ENGINEERING PROBLEMS IN THE DESIGN OF CONTROLLED
THERMONUCLEAR REACTORS*

A. P. Fraas
Associate Director
Reactor Division

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Paper prepared for presentation at the
AIAA 11th Aerospace Sciences Meeting
and Technical Display

Washington, D. C.
January 10-12, 1973

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

ENGINEERING PROBLEMS IN THE DESIGN OF CONTROLLED THERMONUCLEAR REACTORS

A. P. Fraas
Associate Director
Reactor Division

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

Abstract

In the past few years the work on the plasma physics of controlled thermonuclear reactors has progressed sufficiently to make it possible to prepare some conceptual designs that point up the engineering problems that must be confronted when feasibility is demonstrated, hopefully about 1980. The studies have disclosed that a large set of boundary conditions must be satisfied, and meeting these with a well-balanced integrated design presents an exceptionally challenging set of problems. These include 30,000 to 70,000 gauss superconducting magnet coils 10 m in diameter, two-phase heat transfer and fluid flow of liquid helium, 4°K helium refrigeration systems, magnetohydrodynamic effects on pumping power and heat transfer for large ducts carrying lithium at 1000°C in a niobium-zirconium alloy blanket structure, sputtering and radiation damage to the wall confining the plasma, and potassium-steam binary vapor cycle power conversion systems with a peak temperature of about 1000°C and a thermal efficiency approaching 60%.

Introduction

The difficult plasma physics problems have almost completely dominated the thermonuclear reactor program for the past 20 years. These problems have been so formidable that there has been a serious question as to whether they could ever be solved, but in the past few years progress has been sufficiently encouraging so that people have begun to ask, "If you are able to achieve a controlled fusion reaction, what will it be good for?" Thus, although it has not as yet been possible to achieve the required conditions for sustained controlled thermonuclear reactions, we have attempted to envision what a full-scale plant might look like assuming the favorable resolution of the outstanding plasma physics problems. As a consequence, several conceptual designs have been evolved, and each of these has revealed a number of difficult engineering development problems. Many of these, for example the tritium problem, are present in any of the conceptual designs prepared to date whereas others are peculiar to particular concepts.

The Magnetically Confined Fusion Reactor System

About a half-dozen different approaches to problems of obtaining a controlled thermonuclear reactor are under active development. Rather than attempt a description of each of these, it seems best for the purposes of this paper to consider one representative reactor type. Most of the effort in the thermonuclear reactor programs of the U.S., Britain, and the USSR is going into magnetically confined plasmas. While there are many variations of this approach, a favorite is the use of a large solenoid magnet wrapped into a torus as in Fig. 1. The toroidal magnetic field prevents ions in the high temperature plasma from escaping; instead they

swirl about in the magnetic field following complex combinations of elements of helical paths.¹

Choice of Fusion Reaction

The fusion reactions that might be employed are summarized in Table 1. The bulk of the effort is being directed toward the use of the deuterium-tritium fusion reaction because this can be ignited at a temperature roughly 1/10 that for the deuterium-deuterium reaction, and it will be difficult enough to ignite the D-T reaction. The D-T reaction has the disadvantages that it requires fueling with tritium and yields a very penetrating 14 MeV neutron, but both the D-D and D-³He reactions are also accompanied by side reactions that generate both tritium and neutrons. Thus, in any case the fuel cycle will entail handling material containing a substantial fraction of tritium, and the rate of emission of 14 MeV neutrons will be at least 1/10 that for a D-T plasma.² Further, D-D and D-³He reactions will lead to radiation damage effects from fast neutrons and an amount of structural activation within a factor of roughly 2 of the corresponding values for the D-T fuel cycle.³

Table 1. Energies Associated with Fusion Reactions

Reaction Equation	Plasma Temperature	Energy Gain per Fusion
$D+T \rightarrow {}^4\text{He} + n$ (3.5 MeV) (14.1 MeV)	10 keV	1800
$D+D \rightarrow \begin{matrix} {}^3\text{He} \\ T \end{matrix} + \begin{matrix} n \\ p \end{matrix}$ (0.82 MeV) (2.45 MeV) (1.01 MeV) (3.02 MeV)	50 keV	70
$D+{}^3\text{He} \rightarrow {}^4\text{He} + p$ (3.6 MeV) (14.7 MeV)	100 keV	180

