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BLANKET MATERIALS FOR DT FUSION REACTORS

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This paper presents an overview of the critical materials issues that must be considered in the development of a tritium breeding blanket for a tokamak fusion reactor that operates on the D-T-Li fuel cycle. The primary requirements of the blanket system are identified and the important criteria that must be considered in the development of blanket technology are summarized. The candidate materials are listed for the different blanket components, e.g., breeder, coolant, structure and neutron multiplier. Three blanket concepts that appear to offer the most potential are: (1) liquid-metal breeder/coolant, (2) liquid-metal breeder/separate coolant and (3) solid breeder/separate coolant. The major uncertainties associated with each of the design concepts are discussed and the key materials R&D requirements for each concept are identified.

INTRODUCTION

Development of a viable blanket system is essential before the feasibility of fusion as a commercial energy source can be established. Recent fusion reactor design studies [1-15] have defined a number of critical materials and technological problems related to the blanket system. Although many of these problems are generic, to all fusion concepts, the present discussion will focus on those problems specific to an electricity generating tokamak reactor that operates on the D-T-L fuel cycle. The primary functions of the blanket system for this type of reactor are to convert the fusion energy into sensible heat and to breed tritium for the fuel cycle.

The importance of near-term blanket development is due partially to the recognition that breeding tritium in the next generation reactors (after TFTR) may be necessary to supply the tritium needed for projected operating scenerios. Possibly more importantly, near-term blanket development is vital because of the impact on materials research and development requirements. The blanket problems are quite complex since different components such as the breeder, coolant and structure must operate for extended lifetimes at high temperature while exposed to severe radiation and chemical environments. Since solutions to critical blanket problems may be obtained by a combination of design options and by materials selection, the blanket design requires an integrated materials approach. One must identify a compatible combination of materials. This infers not only chemical compatibility but also compatible operating performance. For example, the structural material must maintain acceptable mechanical properties or radiation damage resistance at temperatures appropriate for satisfactory heat recovery from the coolant. The structure in a helium-cooled system would operate at a significantly higher temperature than for a water-cooled system. Numerous tradeoffs are involved in the materials selection process. What may appear to be individually the best structural material or coolant may not produce the most attractive integrated system.

The following sections present a list of the requirements of a tritium breeding blanket, the candidate materials most often considered in the design studies and what are generally considered to be the most viable blanket concepts. The major uncertainties with each of the design concepts are discussed and the key materials R & D requirements for each concept are identified.

BLANKET REQUIREMENTS

The blanket system of a fusion reactor must serve several functions. The key to blanket development is to define a compatible combination of materials that can be integrated into a functional design that will best provide these functions. The primary requirements of the blanket system are to provide for:

- adequate tritium production
- acceptable tritium recovery
- efficient heat recovery
- acceptable lifetime

Important criteria that must be considered in the development of blanket technology include:

- fabricability
- environmental acceptability
- materials availability and cost
- maintainability
- reliability

The blanket system consists of several components which include the following types of materials.

- Tritium Breeder
- Coolant
- Structure
- Neutron Multiplier (?)
- Tritium Recovery Fluid (?)
- Reflector/Moderator (?)
- Tritium Barrier (?)

All blanket concepts that have been proposed require lithium or a lithium bearing material for tritium breeding, a circulating coolant for heat removal and a structural material to contain and support the blanket system. In some design concepts, the same material, e.g., liquid lithium, may be used both as a breeder and coolant [1-3]. Some concepts require a neutron multiplier to provide for adequate tritium production [6]. In several concepts tritium is recovered from the recirculating coolant or liquid metal breeder material [1-3, 6-8]. For some solid breeder concepts, a separate tritium processing fluid is utilized for tritium recovery [6]. Reflectors or moderators have been proposed in some blanket designs to improve breeding performance or to reduce the lithium inventory [16]. Some concepts particularly water-cooled concepts, may require tritium barriers to minimize tritium permeation into the coolant [6,16].

Several candidate materials have been proposed for each of the components in the various blanket designs. Those most often suggested for the breeder, coolant, structure and neutron multiplier are listed in Table 1. The tritium recovery fluid most often suggested is low pressure (~0.1 MPa) helium if the coolant or breeder is not used. Water or graphite are most often suggested as reflector or moderator materials. The oxide that normally forms on steel pipe exposed to water or steam provides an effective tritium barrier.

