TOWARDS NUCLEAR FUSION

The outlook for controlled nuclear fusion has become much more complex than it appeared to be - at least to the general public - when the possibility of taming thermonuclear reactions for the production of useful power was optimistically mentioned at the 1955 Geneva conference on the peaceful uses of atomic energy. Indeed, it may now be impossible to recapture the widespread excitement that followed the prediction about thermonuclear power by the President of the conference, Dr. Homi J. Bhabha of India, and the subsequent disclosures that research on controlled nuclear fusion was actively under way in some of the technically advanced countries.

The significance of this possibility was immediately recognized and there were many enthusiastic accounts of what the generation of power from fusion reactions would mean to the world. "When that happens", as Dr. Bhabha put it in his address at Geneva, "the energy problems of the world will truly have been solved forever, for fuel will be as plentiful as the heavy hydrogen in the oceans". And scientific commentators were quick to point out that for about every 6 500 ordinary hydrogen atoms there is one atom of heavy hydrogen (deuterium) and that even hydrogen-3 (tritium) - rare in nature but useful in fusion reactions - could be produced in adequate quantities by bombarding heavy hydrogen with neutrons from an atomic reactor. In other words, there were virtually inexhaustible reserves of fuel and the day was foreseen when a gallon of water would be more useful than a gallon of petrol.

When, at the end of 1957, first reports of results obtained with Britain's thermonuclear apparatus ZETA appeared in the press, it seemed that this was no longer a mere theoretical possibility and popular enthusiasm reached a new peak. The scientists concerned, however, did their best to put these results in correct perspective, and it soon became evident that their immediate value had been somewhat exaggerated in popular accounts. Further, similar experiments were reported from other countries, and a re-assessment of the ZETA results seemed less reassuring than their initial evaluation.

The Geneva conference of 1958 provided the first major opportunity for an open discussion and a comparison of the results obtained in different countries, and commenting on this exchange of information, Professor Edward Teller of the United States said that it was "remarkable how closely parallel" the developments had been in different countries.

The information made public in 1958 also made it clear that the technical problems that stood in the way of achieving controlled thermonuclear fusion were formidable and their solution was likely to be much more difficult and perhaps take much more time than many people had apparently been led to believe. Professor Teller said that while he believed that thermonuclear energy generation was possible, it was not going to be "quite easy". Professor L.A. Artsimovich of the Soviet Union remarked: "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." Dr. P.C. Thonemann of the United Kingdom thought that an answer to the question whether electrical power could be generated "using the light elements as fuel by themselves" could be given only in the next decade, and if the answer was "yes" a further ten years would be required to answer the question whether such a power source was economically valuable.

Salzburg Conference

More than three years have passed since secrecy about fusion research was removed at Geneva, and these years have been a period of intense activity in this field. The need for an adequate assessment of this activity at an international level has been widely felt in scientific circles for quite some time, and in response to this need the International Atomic Energy Agency held a conference on Plasma Physics and Controlled Nuclear Fusion Research at Salzburg, Austria, in September 1961. More than 500 scientists from 29 countries and six international organizations attended the conference which lasted a week, during which more than 100 papers were presented and discussed.

Opening session of the Salzburg conference on Plasma Physics and Controlled Nuclear Fusion Research

Summing up the discussions, Professor Artsimovich said: "On the whole, with respect to the status of the problem, there can be no doubt that very great progress has been made, by comparison with the situation which was revealed at the 1958 Geneva conference. At that time the main body of scientific information was, essentially, something that might be called a display of ideas. Most of these ideas were only thinly draped with rough and insufficiently verified experimental data, largely exploratory in character. By contrast, we can now point in nearly every part of the general thermonuclear program to a large number of carefully executed experimental studies and to valuable and reliable results which, in the aggregate, constitute a sufficiently reliable foundation for a substantial acceleration in the rate of research in the future."

In another summing-up of the present situation, Dr. M.N. Rosenbluth of the United States, speaking from the point of view of theoretical physics, said: "While it is unfortunately true that theorists have not told the experimentalists how to build a thermonuclear machine, it is also true that we have been looking hard for very many years for a fundamental reason why a plasma fusion reactor should be impossible and we have not found any such reason." Dr. Rosenbluth added: "If I may make a statement from the heart, I believe the chances are very good that in twenty years or so mankind will have solved the problem of controlled fusion if only he has not lost in the meantime the far more difficult struggle against uncontrolled fusion."

The Basic Problem

Before referring to any of the specific topics discussed at the Salzburg conference, it might be useful to consider the nature of the basic problem. The principle of thermonuclear fusion - especially as an explanation of the energy release by incandescent stars - was discovered many years ago, and the quantitative values of the energy released by different fusion reactions were established on the basis of Einstein's famous equation about the equivalence of mass and energy. If two light atomic nuclei fuse to form a single nucleus, there is usually a substantial loss of mass and hence a tremendous release of energy.

