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Fusion Blanket Design and Optimization Techniques

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FUSION BLANKET DESIGN AND OPTIMIZATION TECHNIQUES

ABSTRACT

In fusion reactors, the blanket design and its characteristics have a major impact on the reactor performance, size, and economics. The selection and arrangement of the blanket materials, dimensions of the different blanket zones, and different requirements of the selected materials for a satisfactory performance are the main parameters, which define the blanket performance. These parameters translate to a large number of variables and design constraints, which need to be simultaneously considered in the blanket design process. This represents a major design challenge because of the lack of a comprehensive design tool capable of considering all these variables to define the optimum blanket design and satisfying all the design constraints for the adopted figure of merit and the blanket design criteria. The blanket design techniques of the First Wall/Blanket/Shield Design and Optimization System (BSDOS) have been developed to overcome this difficulty and to provide the state-of-the-art techniques and tools for performing blanket design and analysis. This report describes some of the BSDOS techniques and demonstrates its use. In addition, the use of the optimization technique of the BSDOS can result in a significant blanket performance enhancement and cost saving for the reactor design under consideration. In this report, examples are presented, which utilize an earlier version of the ITER solid breeder blanket design and a high power density self-cooled lithium blanket design for demonstrating some of the BSDOS blanket design techniques.

FUSION BLANKET DESIGN AND OPTIMIZATION TECHNIQUES

I. INTRODUCTION

The fusion blanket has to perform several functions, which are essential for the reactor operation. It has to convert the kinetic energy of the fusion neutrons to recoverable heat at the highest possible temperature through exothermic nuclear reactions as much as possible, breed tritium to fuel the reactor operation and to start another reactor within a reasonable period of time, and remove the first wall surface heat flux without exceeding the allowable temperature or stress limits. In addition, it operates as a part of the radiation shield for reducing the nuclear heating and the radiation damage below the design criteria of the magnetic system and the regulatory radiation dose limits for protecting the operating personnel and the public from the radiation effects.

The blanket design parameters include the selection of different materials for performing several functions including neutron multiplication; tritium breeding; heat generation and removal; electrical insulation; neutron slowing down, absorption, and reflection; containment of the blanket materials and the generated tritium; and accommodating the mechanical, thermal, hydraulic, and electromagnetic loads. The geometrical arrangement of the selected materials and the determination of the required thickness for each blanket zone to perform the designated functions represent an engineering challenge that requires the interaction of several disciplines to achieve the optimum performance and to satisfy the operating requirements of the blanket and the selected materials. These parameters and requirements translate to a large number of variables and constraints, which need to be simultaneously considered in the blanket design process. In addition, the computation on the available reactor space between blanket and shield constrains the total blanket thickness to insure an adequate shield thickness. The lack of a comprehensive design tool capable of determining all these variables to define the optimum blanket design and satisfying all the design constraints for the adopted figure of merit and the blanket design criteria introduces undesirable approximations and simplifications in the design process. Homogenization, fixed material selection, fixed composition, and/or fixed zone thicknesses are typical approximations, which have been used in the design process to define the blanket configuration. These approximations and simplifications do not result in an optimum blanket design, which produce an adverse effect on the reactor economics and performance.

The First Wall/Blanket/Shield Design and Optimization System (BSDOS)[1] have been developed to overcome this difficulty. Over the years, BSDOS results were successfully checked using different fusion blanket designs. In addition, new techniques and improvements have been developed to enhance its performance and utilization. This report describes these blanket design techniques and demonstrates its use. In addition, the use of the optimization technique of the BSDOS is demonstrated for enhancing the blanket performance and the reactor economics. In this report, examples are presented for an earlier version of the ITER solid breeder blanket design and a high power density self-cooled lithium blanket design. These examples demonstrate the parametric and optimization analyses, and the graphic capabilities of the BSDOS.

II. BSDOS BLANKET DESIGN TECHNIQUES

The appropriate materials are selected based on their nuclear, physical, thermal, and mechanical properties for the blanket concept under consideration. The main blanket concepts can be categorized based on the breeder material.[2] Solids, liquid metals, and molten salts breeders represent the main categories. This selection defines the possible materials that can be utilized subject to performance and cost considerations. The selected materials are geometrically configured taken into consideration the neutronics, thermal-hydraulics and mechanical requirements. Then, the blanket concept is analyzed and optimized using an appropriate figure of merit for the reactor design under consideration while satisfying different design constraints and criteria. Reactor operating conditions and performance parameters, materials operating conditions, other systems requirements, interface consideration, regulatory limits, and cost implications related to the blanket design define the figure of merit and the design constraints. In the parametric or optimization blanket analysis, the selected materials, material arrangement, zone dimensions, zone compositions, and total thickness are allowed to vary according the different design constraints and guidelines.

In power reactor design, the blanket energy multiplication factor or the blanket coolant outlet temperature is a typical figure of merit for the blanket design process. However, BSDOS can use any appropriate parameter that depends on the blanket variables as a figure of merit. Linear and nonlinear constraints can be utilized to satisfy any design requirements. For example, a lower limit, upper limit, or lower and upper limits can be specified for each material temperature, material fraction in a mixture, zone thickness, total thickness of specific zones, total blanket thickness, total blanket and shield thickness, coolant velocity, coolant pressure, lithium-6 enrichment, shield energy fraction, neutron wall loading, or surface heat flux. In parametric or optimization study, BSDOS can vary all the blanket variables as specified. In addition, the reactor shield design can be considered during the blanket design process to insure that the shielding requirements are satisfied.[3] The fast neutron fluence in the superconducting material, the change in the copper stabilizer resistance or the copper atomic displacement, the insulator dose, the peak nuclear power deposition in the winding pack, and the total nuclear energy deposited in the superconducting coils are the shielding parameters for the magnetic system. Also, the regulatory limits for the biological dose are considered to protect the operating personnel and the public from the radiation effects. Typically, the blanket is designed first with fixed shield design to observe the impact on the shield performance as the blanket parameters vary. In the second step, the shield design is iterated with the obtained blanket design. Then both the blanket and shield designs are iterated for fine adjustment, which results in very small changes. This last step is required only if the second step significantly changes the shield design at the blanket-shield interface.

Because of the sensitivity and the conflicting requirements of the different design constraints, the initial blanket design will require careful consideration to define the arrangement and composition of the blanket materials. BSDOS provide three different modes for analyzing or defining the blanket design: (a) Single point design analysis, the results are based on the input specifications and the results are reported. (b) Parametric analysis, the nuclear responses and the design constrains are evaluated as a function of the design variables. The results are tabulated and plotted for understanding the impact of each variable on the blanket performance. (c) Optimization mode, the blanket design variables are defined to minimize or maximize the figure of merit while the design constraints are satisfied. In this mode, the results from the iteration process are also tabulated for understanding the progress of the optimization analysis and the blanket design. In the optimization process, the blanket performance is accurately evaluated without any approximations or assumptions while varying the design variables within the allowed limits and checking all the design constraints. BSDOS reports the design visibility and progress during the optimization process and memorizes the blanket performance as a function of the design variables. The memorization of the results reduces the number of iterations during the optimization process. BSDOS can perform the required analyses using one- or two-dimensional models based on the user request. Three dimensional capabilities are under consideration since the main BSDOS modules are capable of performing three-dimensional analyses.

Each blanket concept requires different set of constraints for a satisfactory operating performance. In solid breeder blanket concepts, operating temperature limits are defined for the solid breeder materials based on tritium retention/recovery, material stability, mass transfer, and compatibility with the structural material.[4,5] The minimum temperatures for the candidate solid breeders are within the range of 320 to 450 °C. The maximum temperatures for the same solid breeder materials are in the range of 800 to 1000 °C. This results in a large temperature range for operating these solid breeders. Some blanket design concepts are utilizing a small portion of this range. This results in a design flexibility to accommodate power variation and design uncertainties. An upper temperature limit is also defined for the multiplier materials. For example, an upper temperature limit is set for beryllium to avoid excessive swelling[6] and interaction with the structure material.[7] In addition, material considerations, design details, and reactor objectives affect this value. Radiation induced damage and compatibility issues impose an upper temperature limit for the different structural materials to maintain an acceptable performance.[2,8] This temperature limit defines the maximum neutron wall loading and surface heat flux that the blanket can accommodate.

For liquid metal and salt blanket concepts, temperature limits are defined for the coolant and structural materials. The blanket fluid, liquid metal or molten salt, operates as a coolant and breeder to simplify the blanket mechanical configuration and to eliminate issues of coolant breeder compatibility and reactivity. These blanket concepts can operate 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. The minimum coolant temperature is set to provide adequate design margin above the coolant freezing temperature and the ductile-brittle transition temperature of the structural material. Several issues define the maximum coolant temperature including coolant compatibility with the structural material or the electrical insulator coating, the mechanical properties of the irradiated structural material, and the thermal efficiency of the power conversion system.[9] Also other blanket materials (neutron multiplier, reflector, first wall tile, or spectral shifter) influence the selected coolant temperature limits.

The required combined shielding performance of the blanket and shield imposes a constraint on the blanket thickness to leave adequate space for the shield. This constraint impacts the selection and the dimension of the multiplier, the spectral shifter, and the blanket reflector.

For all blanket concepts, cost considerations can constrain the fraction or the isotopic enrichment of some materials in the blanket. Highly enriched lithium is a typical example because of the enrichment cost. Fabricated beryllium in the form of pebbles is relatively expensive. In addition, the blanket life time and the reactor availability issues add other engineering constraints. For example, corrosion issues constrain the liquid metal coolant velocity, which impacts the heat transfer coefficient. First wall thermal stresses limit the first wall thickness, which is beneficial for accommodating the primary stresses. All these issues require a design tool with an optimization capability to consider simultaneously all the design parameters and constraints.

