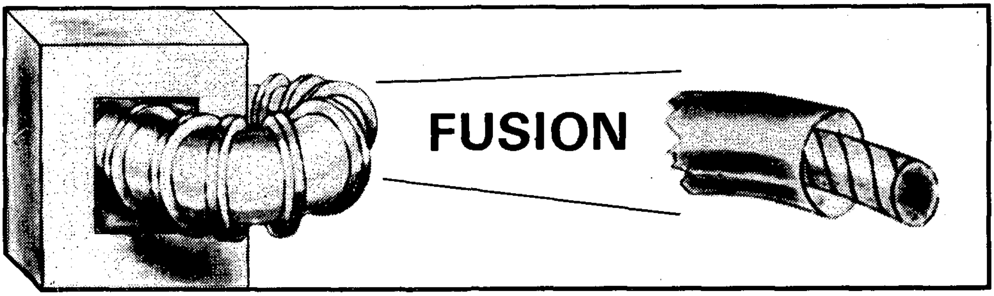

Nuclear Energy from the Hydrogen Isotopes

by J.A. Phillips*

In a darkened room the silence is broken by a clicking pump,
the hum of transformers, and the clunks of closing relays.
A flashing light partially illuminates a complex array of pipes,
wires and coils. In a corner of the room
a group of men peer into cameras or stand in front of panels
ablaze with flickering lights.
A bell sounds, camera shutters close, followed
in a few seconds
by a tremendous bang and a brilliant flash of light.
Someone shouts,
"CALIBRATION OF SCOPES, CLOSE SHUTTERS,
NEXT SHOT IN TWO MINUTES".

Activities such as this are being enacted daily in many laboratories throughout the world. The programmes are called controlled thermonuclear fusion or, for short, fusion. The goal is to bring nuclei of light elements together, **fuse** them into a compound nucleus which subsequently explodes with a release of energy. The reason why this research is supported is that energy is available in the heavy isotopes of hydrogen, in deuterium and tritium. Now deuterium is found in nature; for every 7000 atoms of hydrogen there is one of deuterium and we all know where hydrogen is most readily found — in water. It is calculated that in the atoms of deuterium in a liter of ordinary water there is the energy equivalent of 300 liters of super gasoline. Indeed when one considers the oceans of water that are available to us there is almost an infinite source of energy — if we can but use it.

The interest of the scientific community to tap this source of energy in a controlled way is world wide. The scientific and engineering problems, to be described below, are demanding and up to the present time beyond our capabilities. To proceed, however, as quickly and orderly as possible in this research there is the international exchange of information at conferences, symposia and workshops such as the recent conferences on plasma physics and controlled fusion in Switzerland, United Kingdom and the laser-fusion seminar in Trieste.

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The principal rules that one must follow to release the energy from the isotopes of hydrogen can be stated quite easily: 1) Heat a small quantity of deuterium (a gas) to a temperature of 100 000 000°C; at these temperatures the nuclei are moving so fast that they can fuse. 2) Contain the resulting pressure of the hot gas, a plasma, for times of up to seconds. After a moment's thought there is one serious snag and that is the pot (the reactor vessel) which is to hold this gas. Clearly no material can support these temperatures for long without vaporizing – remember the surface of the sun is only 5 700°C! Here man's ingenuity is challenged and different schemes have been proposed and are being examined. The most likely method appears to be the placing of a magnetic field between the plasma and the reactor wall – an insulating layer which separates the region of high temperature from the material wall across which the transport of energy is minimized. The experiments then have attempted to design and test different **magnetic bottles** which will hold plasma away from material walls and allow the heating of plasma to the temperatures required for fusion.

And with such a bottle how can one now heat the hydrogen gas to the required temperatures? This has turned out to be one of the simpler problems and can be done in a number of ways: pass a current of several thousand amperes through the plasma which will heat it up – as in an electric stove; or inject energetic neutral atoms (which, being neutral, pass unimpeded across the magnetic field) into the plasma where they are ionized and stopped, giving their energy to the plasma; or excite the plasma by radio frequency fields. The conditions for fusion will have been met and the energy released from the burning plasma will appear as intense ultra-violet radiation which will heat up the surface of the reactor wall. In cooling this wall steam can be generated. Also, many energetic neutrons will be emitted during the fusion process; they will be slowed down in hydrogeneous blankets and used to generate tritium, the third isotope of hydrogen in lithium coverings. Tritium can also be used as a fuel.

