

THERMAL-HYDRAULIC CONSIDERATIONS IN MAGNETICALLY CONFINED FUSION REACTORS

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The nature of the heat transfer in a fusion reactor is dependent on both the type of device and the plasma fuel. This paper will emphasize structural-related thermal problems that have developed from work on the tokamak and mirror concepts, though many of the important considerations are generic to all magnetic fusion systems. The fuel in early fusion devices will be a D-T mixture that results in a 20/80% split between the alpha particle energy, which may be deposited on the first wall as a surface heat flux, and the energy deposited by neutron interaction as volumetric heating throughout the system.

These thermal loads place substantial cooling requirements on many components of a fusion reactor, e.g., coils, blankets, shields and first walls. The components of most interest to this paper, however, are those in close proximity to the plasma - first wall and blanket. Heat fluxes, temperatures and temperature fluctuations can be high in this region, leading to creep rupture and thermal fatigue.

Recent fusion power reactor conceptual design studies show trends towards higher plasma power densities and more compact geometries. Plasma power densities range from 2 to 10 MW/m³, corresponding to neutron wall loads of about 1.5 to 5 MW_n/m² and average surface heat fluxes on the first wall of 0.4 to 1.25 MW/m².

The energy deposited in the first wall and blanket is recovered by the reactor coolant and transported to the thermal power conversion system, typically a steam electric plant. Helium, molten salt, liquid metal, steam, subcooled water, and boiling water have been proposed for coolants. For a steam electric plant, maximum coolant temperatures will be less than 600°C. Consideration is also being given to nonelectric applications of fusion, in which coolant temperatures can go up to 1500°C, complicating both thermal and structural design problems.

Present designs of tokamaks are pulsed devices (on the order of 10⁵ cycles/year), with proposed plasma burns lasting from minutes to hours. This results in thermal fatigue in the first wall and blanket, plus a thermal storage requirement to provide a steady electrical power output. (Mirrors and some alternate concepts, including advanced tokamak concepts, offer the possibility of steady state operation.) While external heat storage systems would solve the latter problem, several reactor concepts incorporate phase change within the blanket itself to also mitigate the potentially life-limiting effects of thermal cycling. The magnitude of the first wall and blanket temperature variations depend on the coolant, plasma duty cycle, wall load and specific reactor design features.

1. Introduction

Plasma confinement and materials irradiation damage are usually considered to be the most important potential barriers to the successful commercialization of fusion energy. However, conceptual design studies of fusion reactors have served to identify and prioritize many engineering areas that also require understanding and development. In fact, the eventual cost and reliability of the engineering solutions may well determine the economic acceptability of fusion power.

In this context, the thermal-hydraulic systems in a fusion reactor are of vital importance. Consequently, engineering studies for power generating fusion reactors are placing increasing importance on design approaches which reduce complexity and promise improved performance in thermal systems. On the other hand, the potential to achieve very high temperatures (e.g., 1500°C) in a fusion reactor blanket has led to studies of systems for nonelectrical applications such as chemical production or high temperature electrolysis. These uses obviously place an even greater emphasis on thermal-hydraulic systems.

The internal heat generation which results from the neutronic cascading of plasma-born 14 MeV neutrons gives rise to substantial cooling requirements in many components; e.g., coils, blankets, shields and plasma first wall. In some cases, such as the shields and normal coils, extensive cooling subsystems will be required but thermal-hydraulics will not be a design limiting factor. In superconducting coils utilizing liquid He at 4°K, the major problem is to provide adequate cooling margins to prevent coil transition from the superconducting state to a "normal" state, and this concern is treated extensively in the literature. The main subject of this paper, then, is the high temperature region in close proximity to the plasma--the first wall and blanket. Heat fluxes, temperatures and temperature fluctuations are highest in these components, possibly leading to creep rupture and thermal fatigue.

