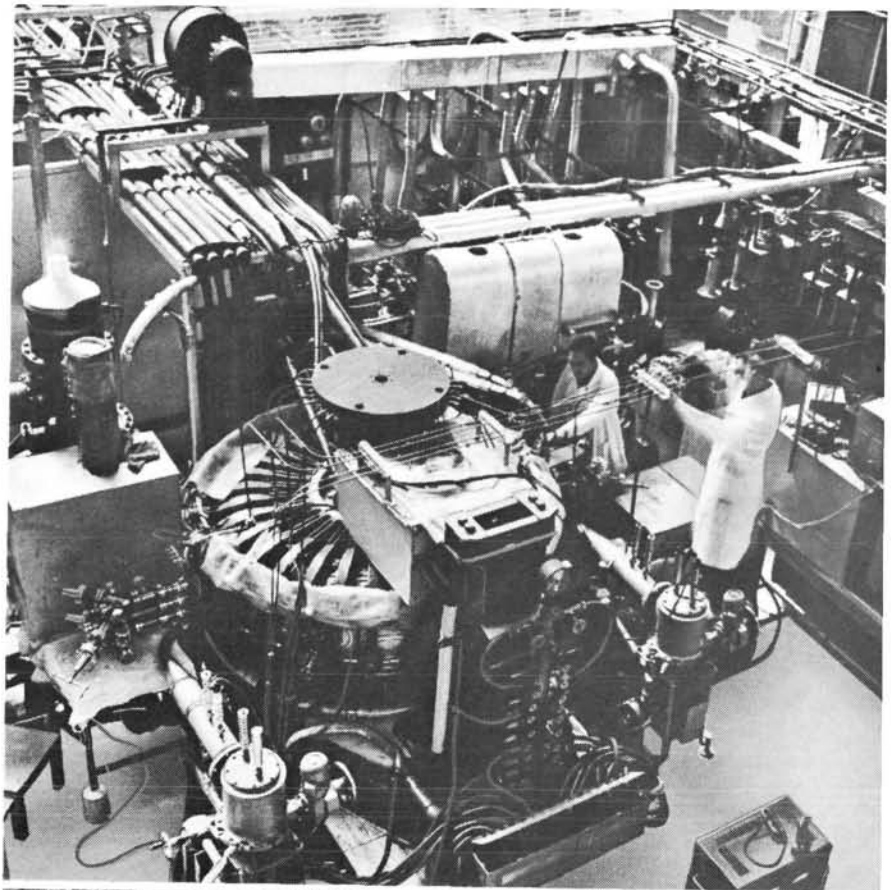
progress in controlled fusion

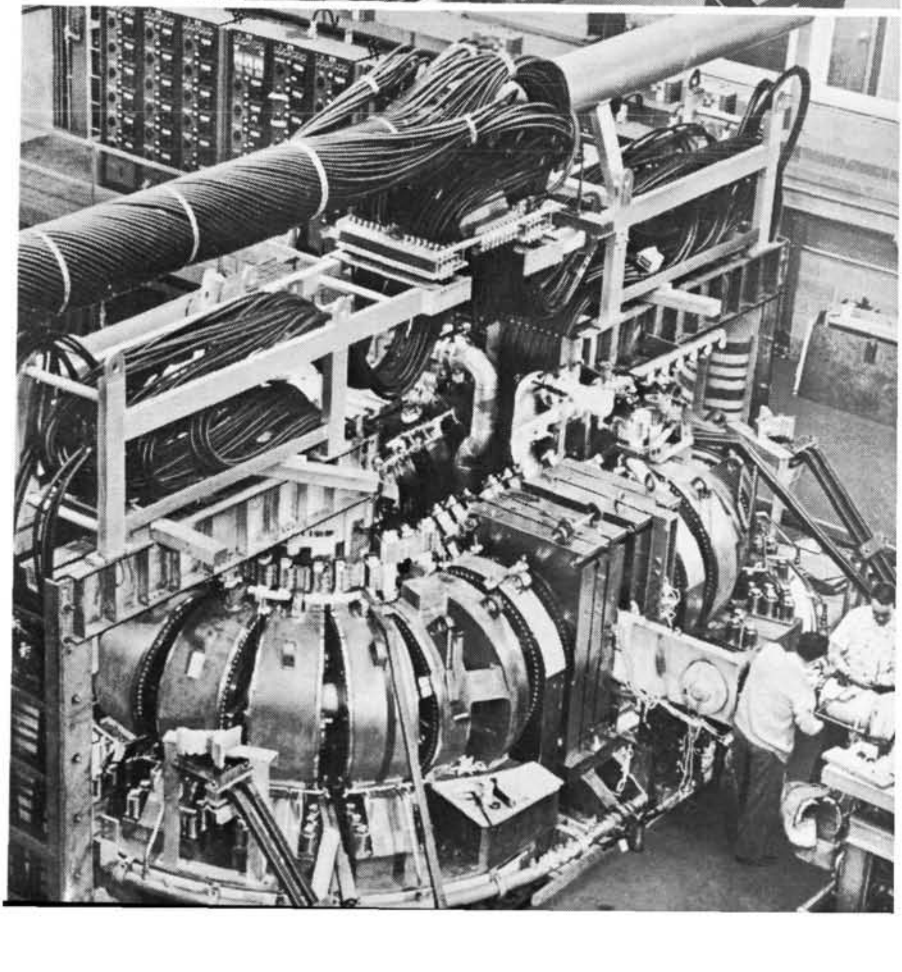
Research on controlled thermonuclear fusion offers the prospect of virtually unlimited energy resources for the future.
The report of a panel of experts convened by the IAEA at Trieste in June indicates that there are real possibilities for the solution of some of the practical problems which remain.