CANDIDATE BLANKET CONCEPTS

Several different types of blanket concepts have been proposed or evaluated in the many design studies that have been conducted. Of these, three concepts that are considered to offer the most potential are described as:

- Liquid Metal Breeder/Coolant
- Liquid Metal Breeder/Separate Coolant
- Solid Breeder/Separate Coolant

Table 2 summarizes the blanket components required for these candidate concepts. Liquid lithium as both breeder and coolant has long been considered an attractive blanket concept. Since lithium appears to be the only element from which acceptable tritium breeding can be achieved, this fact and the attractive heat transfer characteristics of lithium provide a unique option. From both a materials point of view and from design considerations this provides an attractive option because of the simplicity of the system which requires only two materials, viz., structure and lithium. Several structural material options may be feasible. It is conceivable that liquid lithium alloys could also be used for this concept.

The liquid metal breeder/separate coolant concept requires three materials in the system, viz., breeder, coolant and structure. Therefore, additional issues such as breeder-coolant compatibility must be considered in this design. A liquid lithium breeder and water coolant, which are individually attractive breeder and coolant, respectively, probably cannot be used together in a blanket because of their high chemical reactivity. It is also questionable whether any of the liquid lithium alloys could be used in a water-cooled blanket. Also, the structure must be compatible with both the liquid metal breeder and the coolant. This requirement eliminates some otherwise potentially viable structural material candidates.

The solid breeder/separate coolant concept may require a neutron multiplier and separate tritium processing fluid as proposed in the STARFIRE design [6]. The added number of material components greatly increases the complexity of the chemical compatibility issues and the operating constraints. For example, the structure may have to be compatible not only with the coolant and breeder but with the neutron multiplier and tritium processing fluid as well. Additional constraints on the operating temperature may be imposed by the requirements for tritium recovery as indicated in the STARFIRE design. Although solid breeder/separate coolant concepts with fewer components have been proposed, e.g., those with Li_2O as the breeder or helium coolant as the tritium processing fluid [7,8], there are major unresolved problems associated with these concepts.

The primary candidate materials, the justification for their selection and the principle problem areas are discussed in the following subsections for the three blanket concepts.

Solid Breeder/Separate Coolant

The most comprehensive solid breeder blanket design to date was developed in the STARFIRE study [6]. The primary objectives were to define the operating limitations, materials & design

Table 1. CANDIDATE FIRST-WALL/BLANKET MATERIALS

Breeding Materials	Coolants	Structure	Neutron Multiplier
Liquid Metals	Water	First-Wall/Blanket	Solid
Li	H_2O	Austenitic Steel (SS)	Beryllium
Li-Pb	D_2O		Zr_5Pb_3
Li-Pb-Bi	Liquid Metals	Ferritic Steels (FS)	Pb
Intermetallic Compounds	Li	Nickel-base alloys	Zr
Li_7Pb_2	Li-Pb	Vanadium base Alloys	Liquid
Ceramics	Li-Pb-Bi	Limiter/Divertor	Pb
Li_2O	Gases	Vanadium alloys	Bi
$LiAlO_2$	He	Niobium	Pb-Bi
Li_2SiO_3	Steam	Tantalum	
Li_4SiO_4		Tungsten	
Li_2ZrO_3		Molybdenum	
		Copper	

Table 2. MOST VIABLE CANDIDATE BLANKET CONCEPTS

	SOLID BREEDER/ SEPARATE COOLANT	LIQUID METAL BREEDER/ SEPARATE COOLANT	LIQUID METAL BREEDER/COOLANT
Proposed Designs	STARFIRE [6]	ORNL/WEC DEMO [11]	ANL B/S, UWMAK I & III [1-3]
Breeder	$LiAlO_2$, Li_2ZrO_3 (Li_2O ?)	Li-Pb/Bi (Li?)	Li (Li-Pb-Bi ?)
Coolant	H_2O, D_2O (He ?)	He	——
Structure	SS (V, FS ?)	FS (SS ?)	V, SS, FS
Neutron Multiplier	Be (Zr_5Pb_3, Pb ?)	——	——
Tritium Processing Fluid	He/T_2O	——	——

requirements, and uncertainties associated with a solid breeder blanket concept. A relative comparison with other concepts was not attempted. Figure 1 shows a schematic design of the STARFIRE blanket concept and Table 3 summarizes the primary candidate materials for the blanket system [17]. The general design concept consisted of a small grain size porous ceramic breeder material ($LiAlO_2$) contained in a stainless steel module. Water coolant passes through small (1 cm. dia.) stainless steel tubes interspersed in the breeder zone according to the nuclear heating. A neutron multiplier, either beryllium or the Zr_5Pb_3 compound, was contained in a water cooled cell located directly in front of the breeder region was provided to improve the breeding performance. Tritium recovery was accomplished by passing low pressure (~0.1 MPa) helium through 0.2 mm diameter channels within the breeder. Tritium generated within the $LiAlO_2$ grains will diffuse to the surface of the grain, migrate as T_2O through the interconnected grain boundary porosity, percolate through larger interconnected porosity provided by the small particles and convect outside the blanket with the helium purge stream.