III. GEOMETRICAL MODELS

The blanket geometrical model can be defined using the interactive conversation mode of BSDOS. The developed geometrical model is saved for further analyses or design modifications. Seven geometrical configurations are incorporated in BSDOS for the blanket analyses, which cover the typical fusion reactor models used for the blanket design work:

1. One-dimensional plane geometry for the neutronics analyses with two-dimensional plane geometry for the heat transfer and thermal hydraulics analyses,
2. One-dimensional poloidal cylindrical geometry for the neutronics analyses with two-dimensional R-Z or R-θ cylindrical geometry for the heat transfer and thermal hydraulics analyses depending on the coolant flow direction,
3. One-dimensional toroidal cylindrical geometry for the neutronics analyses with two-dimensional R-Z or R-θ cylindrical geometry for the heat transfer and thermal hydraulics analyses depending on the coolant flow direction,
4. One-dimensional spherical geometry with two-dimensional R-θ spherical geometry for the heat transfer and thermal hydraulics analyses to account for the coolant flow direction,
5. Two-dimensional X-Y plane geometry for the neutronics, heat transfer, and thermal-hydraulics analyses,
6. Two-dimensional R-Z cylindrical geometry for the neutronics, heat transfer, and thermal-hydraulics analyses, and

7. Two-dimensional R-θ cylindrical geometry for the neutronics, heat transfer, and thermal-hydraulics analyses.

The BSDOS interactive modeling capability provides a fast and flexible tool to model the reactor components including neutron source, first wall, blanket, shield, vacuum vessel, and magnet system without approximation. BSDOS prepares the required input for the different computer codes checks the input data for mistakes and transfers data between the different codes. In case of error or missing data, BSDOS asks for corrections to complete and update the input.

IV. MATERIAL PROPERTIES, NUCLEAR DATA, AND CALCULATIONAL TOOLS

The nuclear, physical, and thermal properties of the materials required for the different reactor components are stored in BSDOS routines and data files. Additional materials can be added as needed. Table 1 has the current material list more than fifty materials are included. The material density and composition are stored for the neutronics analyses. The thermal conductivity, specific heat, and density are defined as a function of temperature for the heat transfer analyses. The melting points and the latent heat are included for the different solid materials to provide warning about phase change and to allow time dependent safety analyses. For the coolant materials, thermal conductivity, specific heat, density, and viscosity are defined as a function of temperature and pressure for the thermal hydraulics analyses.

Table 1. Current BSDOS Material List

Tile materials	Be, C, W
Tritium breeders:	Li, 17Li83Pb, Li_7Pb_2, Li_2O, $LiAlO_2$, Li_2SiO_3, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3, Li_8ZrO_8, $LiNO_3$
Neutron multipliers:	Be, Pb, BeO, PbO, Zr, Zr_5Pb_3, Bi, BiPb
Coolants:	He (gas), H_2O (liq.), D_2O (liq.), Li, 17Li83Pb, Pb, Bi, BiPb
Structural materials:	Type 316SS, Type 304SS, PCA, HT9, HT9M, V15Cr5Ti, V4Cr4Ti, Fe1422, Tenelon, SiC
Reflector materials:	C, SiC, TiC, ZrC, CaC_2, Any of the above materials
Shielding materials:	B_4C, B, W, WC, W_2C, TiH_2, Concrete, Heavy Concrete, Any of the above materials
Magnet materials:	NbTi, Nb_3Sn, Cu, Al, Mylar, Epoxy, Polyimide, He (liq.), N (liq.)

DANTSYS computer code[10] is used to perform the neutronics calculations with a 67-group coupled nuclear data library (46-neutron and 21-gamma) based on ENDF/B[11,12] or FENDL.[13] BSDOS mixes and prepares binary data file of the used materials from the isotopic data for DANTSYS calculations. This process is automated based on the input process, which enhances the calculational speed. DANTSYS can perform the neutronics analysis using one-, two-, or three-dimensional geometrical model. BSDOS assumes some default values for the neutronics analyses, which can be changed during the problem specification phase. For example the S_n and the P_n order of the calculations as well as any other control parameter of the DANTSYS can be redefined interactively during the input phase, if it is needed.

The heat transfer and the thermal hydraulics analyses are performed in two dimensions even for the one dimensional neutronics analysis. The extra dimension is necessitated to account for the flow direction. A finite element model for the geometrical configuration is automatically generated through an interactive dialogue for the heat transfer and thermal hydraulics analyses. The finite element model can be viewed before any calculation. The three-dimensional mesh generator for modeling nonlinear systems INGRID[14] is employed for modeling the geometry. BSDOS couples the generated model with the nuclear heating from the neutronics analysis to prepare for the heat transfer and the thermal hydraulics analyses. The three-dimensional finite element heat transfer code TOPAZ3D[15] is utilized for the heat transfer calculations. BSDOS performs the energy balance and the thermal hydraulic analyses through direct interaction with TOPAZ3D. The two dimensional temperature plots are produced by TAURUS.[16]

The NPSOL[17] optimization package is utilized for the optimization process, which uses a sequential quadratic programming algorithm to solve unconstrained, linearly, and nonlinearly constrained problems. The blanket design uses linear constraints, nonlinear constraints, and simple upper/lower bounds for the blanket design parameters (variables and performance parameters). The optimizer starts by finding a feasible point that satisfies the simple bounds and the linear constraints. Then a sequence of major iterations is performed. The major iteration includes the solution of a sub-problem to determine a search direction that is used afterward by a bounded line search along this direction to find the optimum design.

V. DESIGN VARIABLES, CONSTRAINS AND OPTIMIZATION PARAMETERS

BSDOS allows all the input parameters to vary according to the user specified specifications. The zone dimensions, composition of each zone, density factor of each material, isotopic enrichment within an element, and coolant parameters (pressure, temperature, and velocity) can be varied. Any variable can vary freely or correlated to other variable.

The blanket and shielding performance parameters are calculated and it can be used in defining the different types of constrains. Table 2 lists the calculated performance parameters, which can used to set different types of constraints for the optimization analysis. Upper and lower bounds can be defined for each variable and constraint. If certain bounds are not present, BSDOS set special values that are treated as - **8** or + **8**. Also, it is possible to have the change of a variable to be reflected in another. For example, a liquid metal breeder-structure blanket zone can use this feature to change the structure fraction while the liquid metal breeder fraction changes in the other direction to maintain a constant total volume content. Any set of the variables can be used to form a linear constraint, which can be used to vary the thickness of certain zones while maintaining a constant total thickness. Any of the performance parameters (tritium breeding ratio, blanket energy multiplication factor, peak power density in any reactor components, energy deposition fraction in the shield, extreme temperatures of the blanket materials, etc.) can be used as nonlinear constraints to satisfy the blanket design requirements.

In the optimization analysis, a figure of merit must be selected. Any performance parameter or blanket variable can be used as a figure of merit, which is dictated by the reactor design requirements. A minimum blanket thickness for a specified blanket performance or a maximum blanket energy multiplication factor for a specified blanket thickness and blanket performance are typical figure of merits for the blanket design.

Table 2. Current BSDOS Performance Parameters

- Neutron and gamma flux profiles
- Total energy deposition in each reactor component
- Energy deposition profiles and peak power density in each reactor component
- Energy multiplication factors
- Temperature profiles
- Coolant parameters (velocity, pressure, pumping power)
- Thermal and electrical insulator dose
- Peak fast fluence in each reactor component
- Atomic displacement in the magnet stabilizer material
- Radiation induced resistance in the magnet stabilizer material

VI. PARAMETRIC STUDIES

The parametric mode of BSDOS is designed to study the effect of the different design variables (material selection, dimensions, compositions, coolant parameters, surface heat flux, neutron wall loading, neutron fluence, etc.) on the blanket and shield performance. In this mode, each variable changes between two values using fixed increment or use a set of predefined values. This process is repeated for all the variables in the form of nested loops. The number of the loops is the number of the variables. The results are tabulated and plotted to help understanding the blanket performance.

The interactive plotting capability for the parametric mode of BSDOS can plot any performance parameter as a function of any variable for all values of the other variables. For multi-variables problem, BSDOS uses the plotting sequence for the different variables as defined in the input of the interactive plotting capability. The user selects the plotting parameters and variables from a detailed menu. An example is given in the paper to demonstrate this capability.

VII. OPTIMIZATION STUDIES

The optimization mode of BSDOS provides the capability to optimize the blanket and shield design using the specified figure of merit subject to linear and nonlinear constraints. The figure of merit can be any of the blanket and shield variables, or the performance parameters of Table 2. For example, BSDOS can minimize the total blanket thickness (variable) or maximize the blanket energy multiplication factor (performance parameter) while satisfying the selected design criteria in the form of linear and nonlinear constraints imposed on the blanket and shield variables and performance parameters.

A typical blanket and shield design problem may have more than fifty variables in addition to the performance parameters, which need to be considered in the design process. Parametric studies can provide understanding of the blanket and shield performance as a function of some variables. However to adjust all the design variables simultaneously for optimum performance while satisfying the design criteria is beyond the simple mean of parametric studies and the trial and error procedures. BSDOS can perform this task that covers different engineering disciplines utilizing the state-of-the-art tools. Also, BSDOS eliminates the difficulties and approximations in transferring large amount of data between different computer codes and allows for iterations between the different engineering disciplines. During the development of this capability, practicality has been a major factor. A significant effort has been allocated to speed the calculations and the communications between the different computer codes. The user interfaces are simplified to provide the largest degree of flexibility in performing the optimization task without approximations.

VIII. BLANKET DESIGN EXAMPLES

Four examples are presented in this report to demonstrate different blanket design techniques using BSDOS. The first example is an earlier version of the ITER breeding blanket design[18], which is used to demonstrate the neutronics, heat transfer, hydraulics, and plotting capabilities of BSDOS. The blanket geometrical parameters are given in Table 3. The blanket has three breeding zones embedded in beryllium with four coolant panels. The first wall has the first coolant panel to remove the surface heat flux and the nuclear heating from the front section of the breeding blanket. The second and third panels are located between two breeder zones separated by beryllium. The last coolant panel is located at the back of the blanket attached to the shield for removing the nuclear heating from the back section of the breeding blanket and the front section of the shield. The breeding zone consists of a thin breeder layer with 0.5 mm thick Type 316LN stainless steel clad to form a panel. These panels have built in helium purge lines for tritium recovery. The first wall consists of 13 mm thick Type 316LN stainless steel plate with built in coolant channels. A 5 mm beryllium is used as a tile material for protecting the first wall from the plasma interaction. The coolant panel design inside the blanket module is similar to the first wall except the total thickness of the panel is 7 mm with built in coolant channels.

