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ABSTRACT

The fusion blanket surrounds the burning hydrogen core of the fusion reactor. It is in this blanket that most of the energy released by the DT fusion reaction is converted into useable product, and where tritium fuel is produced to enable further operation of the reactor. Blankets will involve new materials, conditions and processes. Several recent fusion blanket concepts are presented to illustrate the range of ideas.

INTRODUCTION

The blanket surrounds the burning hydrogen core of the fusion reactor. It is in this blanket that most of the energy released by the DT fusion reaction is converted into useable product, and where tritium fuel is produced to enable further operation of the reactor. Energy removal and tritium production capabilities will be needed for the next generation of fusion devices in the late 1990's, and certainly for subsequent demonstration reactors (1). However, the technology is in a very early stage of development, and will involve new materials, conditions and processes.

There are three general factors that affect the blanket design: reactor application, reactor conditions and material choice. Once these are defined, often based on larger engineering trade-offs or design choices, the particular blanket can be designed.

The applications are primarily electric power and fissile fuel production. However, there are other options to take advantage of the high quality neutron and plasma energy available, including isotope production, synfuel production, nuclear waste burnup, and space propulsion. In most cases, it is in the blanket where these functions are carried out, so the choice of product bears directly on the blanket design.

The reactor conditions are the reactor-related environmental conditions that affect the blanket behavior, particularly the neutron wall load, surface heat load, pulse cycle, lifetime irradiation fluence and magnetic field strength. These conditions vary according to the nature of the device (e.g., experimental test reactor, compact power reactor), and between reactor types (e.g., tokamak, mirror, reversed-field pinch) (2,3). Experimental devices are generally pulsed with relatively low neutron exposures. Since these devices do not have to produce economic product or be tritium self-sufficient, the blanket can operate at lower temperatures and pressures than would be acceptable in a commercial reactor.

The preferred confinement system has not been identified yet, although tokamaks have been the most studied and are the most successful devices so far. However, their low magnetic field utilization efficiency, pulsed operation, and complex geometry have sustained a search for improved tokamaks and for new confinement systems. The latter include reverse-field pinches, with more efficient use of the magnetic field in a more compact device, and tandem mirrors, with simple linear geometry. Alternatively, inertially-confined reactions have been studied where the reaction occurs as a series of small explosions (as in a gasoline engine) initiated by laser or particle beam pulses. The choice of reactor type influences the geometry, magnetic field, and the peak power conditions, although the average fluence, neutron damage, and temperature limits are generally set by more fundamental materials limits.

The material choices are the third major influence on the blanket. The blanket is generally composed of a tritium breeding, coolant, structure, and a neutron multiplier/moderator. There may also be additional material such as fertile fuel for conversion to fissile fuel. Table 1 is a partial list of materials of current interest (1,2,3,4). Although not all combinations are sensible (e.g., liquid lithium breeder with water coolant), there are still a large number of possible combinations, each with its own advantages and problems.

The factors involved in blanket design are illustrated below through a discussion of several recent concepts. Present blanket concepts for fusion-electric applications are typically based on helium-cooled pellets of lithium- bearing ceramics (1,2,5), flowing liquid metal systems with lithium

TABLE 1: PRIMARY BLANKET MATERIAL OPTIONS

Breeder	Coolant	Structure	Multiplier
Liquid metal	Liquid metal	Austenitic steel	Beryllium
Solid ceramic	Helium	Ferritic steel	Lead
Molten salt	Water	Refractory alloy	
Aqueous salt		Martensitic steel	

or lithium-lead as the coolant and breeding medium (2,5), and water-cooled modules containing slowly circulating lithium-lead (1). Alternate concepts based on molten salt cooled systems have been proposed, particularly for fusion-hybrid applications (2,6). Water-based concepts offer good cooling with a relatively conventional technology (2,4). The conditions in inertially-confined reactors are substantially different because of the short-pulse, low vacuum conditions. Blanket concepts here are typically based on 'waterfalls' of liquid metal or solid pebbles to protect the structure and capture the neutron energy (7). Other recent ideas attempt a more efficient conversion of the neutron kinetic energy into electrical energy than through a Carnot-limited thermodynamic power cycle (8).

