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Engineering Options for the U.S. Fusion Demo*

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ABSTRACT

Through its successful operation, the U.S. Fusion Demo must be sufficiently convincing that a utility or independent power producer will choose to purchase one as its next electric generating plant. A fusion power plant which is limited to the use of currently-proven technologies is unlikely to be sufficiently attractive to a utility unless fuel shortages and regulatory restrictions are far more crippling to competing energy sources than currently anticipated. In that case, the task of choosing an appropriate set of engineering technologies today involves trade-offs between attractiveness and technical risk. The design space for an attractive tokamak fusion power core is not unlimited; previous studies have shown that advanced low-activation ferritic steel, vanadium alloy, or SiC/SiC composites are the only candidates we have for the primary in-vessel structural material. An assessment of engineering design options has been performed using these three materials and the associated in-vessel component designs which are compatible with them.

I. INTRODUCTION

The Starlite project has assembled a set of requirements for commercial power plants based on projections of customer needs 25-50 years from now. Based on these, a clear and self-consistent definition of a Demo power plant has been identified [1]. The Demo requirements provide goals for engineering components which are very challenging to meet. Safety and environmental requirements severely limit material choices. Performance requirements provide strong incentives to operate at high coolant temperature. Reliability requirements may be the most difficult to meet. Design solutions must be simple, incorporate adequate performance margins, and be tested fully prior to Demo operation.

In this early phase of the U.S. Demo project, detailed designs have not yet been developed. Instead, various design options have been examined and their potential to meet the Demo requirements assessed. These options include material choices for the structure, breeder and coolant. In order to provide a framework for this assessment, the three primary in-vessel structural material classes are used to distinguish design classes. The design options using these materials are surveyed, paying special attention to the first wall, blanket, shield and divertor, and the support systems required to operate them. For each class of designs, their ability to meet the Demo requirements are summarized and the key issues are assessed. Key issues are those uncertainties which, if not adequately resolved, would lead to an unattractive product which does not meet one or more of the top-level requirements.

II. REQUIREMENTS

System requirements are based on a mission statement and qualitative set of goals for a fusion Demo power plant that were developed in cooperation with utility and government representatives. The requirements listed in Table I allow quantitative goals to be established, such that the design process has specific targets based on customer needs. These are translated into sub-system goals by different means, depending on the nature of the requirement. Some requirements translate directly into subsystem requirements (e.g., every subsystem must meet the Class C low level waste disposal requirement and must be maintainable). Some (e.g., fuel cycle and net electric output) must be established through sub-system tradeoffs. And finally, some require system-wide allocations which are obtained through an iterative process of total system design (e.g., all systems contribute to the cost and availability requirements). A more complete description of the requirements and their implications can be found in Ref. 1.

TABLE I
Top-Level Demo System Requirements

* Must use same technologies as commercial plant
* Must generate no radioactive waste greater than Class C
* Demonstrate robotic or remote maintenance of power core
* Demonstrate a closed tritium fuel cycle
* Net electric output must greater than 75% of commercial
* Must demonstrate operation at 50% load conditions
* No evacuation plan required (1 rem total dose at site boundary)
* Demonstrate public's day-to-day activities not disturbed
* Expose workers to risk no higher than other power plants
* Must demonstrate routine operation with less than 1 unscheduled shutdown/yr including disruptions
* Cost of electricity must be competitive (80-90 mill/kWh in 1995 $)

III. ASSESSMENT OF FERRITIC STEEL DESIGNS

A. Design Options

Conceptual designs using ferritic steel as the structural material have been proposed and developed for both solid and liquid breeder materials, as well as water, helium and liquid-metal coolants. For most breeder, multiplier and coolant materials (except for Pb-Li), ferritic steels are compatible up to the strength-based temperature limit of the material (550deg.C). The design combination which appears to be most appealing from a performance perspective uses beryllium multiplier with solid breeder and is cooled by helium flowing through tubes. Reduced activation designs involve the use of Li2O or Li2TiO3 solid breeders and Fe-9Cr-2WVTa ferritic steel.

B. Evaluation Highlights

The evaluation focussed on the cost of electricity (COE), maintainability without high-risk exposure to workers, and waste disposal. Factors influencing the COE are the material and fabrication costs, the thermal efficiency achievable (limited by the maximum structural temperature allowed), the peak surface and volumetric heat loads allowed, and the lifetime. More expensive than austenitic steels, ferritic steels are only 20-25% of the cost of vanadium alloys. In addition, they are design-code-qualified materials for which there is an extensive database and industrial experience.

