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FUSION REACTOR STUDIES IN THE UNITED KINGDOM

R HANCOX

CULHAM LABORATORY
Abingdon Berkshire

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by

R. Hancox

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U.K.A.E.A. Research Group
Culham Laboratory
Abingdon
Berks.

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Fusion offers the prospect of generating nuclear power by utilizing a new, abundant, and cheap fuel which does not produce highly radio-active residues, and in which there is no prospect of a nuclear chain reaction diverging on a large scale. To reach this objective the fuel must be heated to temperatures in excess of 10^8 °C and the resulting plasma contained in a controlled manner for sufficient time to give a net gain of energy. Thus the physical behaviour of such high temperature plasmas has during the past 20 years become a major topic of research in several countries.

As a result of substantial progress in plasma physics during the last few years there is a growing awareness that its relevance to the ultimate objective of achieving useful fusion power must now be given increasing importance. Many fusion laboratories are extending their activities from plasma physics and its supporting technology into the field of reactor technology and fusion reactor studies. The purpose of this paper is to review the fusion reactor studies now being undertaken in the United Kingdom, emphasizing those aspects of the work which are novel and looking forward to possible future developments.

CHOICE OF REACTOR SYSTEM FOR STUDY

It has been appreciated for a long time that to obtain a net energy gain from fusion reactions the high temperature plasma must be contained for a minimum time, τ, which depends on the plasma density, n, and is given approximately by $n\tau > 10^{14}$ cm^{-3} sec (Lawson criterion). Since the power density is also a function of the plasma density there is a wide range of possible reactor conditions, varying from low density steady state systems ($n \sim 10^{14}$, $\tau \sim 1$) with power densities comparable to other nuclear boilers to explosive releases of energy at very high densities ($n \sim 10^{24}$, $\tau \sim 10^{-10}$). In the United Kingdom low density plasmas have been investigated almost exclusively, aiming at steady or quasi-steady state containment in strong magnetic fields.

Using magnetic confinement a wide range of geometries is possible, involving either open ended or closed configurations. Both theory and experiments suggest that end losses from the open systems will be too great to allow the Lawson criterion to be fulfilled without a high level of external circulating power so that the cost of a reactor based on such configurations might be high. Closed geometries, on the other hand, have theoretical containment times which scale with the physical size of the system and should be at least an order of magnitude higher than is required in a reactor, and thus appear more hopeful. In the United Kingdom the main emphasis of the plasma containment experiments centres around several alternative closed magnetic geometries including stellarators, tokamaks and toroidal pinches.

In stellarators the confining magnetic field is generated entirely by external current carrying conductors which produce both a closed toroidal field and a superimposed helical field. Experiments in several stellarators have shown good agreement between measured plasma containment times and those predicted by theory, although only low plasma pressures have been sustained. Measurements in the Proto-Cleo experiment, for example, with four or six helical conductors have shown close agreement with neo-classical theory in the higher density collisional and intermediate regimes.[1] In the collisionless regime, which is of most relevance to reactors, there is less good agreement partly because the experimental conditions are difficult to obtain in small experiments and partly because the theory does not accurately describe conditions in non-axisymmetric configurations such as the stellarator. Nevertheless adequate containment times are expected in experiments whose size is closer to reactor dimensions, provided sufficient care is given to the design and construction of the magnetic field structure.

In toroidal pinches and tokamaks the confining magnetic field is produced by a combination of currents in external windings and in the plasma itself. Since the plasma current is produced by a changing magnetic flux both are pulsed devices. Experiments in the High-Beta Toroidal Experiment have shown that stable plasma configurations can be set up in a controlled manner by programming the applied magnetic field.[2] High plasma pressures can be supported for a time which is consistent with the decay of the field to a hydrodynamically unstable configuration with a time constant which agrees with theoretical expectation. British measurements on the Russian tokamak T3 confirmed that the electron temperature increased as the square of the plasma current.[3] Extrapolation of empirical relationships for the temperature and containment time suggest that an increase in the plasma current by one order of magnitude above the level achieved in present experiments would give ignition conditions, the point at which the nuclear power released becomes sufficient to maintain the plasma temperature. The rate of progress in plasma physics suggests that this objective could be reached towards the end of the present decade.