Recent fusion power reactor conceptual design studies show trends towards higher plasma power densities and more compact geometries, with neutron wall loads of about 1.5 to 5 MW/m² and average surface heat fluxes on the first wall as high as 0.4 to 1.25 MW/m². Limiters and divertors in tokamaks and plasma leakage ports in mirrors, which can be subjected to considerably higher surface heat fluxes, require high performance heat removal systems and will experience high thermal stresses.

The energy deposited in the first wall and blanket is recovered by the reactor coolant and transported to the thermal power conversion system, typically a steam electric plant. Helium, molten salt, liquid metal, steam, subcooled water, and boiling water have been proposed for coolants. For a steam electric plant, maximum coolant temperatures will be less than 600°C. Nonelectric applications may call for much higher coolant temperatures, typically in the 1000-1500°C range.

This paper will discuss some of the design solutions and thermal-hydraulic results presented in recent fusion reactor conceptual design studies. An excellent and relevant discussion of fundamental fusion heat transfer considerations can be found in an earlier paper by Hoffman et al. [1].

2. Plasma Energy Characteristics

The nature of the energy deposition in a fusion reactor depends strongly on the types of magnetic confinement device and plasma fuel. The fuel for the first generation of fusion

devices will be a deuterium-tritium (D-T) mixture, with 80% of the plasma energy in the form of 14 MeV neutrons and 20% in the form of alpha particles. As result of interactions with the ions and electrons in the plasma, the alpha particle energy is eventually transported via charged particles and electromagnetic radiation. In essence the neutron energy is seen as an internal heat generation and the alpha particle energy as a surface heat flux. (Advanced fusion fuels, such as D-D, D-³He or D-⁶Li, would significantly lower the ratio of internal heat generation to surface flux and consequently impose quite different thermal-hydraulic requirements on the reactor.)

The type of magnetic confinement device will determine the location, periodicity, and intensity of the energy deposition. While the neutrons are always deposited in the reactor components immediately surrounding the plasma, the surface flux need not be. In a mirror reactor, for example, this energy largely exits the plasma chamber via charged particles and is deposited on direct conversion devices. In a tokamak, this component of the energy is deposited directly on the first wall as a surface heat flux, unless some fraction is diverted to a special divertor chamber. Similarly, the mirror reactor is a steady-state device, while the tokamak plasma is a pulsed reactor with a burn period from several to tens of minutes. The plasma power density will depend on many reactor design parameters, typically varying from 1 to 10 MW/m³. Since practically all of the thermal-hydraulic studies of magnetically confined fusion reactors have been carried out on the mainline concepts--the tokamak and mirror reactors--these devices will serve to illustrate important thermal-hydraulic features. Alternate magnetic confinement concepts (e.g., EBT, stellerator, multipoles, pinches) have the same basic considerations, but to a widely varying degree depending on the specific device.

The increased plasma power densities of recent conceptual designs lead to higher surface heat fluxes and volumetric heating rates. Typical thermal design conditions for several recent reactor concepts are given in Table I, including both the magnitude and periodicity of the heat load. A particularly severe thermal loading on the first wall can occur if the plasma goes unstable (plasma disruption), or if the plasma is dumped in a very short time at the end of a discharge. While too little is presently understood of fusion plasma physics to predict how often this may occur or exactly how severe it might be, parametric analyses are possible. A typical commercial fusion reactor might contain on the order of 0.6 J/M³ of thermal energy and a comparable amount of magnetic energy. Assume that half of the magnetic energy is thermalized during a disruption and augments the thermal energy. Then, if it takes 5 ms for the plasma to uniformly disrupt, the wall load would be on the order of 180 MW/m². Even with an order of magnitude increase in disruption time, the instantaneous wall loads will be very high compared to operating fluxes.