The 550deg.C temperature limit restricts the thermal efficiency, and the peak surface heat load for a 5-mm wall is limited to <=0.8 MW/m2. This would restrict the peak neutron wall loading to <4 MW/m2 and result in a larger machine with higher capital costs. The surface heat flux limit also would make ferritic steels unattractive as a divertor structural material. It is desirable for a structural material to tolerate >=1 MW/m2 of surface heat load.

Lifetime limits depend on operating stresses and irradiation effects. By reducing the operating stresses, lifetimes of 12 MW-y/m2 (3 full power years) can be achieved with ferritic steels. Preliminary cost analyses indicate that the required cost of electricity (<= 90 mills/kWh) could be achieved with ferritic steel as a structural material because the lower material and fabrication costs would tend to off-set the cost associated with larger machine size and reduced thermal efficiency. These results assume that a different material is used for the divertor.

Maintenance of any of the candidate structural materials would have to be performed remotely because of the high level of radioactivity and heat following shut-down. In terms of waste disposal, reduced-activation ferritic steels are better than austenitic steels and on a par with vanadium alloys. They qualify as Class C waste according to NRC guidelines.

C. Issues

The lower temperature limit for ferritic steels is not well established. Ferritic steels irradiated at temperatures <= 400deg.C tend to embrittle, as indicated by a decreasing tensile ductility and an increasing ductile-to-brittle-transition temperature (DBTT) with irradiation. Experiments in mixed-spectrum fission reactors result in DBTT values of about 250deg.C under conditions of simultaneous helium production and neutron damage, while experiments at >=365deg.C in fast fission reactors with little helium production give DBTT < 0deg.C for some of these steels. The He production (>= 10 appm-He/dpa) would be relatively high in a fusion reactor. Without fully understanding the role of helium in raising the DBTT, it is difficult to extrapolate the fission reactor results to fusion reactor conditions. If the DBTT were to reach 250deg.C, then the minimum operating temperature would have to be set at 285deg.C, leaving a relatively narrow temperature window for design, and possible problems with start-up, shut-down and off-normal events during shut-down Other problems which have been raised regarding the use of ferritic steels are considered solvable as compared to the loss-of-ductility issue.

IV. ASSESSMENT OF V DESIGNS

A. Design Options

A key design issue associated with V blankets is the compatibility of V-alloy with either hydrogen or oxygen environments at higher temperatures (>300-400deg.C). V has strong affinity for both hydrogen and oxygen, and the material becomes brittle with moderate hydrogen or oxygen concentration. Lithium is one of the few materials which has even stronger affinity to hydrogen and oxygen than vanadium [2]. Thus, it is natural to design the vanadium blanket with lithium acting as both coolant and breeding material [3,4]. A self-cooled blanket simplifies the blanket design. However, electrical insulation between the coolant and metallic walls may be needed to reduce the MHD pressure drop, and the large lithium inventory causes safety concerns.

To reduce or eliminate lithium safety concern, a He-cooled lithium breeding blanket was examined in the BCSS project [5] and also was proposed for the Demo [6]. A closed-cycle gas turbine was proposed for power conversion in the latter design. The elimination of the steam cycle reduces the source term for both hydrogen and oxygen. A surface modification approach is proposed to protect the V-alloy, if necessary. Another design has been proposed using Li2O as the breeding material to enhance even further the safety characteristis [7]. The use of SiC or Al2O3 for V-alloy protection was proposed, but not discussed in detail.

B. Evaluation Highlights

Vanadium-based design options have been evaluated relative to the requirements listed in Table 1. In all cases, the component designs either meet the requirements or are capable of meeting them, depending on the results of complete system integration which is yet to be performed.

C. Issues

For any fusion reactor design, a key issue is associated with the development of the structural material. There is no intense 14-MeV neutron source available. Therefore, the material response to fusion neturons can not be quantified. For a more advanced structural material, there is also a lack of industrial experience. Therefore, large scale fabrication and joining to other structural materials are also cause for concern.

