed in the magneto-hydrodynamic approximation in which the plasma was regarded as a monatomic gas with constant conductivity. Even in this extremely idealized form the problem reduced to a complex system of partial differential equations which can be solved only by numerical integration in large electronic computers.

The solution of this problem yields data on the density, temperature and drift velocity for each part of the plasma column at different instants of time, and also data concerning the distribution of the current density and magnetic and electric fields in the plasma. The volume of this information is far in excess of what can be derived from experimental studies of the properties of plasmas. However, the reliability of theoretical results for a series of the more important special cases can be checked against experimental findings. This can be done for the distribution of current density and radial velocity of the plasma, since these characteristics of the process are accessible to experimental determination. A comparison of theory and experiment of this kind was performed in a number of particular cases, and as a whole resulted in satisfactory agreement, at least as regards the initial stage of the pulsed process up to the second phase of compression. For this reason, one may regard as justified the use of the results of theoretical calculations to estimate the magnitude of quantities which cannot readily be measured experimentally with sufficient accuracy. Most important of such characteristics of the plasma are the temperature at the instant of maximum implosion of the shock wave and the density distribution of the substance at this instant of time.

As numerical calculations have shown, the following equation may be used to evaluate the lower limit of the temperature at the first compression maximum:

$$T = 4.6 \times 10^{12} \frac{I^2}{N}$$  \hspace{1cm} (3)

where $I$ is the current in kA at this instant of time and $N$ is the number of particles of a given sign per unit length of plasma column. This equation gives the mean plasma temperature (in kev) on the assumption of ideal heat exchange between ions and electrons. The temperature distribution along the radius of the column is plotted in Fig. 1. The dashed line is the mean value of $T$. Due to a cumulative effect created by the incident shock wave, the temperature at small distances from the axis rises sharply and exceeds the mean value several-fold. In addition we note that under typical experimental conditions thermal equilibrium between ions and electrons is attained at the instant of maximum contraction only for $T < 0.1$ kev; it should be obvious that the foregoing equation serves as a most cautious estimate of ion temperatures in a real plasma column. We may therefore confidently use it to estimate the lower limit of the temperature achieved in the latest experiments on powerful pulsed discharges.

Figure 2 shows the density distribution of matter at the instant of implosion. The maximum density at this instant is from 30 to 40 times the original density of the gas. One of the interesting peculiarities of the theoretically determined density distribution is the low value in the neighbourhood of the column axis. This type of density variation is directly connected with the temperature rise near the axis (the pressure, proportional to $\rho T$, should level out in this region).

**Experimental**

Experiments conducted during recent years on high-power pulsed discharges have continued the main trend of earlier research, the results of which were published in 1956 and are well known to our colleagues. In the recent experiments, much attention has been devoted to raising the parameters of the pulsed discharge with the aim of attaining higher temperatures.

Design refinements in the spark-gap system and electric power system have made it possible to raise considerably the voltage per unit length of the discharge tube and simultaneously reduce the spurious inductance of the circuit. This has resulted in a several-fold increase in the rate of current build-up and in a rise of the current during the first contraction up to 500 kA (in a discharge tube 50 cm long and 40 cm in diameter). Figure 3 shows the temperature in a plasma column as a function of the initial voltage applied to a discharge tube filled with deuterium at initial pressure of 0.05 mm Hg. The temperature was calculated from Eq. (3) which, as was mentioned above, yields values which are certainly too low. For this reason, we may assume with a high degree of confidence that in the experiments mentioned a temperature exceeding 3 to 4 million degrees was actually attained. One conclusion therefrom is that the neutron emission observed under these conditions is due in large measure to thermonuclear reactions.
In this connection, mention should be made of the fact that in such high-power processes neutrons appear immediately after the first phase of compression, that is, when both the temperature and density are at a maximum, and the neutron pulse is spread out over a period of the order of a microsecond.

At present, however, proof or disproof of the thermonuclear origin of a small burst of neutron emission in the pulse discharge is hardly of such importance as to warrant special attention in discussions on this subject. This is why I do not consider it necessary to insist that in the above-mentioned experiments thermonuclear reactions were actually observed.

The question of whether a given neutron belongs to the noble race of descendants of thermonuclear reactions or whether it is the dubious offspring of a shady acceleration process is something that may worry the pressmen but at the present stage in the development of our problem it should not ruffle the composure of the specialists. When the number of neutrons arising in a single discharge pulse reaches a value in excess of $10^{12}$ then all doubt as to the origin of this effect will vanish.

However, in order to achieve thermonuclear neutron emission of this magnitude in pulsed discharges, it will be necessary to conduct experiments with electric circuits of considerably higher parameters than have been involved heretofore. The chief difficulty in this direction is that further increase of the power of the discharge pulse is impeded by heating of the chamber walls. To a certain degree, this difficulty may be surmounted by using sectional metal-walled chambers. However, attempts should be made in other directions. For example, an interesting possibility would be magnetic protection of the walls and the use of vacuum chambers with local injection of directed streams of gas.

