by
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Fusion Power Program
Technology Development Division
Energy Technology Division

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ANALYSIS AND DESIGN OF HIGH POWER DENSITY SELF-COOLED LITHIUM-VANADIUM BLANKET

by

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Yousry Gohar, Saurin Majumdar and Dale L. Smith

Abstract

A self-cooled lithium-vanadium blanket concept capable of operating with 2 MW/m^2 surface heat flux, 10 MW/m^2 neutron wall loading, and conservative engineering rules has been developed. The blanket has liquid lithium as the tritium breeder and the coolant to alleviate issues of coolant breeder compatibility and reactivity. Vanadium alloy (V-4Cr-4Ti) is used as the structural material because it can accommodate high heat loads. Also, it has good mechanical properties at high temperatures, potential for high neutron fluence capability, good compatibility with the blanket materials, low decay heat, and low waste disposal rating. Self-healing electrical insulator (CaO) is utilized to reduce the MHD pressure drop. A poloidal coolant flow with high velocity at the first wall is used to reduce the peak temperature of the vanadium structure and to accommodate high surface heat flux. The blanket has a simple geometrical configuration and low coolant pressure to reduce the fabrication cost, to improve the blanket reliability, and to increase confidence in its performance. Spectral shifters are utilized to improve the blanket shielding capability and energy multiplication, and to reduce the radial blanket thickness. Natural lithium is used to avoid extra cost related to the lithium enrichment process.

I. Introduction

This study is intended to explore the capability of the self-cooled lithium-vanadium blanket concept for operation at high power density and high performance with conservative engineering rules. Therefore, a new blanket concept has been developed, which is shown in Figure 1 and 2. In this blanket design, the loading conditions and the blanket performance parameters. In addition, the radial blanket thickness is minimized to reduce the total cost of the reactor system. The blanket has liquid lithium as the tritium breeder and coolant to alleviate issues of coolant breeder compatibility and reactivity. Vanadium alloy (V-4Cr-4Ti) is used as the structural material because it can accommodate high heat loads. Also, it has several attractive features including good mechanical properties at high temperatures, potential for high neutron fluence capability, good compatibility with the blanket materials, low decay heat, and low waste disposal rating. Self-healing electrical insulator (CaO) is utilized to reduce the MHD pressure drop. Low-pressure lithium is used to provide simple reliable design with enhanced performance. The blanket configuration is based on slotted poloidal flow concept. This blanket concept allows high lithium coolant velocity at the first wall that reduces the peak temperature of the vanadium structure and accommodates high surface heat flux without excessive MHD pressure drop. Spectral shifter and reflector are utilized to improve the blanket performance and to reduce the total radial blanket thickness. Beryllium is used as spectral shifter (multiplier and moderator) near the first wall and titanium carbide is utilized as a spectral shifter (moderator and reflector). Natural lithium is used to avoid extra cost related to the lithium enrichment process.

Figure 2. Plan view of the self-cooled lithium-vanadium blanket sector design

II. Strategy And Guidelines

In the previous blanket studies (1, 2), reactor parameters were defined at the start of the study including the first wall surface heat flux, the neutron wall loading, the plasma minor radius, the plasma elongation, etc. Then the blanket design was carried out to satisfy these parameters, the engineering design rules, the study guidelines, and any other design constraints imposed by the employed materials. On the contrary, the strategy of this study is to develop a high power density blanket concept, to study the blanket performance as a function of the thermal loading conditions, and to define the blanket capability to maintain its operational performance for a wide range of loading conditions. The top ranked blanket concept from the blanket comparison and selection study (1), the self-cooled liquid lithium with vanadium structure is employed as a starting point for the study. The V-4Cr-4Ti alloy is utilized for this study because of its performance relative to the other vanadium alloys for this application. A brief summary of the relevant material database, compatibility of the vanadium alloys with the other blanket materials, and the insulator coating is presented in the material section.

A special attention is given to maximize the utilization of the unique features of the self-cooled liquid lithium-vanadium blanket concept. Liquid lithium is maintained as the tritium breeder and coolant to simplify the blanket mechanical configuration and to eliminate issues of coolant breeder compatibility and reactivity. Liquid lithium coolant operates at low pressure, which represents a significant design advantage. It results in reduced primary stresses, simplified mechanical design, enhanced safety performance, and higher design margin to accommodate thermal stresses. Vanadium structural material has high thermal conductivity, which permits the first wall to accommodate high surface heat flux. The good mechanical properties of the vanadium alloy at high temperatures allow the use of high outlet lithium temperature to enhance the net thermal efficiency. The low degradation of the mechanical properties of the vanadium alloy due to neutron irradiation increases the operating neutron fluence of the blanket and consequentially the reactor availability. The good compatibility of the liquid lithium with the vanadium structure allows the use of high lithium velocity, which results in reduced

lithium inventory enhancing safety performance and reducing the capital cost of the lithium components. This also results in low corrosion rates, which enhances the lifetime of the vanadium components and reduces the required processing capacity for controlling the lithium chemistry. The low decay heat of the lithium-vanadium blanket simplifies the system design to accommodate loss of coolant and flow events, which reduces the capital cost and enhances the safety performance. The low waste disposal rating of the lithium-vanadium system eases the fusion environmental issues for energy production relative to other systems.

The conventional self-cooled lithium-vanadium fusion blankets (1,2) have poor neutron attenuation characteristics and energy multiplication for the DT fusion neutrons. A blanket thickness of about one-meter is required to recover the DT neutron energy, to generate adequate tritium fuel, and to reduce the energy deposition in the shield. Such blanket has a large thickness of lithium that requires slow circulation of the lithium to generate the temperature difference for the power cycle. The low lithium velocity reduces the heat transfer characteristics of the liquid lithium, which increases the maximum vanadium temperature. Also, this large blanket thickness has a negative impact on the total cost of the fusion reactor.

To overcome these issues, a new design approach is developed for this study. At the start, the conventional blanket design (1) is considered as a basis for comparison with the new design developed in this study. The effect of the reflector material selection and the geometrical parameters including the thickness of the lithium and the reflector zones were analyzed to achieve the best possible performance for the conventional blanket design. As expected, the characteristics and performance of the resulting blanket configurations do not provide significant improvements relative to the previous blanket designs (1, and 2).

In the second step, beryllium material is incorporated in the blanket (3) as a spectral shifter to reduce the required blanket thickness, to enhance the blanket energy multiplication factor, and to reduce the energy deposition in the shield. To achieve high

surface heat flux capability for the first wall, a small zone of lithium coolant is located between the beryllium zone and the first wall. This lithium coolant provides a direct heat transfer path for the surface heat flux that minimizes the maximum first wall temperature. However, the neutronics aspect of the design requires the beryllium material to be very close to the first wall to maximize the $(n,2n)$ reaction rate. Neutronics, heat transfer, hydraulics, and structural analyses were carried out in a parametric fashion to define a possible design window for the first wall and the beryllium multiplier zone. These analyses were performed for different reflector materials including carbon, copper, tungsten, type 316 austenitic steel, manganese steel, vanadium alloy (V-4Cr-4Ti), calcium oxide, tungsten carbide, titanium carbide, zirconium carbide, and calcium carbide to define the best possible blanket performance. In addition, assessment was carried out for these materials to define the best possible candidates for the reflector zone.

Then utilization of beryllium, lead, and zirconium were investigated with the top ranked reflector material from the previous assessment to study the possibility of replacing the beryllium material. Previous assessments for solid breeder blanket designs (4,5) concluded that blankets with beryllium have the top performance. However, the health hazard associated with the beryllium dust during the blanket fabrication promoted this assessment for the self-cooled liquid lithium concept to check the possibility of using other material.

The top ranked spectral shifter and reflector were utilized to develop the blanket design where neutronics, heat transfer, and hydraulics analyses were iterated to satisfy the different design guidelines. The first wall/blanket/shield design and optimization system code (BSDOS) was used to perform all the design iterations. BSDOS (6) represents the new generation of the blanket design tools including modularity and graphic capabilities. New capabilities have been added to the BSDOS to analyze the self-cooled blanket concepts. BSDOS provides fast and accurate tool to design, to analyze, and to improve the performance of the first wall/blanket/shield concept based on multi-dimensional analyses. In addition, BSDOS is capable of performing other functions including:

(a) comparison and evaluation studies using the same database and ground rules, (b) optimization of the first wall/blanket/shield parameters under several design constraints, (c) studying the effect of improving the engineering data base to plan future designs, and (d) evaluating the effect of the data uncertainties on the first wall/blanket/shield performance.

Special attention has been given to the first wall design because of its impact on the blanket structural design and the allowable toroidal span of the blanket sector. The ITER Structure Design Criteria (ISDC) were applied to the first wall design. ISDC provide primary and secondary stress limits as functions of the reduced uniform elongation and ductility of the material with neutron fluence. The first wall lifetime was analyzed as a function of the lithium coolant pressure, toroidal span of the blanket sector, second wall thickness, and the sidewall thickness of the blanket sector. The results from these analyses defined the first wall design and the main structure requirements of the blanket sector.

Material considerations have been carefully considered to insure satisfactory blanket performance. Baseline mechanical properties were compiled for the design process including the effect of neutron irradiation. Vanadium compatibility with the multiplier and reflector materials was assessed in the presence of the thermal bonding material. Current R&D results from electrical insulator work for the lithium channels were reviewed to insure consistency with the design approach.