3. Blanket and Power Conversion

3.1 Design Considerations

The reactor blanket acts principally to convert plasma energy to neutron energy, to provide primary shielding for the magnets and other reactor components, and to breed tritium fuel from lithium or its compounds. The energy distribution in the blanket is more or less exponential, decreasing with distance from the plasma. Thermal-hydraulic considerations in the blanket deal largely with the primary coolant, material temperature levels, thermal

storage requirements for a pulsed device, and the cumulative effects of these factors on the thermal power conversion system. In general, the objective is to remove the thermal energy at a temperature level high enough to give an acceptable power conversion efficiency, while still providing adequate cooling to the structure and breeder without incurring unacceptably large blanket temperature gradients.

Coolant selection is the major design choice from a thermal-hydraulic viewpoint. Ideally the coolant will have good heat transfer and thermodynamic characteristics, low pressure, low pumping power fraction (coolant pumping power/blanket thermal power), and acceptable tritium extraction characteristics. Additionally the coolant should be neutronically, chemically and magnetically inert, impose no unusual module design requirements, and minimize the complexity of the primary coolant transport system.

The plasma chamber vacuum (on the order of 10^{-7} torr) places stringent requirements on the vacuum boundary of the reactor. While early designs placed the boundary at the first wall, more recent concepts move this boundary away from the blanket, or stage the vacuum through several zones. These approaches require that the coolant pressure containment be extremely reliable, for this system becomes the greatest potential leak source to the plasma. Another general design problem is the control of flow distribution in blanket designs, either within individual blanket modules or in the manifolding which distributes the flow from the power conversion system to the modules. This problem is not adequately addressed in present conceptual designs, and may prove to be particularly difficult to solve.

The pulsed nature of the plasma burn causes not only temperature fluctuations within the blanket which could lead to fatigue problems, but also results in a coolant exit temperature fluctuation. The thermal capacitance of the blanket itself leads to some dampening of this effect. However, some auxiliary thermal storage is probably necessary to achieve a steady electrical output, as well as to limit the potentially damaging effects (from thermal fatigue) of temperature fluctuations in the steam generator and the steam turbine inlet.

3.2 Helium Cooling

No coolant best satisfies all the requirements of a fusion blanket, though examination of recent reactor conceptual designs shows that helium has usually been selected. In a helium cooled blanket, important thermal hydraulic tradeoffs must be made between a number of factors. The most critical limitations are the maximum allowable structural temperature in the first wall region, and the allowable pumping power which is set by system considerations of parasitic power loss. The structural temperature is determined, in a thermal-hydraulic sense, by the coolant inlet temperature (T_1), the heat transfer coefficient and the temperature rise (ΔT) through the blanket. The exit coolant temperature ($T_1 + \Delta T$) and the temperature rise are also critical parameters for the efficiency of the power conversion system and the design of the steam generator. In the steam generator, the important parameter is the temperature pinch point which occurs between the helium and the saturated liquid. Additionally, a high helium density (via high pressure) is beneficial because it reduces the pumping power and coolant void fraction, and increases the volumetric heat capacity of the coolant. However, high pressure leads to increased mechanical loads, a higher structure fraction which absorbs neutrons, and a greater leak potential.

Obviously these tradeoffs can be complex and must be made in view of the overall reactor considerations. Hence different conceptual designs have arrived at somewhat different design

choices. The blanket module of the doublet demonstration power reactor (DPR) design [3] is illustrated in Figure 1. In this cannister-type module, the cool inlet flow is directed to the first wall region, moves towards the centerline, and is distributed to pass uniformly through the breeder and shield region. This design chose a high temperature nickel-based alloy (Inconel 718) for the first wall, permitting a helium outlet temperature of 585°C with a temperature rise of 300°C. The pumping power fraction was 4% at a neutron wall load of 1.3 MW/m² and a pressure level of 50 atm. A potential problem exists in this design at the centerline where a stagnation region may exist leading to a local hot spot. Without auxiliary thermal storage, the coolant exit temperature variation for the 19 sec dwell period was 9°C (which results in only a 3% power variation), but this is still at the limit of acceptability for the steam generator and steam turbine. In general, the blanket reaches thermal equilibrium during a burn in a matter of about 2-3 minutes, and it is thus the dwell time between plasma burns which controls the thermal cycling.