The ternary ceramic compound $LiAlO_2$ is considered to be the leading candidate for a breeder primarily because of its greater chemical stability

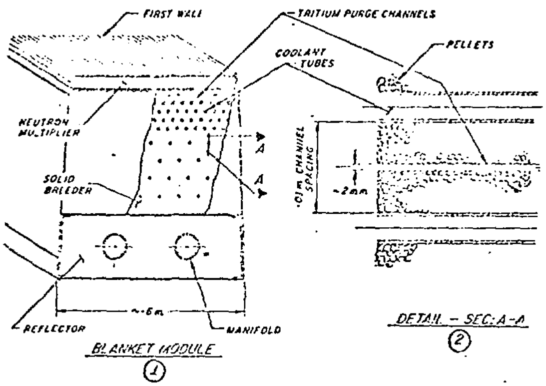

Fig. 1. Schematic diagram of solid breeder/separate coolant blanket concept [6].

and better compatibility with candidate structural materials and coolants. Although further development work is required on fabrication methods, the α-$LiAlO_2$ has the advantage of a higher density than the γ-phase and the α-$LiAlO_2$ is probably more stable under irradiation at the projected operating temperatures, i.e., less than the 930°C α→γ transformation temperature. The Li_2ZrO_3 is quite similar but it appears to have the disadvantage of an even lower thermal conductivity than $LiAlO_2$. The lithium silicates are generally considered to be less stable than the aluminate. The Li_2O is attractive because it appears to offer a potential for adequate tritium breeding without the need for a neutron multiplier. However, the feasibility of Li_2O as a breeding material is more questionable because of its stability in the chemical and radiation environment, poorer compatibility with structural materials and higher reactivity with water to form corrosive LiOH [17,20].

Primary questions regarding the feasibility of $LiAlO_2$ (and most other ceramic compounds) relate to marginal breeding potential and acceptable tritium recovery [6,17,20]. The ternary lithium ceramics all require an effective neutron multiplier and almost complete blanket coverage to provide the necessary breeding performance. The low thermal conductivity characteristics of these materials impacts both their breeding potential & tritium recovery. Acceptable tritium recovery is a key feasibility issue since adequate recovery has not been demonstrated for the high

Table 3. SUMMARY OF KEY CONSIDERATIONS FOR THE SELECTION AND PRIMARY FEASIBILITY ISSUES OF CANDIDATE MATERIALS FOR THE SOLID BREEDER/SEPARATE COOLANT BLANKET CONCEPT.

COMPONENT	KEY CONSIDERATIONS	PRIMARY FEASIBILITY ISSUES
Breeder $LiAlO_2$, Li_2ZrO_3	Tritium Recovery Chemical Stability Compatibility/Structure & Coolant	Low Thermal Conductivity Breeding Potential Tritium Recovery
Coolant H_2O	Operating Temperature (Structure/Breeder)	Tritium Permeation Leakage into Breeder
Structure Aust SS	Data Base Fabricability	Thermal Stresses Radiation Embrittlement
Neutron Mult. Be	Neutron/Energy Mult. Low Density, High Conduct.	Availability Toxicity
Pb	Neutron Mult.	Compatibility/Structure High Density
T Processing Fluid He/T_2O	T Recovery	Li Transport

fluence conditions anticipated in a commercial reactor.

Compared to helium, water coolant offers advantages as a coolant for this concept because of the lower coolant temperature. The limited operating temperature ranges projected for satisfactory tritium recovery from the solid breeders do not appear attainable with the relatively large ΔT (>200°C) desired for a helium system. Other major concerns with helium relate to the difficulty of containment of high pressure helium in the complex geometry and adequate tritium breeding in the blanket geometries required for acceptable pumping power and first-wall heat load capability. If liquid metals are to be used as the coolant, one would most likely use liquid metals for the breeder material also.