Tritium breeding capability, ease, and reliability of tritium recovery, fabrication experience, thermal stability, chemical compatibility with stainless steel, and irradiation performance are the main reasons for selecting the Li_2ZrO_3 breeder material for this blanket. Zirconium activation and low thermal conductivity are the main disadvantages of this breeder. The breeder material form is pebbles to reduce thermal stress and to facilitate the blanket module fabrication. The need for a high tritium breeding ratio dictates the use of beryllium neutron multiplier and enriched lithium with ^6Li isotope. Sintered beryllium blocks are used in the front section of the blanket for several reasons. Sintered beryllium has good thermal conductivity value relative to the pebbles that accommodates the high values of nuclear heating and permits the use of the required beryllium thickness for neutron multiplication without having high operating temperature values. Also, the sintered beryllium improves the shielding performance and the safety characteristics of the breeding blanket. Beryllium pebbles are used at the rear section of the blanket modules for two reasons: a) The nuclear heating values are low, which permit the use of low thermal conductivity material, and b) The required beryllium thickness for neutron multiplication is much less at this location, which favors the use of material form with high porosity. Type 316LN austenitic steel has been selected as the structure material for the breeding blanket and the radiation shield. Good fabricability, extensive data base, and nuclear experience are the main reasons for this selection. Water coolant with low temperature (140 to 190 °C) is used to enhance the steel performance based on swelling and aqueous stress corrosion considerations.

The results from BSDOS analyses of this blanket are shown in Tables 4 and 5, and Figures 1 through 10. The main performance parameters of the blanket are given in Table 4 including the tritium breeding ratio, blanket energy multiplication factor, total (blanket and shield) energy multiplication factor, maximum temperatures, and radiation damage parameters in the different blanket materials. Table 5 gives the extreme temperatures of the different blanket materials, which are important for tritium recovery and radiation induced effects (swelling, creep, etc.). BSDOS generates a summary table of the blanket configuration, operating, and performance parameters. The tabulated results are taken from this summary table. BSDOS plots any performance parameters such as nuclear heating, gas production rate (hydrogen, tritium, and helium), atomic displacement in the structural materials, neutron fluence (fast and total), neutron and photon spectrum at any blanket location, or temperature distribution. Samples of these plots are shown in Figures 1 through 10. These parameters can be plotted for all or selected number of zones.

Table 3. Radial Build of the First Blanket Example

Zone Function	Materials	Zone Thickness-cm (porosity)
Tile	Be	0.5
First Wall	Steel - Water - Steel	0.3 - 0.4 - 0.6
Multiplier	Be	2.4 (0.15)
Breeder	Steel - Li_2ZrO_3 - Steel	0.05 - 1.0 (0.3) - 0.05
Multiplier	Be	5.1 (0.15)
Coolant	Steel - Water - Steel	0.2 - 0.3 - 0.2
Multiplier	Be	5.9 (0.15)
Breeder	Steel - Li_2ZrO_3 - Steel	0.05 - 1.5 (0.3) - 0.05
Multiplier	Be	8.3 (0.15)
Coolant	Steel - Water - Steel	0.2 - 0.3- 0.2
Multiplier	Be	2.4 (0.20)
Breeder	Steel - Li_2ZrO_3 - Steel	0.05 - 1.5 (0.3) - 0.05
Multiplier	Be	3.4 (0.20)
Coolant	Steel – Water - Steel	0.2 - 0.3 - 0.2

Table 4. Main Design Parameters of the First Blanket Example

Neutron wall loading	1.2 MW/m^2
D-T neutron fluence	1.0 $MW.y/m^2$
First Wall and Breeding section thickness	0.357 m
Tritium breeding ratio	1.548
Blanket energy multiplication factor	1.463
Total energy multiplication factor	1.603
Inlet coolant temperature	140 °C
Outlet coolant temperature	190 °C
Max. steel structure temperature	286 °C
Max. steel clad temperature	428 °C
Max. steel atomic displacement	11 dpa
Max. beryllium multiplier temperature	410 °C
Max. breeder temperature	765 °C
Max. steel helium production	168 appm
Max. beryllium multiplier He production	3100 appm
First wall fast neutron fluence (E>.1MeV)	8.6 $10^{21} n/cm^2$

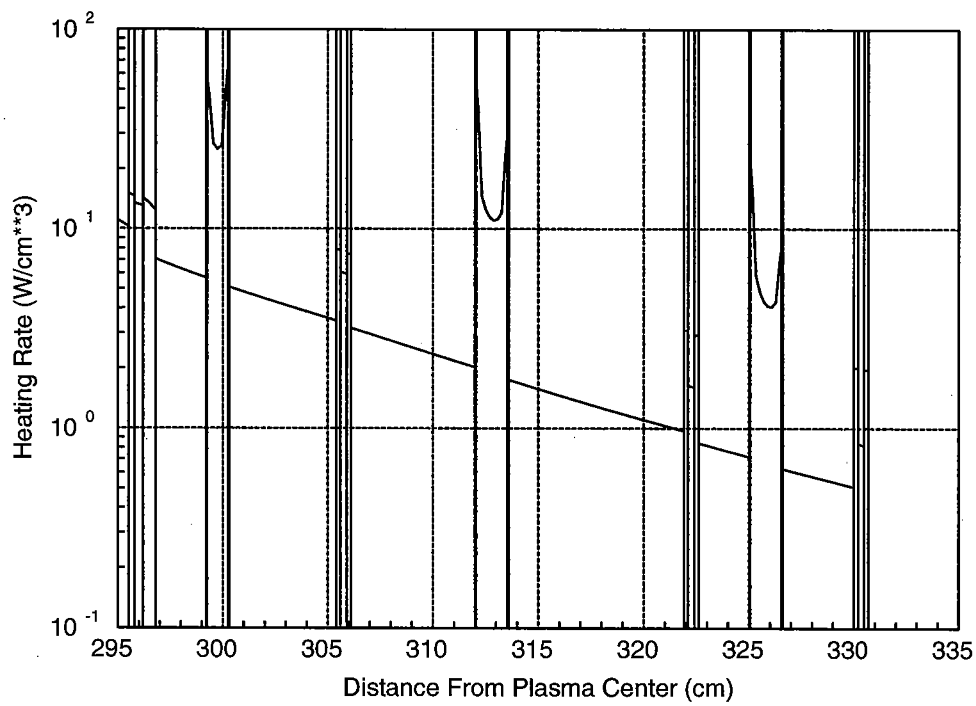

Figure 1. Nuclear heating deposition rate in the different zones of the first blanket example normalized to neutron wall loading of 1.2 MW/m^2

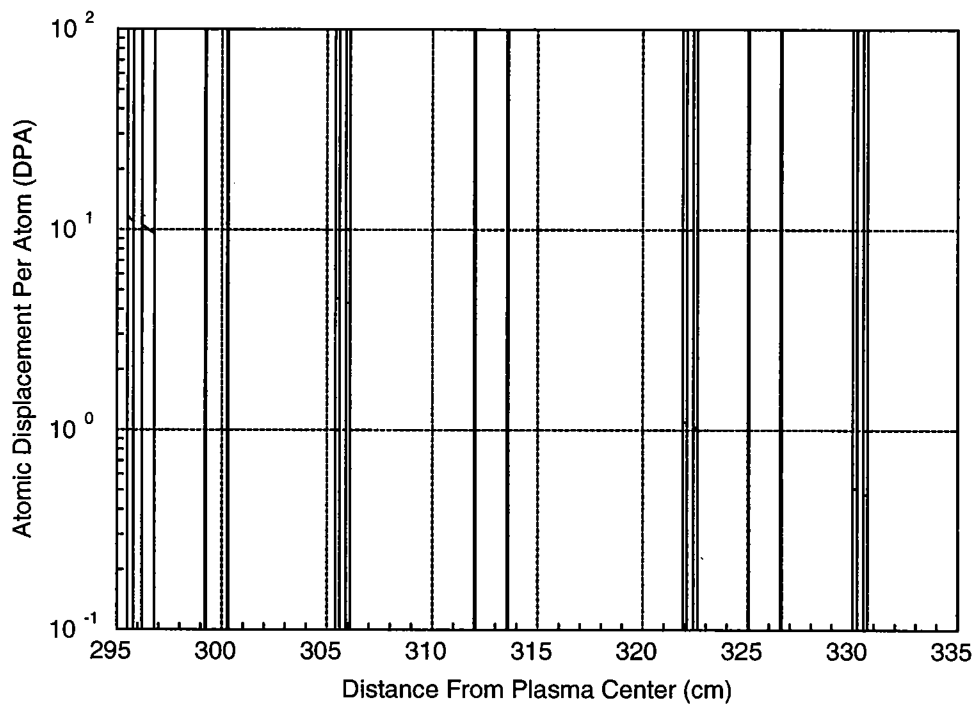

Figure 2. Atomic displacement in the different steel zones of the first blanket example normalized to D-T neutron fluence of 1.0 MW.y/m^2