Blanket for Breeding

Once tractable solutions to the plasma physics requirements have been worked out, the next most important requirement will be that the fusion power reactor must breed tritium. There is no significant natural supply of tritium, and the cost of making it in a fission reactor would be exorbitant. Thus, the first fusion reactor to deliver any significant amount of power must breed its own tritium. There is only one neutron released per fusion reaction, hence at first thought it may appear to be extremely difficult to do this. However, the 14 MeV neutron from the D-T reaction will induce a substantial number of n, 2n reactions in the course of slowing down in either beryllium or lithium. As a consequence, it turns out that, if one supplies a

MASTER

fairly thick blanket of lithium or beryllium around the plasma of a fusion reactor, it is quite easy to breed a surplus of tritium.² Unfortunately, the amount of lithium or beryllium required will be very large — of the order of hundreds of tons per reactor. A check of the world's resources discloses that there is plenty of lithium available to support a world-wide fusion reactor economy based on lithium, but the resources of beryllium, including low grade ore, appear to run only about 10^6 tons, or far less than the amount required for a full-blown fusion reactor economy.³ Thus, the designer has no choice but to provide a thick blanket of lithium surrounding the plasma. A layer of graphite may be introduced to reduce the amount of lithium required to thermalize and absorb the neutrons.

Engineering Design

Figure 2 shows a conceptual design for a full-scale toroidal fusion reactor.⁴ In preparing this design an effort was made to meet all of the boundary conditions that can be defined at this stage and thus it provides a good illustration of the engineering design and development problems with which we are confronted.

Type of Magnet

It is evident from Fig. 2 that an enormous magnet is required. While it is not self evident, the high magnetic field required — in the 25,000 to 250,000 gauss range — would require so much electric power if ordinary water-cooled copper coils were employed that the power going into the magnet would be roughly equal to the entire electrical output of the plant. As a consequence, some sort of cryogenically cooled coils must be employed, and the evidence is accumulating that it will be best to use superconductors.

Operating Temperatures

Figure 3 shows a cross section through the magnet and plasma region of the toroidal fusion reactor shown in Fig. 2 to give some additional insight into the design requirements of a fusion reactor other than plasma physics considerations. Note that in the center the plasma is at a temperature of over a hundred million degrees centigrade, and the vacuum wall surrounding the plasma isolates it from the liquid lithium blanket region which operates at somewhere between 500 and 1000°C (i.e., at or above the fuel temperature of an IMFRR). This is surrounded by thermal insulation, a magnet shield region which operates at perhaps 150°C, and finally a cryogenically-cooled superconducting magnet which would operate at 4°K. Thus, we have nearly as extreme a set of temperature conditions as man can produce. This drawing indicates something of the whole complex of difficult design conditions that must be satisfied if one is to have a commercially viable fusion reactor.

Size of the Plasma Region

Aside from plasma physics considerations, one of the key requirements is that about 2 m of blanket and shielding material be interposed between the plasma and the cryogenic magnets in order to protect them from radiation heating.⁵ This in turn means that to keep the magnet costs in dollars per kilowatt to a reasonable level, the useful volume in the plasma region should be a large

fraction of the total volume enclosed by the magnets. Thus, we must go to a large machine, that is, a plasma region with a minor diameter of perhaps 5 m and a cryogenic magnet diameter of around 10 m. This in turn means that, if we build a toroidal type of machine, the overall diameter of the doughnut will have to be over 30 m. As a consequence, the minimum size of an economically attractive machine of this type appears to be quite large with a power output something like 500 to 1000 MW(e). Fortunately, a large diameter for the plasma region is beneficial from the standpoint of plasma physics. A diameter of only 2 or 3 m might prove acceptable, but a larger diameter will reduce radiation losses to the walls and ease the ignition problem.

