CONF-880417--16

To be presented at the International Symposium on Fusion Nuclear Technology (ISFNT) to be held during the period of April 10-19, 1988, in Tokyo, Japan.

FIRST WALL/BLANKET/SHIELD DESIGN AND OPTIMIZATION SYSTEM*

by

Y. Gohar, C. Baker, H. Attaya,
Y. Cha, S. Majumdar, T. Scandora

CONF-880417--16

DE88 010010

Argonne National Laboratory
9700 S. Cass Ave.
Argonne, IL 60439

February 1988

*Work supported by the U. S. Department of Energy/Office of Fusion Energy under Contract W-31-109-Eng-38.

FIRST WALL/BLANKET/SHIELD DESIGN AND OPTIMIZATION SYSTEM*

Y. Gohar, C. Baker, H. Attaya, Y. Cha, S. Majumdar, T. Scandora
Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439 U.S.A.

ABSTRACT

First wall/blanket/shield design and optimization system (BSDOS) has been developed to provide a state-of-the-art design tool for fast accurate analysis. In addition, it has been designed to perform several other functions: a) allowing comparison and evaluation studies for different concepts using the same data bases and ground rules, b) permitting the use of any figure of merit in the evaluation studies, c) optimizing the first wall/blanket/shield design parameters for any figure of merit under several design constraints, d) permitting the use of different reactor parameters in the evaluation and optimization analyses, e) allowing the use of improved engineering data bases to study the impact on the design performance for planning future research and development, and f) evaluating the effect of the data base uncertainties on the design performance. BSDOS is the first design and optimization system to couple the highly interacting neutronics, heat transfer, thermal hydraulics, stress analysis, radioactivity and decay-heat analyses, tritium balance, and capital cost. A brief description of the main features of BSDOS is given in this paper. Also, results from using BSDOS to perform design analysis for several reactor components are presented.

* Work supported by the U.S. Department of Energy, Office of Fusion Energy, under Contract No. W-31-109-ENG-38.

FIRST WALL/BLANKET/SHIELD DESIGN AND OPTIMIZATION SYSTEM

Y. Gohar, C. Baker, H. Attaya, Y. Cha, S. Majumdar, T. Scandora
Argonne National Laboratory, 9700 S. Cass Ave., Argonne, IL 60439 U.S.A.

1. INTRODUCTION

First wall/blanket/shield (FBS) design and optimization studies are essential elements in any fusion program plan [1]. FBS research and development require a flexible design and optimization tool to provide interaction, consistency, accuracy, and flow of data between different engineering disciplines; neutronics, heat transfer, thermal hydraulics, stress analysis, radioactivity and decay-heat analyses, tritium balance and capital cost. The need for such a tool has been felt clearly in the Tokamak Power System Studies [2] and the Blanket Comparison and Selection Study [3].

A first wall/blanket/shield design and optimization system (BSDOS) has been developed to provide a state-of-the-art design tool for fast accurate analysis. In addition, BSDOS has been designed to perform several other functions: a) allowing comparison and evaluation studies for different concepts using the same data bases and ground rules, b) permitting the use of any figure of merit in the evaluation studies, c) optimizing the FBS design parameters for any figure of merit under several design constraints, d) permitting the use of different reactor parameters in the evaluation and optimization analyses, e) allowing the use of improved engineering data bases to study the impact on the design performance to plan future research and development, and f) evaluating the effect of the data base uncertainties on the design performance.

The main features of BSDOS are the interactive dialogues with extensive menus for input data, input files for production runs, modular structure, flexibility to change or upgrade, and graphics menu for output. Three modes of operation are included: a) one design point or specific analysis, b) parametric study, and c) design optimization. Nuclear, physical, and engineering data are stored in the system for the fusion materials as well as some of the geometrical models. The neutronics module has one- and two-dimensional capabilities which provides the nuclear responses; nuclear heating, gas production rates, neutron fluences, atomic displacements, and decay-heat to other modules. A three-dimensional mesh generator is employed to provide finite element models for the heat transfer, thermal hydraulics and stress analyses. Multivariable linear/nonlinear optimization algorithms are used for the optimization function. All these modules are based on the state-of-the-art tools in each discipline to provide fast and accurate analyses. Interactive interfaces and additional capabilities were developed as needed. BSDOS has been used to provide design analyses for the Tokamak Power Systems Studies [2] and the blanket analysis for INTOR [4]. A brief description of the main features of BSDOS is presented in this paper including design analyses performed for different reactor components.