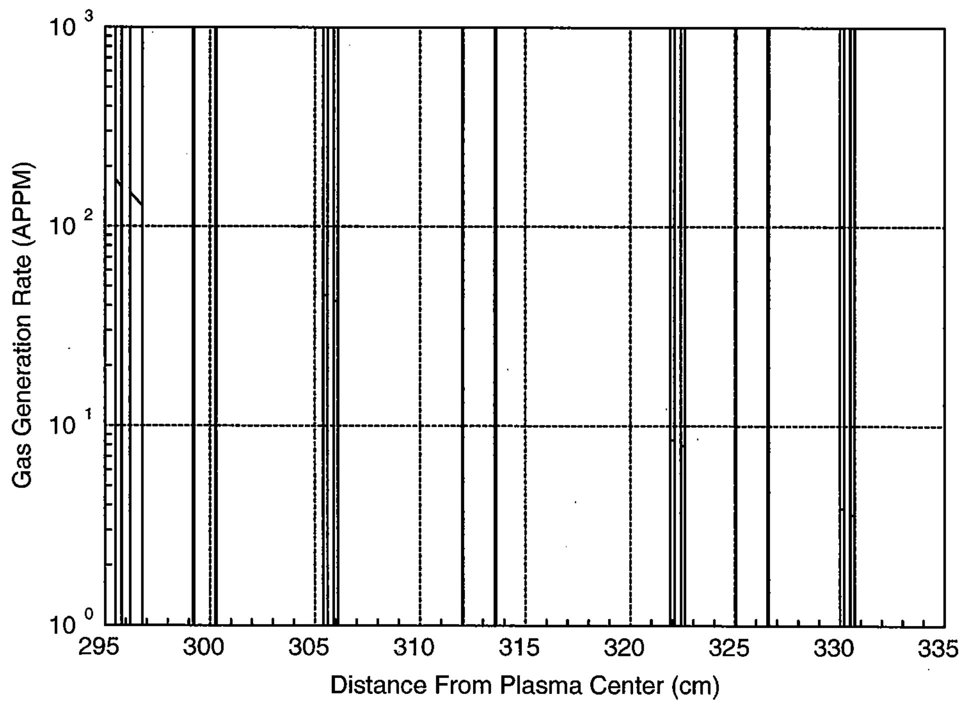

Figure 3. Helium production in the different steel zones of the first blanket example normalized to D-T neutron fluence of 1.0 MW.y/m^2

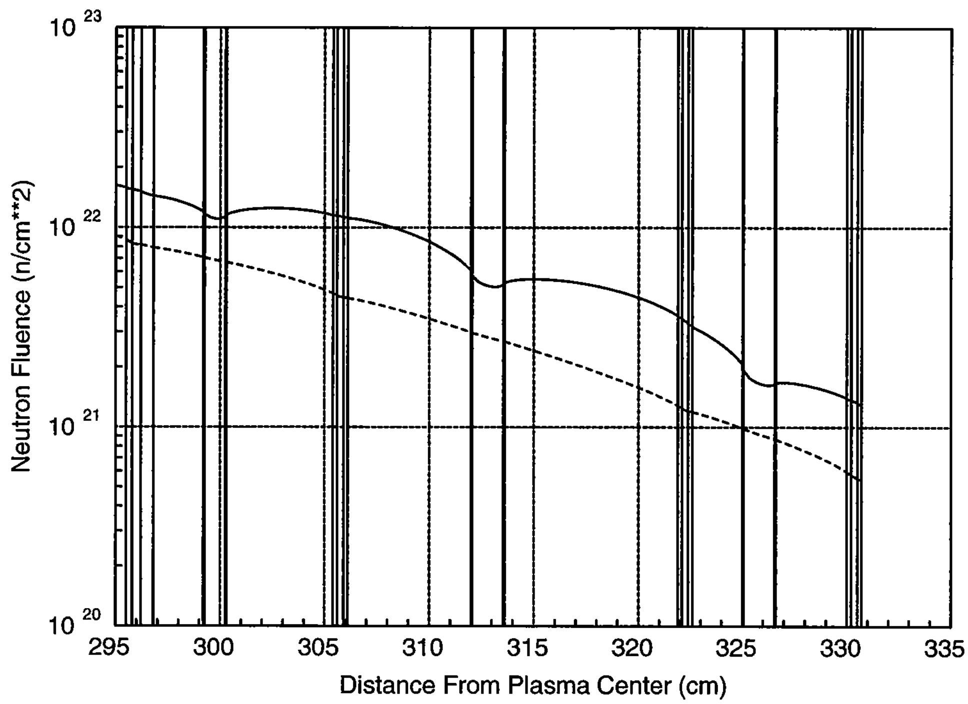

Figure 4. Total and fast neutron fluence in the different zones of the first blanket example normalized to D-T neutron fluence of 1.0 MW.y/m^2

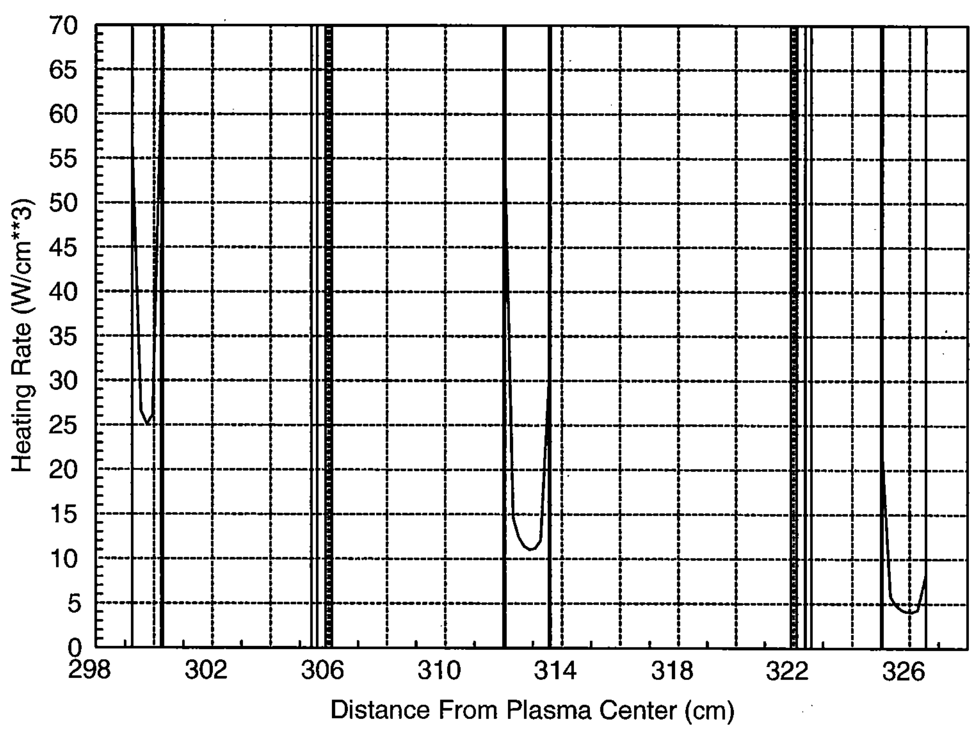

Figure 5. Nuclear heating rate deposition in the breeding zones of the first blanket example normalized to neutron wall loading of 1.2 MW/m^2

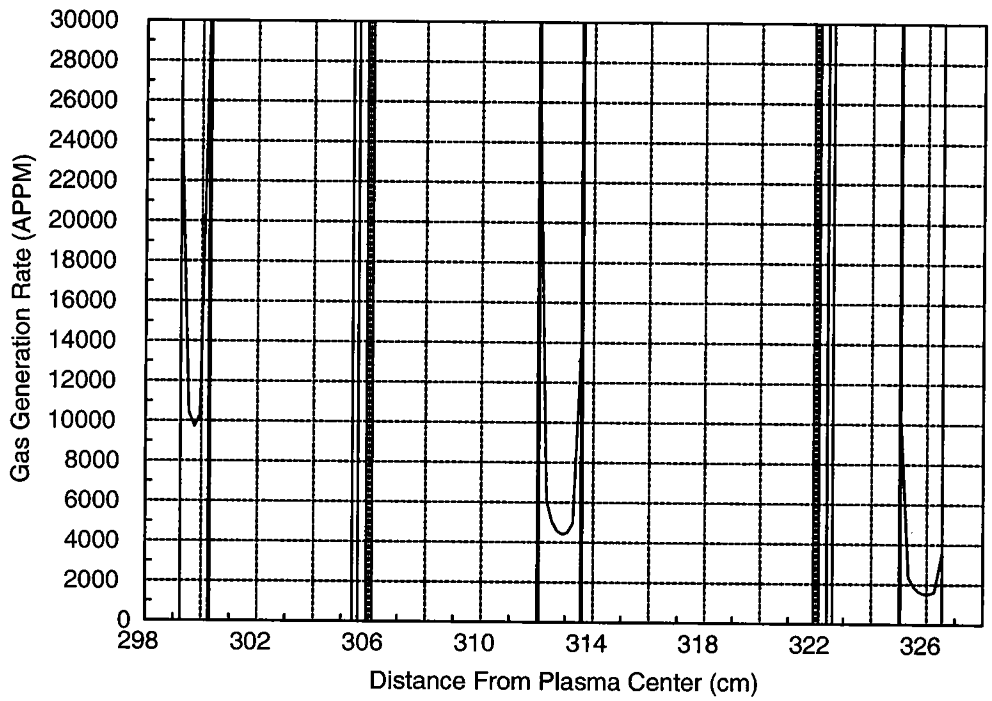

Figure 6. Tritium production in the breeding zones of the first blanket example normalized to D-T neutron fluence of 1.0 MW.y/m^2