Relation Between Size and Cost of the Superconducting Magnet

The design of large, superconducting magnet coils presents some difficult engineering design problems. Fortunately, as the diameter of the plasma region is increased, the strength of the magnetic field required is reduced, and this eases the magnet design problem. The allowable current density in a superconductor increases as the magnet field strength is reduced.⁶ Thus as one increases the diameter of the plasma region and the magnetic field strength required drops, the number of ampere turns required drops, and the current density goes up. Thus, the required number of turns of a given size of superconductor varies inversely as the square of the magnetic field. As a consequence, it appears that, to a first approximation, the amount of superconductor required and the cost of the superconducting magnets will be essentially independent of the diameter of the coils — an at first incredible conclusion. In point of fact there is a substantial incentive to go to coils around 10 m in diameter for which the magnetic field will be about 30,000 gauss. In this region Nb-Sn is an excellent and currently available superconductor. It is ductile whereas the best material available for higher magnetic fields, Nb-Ti, is both brittle and more expensive.

Magnet Cooling and Structure

The superconducting magnet coils for the reactor of Fig. 2 have been designed with the superconductor tapes imbedded in copper and the resulting conductor wrapped like a roll of confetti tape to form a pancake.⁶ Liquid helium cooling passages are provided between adjacent pancakes. Note that these involve not only two-phase heat transfer and fluid flow problems with liquid helium, but the structural details must be adequate to cope with the enormous lateral forces that act to draw adjacent pancakes together. Confining these coils and constraining them to hold their circular shape in the asymmetric toroidal field requires a massive structural ring. In the case of the reactor of Fig. 2, the special stainless steel structural ring is an I-beam section 1.3 m deep with a 4 cm thick web between flanges 50 cm wide by 12 cm thick. The design assumed an allowable stress of 80,000 psi at 4°C.

Blanket Design

The use of a lithium blanket raises some difficult materials problems. To obtain a high thermal efficiency, it is desirable to operate the blanket at as high a temperature as possible. Stainless steel could be used, but it is subject to thermal

by lithium if the temperature is raised above about 500°C. With refractory metals it would be possible to operate at much higher temperatures, and this should make it possible to reduce the waste heat to less than half the amount currently rejected from the best fossil fuel-fired plants. Fortunately, the program for nuclear electrical power sources for space applications has nicely validated the use of lithium in niobium-base alloys at temperatures up to 1200°C.⁷ Further, work for the Air Force at Battelle on structures suitable for hypersonic aircraft has led to the rolling of niobium-alloy sheets in 3 ft widths and the fabrication of these sheets into shell structures suitable for aircraft wings and fuselages.⁸ As a consequence, the feasibility of fabricating niobium alloys into the type of structure implied by Fig. 3 has been demonstrated, although it is clear that structures of this type will be expensive and will require stringent quality control measures.

Another major problem associated with the blanket region is radiation damage to the vacuum wall.⁹ This problem is even more severe than the radiation damage problem in a fast breeder reactor because in this instance we would like to have the vacuum wall last for 20 years to avoid replacing large radioactive parts, whereas in the fast breeder reactor the relatively small fuel elements would be replaced at intervals of a year or less. The extensive radiation damage work currently underway in the Fast Breeder Reactor program will prove enormously helpful to the fusion reactor effort, but additional work will be required because the initial neutron energy in fission reactors is only 1 or 2 MeV whereas in fusion reactors it is about 14 MeV. Not only is a 14 MeV neutron expected to cause from 3 to 7 times as much damage as a fission spectrum neutron, but it may induce radiation damage mechanisms that we have not yet been able to envision.⁹ Yet another possible problem is posed by sputtering of the vacuum wall by stray ions escaping from the plasma. Fortunately, niobium appears to be one of the most resistant to hydrogen ion sputtering of any material that has been tested.¹⁰