HELIUM-COOLED SOLID BREEDER BLANKET FOR ELECTRIC POWER

Solid lithium ceramic breeder blankets bear similarities to conventional fission reactor technology. The breeder is a solid compound with limited chemical reactivity and a high melting point. Consequently, the likelihood and results of accidents are limited. The solid breeder is generally compatible with attractive structural materials over temperature ranges of interest. The coolants can be conventional water or helium, both of which do not interact with the magnetic field. Also, many of the important development issues can be accomplished in existing facilities, primarily fission reactors.

Of all the solid breeders, Li_2O may be able to provide net tritium breeding without the additional complexity of a multiplier. This advantage can only be realized in a blanket design that minimizes non-breeding absorption of neutrons. Therefore, it is most appropriate with helium coolant. The advantages of helium coolant are its chemical inertness, neutron transparency, lack of phase change, and high temperature capability. Helium is nonmagnetic and nonconductive. It is used as a heat transfer medium for fission reactors. The principal disadvantage for all gas coolants is their low volumetric heat capacity. This leads to operating the helium with pressures of several MPa. The pumping power also tends to be large (2-5% of blanket thermal power) because of the relatively low heat transfer coefficient and the consequent need for high flow velocities.

Figure 1 shows a helium-cooled solid breeder blanket concept for commercial fusion-electric conditions of 5 MW/m^2 neutron wall load, 1 MW/m^2 surface heat load, and a 3 year lifetime (2). Since the coolant is relatively high pressure, a lobed first wall mechanical design is used to retain the pressure, although it decreases the space available to breeder and other blanket material. The breeder is placed in a plate geometry, with helium flowing through narrow gaps between the plates, in order to maximize the breeder content. In this example, a net tritium breeding rate (TBR) of 1.1 is achieved. This TBR is slightly more than is believed to be required, but does not offer much margin for present uncertainties.

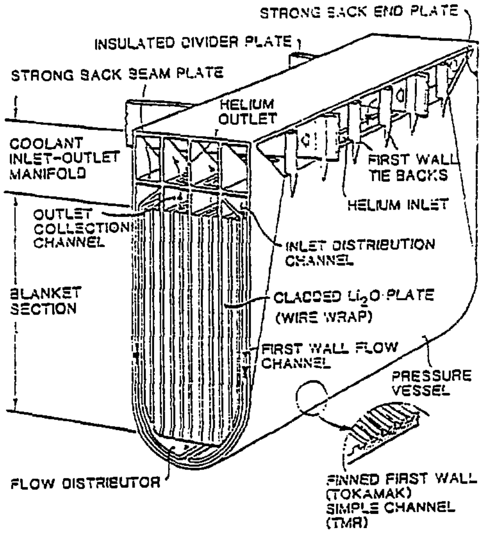

FIGURE 1: HELIUM-COOLED SOLID BREEDER BLANKET FOR ELECTRIC POWER PRODUCTION

Stainless steels are compatible with helium, but are limited by decreasing mechanical strength under irradiation to about 550°C. The first wall has a high surface heat flux across it, and must be a few millimeters thick to provide some erosion allowance. In order to stay within the first wall peak temperature limits, the cold inlet helium is first directed around the curved first wall, and then directed into the blanket interior to cool the breeder.

Lithium oxide, although it may lead to simple designs without multipliers, is hygroscopic and thus more difficult to handle and fabricate. It tends to sinter, creep, and have high vapor pressures at relatively low temperatures (800°C). All solid breeder ceramics have poor thermal conductivity, typically 1-2 W/m-K for the 85% dense sintered product material. Thus, plates of only 1 cm thick are possible before reaching the temperature limits at the front end of the plate with peak heating rates of 40 MW/m^3. This heating rate drops exponentially into the blanket.

The tritium generated in the solid breeder can be removed, in principle, by batch processing the solid breeder, through permeation into the main helium stream, or by a separate breeder helium purge stream. A 1000 MWe fusion reactor would produce about 120 kg tritium per year. Consequently, blanket modules would have to be removed frequently to minimize the tritium inventory and related costs and hazard. Frequent replacement of blanket modules for reprocessing would require far too much down time. On-line refuelling as in CANDU reactors leads to a more mechanically complex blanket with a substantial penalty in tritium breeding due to the increased structure and reduced coverage.