The question is how to make them fuse. That can be done only if the nuclei can be made to collide against each other with sufficient force. The task is to impart to the nuclei such an energy of motion as would enable them to overcome their mutual electrical repulsion (all nuclei being positively charged) and at the same time to keep the nuclei confined within a small volume of space so as to increase the chances of collision.

At the center of the sun and other stars fusion reactions take place under conditions of immense pressures and extreme temperatures. For certain reactions, for example between heavy hydrogen nuclei or between heavy hydrogen and tritium, somewhat less stringent conditions may suffice, but even these would require temperatures of tens of millions of degrees along with the accompanying requirement of confining the accelerated nuclei long enough for reactions to take place on a substantial scale.

So far as the problem of acceleration of the nuclei is concerned, remarkably high temperatures have been obtained by the use of extremely powerful electrical discharges. As for the problem of confinement, a promising fact is that a powerful electric discharge itself creates a magnetic field within which the charged particles are trapped; the resulting constriction of the particles is the so-called pinch effect. The confinement can be reinforced by additional magnetic lines of force through the use of auxiliary magnetic devices. The particles are thus confined within a kind of magnetic bottle.

Although this sounds easy enough, the trouble is that the super-heated nuclei behave much less obligingly than might be expected of them from this simple account. At the temperatures associated with such experiments the atoms of the fusion material become almost completely ionized, i.e. the revolving electrons are set free from the atoms, leaving only the positively charged nuclei. This ionized gas with its freed electrons is called plasma, which has sometimes been described as a fourth state of matter.

The problem is to confine the hot plasma for a sufficient period of time for fusion reactions to start and establish themselves. Unfortunately, in spite of the effect of magnetic fields the plasma tends to develop certain instabilities, as a result of which the particles escape from their trap. Much of the current research is devoted to trying to understand the nature and causes of these instabilities.

Behavior of Plasma

Although the bulk of the matter in the universe exists in the form of plasma (in the incandescent stars, for example) and although even terrestrial plasmas, such as gaseous discharge devices and flames, are commonplace, little is yet known about the behavior of plasma, particularly from the dynamical aspect. Hence, a major trend at present is towards pure research in plasma physics, both theoretical and experimental, in order to gain a fuller understanding of the properties of high-temperature plasma.

The theoretical approach stems from the so-called magnetohydrodynamic approximation, in which plasma is considered as an electrically-conducting liquid interacting with magnetic fields. This treatment ignores the microstructure of the plasma, which in reality consists of energetic particles gyrating in local magnetic fields. The interactions of these particles give rise to subtle effects which can be observed experimentally, and plasma theory is continually being modified in attempts to explain these observations.

The object of much experimental work is to produce pure hot plasmas, virtually completely isolated from material surroundings and stable for times sufficiently long for reproducible observations to be made. In this way the predictions of plasma theory can be checked and unforeseen nuances of plasma properties observed. An important variable in the hands of the experimenter is the configuration of the magnetic field used to contain the plasma. Because of the low inertia of plasma and the large electromagnetic forces required to contain the energetic particles forming the plasma, inherent instabilities tend to grow very rapidly. These instabilities greatly hamper and often nullify observations of plasma behavior.

To prevent or delay the onset of instabilities, complex magnetic field configurations, with spatial and sometimes temporal variation, are required, making severe demands on electromagnetic technology. Thus from plasma physics research stem significant advances in various technical fields, such as electrical energy storage, magnetic coil design and precise high-current switching.

Review at Salzburg

Both the theoretical and practical aspects of the work were examined in detail at the IAEA conference at Salzburg. Among the topics discussed were plasma confinement, stability, oscillations and turbulence; plasma compression, heating and acceleration; shock waves in plasma; interaction of particles and electromagnetic waves with plasma; and plasma waves and radiation.

In his summing-up at the end of the discussions, Professor Artsimovich explained some of the main difficulties that stood in the way of achieving controlled thermonuclear fusion. He pointed out that plasma heated to a high temperature very readily rid itself of the accumulated energy "by means of various instability mechanisms and also by means of radiation". As a result, in the experiments made so far, it had not been possible to contain a dense and hot plasma for more than some hundreds of micro-seconds (i.e. less than one thousandth of a second). Further, the production of a sufficiently pure hydrogen or deuterium plasma was itself a difficult task, because of the interaction of the plasma with substances on the surface of the walls of the vacuum chamber within which the experiments were conducted. Professor Artsimovich also referred to the difficulty of observing the properties of the plasma; "a column of plasma concealed behind metal sheaths and complex windings is, by reason of its inaccessibility and extreme sensitivity to any contact, an extremely inconvenient subject for investigation."