Magnetohydrodynamic Effects

The total pumping power associated with both the conventional resistance of the fluid flow system and the magnetohydrodynamic effects must be kept to a small fraction of the reactor power output. When a liquid metal such as lithium is employed, this poses some difficult problems. Unless the streamlines in the fluid flow are maintained essentially parallel to the lines of force in the magnetic field along the bulk of the flow path and the fluid velocity is kept low, the additional pumping power stemming from electromagnetic effects will be unacceptably high. This imposes a major limitation on the blanket design and presents some challenging problems to the designer. The proportions envisioned for the reactor of Figs. 1 and 2 appear to give a satisfactory solution.¹¹

The heat generated in the first wall, the graphite, and the lithium must be removed by circulating the liquid lithium through a heat exchanger. A subtle hydrodynamic effect that has been given little consideration to date is that stemming from the drastic reduction in the eddy diffusivity in the fluid as a consequence of its flow through a strong magnetic field. Because of

this effect it is likely that the principal mechanism for lateral transport of heat across the streamlines will be simple thermal conduction; in spite of the high Reynolds number, heat transport by eddy diffusion will occur at a relatively low rate. This will greatly reduce the heat transfer coefficient in the high heat flux regions at the first wall, at the wall adjacent to the graphite, and along the heat exchanger walls if the heat exchanger is placed inside the magnetic field.¹²

Power Conversion System

There appear to be a number of reasonably straightforward ways in which the heat energy developed in the blanket region can be employed to produce electricity. If the blanket region is made of stainless steel and cooled with lithium at about 500°C (the highest temperature permitted by corrosion and mass transfer considerations), it would be possible to raise steam at perhaps 450°C to drive a conventional steam power plant, and this should give an overall thermal efficiency approaching the 40% characteristic of the best fossil fuel plants. The steam generator could be similar to that for an IMFRR, and the rest of the steam plant would be conventional. A second approach would be to employ the heat in a gas turbine cycle, in which case there would be a strong incentive to make use of a high temperature blanket region to obtain a good thermal efficiency.¹³ Commercial gas turbines are now operating with turbine inlet temperatures of around 1700°F. With a niobium alloy as the structural material in the blanket and a 1700°F turbine inlet temperature, it should be possible to obtain an overall thermal efficiency for the gas turbine plant within a few percentage points of that obtainable with current fossil fuel-fired steam plants. Unfortunately, experience with niobium in helium indicates that the corrosion rate will be excessive if the niobium temperature exceeds about 800°C and the oxygen concentration is even as much as 1 ppb. It may be possible to develop a protective coating, but efforts to do this have yet to be successful.

A third and still more attractive approach, although novel, would be to employ a potassium-steam binary vapor cycle.¹⁴ The niobium-zirconium alloy required to contain the lithium at high temperatures also shows no signs of corrosion or mass transfer in boiling potassium, so there is no materials compatibility problem.⁷ With this system it would be possible to get an overall thermodynamic cycle efficiency of around 58% as opposed to the 40% thermal efficiency of current fossil fuel-fired plants. This would reduce the waste heat rejection per kilowatt of electricity by more than a factor of 2, and would reduce the fuel consumption by about 30% as compared to a conventional 1000°F steam cycle. Figure 4 shows a schematic diagram for such a power plant. Note that this type of plant also shows promise for obtaining a high thermal efficiency, reduced fuel consumption, and reduced heat rejection for both fission reactor and fossil fuel-fired power plants.^{15,16}

Limitations on Tritium Concentration in the Blanket

A particularly difficult set of requirements is imposed by environmental considerations. The rate with which tritium can diffuse through a

metal walls makes it difficult to contain. Studies of reactor safety problems likely to be posed by full-scale thermonuclear reactors indicate that by far and away the most difficult is that posed by tritium.¹⁷ These studies indicate that there is an extremely strong incentive to keep the tritium concentration in the lithium blanket to something of the order of 1 ppm. If this can be done, it reduces the capital investment in tritium for the initial startup to a minor level and provides a large margin with respect to any possible difficulties from hydrogen embrittlement of the structural metal.