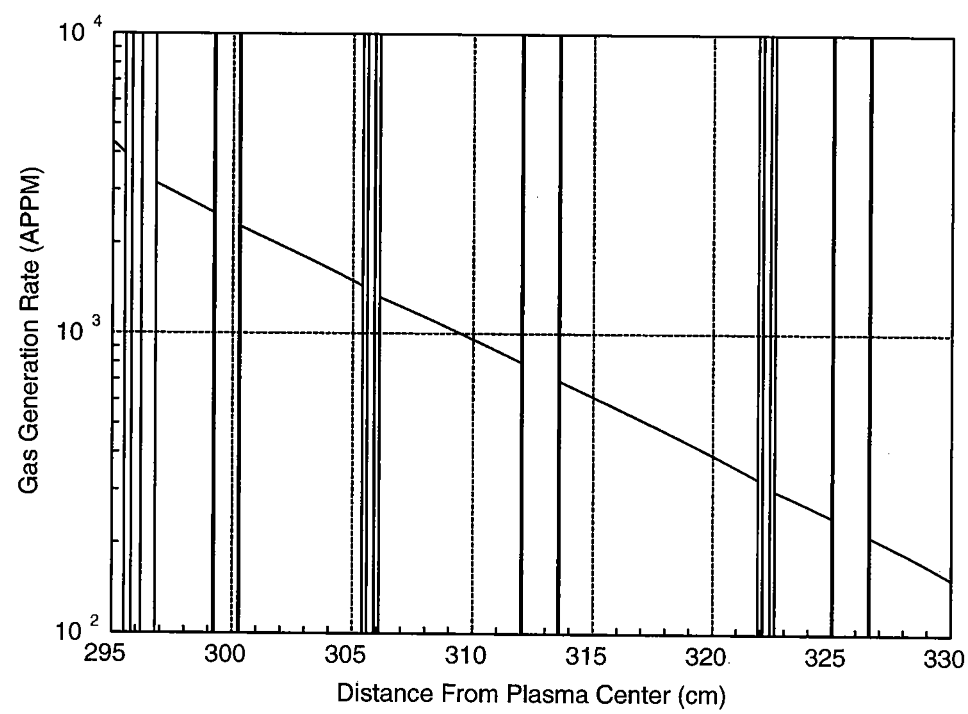

Figure 7. Helium production in the different beryllium zones of the first blanket example normalized to D-T neutron fluence of 1.0 MW.y/m^2

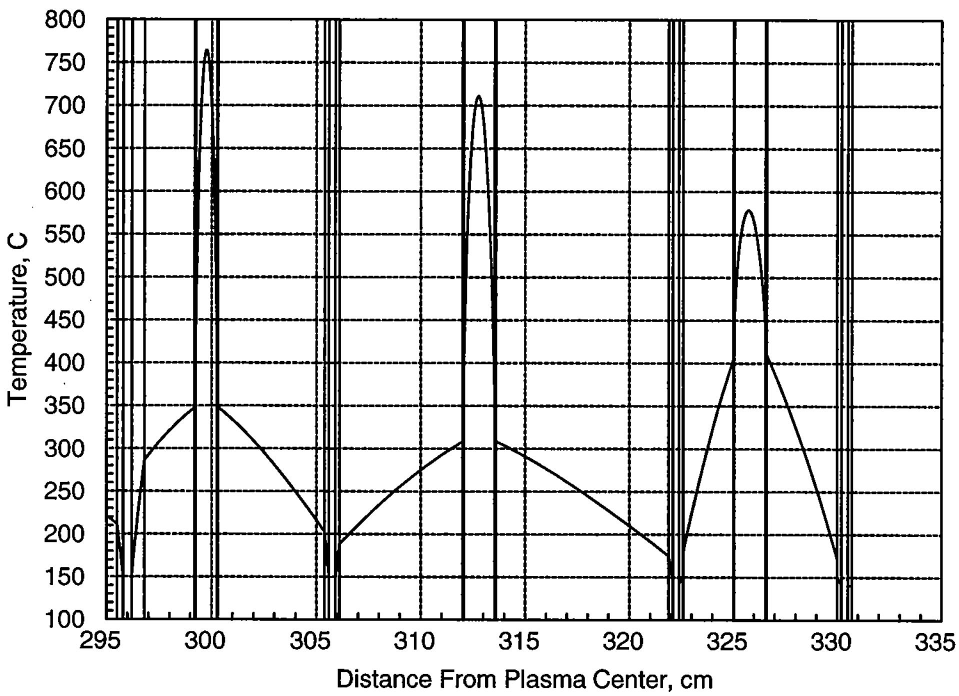

Figure 8. Temperature distribution in the different zones of the first blanket example normalized to neutron wall loading of 1.2 MW/m^2

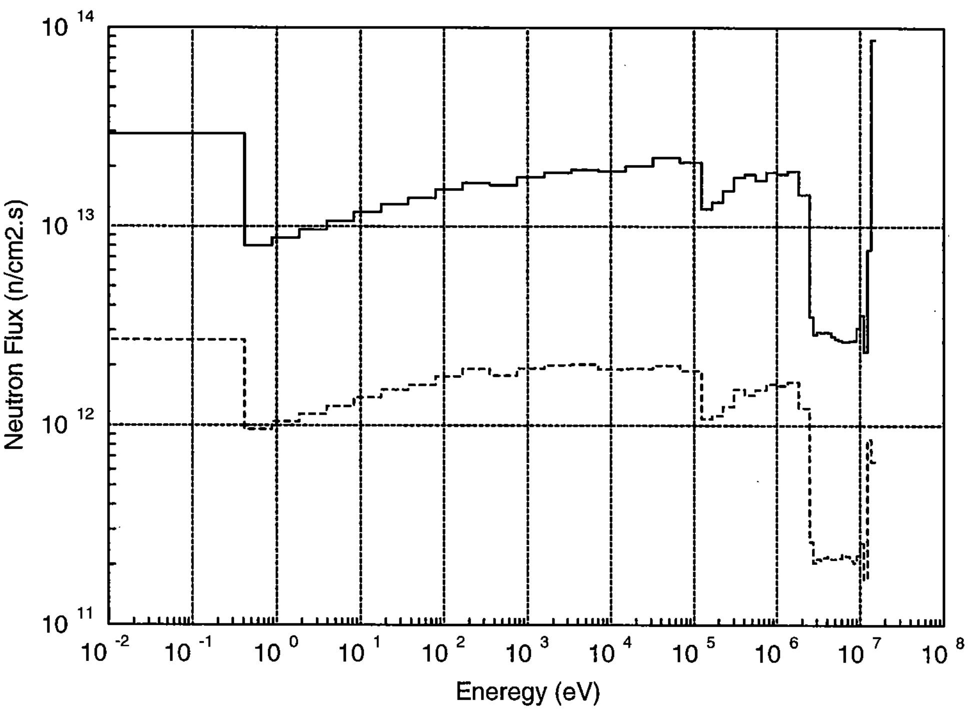

Figure 9. Neutron spectra in the front and back of the first blanket example normalized to neutron wall loading of 1.2 MW/m^2

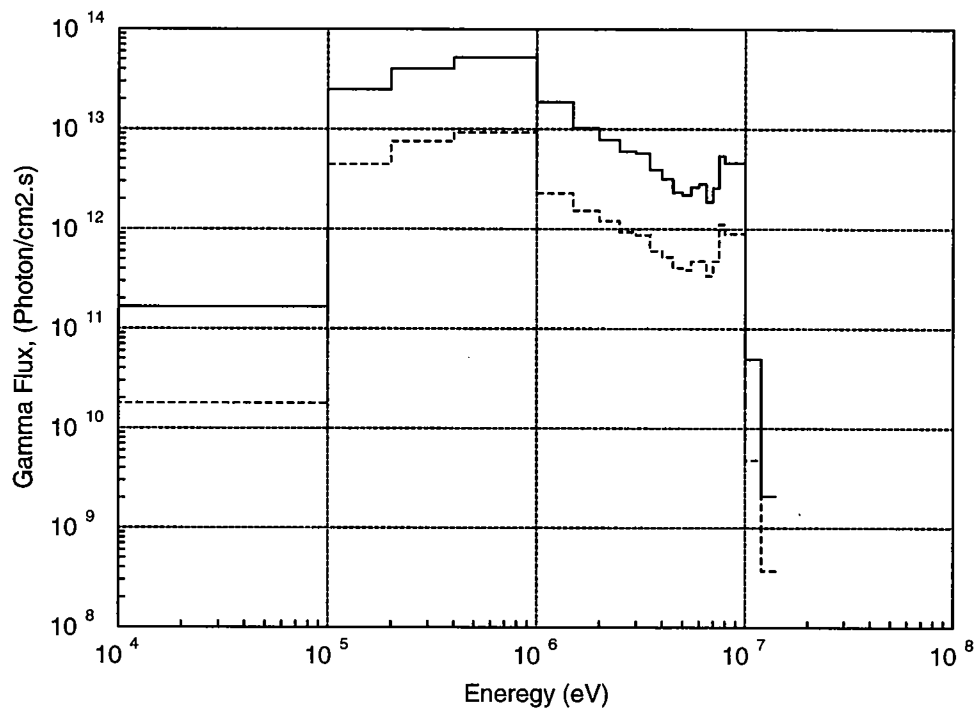

Figure 10. Gamma spectra in the front and back of the first blanket example normalized to neutron wall loading of 1.2 MW/m^2

Table 5. Breeder and Multiplier Extreme Temperatures of the First Blanket Example

Zone Function	Materials	Min.- Max. Temperature, °C
Multiplier	Be	286 - 348
Breeder	Li_2ZrO_3	428 - 765
Multiplier	Be	202 - 348
Multiplier	Be	188 - 308
Breeder	Li_2ZrO_3	361 - 711
Multiplier	Be	175 - 309
Multiplier	Be	181 - 405
Breeder	Li_2ZrO_3	443 - 579
Multiplier	Be	171 - 410

The second blanket example is a two dimensional (r-θ) geometrical configuration that represents a solid breeder blanket module. The radial blanket configuration is similar to the first example except it has only two breeder zones and different radial dimensions. Beryllium tile is not used for this blanket module. The coolant path forms a "U" shape where the bottom of the "U" is parallel to the first wall. BSDOS used TWODANT code of the DANTSYS for the neutronics analysis in conjunction with TOPAZ3D for the heat transfer analysis. This analysis is intended to check the impact of the module side walls on the blanket performance. The tritium breeding ratio and the temperature distribution in the breeder zones are the main concern. Any cold spot in the breeder zones increases significantly the tritium inventory in the blanket, which represents an operation and safety concerns. In addition, it impacts the required tritium breeding ratio for fueling the plasma operation. Table 6 gives some of key blanket parameters and Figure 11 shows the spatial mesh used in the neutronics, heat transfer, and hydraulics analyses. Figure 12 shows the temperature distribution map for the module while Figures 13 through 15 show the same information for each blanket material. The maximum temperature of the steel structure is less than 100 °C except for the shield section where the internal coolant channel are not included in this model. The breeder material has no cold spots as shown in Figure 14. The minimum and maximum breeder temperatures are 369 and 529 °C, respectively for a coolant inlet temperature of 60 °C. The maximum beryllium temperature is 397 °C as shown in Figure 15.