Several design guidelines were adopted for this study to insure a substantial enhancement in the blanket performance. The results from the above analyses were used to develop a blanket configuration capable of 2 MW/m^2 average surface heat flux and 10 MW/m^2 neutron wall loading. The energy multiplication and the shielding capability of the blanket are maximized. The local tritium-breeding ratio is maintained above 1.3 to insure tritium self-sufficiency. Natural lithium is used to avoid the cost of the lithium enrichment process. Simple blanket configuration is selected to reduce the fabrication cost, to improve the blanket reliability, and to increase confidence in the

blanket performance. The total blanket and shield thickness, the energy deposition in the shield, and the first wall nuclear heating are minimized to reduce the reactor capital cost and to enhance the blanket performance. Low activation materials are considered in the material selection process to enhance the environmental acceptance of the fusion reactor. Electrical insulator is used for the lithium channels to maintain low-pressure system and long lifetime for the blanket structure. Parametric studies were carried out to define the effect of the reactor parameters, the lithium inlet temperature, and the maximum temperature of the vanadium structure on the blanket performance.

III. Spectral Shifter (Neutron Multiplier) Materials

A neutron multiplier material is usually utilized for solid breeder blanket concepts to provide adequate tritium breeding capability. In solid breeder blanket concepts, the existence of the other elements in the lithium compound and the high volume fraction of the structural material result in a tritium breeding ratio of less than one. In this study, lithium has a good tritium breeding capability without neutron multiplier. In addition, the blanket has a low volume fraction of the vanadium material, which does not affect the neutron economy. These characteristics of the self-cooled lithium-vanadium are responsible for its poor neutron attenuation performance, which necessitates the large radial thickness to convert the fusion neutron energy into sensible heat and to utilize the fusion neutrons for tritium production. Therefore, a spectral shifter is incorporated in this blanket concept to reduce the large mean free path of the DT fusion neutrons without significant energy loss through endothermic nuclear reactions and neutron loss through parasitic absorption. In this concept, the spectral shifter is also intended to reduce the required blanket thickness, to enhance the blanket energy multiplication factor, and to reduce the energy deposition in the shield. These changes significantly enhance the performance of the self-cooled lithium-vanadium blanket concept. Blanket concepts with lithium-lead eutectic accomplish some of these objectives because of the lead material in the eutectic. In this case, the lead concentration in the breeder material is much more than the blanket requirement for the nuclear design.

Several studies (7, 5, and 4) assessed the possible neutron multipliers and energy converters for fusion blankets. Beryllium, lead, and zirconium have been found to have the highest potential if the fissionable materials are excluded. Bismuth was excluded from the start because it has activation problem due to ^{210}Po production. High (n,2n) and low absorption cross sections are the main factors to achieve the required nuclear performance. The (n,2n) macroscopic cross sections of the three materials are shown in Figure 3 where zirconium has the lowest potential among the three materials. In addition, the zirconium absorption cross section is the highest among the three materials. These three materials are considered further in this study to quantify their performance.

Some relevant physical properties of the three materials are listed in Table I. The high melting temperatures of beryllium and zirconium permit the blanket to operate without phase change. Beryllium has a health hazard associated with its dust during the blanket fabrication that requires special handling procedure. In addition, the blanket design has to accommodate its swelling and the small amount of tritium produced during operation. Beryllium utilization in the blanket results in high values for both the energy multiplication factor and the tritium breeding ratio. This performance is unique for beryllium relative to the other possible materials.

Lead has a low melting temperature that necessitates its use in the liquid phase to avoid volumetric changes at start up and shut down. Lead produces ^{210}Po and ^{205}Pb . ^{210}Po is an α -emitter, which is produced from neutron irradiation of bismuth. Bismuth is a transmutation of lead by neutron capture and a natural impurity of lead. Blankets with lead require on-line removal of polonium or its precursor bismuth to limit the ^{210}Po concentration in lead. ^{205}Pb is very long-lived isotope, which decays by electron capture.

Zirconium produces ^{93}Zr and ^{93}Nb isotopes, which have very long half-lives. In addition, zirconium generates more decay heat relative to beryllium and lead.

Figure 3. (n,2n) macroscopic cross section of beryllium, zirconium, and lead

Table I. Properties of beryllium, zirconium, and lead

Material	Beryllium	Zirconium	Lead
Density, gm/cm ³	1.85	6.5	11.34
Number of atoms per cm ³ x 10 ⁻²⁴	0.1236	0.0429	0.0335
Melting temperature, °C	1283	1852	327
Thermal conductivity, W/m-°k			
at 20 °C	200	22.7	35.2
at 500 °C	109	21.4	18.6

Liquid Phase

In this study, parametric analysis was performed to compare the performance of the three materials. In addition, material activation, cost, and thermal performance are considered in the comparison. The details are given later in this report.

IV. Spectral Shifter (Neutron Moderator) and Reflector Materials

Neutron moderator and reflector materials are used in the blanket to slow down the high-energy neutrons for absorption in the lithium and to decrease the loss of neutrons from the blanket by scattering back many of those that have escaped. The best material consists of elements with low mass number and low absorption cross section. In addition, this material has to contribute to the energy multiplication in the blanket, which favors a material with exothermic nuclear reactions. Water is excluded because of the use of liquid lithium. Beryllium is also excluded from this function because of the desire to reduce the total material cost and other considerations. Carbon, copper, tungsten, type 316 austenitic steel, manganese steel, vanadium, calcium oxide, tungsten carbide, titanium carbide, zirconium carbide, and calcium carbide are examined to select the most promising material(s).

Elemental carbon has the lowest mass number possible for use and a low absorption cross section, which improves the tritium breeding capability of the blanket. In addition, carbon has low activation characteristics. Carbide materials are considered for their carbon content and stability at high temperature. Copper is included because of its high thermal conductivity, which eases the thermo-mechanical design of the moderator/reflector zone(s). The good shielding capability of the tungsten promoted its consideration. The good fabrication characteristics, the low unit cost, and the existing database lead to the steel consideration. Calcium oxide was selected before as reflector material for the self-cooled lithium-vanadium blanket design (8) because it has low activation characteristics and low unit cost.

Parametric analyses were performed to compare the performance of each material. Unit cost, activation, decay heat, shielding performance, and material compatibility with the vanadium structure were considered to select the best candidate(s). These analyses are given later in this report.

V. Blanket Configuration

The blanket configuration was developed to achieve the objective of this study and to utilize the R&D results to enhance the attractiveness of the fusion system. To enhance the first wall capability for accommodating high surface heat flux, a small coolant channel with high lithium velocity is located between the first wall and the spectral shifter. This lithium coolant provides a direct heat transfer path for the surface heat flux that minimizes the maximum first wall temperature. In addition, the high lithium velocity results in a higher heat transfer coefficient, which allows the first wall to accommodate a higher surface heat flux for the same maximum structural temperature. However, the blanket neutronics requires the spectral shifter to be very close to the first wall. Neutronics, heat transfer, hydraulics, and structural analyses were iterated to define the optimum design window for the first wall and the spectral shifter.

In other designs (3 and 8), a poloidal lithium flow with low velocity is utilized to reduce the MHD pressure drop as much as possible. In this study, an electrical insulator is applied to the lithium channels to reduce the MHD pressure drop. In addition, the blanket lithium inventory was reduced to enhance the blanket safety performance during abnormal events.

The previous poloidal design approaches have several disadvantages, which this study is tended to eliminate. First, the blanket has a large radial thickness that has a negative impact on the total cost of the reactor. Second, because of the poor shielding capability of the blanket, a large radial shield thickness is required. Such a configuration reduces

the thermal efficiency of the system because a significant fraction of the reactor power is recovered from the shielding zone at low temperature. In addition, this large radial shield thickness has a negative effect on the total reactor cost. The integrated first wall/blanket/reflector/shield concept was developed to improve the thermal efficiency of such blanket configuration. This approach required a hot shield cooled with the liquid lithium (9). The separate cooling system for the shield is eliminated. Other advantages of the hot shield concept include the nuclear heat removal from the shield at high temperature for efficient energy conversion, the blanket thermal inertia is increased for decay heat accommodation, and the fabrication and maintenance procedures are simplified. However, this configuration requires special attention to the thermal insulation between the hot shield and the other reactor components and it does not reduce the requirement of a large radial shield thickness. The third disadvantage of these poloidal configurations is the low blanket energy multiplication factor, which increases the cost of electricity.

The approach taken for the development of the blanket configuration in this study is to eliminate these three disadvantages while maximizing the blanket capability to operate at high power density. First parametric and comparison studies were performed for different blanket configurations with and without a spectral shifter (neutron multiplier). Then blanket performance with different spectral shifters (neutron multipliers) and reflectors were compared. The top ranked combination of spectral shifter and reflector is considered for further developments. The idea of simple poloidal flow in a poloidal duct is maintained to insure simple fabrication procedure and low total cost. A small lithium coolant zone between the first wall and the neutron multiplier zone is used to accommodate the maximum possible surface heat flux. Then spectral shifter (moderator) zones are distributed radially inside the lithium based on neutronics, heat transfer, maximum temperature limits, and flow consideration. The lithium content in the blanket is reduced, which contribute to the elimination of the three disadvantages discussed before. The dimensions of the different zones were adjusted to accommodate up to 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading, however these values are arbitrary. The configuration can be adjusted to accommodate

higher or lower values as needed by adjusting the blanket design parameters. Figures 1 and 2 show the obtained blanket configuration, which has a very attractive blanket performance as shown in the rest of this report.