The tritium generated in the lithium blanket of a typical plant as a consequence of neutron absorptions in the lithium might be removed by any of quite a number of different techniques. Obvious approaches include fractional crystallization from the lithium or fractional distillation, but studies have shown that neither of these approaches will make possible the 1 ppm concentration desired.¹⁸ However, one can make a virtue of necessity, take advantage of the high permeation rate of the hydrogen into the heat exchanger, and set about removing the tritium from the secondary fluid circuit. This, of course, is not practicable if water is employed because then an isotope separation process would be required and this would be enormously expensive because it would be necessary to reduce the tritium concentration to a much lower level than the deuterium concentration in sea water (i.e., to 3 ppm vs. 100 ppm). Obviously, a much better approach is to make use of a secondary fluid such as helium or potassium so that it would not contain any hydrogen. It is for this reason that the choice of the power conversion system has a controlling effect on the choice of the tritium removal system.

A review of the literature, particularly Ref. 19, indicated that cold trapping tritium from the potassium would be a good basis for the design of a tritium removal system. This stems from the fact that, if a few percent of lithium is added to the potassium, the solubility of LiT in potassium falls off rapidly as the temperature is reduced, so that it can be removed with a cold trap and filter system. Calculations indicate that this approach shows promise of making it possible to hold the tritium concentration to around 1 ppm.²⁰ If this can be done, the total amount of tritium in the fluid circulating systems would be sufficiently low that even in the case of the extreme hypothetical accident that assumes all of the active tritium inventory might be released up a ventilating air stack in a single burst, the maximum dose to anyone downwind would be only a few rem.⁴ Thus, the hazard potential would be relatively low and the reactor safety problems would not be difficult to handle. Of course there would be a large amount of induced activity in the metal of the blanket structure, but that material is refractory and the afterheat power density can be kept low by proper design so that there would be no difficulty with overheating even in the event all of the cooling circuits stopped functioning.⁴

Reactor Cell

The lithium blanket and magnet shield of Fig. 3 attenuate the neutron and secondary gamma flux sufficiently so that heating and activation of the superconducting magnet coils will not be serious.

However, an additional 1.5 m of concrete shielding will be required to protect personnel when operating at power. If adequate space is provided inside this shield to facilitate maintenance, it appears best to go to a large reactor cell such as that in Fig. 5.⁴ It appears desirable to evacuate the cell to a pressure of about 10^{-3} torr to ease the design of both the thermal insulation around the superconducting magnets and the large flanged joints connecting the sextants of the torus. The plasma region must be evacuated to about 10^{-7} torr prior to starting, and this is likely to be very difficult to accomplish unless the inleakage is reduced drastically by evacuating the reactor cell. Although it would be desirable to evacuate the cell to a pressure considerably lower than 10^{-3} torr in order to avoid difficulties with corona discharges and shorting of electrical connections, inleakage around the cell doors and outgassing from the cell walls and equipment such as the overhead crane would give such difficult problems that it appears best to make special provisions for the electrical connections.

It is interesting to note the similarity between the reactor cell of Fig. 5 and the NASA space power plant test facility at Plum Brook, Ohio. This is not sheer coincidence — NASA Lewis Research Laboratory was most helpful in providing design and cost data for their facility for the writer's use in preparing the design shown in Fig. 5.

Summary

The problems outlined in this paper should be considered as simply representative of those that will confront the designers of thermonuclear power plants — space does not permit a more comprehensive survey even for the reactor taken as an example for purposes of this paper. However, it is clear that much of the technology involved in the design of a fusion reactor plant is closely related to that developed in aerospace programs, and our aerospace background is already proving enormously helpful in preparing conceptual designs.

