fusion: where do we stand?

In late June more than 500 scientists from 24 countries and three international organizations assembled in Madison, Wisconsin, to attend the Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research.
During the five days of the meeting 141 papers were presented, 49 individually and 92 in 31 rapporteur presentations ; they contained no major surprises but, in the words of the Scientific Secretary of the conference, they "demonstrated steady progress in the production, confinement and heating of high temperature plasma."

The goal of the research reported is, eventually, to attain demonstration of the feasibility of construction of a fusion reactor — a thermonuclear device releasing more energy through a controlled nuclear fusion reaction than the system used to contain the plasma consumes. Estimates of the time it will still require before this goal is reached differ widely, and it is perhaps best not to put a figure on it at all; but the mood of the participants in the symposium could be described as one of guarded optimism.

Three summary talks were given — by Dr. T. K. Fowler (USA), on theoretical considerations reported; Dr. R. J. Bickerton (UK), on experimental work; and Prof. H. K. Forsen (USA) on possible reactor systems. To quote Dr. Fowler: "In trying to sum up my impressions of this conference, I concluded that perhaps the most important thing was that this is the first IAEA Fusion Conference with an entire session on fusion reactor systems. Perhaps this conference will be remembered as a sort of engagement party between plasma containment and fusion reactors.

"Admittedly, the two seemed a little like strangers from time to time here. But this will change, for we have brought some valuable presents to this party. Consider the number of new experiments we have heard about which are about to push on to the high temperatures and high densities where the real problems lie... The theoretical development is now such that critical questions are posed which these experiments can answer... Even if at first some answere are disappointing, I am confident that we will soon be on the road to building a fusion reactor."

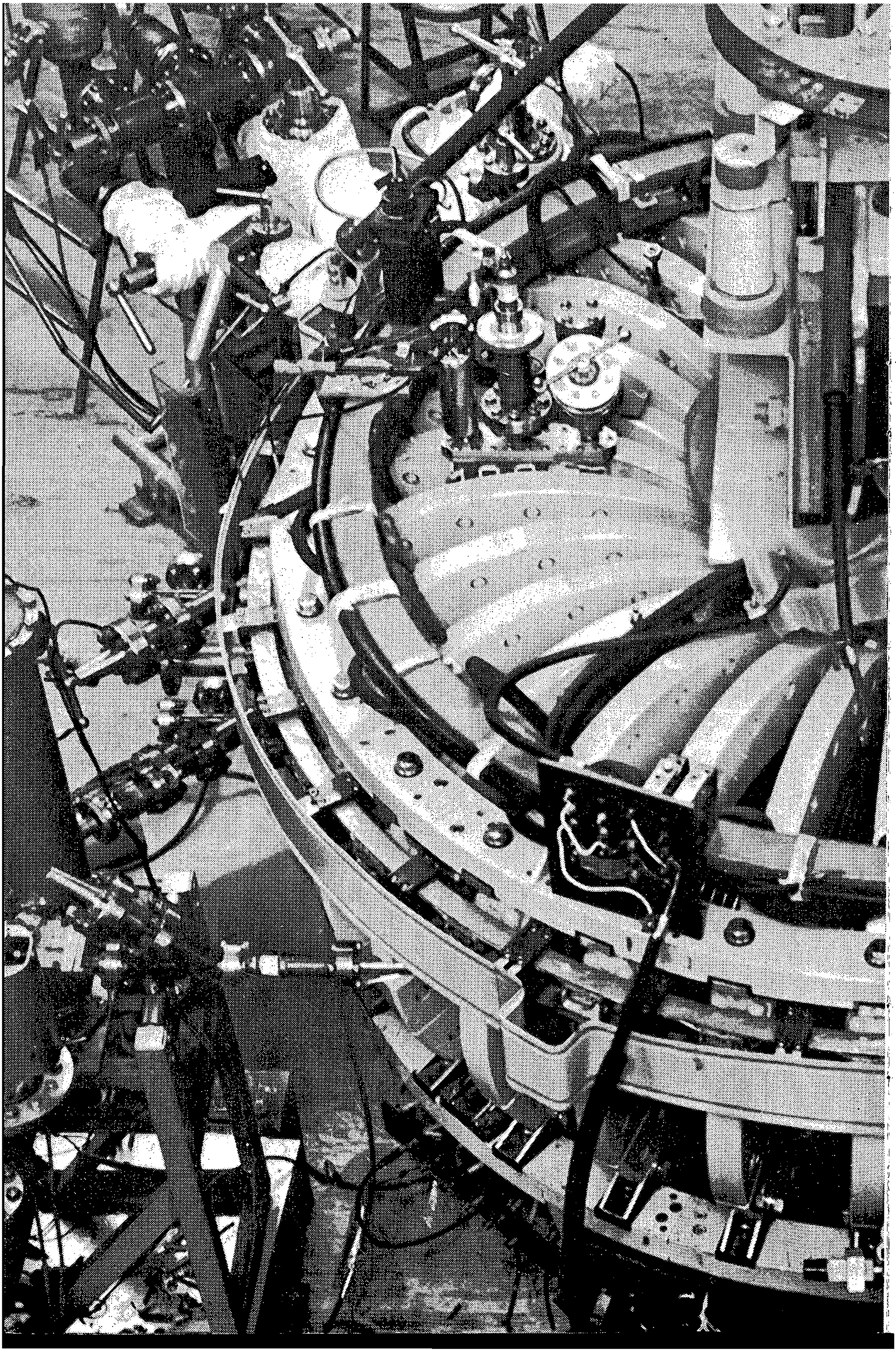
Broadly, two basic conditions must be satisfied in order to demonstrate practicability of a true fusion reactor. First, plasma must be created and sustained at a temperature in the range of 50 to 500 million degrees Kelvin. Secondly, this plasma must be confined for a sufficiently long time to satisfy what is known as the "Lawson criterion" — that the product of plasma density and confinement time exceed a value of about 10^{14} ion-seconds per cubic centimetre. Confinement of the exceedingly hot plasma is generally by magnetic fields which form, in one class of machine, closed traps and in a second class open traps. In the first class the plasma is commonly held within a ring-shaped volume to prevent its escape along magnetic field lines; in the second, the plasma is constricted within a part of the field but it can escape from the ends of the confinement volume unless other measures are taken to prevent this.