The 11 members of the panel and the three members of the Agency's staff who organized and attended the meeting knew what have come to be regarded as inescapable facts. The rapid growth in the population of the world and improvements in living standards world-wide create a demand for more and more power. And existing resources have calculable, and all too finite, limits.

The most important non-nuclear source of energy is the generality of fossil fuels — coal, oil and the like — of which total resources have been estimated to be about 100 Q (where Q is an arbitrary unit, equivalent to 3×10^{14} kWh or 10^{21} Joules). If no other demands were made upon these resources they would alone be sufficient to meet the world's energy needs until the year 2050. But such demands are certain to be



TOKAMAK-3, one of the series of devices with which scientists in the USSR have achieved promising results in controlled fusion research. Photo: USSR



An early model of a Stellarator, as used in plasma physics research at the Princeton Plasma Physics Laboratory. Photo: Princeton University made; the chemical industry alone requires increasing quantities of the hydrocarbons in plastics manufacture, to take just one example. As well, the combustion of fossil fuels has as a by-product the release of carbon dioxide and other residues to the atmosphere, with consequent, well-known harmful effects. Other sources of energy such as the sun (which may be tapped, for example, by solar cells), hydro-electricity generation, the winds and the tides seem unlikely to make a contribution of any size to meet demands.

So the development of nuclear power is essential. Nuclear fission is already being called upon. At the end of last year there were 91 power reactors in operation in 14 countries, with a total generating capacity of 15 500 megawatts; and it has been estimated that by 1980 nuclear generating capacity will rise to about 330 000 megawatts and account for about 15 per cent of all electricity produced at that time.

Reserves of high-grade uranium and thorium ores are thought to be about 100 Q, too, although these may be extended if low-grade deposits prove to be capable of economic exploitation.

In the view of the panel, however, nuclear fusion could be the source of practically unlimited power for the future. Fusion power plants now being considered could use deuterium and tritium, with lithium being used in a breeding cycle to regenerate tritium. High-grade resources of lithium are expected to be more than sufficient for the first few decades of fusion power, and the panel considered that if lithium resources in the sea and in low-grade ores prove usable an additional 10 million Q may be available.