Table 6. Some Design Parameters of the Second Blanket Example

Neutron wall loading	1.2 MW/m^2
D-T neutron fluence	1.0 $MW.y/m^2$
First Wall and Breeding section thickness	0.326 m
Tritium breeding ratio	1.220
Total energy multiplication factor	1.602
Inlet coolant temperature	60 °C
Outlet coolant temperature	100 °C
Maximum beryllium multiplier temperature	397 °C
Minimum beryllium multiplier temperature	99 °C
Maximum breeder temperature	529 °C
Minimum breeder temperature	369 °C

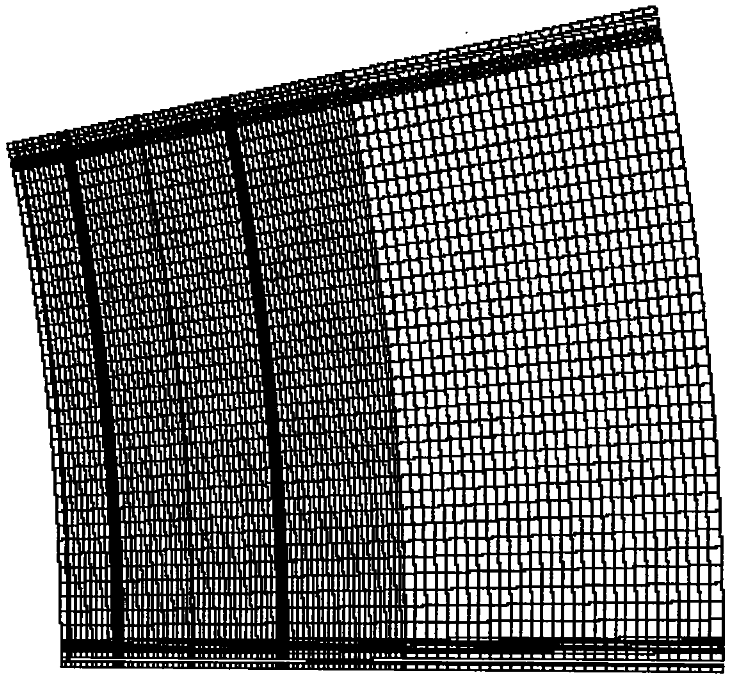

Figure 11. Spatial mesh used in the neutronics, heat transfer, and hydraulics analyses

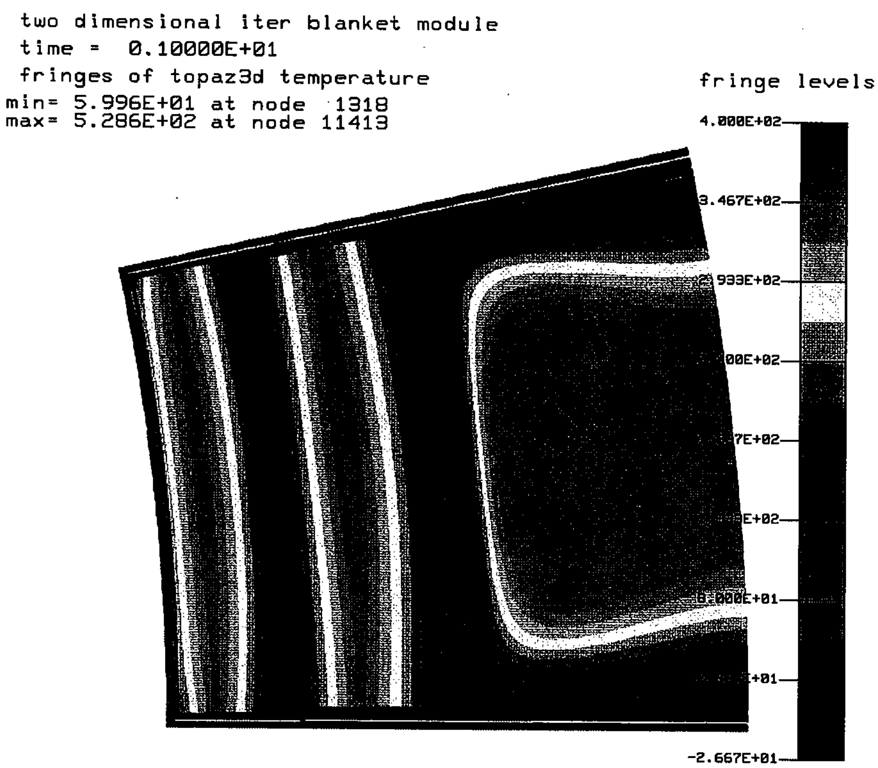

Figure 12. Temperature contour map for the different blanket zones of the second blanket example. The internal cooling channels of the steel shield section are not included.

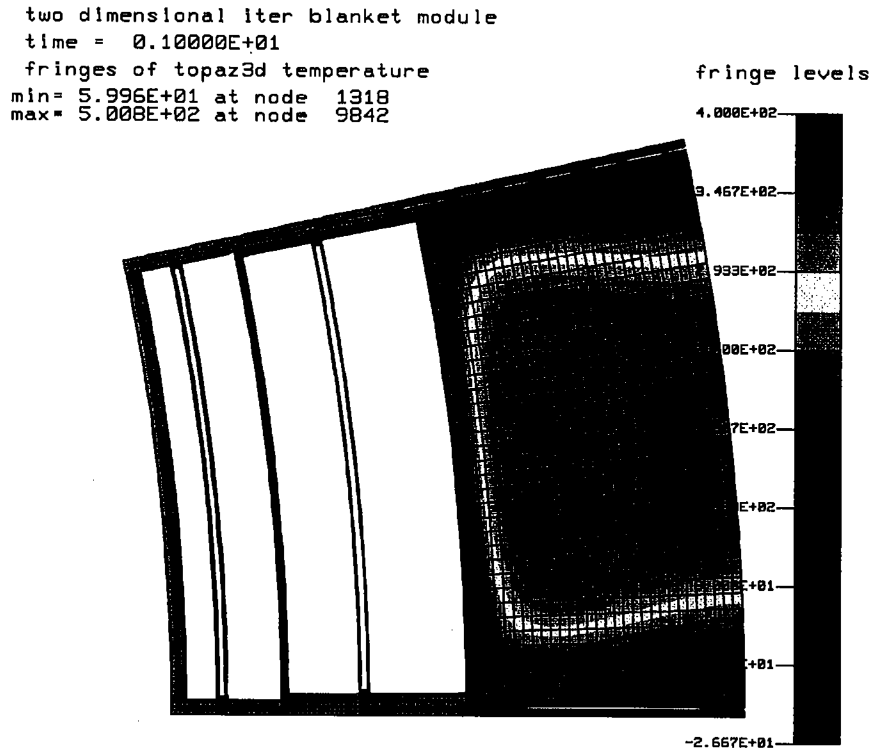

Figure 13. Temperature contour map for the different steel blanket zones of the second blanket example. The internal cooling channels of the steel shield section are not included.

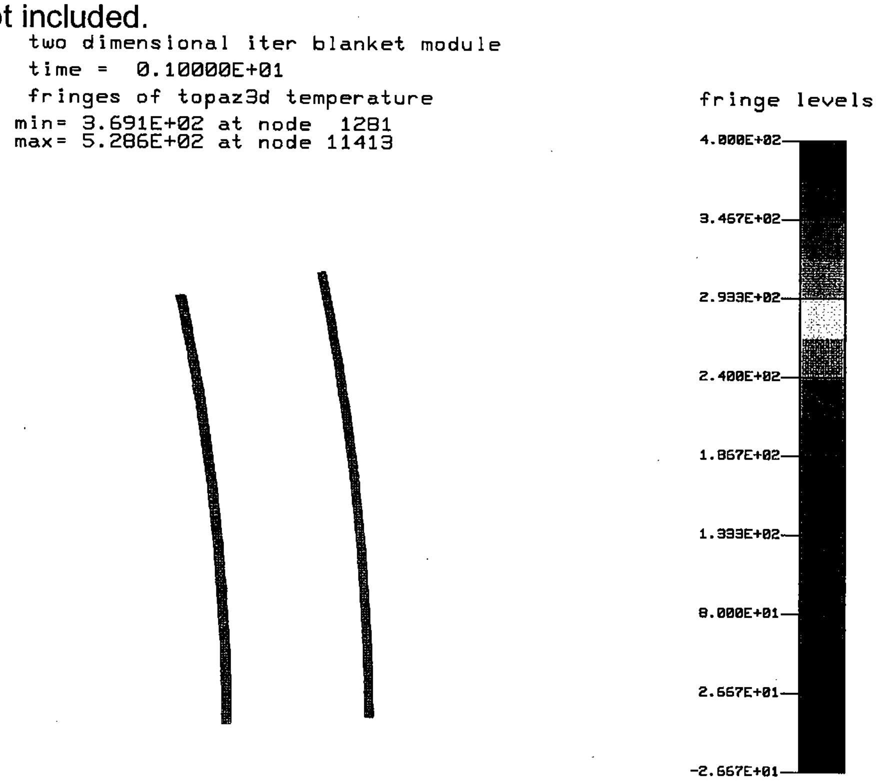

Figure 14. Temperature contour map for the two breeder zones of the second blanket example