Besides the series of experiments with high-power discharges, a number of other investigations were carried out to study the different properties of the high-temperature plasma in a pulsed discharge.

Much headway has been made in spectroscopic studies of plasma. After a method had been developed for obtaining streak photographs of discharge spectras, it was found that at the instant of the first maximum compression a sharp flash of the continuum was observed throughout the whole range. This flash is particularly vivid in the photograph in Fig. 4, which is a streak photograph of the spectrum of a discharge in hydrogen at an initial pressure of 0.1 mm Hg and an initial voltage of 35 kv. The flash of the continuum is explained by the fact that at the instant of maximum compression there is a jump in the degree of ionization of the plasma and, consequently, in the concentration of free electrons, the result being an intensive bremsstrahlung and recombination glow. By measuring the intensity of the continuum in a given spectral range, it is possible to measure the density of the plasma with sufficient accuracy (on the assumption of total ionization).

As calculations show, due to a fortuitous play of numbers, the intensity of the emission is very insensitive to the magnitude of the electron temperature. For this reason, any arbitrariness in choice of the electron temperature produces practically no effect on the value of the density derived from measurements of the spectral continuum. Density measurements carried out in this way yield data that are in good agreement with the values obtained from magneto-hydrodynamic theory.

Spectral investigations likewise permit evaluation of the plasma temperature from Doppler broadening of impurity lines. As yet this method has been applied only to discharges under standard conditions (initial voltage 35 kilovolts, hydrogen pressure 0.05 mm Hg, tube length 90 cm). Under these conditions, the plasma temperature at the instant of maximum compression as measured from the width of the nitrogen line $NIV 3479$ works out at roughly 100 ev, as against 65 ev predicted by Eq. (3).

The aim of a number of studies was to determine the properties of hard radiation arising in the plasma and of the mechanism of production of this radiation. Cloud chambers were used to investigate the spectrum of electron produced by hard X rays from pulsed discharges. These studies confirmed the earlier
estimate of the maximum X-ray energy (about 350-400 kev).

Also successful was an attempt at mass-spectroscopic analysis of fast particles produced in the discharge. The parabola method was used to measure the value of $e/m$ and the energies of ions extracted from the discharge chamber through openings in the side wall or in the electrode. It was found that the deuteron energy reaches 200 kev.

In discussions of the possible mechanism of processes that could lead to the appearance of hard radiations, a frequent opinion was that an essential role is played here by column instability of the "neck" type which enhances cumulation of the shock wave. To check this supposition, experiments were conducted with a discharge geometry which from the start created conditions that would make the compressing plasma assume an approximately spherical shape. These experiments yielded interesting results in that they proved that artificial creation of spherical implosion in the compressing plasma radically alters the emission of hard radiations.

Now let us briefly touch on the question of the future of thermonuclear reactions based on the utilization of powerful fast discharges. From the purely physical point of view, everything ultimately depends on two basic characteristics of the pulsed discharge:

(a) the degree of compression of the plasma column, which is characterized by the minimum value of the column radius $a$;

(b) the duration of the compressed state $\tau$.

It is easy to see that the energy efficiency of a powerful pulsed discharge viewed as a source of thermonuclear reactions is proportional to the square of the current and to the quantity $\tau/a^2$. Theoretical estimates of the numerical value of the quantity $\tau/a^2$ in the case of very powerful pulsed devices vary more than two orders of magnitude, depending on the portion of optimism which either explicitly or implicitly enters into the initial conditions of the calculation. However, even with optimum prerequisites, it is found that the efficiency of a thermonuclear reactor based on pulsed discharges can approach unity only if an enormous amount of energy is concentrated in the system (of the order of $10^{10}$ joules when operating on a D-T mixture). This energy is initially stored in the power sources and then for a brief moment of time it is converted, to a large extent, into the thermal and mechanical energy of the expanding plasma column. This stage of the process would have the nature of a powerful explosion, at the least estimate equivalent to that of 10 tons of TNT. At the present level of technical development we do not know of any way of rationally utilizing this explosive energy nor do we know of any means of protecting the unwieldy and expensive apparatus from the destruction that should occur after each pulse. Still we do believe that continued research on pulsed discharges at a technical level higher than so far achieved is of definite interest, with current build-up rates approaching $10^{13}$ amp/sec and in conditions where gases from the walls of the discharge chamber do not play any part at the initial stage of compression. Such experiments would not go beyond what is technically feasible at present. However, they may unexpectedly lead to the discovery of new facts which may effect in a fundamental way the general development of research into this problem. Studies of powerful fast discharges have been developing mainly in the Institute of Atomic Energy of the Academy of Sciences of the USSR. Certain questions in this domain have been the subject of investigations carried out at the Physics Department of the Moscow University. The Institute of Atomic Energy of the Academy of Sciences of the USSR, as well as the Ukrainian Physico-Technical Institute and the Sukhumi Institute of Electron Physics have also carried out experimental investigations of some other types of pulsed processes in which the plasma is acted on by strong magnetic fields.