Stellarators and tokamaks are often considered as quite separate and distinct systems. Recent theory suggests, however, that even where confinement is entirely by means of external currents as in the stellarator, there is an additional current induced in the plasma due to the outward diffusion of the plasma across the magnetic field.[4] The magnitude of this current is below the level of detection in present experiments, but in a reactor it may be of the same order as the induced current required in a tokamak for containment. Thus the possibility exists of a steady state tokamak reactor with the plasma current indefinitely maintained by plasma diffusion.

CONCEPTUAL REACTOR DESIGNS

One approach to combining our present understanding of plasma physics and reactor technology is through conceptual reactor design studies. In this way the possible development of any particular confinement system towards a reactor can be explored. Such a study in the United Kingdom is based on a steady state toroidal system with magnetic confinement and burning a deuterium-tritium fuel mixture. Since it is not desirable in the early stages to be too specific about the magnetic field geometry this study is at present based on a rather generalized toroidal reactor. It most closely resembles the supposed steady state tokamak, but sufficient flexibility is retained to allow its modification to a more conventional stellarator or pulsed tokamak if necessary.

The basic geometry of any fusion reactor is dictated primarily by physics requirements, but the design and arrangement of its components is determined by engineering considerations. The disposition of the magnet windings, for example, may be a compromise between a complex conductor arrangement which would give the ideal magnetic field configuration and a simpler and more convenient coil system. In the same way, even the final choice of the containment system for development into a reactor will depend on a compromise between desirable physical requirements and practical limitations, and continual interaction between plasma physics and reactor studies is essential if fusion research is to progress towards a practical power system.

One area in which engineering considerations will be particularly important is in the need for access to the reactor for maintenance and repair. The neutron flux seen by the inner most part of the reactor structure (the first wall) is of the order of 1 x 10^{15} neutrons/cm^2.s so that the dose after 25 years operation at 65% load factor will be 5 x 10^{23} neutrons/cm ^{2}, equivalent to about 1000 displacements per atom. It is not known whether it will be possible to develop materials capable of retaining their high temperature structural strength at such levels of damage, so that it is prudent to assume that this structure must be replaced at some stage during the life of the reactor. Even if such replacement proved unnecessary it would not be possible to guarantee 100% reliability of all components inside the reactor, so that access for maintenance would be essential. In a toroidal vessel this can only be achieved by designing the structure as a set of interchangeable segments, as illustrated in figure 1, each of which could be completely removed for essential maintenance. Such an operation would not be easy, since each segment might weight several hundred tons and give radiation levels of the order of 10^7 rem/hr even 1 month after reactor shut down, but is nevertheless conceivable.

A possible constructional arrangement for such a segmented reactor is shown in figure 2. The main mechanical structure takes the form of a doubled walled vessel, analogous to a submarine hull, in the shielding region of the plasma containment vessel.[5] Inside this structure is supported the breeding blanket which contains lithium for breeding tritium. Since about two thirds of the fusion energy is released in neutrons the breeding blanket must also absorb most of the neutron energy and will contain a heat transfer system using either lithium or a lithium bearing salt as primary coolant or a secondary coolant such as high pressure helium. At this stage the choice of coolant is not particularly important, although for the purposes of more definite discussion the use of liquid lithium is suggested for both breeding and cooling.[6] A cellular blanket structure is proposed which will simplify manufacture and minimise the amount of structural material. The neutron flux in the breeding blanket falls from its level of 1 x 10^{15} neutrons/cm2.s at the first wall to 1 x 10^{13} neutrons/cm^2.s at the back and must be further attenuated to 10^8 neutrons/cm^2.s by a nuclear shield.[7] This shield is composed of iron and borated water contained within the main mechanical structure. Typical thicknesses of the breeding blanket and nuclear shield are 65 and 75 cm respectively.