The major feasibility issue regarding water coolant relates to the potential for tritium permeation into the coolant, particularly through the first wall. The oxide film characteristic of a water-steel interface is a fairly effective barrier. Detailed analyses are required to evaluate this problem for specific designs and operating conditions. Pressure transients produced by leakage of high-pressure water into the porous, high-temperature ceramic breeder region is an important safety concern. Also, damage produced by the formation of corrosive LiOH could be serious for the case of an Li_2O breeder.

Austenitic stainless steel appears to be the most appropriate structural material for this concept because of its more extensive data base, good fabricability and acceptable radiation damage resistance at the projected operating temperatures for water coolant. Since the lifetime of the solid breeder is limited because of lithium burnup, structure lifetimes in excess of ~15-20 MW·y/m^2 are less important. Coolant chemistry must be carefully controlled to avoid stress-corrosion cracking problems. Ferritic steels could be used providing the magnetic effects are not prohibitive and other concerns such as fabricability problems and increases in the DBTT caused by radiation are satisfactorily resolved. Use of vanadium-base alloys might be feasible if the oxidation rates can be satisfactorily controlled at the relatively low operating temperatures.

Development of an acceptable neutron multiplier is a key feasibility issue for the solid breeder concept. Beryllium appears to be the most favorable option because of its excellent neutron and energy multiplication characteristic, its low density, high thermal conductivity, high heat capacity and low activation. Questions posed regarding the use of beryllium relate primarily to toxicity and availability. Since one must deal with activated material and tritium, the added constraints imposed by the toxicity problem do not appear to be excessive. Procedures have been developed for handling beryllium. Analyses indicate that for 10^5 MWe generating capacity (~100 reactors with 30 year life), the total beryllium burnup would be less than 1% of the U.S. resources. Reprocessing of beryllium appears feasible. Lead provides good neutron multiplication; however, because of its low melting temperature (327°C) it would most likely operate in the liquid state. Therefore compatibility with the structure is an important issue. It is questionable whether austenitic steel can be used to contain liquid lead unless some type of inhibitor or barrier proves successful. Ferritic steels are generally more compatible with lead than the austenitic steels. A lead compound, Zr_5Pb_3, with a higher melting temperature (~1400°C) was considered in the STARFIRE study. The neutron multiplication of this material is marginal and the data base is very limited.

The tritium recovery scenerio proposed in the STARFIRE study is generally considered to be the best option. Further development is required to prove the feasibility and optimize the design and performance characteristics. Important concerns relate to possible lithium transport in the processing stream, possibly as LiOT, and the compatibility problems in the breeder/processing fluid/structure system.

Liquid Metal Breeder/Separate Coolant

The ORNL/WEC demonstration reactor design study provides an excellent analysis of the design characteristics and materials options that must be considered for a liquid metal breeder/separate coolant concept [11]. Figure 2 is a schematic diagram of this design. As indicated in Table 4, only three components are necessary. An important characteristic of this type of design is the large number of small modules required to contain the high pressure coolant. This requirement results in a relatively large amount of structure in the blanket and limited breeder coverage because of the void between modules. In this concept, breeding in the inner blanket region appears essential. The key considerations in the selection of primary candidate materials and the important feasibility questions for this concept are summarized in Table 4.

Although the ORNL/WEC design proposed lithium as the breeder, lithium-lead or lithium-lead-bismuth may be more appropriate candidates in this concept. They provide excellent breeding potential because of the neutron multiplication in the lead and bismuth and the chemical reactivity of these alloys is less than that for lithium. Important feasibility questions regarding the use of Li-Pb or Li-Pb-Bi relate to tritium recovery and compatibility. Viable tritium recovery scenerios for these lithium alloy breeders are yet to be developed. Because of the low solubility of tritium in the Li-Pb alloy, either large volumes of liquid metal must

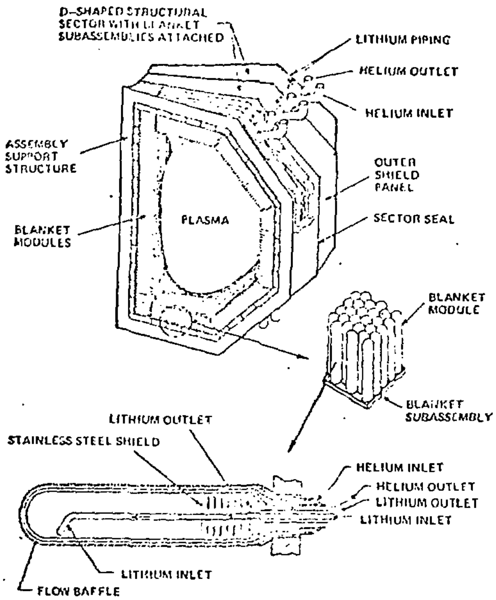

Fig. 2. Schematic diagram of liquid metal breeder/separate coolant blanket concept [11].

