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Materials integration issues for high performance fusion power systems [1]

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Abstract

One of the primary requirements for the development of fusion as an energy source is the qualification of materials for the first-wall/blanket system that will provide high performance and exhibit favourable safety and environmental features. Both economic competitiveness and the environmental attractiveness of fusion will be strongly influenced by the materials constraints. A key aspect is the development of a compatible combination of materials for the various functions of structure, tritium breeding, coolant, neutron multiplication and other special requirements for a specific system. This paper presents an overview of key materials integration issues for high performance fusion power systems. Issues such as: chemical compatibility of structure and coolant, hydrogen/tritium interactions with the plasma facing/structure/breeder materials, thermomechanical constraints associated with coolant/structure, thermal-hydraulic requirements, and safety/environmental considerations from a systems viewpoint are presented. The major materials interactions for leading blanket concepts are discussed.

1. Introduction

There are two primary requirements for the development of fusion into a viable energy source. First, it must be economically competitive and second, it must have public acceptance. Decisions regarding the viability of fusion energy will depend on the alternatives and competition for energy generation, and the risk associated with the implementation of a new technology. It is widely recognized that fusion offers a potential for significant safety and environmental advantages as an energy source. However, it is generally concluded that it will be a major challenge to make fusion energy economically competitive. It is also clear that the first-wall/blanket system will have a dominant impact on both the economic and the safety/environmental issues. Since most of the fusion energy is recovered in this system, it will operate at the highest temperature and will be exposed to the highest radiation levels.

Design studies [1–9], including safety and environmental analyses, provide a basis for analysis, evaluation of the potential, comparision of concepts performance, and identification of R&D priorities. These studies indicate that fusion energy involves high technology and that it will have a high capital cost. This requires that the fusion energy system must have high performance to be economically competitive. It is also recognized that materials limitations pose a primary constraint to the achievement of high performance, since materials for the first-wall/blanket system must operate in a highly complex and very demanding environment.

In addition to the high performance requirements of the fusion system, it is important to utilize "low activation" materials in the first-wall/blanket system in order to achieve the ultimate safety and environmental advantages of fusion. The products of the deuterium–tritium (D–T) fusion reaction are helium, which is environmentally benign, and an energetic neutron, which is needed to react with lithium to breed tritium for the fuel cycle. Therefore, if materials for the in-vessel systems, viz., first-wall/blanket, shield, divertor, and auxiliary heating systems, can be constructed of materials that do not produce hazardous isotopes, the attractive features of fusion can be realized.

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Therefore, integration of a compatible combination of materials for the nuclear system that provides high performance with attractive safety and environmental features is one of the keys to the successful development of fusion as a viable energy source.

2. Candidate materials and systems

The materials requirements for a fusion power system are very complex and highly demanding. Only a limited number of materials for each application, e.g., structure, breeding, cooling, etc., appear to offer a potential to meet even the minimum requirements. In most cases system performance and the safety/environmental attractiveness of fusion will be limited or significantly influenced by the materials constraints. There are no ideal materials for any application but there are candidate materials that exhibit desirable properties. Table 1 lists the materials considered as leading candidates for each application, viz., structural materials, tritium breeding materials, coolants, neutron multipliers, plasma facing materials and special purpose materials, in a fusion power core. Most of the materials listed in the table exhibit low activation characteristics. The compositions of the structural materials are specified such as to maintain low long-term activation properties.

Table 2 lists the blanket concepts, in terms of materials combinations, for the breeder, coolant, structure and neutron multiplier, that are currently considered among the international fusion community to be the leading concepts [2–8]. Some materials can serve multifunctions, e.g., lithium, PbLi and Flibe can all serve as breeder, coolant and neutron multiplier as well as the tritium recovery processing fluid.