2. BSDOS DESCRIPTION

BSDOS is a modular system for performing first wall/blanket/shield design and optimization. BSDOS has been developed with provisions for the following key features: 1) The user engages in an interactive dialogue with extensive menus for generating the necessary input data files for the different modules. 2) The user's input is checked for wrong data. 3) Provisions are provided to correct wrong input data. 4) The modules are independent of each other and communicate only through well-defined data files. Each module has its own structure, memory allocation, and data files which improves flexibility to change or upgrade the different modules, and allows modular structure. 5) Interactive and batch graphics are included to help in the design process.

BSDOS has three modes of operation: a) one design point or specific analysis, b) parametric study, and c) design optimization. In the first mode, a complete or specific analysis is performed for the given FBS configuration where the configuration parameters are not allowed to change. In the parametric mode, the system performance parameters are calculated as a function of several configuration parameters. In the optimization mode, any of the configuration or performance parameters can be defined as a figure of merit (objective function) for the optimization purpose (minimization or maximization). Unconstrained, linear constrained, or nonlinear constrained optimizations are allowed in this mode of operation.

BSDOS is planned to have all the design aspects of FBS including neutronics, heat transfer, thermal hydraulics, structural analysis, radioactivity and decay-heat analyses, limited safety analysis, tritium balance, and capital cost calculations. A brief description of the BSDOS capabilities and the codes used to carry out the analysis are highlighted.

2.1 Neutronics

BSDOS has a data base for the fusion materials listed in Table 1. Densities and compositions of these materials are included in the data base. Also, the nuclear data for the different elements in these materials are stored on separate data files. At the start, BSDOS requests the names of the materials which are included in the first wall/blanket/shield/magnet configuration. Then it produces a compact nuclear data library for the transport calculations. Two 67-coupled group nuclear data libraries (46 neutron and 21 gamma) based on ENDF/B-IV and -V are available in BSDOS.

VITAMIN-C [4] and MACKLIB [5] Libraries with corrected lithium-7 data were used to obtain the first library based on ENDF/B-IV. The second library was generated from VITAMIN-E [6] and KAOS/LIB-V [7] based on ENDF/B-V. The one- and two-dimensional discrete ordinates codes ONEDANT [8] and TWODANT [9] were employed for the transport calculations. BSDOS translates the engineering parameters of the FBS to input for the transport codes. It also calculates all performance parameters summarized in Table 2. The radioactivity and decay heat analyses are performed by RACC [10].

2.2 Heat Transfer and Thermal Hydraulics

The heat transfer and thermal hydraulics analyses are performed in two- or three dimensions, one step higher than the neutronics analysis. The extra dimension is necessitated by the flow direction. In this analysis, a finite element model for the input configuration is generated through an interactive dialogue where it is possible to view the geometrical model before any calculation. The three-dimensional mesh generator for modeling nonlinear systems INGRID [11] is employed for the modeling part of the problem. BSDOS has several standard geometries which require only basic dimensions to simplify the model generation. However, any arbitrary geometry can be modeled and used in the calculations. Then, BSDOS couples the generated model with the nuclear heating from the neutronics analysis to prepare for the heat transfer and thermal hydraulic analyses. The three-dimensional finite element heat transfer code TOPAZ3D [13] is employed for the heat transfer calclations. BSDOS performs the energy balance and the thermal hydraulic analyses through direct interaction with TOPAZ3D.

2.3 Stress Analysis

Based on the input configuration, INGRID [11,12] is also used to generate a finite element model for the stress analysis. The finite element program for automatic dynamic incremental nonlinear analysis ADINA [13] is employed for the static and dynamic displacement, and stress analysis. A linear and nonlinear analysis can be performed. The nonlinearities due to material characteristics, large strains, or large displacements can be analyzed. The results from ADINA are used for graphic output and stored for further processing. The optimization section of BSDOS uses this output to check the various engineering limits. It should be noted that the temperature profiles are calculated by TOPAZ3D or ADINAT [14] for the stress analysis.

2.4 Optimization

After trying different optimization software packages, two of these packages have been implemented in BSDOS. The first one is MINOS [15], which can solve linear problems utilizing the primal simplex method; linearly constrained nonlinear problems employing the reduced-gradient algorithm in conjunction with the quasi-Newton algorithm; and nonlinear constrained problems using projected augmented-Lagrangian algorithm. The second optimization package is NPSOL [16] which uses a sequential quadratic programming algorithm to solve unconstrained, linearly, and nonlinearly constrained problems.