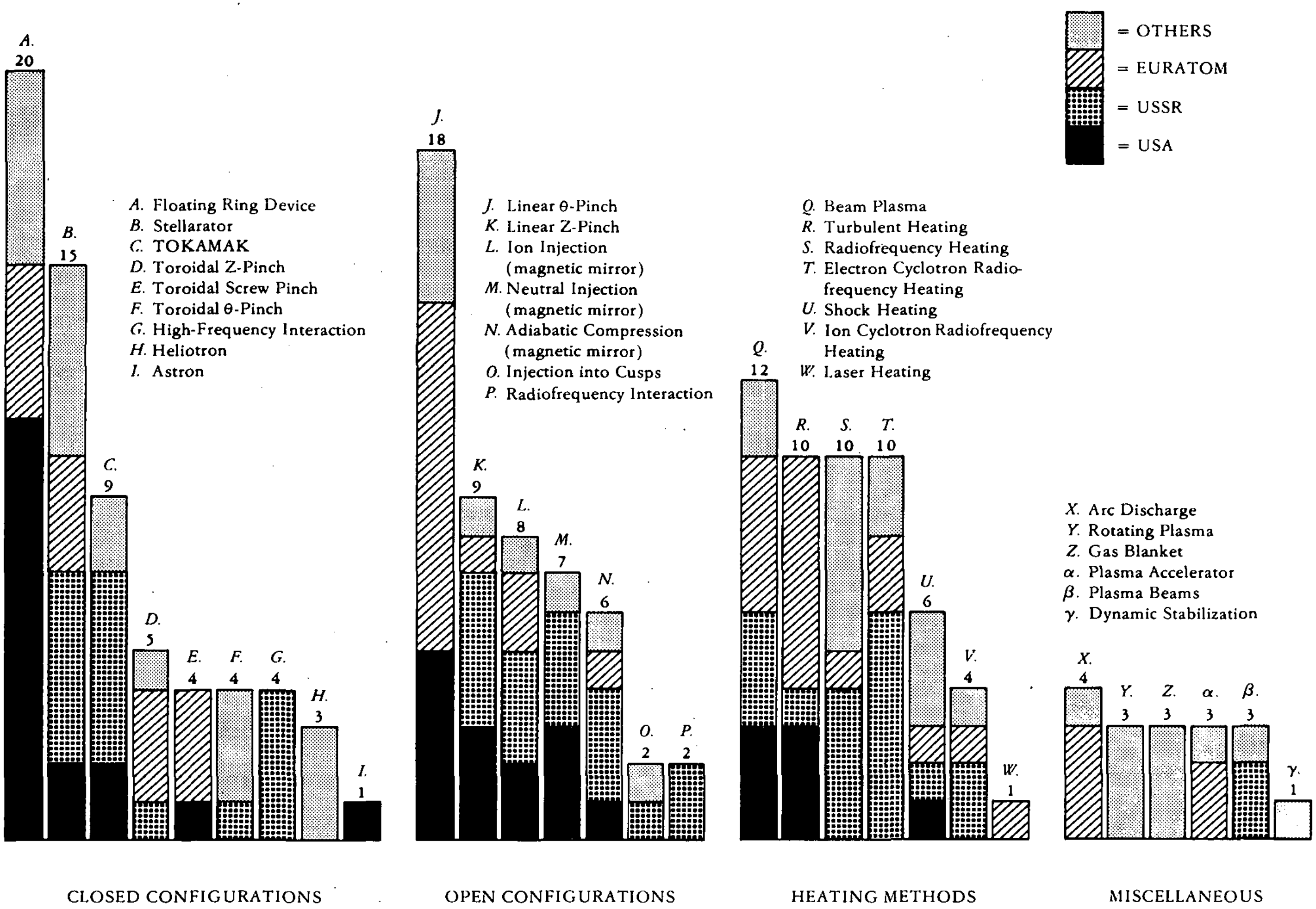
The experts at the panel meeting hoped, however, that well before the high-grade lithium resources were exhausted the deuterium-deuterium fusion reaction would be found to be feasible. If this does prove to be the case, energy resources may be said to be virtually limitless; the best estimate is roughly 10^{10} Q.

Studies indicate that two basic conditions must be satisfied before a true fusion reactor will be practicable. First, plasma must be created and sustained at a temperature of from 50 to 500 million degrees Centigrade. Secondly, this plasma must be confined for a sufficiently long time to satisfy what is known as the "Lawson criterion" — that is, that the product of plasma density and confinement time exceed a value of about 10^{14} ion — seconds per cubic centimetre. Work in the USSR, using a machine of what is known as the TOKAMAK design, and in the United States using a machine of the SCYLLA design, has already achieved values of between 3 and 6×10^{11}, values which are admittedly two or three orders of magnitude below the desired product. Nonetheless, it is considered by some research workers that the first really large-scale machine which is built may demonstrate feasibility satisfactorily.

Theoretical and experimental understanding of the problems which remain, and of ways in which they might be surmounted, is increasing rapidly. But much remains to be done.