Three types of materials integration issues must be considered in selecting materials for a high performance system. The first type involves the complex or conflicting requirements for specific candidate materials. An example is the pressure tradeoff for helium coolant. Higher pressure provides for improved heat transfer and a possibility for higher performance; however, higher pressure presents additional safety concerns and structure lifetime limitations. Similarly, higher performance may be obtained by operating the structure at higher temperature; however, the strength properties of structural materials typically decrease with increasing temperature, which may impose more restrictive surface heat flux and lifetime limitations. A second type involves materials integration issues within the first-wall/blanket system. Examples of such issues include structure temperature limits imposed by coolant corrosion constraints, or coolant pressure which translates to stress limitations. Additional materials integration issues arise from potential interactions with other systems. For example, chemical reactivity considerations may preclude the use of water coolant for the divertor because of potential reaction with candidate plasma facing materials on the first wall or liquid metal coolants in the first-wall/blanket.

Table 3 is a list of specific materials integration issues that are primary factors in the evaluation of the feasibility, performance limits and safety/environmental attractiveness of the various concepts. Preliminary evaluations of these issues for leading candidate first-wall/blanket systems are discussed in later sections.

3. Criteria and performance goals

Key criteria have generally been defined both for high performance systems, and for safety and environmental issues. The key criteria for high performance systems involve high power conversion efficiency, high

Table 1
Primary candidate materials considered for the first-wall blanket system of a fusion power system

Structure materials	Tritium breeding materials	Coolant	Neutron multiplier	Plasma facing materials	Other materials
Vanadium alloys	Lithium	Li	Be	Be	T-Barriers
Ferritic steels	Pb–Li	He	Pb	C	Insulator coatings
SiC/SiC	Li–Ceramic	H_2O	Li	W	Insulator ceramics
	Flibe	Flibe		Structural materials	He/Corrosion barriers

Table 2
Blanket concepts currently being evaluated or recently proposed [(Breeder/Coolant/Structure/Neutron Multiplier (NM))]

Leading concepts	
Li–Ceramic/He/FS/Be	He purge for T-Recovery
Li/V	Li serves as Breeder/Coolant/NM and for T-Recovery
PbLi/H_2O/FS	PbLi serves as Breeder/NM and for T-Recovery
Li–Ceramic/H_2O/FS/BE	He purge for T-Recovery

Table 3
Material integration issues for a high performance fusion first-wall blanket system

Neutron wall load and surface heat flux limits
High power conversion efficiency
Neutronic effects including tritium breeding and nuclear transmutations
Electromagnetic effects
Environmental and safety considerations
Hydrogen (tritium) interactions including tritium inventory and containment
Coolant pressure and hermeticity considerations
Chemical compatibility and corrosion/mass transfer
Special materials requirements such as insulator coatings and tritium barriers
System reliability

wall load capability, reliability for a high availability factor, and long component lifetime. High power conversion efficiency generally relates to higher operating temperatures with an adequate system ΔT. The higher wall load capability permits higher power density which translates to smaller lower-cost devices. Reliability is more difficult to quantify but can generally be related to design simplicity and design margin for the materials and/or system. A long component lifetime will minimize scheduled maintenance downtime and typically tends to reduce unscheduled maintenance requirements. Safety criteria can be characterized by normal operating emissions, accidental release issues and waste management issues. Normal operating emissions include primarily tritium and radioactive isotope release during normal operation. Accidental release includes tritium, radioactive isotope and chemical toxicity releases during off-normal events. The waste management criteria involve long-term radioactive material disposal and material recycle considerations.

Suggested performance goals for an advanced fusion energy system given in Table 4 are based on US estimates which were derived primarily for a tokamak configuration but are assumed to be generic to magnetic confinement fusion devices [10]. Minimum values represent the minimum acceptable performance parameters while the Goal values are representative of a high performance system.

4. Design performance limits

Design performance limits for the various materials integration issues listed in Table 3 are predicted based on available materials properties data, design criteria and currently used design analyses. The primary objective of these analyses is to identify the primary constraints for the various systems and to identify critical R&D that will provide more precise definition of these constraints.