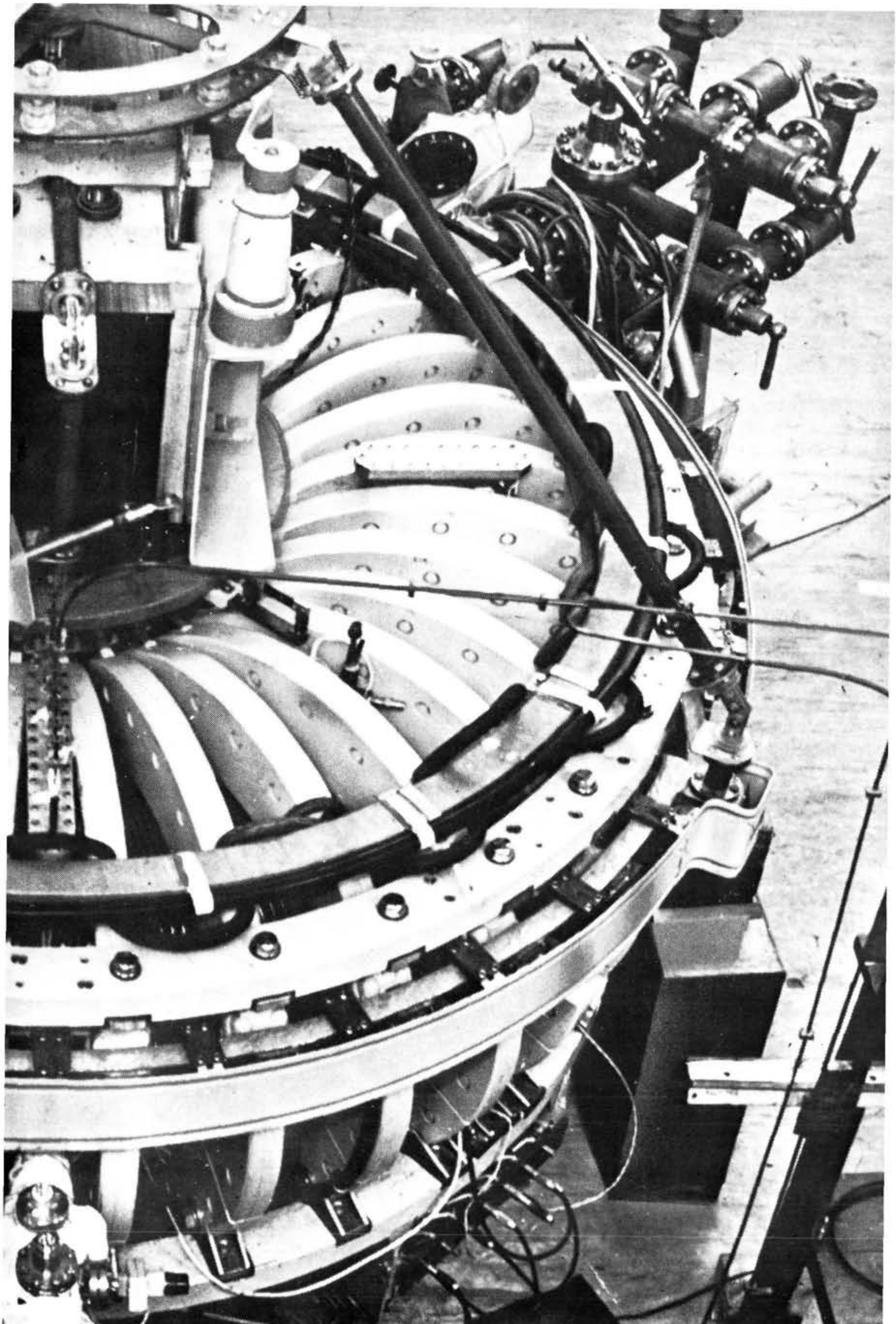
Tokamaks *et al.*

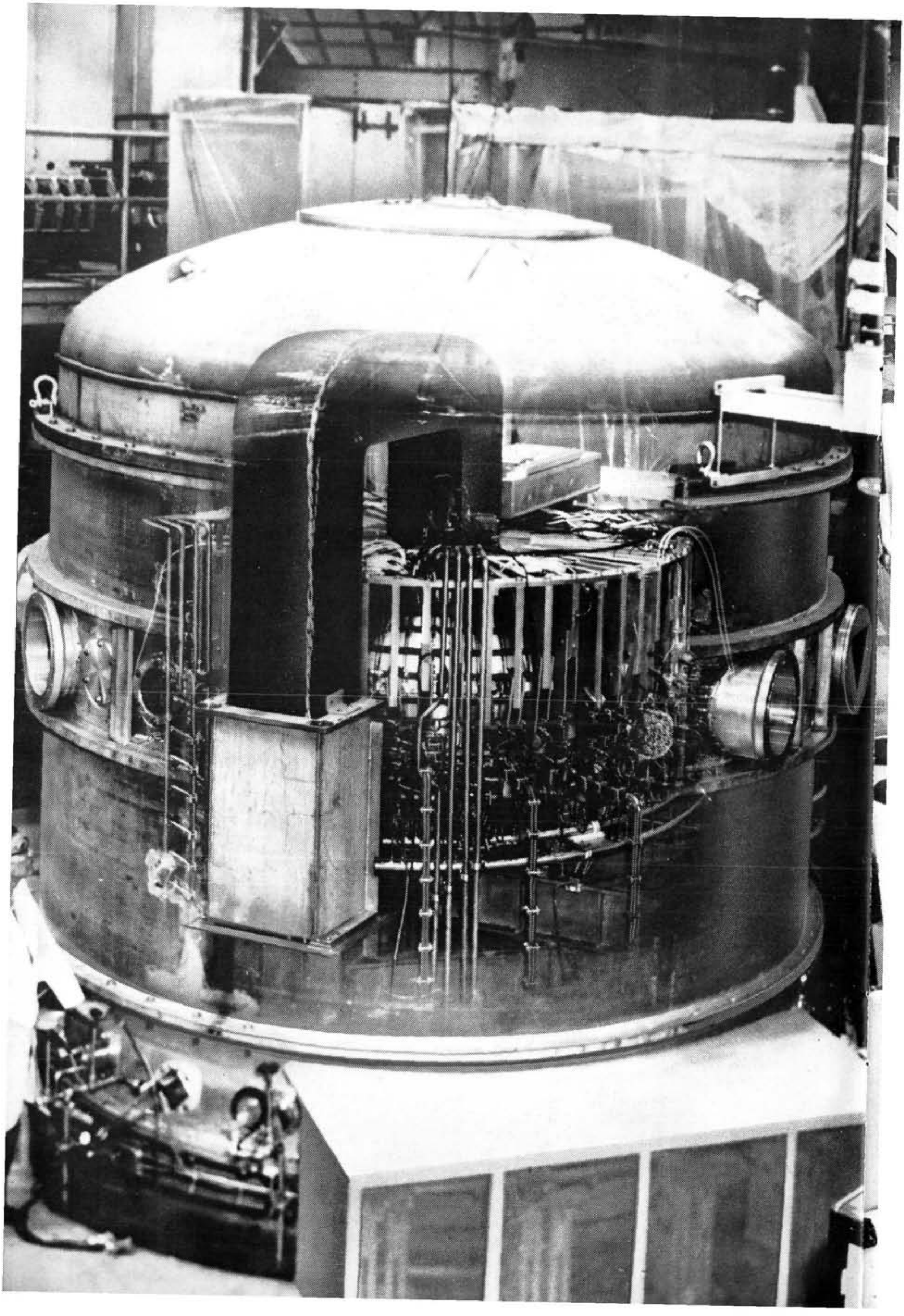
The majority of the papers presented at this conference dealt with closed confinement systems. The theory of plasma confinement and transport processes in toroidal geometry is difficult, and no single theory exists to explain all the experimental results. But theories relevant to particular devices, or to particular plasma régimes, are being refined steadily, and there is an increasing interaction between theory and experiment. Papers presented at the conference reported increases in plasma densities, temperatures and confinement times as compared with those reported at the previous conference in the series, held at Novosibirsk in the USSR in 1968.