VI. Self-Cooled Lithium-Vanadium Blanket Without Spectral Shifter

Analysis was performed to study the blanket performance without the use of spectral shifter. Carbon and steel were used as reflector materials. For each reflector material, the blanket configuration with the best performance was defined to compare with the other blanket configurations developed for this study. Table II gives the blanket model used in the analysis. The blanket has vanadium alloy (V-4Cr-4Ti) structure material and helium-cooled steel shield. In this analysis, the lithium zone thickness was varied from 0.2 to 1.0 m while the reflector zone thickness was varied from 0.2 to 0.5 m. The tritium breeding ratio, the blanket energy multiplication factor, the shield energy multiplication factor, the total (blanket and shield) energy multiplication factor, and the energy fraction deposited in the shield are plotted in Figures 4 through 13 for both materials.

The results of the blanket neutronics performance parameters with carbon reflector show that the tritium-breeding ratio increases as the lithium zone thickness increases to reach saturation. Increasing the carbon reflector zone thickness from 0.2 to 0.5 m has insignificant effect on the tritium-breeding ratio as shown in Figure 4. However, the blanket energy multiplication factor increases as the lithium zone thickness or the reflector zone thickness increases as shown in Figure 5. The total energy multiplication in Figure 7 shows different behavior due the difference between the kerma factors of the carbon reflector and of the steel shield. The shield multiplication factor decreases as the lithium zone thickness or the reflector zone thickness increases as shown in Figure 6, which is the contrary to the blanket energy multiplication factor. The total energy multiplication factor is the summation of the blanket and shield energy multiplication factors, which is shown in Figure 7. From these results, it is possible to define the blanket configuration shown in Table III that satisfies all the design guidelines and has

the best possible performance for this selection of materials. For this configuration, it is possible to increase the thickness of the lithium zone and reduce the reflector zone thickness while maintaining the same blanket performance and total thickness. The blanket configuration with the small lithium zone thickness is selected because of cost, safety, and tritium consideration.

In the case of the steel reflector, the tritium-breeding ratio is only a function of the lithium zone thickness as shown in Figure 8. The steel shield behind the steel reflector is too thick and it is acting as a reflector material. This causes the tritium-breeding ratio to be independent of the reflector zone thickness. The blanket energy multiplication factor decreases as the lithium zone thickness increases as well as the total blanket multiplication factor. Similar to the tritium-breeding ratio, the total energy multiplication factor does not change with the reflector zone thickness as shown in Figure 12. A blanket configuration is selected in table III, which satisfies the tritium breeding requirement, the energy deposition in the shield, and the minimum blanket thickness. It is possible to increase the reflector zone thickness of this configuration to enhance the blanket energy multiplication factor as shown in Figure 9 and to reduce the energy deposition in the shield zone as shown in Figure 11. For example, changing the reflector zone thickness from 0.32-m to 0.5-m increases the blanket energy multiplication factor from 1.28 to 1.33. This enhancement results in a thicker blanket and thinner shield that produces insignificant change in the total blanket and shield thickness.

The two blanket configurations in Table III possess some unattractive features. The blanket thickness with carbon reflector is 1.16-m thick, which increases the size and the cost of the reactor. In addition, it has low blanket energy multiplication factor. The blanket with steel reflector uses less radial space and it has higher energy multiplication factor. However, the steel reflector increases the radioactive waste and the blanket decay heat, which eliminate significant advantages of the self-cooled lithium-vanadium system. Also, the heat transfer and the hydraulics of the lithium zone prefer a thinner radial thickness for improved performance.

Table II. Geometrical blanket model

Zone	Material - Dimension
First wall	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Breeder	Natural liquid lithium – 0.02 to 0.1 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Reflector	Carbon or Type 316-Austentic Steel – 0.2 to 0.5 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Shield	Steel shield (90% steel and 10% He)

Table III. Configuration and performance of self-cooled lithium-vanadium blanket without spectral shifter

Reflector Material	Carbon	Steel
Reflector zone thickness, cm	40	32
Lithium zone thickness, cm	74	38
Minimum total blanket thickness, cm	116	72
Blanket Energy Multiplication Factor (BEMF)	1.19	1.28
Local Tritium Breeding ratio (TBR)	1.69	1.30
Shield Energy Fraction (SEF)	0.03	0.03

Figure 4. Tritium breeding ratio as a function of the lithium zone thickness for different carbon reflector zone dimensions

Figure 5. Blanket energy multiplication factor as a function of the lithium zone thickness for different carbon reflector zone dimensions

Figure 6. Shield energy multiplication factor as a function of the lithium zone thickness for different carbon reflector zone dimensions

Figure 7. Total energy multiplication factor as a function of the lithium zone thickness for different carbon reflector zone dimensions

Figure 8. Shield energy fraction as a function of the lithium zone thickness for different carbon reflector zone dimensions

Figure 9. Tritium breeding ratio as a function of the lithium zone thickness for different Type 316-Austenitic Steel reflector zone dimensions

Figure 10. Blanket energy multiplication factor as a function of the lithium zone thickness for different Type 316-Austenitic Steel reflector zone dimensions

Figure 11. Shield energy multiplication factor as a function of the lithium zone thickness for different Type 316-Austenitic Steel reflector zone dimensions

Figure 12. Total energy multiplication factor as a function of the lithium zone thickness for different Type 316-Austenitic Steel reflector zone dimensions

Figure 13. Shield energy fraction as a function of the lithium zone thickness for different Type 316-Austenitic Steel reflector zone dimensions

VII. Self-Cooled Lithium-Vanadium Blanket With Beryllium Spectral Shifter (Neutron Multiplier) And Different Reflector Materials

The analysis of the self-cooled lithium-vanadium blanket without a neutron multiplier shows that the best possible configuration has some unattractive features including large radial thickness, low blanket energy multiplication factor, and large lithium zone. A beryllium neutron multiplier incorporated in the blanket to eliminate these unattractive features. The main idea is to use the beryllium neutron multiplier as spectral shifter and energy converter (7) for the DT-neutrons. The slow down of the fusion neutrons shortens the average neutron mean free path, which reduces the required blanket thickness and increases the shielding performance of the blanket. In addition, the beryllium neutron multiplication increases the tritium production from lithium-6, which overcomes the loss of the tritium generated from lithium-7. The change in the tritium production route and the extra neutron absorption in the reflector material enhance the blanket energy multiplication factor.

The blanket performance was studied as a function of the beryllium material location relative to the first wall and the radial thickness of the beryllium. Other design considerations, maximum beryllium and vanadium temperatures and thermal hydraulics of the lithium coolant constraint the possible design range for these parameters. Table IV shows the geometrical model used to carry out this analysis. The beryllium zone thickness was varied from 0.02 to 0.1 m while the lithium zone thickness between the first wall and the beryllium zone was also varied from 0.02 to 0.1 m. Several reflector materials including carbon, copper, tungsten, type 316 austenitic steel, manganese steel, vanadium alloy (V-4Cr-4Ti), calcium oxide, tungsten carbide, titanium carbide, zirconium carbide, and calcium carbide are considered in the analysis to define the best possible candidates. Both the reflector zone and the lithium zone between the beryllium and the reflector zone are 0.3 m thick based on the results of the blanket configurations without a neutron multiplier.

The tritium breeding ratio, the blanket energy multiplication factor, the total energy multiplication factor, and the shield energy fraction results with different reflector materials are displayed in Figures 14 through 49. The tritium breeding ratio shows a small increase as the lithium zone thickness between the first wall and the beryllium zone increases. On the contrary, for a fixed lithium zone thickness between the first wall and the beryllium zone, the tritium breeding ratio shows a significant increase as the beryllium zone is increased from 0.02 to 0.08 m. A tritium breeding ratio in the range of 1.35 to 1.53 is obtained with 0.04-m thick beryllium zone as shown in Table V.

For a fixed beryllium zone thickness, the blanket and the total energy multiplication factors slowly decreases as the lithium zone thickness between the first wall and the beryllium zone increases. Similar to the tritium breeding ratio, both parameters show a large increase as the beryllium multiplier zone thickness increases. A blanket energy multiplication factor up to 1.48 is achievable with 0.04-m beryllium zone as shown in Table V.

The shield energy fraction decreases slowly with the increase of the lithium zone thickness between the first wall and the beryllium zone. However, it shows a fast decrease as the beryllium zone thickness increases. As explained before, it illustrates the positive effect of the beryllium material on the blanket performance as spectral shifter and energy converter.

Although the change in the blanket performance as a function of the zone thickness of beryllium or lithium is similar, the obtained performance depends on the choice of the reflector material. Table V compares the blanket performance parameters for the same dimensions with different reflector materials. Because of poor shielding performance, carbon, calcium oxide, and calcium carbide can be discarded. Steel, copper, and zirconium carbide are also eliminated because of activation and decay heat concerns. Low energy multiplication, high cost, and decay heat concerns discourage the use of tungsten and tungsten carbide. Among the other two materials, titanium carbide

material is the first choice for the reflector zone. In addition to the good blanket performance, it has attractive characteristics including good material stability and mechanical properties. Low activation manganese steel is the backup candidate although it has high decay heat.