References

1. D. J. Rose and M. Clark, Jr., Plasmas and Controlled Fusion, The M.I.T. Press, 1961.
2. D. Steiner, The Nuclear Performance of Fusion Reactor Blankets, Nuclear Applications and Technology, Vol. 9, p. 85-92 (July 1970).
3. Mineral Facts and Problems, 1970 Edition, U.S. Bureau of Mines Bulletin 650, United States Department of the Interior.
4. A. P. Fraas, Conceptual Design of the Blanket and Shield Region and Related Systems for a Full-Scale Tokamak Fusion Reactor, USAEC Report ORNL-TM-3096, to be published.
5. D. Steiner, Neutron Irradiation Effects and Tritium Inventories Associated with Alternate Fuel Cycles for Fusion Reactors, Nuclear Fusion, Vol. 11, p. 305-306 (1971).
6. M. S. Lubell et al., Engineering Design Studies on the Superconducting Magnet System of a Tokamak Fusion Reactor, Proceedings of the Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research, June 1971.

7. W. O. Harms and A. P. Litman, Compatibility of Materials with Alkali Metals for Space Nuclear Power Systems, Nuclear Applications, Vol. 5 (September 1968).
8. J. A. Houck and E. S. Bartlett, The Roll-Diffusion Bonding of Structural Shapes and Panels, DMIC Report S-17, Defense Metals Information Center, Battelle Memorial Institute, October 1967.
9. M. T. Robinson, Energy Dependence of Neutron Radiation in Solids, paper for the Nuclear Fusion Reactor Conference, September 17-19, 1969, British Nuclear Society.
10. O. C. Yonts, Sputtering of Niobium by D^+ and He^+ Ions, British Nuclear Energy Society Nuclear Fusion Reactors Conference at Culham Laboratory, September 1969 Proceedings.
11. A. P. Fraas, Analysis of a Recirculating Lithium Blanket Designed to Give a Low Magnetohydrodynamic Pumping Power Requirement, USAEC Report ORNL-TM-3756, to be published.
12. S. J. Leverette, An Investigation of the Temperature Distribution in the Lithium Blanket of a Fusion Reactor, USAEC Report ORNL-TM-3701, Oak Ridge National Laboratory, May 1972.
13. A. P. Fraas, Problems in Coupling a Gas Turbine to a Thermonuclear Reactor, presented at the ASME Gas Turbine and Fluids Engineering Conference, San Francisco, California, March 26-30, 1972.
14. A. P. Fraas, Conceptual Design of a Fusion Power Plant to Meet the Total Energy Requirements of an Urban Complex, paper for the Nuclear Fusion Reactor Conference, September 17-19, 1969, British Nuclear Society.
15. A. P. Fraas, A Potassium-Steam Binary Vapor Cycle for a Molten-Salt Reactor Power Plant, Journal of Engineering for Power (October 1966).
16. A. P. Fraas, A Potassium-Steam Binary Vapor Cycle for Better Fuel Economy and Reduced Thermal Pollution, ASME Winter Annual Meeting, Washington, D. C., November 28-December 2, 1971.
17. A. P. Fraas and H. Postma, Preliminary Appraisal of the Hazards Problems of a Fusion Reactor Power Plant, USAEC Report ORNL-TM-2822, Oak Ridge National Laboratory, November 1970.
18. J. S. Watson, An Evaluation of Methods for Recovering Tritium from the Blanket - Coolant Systems of Fusion Reactors, USAEC Report ORNL-TM-3794, July 1972.
19. E. L. Compere et al., SNAP-8 Corrosion Program Summary Report, USAEC Report ORNL-3898, Oak Ridge National Laboratory, December 1965.
20. A. P. Fraas, Comparison of Two Tritium Removal Systems Designed to Minimize Contamination of Steam Systems in Full-Scale Thermonuclear Power Plants, USAEC Report ORNL-TM-2932, May 1970.

Fig. 1. Toroidal Fusion Device

TOROIDAL FUSION REACTOR (1000 MWt)

Fig. 2. Conceptual Design for a Toroidal Fusion Reactor (1000 MWt)

Fig. 3. Section through the minor diameter of a toroidal fusion reactor showing the plasma, blanket, magnet shield, and magnet regions.

[illegible]

TOROIDAL FUSION REACTOR POWER PLANT
1000 MW(e)

Fig. 5. Layout for a Full-Scale Thermonuclear Reactor Plant Including the Tritium Handling Equipment