Four of the configurations which are being studied seem to be of particular interest in terms of their prospects for fusion reactor development; high on the list are machines of the type known as Tokamaks. These are pulsed devices in which plasma in the form of a ring is confined by a magnetic field generated by an induced current flowing around it. Results obtained in work with large Tokamak machines in operation at Kurchatov, in the USSR, and at Princeton in the United States showed similar values of particle density (10^{14} per cubic centimetre), electron temperatures (up to 30×10^6 °K), ion temperatures ($5-6 \times 10^6$ °K) and confinement times (20 milliseconds) under optimum conditions. One paper which was of particular interest, by Kadomtsev and Shafranov (USSR) discussed the possibility of obtaining steady state operation of a Tokamak by utilising current driven around the ring by the interaction of radial plasma diffusion with the magnetic field. This idea, also published recently by Bickerton and others (UK), is regarded as constituting an important advance in Tokamak theory.

Photo next page:
Tokamak T-6, one of the large experimental devices being used in fusion research in the USSR. Photo: USSR







The three other closed confinement systems which are being most actively studied are devices in which the plasma is trapped within a diffuse pinch; Stellarators and related devices in which, in contrast to Tokamaks and diffuse pinches, there is no net plasma ring current; and toroidal "theta pinches", perhaps best illustrated for the purposes of this article by the large Scyllac machine at the Los Alamos Scientific Laboratory, in which a helical magnetic field is superimposed on the basic longitudinal field in the torus. This device was first operated shortly before the conference, and produced stable plasma of high temperature and density for short periods, of the order of a few microseconds.

The descendants of the magnetic bottle

It has been known for some years that plasma in magnetic well systems, open confinement devices known earlier as magnetic bottles or mirror machines, is macroscopically stable. The Madison conference showed that research is now concentrated on loss mechanisms and on micro-instabilities that occur as the plasma is built up. These devices can contain very hot ($10-100 \times 10^6$ °K) plasma at relatively low densities (of the order of $10^{12}-10^{13}$ per cc); they are probably the best understood confinement devices.

A number of papers dealt with various aspects of hypothetical reactor systems based on existing devices, Tokamaks, Stellarators, open traps and so on. It must be emphasised that at this stage such papers do deal very much in hypothesis — but the results which are being obtained are promising. The summary talk given by Dr. Bickerton noted that "the most exciting advances have been made in Tokamak research. The Princeton group have confirmed the earlier Russian results, while the Russians themselves have gone on to obtain still higher temperatures with increased plasma current." After the Novosibirsk conference a number of laboratories started work on new projects and, in particular, several large Tokamaks were planned and are now being constructed. Dr. Bickerton commented that "at present, and in the simplest terms, future progress apparently depends only on increasing the gas current and on applying auxiliary heating methods. There may well turn out to be insurmountable barriers across this golden road to riches; however, only by travelling along it will their presence or absence be discovered."

Coordination and collaboration

Dr. Bickerton's "barriers across the golden road" may exist, but in a real sense the Madison conference demonstrated just how few barriers there are between scientists worldwide. In particular, the opportunity of the conference was taken to hold the first meeting of the International Fusion Research Council, set up to consider long-range planning and international cooperation in fusion work. At future meetings the Council

The Ormak, a toroidal plasma containment device similar to Tokamak, developed at the Oak Ridge National Laboratory. This is a composite photograph, showing both interior and exterior of the device. Photo: ORNL is to discuss national research programmes in detail and, possibly, will suggest initiation of international projects.

As has been noted previously, the frequency of publicaton of the IAEA journal *Nuclear Fusion* has now been increased to six issues per year. This, and the expansion of its contents to include technological aspects of fusion, is regarded as having significantly increased its importance. It is intended that a paper reviewing the work of the Madison conference should appear in an early issue.

The conference was sponsored by the IAEA and organized in cooperation with the United States Atomic Energy Commission and the University of Wisconsin, which acted as host. Previous conferences in the series were held in 1961 at Salzburg, Austria; in 1965 at Culham, UK; and in 1968, at Novosibirsk. It is expected that the proceedings of the Madison conference will be published in a few months.