"It is significant", said Professor Artsimovich, "that the stock of fundamental physical conceptions has remained practically unchanged. During the past three years not one essentially new method for obtaining a high-temperature plasma has been proposed.

Sir George Thomson, the famous British physicist, who attended the conference, being interviewed for TV and radio

At the same time there has been a noteworthy shift of emphasis in the efforts to develop the various trends within the over-all program. In the initial stage of work on the problem of controlled thermonuclear reactions, much attention was paid to investigation of the most simple method of obtaining high temperatures. The basis of this method is the use of linear impulse discharges of very great magnitude and very short duration. This is what is known as the fast linear pinch. The efforts devoted in Britain, the Soviet Union and the United States to investigating the fast pinch - research which was carried on independently - enabled all concerned, both jointly and singly, even before the Geneva conference, to get a clear picture of the phenomena taking place in discharges of this type and to discover the basic mechanism underlying the dynamics of a plasma column. As is known, this mechanism consists in the acceleration of the plasma under the action of electrodynamic forces. Although plasma temperatures of over one million degrees were obtained in experiments with linear pinches, it soon became clear that serious consideration could hardly be given to this method as a practical means of obtaining intensive thermonuclear reactions on a scale which was of technological or even of physical interest."

Professor Artsimovich then discussed the various other methods and installations to which interest of research workers in the Soviet Union, United Kingdom and United States had subsequently turned - in particular, the "theta pinch", the "Zeta", "Alpha" and "Sceptre" installations, the "Stellarator", "Astron", "Tokamak", "Ogra" and "DCX".

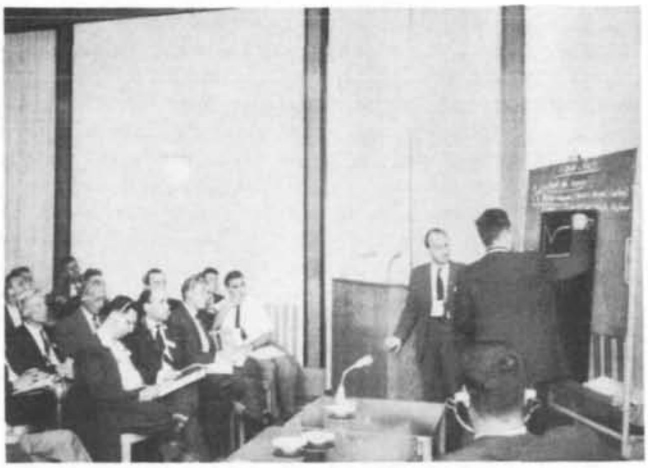
Concluding, Professor Artsimovich said: "It is now clear to all that our original beliefs that the doors into the desired region of ultra-high temperatures would open smoothly at the first powerful pressure exerted by the creative energy of physicists have proved as unfounded as the sinner's hope of entering Paradise without passing through Purgatory.

Andyet there can be scarcely any doubt that the problem of controlled fusion will eventually be solved. Only we do not know how long we shall have to remain in Purgatory. We shall have to leave it with an ideal vacuum technology, with the magnetic configurations worked out, with an accurate geometry for the lines of force and with programmed conditions for the electrical parameters, bearing in our hands the plasma, stable and in repose, heated to a high temperature pure as a concept in theoretical physics when it is still unsullied by contact with experimental fact."

The broad trends of thinking in the theoretical field as revealed at the conference were reviewed by Dr. Rosenbluth. He also noted the spirit of cooperation and friendship with which information and ideas had been freely exchanged at the conference.

There were ten formal sessions of the conference, including one at the end at which the discussions were summed up. They were presided over by B. Lehnert (Sweden), A. E. Ruark (USA), M. A. Leontovich (USSR), G. von Gierke (Federal Republic of Germany), J. G. Linhart (Italy), E. Nagy (Hungary), P.C. Thonemann (UK), L. Spitzer (USA), L.A. Artsimovich (USSR), and C. Vendryes (France).

Apart from the discussion at the formal sessions, much useful ground was covered at 14 informal sessions organized at the request of the participants.



An informal session of the conference

It was generally felt that these informal discussions, which were often very lively, contributed greatly to the success of the conference as a whole.

The proceedings of the conference will be published in three special issues of the IAEA scientific journal "Nuclear Fusion".

An advanced international training course in the biological effects of radiation is being conducted by IAEA and the Government of Israel at the Radioisotope Center near Rehoveth, Israel. Picture shows the participants in the course, which started in October 1961

The national radioisotope center of Israel was opened in October 1961 by Mr. David Toll (center, foreground), of IAEA, on behalf of Mr. Sterling Cole. Extreme left: Mr. I. Keenan, Israel's Resident Representative to IAEA