be processed or the tritium pressure in the liquid metal must be maintained at much higher levels than typically considered for lithium. The higher tritium pressures create more difficulties in tritium containment. Further analyses are required to evaluate the feasibility of tritium recovery from the coolant after permeation through the structure. The impact of an oxide film (barrier) at the coolant-structure interface will be an important consideration. Since the Li-Pb (or Li-Pb-Bi) alloys are generally more corrosive than lithium, compatibility with the structural containment is an important feasibility issue.

This concept appears to be the most reasonable blanket concept for helium coolant. The excellent breeding performance of the Li-Pb compensates for the high structure fraction and void fraction inherent in this design concept. Also, helium does not chemically react with the breeder. However, as indicated in the ORNL/WEC design, the module must be designed so that leakage of high pressure helium into the breeder region will not rupture the module [11].

The major feasibility issues regarding the use of helium in this concept relate to the containment of helium and designing for efficient heat recovery. Containment of high pressure helium in approximately 100,000 modules with an equivalent number of welds is an important feasibility issue. Since helium generation in the plasma is only a few hundred grams per day, leakage rates of this order of magnitude into the plasma chamber would greatly impact the plasma impurity control and vacuum systems. The minimum blanket outlet temperature for efficient energy conversion with helium is of the order of 450-500°C. As a result, compatibility of the breeder with the structure will be critical at these temperatures.

Water is probably not an acceptable coolant with liquid metal breeders. Although the chemical reactivity of the Li-Pb alloy with water is much less than that of liquid lithium, leakage of high pressure (~12 MPa) water into hot (~500°C) liquid metal could possibly produce both chemical reaction and vapor explosions. Experiments conducted by Finn et al. [21] indicate vapor explosions under certain conditions and no detonation under different conditions. Since all of these tests have been conducted under conditions much different than those of interest in a reactor blanket, further work is required to resolve this issue.

Table 4. SUMMARY OF KEY CONSIDERATIONS FOR THE SELECTION AND PRIMARY FEASIBILITY ISSUES OF CANDIDATE MATERIALS FOR THE LIQUID METAL BREEDER/SEPARATE COOLANT BLANKET CONCEPT.

COMPONENT	KEY CONSIDERATIONS	PRIMARY FEASIBILITY ISSUES
Breeder Li-Pb, Li-Pb-Bi	Breeding Potential *Chemical Reactivity*	Compatibility/Structure *Tritium Recovery (Containment)* Breeder Stability
Coolant He	Compatibility/Breeder	Efficient Heat Recovery Containment (Plasma Chamber)
Structure Ferr. St.	Compatibility/Breeder Low Swelling	Magnetic Properties Fabricability DBTT (Radiation) Compatibility/Breeder

Ferritic steels may be the best structural material for this concept because of better compatibility with the Li-Pb than the austenitic steels. Because of the high solubility of nickel in both lithium and lead, the austenitic steels are probably not acceptable for containment of Li-Pb at the temperatures of interest unless some type of reliable corrosion barrier can be developed. The refractory metals are generally not compatible with helium that contains impurities at levels characteristic of large heat-transfer systems.

Critical feasibility issues related to the use of ferritic steels in fusion reactor blankets relate to their magnetic properties, fabrication difficulties and radiation embrittlement. The impact of a ferritic steel blanket on plasma performance has not been assessed. The importance of magnetic forces on the blanket support also requires further analysis before the feasibility of using ferritic steels can be established. Welding difficulties associated with the characteristic requirements for preweld and postweld heat treatment of ferritic steels are an important feasibility issue. Further development is required to demonstrate the capability of producing highly reliable welds under conditions of interest. Even though the ferritic steels tend to show better corrosion resistance to lead and Li-Pb than austenitic steels, further investigations are required to define the operating limitations.