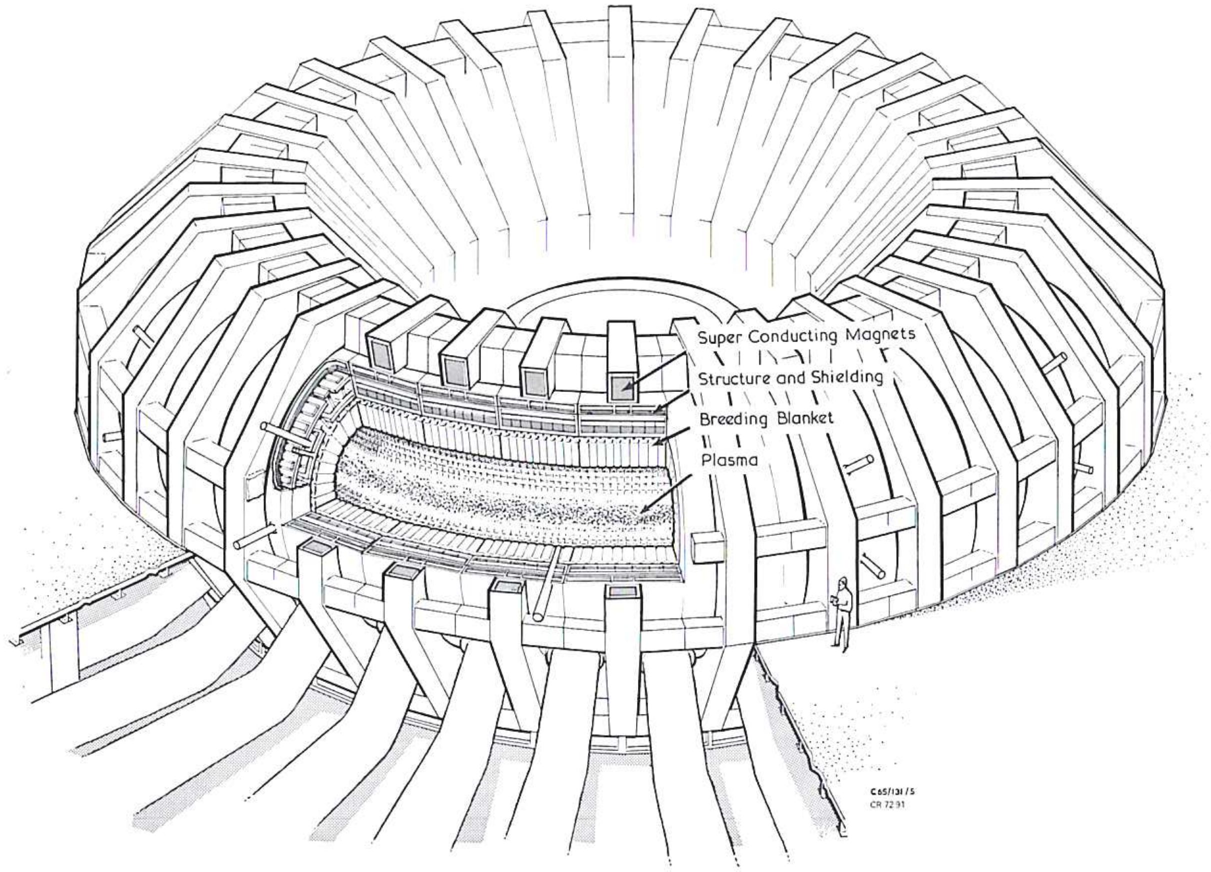

Fig.1 General view, in part section, of a 2500 MW(e) toroidal fusion reactor constructed in 32 segments.

The magnetic field winding is situated outside the breeding blanket and nuclear shield. In a steady state reactor this must be a superconducting winding otherwise the power consumption of the magnet would exceed the power produced by the reactor. Superconductors such as niobium-titanium or niobium-tin would be used to generate magnetic fields of the order of 100 kgauss, operating in gaseous or liquid helium at temperatures around 4 ^{o}K. Because of the very low temperatures the windings must be surrounded by cryogenic insulation and the high forces between the segments of the magnet winding must also be contained within the cryogenic environment. The plasma containment vessel and the magnet winding will be separately supported to minimize heat losses from one to the other, and to allow the active structure to be easily separated from the more expensive magnet during any maintenance operation.

Equally as important as the items shown in the present conceptual design are those components which have been omitted. For example, the means of refuelling the reacting plasma or the method of removing reaction products, unused fuel, and accumulated impurities are not yet included. This is mainly because suitable methods to accomplish these essential functions have not yet been developed. The most probable method of refuelling is the injection of high velocity liquid or solid fuel pellets; and the removal of plasma from close to the first wall of the breeding blanket will require a magnetic divertor and dump chamber. Other items such as the primary windings to initiate the plasma current or the vertical field windings to maintain plasma equilibrium also have to be added and may seriously complicate the segmented concept.