Research into ways of confining the exceedingly hot plasma is going ahead along several lines, of which the use of very strong magnetic fields appears to be the most promising. There are two main classes of machine in which magnetic confinement is used: those using closed, and those using open magnetic traps. In the first class the plasma is commonly confined within a ring-shaped volume so that it cannot

MAJOR CONTROLLED THERMONUCLEAR RESEARCH EXPERIMENTS THROUGHOUT THE WORLD

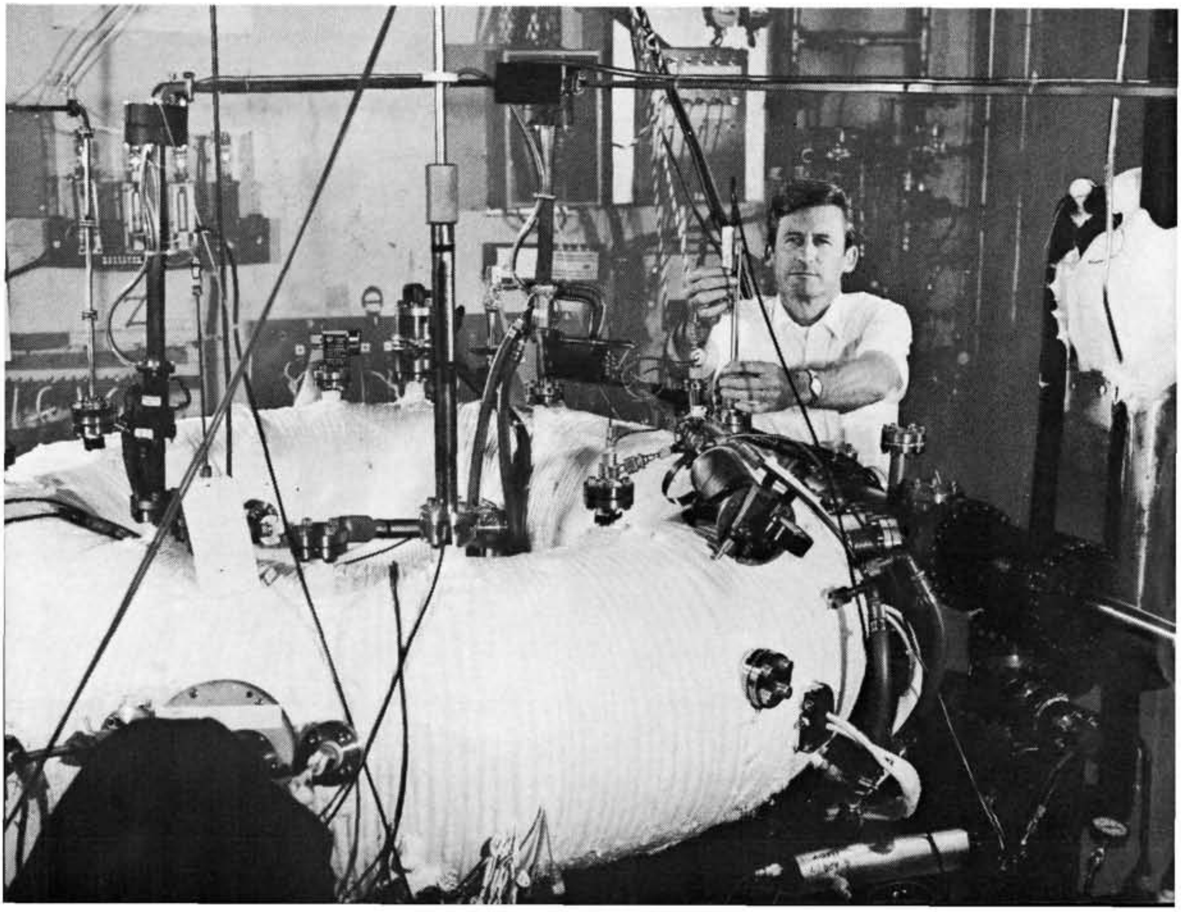


escape by moving along magnetic field lines; in the second the plasma is constricted, but can escape from the ends of the confinement volume unless special measures are taken. TOKAMAK machines are of the first class, and SCYLLA of the second.

The panel considered that the results which have been obtained in work with TOKAMAK machines "are the most favourable obtained so far in fusion research with closed systems. Thus, the TOKAMAK is likely to provide one of the possible ways to realise a fusion reactor." Remaining important problems concern the establishment of the validity of scaling laws for the building of bigger devices, especially so far as they concern extension to higher temperatures and densities of the plasma, heating of the plasma to thermonuclear temperatures, and understanding the ways in which plasma interacts with the walls of the chamber within which it is contained.