The Westinghouse/ORNL blanket study [7] examined helium cooling for small 10cm diameter cannisters containing liquid lithium, in which the helium flows along the outer surface (Fig. 2). Here the choice of austenitic stainless steel required that the maximum structural temperature be limited to 450-500°C depending on stress factors, and at a neutron wall load of 4 MW/m² the coolant inlet/outlet temperatures were selected to be 200/435°C. Other features of this design are a pressure of 54 atm, a pumping power fraction of 2.2%, and a gross cycle thermal efficiency of 31%. During the assumed plasma dwell period of 1 min. the coolant temperature falls from 435°C to 300°C, making external thermal storage a necessity. Examination of the heat transfer at the center of the first wall dome indicated that jet mixing would enhance cooling there. The design of the helium flow passages included, in addition to pumping power tradeoffs, a stagnant helium gap between the cold inlet and hot outlet channels in order to reduce regenerative heat loss.

In the helium-cooled blanket parameter study of Misra and Maroni [8], a configuration was analyzed which consisted of a helium cooled stagnant lithium blanket using a stainless steel structure, with a first wall fabricated of a single layer of closely-packed stainless steel tubes. Some of the independent parameters were allowable structural temperatures of 500°C or 650°C, helium pressure of 68 atm, pumping power fraction of 5%, helium temperature rise of 200°C or 300°C, helium velocity of 61 m/s, blanket void fraction of 5%, and allowable first wall stresses of 117 or 234 MPa (17 or 34 ksi). As an example of the results, it was found that thermal stress criteria limited the maximum wall load to ≤ 2.5 MW/m² without a divertor and ≤ 6.0 MW/m² with a divertor (heat flux reduced to 10% of neutron flux). The study did not include tradeoffs on power conversion cycle efficiency or cyclic fatigue in the first wall.

3.2.2 Lithium Cooling

Even though helium coolant has been adopted in most recent reactor design studies, liquid lithium is a strong contender for eventual adoption. The characteristics and MHD relations for liquid lithium are described in [1], which states that "perhaps the most elegant concept for a blanket design is one employing molten lithium or a lithium-bearing fluid to perform all three blanket functions--neutron moderation, cooling, and tritium breeding." Like other liquid metals, lithium has superior heat transfer characteristics. It is the influence of the fusion magnetic field which gives rise to various adverse thermal-

hydraulic effects, including flow separation, suppression of convection, modification of velocity profiles and creation of a boundary layer, and the development of large MHD pressure losses [8]. Handling, material compatibility and safety concerns have also led designers away from use of liquid metals in fusion reactor concepts.

Wells [9] argues that with the trend towards smaller reactor sizes and reduced magnetic field strengths (by virtue of higher β), lithium cooled designs have become more feasible. Since the heat is generated largely within the lithium itself, energy can be withdrawn very nearly at blanket peak temperature without the constraint of a coolant film temperature drop. In developing a lithium cooled blanket design, Wells finds a gain of 60°C in coolant temperature is possible compared to helium. The adopted design is a configuration consisting of round tubes filled with flowing lithium. The first wall, of similar construction, might use helium coolant as an alternate. The most important design consideration was the routing and orientation of the lithium ducting to minimize the MHD pressure drop and to arrive at an acceptable header and ducting arrangement compatible with the reactor.

The result was a lithium pressure drop of 10 MPa (1450 psi) in the first wall and ≤ 1.5 MPa (213 psi) in the blanket, and a blanket coolant pumping power fraction of $\leq 1.1\%$. The lithium enters at 236°C and exists at about 500°C. It is advantageous that the high pressure (at the duct inlet region) also occurs at the regions of lower temperature. There are various means, however, by which the MHD pressure drop might be decreased. Given a conducting fluid flowing through a uniform magnetic field over a distance ΔL , the pressure drop ΔP is, from [9],