For the self-cooled liquid metal design, the key issue is to develop and assure long term reliability of the insulating coating. Only some preliminary work in this area has been started. Although preliminary results are encouraging, some important effects, such as neutron irradiation and thermal cycling, have not been included in the experimental process. Tritium recovery from lithium to the design goal of ~ 1 appm has yet to be demonstrated. For a blanket with lithium as the breeding material, safety is always a key concern. Lithium will react with water, air, concrete, nitrogen, etc. The chemistry of lithium can not be changed. However, design of the power plant can minimize the frequency and the consequence of the lithium reaction when an accident occurs.

V. ASSESSMENT OF SiC DESIGNS

A. Design Options

SiC composite material with a projected allowable temperature capability of >= 1000[[ring]] C was selected as the structural materials for ARIES-I and ARIES-IV reference and alternate blanket and divertor designs. These designs have been used as the basis for assessing the advantages and issues associated with a possible Demo power plant based on SiC composites as the primary in-vessel structural material.

To take full advantages of the low activation and high temperature capability of SiC composite material, 5-10 MPa helium was used as the coolant. ARIES-I used Li2ZrO3 as the solid tritium breeder, Be metal sphere-pac as the neutron multiplier, and W as the divertor coating material. Due to the induced activation of Zr and W, the safety rating of this design was Level of Safety Assurance (LSA)-2. Based on new experimental results, Li2O was selected as the solid breeder for the ARIES-IV designs. If the use of W can be avoided as the PFC coating material, then a completely passively safe design of LSA-1 can be obtained, if Be chemical energy and toxicity concerns are eliminated.

Both ARIES-I and ARIES-IV alternate designs used the toroidal flow, nested shell blanket configuration, where the SiC composite components can be made from smaller ceramic (about 1 m x 1 m) parts. Reliability of this configuration depends on the successful development of ceramics joining techniques. The ARIES-IV reference design has a poloidal flow configuration. This relies on the successful development of the fabrication of large (>1 m wide, ~1 m deep and >7 m in height components) leak-tight SiC composite components.

B. Evaluation Highlights

Both ARIES-IV reference and alternate blanket designs satisfy all of the neutronics and thermal hydraulic performance requirements of Demo. Except for the need of Be-neutron multiplier, both designs will have excellent safety characteristics. We also found that by increasing the helium pressure to about 12 MPa, and taking advantages of the improved recuperator performance of the closed cycle gas turbine system, at a helium outlet temperature of about 950[[ring]]C, a gross thermal efficiency of about 55% can be expected. In the evaluation for the use of SiC-composite as the structural material for the Demo design, there was no doubt of its projected benefits; the key question is on whether its development schedule can meet the project schedule of Demo.

C. Issues

Key issues for the application of SiC composite are in the areas of material development that can match the schedule of the US Demo design, the behavior of the composites in a fusion environment, the need for metallic components to stabilize the plasma, and the development of robust plasma facing components (PFC).

Fundamental improvements in material irradiated properties, such as thermal conductivity, are needed, for example by using advanced SiC fiber and interface materials. Other material development issues include economic fabrication of large SiC-composite components, development of vacuum leak-tight components, the technique of brazing ceramic parts, and the development of the joining techniques of SiC-composite to metallic parts. Under the current Demo physics scenario (i.e., reversed shear), a close conducting shell is needed for plasma equilibrium stabilization, and separate passive and active, toroidally connected and electrically conducting rings for vertical stabilization. This will determine the amount of metallic elements that will be needed close to the plasma, thus impacting the safety rating and thermal performance of the plant. Various techniques of leveling the surface heat flux, such as the use of the radiative divertor approach is essential, since it dictates the feasibility of removing surface heat flux by helium coolant and the utilization of low activation material for the PFC surface and components. The concurrent reduction in the ion energy to < 5 eV is necessary to maintain low surface erosion and therefore, adequate component lifetime and to maintain the low activation benefits of the SiC composite design without the use of high-Z surface material.

VI. NEUTRONICS ASSESSMENT

The US Demo will utilize either a liquid metal (LM) or solid breeder (SB) for tritium breeding. A prime goal for the breeder is to provide tritium self-sufficiency. Neutronics analyses have been performed for 20 breeders to examine their ability to breed adequate tritium and to multiply the neutron energy [8].