Table IV. Geometrical blanket model

Zone	Material - Dimension
First wall:	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Breeder:	Natural liquid lithium – 0.02 to 0.1 m
Structure:	Vanadium alloy (V-4Cr-4Ti) – 0.5 m
Multiplier:	Beryllium – 0.02 to 0.1 m
Structure:	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Breeder:	Natural liquid lithium – 0.3-m
Structure:	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Reflector:	carbon, copper, tungsten, type 316 austenitic steel, vanadium alloy (V-4Cr-4Ti), calcium oxide, tungsten carbide, titanium carbide, zirconium carbide, calcium carbide, or manganese steel – 0.3 m
Structure:	Vanadium alloy (V-4Cr-4Ti) – 0.01 m
Shield:	Steel shield (90% steel and 10% He)

Figure 14. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with carbon reflector

Figure 15. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with carbon reflector

Figure 16. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with carbon reflector

Figure 17. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with carbon reflector

Figure 18. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with steel reflector

Figure 19. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with steel reflector

Figure 20. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with steel reflector

Figure 21. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with steel reflector

Figure 22. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten reflector

Figure 23. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten reflector

Figure 24. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten reflector

Figure 25. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten reflector

Figure 26. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with copper reflector

Figure 27. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with copper reflector

Figure 28. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with copper reflector

Figure 29. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with copper reflector

Figure 30. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with manganese-steel reflector

Figure 31. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with manganese-steel reflector

Figure 32. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with manganese-steel reflector

Figure 33. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with manganese-steel reflector

Figure 34. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium oxide reflector

Figure 35. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium oxide reflector

Figure 36. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium oxide reflector

Figure 37. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium oxide reflector

Figure 38. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten carbide reflector

Figure 39. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten carbide reflector

Figure 40. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten carbide reflector

Figure 41. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with tungsten carbide reflector

Figure 42. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with titanium carbide reflector

Figure 43. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with titanium carbide reflector

Figure 44. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with titanium carbide reflector

Figure 45. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with titanium carbide reflector

Figure 46. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with zirconium carbide reflector

Figure 47. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with zirconium carbide reflector

Figure 48. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with zirconium carbide reflector

Figure 49. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with zirconium carbide reflector

Figure 50. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium carbide reflector

Figure 51. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium carbide reflector

Figure 52. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium carbide reflector

Figure 53. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions with calcium carbide reflector

Table V. Self-Cooled Lithium Vanadium Blanket Configuration With Beryllium Neutron Spectral shifter And Different Reflector Materials

Reflector Material	C	Steel	W	Cu	Mn- steel	CaO	WC	TiC	ZrC	CaC ₂
Beryllium thickness, cm	4	4	4	4	4	4	4	4	4	4
Lithium thickness, cm	33	33	33	33	33	33	33	33	33	33
Blanket thickness, cm	70	70	70	70	70	70	70	70	70	70
BEMF	1.26	1.39	1.03	1.43	1.48	1.25	1.05	1.35	1.37	1.42
TBR	1.53	1.46	1.38	1.43	1.35	1.47	1.36	1.50	1.52	1.47
SEF	.080	.024	.006	.015	.030	.071	.003	.029	.033	.081
Possible Selection	No ¹	No ²	No ^{3,4,5}	No ²	Yes ³	No ¹	No ^{3,4,5}	Yes	No ²	No ¹
Material Ranking					2			1		

1 – Poor shielding performance

2 – Reflector activation

3 – High decay heat

4 – High cost

5 – Low blanket energy multiplication

VIII. Self-Cooled Lithium-Vanadium Blanket With titanium carbide reflector and different Neutron Spectral shifters

In the previous section, beryllium is utilized in the blanket as spectral shifter material because of its unique performance. Lead and zirconium are analyzed in this section to compare and to define other possible candidate(s). A self-cooled lithium-vanadium blanket with titanium carbide reflector is used with beryllium, lead, and zirconium to define the performance of these blanket configurations. Table VI gives the geometrical model used for the analysis where the zone dimensions were varied parametrically. The results for the three materials are shown in Figures 42 through 45 and 54 through 61.

The tritium breeding results show that both beryllium and lead enhance the tritium production while zirconium reduces the blanket capability for tritium breeding. Beryllium does better than lead for improving the tritium breeding performance as shown in Figures 42 and 54. In addition, beryllium improves significantly the blanket energy multiplication factor while lead does the opposite as shown in Figures 43 and 55. This confirms the beryllium selection as the best spectral shifter for the self-cooled lithium-vanadium blanket. The use of zirconium spectral shifter reduces the tritium breeding capability of the blanket because the extra neutrons from the $(n,2n)$ reactions available for tritium production does not compensate for the tritium loss from ${}^7\text{Li}(n,n'\alpha)t$ reaction. This disqualifies the use of zirconium as spectral shifter for this type of blankets. Therefore, lead is selected as the backup material for beryllium spectral shifter although lead has the disadvantages of low blanket energy multiplication factor and low melting point.

Beryllium also enhances the blanket shielding performance, which increases the attractiveness of the blanket concept. Lead and zirconium produce the same effect with respect to the shield energy fraction as shown in Figures 57 and 61. Table VII compares the blanket performance with the three spectral shifter materials for the same blanket thickness. The results in this table show clearly the excellent performance of the beryllium spectral shifter.

Table VI. Geometrical blanket model

Zone	Material - Dimension
First wall	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Breeder	Natural liquid lithium – 0.02 to 0.1 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.5 m
spectral shifter	Beryllium, lead, or zirconium – 0.02 to 0.1 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Breeder	Natural liquid lithium – 0.3 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.05 m
Reflector	Titanium carbide, – 0.3 m
Structure	Vanadium alloy (V-4Cr-4Ti) – 0.01 m
Shield	Steel shield (90% steel and 10% He)

Figure 54. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different lead spectral shifter zone dimensions with titanium carbide reflector

Figure 55. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different lead spectral shifter zone dimensions with titanium carbide reflector

Figure 56. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different lead spectral shifter zone dimensions with titanium carbide reflector

Figure 57. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different lead spectral shifter zone dimensions with titanium carbide reflector

Figure 58. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different zirconium spectral shifter zone dimensions with titanium carbide reflector

Figure 59. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different zirconium spectral shifter zone dimensions with titanium carbide reflector

Figure 60. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different zirconium spectral shifter zone dimensions with titanium carbide reflector

Figure 61. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different zirconium spectral shifter zone dimensions with titanium carbide reflector

Table VII. Blanket performance with and without spectral shifter material

Multiplier Material	None	Be	Pb	Zr
Multiplier thickness, m	0	0.04	0.04	0.04
Lithium thick., m	33	0.33	0.33	0.33
Blanket thickness, m	0.66	0.70	0.70	0.70
Blanket Energy Multiplication Factor	1.24	1.35	1.06	1.27
Local Tritium Breeding ratio	1.26	1.50	1.31	1.21
Shield Energy Fraction	.046	.029	.041	.034
Possible Selection	No ¹	Yes	Yes ³	No ^{1,2}
Ranking		1	2	

1 – Poor performance

2 – Activation problem and low tritium breeding ratio

3 – Liquid form

IX. Heat Transfer Considerations

Heat transfer analyses were performed and iterated within the design parameters obtained from the neutronics results. This approach was performed for the first wall, the beryllium spectral shifter, and the titanium carbide reflector. Some of this analysis was performed in parallel to the neutronics analysis to obtain the best possible blanket performance.

IX.1. First Wall

The first wall design has to satisfy two design requirements for acceptable performance a) structural design rules to achieve the required lifetime, and b) minimum and maximum material temperature guidelines. The structural design rules and analysis are given later in different section. The vanadium alloy needs to operate in the temperature range of 400 to 800 °C. The minimum temperature of 400 °C is intended to insure that the vanadium structure operate above the ductile-brittle transition temperature. The upper temperature is selected to insure adequate creep strength and to avoid helium embrittlement. In addition, the results from the structural design analysis requires a temperature difference across the first wall material of less than 250 °C to achieve an acceptable lifetime. The exact value depends on the first wall loading conditions and the structural design details of the blanket sector such as the first wall curvature, the second wall thickness (the clad of the spectral shifter), the toroidal span of the blanket sector, and the thickness of the side walls. A detailed structural analysis is given later.

As explained before, a coolant channel is positioned between the first wall and the beryllium spectral shifter to maximize the thermal loading conditions of the first wall. This minimizes the thermal resistance for transferring the surface heat flux and the nuclear heating to the lithium coolant and subsequently minimizes the maximum vanadium temperature. In addition, the lithium coolant is first introduced in this channel with the inlet temperature of 400 °C to minimize the maximum operating temperature of the first wall. The minimum operating temperature of the vanadium structure is satisfied by the use of lithium inlet temperature of 400 °C.

The first wall temperature is analyzed as a function of the loading conditions and its wall thickness. The loading conditions include the surface heat flux and the nuclear heating of the self-cooled lithium-vanadium blanket with beryllium spectral shifter and titanium carbide reflector. The neutron wall loading is varied from 1 to 10 MW/m² and the surface heat flux is taken as 0.2 the neutron wall loading value. The temperature difference across the first wall thickness is shown in Figure 62 as a function of the loading

conditions for different wall thicknesses. The maximum temperature of the first wall corresponding to the same loading conditions and 400 °C inlet lithium temperature is shown in Figure 63. For the poloidal cooling design, the maximum first wall temperature occurs at the last point of the poloidal path of the lithium coolant where the coolant temperature is the highest. For the 600 °C-outlet lithium temperature, the coolant temperature at this point is 470 °C for the peak loading conditions of 10 MW/m² neutron wall loading and 2 MW/m² surface heat flux. These results require a first wall thickness of 4 mm or less to accommodate the peak loading conditions based on the above requirements.

Figure 62. Temperature difference across the first wall as a function of the loading conditions for different first wall thicknesses.

Figure 63. Maximum first wall temperature as a function of the loading conditions for different first wall thicknesses for lithium inlet temperature of 400 °C

IX.2. Spectral Shifter

Beryllium is selected as the primary spectral shifter material based on its superior performance shown in the previous section and lead is the backup. Vanadium clad is used for both materials. Liquid sodium is utilized as thermal bonding material between the vanadium clad and the beryllium material. In addition, the use of the sodium bonding provides a mechanism to accommodate beryllium swelling. This bonding technology was developed and used for both functions successfully in fuel rods of fission reactors. Other liquid metal bonding materials are also under consideration. The lead spectral shifter has good thermal contact with vanadium clad because it operates in liquid form due to the 400 °C inlet lithium temperature.