$$\Delta P = \sigma_w t v B_{\perp}^2 \Delta L/d, \quad (1)$$

where σ_w is the wall electrical conductivity, t the wall thickness, v the fluid velocity, B_{\perp} the magnetic field strength transverse to the flow, and d the tube diameter. While an insulator wall material would eliminate the MHD-induced ΔP , no known ceramic insulator is compatible with hot lithium. It can be seen from eq. (1) that other ΔP reduction techniques are possible, such as ducts of tapered wall thickness to reduce t in regions of lower pressure, insulator walls with a thin inner metallic layer for corrosion protection, or subdividing the crosssection of round ducts. MHD effects also reduce the heat transfer coefficient causing laminarization of liquid lithium under typical reactor magnetic and fluid conditions. In comparing the total duct crosssectional area for helium and lithium coolants at the same thermal load conditions, Wells finds that approximately the same requirement exists for each. However, excessive void and metal fractions can be problems in tubular designs of this type.

Reference [8] analyzed a reference blanket configuration using a flowing lithium coolant. Two structural materials were considered: stainless steel limited to a maximum temperature of 500°C and vanadium limited to 650°C. Allowable thermal stresses were taken to be 117 and 351 MPa (17 and 51 ksi), respectively, and the lithium inlet temperature was 235°C. Pumping power fractions were consistently less than 1%. It was found that for stainless steel the neutron wall loading and coolant exit temperature were limited to ≤ 2 MW/m² and ≤ 480 °C. For vanadium, the corresponding values were ≤ 8 MW/m² and ≤ 620 °C. With a divertor the maximum wall loadings were increased 40% for vanadium and 90% for stainless steel.

3.2.3 Other Designs

Two blanket designs proposed by Sze [10,11] attempt to avoid some of the problems with helium and lithium coolants. The first concept deals with blanket leak potential by eliminating a pressurized coolant. This design utilizes a coolant consisting of microspheres of lithium oxide (Li_2O) pellets flowing by gravity in a vacuum. The first wall is graphite, cooled by radiation to the Li_2O . The coolant temperature rises from 400°C at the inlet to 600°C at the outlet, entering a steam generator producing 17 MPa/ 538°C / 538°C steam for a gross thermal cycle efficiency of 42%. From a thermal-hydraulic viewpoint, the main concerns are the operating temperature (1400°C) and life of the graphite first wall, the mechanical circulation of the Li_2O pellets, the blanket void fraction and the steam generator design.

The second approach was conceived to ease a variety of blanket problems. The cited thermal and structural advantages include reduced thermal cycling in the first wall, a nearly constant blanket coolant temperature, and a unique blanket thermal storage system. These features are accrued via a boiling water coolant at 300°C and 8.6 MPa (1250 psi) and a $\text{Li}_{62}\text{Pb}_{38}$ eutectic, operating at the melting point, as the breeding material. The coolant maintains the titanium alloy structure at 300°C and achieves a gross thermal efficiency of 35%, and significantly reduces first wall thermal cycling. Analysis showed that during the 20 sec dwell period, as the coolant drops to and is maintained near the 464°C melting temperature of the eutectic, the coolant temperature change is $\leq 30^\circ\text{C}$. This fluctuation is still unacceptable for the steam turbine, necessitating some auxiliary thermal storage.

Consideration of high temperature blankets for nonelectrical fusion applications, such as synthetic fuel production or high temperature electrolysis, is just beginning [12,13]. Reference [13] discusses two possible blanket configurations, each containing a high temperature ceramic (e.g., MgO or SiC) which is cooled by steam at 10 atm with inlet/outlet temperatures of about 1230°C / 1380°C . Thermal insulation from a separately cooled structural shell is a necessity, and careful attention must be given at these high temperatures to coolant flow distribution, heat losses and local hot spots. In essence all the thermal-hydraulic problems of lower temperature blankets are present to an even greater degree in these higher temperature applications.