4.1. Surface heat flux limits

Several factors must be considered to define surface heat flux limits for candidate first-wall materials. One factor is simply the acceptable operating temperature range for the structural material. Table 5 presents the calculated surface heat flux limits for the three low-activation structural materials, vanadium alloys, ferritic steel, and SiC/SiC composite, for a set of representative design parameters. Based on the representative parameters in Table 5, the first-wall heat flux limits for the indicated temperature criteria are $\sim$1.5 MW/m^2 for ferritic steel and $\sim$2.5 MW/m^2 for the vanadium alloy. A key conclusion is the limit for the SiC/SiC composite. Although the heat flux limit based on unirradiated properties data are very high (4–6 MW/m^2), results based on the thermal conductivity of irradiated SiC/SiC

Table 4
Suggested performance goals for a high performance fusion energy system

Criteria	Minimum values	Goal values
Average neutron wall load (MW/m^2)	2–3	5–10
Peak heat flux capability (MW/m^2)		
High heat flux components	5–7	50
First wall	1–1.5	2–4
First-wall lifetime (MW y/m^2)	10	20
(dpa)	$\sim$100	$\sim$200
Average cost of core materials ($/kg)	$\sim$100	$\sim$50
Net cycle efficiency (%)	$\sim$40	>50

Table 5
Surface heat flux limit for candidate structural materials based on estimated temperature limits

Structural material	Ferritic steel	Vanadium alloy	SiC/SiC composite
Maximum temperature, °C	550	750	950
Maximum coolant system ΔT, °C	250	350	450
Maximum first wall ΔT, °C [a]	200	300	400
Heat flux limit (MW/m^2) [b]			
5 mm thick wall	1.2	2.0	4.0 (unirrad) 0.4 (irrad)
3 mm thick wall	1.9	3.2	6.4 (unirrad) 0.6 (irrad)

[a] Assumed maximum wall ΔT.
[b] Value based on data for existing materials.

[11] are well below the suggested minimum values (Table 4). The performance capability of SiC/SiC will be severely limited unless composites can be developed in which the thermal conductivity is not degraded to the extent it is in currently available material.

The surface heat flux can also be limited by stress considerations. Fig. 1 presents the results of first order heat flux limits based on conventional S_m analysis for candidate structural materials and thermal stress criteria for (unirradiated) ductile materials [8]. Since no primary tensile or creep stress is included for this case, these values represent an upper bound. Values for the vanadium alloy and ferritic steel are higher than those obtained above for the temperature limit criteria. However, values for unirradiated SiC/SiC are considerably lower than the limits based only on temperature. These design criteria may also be more questionable for SiC/SiC type materials since conventional design rules may not be applicable for these types of materials. The other main observation is the relatively strong temperature dependence for the ferritic steel. This strong temperature dependence is also prominent for the thermal creep-rupture data shown in Fig. 2. Creep limits may impose additional critical structural temperature constraints, particularly for systems with high pressures coolants.

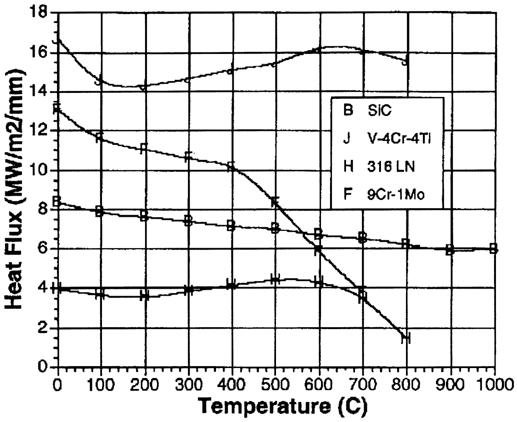

Fig. 1. Heat flux limit based on $3S_m$ for candidate structural materials.

A plot of heat flux limits based on recent design criteria [12] for a specific set of design parameters (including channel geometry and coolant temperature and pressure) is given in Fig. 3 for type 316 stainless steel as a function of wall thickness. This analysis illustrates limits based not only on the conventional S_m stress criteria but includes stress limits for nonductile material (S_d) such as occurs with Type 316 steel after irradiation,

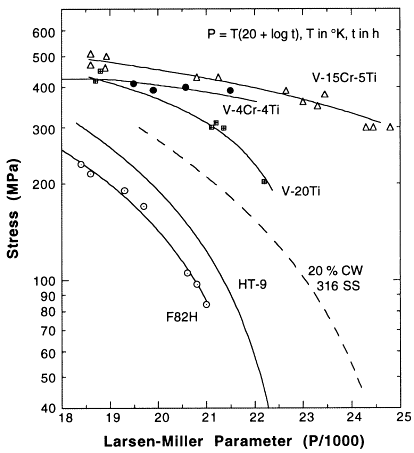

Fig. 2. Thermal creep properties for candidate structural materials.