Plasma acceleration by electrodynamic forces is achieved in its purest form in devices such as the electrodynamic gun. The simple principle underlying all such devices consists in the following. A plasmoid produced as a result of the passage of a large current through a fine wire or a gas cloud is accelerated along metallic rails under the action of a force $F$ due to interaction of the current $I$ with the magnetic field of the leads (or, in another version, with an external magnetic field). Experiments have shown that in systems of this type, plasma velocities up to $5 \times 10^7$
cm/sec can be attained without special effort. Probably considerably greater velocities are attainable.

Another method of obtaining plasmoids has been investigated at the Institute of Atomic Energy. It consists in the following. First a circular plasma loop containing a current is produced in an alternating external magnetic field $H_{\text{e}}$, the lines of force of which are normal to the plane of the loop (Fig. 5a). The loop is created as the result of breakdown of the gas formation of the loop, the latter begins rapidly to contract to the axis and changes into a plasmoid (Fig. 5b). Experiments have shown that in this way it is possible to obtain plasmoids with particle concentrations up to $10^{16}$ cm$^{-3}$ and with an initial temperature of at least 100–200 ev. One of the imaginable practical consequences of these experiments may be the development of a method of injecting hot plasmas into magnetic traps.

A pulsed thermonuclear reaction may also be possible under conditions when a high temperature is reached during the compression and implosion produced not by electromagnetic forces, but by a charge of conventional explosives (such as TNT or something more powerful) surrounding a capsule of deuterium or a mixture of deuterium and tritium. Without going into details of the experiments, it should be mentioned that conditions have been found under which the generation of neutrons both in the $D + T$ and the $D + D$ reactions is detected with absolute reliability and reproducibility. In this case the recording apparatus is destroyed. However, the signal from the neutron pulse reached buildings located at a greater distance before the explosion has time to destroy the instruments. In experiments conducted in 1952 it was possible to record both fast neutrons that passed through the charge without any great loss of energy as well as neutrons that were slowed down in the explosive and entered the apparatus gradually, creating a pulse with a width of several tens of microseconds. In this case, obviously, the notorious question of whether these neutrons are thermonuclear or not is not present. We surely observed in this case neutrons produced as the result of the heating of matter to extremely high temperatures.

The chief difference between this process and electromagnetic compression is that the former proceeds under conditions in which the density of the substance is very great, considerably exceeding that of solids. The brief duration of the heating process makes it possible to dispense with magnetic thermoinsulation. It is quite obvious that this process can be of economic interest only if the release of thermonuclear energy can balance the cost of the expensive explosives.

Just as in the case of large pulses of electric energy with power yields up to 10 tons of TNT (see above), difficulties connected with the explosive nature of the process are encountered on the way towards a practical utilization of implosive heating.

**SLOW PULSED DISCHARGES IN TOROIDAL CHAMBERS**

In cases where the current builds up at a slow rate the discharge conditions should be expected to differ fundamentally from those observed when the current rises at a fast rate. A quantitative criterion which may be used to differentiate between "slow" and "fast" discharges is the ratio of the current rise-time to the period of inertial radial oscillations of the plasma column. Hundreds of inertial oscillations may occur in rarefied gas discharges with peak currents of the order of $10^{5} - 10^{6}$ amp and durations of the first half-period of the order of $10^{-8}$ sec. Such discharges may be called "slow", in contrast to "fast" discharges, in which only two or three radial oscillations occur before the current reaches its peak value.

**Theoretical**

In slow discharges the gas-kinetic pressure of the plasma may be expected to balance the electrodynamical forces and the column temperature will be raised at the expense of Joule heat.

An equilibrium state of this type will be suitable for heating of the plasma to very high temperatures only if the following two conditions are satisfied:

(a) The plasma column should not be in contact with the walls.

(b) The state under consideration should not only be in equilibrium but be stable as well.

Progress in the theoretical investigation of equilibrium and stability conditions of plasma columns and of their laws of heating has been made in work carried out in the Institute of Atomic Energy of the Academy of Sciences of the USSR under the guidance of M. A. Leontovich. It was first shown in this work that stability of a plasma column with a more or less sharply defined boundary can be attained only if the discharge chamber is enclosed in a conducting sheath (which must be close to the chamber walls) and also only if a stabilizing magnetic field produced by external coils and directed along the column exists at the same time as the field produced by the plasma current. Two different stability regimes were inferred. One of these is realized when the contracting plasma column captures a large part of the magnetic flux of the longitudinal field which initially exists in the chamber ("paramagnetic
In this case the longitudinal field inside the column is approximately equal to $H_o \left(\frac{b}{a}\right)^2$, where $H_o$ is the initial field strength, and $b$ and $a$ denote the inner radius of the discharge chamber and the radius of the plasma column, respectively.