4. First Wall

The first wall presents the most difficult cooling problem in a fusion reactor because of the pulsed plasma heat flux in addition to the neutron load. Reactors without this first wall heat flux, such as the mirror reactor, and steady-state devices (e.g., mirror, EBT) ease but do not eliminate first wall cooling requirements. First wall thermal behavior is critical in regard to wall lifetime, which is dictated by fatigue, creep-fatigue, flaw growth and creep rupture [3,14] in a high temperature, high irradiation environment.

One configuration often suggested for a first wall is an array of tubes, either metallic in typical designs or possibly ceramic for high temperature nonelectrical applications and for low activation concepts. The associated heat transfer problem using single phase fluids is that of turbulent heat transfer in a circular tube with variable circumferential heat flux and volumetric heat generation. Fillo and Powell [15] have analyzed this coupled conduction-turbulent convection problem at steady-state, extending previous work to include radial temperature gradients in the tube wall. Based on a few preliminary numerical results, they found this effect to be important, giving maximum temperature increases on the order of 25-50% for

thick wall tubes ($0.25 \leq t/d \leq 0.5$).

4.1 Transient Behavior

First wall temperature responses during the burn were determined in many of the blanket studies. The wall temperature depends on numerous factors, including the heat load; coolant inlet temperature, mass flow rate and properties; and the thermal characteristics of the wall and blanket. Due to its low thermal capacitance, the first wall responds quickly to changes in heat load and surface conditions. This response is strongly influenced by thermal lag in the coolant, which may be significant if the coolant first passes through massive regions of the blanket.

Figure 3 shows typical variations over a burn cycle for a helium cooled wall, for both the maximum wall temperature and the temperature drop across the wall. These results are strongly design dependent, and Table II summarizes the findings from several design studies. Reference [11] finds that the maximum first wall surface temperature rises 100°C during the burn with a boiling water coolant, whereas it would rise close to 1000°C were helium used in that design. Similarly, lithium-cooled walls respond less quickly than helium-cooled walls because of the thermal lag in the coolant temperature. In summary, the thermal behavior of the first wall during normal operation is critically important to wall lifetime in pulsed magnetically-confined reactors, and is determined by the strong interplay between the coolant, wall and blanket design, and the plasma burn cycle.

4.2 Plasma Disruption

The first wall should be capable of withstanding a selected number of energy dumps by the plasma, resulting from either a disruption or a plasma shutdown sequence in a tokamak. Plasma dumps are unlikely to be uniform, resulting in local hot spots.

Two studies have carried out preliminary evaluation of the first wall response under disruption conditions. Smith and Charak [16] determined the extent of ablation of the first wall during a plasma dump, assuming that both the plasma thermal energy and magnetic energy (a conservative assumption) are deposited. For a plasma with a normal 1 MW/m^2 wall load, the extent of ablation of stainless steel and graphite walls was calculated parametrically for different dump times and effective wall areas. Figure 4 shows the results for graphite. The ablation of steel is greater by up to a factor of about 5 for similar conditions. The authors conclude that first walls of stainless steel and graphite should be able to withstand a moderate number of plasma disruptions if the plasma energy is effectively distributed over at least 25% of the wall area. Lee [7] carried out a simple calculation in which a pulsed heat flux of 10 ms duration was applied to a stainless steel wall for various particle heat fluxes up to 80 MW/m^2 . It was found that, for an initial first wall surface temperature of about 450°C , the peak temperature reached 850°C for a 40 MW/m^2 pulse, and about 1100°C for 60 MW/m^2 . In general, considerable work needs to be done both in defining disruption conditions and evaluating the effects on first wall integrity and lifetime.

5. Conclusions

Significant progress has been made in recognizing the potential thermal-hydraulic problems in magnetically confined fusion reactors. Only the potential barrier problems were discussed here, though many other routine but significant cooling requirements must be met. Experimental programs are required to examine the extent and significance of the identified problem areas, as well as more detailed analyses of selected design concepts. While

solutions appear to exist for all identified thermal-hydraulic problems, the true breadth of these problems, and others not yet cited, is more than likely yet to be appreciated.

