PRESENT STATE OF CONTROLLED NUCLEAR FUSION RESEARCH

In his review, at the eleventh session of the General Conference, of research aimed at making use of practically inexhaustible fuel through the fusion process, Academician Lev A. Artsimovich stressed the importance of continued effort. A member of the Praesidium of the USSR Academy of Sciences and head of the Division of General and Applied Physics, as well as of the Department of Plasma Physics, he considered that advances had been made in developing the methods for obtaining a new nuclear fuel — a high temperature plasma.

Academician Artsimovich's address is summarised here.

The speaker explained that the problem was to develop methods for making use of surplus nuclear energy stored in the hydrogen isotopes known as deuterium and tritium. (Hydrogen has one proton in its nucleus, deuterium has an additional neutron and tritium two neutrons). The energy which could be released by fusing these isotopes was several times greater, if related to unit weight of nuclear fuel, than that yielded by the more conventional fission reactions of uranium and other heavy elements. Resources of deuterium were practically inexhaustible, and that was why the prospect of using the surplus energy stored in it was extremely alluring. Fusion reactions, however, could only take place at temperatures of at least some 100 million degrees. It was only at such temperatures that the nuclei would have sufficiently high velocities to overcome mutual electrostatic repulsion when approaching each other and to enter into reaction. That was why such reactions were called controlled thermonuclear reactions.

At these temperatures substances could no longer exist as a neutral medium, but only as a fully ionized hot plasma, an inseparable mixture of fast positive ions and negative electrons. To use this as a fuel for a future energy generator, the energy released by fusion must exceed the losses of thermal energy, and in particular what seemed to be unavoidable losses due to X-radiation caused by collisions of particles. This meant that if pure deuterium were used, excess energy could occur at temperatures above 300 million degrees or, if equal parts of deuterium and tritium were the components, 200 million degrees. A thermonuclear reactor could operate with a positive output only if every nucleus had a good chance of fusion. Indications were that the mixed composition of deuterium and tritium was the most efficient, but unfortunately there was practically no tritium in nature. It could perhaps be manufactured during operation, but in the long run the main part would be played by deuterium.

CREATING INSULATION IN A VACUUM

Heating of plasma must be linked with conservation of the thermal energy for long periods, and here was a main stumbling block in tackling the problem. High temperature plasma was nearly a perfect heat conductor and must therefore be completely insulated from the walls of its container in a high vacuum. The idea of using a magnetic field for this insulation was the basis for all developments. In the early stages it seemed that this idea would play the part of a magic wand to make nature open all the doors, but it had run into great difficulties. As a result it very soon became clear that the technological aspects could be seriously treated only after founding a new branch of science — the physics of high temperature plasma.