It is seen that the present concept of a fusion reactor is not yet fully developed. In some areas, especially those which are common to fission and fusion there has been rapid progress and materials and dimensions can be specified with confidence. In other areas there has been much less progress, and further work is needed to establish the credibility of the reactor design. Since many of the areas of ignorance are closely linked with plasma physics problems they will have an important influence on the ultimate choice of which confinement system is to be used as a basis for development to a reactor. For these reasons fusion reactor studies cannot be considered in isolation from plasma physics but rather these two areas of activity must increasingly interact if rapid progress is to be made towards a feasible fusion reactor.

DESIGN ASSESSMENTS

As conceptual reactor designs develop they will allow continuous reassessment not only of the feasibility of fusion power but of its merits relative to other power sources. Apart from the obvious advantage of a new and widely available fuel, which will ultimately force its development, fusion must compete in the next century with a range of alternative energy sources, particularly fast breeder fission reactors. The claim is currently made that fusion reactors will have generating costs comparable with those of other systems, and will have safety and environmental advantages over fission reactors. Such claims will have to be justified in more detail before the large sums of money necessary for the full development of fusion will become available. Such justification can only be made on the basis of fairly detailed designs of the reactor in which all the components are included and their construction and operation are specified, so that the development and assessment of such designs is an important area of fusion reactor studies.

A preliminary economic assessment has already led to some definite conclusions.[8] For example, in any system which relies on steady or quasi-steady state magnetic confinement of the plasma the superconducting magnet will be a major item of capital cost, and the superconducting material will be the largest component of that cost. Substantial reductions in the price of superconducting materials must be achieved if reasonable capital costs are to be obtained, and reductions from present day prices by factors of between 10 and 30 will be required, depending on which confinement geometry is finally chosen. That such reductions are possible by the simplification of production processes, by the economies of bulk production, and by improvements in physical properties has been shown from detailed considerations of the manufacturing process, provided that relatively simple conductor configurations are employed. What is not certain at present is whether a simple conductor is capable of satisfactorily fulfilling the requirements of stability in changing magnetic fields, adequate cooling during nuclear heating, and mechanical strength to withstand large magnetic forces.

Even when substantial reductions in the price of superconducting materials are assumed, economic assessments show the advantage of confinement systems in which simple magnetic geometries are used. Thus a stellarator reactor, with its complex field geometry, has a capital cost well above target costs based on expected fast fission reactor costs. A tokamak reactor, on the other hand, has a much lower magnet cost and looks more attractive in this respect. At present, however, such assessments can only be made on the basis of the expected performance of any system in containing a plasma, and further understanding of the limiting plasma pressure which can be sustained with a given magnetic field may alter our present evaluation. For example, the theory of diffusion driven currents which indicates that a steady state tokamak may be possible also predicts that the equilibrium plasma pressure will be $\beta_p \sim \sqrt{R/a}$ (where (R/a) is the aspect ratio of the toroidal reactor) compared with the value $\beta_p \sim R/a$ previously assumed, a change which is equivalent in present cost estimates to more than doubling the capital cost of the nuclear boiler. Such large uncertainties again emphasize the need for interaction between plasma physics and reactor studies in seeking to define the important areas for future development.

Economic criteria will also strongly influence the choice of many of the reactor dimensions and parameters. High power densities give a compact design, but imply a high thermal loading of the first wall and high neutron fluxes, so that high performance materials or frequent changes of the breeding blanket structure will be required, either of which are expensive. On the other hand, low power densities imply very large structures and underrated materials in the breeding blanket and nuclear shield. Thus a compromise is required to optimize generating costs. Experience from the development of other power systems suggests that first generation fusion reactors will operate at a relatively low power density using conventional structural materials, such as stainless steel, and employing direct cooling of the blanket by lithium, but that later generations may use more refractory materials with more efficient blanket cooling in order to achieve better economics from more compact designs.