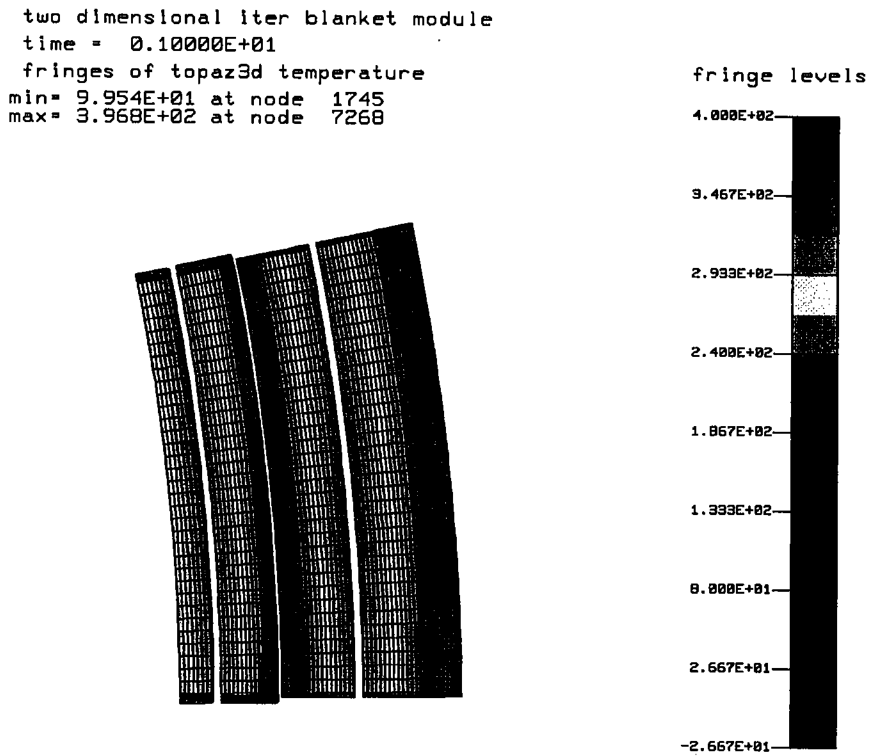

Figure 15. Temperature contour map for the beryllium multiplier zones of the second blanket example

In the third breeder blanket example, a self cooled liquid lithium vanadium blanket is analyzed. This blanket uses the beryllium neutron multiplier as spectral shifter and energy converter[19,20] for the fusion neutrons. The slowing 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 BSDOS parametric capability is used to study the blanket performance as a function of the beryllium material location relative to the first wall and the radial thickness of the beryllium zone. Other design considerations are the maximum temperatures of different materials and the maximum lithium coolant velocity. Table 7 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. The radial dimensions of the reflector zone and the lithium zone between the beryllium and the reflector zone are 0.3 m thick.

BSDOS plotting capability was used to show the tritium breeding ratio, the blanket energy multiplication factor, the total energy multiplication factor, and the shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions. Figures 16 through 19 display the requested plots. 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. For a fixed beryllium zone thickness, the blanket and the total energy multiplication factors decreases slowly as the lithium zone thickness between the first wall and the beryllium zone increases. Similar to the tritium breeding ratio, the blanket energy multiplication factor and the total energy multiplication factor show a large increase as the beryllium multiplier zone thickness increases. 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.

Table 7. Liquid Metal Geometrical Blanket Model for the Parametric Study

Zone Function	Materials	Zone Thickness-m
First Wall	Vanadium alloy	0.05
Breeder	Natural liquid lithium	0.02 to 0.1
Structure	Vanadium alloy	0.5
Multiplier	Beryllium	0.02 to 0.1
Structure	Vanadium alloy	0.05
Breeder	Natural liquid lithium	0.3
Structure	Vanadium alloy	0.05
Reflector	Titanium carbide	0.3
Structure	Vanadium alloy	0.2 - 0.3- 0.2
Shield	Steel shield (10% He)	0.5

The fourth blanket example demonstrates the BSDOS blanket optimization capability. A self cooled liquid lithium blanket concept with Type 316 stainless steel as a reflector, shield, and structural material is used. This blanket has a beryllium spectral shifter/multiplier for performance enhancement. The BSDOS optimizer is utilized to maximize the blanket energy multiplication factor. Six variables are used in the optimization process. Four zone dimensions (two breeders, multiplier, and reflector) and lithium-6 enrichment of the two breeder zones are allowed to vary. Four blanket constraints are imposed on the blanket optimization analysis. The tritium breeding ratio is constrained to = 1.2 (non linear constraint). The total blanket thickness is constrained to 0.6 m (linear constraint). The energy fraction deposited in the reactor shield is constrained to = 0.03 (non linear constraint). The lithium-6 enrichment is the same for both lithium breeder zones (linear constraint). The dimensions of the different blanket zones are allowed to vary within the possible engineering ranges. Table 8 gives the blanket configuration, which is used in the optimization process. The BSDOS optimizer converged and produced very interesting result for this blanket concept. Table 9 gives the obtained blanket configuration as well as the main performance parameters. The previous parametric study showed that the blanket energy multiplication factor increases as the first lithium zone thickness is decreased and the beryllium zone thickness is increased. The obtained optimized results agree with these conclusions. However, the optimization study enhanced significantly the blanket energy multiplication relative to other liquid lithium designs[2,19,20] by about 40 % more energy production. This was achieved by reducing the lithium-6 enrichment of the lithium breeder to allow for more energy production in the reflector zone. In most of the blanket concepts that use beryllium multiplier, natural or enriched lithium with lithium-6 isotope is used. This shows clearly the benefit of using the optimization capability of BSDOS to enhance the blanket performance, which improves the reactor economics.

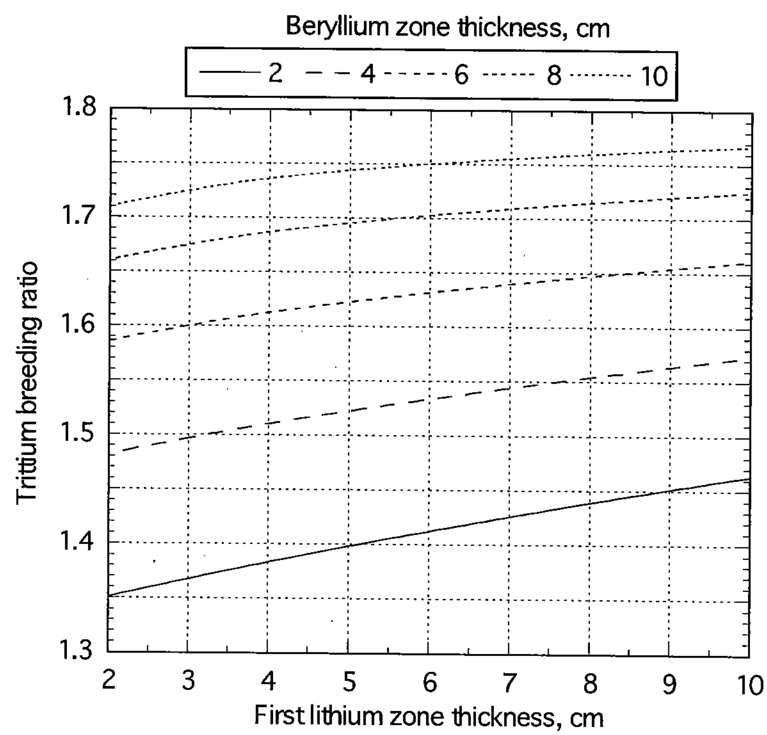

Figure 16. Tritium breeding ratio as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions

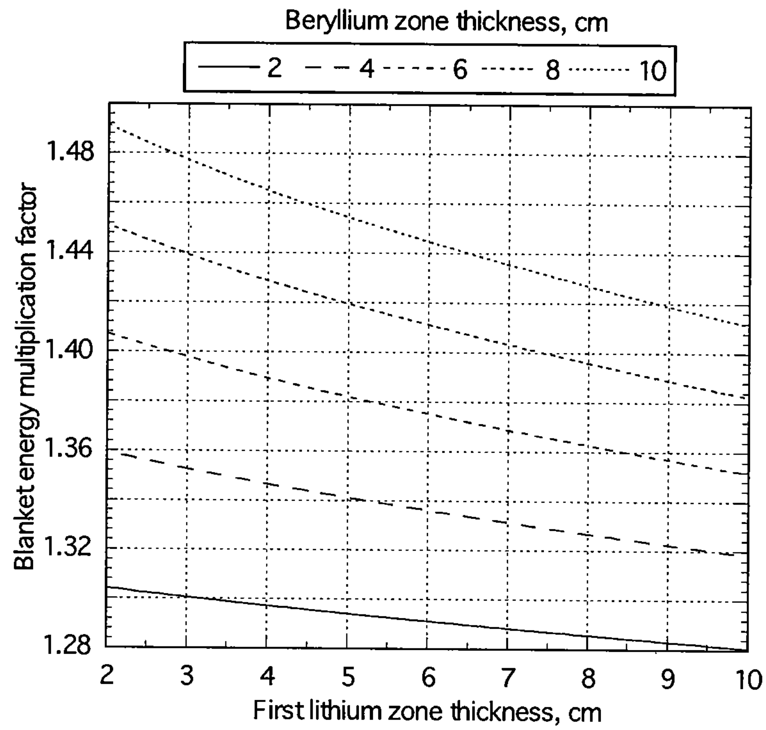

Figure 17. Blanket energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions

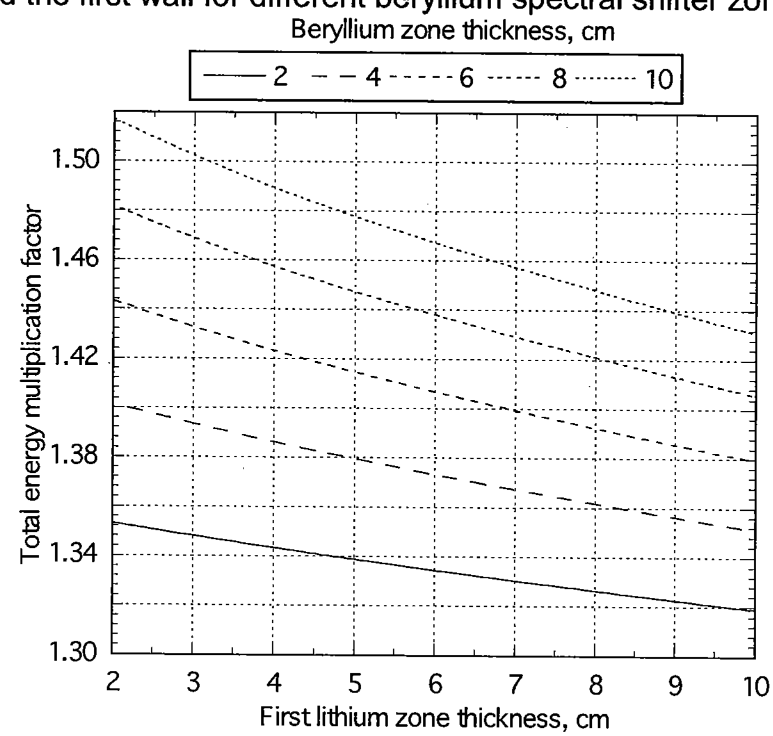

Figure 18. Total energy multiplication factor as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions