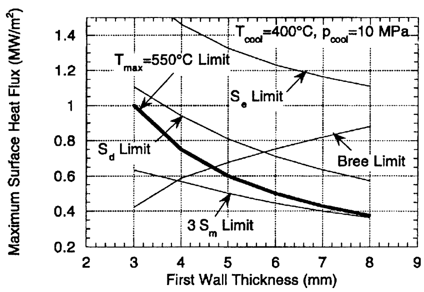

Fig. 3. Calculated surface heat flux limits for stainless steel first wall with 5 mm thick back wall and 10 mm wide by 20 mm high coolant channel.

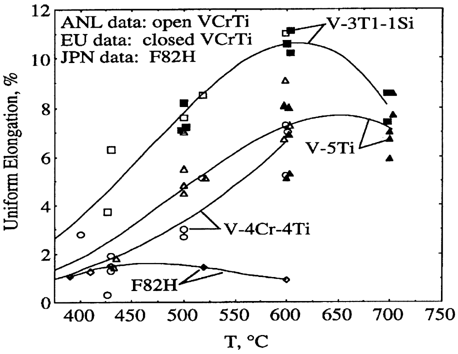

Fig. 4. Uniform elongation of irradiated (6–33 dpa) vanadium alloys and irradiated (~36 dpa) F82H steel.

limits imposed by an arbitrary temperature limit (550°C in this case), and limits imposed by the Bree criteria (ASME Code). The maximum heat flux limit is determined as a function of wall thickness by following the appropriate set of criteria. For the case shown, the maximum surface heat flux limit is ~0.65 MW/m^2 with a wall thickness of ~4.5 mm (defined by T_{max} and Bree curves). If the temperature limit were relaxed, e.g., to 650°C, the heat flux limit would increase with thickness along the Bree curve until the temperature limit was reached (~0.8 MW/m^2 at ~6.5 mm for a ductile material) or to the S_d limit (~0.72 MW/m^2 at ~5.7 mm) if the material is embrittled ($\varepsilon_u < 2\%$). Sufficient data on the mechanical behavior of the ferritic steels and vanadium alloys are not available to reliably perform the same type of analysis; however, preliminary results obtained on irradiated F82H ferritic steel [13] indicating low uniform elongation (see Fig. 4) suggest that the allowable surface heat loads for this material may be constrained by the S_d limit. Similar results for vanadium alloys [14] indicate that the allowable surface heat loads for this material may be constrained by the S_d limit at temperatures below 430–450°C (Fig. 4) and by the temperature limit at temperatures above 450°C. This type of evaluation cannot be made for SiC/SiC at this time. Additional constraints may be imposed by thermal or irradiation-induced creep, cyclic strees effects or possibly high strain rate effects induced by disruptions. Additional data and analysis are required to evaluate those factors.

4.2. Neutron wall load limits

Neutron wall load limits will also be imposed by the breeder material or beryllium for some systems because of temperature limits for these materials. The primary constraint results from the impact on tritium breeding which must be maintained above unity to provide for tritium self sufficiency. The example presented here is based on the layered helium-cooled pebble bed (HCPB) blanket design developed in Europe for the DEMO [2,3] and results from the US ARIES studies [15]. For the HCPB design the breeder temperature limits were set at 900°C maximum and 350°C minimum or a 550°C ΔT. Based on nuclear heating rates and the thermal conductivity of the solid breeder, the thickness of the breeder zone was calculated to be 11 mm to maintain the design ΔT limit of 550°C for the neutron wall load of 2.3 MW/m^2. The material distribution within the HCPB blanket, not including the blanket containment structure and coolant volume, was ~60% Be zone, 16% breeder zone, and ~24% structure and coolant. The breeding ratio was calculated to be 1.13. Results obtained from both studies indicate that the maximum neutron wall load for ceramic breeder materials based on current materials properties and designs is in the range 2–3 MW/m^2, which meets the minimum accepted values but is considerably below the goal values indicated in Table 4.