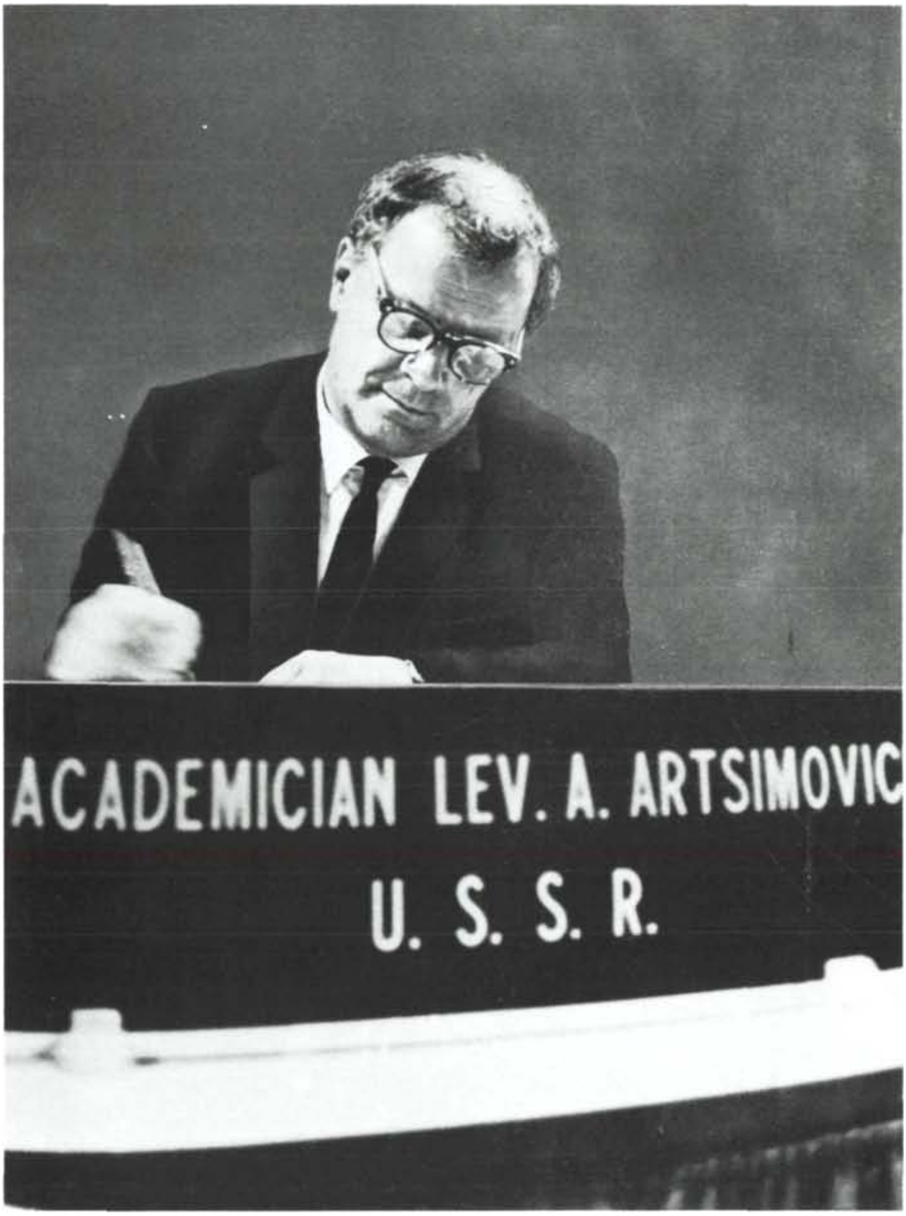
Three main trends had emerged. The first was based on using so-called magnetic traps with open ends, containing plasma inside a region from which the magnetic lines of force came from outside. Confinement was based on the fact that a charged particle moving along a force line towards the increasing field was slowing down. If the angle between its direction and the line of force was sufficiently large the particle would, when approaching the region of the strong magnetic field, be reflected back as from a mirror. Therefore if the magnetic field strength increased along the lines of force towards both sides from a central region, then there appeared a possibility of trapping the plasma particles within a restricted volume between the magnetic mirrors.

The second main trend was the study of the behaviour of closed ring plasma columns produced in toroidal (ring-shaped) type magnetic systems. In a system of this type the plasma could flow freely along the magnetic lines of force. There was a number of varieties of such systems, usually referred to as closed magnetic traps.

Both open and closed magnetic traps could be called quasi-stationary, meaning that the lifetime of a fast particle in the trap was many orders of magnitude greater than the time required for the particle to traverse once the volume of the trap. In other words, the particle could oscillate many times between the boundaries limiting the region occupied by the plasma.

In addition to the quasi-stationary confinement systems, there were devices designed for very rapid plasma heating during its compression by the increasing magnetic field. Here maximum energy concentration could be achieved within a very small volume for very short time intervals. The devices were known as the "fast pinch" type, and used magnetic fields increasing during time of the order of a few millionths of a second. The simplest method was to initiate a gas discharge with the help of a high voltage source having a large stored energy. Current passing through the gas produced plasma and the magnetic field constricted it, converting it into a thin hot filament. The dis-

A study of Academician Lev A. Artsimovich during his lecture.



charge current also heated the plasma, and such a method was attractive due to its simplicity and in the earlier stages of research great attention was paid to it. It very soon became clear, however, that the energy conservation time in this process was very short, and that positive energy output could be achieved only by immediate energy release equivalent to a great explosion of the order of a few tons of TNT. It was with this type of approach that physicists first encountered the main obstacle to achieving the main goal. This was that a plasma in a magnetic field is usually very unstable. Such instability was called hydromagnetic and was observed in varying forms with different methods of obtaining a high temperature plasma. It was the most dangerous "illness" of a hot plasma trapped in a magnetic field, since deformations of the plasma body grew rapidly and resulted in a complete breakdown of the magnetic insulation.