A preliminary assessment of the safety of a fusion reactor has also been completed. Since fusion is a nuclear reaction there is always the possibility of a hazard to people and the environment from any radio-active materials used in, or arising from,

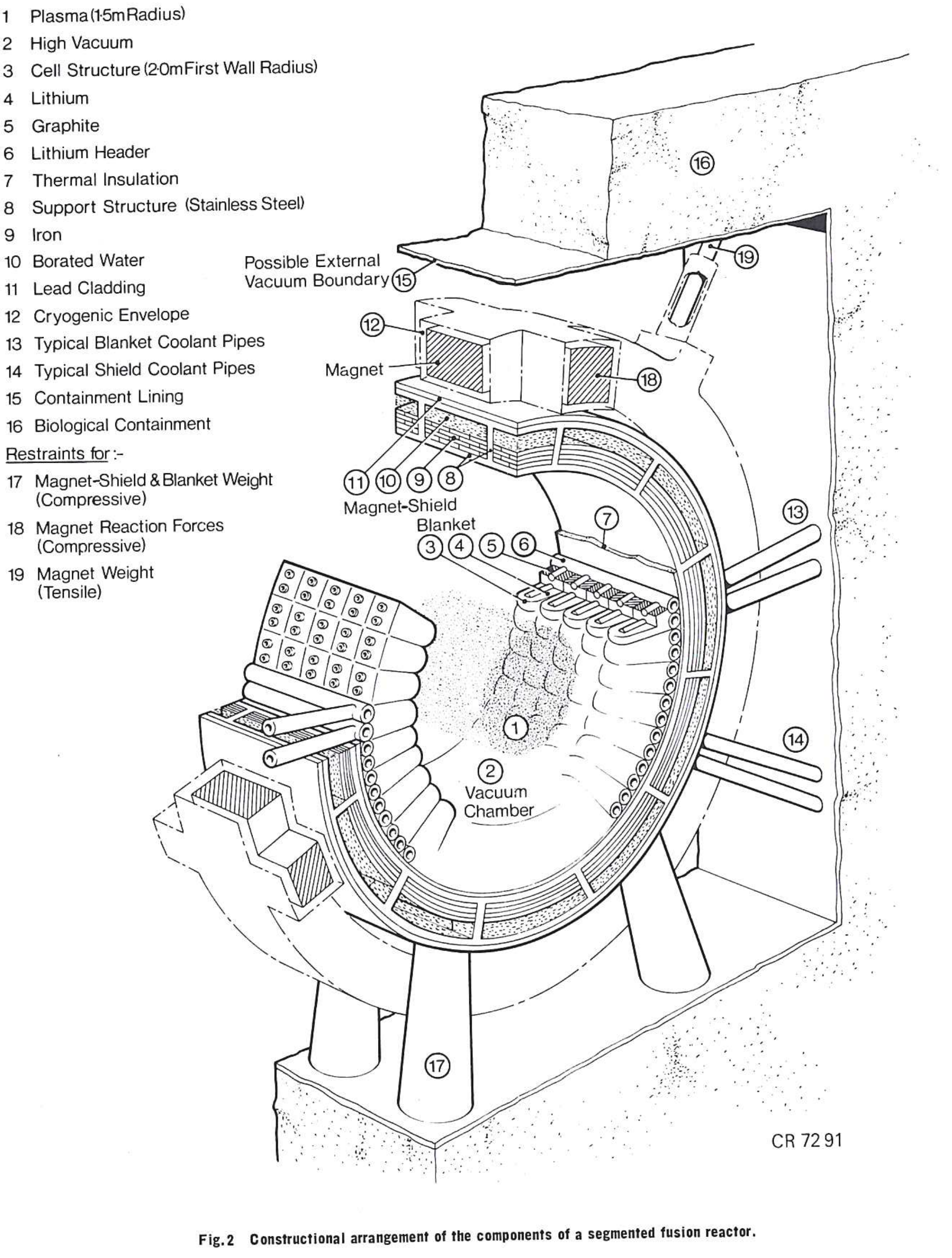

Fig. 2 Constructional arrangement of the components of a segmented fusion reactor.

the reactor. Nevertheless fusion has an immediate advantage over fission in that the possibility of an uncontrolled run-away is much less, and that the consequences of an instantaneous and complete burn-up of the fuel would probably be slight and could certainly be contained within the reactor vessel. This important feature of a fusion reactor is due to the fact that the fuel contained in the reacting zone per 1000 MW(e) of output power is only about 0.25 grams of deuterium-tritium mixture, compared with 3 tonnes of plutonium and 10 tonnes of uranium in the core of a fast fission reactor.

Other advantages of a fusion reactor are that the primary fuels, deuterium and lithium, are non-radioactive and that the primary reaction product helium is also non-radioactive. Furthermore the secondary fuel tritium, which must be regenerated by nuclear reactions in the blanket, can be processed and re-injected into the reactor with a delay of only a few hours and without removal from the close vicinity of the reactor. An important aim of reactor design, however, will still be to minimize the tritium inventory and to prevent the loss of tritium from the reactor system. Present estimates are that the total tritium inventory in the system will be of the order of 2 gms/MW(e) and that a daily loss of 1 ppm of this inventory in the form of oxide would give a maximum annual dose to critical groups of the population of 6 mrem/year at 500 m from the point of release, which is about 1% of the ICRP and UK recommended maximum.