6. Acknowledgement

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Table I. Plasma Power Parameters for Selected Fusion Reactor Concepts.

| Reactor | Power Level (MW _e) | Plasma Power Density (MW/m ³) | First Wall | | Duty Cycle (l) | Cycle Time (Sec) |
|----------------------|-----------------------------------|--|--------------------------------------|--------------------------------------|-------------------|---------------------|
| | | | Neutron Flux (MW/m ²) | Surface Flux (MW/m ²) | | |
| Tandem Mirror [2] | 1000 | 5 | 2 | <<1 | 1 | * |
| Doublet DPR [3] | 307 | 2 | 1.3 | 0.3 | 0.85 | 125 |
| Elmo Bumpy Torus [4] | 875 | 3.4 | 1.8 | 0.45 | 1 | * |
| HFCTR [5] | 775 | 8 | 4 | 1 | 0.85 | 588 |
| NUMAK [6] | 690 | 10 | 5 | 1.25 | 0.92 | 218 |

* Steady-state

Table II. Transient Responses of First Walls in Pulsed Reactors.

| Ref. | Coolant | Wall Load (MW/m ²) | Neutron Burn Time (sec) | Dwell Time (sec) | Matl | Max/Min | |
|------|--------------------------|-----------------------------------|----------------------------|---------------------|----------|----------------------|-----------------|
| | | | | | | Surface Temp (°C) | Wall ΔT (°C) |
| [3] | He | 1.3 | 106 | 19 | Inc 718 | 620/350 | 122/13 |
| [7] | He | 4.0 | 1140 | 60 | 316SS | 452/200 | 71/<1 |
| [16] | H ₂ O | 1.0 | 65 | 15 | SS | 402/321 | 48/2 |
| [11] | Boiling H ₂ O | 4.3 | 225 | 20 | Ti Alloy | 400/300 | 100/0 |

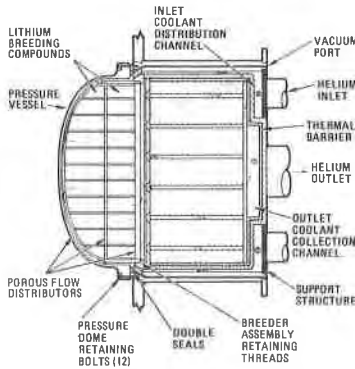


Fig. 1 General Atomic DPR blanket module design - 0.75 m dia, internal cooling passages [3].

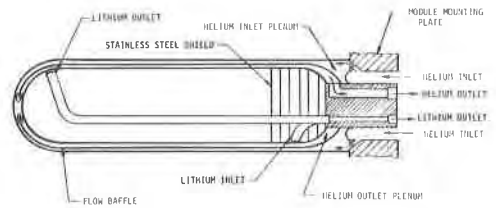


Fig. 2 Westinghouse/ORNL module design - 0.10 m dia, surface cooling passage [7].

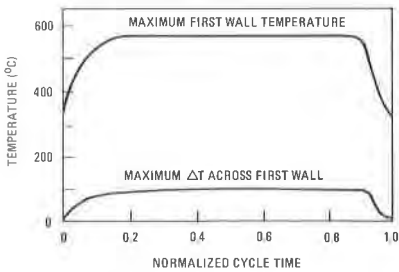


Fig. 3 First wall temperature variations for helium-cooled wall (burn 106 sec, dwell 19 sec, wall load 1.3 MW/m²) [3].

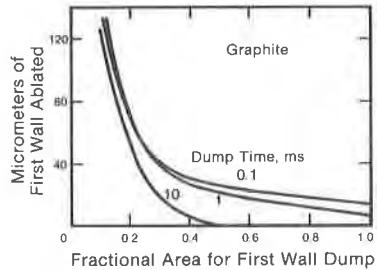


Fig. 4 Ablation of graphite first wall during plasma disruption [16].