The conditions considered above were investigated in detail by English physicists working with Zeta. Theoretically this approach seems to be the most promising as far as stabilization of the shape and size of the plasma column is concerned. In the magnetohydrodynamic approximation, the main condition for damping of all dangerous perturbations in highly conducting plasma columns is that $H_z$ within the column should be sufficiently close to the field strength of the current on the boundary of the latter and should exceed several-fold the longitudinal field strength beyond this boundary (see Fig. 6, where the distribution of the longitudinal field $H_z$ and current field $H_\phi$ are represented graphically). Another requirement is that the column radius $a$ should not be too small compared to the radius of the chamber cross section, or else the stabilizing effect of the conducting sheath will vanish.

In order to realize the conditions discussed above a comparatively small initial value of the longitudinal field $H_o$ should suffice. Another advantage is that these conditions naturally arise during the development of pulsed discharges, which are initially spread over the whole cross section of the chamber and then, after $H_\phi$ becomes equal to $H_o$, begin to contract, dragging along the lines of the longitudinal field. From a theoretical point of view, this possibility also possesses some weak points. Thus for a paramagnetic column to be stable, $H_z$ and $H_\phi(a)$ should differ but slightly. Therefore only a minor part (0.3-0.4) of the electrodynamic pressure produced by the current will be able to counteract the gas-kinetic pressure. This means that for equal values of $I$ and $N$ the temperature of the paramagnetic column will be several times smaller than if the longitudinal field were uniformly distributed over the cross section of the discharge chamber. It should also be added that in order to ensure satisfactory heat exchange between the electrons and ions under paramagnetic conditions the value of $N$ should exceed at least by an order of magnitude the value corresponding to the case when the field is not captured.

The magnetohydrodynamic theory also predicts the existence of another stable discharge regime. In this case stabilization of the plasma column is attained with help of a strong longitudinal magnetic field $H_z$ which everywhere is larger than $H_\phi$. According to the theory, a necessary condition for stability in this case is

$$\frac{H_z}{H_\phi} \geq \frac{L}{2\pi a}$$

where $L$ is the column length (equal to $2\pi R$ for an annular column in a toroidal chamber of radius $R$). However, even if this requirement is met there still exist some types of unstabilized perturbations that tend to modify the shape of the column. The character of these perturbations is schematically depicted in Fig. 7. Apparently they should not be dangerous as they are not associated with displacement of the axis of the plasma column.

In the case under consideration the longitudinal magnetic field covers the whole cross section of the chamber and should not appreciably change near the column boundary (see Fig. 8). An advantage of this method of discharge stabilization is that the time during which the corresponding conditions are maintained does not depend on the skin-effect period but only on the time during which $I$ and $H_z$ persist. Another advantage is that a much higher ion temperature can be obtained than under "paramagnetic" conditions involving currents of the same magnitude. However, a high price must be paid for these possible advantages since very strong magnetic fields are required. Thus, magnetic fields of the order of $3 \times 10^4 - 5 \times 10^4$ gauss will be needed in a large volume just to enable one to approach the threshold of temperatures of practical interest, and in order to produce such fields some very serious engineering
problems will have to be surmounted. Difficulties will also be encountered when establishing the necessary conditions in the system.

The results of magnetohydrodynamic theory briefly considered above nevertheless give good reason to believe that the approach suggested here should be a promising line of advance. It should be kept in mind that the preceding results were based on a simplification of the physical picture of the discharge and many important points may have escaped attention. The theory does not apply to displacements from the equilibrium position which possess wavelengths smaller than the thickness of the skin-effect layer and which evidently cannot be damped by methods suitable for perturbations with larger wavelengths.

It should furthermore be noted that by its very essence magnetohydrodynamic theory cannot be employed to study, for example, such kinetic effects as transition of electrons to a state of continuous acceleration in an electric field. Due to the low density of matter and to resultant diminution in the retarding force which the ions exert on the electrons, such processes may occur near the boundary of the plasma column. They may also occur inside the column since in the electron energy spectrum there must be particles which possess energies considerably exceeding the mean energy, and for such particles acceleration may commence even at large values of $N$. It is well known that accelerated electron beams can excite various types of plasma oscillations and thus violate the normal course of the process. Other types of perturbations are conceivable which do not fit the simple magnetohydrodynamic picture and which are potentially dangerous as far as stability of the column is concerned.

Experimental

We now proceed to a discussion of the experimental results. In the early experiments all basic investigations were carried out with chambers made of insulating materials (glass, quartz and porcelain). Because of the gaseous efflux from the chamber walls reliable results could be obtained with these chambers only for relatively high gas densities in the chamber and for not too powerful discharges.