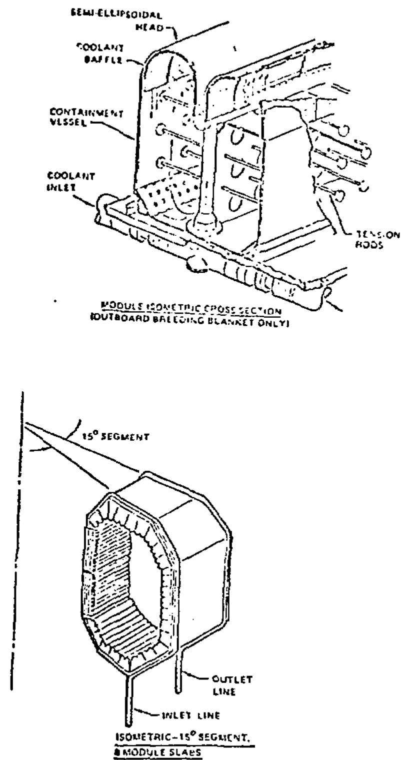

Fig. 3. Schematic diagram of liquid metal *breeder/coolant concept* [1].

Liquid Metal Breeder/Coolant

Liquid lithium offers several potential advantages relative to other options for the breeder/coolant application. Early recognition of this fact has led to several proposed blanket concepts that take advantage of the inherent simplicity resulting from this dual role [1-3]. As example, Figure 3 is a schematic diagram of a blanket concept that typifies the many designs. In these relatively simple designs, the lithium is contained in large modules with a low structure fraction and a minimum weld requirement, which translates to higher reliability. Most of the fusion energy is deposited in the coolant (breeder) by the high energy neutrons. Because of the excellent heat-transfer properties and the low operating pressure, the wall of the module can accept the high surface heat flux from the plasma and serve as the first wall. The ANL concept, which utilizes a vanadium alloy structure to attain long blanket life, high efficiency (temperature) operation, and low long-term residual radioactivity, is used as a basis for evaluating the characteristics of blanket concepts with lithium as the breeder/coolant. A more detailed analysis of the design features is presented in References 1, 22 and 23.

As summarized in Table 5, lithium possesses several favorable properties for the combined breeder/coolant application. Lithium provides adequate breeding performance, low activation and possesses excellent physical properties for the dual application. Also, the feasibility of tritium recovery has been demonstrated and compatibility with certain structural materials appears acceptable.

Many design studies have indicated that adequate tritium breeding can be achieved with liquid lithium as the breeder/coolant, possibly without breeding in the inner blanket region [1]. This latter potential has both economic and reactor maintenance advantages. The good breeding performance is partially the result of the simple blanket design which requires a relatively low structure fraction. The low structure fraction required plus the fact that lithium produces no activation products except for tritium, potentially permits the development of a low-activation blanket. Lithium also produces no after heat problem.

Lithium is an excellent heat transfer fluid because of its high thermal conductivity, high

Table 5. SUMMARY OF KEY CONSIDERATIONS FOR THE SELECTION AND PRIMARY FEASIBILITY ISSUES OF CANDIDATE MATERIALS FOR THE LIQUID METAL BREEDER/COOLANT BLANKET CONCEPT

COMPONENT	KEY CONSIDERATIONS	PRIMARY FEASIBILITY ISSUES
Breeder/Coolant Li	Physical Properties (K, C, ρ) Breeding Performance Tritium Recovery Low Activation/Afterheat	MHD Effects Safety Compatibility/Structure
Structure		
V-Alloy	Compatibility/Li Radiation Effects Mechanical Properties Low Activation	Fabricability Compatibility/Environment Limited Data Base
Aust. SS	Fabricability Compatibility/Air Data Base	Compatibility/Li Thermal Loading

heat capacity and low density. The high heat capacity and low density tend to minimize pumping requirements. The low density, which is about a factor of 20 less than that for the 17% Li-83% Pb alloy, minimizes the total blanket weight. The high heat capacity and thermal conductivity tend to effectively accommodate transient and after heat problems that could occur during off-normal conditions.

Methods for tritium recovery from lithium have been demonstrated in principle. Three methods that are potentially applicable include: trapping in solid getters such as yttrium, [24], molten salt extraction[25], and trapping in a secondary fluid after permeation through a membrane[26]. It is generally believed that tritium concentrations in lithium can be maintained at 1 wppm or less. Further development is required to demonstrate which of these methods are most favorable for large-scale commercial systems.