EXPERIMENTS

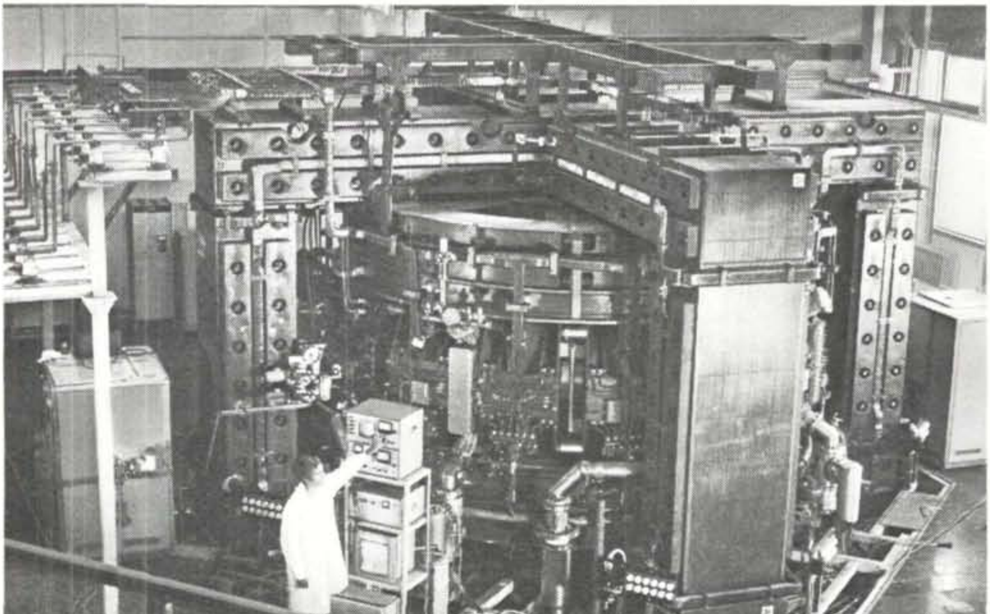
Serious efforts in fusion were started in the early 1950's with unbounded enthusiasm. Experimental devices were constructed with exotic names as Perhapsatrons (maybe you can, maybe you cannot), Scyllacs, Stellarators, Zetas (photo 1), Mirror Machines and so forth. In the late 1950's in the USA the first bit of plasma was heated to thermonuclear temperatures with a detectable nuclear burn. Quickly it was found, however, that Mother Nature had a few surprises up her sleeve; in particular the plasma-magnetic field interface did not remain stable but quickly, in one thousandth of a second or less, disrupted, allowing the hot plasma to rush across the magnetic field. The plasma was thus cooled with loss of confinement. Looking back over these times, one can say it was a field day for theorists who at every fusion conference disclosed to the dismayed experimentalists a new instability, a different way by which plasma could be lost. Oscillations were found to first perturb the surface which broke into kinks and waves which led to a tearing of the surface followed by a general turbulence.

TOKAMAK

In the last few years with a lot of hard work in theory and with experiments it appears that a basic understanding of the physics of plasma confinement may now be in hand. In addition an approach initiated in the USSR, the tokamak, has produced results which are most encouraging, the confinement of hot (10 million degree), relatively quiescent plasmas for milliseconds. Most of the major laboratories in the world have by now constructed experiments along the same line and have reproduced these results.

Scyllac, the toroidal theta-pinch experiment at the Los Alamos Scientific Laboratory, New Mexico, USA. The quartz discharge chamber is contained in the circular aluminium ring, with the many cables carrying the current required to energize the heating and confining magnetic fields. Photo: Los Alamos Scientific Lab. (photo 1)

The large T-10 tokamak experiment recently completed at the Kurchatov Institute, Moscow, USSR. The discharge tube has an inside diameter of 78 cm, a toroidal magnetic field of 5 Tesla and a discharge current of 0.8 million ampères. Photo: Kurchatov Institute (photo 2)



At recent conferences technical advances were reported from research centers around the world. In tokamak research stable plasmas are being contained for tens of milliseconds at temperatures of 20 000 000 degrees. The dangerous contamination by heavy atoms released from metal parts of the machine are being suppressed, in some experiments, with others being relatively clean. The energy confinement times, a measure of how well the insulating layer (the magnetic field) shields the hot gas from the cold walls, still remain in all experiments, however, rather short at about 20 thousandths of a second. For a fusion reactor it is estimated that this time must be extended a factor of one hundred or even perhaps a factor one thousand.