The most hazardous accident envisaged in the present conceptual design, which uses lithium in the breeding blanket, is a fire involving the lithium and the release of part of the tritium inventory with the combustion products. To limit the amount of tritium which could be released in this way the breeding blanket would be sub-divided, and gas blanketed dump tanks provided, but even so the quantity of tritium involved in one circuit if completely released could reach the calculated emergency reference level. The reduction of the tritium inventory by at least an order of magnitude and the use of a less hazardous breeding material than lithium would be very desirable in this respect. The other major safety problem associated with fusion is the activity induced in the structure of the breeding blanket, which is estimated to rise rapidly ($\sim$ 3 months) to around 100 kcuries/MW(e). Whilst not affecting the general public this activity prevents access to the reactor and complicates all maintenance operations. The magnitude of the problem is comparable to that already faced in fission reactors, except that because neutron economy is not such a serious problem there may be a wider range of structural materials from which to choose one showing the lowest level of activity.

REACTOR DEVELOPMENT PROGRAMME

The discussion in previous sections has centred around a conceptual design for a power producing fusion reactor. Whilst much remains to be done in extending this outline design, it is also necessary to ask how development should proceed from the present small scale plasma physics experiments towards such a power reactor. In particular, it should be possible to assess the stages at which various technological problems must be solved and indicate whether additional problems will arise.

The first stage would be the construction of several large scale experimental assemblies to establish the confinement principles upon which