The neutronics analyses in the previous sections concluded that the thickness of the beryllium spectral shifter is about 0.04 m to satisfy the design guidelines. The extreme

temperatures of the beryllium spectral shifter were studied as a function of the beryllium thickness for different vanadium clad thicknesses with loading conditions of 10 MW/m^2 neutron wall loading and 2 MW/m^2 surface heat flux. For the 0.035-m thick beryllium, the maximum and minimum temperatures are 733 and 563 with 3-mm vanadium clad thickness, respectively. The corresponding values for the case of 5-mm vanadium clad thickness are 803 and 643 °C as shown in Figure 64. The neutron irradiation of the beryllium materials shows the swelling increases as the operating temperature increases (10). Therefore, it is desirable to minimize the beryllium operating temperature, which gives preference to the use of minimum possible clad thickness. However, the first wall performance benefits from increasing the vanadium clad thickness as will be shown later. To satisfy both requirements, unequal clad thicknesses are considered for two sides of the beryllium, the first side facing the first wall is 8-mm thick and the second side is 2 to 3-mm thick. This configuration provide thick clad thickness that improves the first wall strength and maintains 800 °C maximum beryllium temperature. Figure 65 shows the extreme beryllium temperature for this configuration. At 8-mm front clad thickness, the minimum beryllium temperature change from the front surface facing the plasma to the back surface, which explain the change in the minimum temperature gradient shown in Figure 65 at this clad thickness.

Figure 64. Extreme temperatures of the beryllium spectral shifter as a function of its thickness for different clad thicknesses

Figure 65. Extreme temperatures of the beryllium spectral shifter as a function of the front clad thickness for different back clad thicknesses

IX.3. Reflector

Titanium carbide utilization in self-cooled lithium-vanadium blanket with beryllium spectral shifter enhances the neutronics performance as shown in the previous sections. In addition, titanium carbide has other attractive features that further enhance the blanket performance and design. Titanium carbide has low activation characteristics that maintains the good environmental characteristics of the lithium-vanadium system. It has very high melting point as shown in Table VIII that has positive contribution to the blanket performance during abnormal operating conditions. In addition, it has good thermal conductivity that simplifies the heat removal with low thermal stresses. Figures 66 and 67 show the specific heat and the thermal conductivity of the titanium carbide (11).

The maximum nuclear heating rate in the titanium carbide material is 17.4 W/cm^3 for 10 MW/m^2 neutron wall loading as shown in Figure 68. The nuclear heating slowly decreases with the reflector zone thickness; it drops to 2.6 W/cm^3 at the end of the 30-cm reflector zone. Heat transfer analysis of this configuration shows that internal cooling inside the reflector zone is necessary to maintain peak temperature of less than 900°C . Also, this is required to keep the peak vanadium structure temperature at the back of the blanket in the range of 750 to 800°C . Therefore, the reflector zone was divided into several zones cooled with lithium from both sides to obtain acceptable temperature distribution. In addition, distributing the titanium carbide material inside the lithium zone enhance further the blanket performance, which is considered in the final iteration of the blanket design. The heat transfer analyses of the titanium carbide zones are presented in the next two sections.

Table VIII. Titanium carbide physical properties

Chemical form	TiC
Density, gm/cm ³	4.93
Melting point, °C	3140
Boiling point °C	4820

Figure 66. Specific heat of titanium carbide

Figure 67. Thermal conductivity of titanium carbide

Figure 68. Nuclear heating distribution of lithium-vanadium blanket with beryllium spectral shifter and single titanium carbide reflector zone

X. Hydraulics Considerations

In each blanket sector, all the mass flow is introduced in the first channel (first wall channel) to cool the first wall first then the mass flow is distributed to all the other blanket channels at the blanket bottom. All the blanket cooling channels have the same radial thickness, which satisfy the neutronics performance and provide about the same mass flow rate in each blanket channel. The radial thickness of the first wall channel can be equal or exceed the radial thickness of the blanket channel. The poloidal length of the blanket sector and the lithium velocity define the radial thickness of the first wall channel. For the inboard blanket, the first wall channel has the same radial thickness as the blanket channel. In the outboard blanket, the radial thickness of the first wall

channel is larger than the thickness of the blanket channel and it is less than twice the same thickness.

The inlet lithium temperature is set at 400 °C to operate the vanadium structure above the ductile-brittle transition temperature. The lithium mass flow rate is adjusted to achieve 600 °C outlet lithium temperature. This temperature operating range results in thermal efficiency of about 43 % (12).

The first wall structural analysis results show that the allowable toroidal span for the current blanket configuration is 0.4 m. The ARIES-RS reactor geometrical parameters (13) are used as an example for this blanket with average neutron wall loading of 10 MW/m² and surface heat flux of 2 MW/m². For the 330-m² first wall surface area of ARIES-RS, this loading deposit 5046 MW in the blanket based on a blanket energy multiplication factor of 1.33. The inboard blanket of ARIES-RS consists of 16 sectors and the poloidal length of the sector is 4.4 m. Each sector has four sub-sectors and each sub-sector has 1.76 m² surface area. The thermal power of the inboard blanket sector is 26.9 MW. The required lithium mass flow rate is 38.53 kg/s for 200 °C increase in the lithium temperature. This mass flow rate produces lithium velocities of 6.06 and 1.21 m/s in the first wall and the blanket channels, respectively, assuming five blanket channels and all the channels have 3-cm radial thickness.

For the outboard blanket, the poloidal length is 1.6 times the inboard, which increases the outboard sub-sector power to 43.1 MW for the same loading conditions. The required lithium mass flow rate is 61.65 kg/s for the 200 °C increase in the lithium temperature. To use the same maximum lithium velocity of the inboard blanket, a 4.8-cm radial thickness is required for the first wall channel. Another option is to change both the maximum lithium velocity and the radial thickness of the first channel. In addition, the lithium velocity in the blanket channels is slightly increased, which improves the heat transfer coefficient and consequently reduces the maximum material temperatures in these channels.

The blanket utilizes rectangular coolant channels with large aspect ratio (length/width) of 13.3 with the length parallel to the toroidal magnetic field to reduce the magnetohydrodynamic (MHD) pressure drop and to improve heat transfer coefficient (14). For perfectly insulated channels, the MHD pressure drop can be calculated with the following equation (15)

$$\Delta p = \frac{VBL(\sigma\eta)^{1/2}}{a}$$

Where V is lithium velocity, B is the magnetic field, L is the poloidal length of the channel, σ is the lithium electrical conductivity, η is the lithium viscosity, and $2a$ is the coolant channel length in the magnetic field direction. Therefore, increasing the channel length in the direction of the magnetic field reduces the MHD pressure drop. Using this equation for the inboard blanket configuration results in a pressure drop of less than 0.04 MPa. This pressure drop does not cause any concern for the blanket design however; the total pressure drop is dominated by the pressure drop in the headers and the bottom section of the blanket. The blanket sector is designed for 0.5 MPa lithium coolant pressure.

The other important aspect is the influence of the toroidal magnetic field on the heat transfer characteristics of the lithium flow in the rectangular channel. Few experimental and analytical studies (14) were performed to quantify the magnetic field effects on the heat transfer with turbulent flow. For turbulent flow, the magnetic field changes the flow pattern, which effects the heat transfer mechanism in the channel. The magnetic field has two effects on the flow. First, the velocity and the velocity gradients near the channel wall parallel to the magnetic field are increased to generate an M-shaped velocity distribution, which has a positive effect on the heat transfer coefficient. The electrical insulator used to reduce the MHD pressure drop reduces the degree of this change. Second, the velocity fluctuations (eddies) are damped, which has a negative effect on the heat transfer coefficient. These two conflicting effects define the net impact on the heat transfer coefficient, which is difficult to calculate without experimental verification. The limited experimental results (16) for rectangular channel flow in transverse magnetic field with heat transfer and without electrical insulator shows that

MHD heat transfer is 1.2 – 1.3 times better than turbulent flow without magnetic field for Peclet number of 200 and Hartmann number of 800. Also, the experimental results show that the heat transfer coefficient increases as the Hartmann number changed from 0 (no magnetic field) to 800 or the Peclet number changed from 12.5 to 200. In this blanket study, no improvements are assumed in the thermal-hydraulics analysis because of the magnetic field and a large design margin is included in the first wall design to accommodate the MHD heat transfer uncertainties.

XI. Structural design criteria and first wall stress analysis

It has been customary in past design studies (1 and 13) to limit the maximum surface heat flux capability of a design on the basis of explicit or implicit peak temperature limits for the structural alloys used for the plasma facing components. This was done without detailed consideration or analysis of damages due to creep, neutron, or helium-induced embrittlement. The analysis presented in this section show that such limits could be exceeded. Detailed deformation and damage analyses together with material properties data show that the maximum stresses and strains due to the expected loading conditions can meet the lifetime requirements of the design. In addition, the results show that the maximum surface heat flux capability of the first wall depends not only on the mechanical properties of the first wall material but also on the blanket design details and the structural design criteria used to set limits on stresses and strains.

ITER Structural Design Criteria (ISDC) is used to analyze the first wall for the developed blanket design. Some of the basic design allowables and rules for handling embrittlement and thermal creep of the first wall are included in this section. Fatigue, creep-fatigue, and brittle fracture from pre-existing flaws are not yet considered.