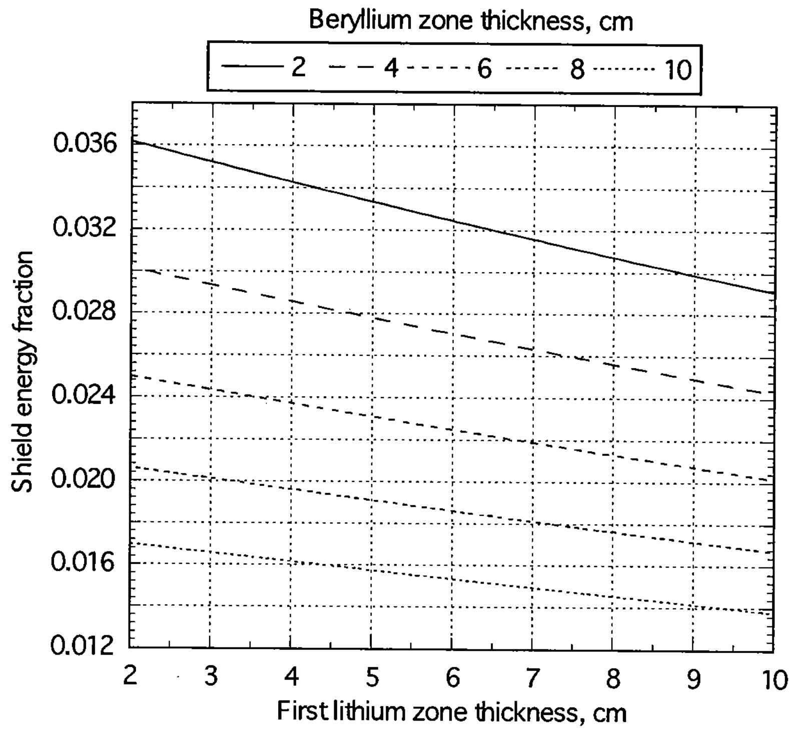

Figure 19. Shield energy fraction as a function of the lithium zone thickness behind the first wall for different beryllium spectral shifter zone dimensions

Table 8. Liquid Metal Geometrical Blanket Model for the Optimization Study

Zone Function	Materials	Zone Thickness m
First Wall	Type 316 stainless steel	0.005
Breeder	liquid lithium with **variable lithium-6 enrichment (0.01 to 0.90)**	**0.005 to 0.1**
Structure	Type 316 stainless steel	0.0025
Multiplier	Beryllium	**0.005 to 0.1**
Structure	Type 316 stainless steel	0.0025
Breeder	liquid lithium with **variable lithium-6 enrichment (0.01 to 0.90)**	**0.1 to 0.25**
Reflector	Type 316 stainless steel	**0.01 to 0.4**
Shield	Type 316 stainless steel	1.00

Table 9. Configuration and Performance Parameters of the Liquid Metal Blanket from the Optimization Study

Figure of merit and constraints	
Maximize blanket energy multiplication factor (figure of merit)	
Tritium breeding ratio = 1.2 (non linear constraint)	
Total blanket thickness equal 0.6 m (linear constraint)	
Shield energy fraction = 0.03 (non linear constraint)	
Same lithium-6 enrichment in both lithium breeder zones (linear constraint)	
Performance Parameters	
First lithium zone thickness	0.005 m
Beryllium zone thickness	0.10 m
Second lithium zone thickness	0.165 m
Reflector zone thickness	0.32 m
Total blanket thickness	0.60 m
Lithium-6 enrichment	1.26%
Blanket energy multiplication factor	1.663
Tritium breeding ratio	1.200
Shield energy fraction	0.021

IX. CONCLUSIONS

Different Blanket design and optimization techniques have been demonstrated utilizing the First wall/blanket/shield design and optimization system (BSDOS) for different blanket concepts. BSDOS provides the state-of-the-art design tool for fast accurate blanket design analyses and optimization. This system permits the simultaneous consideration of different blanket parameters to understand the effect of each parameter on its performance or to optimize its configuration based on the adopted design criteria. BSDOS use results in significant blanket performance enhancements, improved fusion reactor economics, and saving effort for performing blanket analyses and design optimizations.

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References

[1] Y. Gohar, C. Baker, H. Attaya, Y. Cha, S. Majumdar, and T. Scandora, "First Wall/Blanket/Shield Design and Optimization System," Fusion Engineering And Design 8-10, 1989.

[2] D. L. Smith, et al., Blanket comparison and selection study - Final report, Argonne National Laboratory report, ANL/FPP-84-1 (1984).

[3] Y. Gohar and S. Yang, "Energy Deposition and Shielding Requirements for all Concepts of the Blanket Comparison and Selection Study," Fusion Technology, 8, 1985.

[4] M. C. Billone, W. Dienst, T. Flament, P. Lorenzetto, K. Noda and N. Roux, "ITER Solid Breeder Blanket Materials Database," Argonne National Laboratory Report ANL/FPP/TM-263, November 1993.

[5] Y. Gohar, M. Billone, A. Cardella, W. Dänner, K. Ioki, T. Kuroda, D. Lousteau, P. Lorenzetto, S. Majumdar, R. Mattas, K. Mohri, R. Raffray, Y. Strebkov, H. Takatsu, and E. Zolti, "ITER Tritium Breeding Blanket," Proceedings of the Fourth International Workshop on Ceramic Breeder Blanket Interactions, Japan-US Workshop P260/IEA Specialist's Workshop, Kyoto, Japan, October 1995

[6] F. Scaffidi-Argentina, M Dalle Donne, C. Ronchi, and C. Ferrero, ANFIBE a comprehensive model for swelling and tritium release from neutron irradiated beryllium, II: Comparison of model prediction with experimental results, Fusion Technology 33, 146-163, March 1998.

[7] Y. Gohar, "Tritium Breeding (Driver) Blanket," U.S. ITER Background Summary Papers, DOE/ER-ITER-0002, ITER/US/91- PC-06-2, May 1991.

[8] D. Smith, A. Antipenkov, C. Baker, M. Billone, W. Dänner, Y. Gohar, T. Kuroda, P. Lorenzetto, K. Maki, S. Mori, A. Raffray, G. Shatalov, A. Sidorov, G. Simbolotti, I. Sviatoslavsky, H. Takatsu, H. Yoshida, "ITER Tritium Breeding Blanket," The Thirteen International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington DC, USA, 1990.

[9] Y. Gohar and D. L. Smith, "Multiplier, Moderator, and Reflector Materials for Advanced Lithium-Vanadium Fusion Blankets," Journal of Nuclear Materials 283-287, 2000.

[10] R. E. Alcouffe, R. S. Baker, F. W. Brinkley, D. R. Marr, R. D. O'Dell, and W. Walters, " DANTSYS: A Diffusion Accelerated Neutral Particle Transport Code System," Los Alamos Laboratory, LA-12969-M, June 1995.

[11] R. W. Roussin et al., "VITAMIN-E: A Coupled 174 Neutron, 38 Gamma-Ray Multigroup Cross Section Library for Deriving Application Dependent Working Libraries for Radiation Transport Calculations," RSIC DATA LIBRARY DLC-113, Oak Ridge National Laboratory, ORNL-RSIC Report, 1987.

[12] Y. Farawila, Y. Gohar and C. Maynard, "KAOS/LIB-V: A Library of Nuclear Response Functions Generated by KAOS-V Code from ENDF/B-V and Other Data Files," Argonne National Laboratory, ANL/FPP/TM-241, 1989.

[13] A. B. Pashchenko and H. Wienke, "Summary Documentation: FENDL/E-2.0 Evaluated Nuclear Data Library of Neutron-Nucleus Interaction Cross Sections and Photon Production Cross Sections and Photon-Atom Interaction Cross Sections for

Fusion Applications," International Atomic Energy Agency, IAEA-NDS-175 Rev. 3, October 1998.
[14] D. W. Stillman and J. D. Hallquist, "INGRID: A Three-Dimensional Mesh Generator for Modeling Nonlinear Systems," Lawrence Livermore National Laboratory, UCID-20506, 1985.
[15] Arthur Shapiro, "TOPAZ3D – A Three-Dimensional Finite Element Heat Transfer Code," Lawrence Livermore National Laboratory, UCID-20484, 1985.
[16] Thomos Spelce, J. Q. Hallquist (Originator), "TAURUS: An Interactive Post Processor for the Analysis Codes NIKE3D, DYNA3D, and TOPAZ3D," Lawrence Livermore National Laboratory Report, UCRL-MA-105401, May 1991.
[17] P. E. Gill et al., "User's Guide for NPSOL (Version 4.0): A FORTRAN Package for Nonlinear Programming," Stanford University, SOL 86-2, 1986.
[18] D. Smith, W. Dänner, Y. Gohar et al., "ITER Blanket, Shield and Material Data Base - Part A (ITER Blanket and Shield)," International Atomic Energy Agency, Vienna, ITER Documentation Series, No. 29, 1991.
[19] Y. Gohar, S. Majumdar, and D. Smith, "Analysis and Design of High Power Density Self-Cooled Lithium-Vanadium Blanket," Argonne National Laboratory Report, ANL/TD/00-01, January 2000.
[20] Y. Gohar, S. Majumdar, D. Smith, "High Power Density Self-Cooled Lithium-Vanadium Blanket," Fusion Engineering and Design Volume 49-50, 2000.

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