A study of the effect of a longitudinal magnetic field on the properties of slow discharges revealed that the paramagnetic effect earlier discovered by Soviet physicists in fast pulsed discharges could also be observed in discharges in which the plasma current build-up was slow. At low values of $H_z$ the effect leads to contraction of the plasma column. The influence of the longitudinal magnetic field on plasma conductivity was found to be small. Irrespective of the initial pressure, the induced electric field strength and the value of $H_z$, the conductivity was approximately $1-3 \times 10^{14}$ esu which signifies a low plasma temperature in chambers with insulating walls. The assumption of pronounced instability of the discharge process at small values of the ratio $H_t/H_s$ is confirmed by studies in which the shape of the plasma column was recorded by ultra-high-speed cinematography and also by an analysis of oscillograms of the variation of the electric and magnetic parameters of the discharge. With growth of the external field the discharge becomes more stable but the conductivity does not exhibit an appreciable rise. In order to determine the stability conditions for a plasma column detached from the walls, experiments were performed with discharge tubes in which the discharge started near the axis and then began to expand towards the walls. These experiments qualitatively confirmed the theoretical conclusion that when inequality (4) is satisfied the column becomes stable. However, because of large losses at the electrodes there could be no hope of obtaining high plasma conductivities in these experiments.

The next step was the transition to chambers with metallic walls. It was hoped that in such chambers sufficient purity of the gas could be maintained during powerful discharges. Several large assemblies with
metallic toroidal chambers were built at the Institute of Atomic Energy. A photograph of one of them designed for investigation of high-current discharges at various values of the external longitudinal field is shown in Fig. 9. A cutaway of the assembly is shown in Fig. 10. The discharge takes place in a closed toroidal chamber made of stainless steel 0.2 mm thick. This chamber was enclosed in a toroidal copper sheath 20 mm in thickness. Two insulated cuts in a plane parallel to the torus axis and an insulated cut along its generatrix are incorporated in the copper sheath. The inner thin-walled chamber and the space between it and the sheath are evacuated by separate vacuum systems. The diameter of the inner cross section of the discharge chamber is 0.5 m and the mean diameter of the torus 1.25 m. The chamber is the secondary coil of an air-core transformer. The primary coil is formed by 20 turns of a thick copper strip wound near the surface of the sheath. A copper shield which encloses the sheath is arranged between the turns and the sheath and is employed to remove stray magnetic fields. The coils for producing the longitudinal field were wound directly on the surface of the copper sheath. The field can be increased up to 12,000 gauss. Electrical energy for the discharge circuit and longitudinal field coils is supplied by capacitor banks (at peak voltage the total amount of stored energy is 1.2 million joules). In the experiments carried out with the device described here the peak gas current was 400 ka (for a discharge voltage of 0.45 kv and longitudinal field strength of 12,000 gauss).

The main results obtained in the first stages of our experimental study of discharge processes in toroidal metallic chambers can be summarized as follows:

1. In hydrogen and deuterium, at initial pressures from $3 \times 10^{-4}$ to $5 \times 10^{-3}$ mm Hg, the peak current of a discharge whose first half-period lies between 300 μsec and 1200 μsec is approximately proportional

![Figure 10. Cutaway of the apparatus of Fig. 9](image-url)

- a Primary winding
- b Copper shield
- c Coils for axial magnetic field
- d Copper sheath (20 mm) surrounding discharge chamber
- e Stainless steel (0.2 mm) chamber with 0.5 m bore
- f, g, h Ports
The general character of the dependence of $z_{\text{max}}$ is represented in Fig. 11. First increases and then remains practically constant. With increasing $H$, the current to the initial discharge voltage and is weakly dependent on the gas density. With increasing $z$, the current decreases from the walls, and its radius grows with increase of $H$. $H \gg 0.2$ $z$ is the radius of the chamber cross section, the plasma column will always be in contact with the walls.

2. At small values of $H$, the plasma column separates from the walls, and its radius grows with increase of $H$. If $H \gg 0.2 I_{\text{max}}/b$ where $b$ is the radius of the chamber cross section, the plasma column will always be in contact with the walls.

3. Under conditions involving small values of $H$, when the column contracts and separates from the walls the plasma conductivity (computed on the assumption of uniform distribution of the current over the cross section of the column) approaches the value $1 \times 10^{14}$ esu. In discharges located in strong longitudinal fields, when the plasma completely fills the cross section of the chamber, the conductivity drops to $1-2 \times 10^{14}$ esu.

The results presented above compel us to admit that in our experiments the electron temperature (deduced from the conductivity) probably did not exceed 15-25 ev.

This means that even under conditions in which one would expect the plasma column to be completely detached from the walls, energy losses are still very large and it is for just this reason that the plasma temperature does not reach the high value predicted by the theory. The mechanism of these energy losses is not clear at present. A possible explanation is that either the plasma column is not sufficiently stable or that impurity atoms emitted by the chamber walls contaminate the plasma.

These conclusions are of a preliminary nature since experimental investigations with metallic chambers are still in progress.

In the near future our main aim will be to create conditions which will significantly diminish the deleterious effect of impurities on plasma processes.