FBS problems have linear constraints, nonlinear constraints, and simple upper/lower bounds on the configuration parameters (variables). 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. Each major iteration includes the solution of a subproblem to determine a search direction that is used afterward by a bounded line search along this direction to find the optimum point.

In MINOS, for example, the subproblem contains the original linear constraints and bounds, as well as a linearized version of the nonlinear constraints. The objective function, in MINOS, is an augmented Lagrangian which contains a modified quadratic penalty function that is formed from the Jacobian of the nonlinear constraints and a penalty parameter. The reduced gradient method is applied to the subproblem with the partition of the variables into a nonbasic set, a basic set, and a superbasic set. In the nonbasic set the variables are being held equal to one of their bounds. The basic set contains the variables of the active (binding) constraints. The superbasic set contains the remaining variables which are regarded as the independent variables that are free to move in a desirable direction to improve the objective function. The selection of the variables in the nonbasic and superbasic sets is determined by the largest improvement in the objective function. The search direction of the superbasic variables is obtained by the quasi-Newton algorithm. In this algorithm an approximation of the curvature (the second derivatives, the Hessian) of the nonlinear objective function is obtained by using only the accumulated first-order information, i.e. the gradient of the function. Once the search direction is evaluated, a line search along this direction is carried out on the objective function to determine the local optimum in this direction. The major iteration is repeated until specified termination criteria are met. Both NPSOL and MINOS performed well for several problems, with NPSOL slightly faster than MINOS. MINOS is expected to be more efficient in the case of large sparse problems, where a large number of independent variables and constraints exist and each constraint depends on few variables.

Both optimizers require the evaluation of the objective function and constraints for the same values of the independent variables that have already been calculated before. This happens especially when the gradient of the objective/constraints functions are being evaluated. A scheme was developed to avoid this problem which reduces significantly the computational time.

3. BSDOS UTILIZATION

BSDOS has been used to perform the design and optimization analyses for several reactor studies: a) first wall and limiter designs for Tokamak Power System Studies [2], and b) INTOR first wall/blanket/shield optimization [17]. A sample of these analyses will briefly be presented.

3.1 First Wall Design

Temperature and thermal stress analyses of a first wall design using graphite tiles, as proposed for INTOR, were carried out for the following conditions: 1) graphite tiles cooled entirely by radiation to the stainless steel tubes, and 2) graphite tiles cooled by combined radiation/conduction to the stainless steel tubes, with the contact between the two being limited to an arc of ± 15° at the top.

Thermal contact between the tile and the tube is simulated by introducing two interface elements joining the graphite tile and the stainless steel tube at the top. The conductivity of these two elements is chosen to achieve the desired contact resistance. The interface elements are not used in the stress analysis, which has been conducted on the assumption of elastic 2-D generalized plane strain conditions. The emissivity of all radiating surfaces is assumed to be 0.9.

The results show that the maximum and minimum temperatures of the graphite tiles, when radiatively cooled, are 1365°C and 930°C (Figure 1) respectively for an average surface heat flux of 0.2 MW/m^2. These temperatures drop significantly for the contacting cases when the contact resistance is sufficiently low. In most cases, the stresses in the stainless steel tubes and graphite tiles (Figure 1) are within allowable design limits. However, the first wall is assumed to be axially unconstrained by the rest of the blanket in these analyses. If the axial constraint provided by the rest of the blanket on the first wall is significant, then the stresses will be increased depending on the degree of constraint.

3.2 Tritium Breeding Optimization

An optimization analysis was performed to maximize the tritium breeding of a solid breeder blanket concept. The blanket has a 1 cm first wall consisting of uniform mixture of type 316SS and water (50% type 316SS and 50% water by volume). A beryllium multiplier zone with a 0.8 DF is used behind the first wall. The breeding zone has a 40 cm thickness consisting of water, steel, and lithium oxide (5% H_2O, 10% type 316SS, 5% He, 80% Li_2O with a 0.8 DF). The analysis was performed to determine the beryllium zone thickness and the lithium-6 enrichment to produce the maximum possible tritium breeding ratio for this configuration. The results show that a 10.9 cm of beryllium with 30.88% lithium-6 enrichment achieved 1.4987 tritium breeding ratio which is the same result obtained for INTOR design.