4.3. Power conversion efficiency

The power conversion efficiency depends primarily on the coolant parameters. The estimated power conversion efficiencies for candidate blanket concepts incorporated into the ARIES Reactor Design are summarized in Table 6 along with representative parameters for each system. The net efficiency of the helium-cooled solid breeder concept is limited to ~20%, primarily because of the temperature limit (~520°C) imposed for the ferritic steel structure and the significant

Table 6
Estimated power conversion efficiencies for candidate blanket concepts

Concept	He/SB/FS/Be	H_2O/PbLi/FS	Li/V	He/SB/SiC/Be [b]
Coolant	He	H_2O	Li	He
Coolant pressure (MPa)	8	15	0.4	15
T_{in}, °C	250	265	330	350
T_{out}, °C	450	325	610	650
Approx. gross efficiency (%)	28	35	46	49
Approx. net plant efficiency (%) [a]	19	28	39	39

[a] Based on ARIES reactor design.
[b] Assumes high conductivity SiC.

pumping power required for the helium. High temperature helium can provide high power conversion efficiencies as illustrated for the design with a SiC/SiC structure (~40%). However, there are greater uncertainties associated with the design rules for this type of structure. The water-cooled blanket provides a net efficiency of ~30%, limited primarily by the water coolant. The self-cooled lithium blanket concept also provides a high power conversion efficiency of ~40%. This is also limited primarily by the assumed structure temperature limit of ~700°C for vanadium alloys.

4.4. Magnetic interactions

Two types of magnetic interactions must be considered, viz., magnetohydro-dynamic (MHD) effects associated with a flowing liquid metal and effects associated with a ferromagnetic material (ferritic steel). The MHD interactions will cause a large pressure drop in a flowing system affecting the system pressure and the pumping power riquirements. The heat transfer in the coolant will also be degraded since the magnetic field will tend to laminarize the flow. Previous analyses conclude that electrically insulating walls will be required to mitigate the MHD pressure drop for projected liquid metal coolant parameters [16]. Since the dielectric requirements are not severe, the primary solution involves formation of thin, self-healing coatings (~10 μm thick) on coolant channel walls [16,17]. Calcium oxide and aluminum nitride are currently the leading candidate coating materials for the Li/V system. The effort to date on coating development has been limited and a satisfactory coating has not been demonstrated. However, encouraging results have been obtained with CaO coatings, which indicate that in situ formation of coatings on complex shapes, rehealing of defects in the coating, and stability of the coating in lithium all appear feasible. Although consistent results have not been obtained, a thin (~10 μm) CaO coating on a vanadium alloy provided a resistivity ~5 orders of magnitude higher than required during a 200 h exposure to lithium at ~435°C [18]. Development of a viable insulator coating is a critical issue for self-cooled liquid metal blankets.

The effects of incorporating a ferromagnetic material in a magnetic fusion device have not been analyzed in detail. Two issues are of concern, viz., additional mechanical loads induced in the structure and effects of the ferromagnetic material on plasma control. Limited analyses indicate that effects of utilizing ferritic steels in the first-wall/blanket system are not prohibitive [19]. However, ferromagnetic materials have not been used in current fusion devices. Primary concerns relate to non-uniform coverage within the device such as test modules in ITER, effects of disruptions which produce transient magnetic fields, and increased mechanical loads in regions with large magnetic field gradients. It is important to resolve these issues to assure that ferritic steels can be used in a fusion power plant.

4.5. Hydrogen/tritium interactions

Hydrogen and/or tritium interactions can affect both performance and safety/environmental aspects of fusion power. Predominant sources of hydrogen isotopes include the D–T plasma (both energetic and thermalized), tritium breeding in the blanket materials, and hydrogen transmutations in the structure. Key issues include:

- tritium inventory in the structure or plasma facing material from plasma interactions;
- tritium inventory in the breeder/multiplier materials from transmutations;
- tritium inventory in the structure from the breeder material;
- tritium containment within the system;
- hydrogen embrittlement of the structure from transmutations.