In-situ recovery by a separate helium purge stream flowing through the porosity in the solid breeder is the preferred approach. Tritium generated in the breeder diffuses to the grain surface, is desorbed by isotopic exchange with a small amount of H_2 in the purge stream, and is swept away to a tritium recovery system external to the blanket. Since this is not the primary heat transport system, the helium purge does not need to run at high pressures and flow rates, simplifying the tritium recovery and control systems. Tritium recovery from the primary coolant is possible, but requires the extraction system to operate on a hot, high flow rate, high pressure coolant while minimizing tritium losses through permeation across the steam generator (5).

Helium-cooled solid breeders are attractive with respect to maintenance (easy spill cleanup, modest leak tolerance, relatively simple sector removal); safety (no chemical reactivity); and high thermodynamic efficiency (36%).

SELF-COOLED LITHIUM BLANKET FOR ELECTRIC POWER

The use of the same liquid metal as both tritium breeder and coolant greatly simplifies both design and materials considerations since the blanket requires only a structural material and a non-structural coolant/breeder. There is no coolant/breeder compatibility concern, although the chemical reactivity of the liquid metal is. Heat removal is simplified since the heat is deposited directly into the coolant and does not need to be conducted through regions of low thermal conductivity. Liquid metals offer high boiling points, so can provide excellent thermal efficiencies at lower pressures than water.

Both lithium and a lithium-lead eutectic ($Li_{17}Pb_{83}$) offer relatively high tritium breeding rates. Since the tritium is generated in the coolant, it is automatically circulated to outside the reactor without requiring a separate tritium purge system. It is easier to recover tritium from lithium, but the inventory is lower and the tritium breeding higher in lithium lead. Lithium-lead is also less chemically reactive, particularly with water which may be required for cooling nearby high heat flux components (2).

The temperature of the liquid metal is generally limited by compatibility of the coolant and the structure. Vanadium alloys may allow higher temperature mechanical strength as well as improved compatibility with the liquid metal. The pressure drop of a liquid metal flowing across a magnetic field is substantial, and increases as the channel wall thickness increases. Because of the complex geometry of most fusion devices, it is not possible to orient the liquid metal entirely parallel to the field. Consequently, the blanket must operate at reasonably high pressures (a few MPa at least), and sustain these pressures through limited thickness structural members. Furthermore, the pressure drop is only tolerable if high flow rates, such as required at the first wall, only occur in regions parallel to the field. This complicates the mechanical design.

An attractive liquid metal blanket is illustrated in Figure 2 (2). This is a lithium-cooled, lithium-breeder blanket with vanadium structure. The lithium flows slowly in large channels through much of the blanket, across the magnetic field. In the vicinity of the first wall, the channels are smaller and parallel to the field to allow rapid flow with minimum pressure drop.

Tritium is soluble in lithium, which limits the vapor pressure of tritium gas and consequently the tritium permeation from the coolant out of the primary heat transport system. It can be reasonably extracted and maintained to about 1 appm based on, for example, molten salt exchange processes. This blanket has exit temperatures of 500°C, and an estimated net thermal efficiency of 42%.