Among the 6 liquid breeders and 14 solid breeders considered in the analysis, lithium provides the highest breeding, followed by lithium lead then Li2O. The most promising LM (Li, Li17Pb83) and SB (Li2O, Li2TiO3) breeders were selected for further analysis to illustrate the impact on breeding of the candidate structures (V, SiC, and FS) and neutron multipliers (Be, Be2C, BeO, and Pb). The study concluded that Li and Li17Pb83 have the potential for tritium self-sufficiency without a neutron multiplier. Solid breeders will most likely require a neutron multiplier to achieve net breeding in realistic designs.

All structures degrade the breeding and enhance the energy multiplication, except SiC, that degrades both. Vanadium has the least impact on the breeding of LM and SB, followed by SS and SiC, except for Li17Pb83. All multipliers enhance the SB breeding, except BeO, and the SB energy multiplication, except Pb.

The tritium breeding requirements for the U.S. Demo were identified. The blanket will supply all the tritium (T) needed for operation (0.2-0.3 kg/d). An external T supply is only needed to start the Demo and for a short time till steady state production of T is reached. To guarantee T self-sufficiency for Demo, the uncertainties in all design elements should be accounted for when estimating the breeding level for the various blanket options. The largest source of uncertainty is the basic nuclear data and the calculational model (~10%). The calculated overall T breeding ratio (TBR) should exceed 1.1 to assure that the actual achievable TBR from the blanket after Demo operation is >1.01. In order to enhance the breeding capability of the blanket, it is recommended to reduce the structural content, maximize the blanket coverage, and locate penetrations off midplane as much as practically possible. Other options, particularly for blankets with marginal breeding, include the use of neutron multipliers and/or enriching the lithium.

A list of top level requirements was compiled for the Demo shield (bulk, penetration, and biological). The bulk shield will provide a lifetime protection for the vacuum vessel and magnets, must have low safety and environmental impact, and should be reliable, maintainable, and replaceable. The shield is a lifetime component and the blanket/reflector will provide the lifetime protection for the bulk shield. As the bulk shield has major impact on the overall machine size and cost, it should be optimized for high performance, low cost, and minimal safety impact. Steel has the best shielding performance , followed by V and then SiC. General directions were identified for designing an efficient and cost-effective bulk shield. These include the use of steel structure for the outer layers of the shield and employing higher performance materials in the inboard region and cheaper but efficient shielding materials in the less constrained outboard and divertor regions.

The safety features of breeders and structures will be a key factor in selecting the Demo materials. SiC composites possess the lowest activation and afterheat characteristics, followed by V and then FS (modified HT-9 or F82H alloys). All candidate structural materials would qualify for Class C low level waste according to NRC limits. Safety-related issues for the candidate materials are well documented in the literature and design solutions will be identified in the Demo study to address the various safety concerns associated with the selected breeder and structure.

VII. SUMMARY

Three candidate primary in-vessel structural materials - ferritic steel, vanadium alloy, and SiC composite - have been examined to determine if they meet the Demo requirements and to characterize the remaining technical issues.

SiC composite has a unique potential for safety and high performance, but the database requires substantial improvement in order to identify and develop a satisfactory material composition. Significant improvements are needed in the basic properties, and several key material issues such as joining and hermeticity must be resolved. It was judged premature to adopt such a material for Demo, which has a relatively near-term schedule.

Ferritic steel has the largest database, and hence the smallest uncertainty in its performance. However, as with all materials, behavior after long-term operation in a complete fusion environment is highly uncertain. The features of ferritic steel which cause the greatest concern is its restricted temperature window, which limits the maximum achievable therml conversion efficiency, and its loss of ductility. It is not clear how one would operate a high-power device with potentially brittle materials. Economic studies are continuing to determine whether the lower cost of steel (as compared with vanadium alloy) will adequately offset the lower power density and lower efficiency.

Vanadium offers significant advantages in its high temperature and high thermal performance capability, and its low activation. The combination of V and Li appears particularly unique in material chemistry, offering good compatibility up to very high temperatures. The primary concerns with vanadium alloy are high cost and liquid metal MHD effects (including the need for and feasibility of insulating coatings). Minimization of vanadium in the shield and external systems is an important cost-reduction strategy. The absence of an established industrial base is also an important consideration, but not one of the top-level requirements as elaborated above. Due to it's greater ultimate potential for attractive commercial power plants and a development path which appears practical within a 25-year timeframe, the combination of Li breeder/coolant and vanadium-alloy structure was chosen as the first design concept to undergo full system design and analysis in Demo.

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