4. SUMMARY

BSDOS: a first wall/blanket/shield design and optimization system has been developed to provide a state-of-the-art design tool for fast accurate analysis. The different engineering disciplines required for the first wall/blanket/shield are included. BSDOS has been employed to perform design analyses in several fusion reactor studies.

REFERENCES

[1] Technical Planning Activity Report, Argonne National Laboratory Report, ANL/FPP-87-1 (January 1987).

[2] D. Ehst et al., Tokamak Power System Studies FY 1986; A Second Stability Power Reactor, Argonne National Laboratory Report, ANL/FPP/86-1.

[3] D.L. Smith et al., Blanket Comparison and Selection Study - Final Report, Argonne National Laboratory Report, ANL/FPP/86-1.

[4] R.W. Roussin et al., The CTR Processed Multigroup Cross Section Library for Neutronics Studies, Oak Ridge National Laboratory Report, ORNL/RSIC-37 (1979).

[5] Y. Gohar and M.A. Abdou, A Library of Nuclear Response Functions Generated with MACK-IV Computer Program from ENDF/B-IV, Argonne National Laboratory Report, ANL/FPP/TM-106 (1979).

[6] 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, Oak Ridge National Laboratory Report, ORNL/RSIC-XX (August 1984).

[7] 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, Argonne National Laboratory Report (to be published).

[8] R.D. O'Dell, F.W. Brinkley, and D.R. Marr, User's Manual for ONEDANT: A Code Package for One-Dimensional Diffusion-Accelerated, Neutral-Particle Transport, Los Alamos National Laboratory Report, LA-9184-M (February 1982).

[9] R.E. Alcouffe, F.W. Brinkley, D.R. Marr, and R.D. O'Dell, User's Guide for TWODANT: A Code Package for Two-Dimensional, Diffusion-Accelerated, Neutral-Particle Transport, Los Alamos National Laboratory Report, LA-9184-M (January 1986).

[10] J. Jung, Theory and Use of the Radioactivity Code RACC, Argonne National Laboratory Report, ANL/FPP/TM-122 (May 1979).

[11] D.W. Stillman and J.D. Hallquist, INGRID: A Three-Dimensional Mesh Generator for Modeling Nonlinear Systems, Lawrence Livermore National Laboratory Report, UCID-20506 (July 1985).

[12] R. Rainsberger, Lawrence Livermore National Laboratory, private communication.

[13] K.J. Bathe, ADINA: A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis, Massachusetts Institute of Technology Report, Report 82448-1 (December 1978).

[14] K.J. Bathe, ADINAT: A Finite Element Program for Automatic Dynamic Incremental Nonlinear Analysis of Temperatures, Massachusetts Institute of Technology Report, Report 82448-5 (May 1977).

[15] B.A. Murtogh and M.A. Saunders, MINOS 5.1 User's Guide, Stanford University Report, SOL 83-20R (January 1987).

[16] P.E. Gill et al., User's Guide for NPSOL (Version 4.0): A Fortran Package for Nonlinear Programming, Stanford University Report, SOL 86-2 (January 1986).

[17] Y. Gohar et al., Low Technology High Tritium Breeding Blanket Concept, Fusion Technology (to be published).

TABLE 1 -- Materials Currently in Data Base

Tritium Breeder:	Li, 17Li83Pb, Li_7Pb_2, Li_2O, $LiAlO_2$, Li_2SiO_3, Li_4Si_4, Li_2TiO_3, Li_2ZrO_6
Neutron Multipliers:	Be, Pb, BeO, PbO, Zr, Zr_5Pb_3, Bi, BiPb
Coolant Materials:	He (gas), H_2O (liq.), D_2O (liq.), Li, 17Li83Pb
Structure Materials:	Type 316SS, Type 304SS, PCA, HT9, HT9M, V15Cr5Ti, Fe1422, Tenelon
Reflector Materials:	C, SiC, Any of the above materials
Shield Materials:	B_4, W, TiH_2, Concrete, H. Concrete, Any of the above materials
Magnet Materials:	NbTi, Nb_3Sn, Mylar, Cu, Al, Epoxy, Polyimide, Liq. He, Liq. N

TABLE 2 -- First Wall/Blanket/Shield Performance Parameters

Neutronics

Tritium breeding ratio
Energy generated per fusion neutron
Neutron flux profiles
Nuclear heating profiles
Nuclear response in the torodial field coils
First wall/blanket/shield compositions/dimensions
Radioactivity concentration, biological hazard potential, decay-heat source
Biological dose after shutdown

Heat Transfer and Thermal Hydraulics

Temperature profiles
Coolant flow rates and velocities
Pressure drop, pumping power
Temperature profiles after shutdown under several conditions

Stress Analysis

Stress profiles
Structural displacements

Tritium

Tritium permeation rates
Tritium inventories

General Parameters

First wall/blanket/shield capital cost
Capital cost per KW
Total mass
Mass utilization (power per unit mass)

FIGURE CAPTION

Figure 1. Geometrical model, temperature disruptions, and stress distributions for the graphite tile and the stainless steel tube of the first wall.