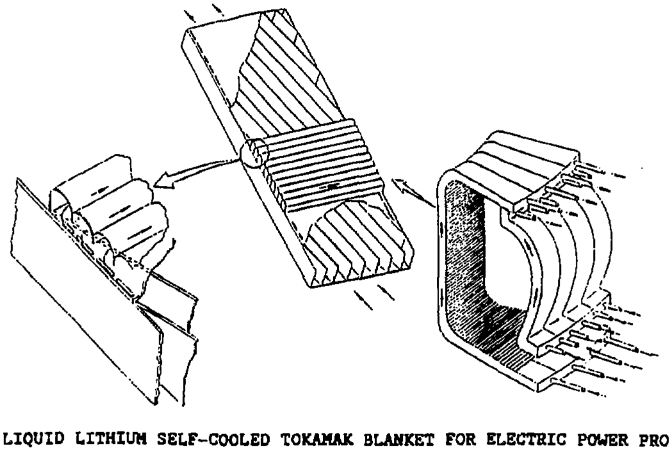

FIGURE 2: LIQUID LITHIUM SELF-COOLED TOKAMAK BLANKET FOR ELECTRIC POWER PRODUCTION

WATER SELF-COOLED BLANKET FOR NEAR-TERM EXPERIMENTAL DEVICES

Water is an excellent coolant with substantial industrial experience. Its primary drawbacks for power production are the high pressures and lower thermal efficiencies achievable. Reasonable water-based blankets have been proposed for commercial reactor applications (1,2).

Next-generation experiments will have neutron wall loads of about 1 MW/m^2 over sufficiently long pulses to achieve thermal equilibrium. Adequate cooling is required. The main blanket need not necessarily operate at commercial conditions, although some test blankets would. It may be more useful to have the bulk of the blanket and shielding functions performed by as simple, reliable and conventional a technology as possible - for example, with water cooling and stainless steel structure.

Figure 4 shows that a blanket based on a small amount of lithium salt (1 wt.% Li^6) dissolved in the blanket/shield water coolant could provide net tritium breeding ratios of 80% with reasonable coverage of the machine (4). This concept offers simplicity and conventional materials. At low temperatures (50°C) and pressures (0.2 MPa), corrosion is expected to be negligible with suitable salts. Tritium recovery by conventional techniques is feasible and economic at acceptable tritium levels (e.g., 10 Ci/L, based on the CANDU reactor moderator heavy water operation experience at comparable temperature and pressure).

The tritium breeding is improved with higher salt concentrations, neutron multiplier, zirconium alloy structure and heavy water. The concept may be extended to provide reasonable power reactor performance with blankets operating at conditions and with materials similar to those in present CANDU reactors. It may be especially attractive for very high power density devices such as reverse-field pinches.

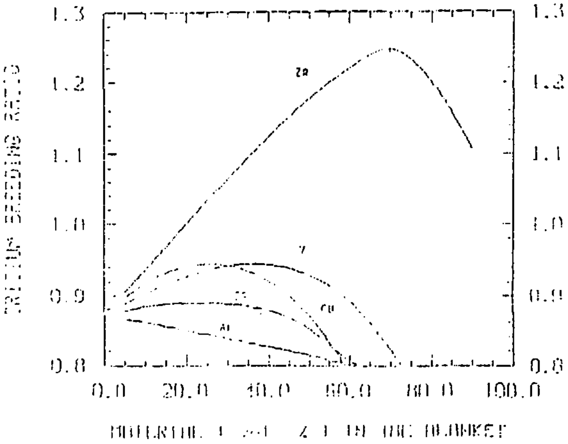

FIGURE 3: FULL-COVERAGE TRITIUM BREEDING RATIO WITH 1 WT.% LI^6 DISSOLVED IN H_2O

HELIUM-COOLED MOLTEN SALT BLANKET FOR FISSILE FUEL PRODUCTION

Fusion reactors to produce fission fuel take advantage of the existing electric utility investment in fission reactors, the higher neutron/power ratio of fusion, and the reduced requirements on the fusion reactor. A near-term fusion device could be economically attractive as a fission fuel producing device. The major disadvantage is the addition of fission reactor safety concerns to fusion.

Figure 4 shows a fissile fuel production blanket (6). Fission is suppressed to minimize criticality concerns by using beryllium to multiply neutrons, rather than uranium, and by minimizing the fissile inventory. The fertile and fissile material are in a molten salt medium ($LiF+BeF_2+ThF_4$) which is constantly circulated outside the blanket and the U^{233} and tritium extracted. Helium cools the blanket, including the steel tubes containing the molten salt, by circulating through the beryllium pebble bed. Austenitic steel structure is used for ease of fabrication, adequate irradiation lifetime, and low corrosion rate by molten salts.

The molten fluoride salt is stable to both thermal and radiation decomposition because of the speed of recombination. Corrosion rates of iron-based alloys are low when the salt is maintained in a reducing state. This salt is similar to one used in an experimental fission reactor at Oak Ridge National Laboratory. It operates at relatively low pressure but high temperature - its melting point is 530°C. Helium is used as coolant for safety and compatibility with the other materials. It is operated at higher than 5 MPa pressure in order to have adequate heat capacity.