**MAGNETIC TRAPS**

Generally speaking, the term “magnetic trap” can be applied to any device used to obtain ultra-high temperatures and based on the principle of magnetic confinement. However, it seems expedient to narrow the meaning of this term to denote a more definite type of system.

In the devices considered above, the plasma current maintained by external sources of voltage was the main factor in confining the heated substance. This implies that in such systems the particles appear to “hold on to each other” by means of the self-consistent magnetic field which they produce. External magnetic fields in this case play the subsidiary role of a medicine for combating the instability. In systems with large plasma currents the hydrodynamic pressure $p$ is of the order of $H^2/8\pi$ and hence the plasma exerts a strong counterforce on the magnetic field, a consequence being the appearance of characteristic instabilities.

In contrast to devices of this type we shall apply the term magnetic traps to systems in which only external fields are employed to confine the plasma and in which plasma conduction currents do not play a decisive role. Therefore in magnetic traps $8\pi n p / H^2$ may be small compared with unity, i.e., the rarefied plasma does not appreciably affect the external magnetic field.

Various methods can be employed to obtain highly heated matter in magnetic traps. One possibility is to fill the magnetic system with fast ions introduced, for example, by injection from a powerful accelerator. Another way would be to fill the trap with a plasma and then heat the plasma by dynamic magnetic fields or by a high-frequency electromagnetic field. Still another possibility is that of producing fast ions inside the trap itself, by accelerating ions from the plasma in the trap with the aid of a constant or variable electric field.

**Theoretical**

The most natural way of attacking the magnetic-trap problem would be to start with an analysis of the problem of the bounded motions of a single particle in an external field; after a satisfactory solution of this problem the next step would be to investigate the behavior of a large number of particles comprising a plasma. Despite obvious shortcomings in this procedure, it has the advantage of being graphic and, what is more, it permits one as a first step to bypass the difficulties inherent in an exact theory of the behavior of plasmas in fields of complex configuration.

Many Soviet physicists have been occupied with the problem of devising a magnetic trap which at least in principle could be realized practically. The work of Tamm and Sakharov stimulated discussion of this problem. In 1950 these authors proposed the first concrete model of a magnetic thermonuclear reactor. It was suggested that rarefied deuterium be ionized and heated in a toroidal chamber in which a strong longitudinal magnetic field is produced by a coil wound on the outer surface of the chamber.

As a prototype of a magnetic trap, however, this system is fundamentally defective. Each particle located in the inhomogeneous field inside the toroidal chamber would acquire a drift velocity perpendicular to the field lines; the drift would terminate only
The lifetime of particles of the plasma in the magnetic field depends on the initial velocity. If the velocity vector lies outside these cones, the particle will escape. If, however, the velocity vector lies within any of the cones defined by the condition \( \sin^2 \alpha < \frac{H}{H_m} \), the particle remains trapped in the magnetic field region and hence is trapped in the magnetic system.

The authors of the toroidal generator model were aware of this circumstance and subsequently suggested that the drift could be suppressed by using the magnetic field of a plasma current. Further work in this direction confirmed the fruitfulness of the original idea; several types of magnetic systems were found which could be used to confine the particles to a restricted region of space. As a result, new horizons opened up for experimental work on different types of magnetic traps. However, the final goal, which is the invention of an ideal trap confining all particles regardless of direction of velocity, has not been reached and the question as to whether a system of this type can be devised at all still remains open.

The specific types of magnetic traps studied so far can be divided into two main classes:

1. Traps with magnetic plugs.
2. Traps with restricted drift.

A theoretical study of systems of the first type was started by G. I. Budker in 1953. In these systems, the magnetic field increases along the lines of force, which possess velocities which form sufficiently large angles with the lines of force are reflected back when they approach the strong field region and hence are trapped in the magnetic system. For the sake of simplicity, the field in the central region will be considered to be uniform. Let \( H \) denote the strength of this field and \( H_m \), the maximum field strength at points of concentration of the lines of force (magnetic plugs). Then, if the velocity vector of a particle located in the uniform field region lies within any of the cones defined by the condition \( \sin^2 \alpha < \frac{H}{H_m} \), the particle will be trapped.

Suppose now that a thermonuclear generator is to be built on the basis of the magnetic trap considered above. A question which immediately arises in this case is that concerning the role of collisions between the particles. Evidently, one collision is sufficient for the velocity vector to enter the escape cone. The lifetime of particles of the plasma in the magnetic plug trap will equal in order of magnitude the mean time between two coulomb collisions of the ions. In order that the energy released in a system of this type as a result of thermonuclear reactions be sufficient to balance energy losses due to fast particle escape as a consequence of coulomb collisions, the following condition must be satisfied:

\[ \sigma_a W_n \sim \sigma_b kT. \]

Here, \( \sigma_a \) is the effective cross section for the nuclear reaction, \( \sigma_b \) is the effective cross section for coulomb collisions and \( W_n \) is the energy released in an elementary nuclear fusion event.