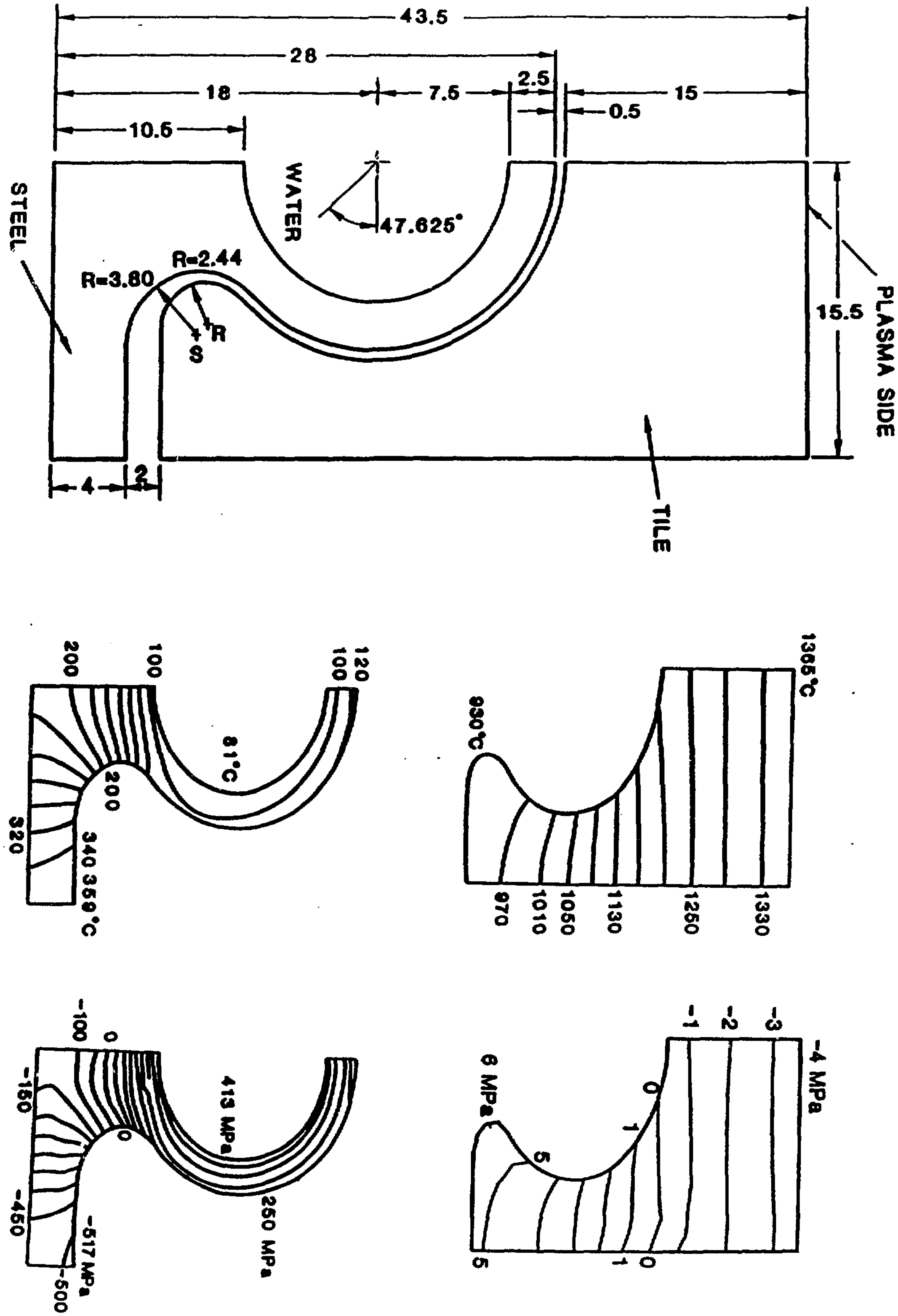

FIGURE 1. Yousry Gohar