University of Wisconsin Tokamak Power Reactor Design

C.W. Maynard, R.W. Conn, and H.K. Forsen

May 1973

UWFDM-46

Presented at the YI European Conference on Controlled Fusion and Plasma Physics, July 30-August 3, 1973, Moscow, USSR.

University of Wisconsin Tokamak Power Reactor Design

C.W. Maynard, R.W. Conn, and H.K. Forsen

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

May 1973

UWFDM-46

Presented at the YI European Conference on Controlled Fusion and Plasma Physics, July 30-August 3, 1973, Moscow, USSR.

UNIVERSITY OF WISCONSIN TOKAMAK POWER REACTOR DESIGN

By

C. W. Maynard
R. W. Conn
&
H. K. Forsen

May 1973

University of Wisconsin

FDM 46

These FDM's are preliminary and informal and as such may contain errors not yet eliminated. They are for private circulation and are not to be further transmitted without consent of the authors and major professor.

*To be presented the YI European Conference on Controlled Fusion and Plasma Physics in Moscow, USSR - July 30-August 3, 1973.

UNIVERSITY OF WISCONSIN TOKAMAK POWER REACTOR DESIGN

Abstract

The basis for design decisions and summary of the main system parameters for a 5,000 MW_{th}. Tokamak designed by the Fusion Feasibility Study Team at the University of Wisconsin is presented.

Introduction

There is no minimum or sharp break in the dependence of the cost per unit on the total power of a D-T fueled Tokamak reactor. This measure of performance decreases slowly with increasing power and thus the size of the plant is likely to be determined more by the needs of the constructing agency than by the plant characteristics. As cost decreases with increasing plant size, the unit described here is 5,000 MW_{th} which is as large a plant as seems reasonable today. With the output fixed in this somewhat arbitrary manner, a design philosophy has been adopted which chooses existing technology to the maximum extent possible. This has dictated use of stainless steel as the structural material in spite of the appealing potential of the refractory metals. The choice of liquid lithium as coolant seems very satisfactory despite the problems of flow of a conducting fluid in the magnetic fields present here. The remaining first order feature of the system to be fixed is the choice of Nb-Ti as the superconductor which is in keeping with our actual field requirements and current technological capabilities.

Geometry

There are a number of constraints which could limit the choices of the major radius and the aspect ratio. These include the maximum attainable field, yield stresses, and radiation effects. In fact, the most restrictive limit can be stated as the neutron wall loading, which is the power associated with the fusion generated neutrons per unit area of the first wall. The wall loading constraint is a result of several radiation effects which limit the useful life of this wall. Bulk effects due directly to the neutron flux are usually dominated by swelling due to void formation and embrittlement caused by atom displacement and by helium production. As these effects are also temperature dependent, the operating temperature is also related to this constraint. In addition, the electromagnetic and charged particle flux produces surface damage which must be considered. These include the sputtering of wall atoms into the containment chamber and blistering and flaking of the wall. The limiting constraint is one of the above two bulk effects, depending on the operating temperature. Data currently available indicate the embrittlement is prohibitive at any acceptable wall loading unless the temperature remains below that at which helium form bubbles. This will limit the operating temperature to approximately 500°C in the case of a stainless steel wall. The wall loading is then limited by radiation induced embrittlement due to displacements to around 0.5 MW/m^2 if it is assumed that the first wall is replaced every two years. Due to the extensive extrapolations and uncertainties of the data, a somewhat more optimistic limit of 1 MW/m^2 has been used in our feasibility design. With the total power and the wall loading fixed, the surface area of the wall is fixed leaving only the aspect ratio of the torus to be chosen in determining the general geometry. Optimization studies of the cost, considered as proportional to the energy stored in the magnetic field, show a minimum at a very low aspect ratio. However, this ratio cannot be reached when the finite blanket, shield and magnet thickness plus the Tokamak transformer space requirements are considered. The optimum aspect ratio is then the smallest consistent with the above constraints.

The optimization just described includes the main plasma physics requirements for confinement. The stability factor "q" should be as small as possible to optimize the power density of the plasma, but for stability must exceed unity by a safe margin. At the same time, if steady state operation is to be possible, the bootstrap current must provide the shear necessary for stability. This fixes beta poloidal as the square root of the aspect ratio. The temperature can still be adjusted to an optimal value by introducing the proper percentage of a high atomic number impurity to enhance radiation losses allowing a higher fusion rate at a different temperature. The resulting fractional burnup would then become too high and it is necessary to assume one can spoil confinement relative to the extrapolated neo-classical, possibly by intentional field errors, to adjust the fractional burnup. There are two steady state operating points, one stable at a relatively high ion temperature and the other unstable at a lower temperature. The unstable point requires a considerably smaller confining field and thus has a lower cost. A premium can be paid for an adequate control system to allow use of the unstable point, but the requirements for such a control system is still under investigation.

Divertor

Sputtering and blistering of the first wall as well as contamination of the plasma result from charged particles striking the wall. To minimize these effects, a divertor capable of carrying away most of the particles diffusing from the plasma is employed. This operates by introducing additional windings with an appropriate current to produce a field configuration such that field lines outside a particular surface close outside the confinement chamber. The path of particles following these field lines is interrupted by a medium capable of absorbing the energy and impact of these exhaust particles. The divertor can be a single of double null system. The design chosen is a double null one which simplifies the task of obtaining greater curvature of the divertor slots, and this in turn reduces leakage and the associated shielding requirements at the outer end of the slots. There is also some merit in reducing the exhaust load to be handled in a single slot. However, the main advantage of the double null system is the elongation of the plasma in the vertical direction which allows the toroidal windings to be smaller for a given plasma volume. The efficiency of a divertor in reducing the charged particle current to the wall is not yet known. However, it hardly seems worth while if it isn't at least 90% efficient, while on the other hand, there are other wall limitations which are at least as restrictive as the sputtering and blistering at this efficiency. Thus, it is felt that the wall and plasma radii must in practice be adjusted to achieve at least 90% efficiency even though no figures are yet available.