This condition can be used to estimate the minimum temperature at which the thermonuclear generator should begin to produce surplus energy. For D–T mixtures it is of the order of several tens of kilovolts, and for pure deuterium of the order of 1 Mev. Thus, for practical purposes pure deuterium evidently cannot be employed in such systems. This conclusion can be confirmed by more rigorous calculations in which other types of losses (bremsstrahlung and beta-electron radiation of fast electrons) are taken into account.

Theoretical studies of the stability of a plasma in traps with magnetic plugs carried out at the Institute of Atomic Energy predict the existence of perturbations of the equilibrium state which are unstable by themselves. Additional causes of instability in systems of the type considered here are anisotropy of the pressure in the plasma and the pronounced deviation of the component of the particle velocity (directed along the lines of force) from the Maxwellian distribution.

Some types of instability are closely related to the geometry of the magnetic field in the traps. It is therefore possible that a given type of disturbance can be stabilized for trap fields of some definite shape and will grow in traps of other types. Thus, for example, a dangerous type of instability can arise in systems in which the external boundary of the plasma has a negative curvature (Fig. 13). At points of negative curvature, the plasma may leak out in the form of protuberances perpendicular to the lines of force. However, instability of this type should not be observed in systems with lines of force of positive curvature (Fig. 14).

The adverse effect of the chief types of instability should sharply increase with the ratio \( p/H^2 \). Therefore, even if the practical value of traps with magnetic plugs turns out to be negligible such traps nevertheless may be used to demonstrate the physical feasibility of thermonuclear reactions at small values of \( 8\pi p/H^2 \).
Experimental investigations of traps with magnetic plugs were initiated at the Institute of Atomic Energy several years ago. The first experimental system was built with the purpose of studying the storage of fast ions extracted from a cylindrical plasma column produced along the axis of the magnetic system (Fig. 15). Plasma columns with ion concentrations of the order of \(10^{14} \text{ cm}^{-3}\) were produced by arc discharges in a longitudinal field. A general view of the apparatus with which the chief experiments in the indicated direction are being carried out at present is shown in the photograph in Fig. 16. The length of the vacuum chamber is 2 m and the magnetic field strength is 8500 gauss in the central region and 12,000 gauss in the plugs. During operation of the ion source the pressure is maintained at \(10^{-7} \text{ mm Hg}\) by means of titanium pumps. A voltage of 40 kv between the plasma column and lateral wall of the chamber is applied for acceleration of the ions. The main aim of these experiments is the determination of the lifetime of fast ions for various ion concentrations in the magnetic system. The mean lifetime can be derived from the rate of decrease of the ion concentration after instantaneous switching off of the accelerating voltage.

Results of the first experiments permit one to conclude that in a system of the type considered plasmas containing fast ions exist during a period of the order of a few milliseconds. The lifetime increases with improvement of the vacuum and with increase of \(H\).

In the summer of this year the construction of a large experimental assembly with magnetic plugs was completed at the Institute of Atomic Energy. The external injection of particles will be studied with this machine. For accumulation of \(\text{D}^+\) ions, use is made of dissociation of \(\text{D}_2^+\) molecular ions which are introduced from the injector into the central part of the trap. Dissociation of the molecular ions occurs either in collisions with the molecules and atoms of the residual gas or as a result of interaction with ions of the rarefied deuterium plasma previously produced inside the chamber. A schematic diagram of the apparatus is depicted in Fig. 17. The distance between the centers of the plugs is 12 m; the inner diameter of the vacuum chamber is 1.4 m. The field strength in the central part can be raised to 5000 gauss and the field in the plugs up to 8000 gauss. An arc source with a transverse magnetic field is employed to produce the intense \(\text{D}_2^+\) ion beam. The \(\text{D}_2^+\) ions, accelerated by a voltage of 200 kv, are focused and injected into the magnetic trap by a system of electric and magnetic fields. It is expected that after adjustment of the apparatus it will be possible to raise the \(\text{D}_2^+\) ion current entering the vacuum chamber to several hundred milliamperes. It is hoped that with injected ion beams of this intensity the concentration of the \(\text{D}^+\) ions in the trap will reach \(10^{12}\).

An experimental study has also been started on systems possessing the field geometry shown in Fig. 14. This type of field is interesting in several respects. In particular, as mentioned above it is hoped that for some types of disturbances a higher degree of plasma stability will be attained.

**Other types of traps**

One may attempt to discover magnetic systems suitable for magnetic traps by applying a somewhat different method. The main problem is to ascertain under what conditions the particles do not escape from a restricted space region as a result of drift in an inhomogeneous field. A magnetic system which may be considered as illustrating one possible approach to this problem is represented in Fig. 18. In this system the magnetic field along the straight sections is "corrugated" (by a non-uniform winding on the chamber surface). A particle moving in such an inhomogeneous field will be subjected to rotational drift and its trajectory will therefore turn about the axis of the field. Thus, despite the presence of curvilinear crosspieces the particles should not approach the walls after a complete circuit, as rotation of the trajectories in the long linear parts should balance the effect of the directed drift in the crosspieces.