HISTORY OF THE AGENCY'S INTERNATIONAL FUSION RESEARCH COUNCIL

In 1968 the IAEA felt that so much work was being accomplished in the field of nuclear fusion that it might be wise to establish an international forum where the countries involved in fusion research programmes could exchange their ideas and discuss their programmes whilst at the same time advising the Agency. After preliminary discussions between the senior experts of those countries involved in fusion research programmes, an introductory meeting was scheduled for early 1970. As a first step it was decided to assess the present state of the possibility of arriving at fusion power and to distribute a world list of major facilities. In June 1970 this meeting took place in Trieste and a report was subsequently published in the Agency's Nuclear Fusion Journal. After consultations with Governments it was decided to establish, on a permanent basis the IAEA International Fusion Research Council. The 10 most advanced countries in fusion research were invited to each nominate one member for the Council, and the first official Fusion Research Council meeting took place during one of the Agency's Fusion Conferences in Madison USA in 1971.

In this connection the fusion programme is entering an exciting and important time. Two large experiments, the PLT (Princeton Large Tokamak) in the USA and the T—10 (Tokamak—10) in the USSR (see photo 2) are in the first stages of their operation. A most important feature of these experiments is their increased size with the greater thickness of the insulating space between the hot gas and the metal wall. If our ideas on the scalong laws are correct the confinement times in these machines should be increased many times over those in earlier experiments. If confirmed, there will then be a strong incentive to construct very large expensive machines which may produce the energy equivalent to that needed to heat the plasma (meet the so-called Lawson criteria). This would be an outstanding accomplishment. These large experiments are now being designed in the USSR, Japan, EURATOM and the USA. Plans are being drawn up to construct a fusion reactor to produce electrical power, in the late 1990's or early 2000's, when the information for these machines is available. Budgets for fusion research are following the technical progress. In the USA, for example, $140 M is planned for the fiscal year 1976, with requirements for still higher sums in the following years.

LASERS

During the last few years there has also been work on alternative methods of releasing the energy available in fusion, e.g. shine an intense beam of light on a small pellet of deuterium which vapours the surface. The expanding hot gas in turn squeezes the pellet, increasing its density and raising the temperature to that required for thermonuclear burn. The required power of the light beam is enormous, $\sim 10^{14}$ watts, or $\sim$100 000 joules in 1 picasec (10^{-9} seconds) and can only be achieved by the development of very powerful lasers. Experiments on the laser-fusion approach, as it is called, are being explored in many countries and the first nuclear reactions from a true thermonuclear temperature are now being reported.

Since then, the Fusion Council has met at least once a year, usually at a place where a major Fusion Conference was taking place.

This Council has become a forum at which the major programmes in fusion research conducted in the different countries are freely discussed. This is the first time that costly research experiments still to be started in the future are ventilated beforehand at a truly international level.