Blanket and Shield

The thickness of the first wall is determined by stress and erosion. The stresses due to the pressure of the flowing coolant and the thermal gradients combine to give a stress curve with a minimum when plotted against the wall thickness. The stress at the minimum must lie below the maximum tolerable in the wall material. Thus, there is normally a range of thicknesses that are allowable from the stress considerations. However, wall erosion will necessitate a minimum thickness which is the stress limit plus the thickness eroded by the charged particle surface effects on the outside and liquid metal corrosion on the inside. This in turn must not exceed the maximum thickness set by stress alone. All of the conditions above can be met in the present design if it is based on replacement of the wall every two years instead of a twenty year plant life. The wall is thin compared to a mean free path for 14 MeV neutrons and has little influence on the neutron flux, but for cost and radioactivity reasons, the wall is chosen as the thinest of those allowed above.

The region behind the first wall contains liquid lithium and the structure needed to channel the lithium flow. The thickness of the region is fixed by the need to breed tritium, to remove most of the energy being produced, and to allow for proper flow of the electricity conducting coolant in the presence of the required magnetic field. All of these needs are met with a 50 centimeter blanket zone followed by a 10 centimeter steel reflector and a final 5 centimeter lithium zone. This blanket absorbs about 95% of the neutron energy and further attenuation in the coolant is achieved at too high a price. The energy will be recovered in the shield, but at a lower temperature. The breeding is still higher than is really necessary to allow for losses from divertor slots and fueling ports and for nuclear data errors. Adequate flow configurations are very important since pumping power may be greatly increased if fast flow transverse to the field is demanded.

Behind the blanket, the shield composition and thickness are to be fixed by the limit on the radiation to the magnets. This limit which is set by constraints to be discussed later fixes the attenuation that must be achieved at the least cost to the system. Iron, or in the non-magnetic case, stainless steel attenuated the 14 MeV neutrons most rapidly and allows the smallest magnets. This should actually be a misture of stainless steel and boron carbide to insure suitable attenuation of the lower energy neutrons. However, the high fabrication costs for steel indicates a shield consisting partly of lead may be optimal because the lost cost of the lead more than offsets the increased cost of the magnets due to slight increase in the shield thickness. The amount of lead is severely restricted since the shield in part consists of the steel necessary to support the magnet structure which cannot be diverted to another use.

Magnets

The magnets are subjected to a number of radiation, stress, and super conducting limits. The most obvious constraint is that of not exceeding the critical current density as in all superconducting magnets. To insure reliable operation, it is also necessary to provide stabilization against thermal fluctuations by providing an alternative flow path for the current. This stabilizer is usually copper. The radiation limits must consider damage effects to the superconductor, insulation, stabilizer and the energy load to the cryogenic refrigeration system. The most serious damage problem is in the stabilizer but proper design can allow for the expected resistivity changes. The actual limit seems to be the refrigeration load and is thus basically an economic one. The normal thermal lasers from the magnet cryogenic system from radiation and leakage is of the order of 5 Kw. However, in order to cool the system down in an acceptable time (30 days seems a practical maximum) the refrigeration capacity must be about 15 Kw. Thus without increasing the capital investment and for an acceptable operating cost, the radiation load to the magnets can be set at 10 Kw. For our 5,000 MW_{th} plant, this requires an attenuation of 5×10^5 in the combined blanket and shield.

The main feature of the magnets is the amount of structural steen necessary to support the induced stresses. These are so large that the principal cost of the reactor is the magnet structural costs and the superconductor costs are expected to be minor. Costs have been minimized to the maximum extent possible by elongating the plasma and using a constant tension configuration over as much of the toroidal windings as possible. In spite of this, the cost of the magnets is expected to be the largest contribution to total costs.

Summary

The system parameters for the reactor determined as described above are given in Table I. The considerations used as a basis are primarily technical. While costs have not been ignored, no attempt has been made to be systematic with regard to the economics.

Acknowledgement

The reactor described in the work of our feasibility study team and the authors have simply summarized their efforts.

TABLE I

Dimensions
- Major radius - 13 meters
- Plasma minor radius 0 5.0 meters
- First wall minor radius - 5.5 meters

Power
- 5,000 MW_{th}
- 0.795 MW/m^3 average

Wall Loading
- Neutron 1 MW/m^2
- Bremsstrahlung 0.194 MW/m^2
- Lynch 0.0284 MW/m^2
- Fuel loss rate 2 x 10^{22} ions/sec

Plasma
- $q = 1.75$
- $\beta_p = \sqrt{A}$, $A = 2.6$
- $\tau_i = 13.5$ seconds
- $T_i = 14.5$ Kev - unstable
- $M_i = 0.85 \times 10^{20}/m^3$
- Fractional burnup 12.3%

Blanket and Shield

First Wall Thickness (Stainless Steel)	2.5 mm
Primary cooling and breeding region 95% lithium 5% stainless steel	50 cm
Stainless steel reflector	10 cm
Secondary cooling and breeding region	5 cm
Shield stainless steel inner wall	5 cm
Successive 5 cm regions of alternating B_4C (90% theoretical density) and lead to	
B_4C	25 cm
Lead	20 cm
Outer shield wall and dewar support structure (Stainless Steel)	25 cm

Magnets
- 1.25 m thick by 2.65 m wide
- Total Mass 31.2 x 10^6 lbs. of which 22.7 x 10^6 lbs. is stainless steel
  7.66 x 10^6 lbs. is copper