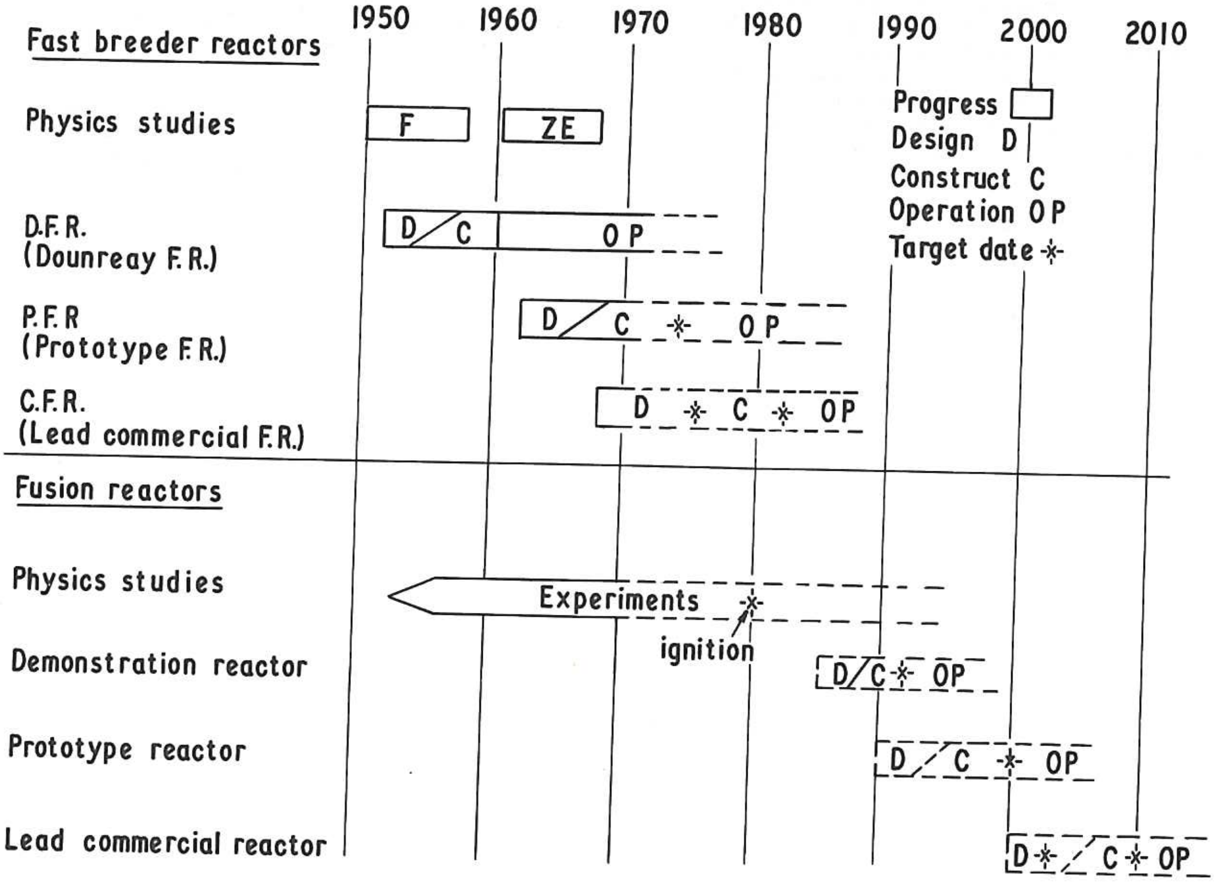

Fig. 3 Comparison of development programmes for the fast breeder reactor and a possible fusion reactor.

subsequent reactor development will be based. The detailed objectives would be to fix the confinement geometry (e.g. open or closed systems, pulsed or steady state operation) and to give a sufficiently clear experimental and theoretical understanding of plasma containment to justify proceeding to a demonstration reactor. Ignition should be obtained in these experiments, but is is unlikely that quasi-steady conditions could be maintained in the reacting plasma.

The second stage of development would be a full-scale confinement demonstration with plasma parameters equal to those required in a reactor. The initial experiments would be performed with a non-reacting plasma , and ideally this should be a steady-state or continuously operating device but plasma heating limitations will probably restrict operation to pulses. The objectives would be to demonstrate confinement of a plasma with reactor parameters, including plasma density, temperature, pressure, and containment time, and also to confirm scaling laws both at and beyond reactor parameters to allow optimization of the design of a prototype reactor. At this stage it will also be necessary to experiment with methods of independently controlling plasma parameters in space and time, with and without refuelling, including the development of fast diagnostic and control loops. The reliable operation of all engineering components must also be established, including superconducting or pulsed magnets, power supplies, injection, heating and direct recovery systems, divertors and vacuum systems, etc.

When these objectives have been fulfilled as far as possible with non-reacting plasmas, the experiment would be operated with a deuterium-tritium plasma. Sufficient nuclear blanket would have to be added to protect the superconducting magnet from becoming active. Pulsed operation is again envisaged to overcome the need for continuous heat removal from the blanket, but pulses must be long enough to allow thermalization of charged reaction products. The main objectives would be to study the effect of the high energy reaction products and to demonstrate control of the self heated plasma.

Finally a prototype reactor would be constructed. Its principal objective would be to demonstrate the feasibility of continuous and reliable power generation. The size would be the smallest possible, consistent with both this aim and the need to demonstrate a technology which could be extended to a full-size commercial system. This will be the first device with a full-scale nuclear blanket, tritium breeding, and electricity generation. It may also be the first source of 14 MeV neutrons with sufficient flux to cause radiation damage, so that a secondary purpose of the reactor will be for materials testing. This requirement could strongly influence the design of the reactor, since it may be desirable to aim for higher plasma pressures and higher magnetic fields than will ultimately be required for economic power generation simply to increase the neutron flux in order to facilitate material testing in the prototype.

As with prototypes of other reactor systems, this prototype will be operated for many years with a wide range of detailed engineering and materials experiments to establish confidence and collect design information. The reactor must be designed to permit safe maintenance and a degree of flexibility or interchangeability to allow these experiments to be undertaken. An important question is the size of the prototype reactor. It has been shown that for toroidal reactors there will be a minimum physical size corresponding to an output around 100 to 500 MW(th), but that if progress in plasma physics falls much below our present expectations this minimum size could approach the size of a full-scale power reactor. Such a situation would undoubtedly delay the building of a prototype.

The rate at which the development of the programme outlined above could be pursued depends in part upon the resources devoted to it, which in the United Kingdom are at the moment around a tenth of those currently spent on the fast breeder reactor. If the advantages of fusion were considered to justify a substantial increase in this level of activity the fusion development programme might be expected to progress at a rate comparable to that already achieved by the fast breeder reactor. Such a comparison is shown in figure 3 and indicates that the operation of a commercial fusion power station could be practical by the year 2010.

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