As a result, each of the main approaches in the research programme had to go through a phase when the most important problem was the development of methods for plasma stabilization.

PLASMA CONFINED

After it became clear that the simplest systems of the "fast pinch" type did not look very promising, attention was directed to the quasi-stationary processes, with a certain preference being given to the open systems. The latter had the advantage that they could be used for studying various methods of producing high temperature plasma. Theory and experiment showed that large-scale instability of the plasma in open-type traps could be avoided by altering the magnetic field configuration. Experiments in the Soviet Union in 1961-63 indicated that the hydromagnetic instability could be completely suppressed, and a stable confinement was achieved with a temperature of the order of a few million degrees at a certain density.

"Thus an efficient method for suppressing the most dangerous plasma instability has been found" said Academician Artsimovich.

After this it was generally acknowledged that the open-type traps would satisfy confinement criteria, and many big new installations had been built recently in the USSR, UK and USA. The success did not mean, however, that a straight way to the desired goal had been found. Increases in the plasma density were accompanied by the appearance of new kinds of instability. Theory showed a path to be followed to suppress the action of a number of high-frequency instability mechanisms, and experiments were generally in agreement with these predictions.

They were operating at values five orders of magnitude less than those needed for a thermonuclear reactor using a deuterium and tritium mixture but only a few years ago the neutron and fast particle lifetimes were even smaller by a few tens of thousands. Calculations led the speaker to the conclusion that "We have already passed about a half of the road leading through the development of open magnetic traps to the final goal. Certainly we do not yet know what difficulties are waiting for us in the second half of the road, but nevertheless we should not underestimate what has already been achieved". One disadvantage was loss of particles along the lines of force.

In the closed magnetic systems, which at present seemed more advantageous from the point of view of future technical application, there were three main types. One was the toroidal system with plasma maintained in equilibrium by the help of a magnetic field produced by current flowing along a plasma ring, the USSR Tokamak installations providing an example. Another had a ring plasma current similar to the English device ZETA, but here experiments had shown that a weak longitudinal field could not provide a good stabilization of the current-carrying plasma column. The third was the Stellarator, in which a closed plasma column could be confined with the help of an external field only, of a complicated configuration. Investigation of the plasma properties in Stellarators was one of the most important elements in the USA programme. Hopes that a reactor based on the Tokamak or Stellarator ideas could be built in future seemed to have some basis.

TASK FOR THE IMMEDIATE FUTURE

Calculations gave the impression that though the requirements for future thermonuclear reactors exceeded the limits of modern technology, technical progress could lead to the construction of a reactor operating with the deuterium-tritium mixture. With the Tokamak system an important problem of heating methods had to be solved. Promising methods seemed to be (a) heating the plasma by high-frequency electromagnetic fields (b) injection of fast neutral particles or (c) application of the laser techniques to far infrared regions. Development and testing of new methods of plasma heating in closed systems should be one of the main elements of high temperature plasma research in the immediate future.

Stellarator systems could become a serious rival to the Tokamak installations if considered as a prototype of a future thermonuclear reactor but they also had caused a number of inherent difficulties and were very complicated. They provided much room for further improvement.

Experiments with a system for compressing plasma into a focus of very small volume were being conducted in the USSR and USA, and the main results were close to each other and showed an encouraging rate of fusion reactions. Enormous technical difficulties might in the long run be overcome, but this would take many years of hard work. Other investigations were developing on the methods for obtaining high temperature plasma. Those devoted to the constriction of a plasma by using a rapidly growing external magnetic field might also be a starting point on the road leading to the practical solution of the main problem.

After more than fifteen years they had not yet acquired the keys to the case in which the design for a future thermonuclear power station was locked, but they had advanced rather far in developing the methods for a new nuclear fuel — high temperature plasma. To bring the future nearer they ought not to reduce the efforts now being made. Plasma physics was of great importance by itself, one of the touchstones of modern natural science. It was leading to a solution of the most important technological problems of the near and distant future, and had the right to be favoured by the leaders of the modern atomic industry.