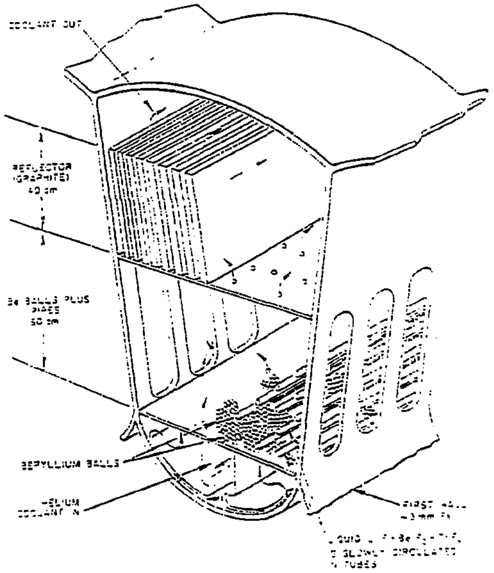

FIGURE 4: HELIUM-COOLED MOLTEN-SALT BLANKET FOR FISSILE FUEL PRODUCTION

The blanket has a small amount of lithium breeder present in the molten salt, but the large amount of multiplier allows sufficient tritium breeding (but little margin). Beryllium swells at modest fluences, so a pebble bed geometry is used to minimize stresses, add porosity, and simplify pebble replacement.

The tritium will be present in the molten salt as T_2 gas, which will permeate readily through the hot steel walls. Tritium removal from the helium will be necessary because of this tritium and that generated in the beryllium. Permeation barriers will probably be needed for the steam generator, and possibly on the molten salt tubes.

Energy recovery from the helium can take advantage of direct gas turbine cycles, or by steam-generators using state-of-the-art technology. The ^{233}U produced is estimated to be worth the equivalent of about $60/kg of U_3O_8. One 3000 MWth fusion device could supply 40 GWe of CANDU reactors at a capital cost of 2-3 times that of a 3000 MWth fission reactor.

ADVANCED ENERGY CONVERSION BLANKET CONCEPTS

One of the features of fusion is the very high quality energy available from the reaction in the form of energetic neutrons, short-wavelength radiation, and plasma kinetic energy. In some devices, escaping plasma kinetic energy can be directly recovered through direct electrical converters at efficiencies of 60% for simple grid systems.

In the blanket, most of the energy flux is in the form of neutrons and short-wavelength radiation that are not normally converted into electricity other than through Carnot-limited thermal power cycles. Recently, concepts have been proposed for recovering this energy as electricity at higher efficiencies (8).

One approach is the radiation-enhanced MHD blanket. Conventional non-fusion MHD electric power concepts based on coal, for example, suffered from several drawbacks that have limited commercial interest in the technology. In particular, the large magnets are expensive, and the hot gases were not sufficiently conducting. In fusion, large and efficient superconducting magnets have been developed, built and tested. Such magnets are required to maintain the basic fusion reaction in many confinement systems. Consequently, large volumes of high magnetic field are available in the blanket at small additional cost. A liquid metal vapor can be generated through the neutron thermal energy. Then, by appropriate design, radiolysis of the vapor species by incident synchrotron or X-ray radiation may make the vapor sufficiently conducting to support efficient electrical power generation. This could be arranged by passing the vapor through low Z structural regions near the first wall (for X-ray transmission) or by passing the incident synchrotron radiation through waveguides around the breeding blanket and then into the vapor. These concepts, although in a very early stage, could entirely eliminate the conventional heat transport and turbine-generator systems.

SUMMARY

There are many possible blanket concepts. The apparent wide range of options is important since blanket technology is in its infancy. Thus, the range of potential ideas makes it probably that at least once concept will prove commercially viable for each application. Indeed, there are many concepts that are probably feasible, and it is perhaps a question of determining which are the most attractive. Attention is turning to blanket development in anticipation of their use in next-generation devices. This initial data will help to screen out the concepts and focus the effort.

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