XI.1. Design allowables

XI.1.1. Allowable primary membrane stress intensity (S_m)

S_m is a temperature (T) and fluence (Φt) dependent allowable stress intensity. It is defined as the least of the following quantities

$$\text{Min } [1/3S_{u,\text{min}}(\text{RT}, 0), 1/3S_{u,\text{min}}(T, 0), 1/3S_{u,\text{min}}(T, \Phi t), 2/3S_{y,\text{min}}(\text{RT}, 0), \\ 2/3S_{y,\text{min}}(T, 0), 2/3S_{y,\text{min}}(T, \Phi t)],$$

where $S_{y,\text{min}}$ and $S_{u,\text{min}}$ are the minimum yield and ultimate tensile strengths, respectively, and RT is room temperature. No credit is taken for irradiation hardening, but any softening due to irradiation or thermal aging effects is taken into account. Variation of S_m for V-4Cr-4Ti with temperature is shown in Figure 69.

Figure 69. Tensile curves and allowable primary stress intensity S_m for unirradiated V-4Cr-4Ti

XI.1.2. Allowable primary plus secondary membrane stress intensity (S_e)

S_e is a temperature (T) and fluence (ϕt) dependent allowable stress intensity for a material with severe loss of uniform elongation due to irradiation. It is defined as follows

$$S_e = \begin{cases} \frac{1}{3} \left[S_{u,\min}(T, \phi t) + \frac{E \alpha_1}{r_1} (\epsilon_u(T, \phi t) - 0.02) \right] & \text{if } \epsilon_u \geq 0.02 \\ \frac{1}{3} [S_{u,\min}(T, \phi t)] & \text{if } \epsilon_u < 0.02 \end{cases} \quad (1)$$

where E is Young's modulus, ϵ_u is uniform elongation, $\alpha_1 = 0.5$, and

$$r_1 = \begin{cases} \infty & \text{for } \epsilon_u \leq .02 \text{ (2\%)} \\ 4 & \text{for } \epsilon_u > .02 \end{cases} \quad (2)$$

If the operating temperature of V-4Cr-4Ti remains higher than 400°C, the material retains sufficient ϵ_u so that the values of S_e are much greater than maximum stresses expected.

XI.1.3. Allowable total stress intensity (S_d)

S_d is a temperature (T), fluence (ϕt), and r -factor dependent allowable stress intensity for total primary plus secondary stress in radiation embrittled materials. It is defined as follows

$$S_d = \frac{2}{3} \left(S_{u,\min}(T, \phi t) + \frac{E \epsilon_{tr}(T, \phi t)}{r \cdot TF} \right) \quad (3)$$

where ϵ_{tr} is true strain at rupture, TF is a triaxiality factor to account for the effect of hydrostatic stress on ductility, r is the elastic follow-up factor whose value is r_2 in zones of stress concentration (i.e., peak stress due to stress concentration is included), and r_3 away from zones of stress concentration.

$$r_2 = \text{Max} \{K_T \text{ and } 4\} \quad (4a)$$

where K_T is the elastic stress concentration factor and

$$r_3 = \begin{cases} \infty & \text{for } \epsilon_u \leq .02 \text{ (2\%)} \\ 4 & \text{for } \epsilon_u > .02 \end{cases} \quad (4b)$$

In contrast to S_m , we take credit for irradiation hardening, as reflected in the increase in S_u with fluence, in the definition of S_e and S_d . Thus, the loss of allowable stress due to reduction of ductility can be partly offset by the increase in S_u if the material is hardened by irradiation. The ϵ_{tr} values of irradiated V-4Cr-4Ti remains sufficiently high at all temperatures so that the values of S_d are much greater than maximum stresses expected.

XI.1.4. Time-dependent allowable primary stress intensity (S_t)

S_t is a time and temperature-dependent allowable primary stress intensity defined as the least of the following

- (1) two thirds of the minimum stress corresponding to average creep rupture time t at temperature T ,
- (2) 80% of the minimum stress corresponding to time t and temperature T for onset of tertiary creep, and
- (3) minimum stress to cause a creep strain of $\min[1\%, \epsilon_C/5]$ in time t and temperature T ,

where ϵ_C is the minimum creep ductility. Available data for creep rupture time and time to 1 % creep strain of V-4Cr-4Ti are plotted in Figures 70a and 70b, respectively, using a Larson-Miller parameter. In the absence of data on tertiary creep, the variation of S_t for V-4Cr-4Ti with time and temperature are shown in Figure 71. Note that if the creep

ductility of V-4Cr-4Ti is reduced to $\leq 1\%$ due to He-embrittlement, the value of S_t might be reduced from those shown in Figure 71.

Figure 70. Larson-Miller parameter plots of (a) creep rupture time and (b) time to 1% creep strain for V-alloys.

Figure 71. Variation of S_m and S_t for V-alloys with temperature and design lifetime

XI.2. Low temperature design rules

XI.2.1. Necking and plastic instability limits

To prevent failure by necking and plastic instability, the following limits must be satisfied at all times

$$\overline{P_m} \leq S_m(T_m, \phi t_m) \quad (5a)$$

$$\overline{P_L + P_b} \leq K S_m(T_m, \phi t_m) \quad (5b)$$

where P_m is general primary membrane stress (bar over a stress denotes its intensity), P_L is local primary membrane stress, P_b is primary bending stress, K is bending shape factor ($K = 1.5$ for solid rectangular section), and S_m is evaluated at the thickness-averaged temperature (T_m) and fluence (ϕt_m).

XI.2.2. Plastic flow localization limit

To prevent cracking due to plastic flow localization (in a material with significant loss of uniform elongation due to irradiation), the following limit must be satisfied at all times during the life of the component

$$\overline{P_L + Q_L} \leq S_e(T_m, \phi t_m), \quad (6)$$

where Q_L is the secondary membrane stress. As mentioned earlier, for the material considered here with the operating temperature $> 450^\circ\text{C}$, this rule is always satisfied.

XI.2.3. Ductility exhaustion limits

To prevent local fracture due to exhaustion of ductility (due to embrittlement), the following limits must be satisfied at all times during the life of the component

The total stress, including peak stress, is limited by

$$\overline{P_L + P_b + Q + F} \leq S_d(T, \phi t, r_2), \quad (7a)$$

where F is peak stress (e.g., due to stress concentration), and the total stress, excluding peak stress, is limited by

$$\overline{P_L + P_b + Q} \leq S_d(T, \phi t, r_3). \quad (7b)$$

As mentioned earlier, this rule is always satisfied for first wall made of V-4Cr-4Ti.

XI.2.4. Ratcheting limits

To prevent ratcheting due to cyclic loading, either of the following two limits should be satisfied at all times

$3S_m$ limit

$$(\overline{P_L + P_b})_{\max} + \Delta[\overline{P} + \overline{Q}]_{\max} \leq 3S_m(T_m, \phi t_m) \quad (8)$$

where Δ denotes range of primary (P) or secondary (Q) stress due to cyclic loading.

Bree-diagram limit

$$Y \leq \begin{cases} \frac{1}{X} & \text{for } 0 \leq X \leq 0.5 \\ 4(1 - X) & \text{for } 0.5 < X \leq 1 \end{cases} \quad (9a)$$

where X denotes range of primary (P) or secondary (Q) stress due to cyclic loading.

$$X = \frac{\overline{P_m}}{S_y} \text{ or } X = \frac{\overline{P_L + \frac{P_b}{K}}}{S_y} \text{ and } Y = \frac{\Delta[\overline{P} + \overline{Q}]}{S_y}, \quad (9b)$$

and the yield stress S_y is evaluated at the average of the thickness-averaged temperatures at the "cold" and "hot" ends of the cycle.

XI.3. High temperature design rules

XI.3.1. Creep damage limits

To guard against creep damage, the following limits must be satisfied

$$\overline{P_m} \leq S_t(T_m, t) \quad (10a)$$

$$\overline{P_L + P_b / K_t} \leq S_t(T_m, t) \quad (10b)$$

where t is the design lifetime, and $K_t = (K+1)/2$. If the lifetime involves variable stress and temperature history, Equations 10a-b are replaced by limits on usage fraction sums.

XI.3.2. Creep-ratcheting limit

In addition to satisfying the low temperature ratcheting limit based on Bree diagram (Equation 9a), the high temperature-ratcheting limit should be satisfied by first calculating an effective core stress σ_c for creep calculations as follows

$$\sigma_c = Z S_{yL} \quad (11)$$

where S_{yL} is the S_y value at the "low" temperature extreme of the cycle and Z is a creep stress parameter defined in terms of X and Y (which are defined in Eq. 9b),

$$Z = X \text{ for } X + Y \leq 1 \quad (12a)$$

$$Z = Y + 1 - 2\sqrt{(1-X)Y} \text{ for } 1-X \leq Y < 1/(1-X) \quad (12b)$$

$$Z = XY \text{ for } Y > 1/(1-X) \quad (12c)$$

The total creep strain accumulated during the lifetime due to a stress $1.25 \sigma_c$ should be less than $\min [1 \%, \epsilon_c / 5]$ where ϵ_c is the minimum creep ductility during the cycle. If the lifetime involves more than one type of cycles of stress and temperature, the criterion is satisfied by the use of usage fraction sums.

The variations of maximum allowable cyclic secondary (thermal) stress intensity range with steady primary stress intensity for V-4Cr-4Ti at various peak temperatures and for design lifetimes of 25,000 h and 80,000 h are shown in Figures 72a and 72b,

respectively. The plots assume a coolant (lithium) temperature of 500°C and a film temperature drop of 50°C at the coolant-first wall interface (corresponds to a heat transfer coefficient of 40,000 W/m²/°C at a surface heat flux of 2 MW/m²).

Figure 72. Allowable cyclic secondary stress intensity range at various peak temperature of a V-alloy first wall for given steady primary stress intensity for design lifetime of (a) 25,000 h and (b) 80,000 h. The temperature of the first wall at the coolant edge, with surface heat flux on, is 550°C and the temperature at the "cool" end of the cycle is assumed to be the same as the coolant temperature (500°C).