The major concerns regarding the use of lithium relate to the MHD effects resulting from a moving conductor in a magnetic field, the chemical reactivity of lithium with water and air, and compatibility with the structure. Three problems caused by interactions with the high magnetic field are (1) higher hydraulic pressures in the lithium, (2) increased pumping power requirements, and (3) reduced heat-transfer efficiency caused by laminar flow characteristics produced by a magnetic field. Relatively well developed analyses indicate that the pressure drop of a conducting fluid flowing perpendicular to a magnetic field is a function of the magnetic field ($\sim B^2$), the velocity of the fluid, the channel geometry, and the physical properties of the fluid and channel structure. General design solutions, therefore, involve minimizing flow velocity as much as possible, flowing parallel to the magnetic field when possible, and placing manifolds in the lowest flux regions possible. Of the six tokamak reactor blanket concepts reviewed in Ref. 1, all concluded that the pumping power could be maintained less than 1% of the total reactor thermal power. The major contributions to the pressure drop were in the manifolds and inner blanket region. Recent investigations by Dunn [27] have indicated that measured pressure drops were less than those calculated and the trend of the deviation becomes greater with increasing field up to ∿ 1 Tesla. Extrapolations of these data would indicate lower pressure drops than those predicted in the previous designs. The MHD effects are also known to be dependent on channel geometry, at least at fields less than 1 Tesla. General inefficiencies obtained with liquid metal electromagnetic pumps [29] and MHD channels [28], both of which attempt to optimize the magnetic interaction, tend to provide further practical support that the calculated pressure drops and resulting pumping power requirements for tokamak reactor blankets are conservative, i.e., too high. Of these effects, the increased pressure in the module is of greatest concern. The maximum hydraulic pressures in the reference blanket design are predicted to be < 2 MPa, or a factor of 3-6 less than required for helium and water coolants [1]. The effects of laminar flow induced in lithium by the magnetic fields are not of great concern because of the high thermal conductivity of lithium and the fact that most of the neutron energy is deposited directly in the lithium. In addition, changes in the smaller poloidal magnetic fields will probably induce eddy currents in flow channels parallel to the toroidal field.

The reactivity of lithium with water, air, or concrete is a major concern in the design of liquid lithium blankets. These reactions will occur only during accident conditions. One proposed solution is to eliminate water from the reactor system and use a less reactive organic coolant in the shield, conventional magnets and other systems in close proximity to the reactor. In either case, a double or possibly a triple barrier between lithium and the low temperature (water or organic) coolant can easily be maintained at modest economic penalty if a design similar to the STARFIRE [6] design is used. The blanket region itself is considered to be by far the region with the highest probability of a lithium leak. A leak in this region should not present a significant hazard since the other materials inside the vacuum wall shield are not highly reactive with lithium and the environment is basically vacuum. A metal cover on any concrete, which may be necessary for tritium control, would provide a third barrier for control of a lithium-concrete reaction.

Acceptable compatibility with the structure is an important consideration. As discussed below, compatibility considerations will limit the selection of candidate structural materials.

Two types of structural alloys are generally considered for the lithium breeder/coolant blanket concept. Design studies have concluded that selected vanadium-base alloys, in particular the V-Cr-Ti alloys potentially offer the best combination of properties for the structural material in this concept [1,22,23[. Austenitic steels may be a viable candidate for limited temperature operation if a satisfactory corrosion barrier can be developed. The vanadium base alloys are among the most corrosion resistant materials in high purity lithium. The relatively high thermal conductivity and low thermal expansion provides for much lower thermal stresses than do the austenstic steels. Limited data indicate excellent tensile and fatigue properties at temperatures up to ~650°C [30]. Although data are also limited on the effects of radiation, the body-centered-cubic vanadium-base alloys appear to be highly radiation damage resistant. Both ion and neutron irradiation studies indicate good swelling resistance. Some loss of ductility has been observed, however, the residual ductility is higher than most other materials at temperatures and fluences of interest. The helium generation rate in vanadium during exposure to 14 MeV neutrons is about a factor of three less than that for Type 316 stainless steel. The residual activation and after heat dissipate much more rapidly than for stainless steel. Therefore, it may be feasible to recycle the vanadium alloys after about 30 yrs.

The major concerns regarding the use of vanadium-base alloys relate to fabricability, compatibility with the environment (oxidation resistance) and the limited data base. Few results on fabrication and welding of vanadium alloys have been reported. A considerable amount of vanadium alloy cladding was fabricated early in the LMFBR program. Small corrosion test loops have been fabricated from vanadium alloys and some test welds have been conducted [31]. Preliminary scoping studies of the microstructures and toughness of welds were particularly optimistic for the V-Cr-Ti system. Welding must be conducted in an inert atmosphere. Although further work must be conducted on fabrication and welding of vanadium alloys, preliminary results indicate the problem is more one of lack of effort than extreme difficulty as in the case of molybdenum. Weld properties may indeed influence the selection of optimum alloys.