Other machines of this "closed" type have names which suggest that a science fiction writer has been at work: the Stellarator, the Torsatron, the Helical Heliotron, the Bumpy Torus and so on. The names of some open systems are equally picturesque — Scylla, the theta pinch, Pharon, Chalice, the famous Zeta experiment, Megatron and the like. Reactors

This photograph shows clearly the toroidal shape of the Levitron, one of a series of devices used in the study of the properties of plasma as part of world-wide research into the possibility of achieving controlled thermonuclear fusion. Photo: USAEC/San Francisco, Operations Office



using open magnetic configurations may offer advantages in terms of ease of refuelling, removal of reaction products and smaller unit size (theoretical studies suggest that an "open" fusion reactor system might be built in a size of about 1000 MW(e)); but the difficulty of confining the plasma seems likely to be greater. One such type of machine, known as the linear theta pinch design, has produced already plasma with good characteristics and no instability — but end losses are such that it seems that a positive power output could be obtained only with a device several kilometres long and delivering about 100 000 megawatts. The panel comment in their report: "According to several authors, one can hope that the engineering feasibility of this kind of reactor should perhaps not be insurmountable, but at the present time a general opinion is that it is difficult to imagine an economic justification for so large a power station." Nevertheless, work on small-scale versions of such devices does aid in increasing understanding of the behaviour of high-temperature plasma.

The present research activity is reviewed, country by country, in a recent publication of the Agency entitled "World Survey of Major Facilities in Controlled Fusion," issued as a special supplement to the IAEA journal Nuclear Fusion. Fourteen countries with programmes in controlled fusion research provided technical details for inclusion in this survey, including operating principles, main characteristics, major results and, where possible, an indication of future plans. They are Australia (which gave information on six devices), Czechoslovakia (3), Denmark (2), France (20), the Federal Republic of Germany (16), Italy (4), Japan (15), the Netherlands (13), Poland (2), Sweden (5), Switzerland (1), the USSR (51), the United Kingdom (11), and the USA (38). A chart, reproduced here, indicates the lines along which research work is proceeding. [page 3 of the publication cited]

It is apparent that it will be years before the present research effort comes to fruition. It must be repeated, that there *are* formidable theoretical and practical difficulties still to be overcome; but the indications are that they *can* be overcome. In particular, it seems that it will be possible quite soon to attain the confinement times and temperatures necessary to sustain a thermonuclear reaction. Existing TOKAMAK devices, scaled up to a larger size, could very probably satisfy the Lawson criterion. The best estimate is that the scientific problems in the path of achievement of controlled fusion will be solved, for at least one of the configurations being studied at present, within the decade. It should then be possible to build a device in which the energy released by thermonuclear reactions within a mixture of deuterium and tritium would amount to an appreciable fraction of the input power.

Such a device would be an intermediate stage on the road to a prototype fusion reactor with a positive power output, and would enable study of the remaining practical problems. It is extremely difficult to estimate how long this work will take — and it is especially difficult to estimate how much money will have to be spent.

But fusion power has a number of attractive features. First, as has been said, it can call on virtually unlimited resources for fuel. Secondly, such a reactor could not be subject to nuclear excursions, or runaway. Thirdly, there are no fission products from its operation; nor are there radioactive waste products such as those from the operation of even the most efficient fission reactor system. It is admitted that there could be problem connected with the safe storage and handling of the tritium inventory of a fusion plant, but these are not insuperable. The radioactivity produced by neutron irradiation of the structure of the fusion reactor is expected to be comparable with that induced in a fission reactor. And, fourthly, the fuel of a fusion power plant could not be used by itself, on the basis of present knowledge, to make nuclear weapons. It would technically be possible to use surplus neutrons from the fusion reaction to breed plutonium in a uranium blanket on much the same principle as in a fast breeder reactor; but this would greatly increase the technological complexity of the fusion plant and there would be clear evidence of such a move. The introduction of fusion power reactors could thus lessen the problems attendant upon the application of safeguards.

Participants in the panel meeting, whose report on "International Cooperation in Controlled Fusion Research and its Application" will be published in a few months, were drawn from Australia, France, the Federal Republic of Germany, Italy, Japan, the Netherlands, Sweden, the USSR, the UK and the USA.