Tritium and hydrogen issues do not appear to be a serious problem in the Li/V system. Methods for maintaining the tritium concentration in lithium at acceptable levels, ie., ~1 appm, appear feasible [20]. The equilibrium hydrogen concentration in vanadium alloys is very low (~30 appm at 10^{-2} Pa and 500°C) at hydrogen pressures in the plasma chamber and in lithium [21,22]. Hydrogen generated in vanadium alloys (~20 appm/dpa) is lower than for other candidate materials. Since hydrogen is highly mobile in vanadium at projected operating temperatures, hydrogen will transfer to either the plasma chamber or the lithium. The insulator coating will tend to limit hydrogen transfer to the lithium; however, preliminary analyses indicate that pathways for the removal of hydrogen from the vanadium structure are adequate. This issue is much more critical with other breeding materials (PbLi, Flibe and solid breeders) which exhibit much higher hydrogen (T) pressures and their use may not be acceptable with vanadium alloys.

For the He/SB/FS/Be blanket concept, the ranges of temperatures for acceptable tritium recovery from the breeder are adequate [2,8,23–25]. The relatively high H pressure in the purge stream is not a problem for the ferritic steel. However, significant buildup of tritium in the beryllium (~2 kg at 4.4 MW-y/m^2 in HCPB design) [2], is a safety concern. Since the solid breeder system will operate at a relatively high hydrogen/tritium pressure, a tritium barrier is required to reduce tritium permeation to the stream-generator at acceptable levels [2]. The effect of hydrogen generation in the ferritic steel structure (~45 appm H/dpa) on the mechanical properties is an important issue, particularly at the lower temperatures.The mobility of hydrogen in ferritic steel is limited at the lower temperatures and transport out to the coolant will be inhibited by the oxide barrier proposed for tritium containment. Critical data on the effects of significant hydrogen concentrations on the mechanical properties of ferritic steels are not available.

Tritium recovery from Pb–Li in the H_2O/PbLi/FS system appears acceptable; however, the tritium partial pressure in the system will be quite high. Therefore, tritium permeation into the water coolant and tritium containment are major issues. The design solution is a tritium barrier to inhibit permeation into the water [2,4]. Significant progress is being made on barrier development with an Al_2O_3 coating as the leading candidate; however further development is required to demonstrate adequate barrier performance [4,26,27]. The issue of H transmutation on the mechanical performance of the ferritic steel structure is similar to the previous case. The tritium barriers will tend to inhibit hydrogen transport out of the steel, thus exacerbating the problem.

The hydrogen/tritium issues for the He/SB/SiC/Be concept are less-well defined. Conventional SiC/SiC composites have utilized a carbon bond between the fiber and the matrix. This carbon appears to be a sink for tritium, which requires development of a different bond material. Hydrogen transmutation rates in the SiC/SiC are similar to those for the steels. Effects of the very high He transmutation rate ($\sim$150 appm/dpa) on hydrogen/tritium interactions is not known.

4.6. Hermiticity

The issue of hermiticity, particularly inhibiting coolant transport into the plasma chamber, is a critical issue for the high pressure helium coolant. Because of the inherent porosity of SiC/SiC composites, hermiticity is a feasibility issue for the He/SB/SiC/Be system. The proposed design solution is to apply a coating or cladding on the SiC composite. Monolithic SiC and metal cladding have been suggested [23]; however, this issue has not been addressed in detail. The concerns relate to the integrity and radiation resistance of the cladding. The issue of hermiticity for the SiC composite is exacerbated by the very high He transmutation rate ($\sim$1600 appm He per MW-y/m^2). Inhibiting He transport and simultaneously accommodating the high He generation rate appear to be conflicting requirements.

4.7. Special materials issues

Several special materials issues are important for the various concepts. Some have been discussed in the previous sections and others are probably yet to be defined. The coating/barrier issues appear to be essential for all concepts, albeit for different reasons. The insulator coating discussed previously is considered a feasibility issue for the Li/V system. Tritium barriers, also discussed above, are required for the He cooled systems to avoid excessive tritium permeation into the steam generator, and for the PbLi breeder to reduce tritium permeation into the water coolant. A coating or cladding on SiC/SiC is required to maintain hermiticity. Although satisfactory performance of the insulator coating and the tritium permeation barriers has yet to be demonstrated, preliminary investigations have defined potential solutions with some encouraging results [20,26,27].