XI.4. High power density self-cooled lithium blanket stress analysis

The geometrical cross-section of the design is shown in Figure 73. The first wall is curved in order to maximize its toroidal span by increasing its capability to resist the coolant pressure. For this analysis, a unit poloidal thickness of the blanket with a coolant pressure of 0.5 MPa is considered. The pressure exerted by the beryllium and titanium carbide materials on the surrounding structures is 0.1 MPa in this analysis. The maximum primary stress in the first wall is a strong function of the thickness, height h and toroidal span of the first wall, and the thickness of the sidewall and the second wall. In this analysis, the first wall thickness is kept constant at 4 mm in order to keep the thermal stresses within acceptable limits. This still leaves us with a number of geometrical parameters which, if necessary, can be chosen to optimize the surface heat

flux capability of the design while at the same time satisfy various design rules. After a number of trial analyses, the following parameters are chosen as the reference geometry for the blanket

First wall toroidal span	0.4 m
First wall height h	100 mm
First wall thickness	4 mm
Side wall thickness	10 mm
Second wall thickness	8 mm

In this analysis, the surface heat flux on the first wall is treated as a variable without changing the temperature distribution in the rest of the blanket structure. Note that at a surface heat flux of 2 MW/m² with a coolant temperature of 470°C, the peak temperature of the first wall is 743°C.

Figure 73. Half of cross-section of high power density self-cooled lithium blanket with a curved first wall of height h.

XI.4.1. Coolant pressure induced stresses

XI.4.1.1. Side wall thickness

The maximum allowable toroidal span of the curved first wall can be increased significantly by increasing the side wall thickness, as shown in Figure 74. A side wall thickness of 10 mm is more than sufficient for satisfying the low temperature primary stress criteria (Eqs 5a-b) for a coolant pressure of 0.5 MPa and a first wall toroidal span of 0.4 m.

Fig. 74. Maximum permissible toroidal span of a curved 4 mm thick first wall (with height $h=10$ cm) for satisfying the low temperature primary stress criterion as a function of coolant pressure and side wall thickness.

XI.4.1.2. First wall curvature

The maximum toroidal span permitted, without violating the low temperature primary stress requirements for a given coolant pressure, is a strong function of the first wall height h , as shown in Figure 75. These allowable toroidal spans can be further increased by increasing the side wall thickness. In a similar fashion, the maximum primary stress (for high temperature rules) in the curved first wall is a strong function of both the toroidal span and the first wall height h , as shown in Figure 76. A first wall height of 100 mm is sufficient to satisfy the primary stress creep rupture requirements (Equations 10a-b) for a toroidal span of 0.4 m. It can be verified by referring to Figure 71 (average first wall temperature for a surface heat flux of 2 MW/m^2 is 630°C).

Fig. 75. Maximum toroidal span vs. coolant pressure for satisfying low temperature primary stress requirements in a curved first wall as a function of height h of the first wall. The side wall thickness is 5 mm.

Figure 76. Maximum primary membrane plus bending stress intensity (for high temperature rules) in a curved first wall as a function of height h and toroidal span of first wall.

XI.4.1.3. Second wall thickness

The second wall thickness has a significant influence on the maximum primary stress in the first wall. For example, the toroidal span of the curved first wall can be increased without increasing the maximum primary stress in the first wall if the second wall thickness is also increased (Figure 77).

Figure 77. Variation of second wall thickness with the toroidal span of a curved 4 mm thick first wall with height $h=10$ cm for keeping the maximum primary membrane plus bending stress intensity in the first wall a constant.

XI.4.2. Surface heat-flux induced stresses

The thermal stress in the first wall due to the surface heat flux is controlled by the generalized plane strain assumption of the model and is, therefore, relatively insensitive to all the blanket geometrical parameters except the first wall thickness (which is assumed to be fixed at 4 mm). However, because of the interplay between primary stress and secondary stress, the blanket geometry has a significant influence on the creep ratcheting lifetime of the first wall.

XI.4.2.1. Second wall thickness

The second wall thickness has a significant influence on the lifetime requirement of the first wall. Figure 78 shows the allowable creep rupture time due to primary stresses and the allowable lifetime for satisfying creep-ratcheting rule as functions of the second wall thickness. Note that the creep ratcheting rule puts a more stringent requirement on the lifetime than the creep rupture rule.

Figure 78. Allowable lifetime at a surface heat flux of 2 MW/m^2 vs. second wall thickness for satisfying primary stress and creep ratcheting rules. A toroidal span of 0.4 m with a first wall height h of 100 mm is used.

XI.4.2.2. Coolant temperature

Because of the exponential dependence of creep rate on temperature, the coolant temperature has a significant influence on the first wall creep-ratcheting lifetime. Figure 79 shows that by decreasing the coolant temperature by 30°C, the creep ratcheting lifetime at a surface heat flux of 2 MW/m² can be increased by a factor of >5.

Figure 79. Allowable surface heat flux on the reference design first wall to satisfy creep ratcheting rule versus lifetime as a function of the bulk coolant temperature

XI.4.2.3. First wall stress analysis concluding remarks

The maximum primary stress in the first wall of the high power density self-cooled lithium blanket is controlled by many of the geometrical parameters of the blanket, such as, first wall span, first wall height, first wall thickness, side wall thickness, and second wall

thickness. In contrast, the maximum thermal stress in the first wall due to surface heat flux is relatively insensitive to the same parameters. However, because of the combined effect of primary and secondary stresses on creep ratcheting, the blanket geometrical parameters have a significant influence on the creep-ratcheting lifetime of the blanket. Thus, by suitably choosing the blanket geometrical parameters and the coolant temperature, the surface heat flux capability of the blanket can be optimized with a long creep ratcheting and creep rupture lifetime.

Therefore, the maximum surface heat flux capability is determined not only by the mechanical properties of the first wall material but also by the geometrical configuration of the blanket.

XII. Self-Cooled Lithium-Vanadium Blanket configuration With Beryllium And Titanium Carbide Spectral Shifters

Neutronics, heat transfer, and hydraulics were iterated using the first wall and the beryllium spectral shifter parameters obtained from the previous analysis to define the blanket geometrical configuration with the titanium carbide spectral shifter that satisfies the different design guidelines and constraints.(17) For the loading conditions of 2 MW/m² surface heat flux and 10 MW/m² neutron wall loading, the heat transfer results show that the 4 mm thick first wall has a maximum temperature of 754 °C. In addition, this 4-mm thick first wall satisfies the structural design rules under consideration. The neutronics and the heat transfer analyses show that a 35 mm thick beryllium spectral shifter achieves a blanket energy multiplication and a tritium breeding ratio greater than 1.3, a shield energy deposition fraction less than 0.03, and a reduced blanket thickness. In addition, the clad thickness of the spectral shifter is constrained by the first wall structural requirements. An 8-mm thick clad used for the beryllium front section facing the plasma and 2 mm on the backside. The maximum temperature of the beryllium spectral shifter is 800 °C that occurs at the blanket exit. The beryllium spectral shifter

has no mechanical or structural function in the blanket; therefore, the high temperature operation is allowable.

In this iteration, the titanium carbide spectral shifter zone was divided to several zones where each zone is cooled from both sides. These zones have unequal thicknesses because of the exponential distribution of the nuclear heating. The iteration was performed to achieve a maximum titanium carbide temperature of less than 900 °C in each zone. The high melting point and the good thermal stability of the titanium carbide material allow its operation at high temperature. In addition, the titanium carbide spectral shifter has no mechanical or structural function in the blanket. The iteration started with two, three, and then four zones until acceptable neutronics performance and temperature distribution are obtained. Table IX gives the initial geometrical model with the four zones while the final blanket configuration is given in Table X. The nuclear heating distribution is shown in Figure 80, where the maximum nuclear heating in the vanadium structure is 65 W/cm³ for the 10 MW/m² neutron wall loading. The corresponding values for lithium, beryllium, and titanium carbide are 67, 62, and 39 W/cm³, respectively. The temperature distribution is shown in Figure 81 and 82 at the two extreme poloidal points of the blanket. The inlet and outlet coolant lithium temperatures are 400 and 600 °C where the beryllium and titanium carbide maximum temperatures occur. The maximum first wall temperature occurs at the lowest poloidal point of the blanket sector as shown in Figure 82. At this point, the first wall coolant temperature is 470 °C and the coolant is leaving the first wall channel to cool the blanket internals.