Vanadium will oxidize readily in air at elevated temperatures. The effect of alloying on the oxidation rate has not been investigated in detail. The blanket design studies indicate that the vanadium can be protected from air during normal operation. Further studies are required to investigate the effects during potential off-normal conditions.

The general lack of a data base for vanadium-base alloys is a major concern. Because of the many apparent favorable characteristics of vanadium alloys, further development work should be conducted. Since most of the feasibility issues relate to non-irradiation problems, these should be addressed initially.

A second important advantage of the liquid metal breeder/coolant concept relates to the greater flexibility in the selection of structural materials than most other concepts because of the reduced blanket complexity. Austenitic steels must also be considered as a candidate structural material because of ease of fabrication, extensive and generally favorable data base, and compatibility with air. These factors are generally applicable to all blanket concepts and have been discussed earlier. The major questions regarding the viability of austenitic steel relate to limited compatibility with lithium and the relatively poor physical properties that potentially result in high thermal stresses. The corrosion rate of austenitic stainless steel in flowing lithium appears to be excessive unless some type of corrosion barrier is developed. The aluminized coating, which has been investigated, may be acceptable [32,33]. The impact of this coating under reactor conditions will require further analysis. Coatings are generally not attractive solutions to corrosion problems if conditions exist where loss of coating integrity can lead to enhanced localized attack.

CONCLUSIONS AND SUMMARY

Design studies which have been conducted indicate that several blanket design options for fusion reactor applications may be feasible. These studies have also identified which combinations of materials appear to offer the most potential for acceptable blanket operation on the basis of existing materials properties data. Three tritium-breeding blanket concepts that are regarded as the most viable include: (1) solid breeder/separate coolant, (2) liquid metal breeder/separate coolant, and (3) liquid metal breeder/coolant.

The key feasibility questions for each of these concepts are summarized in Table 6. These issues provide the basis for establishing a cost-effective program for the development of a tritium-breeding blanket. For the case of the solid breeder/separate coolant concept tritium recovery from solid breeders is the key feasibility issue. The ceramic oxides, in particular selected ternary oxides, appear to offer the most potential for acceptable tritium recovery. The primary problems relate to chemical stability of the breeder in the tritium processing fluid, potential effects of radiation such as sintering and tritium trapping on the tritium release kinetics, and control of the temperature of the low thermal conductivity breeder within limits required for tritium release. The feasibility of water coolant may depend on acceptable tritium permeation rates through the first wall. The major effect relates to the energetic tritium injected into the surface of the first wall. Unless Li_2O can be used as the breeder material selection and integration of an acceptable neutron multiplier into the blanket is required for a viable solid breeder blanket concept. Although several candidate neutron multipliers have been proposed, the operating limitations have not been satisfactorily defined.

For the leading liquid metal breeder/separate coolant concept, adequate containment of helium coolant in the complex blanket geometry is an important feasibility issue. A second important question is the identification of a structural material that is compatible with both coolant and breeder at temperatures appropriate for helium-cooled systems. Major concerns relate to stress-corrosion effects. At present, an acceptable tritium recovery scenerio has not been developed for the liquid Li-Pb breeder system. Important concerns relate to tradeoffs between relatively high tritium inventories and difficulties of tritium containment at high partial pressures.

The major feasibility question related to the lithium breeder/coolant concept involves demonstration of acceptable MHD performance. The allowable pressure is of most concern. The important safety issue for this concept involves isolating the lithium from water. The impact of this isolation on the design requires further development. The acceptable performance of vanadium alloys or acceptable compatibility of austenitic stainless steel with lithium must be demonstrated. The complexities associated with a liquid metal system must be evaluated. Of particular concern is the acceptability of liquid metal pumps.

A major materials R&D effort is required to provide a basis for evaluating the viability of the candidate blanket concepts. However, focusing on the key issues as defined by the blanket design studies should tend to minimize the effort required.

Table 6. KEY FEASIBILITY QUESTIONS FOR CANDIDATE BLANKET CONCEPTS

SOLID BREEDER/SEPARATE COOLANT

- Tritium Recovery from Breeder
  - Effect of Radiation
  - Thermal Conductivity
  - Chemical Stability (HE/T_2O)
- Tritium Permeation into H_2O (First Wall)
- Acceptable Neutron Multiplier

LIQUID METAL BREEDER/SEPARATE COOLANT

- Tritium Recovery Scenerio
- Compatible Structure (High T)
- Adequate Helium Containment

LIQUID METAL BREEDER/COOLANT

- Acceptable MHD Design
- Safe Design (Isolate H_2O)
- Liquid Metal System

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