Special joining requirements are critical to several systems. Since the SiC composite is not weldable, some type of braze or bond is required to join this material. The performance and safety/environmental implications associated with a braze have not been evaluated in detail. Similarly brazes or bonds for joining plasma facing materials to the first-wall structure require additional evaluations for the fusion power application, particularly for irradiation effects. Additional evaluation of weldments and weld requirements, e.g., post-weld heat treatment, is important for vanadium alloys and ferritic steels.

4.8. Safety/Environmental issues

The safety and environmental issues for fusion will be dominated by the first-wall blanket system and the related materials integration issues. Because of space limitations, the safety and environmental issues are only highlighted here. More comprehensive evaluations are available in the literature [9]. The safety and environmental issues can be characterized according to normal operating emissions, accidental releases, and waste management requirements.

Tritium containment is probably the greatest concern for normal emissions. Lithium is unique among the tritium breeding materials because the tritium partial pressure is many orders of magnitude lower than that for the other candidate materials. The tritium partial pressure increase per pass of the tritium recovery fluid is $\sim 10^{-13}$ Pa for the V/Li system, $\sim$0.1 Pa for PbLi/H_2O/FS system, and 5 Pa for a self-cooled Flibe or a He-purged solid breeder system. These values represent the minimum tritium pressure in the system for the various blanket systems with representative parameters; values will be much higher in practical systems. The tritium partial pressures for PbLi, Flibe and the ceramic breeders (with a He purge stream) are similar. Containment of the tritium at elevated temperatures is an issue for these systems.

Release of radioactivity, chemical reactivity/toxicity, and tritium are the main concerns related to accident scenarios. The primary contributing factors associated with accidental releases include system pressure, system complexity, nuclear decay heat, and design margin. The chemical reactivity of lithium with air and water is the dominant issue for the Li/V system. Favorable characteristics relate to design simplicity since lithium serves as breeder, coolant, neutron multiplier and for tritium recovery; low operating pressure; and low activation (decay heat and long-term activation). The most likely failures for any system are within the vacuum chamber. Since lithium is low pressure and will not react with any of the candidate in-vessel materials, an in-vessel failure should not present a safety issue. Design solutions proposed to mitigate the chemical reactivity problem in the event of an ex-vessel failure involve elimination of water from the reactor room and use of an inert cover gas in the reactor room. This inert cover gas provides additional benefits associated with chemical reactivity of plasma facing materials in the event of a vacuum chamber rupture.

Helium coolant has an advantage of being chemically inert; however, it must be used at high pressure (5–20 MPa). The primary concern relates to the possibility of a vacuum chamber rupture in the event of an in-vessel coolant tube failure for both the He/SB/Be/FS and the He/SB/SiC/Be concepts. This effect is more significant since helium is noncondensable. Propagation of a pressure induced rupture could lead to dispersion of the ceramic breeder and beryllium. A second issue relates to potential thermal excursion in the event of a loss of coolant accident. The SiC structure has an advantage over the ferritic steel structure because of the lower decay heat and the higher temperature properties. The chemical reactivity of beryllium is also an issue. Petty [9] has shown that the chemical energy release (GJ/m^3) from a water reaction, the H_2 release (kg/m^3) from a water reaction and the chemical energy release (GJ/m^3) from an air reaction with beryllium are approximately one order of magnitude greater than for corresponding reactions with lithium and approximately two orders of magnitude greater than for corresponding reactions with PbLi.

The water coolant presents different safety issues. Water coolant for power producing systems must also operate at high pressures, typically 12–15 MPa. Propagation of pressure induced failures similar to the helium case are of concern; however, water has an advantage in that it will condense on cooling, thus relieving the pressure. Chemical reactions with plasma facing materials with hydrogen generation in the event of an in-vessel failure are a major concern. Reaction of water with PbLi in the H_2O/PbLi/FS concept can also lead to hydrogen generation. Generation of Po (210) is a major concern with Pb.