The performance parameters of the blanket are given in Table XI for the loading conditions of 2 MW/m² surface heat flux and 10 MW² neutron wall loading. The energy multiplication factor is 1.33 with a total blanket thickness of 0.57 m. The blanket deposits only 2.5% of total nuclear heating in the shield. The tritium breeding ratio is 1.32 with natural lithium. The maximum vanadium temperature is 754

Table IX. Geometrical blanket model for the final neutronics, heat transfer, and hydraulics iteration

Zone	Material	Thickness, cm
First wall	Vanadium	0.4
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	0.8
Spectral Shifter	Beryllium	3.5
Structure	Vanadium	0.2
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	0.5
Spectral Shifter	Titanium carbide	Variable
Structure	Vanadium	0.5
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	0.5
Spectral Shifter	Titanium carbide	Variable
Structure	Vanadium	0.5
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	0.5
Spectral Shifter	Titanium carbide	Variable
Structure	Vanadium	0.5
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	0.5
Spectral Shifter	Titanium carbide	Variable
Structure	Vanadium	0.5
Breeder/Coolant	Lithium	Variable
Structure	Vanadium	1.0
Shield	Steel/He	

Table X. Blanket configuration for the loading conditions of 2 MW/m² surface heat flux and 10 MW² neutron wall loading

Zone	Material	Thickness, cm
First wall	Vanadium alloy	0.4
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	0.8
Spectral Shifter	Beryllium	3.5
Structure	Vanadium alloy	0.2
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	0.5
Spectral Shifter	Titanium carbide	3.5
Structure	Vanadium alloy	0.5
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	0.5
Spectral Shifter	Titanium carbide	5.0
Structure	Vanadium alloy	0.5
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	0.5
Spectral Shifter	Titanium carbide	8.0
Structure	Vanadium alloy	0.5
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	0.5
Spectral Shifter	Titanium carbide	13.5
Structure	Vanadium alloy	0.5
Breeder/Coolant	Lithium	3.0
Structure	Vanadium alloy	1.0
Shield	Steel/He	

Table XI. Blanket Performance Parameters with 2 MW/m² surface heat flux and 10 MW² neutron wall loading

Parameter	Value
Blanket energy multiplication factor	1.33
Tritium breeding ratio	1.32
Shield energy fraction	0.025
Total radial blanket thickness, m	0.57
Lithium enrichment	Natural
Lithium coolant inlet temperature, °C	400
Lithium coolant outlet temperature, °C	600
Maximum vanadium temperature, °C	754
Maximum beryllium temperature, °C	803
Maximum titanium carbide temperature, °C	866
Lithium coolant velocity, m/s	
First wall coolant channel	6.06
Blanket channels	1.21
Calculated first wall lifetime MW.y/m ²	272

Figure 80. Nuclear Heating distribution.

Figure 81. Radial temperature distribution at the coolant inlet/outlet position

Figure 82. Radial temperature distribution at the lowest poloidal position

XIII. Materials considerations for vanadium-lithium blanket

A brief summary of the pertinent materials properties for the vanadium alloy structure, compatibility of vanadium alloys with the other blanket materials, and the insulator coating is presented in this section.

XIII.1.1. Baseline mechanical properties of vanadium alloy V-4Cr-4Ti

The baseline tensile properties of V-4Cr-4Ti are presented as a function of temperature in Figures 69 and 83. Thermal creep properties used for this study are presented in Figure 70. The ductile - brittle transition temperature for annealed (unirradiated) V-4Cr-4Ti alloy based on 1/3 size Charpy data is <100 K as indicated in Figure 84. (18 and 19)

XIII.1.1.1. Properties of irradiated vanadium alloys

The effects of neutron irradiation on the mechanical properties of vanadium alloys have been summarized in References 19 and 20. At temperatures ~400-700°C the total elongation of several vanadium alloys irradiated to 6-33 dpa varies from about 6-13% and the uniform elongation varies from ~2-10% (Figure 85). Significant increases in the tensile and yield strength occur as indicated in Figure 86. The Charpy impact properties of irradiated vanadium alloys (420-600°C) are given in Figure 87. Recent results on the irradiation creep response of V-4Cr-4Ti alloy are presented in Figure 88.(21)

XIII.1.2. Chemical compatibility of vanadium alloys with candidate spectral shifter materials

Only limited data have been reported on the chemical compatibility of vanadium alloys with candidate spectral shifter materials. However, a reasonable assessment of the compatibility of these materials can be obtained from these data and from fundamental thermodynamic information.

Beryllium and vanadium should be compatible at temperatures of interest. At very high temperatures intermetallic compounds could form. No data on corrosion of vanadium alloys by liquid lead have been found. However, Nb and Ta generally exhibit rather good corrosion resistance, particularly if the nonmetallic impurities are controlled. Vanadium is expected to be resistant to attack by lead to at least 600°C if the impurities, particularly oxygen, in lead are controlled.

TiC is expected to be compatible with vanadium alloys if the TiC contains a slight excess of Ti to prevent carburization of the vanadium. Similarly, CaO should be compatible with vanadium alloys as long as excess oxygen is controlled.

XIII.1.3. Thermal bonding material

A liquid metal, either sodium or lithium, is considered as a bond material between the vanadium alloy structure and the spectral shifter materials in order to improve the thermal contact. Corrosion or material transport through the liquid metal bond must be considered. In general, the compatibility issues are similar to those discussed in the previous section. Both sodium and lithium should be compatible with the candidate spectral shifter materials. The liquid metal will generally tend to enhance any interaction. Since the amount of liquid metal bond is small, the purity will be controlled by the contact materials. For the proposed conditions, the compatibility of the bond material with the multiplier and reflector materials is not expected to be a problem,

however, proof tests under thermal gradient conditions should be performed. The primary concern involves reactions with the Mn-steel. However, because of the small liquid metal volume and the fact that the system is closed, even this system is probably acceptable.

XIII.1.4. Electrical insulating coating

An electrically insulating coating on the vanadium alloy channel walls is proposed to mitigate MHD pressure drop in the flowing lithium coolant in the magnetic field. The proposed materials are CaO as the reference with AlN as an alternate option. Development of a reliable insulator coating is clearly an important issue for this concept. Preliminary investigations indicate that development of a satisfactory insulator coating appears promising; however, further research is required to demonstrate reliable performance. Results to date indicate that CaO can be formed on vanadium alloys and that the resistance of the coating is sufficient for the proposed applications (22). Figure 89 shows the resistance values obtained on a coating during exposure to liquid lithium. A resistance value of $\sim 100 \Omega\text{-cm}^2$ is considered necessary for projected conditions. Recent results (23) also indicate that AlN coatings formed by thermo chemical processes are compatible with lithium and exhibit good electrical resistance in short term (~ 20 hr) exposure tests (see Figure 90). Clearly substantial work on coating research is required, but current results are encouraging.

Figure 83 Uniform elongation of unirradiated V-4Cr-4Ti and V-5Cr-5Ti as compared to ferritic/martensitic F82H in the unirradiated condition.

Figure 84. Charpy impact energy for four heats of V-(4-5)Cr-(4-5)Cr(4-5)Ti alloys in the solution annealed (unirradiated) condition (1 hr @ 1000°C)

Figure 85. Uniform elongation of irradiated (6-33 dpa) vanadium alloys compared to irradiated (~36 dpa) F82H (test temperature $\approx$ irradiation temperature).

Figure 86. Temperature-dependent yield strength of unirradiated and irradiated V-(4-5%)CR (4-5%) Ti. The open symbols refer to data obtained in lithium-bounded fast reactor irradiation capsules, whereas the filled symbols correspond to unirradiated or mixed spectrum reactor irradiation data.

Figure 87. DBTT as a function of combined Cr and Ti contents measured on one-third-size Charpy specimens of V-Ti, V-Cr-Ti, and V-TiSi alloys after irradiation.

Figure 88. Data set of effective strain rate from ATR experiment and torsional creep tests in BR-10

Figure 89. In-situ $R \times A$ (solid symbol) and temperature (open symbol) vs. time for CaO coating on V-15Cr-5Ti

Figure 90. Product of resistance times area ($R \times A$) as a function of temperature for V-4Cr-4Ti alloy with Ca deposition/oxidation/Ca deposition process

Conclusions and future work

An advanced self-cooled lithium-vanadium blanket concept has been developed, which utilizes two spectral shifter materials, beryllium and titanium carbide. The blanket has very attractive features and enhanced performance using conservative engineering rules. It is designed to operate with 2 MW/m^2 surface heat flux and 10 MW/m^2 neutron wall loading. The lithium operates in the temperature range of 400 to 600 °C to enhance the plant thermal efficiency. The total blanket radial thickness is reduced to 0.57 m that has a significant influence on reducing the total reactor cost. The energy multiplication and the shielding capability are maximized while the energy deposition in the shield is minimized. The structural analysis of the first wall shows that its maximum thermal capability is determined not only by the thermal and the mechanical properties of the first wall material but also by the geometrical parameters of the blanket.

Further work is required to complete the developments of this advanced blanket concept. The radioactive waste volume and the decay heat require analysis to define the environmental aspects of the reactor system. Material selection and geometrical configuration of the shield need analysis to minimize the decay heat and the total radioactive waste volume. Assessment is required to find the best possible shielding materials for this concept. The first wall design deserves further analysis because of its impact on the allowable loading conditions, the reactor availability, the attainable structural lifetime, the blanket structural design, the blanket toroidal span, the coolant parameters, and the maintenance requirements. Detailed analysis is required for the spectral shifters including the thermal bonding with the vanadium structure. Vanadium compatibility with the spectral shifter materials needs further assessment in the presence of the thermal bonding material.

Reliability and availability of the blanket can be improved by using advanced fabrication methods, and design simplifications. Assessment is needed to define the technological requirements, the missing design data, and the R&D issues of this blanket concept.

Detailed lithium velocity profiles in the different coolant channels need analysis to calculate the pressure drop and the heat transfer characteristics including the MHD effects. The results need to be iterated with the blanket geometrical design to enhance the blanket thermo-mechanical performance. The Brayton thermodynamic cycle with helium gas was utilized for the power generation. This approach eliminates water from the system, which removes the possibility of water lithium interaction associated with the steam Rankine cycle. In addition, net thermal efficiency above 40% will be obtained.

Special effort is required to study the safety performance of the blanket. Abnormal operating events including first wall leakage, loss of flow, loss of coolant need to be analyzed. The analyses will study the consequences from these events and it will define the necessary procedure for re-operation. Blanket simplification need to be emphasized to reduce the fabrication cost, to improve the blanket reliability, and to increase confidence in the blanket performance. Blanket design analysis will be performed for a wide range of operating conditions to define the impact on its performance including reliability and safety.

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