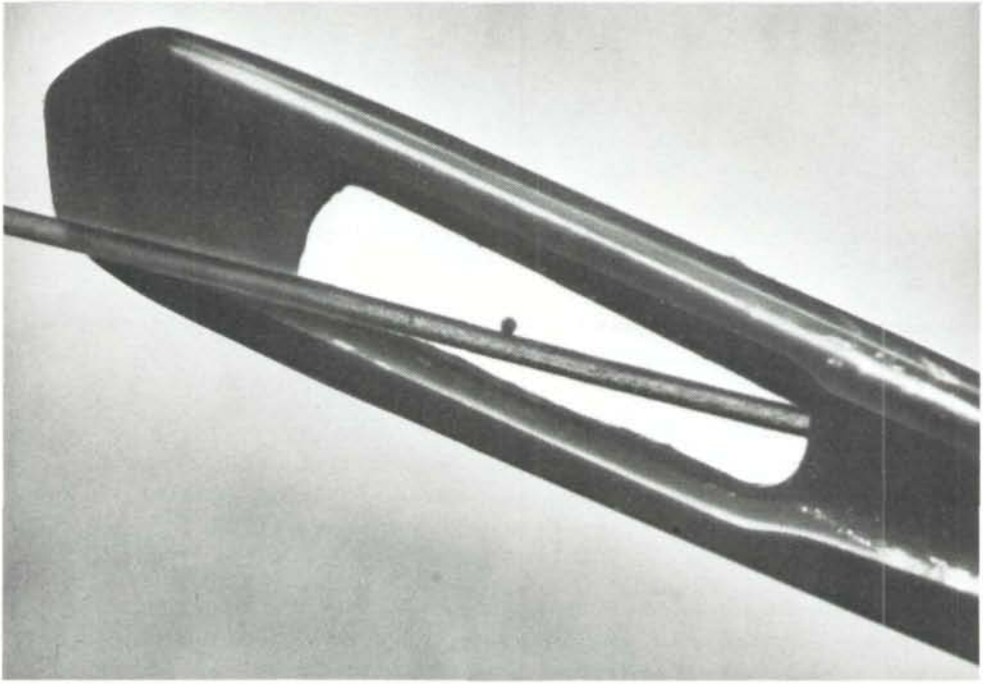
This Council was and is in an excellent position to advise the Agency on its coherent programme in fusion research, covering all the Agency's activities from Technical Assistance and Fellowships, Research Programmes, Workshops, Panels and Symposia, to publications including the Nuclear Fusion Journal. It is believed that this unique collaboration may possibly result in large, international projects.

It is with gratitude that the IAEA looks back over the last 5–6 years, thanking the countries involved in sizeable fusion projects for the great help and valuable advice they have given, thereby manifesting the international common aim in achieving fusion power at the earliest possible date. The IFRC established by the IAEA has become recognized as the authority for international fusion research.

H. Seligman

At present the available laser powers are very low and the target pellets are necessarily exceedingly small. In photo 3 is shown one of the micro-balloons, a hollow glass sphere of about 5 thousandths of a centimeter diameter containing hydrogen gas at pressures of more than 50 atmospheres. In the photograph the micro-balloon is resting on a length of hair and the large opening is the eye of a needle! It is with these targets that it is now generally believed that mixtures of deuterium and tritium gas have been brought up to the conditions necessary for thermonuclear burn. With the operation of powerful lasers now being designed and constructed the conditions for the Lawson criteria may be realized in the late 1970's or early 1980's.

The interest in fusion is primarily motivated by the potential of the large source of energy available to us in the heavy isotopes of hydrogen. (The first fusion reactor will burn deuterium and tritium, the two heavy isotopes of hydrogen, which will require breeding the tritium in lithium blankets; in effect, then, burning deuterium and lithium. In the second phase with more advanced reactors deuterium alone might be used). Also a fusion reactor by its very nature is safe in the sense that the amount of fuel present at any one time in



Photograph of a micro-balloon now in use in laser-fusion experiments. The micro-balloon (diameter ~ 50 millionth of a meter, holds D-T gas at a pressure of 50 atmospheres) rests on a hair. The large opening in the photograph is the eye of a needle. Photo: Los Alamos Scientific Lab. (photo 3)

the reactor has negligible explosive power. No fissile material need be present. However, even the most ardent proponent recognizes that fusion reactors do have an environmental impact, including a radioactivity hazard. There will be the problem of handling safely the tritium gas, and there will be the radioactivity induced in the metal structure. These problems can be solved and it is fortunate that there is still time before the fusion reactor becomes a reality.

IAEA

The challenge of fusion is an exciting one to the international scientific community and here the Agency plays an important role: holding international conferences on plasma physics and controlled thermonuclear research every two years, organizing workshops and seminars on specific topic with international participation, the publishing of scientific articles and review papers in the journal "Nuclear Fusion", and in the collecting and collating of nuclear and atomic molecular data for fusion from data banks around the world.

Over the past twenty or so years, fusion research for some of us has been a frustrating but challenging research project. The field is expanding with the influx of men, new ideas and money. Even if unexpected obstacles prop up to impede progress, of one thing we may be sure, man being the kind of being that he is, power will undoubtely be developed some day from controlled thermonuclear reactions.