Waste management is an important issue for fusion, which is dominated by the materials for the nuclear system. The two primary issues relate to long-term radioactivity and waste disposal requirements, and issues associated with potential for recycle. Activation analysis for the three structural materials (V, FS, SiC), indicate that SiC has the lowest short-term radioactive decay heat and contact dose at short times (<10 yr), and the vanadium alloy (V–4Cr–4Ti) exhibits the lowest long-term decay heat and dose [28,29]. For all three materials the long-term activation is dominated by trace impurities. It is generally concluded that impurities can be controlled at low levels with some economic penalty. A preliminary evaluation indicates that recycle of vanadium is possible [30]. Lithium will not produce activation products except for tritium, which is recovered and used in the fuel cycle. Recycle of lithium involves simply draining and reuse. After extended use, addition of ^{6}Li would be required. Beryllium also produces no long-lived radioactive products except tritium. Recycle of beryllium is considered necessary because of resource limitations. Careful handling will be required because of the tritium and chemical toxicity of beryllium. The Pb in PbLi will produce activation products including Po 210 which is a gas. Recycle of PbLi should be similar to that for Li with replenishment of ^{6}Li required periodically. The activation of solid breeder materials depends on which of the Li ceramics is used, e.g., Li_2O, Li_4SiO_4, Li_2ZrO_3, Li_2TiO_3, $LiALO_2$. Since neither Li nor oxygen produce long-lived radioactive products (assuming T is recovered), the activation depends on the ternary element. The zirconium is the least desirable and titanium is preferred for low long-term activation. Recycle is generally considered necessary because of the use of highly enriched Li-6. Reprocessing of these ceramics will be considerably more difficult than for the other breeder materials.

4.9. Reliability

High reliability of the nuclear system will be essential because of the difficult maintenance for the first-wall/blanket of a fusion system. Reliability is very difficult to evaluate quantitatively, however, qualitative considerations for evaluating reliability include: (a) design complexity including number of materials, number of interfaces (e.g., number of coolant tubes), and configuration; (b) design margins for stress and temperature limits; (c) system pressure which impacts primary stresses; and (d) number or length of pressure boundary joints or welds. The low pressure systems which employ multifuction materials, e.g., the same material for coolant, breeder, neutron multiplier, should enhance the system reliability.

5. Summary and conclusion

Development of a compatible combination of materials for the nuclear system that provides high performance with attractive safety and environmental features is one of the keys to the successful deployment of fusion as a viable energy source. The material requirements for a fusion power system are exceedingly complex and only a limited number of materials offer a potential for high performance. Leading blanket concepts have been identified within the international community and the critical issues and limitations for each concept have been defined.

Key materials integration issues for the He/SB/FS/Be concept relate to: (a) the low power conversion efficiency, which is limited primarily by the ferritic steel temperature constraint; (b) the neutron wall load limit for He/FS; (c) uncertainties associated with the ferromagnetic properties of ferritic steel; and (d) radiation damage, including He and H transmutations, on properties of ferritic steel.

Key materials integration issues for the Li/V concept relate to: (a) development of an acceptable insulator coating to mitigate MHD pressure drop; (b) He and H transmutation effects on irradiated vanadium alloys; (c) ability to maintain tritium inventory at acceptable levels; and (d) design to accommodate the chemical reactivity of lithium.

Key materials integration issues for the H_2O/PbLi/FS concept relate to: (a) development of acceptable tritium barrier to reduce tritium transport into water coolant; (b) safety associated with pressurized water reactions with PbLi and plasma facing materials; (c) the low power conversion efficiency associated with water coolant; (d) uncertainties associated with the ferromagnetic properties of ferritic steel; and (e) radiation damage, including He and H transmutations, on properties of ferritic steel.

Key materials integration issues for the He/SB/SiC/Be concept relate to: (a) radiation effects on thermal conductivity of SiC composite which result in unacceptable low heat flux capability; (b) development of an acceptable coating or cladding to provide adequate hermiticity; (c) development of acceptable joining methods that can withstand the projected fusion environment; (d) radiation damage, including the high He transmutations rates, on the properties of the SiC composite; and (e) development of design codes relevant to composite materials for fusion applications.

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