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**Figure 14. Theoretically stable configuration**

**Figure 15. Experimental arrangement of magnetic trap experiment**

(1) Plasma source
(2) Plasma beam
(3) Region with strong electric field
(4) Region of motion of fast ions
It is easy to see that the system described above has the same defects as a trap with plugs. It is capable of confining only particles whose velocity vectors lie within an allowed range of directions. Any particle entering the curvilinear interval with a small longitudinal velocity will drift to the wall before escaping from this interval. However, in all probability further development of the principle mentioned above should lead to systems in which the escape cone will be so narrow that the properties of these systems will approach those of ideal traps.

The methods described above for obtaining magnetic traps are based on the application of constant or slowly varying magnetic fields. Theoretical studies indicate broad possibilities of applying high-frequency electromagnetic fields for confinement and insulation of plasmas. Here, the term “high frequencies” means that the oscillation period of the field is much smaller than the periods characteristic of the behavior of the plasma. The respective frequencies ranged from tens of megacycles up. The plasma-confining force in this case is determined not by the instantaneous value of $H$ but its mean-square-value.

Evidently, high frequency fields can be most effectively employed in conjunction with constant magnetic fields which perform the auxiliary task of eliminating energy losses due to corpuscular beams. For example, high-frequency electromagnetic fields can be used as “plugs” which trap particles escaping...
along the lines of force from the strong constant field region.

The possibility of confining plasmas by means of field combinations of this type was experimentally confirmed with a small-size device at the Institute of Atomic Energy. Practically, the application of high-frequency fields for confinement of a heated plasma seems to be very unpromising because of the large amount of energy which will be required to maintain such fields. Nevertheless investigation of various possibilities of high-frequency thermal insulation deserves close attention.

High-frequency electromagnetic fields may also be used to heat the plasma. In this respect a study of the potentialities of ion cyclotron resonance would be of special interest. Investigations carried out in the USSR in this direction will be presented in a report from the Ukrainian Physico-Technical Institute.

CONCLUSION

In his speech at the First Geneva Conference on the Peaceful Uses of Atomic Energy, the President of the Conference, Dr. H. Bhabha said:

"The historical period we are just entering in which atomic energy released by the fission process will supply some of the power requirements of the world may well be regarded one day as the primitive period of the atomic age. It is well known that atomic energy can be obtained by fusion process as in the H-bomb, and there is no basic scientific knowledge in our possession today to show that it is impossible for us to obtain this energy from the fusion process in a controlled manner. The technical problems are formidable, but one should remember that it is not yet fifteen years since atomic energy was released in an atomic pile for the first time by Fermi. I venture to predict that a method will be found for liberating fusion energy in a controlled manner within the next two decades. When that happens, the energy problems of the world will truly have been solved forever for the fuel will be as plentiful as the heavy hydrogen in the oceans."

Three years have passed since this prophecy and now, before our eyes, there begins to emerge a rough outline of the scientific foundation on which the methods of solving the problem of controlled fusion reactions will probably rest. This foundation has been laid by the numerous experimental and theoretical results obtained in recent years in Great Britain, the USA, the USSR and other countries. For the first time these results will be discussed on an international scale, and this is probably the most important step which has been made towards the solution of this problem. The importance of this fact is greater than that of the separate investigations, which as yet have not brought us very much nearer to our ultimate goal.

We do not wish to be pessimistic in appraising the future of our work, yet we must not underestimate the difficulties which will have to be overcome before we learn to master thermonuclear fusion. In the long run, the main difficulty lies in the fact that in such a light substance as rarefied plasma, any manifestation of instability develops at an enormous rate. The creation of an automatic monitor that could quickly damp various deviations from the equilibrium state is no simple task. It would therefore seem that the most radical solution of this problem would be to create a system in which all types of instability are removed beforehand.

Most likely the solution of this problem will be simpler when the reaction of the plasma on the magnetic field is small, that is for $p \ll \beta$. Returning now to a more general appraisal of the present state of affairs, it may be asserted that so far not a single one of the ideas regarding controlled fusion reactions is decisively superior to any other. Therefore, investigations in the near future should be carried out in diverse directions.

A most important factor in ensuring success in these investigations is the continuation and further development of the international cooperation initiated by our conference. The solution of the problem of thermonuclear fusion will require a maximum concentration of intellectual effort and the mobilization of very appreciable material facilities and complex apparatus.

This problem seems to have been created especially for the purpose of developing close cooperation between the scientists and engineers of various countries, working at this problem according to a common plan, and continuously exchanging the results of their calculations, experiments and engineering developments.

The combining of efforts on an international scale in the field of controlled fusion reaction investigation will undoubtedly shorten the time needed for us to arrive at our ultimate goal.

REFERENCES