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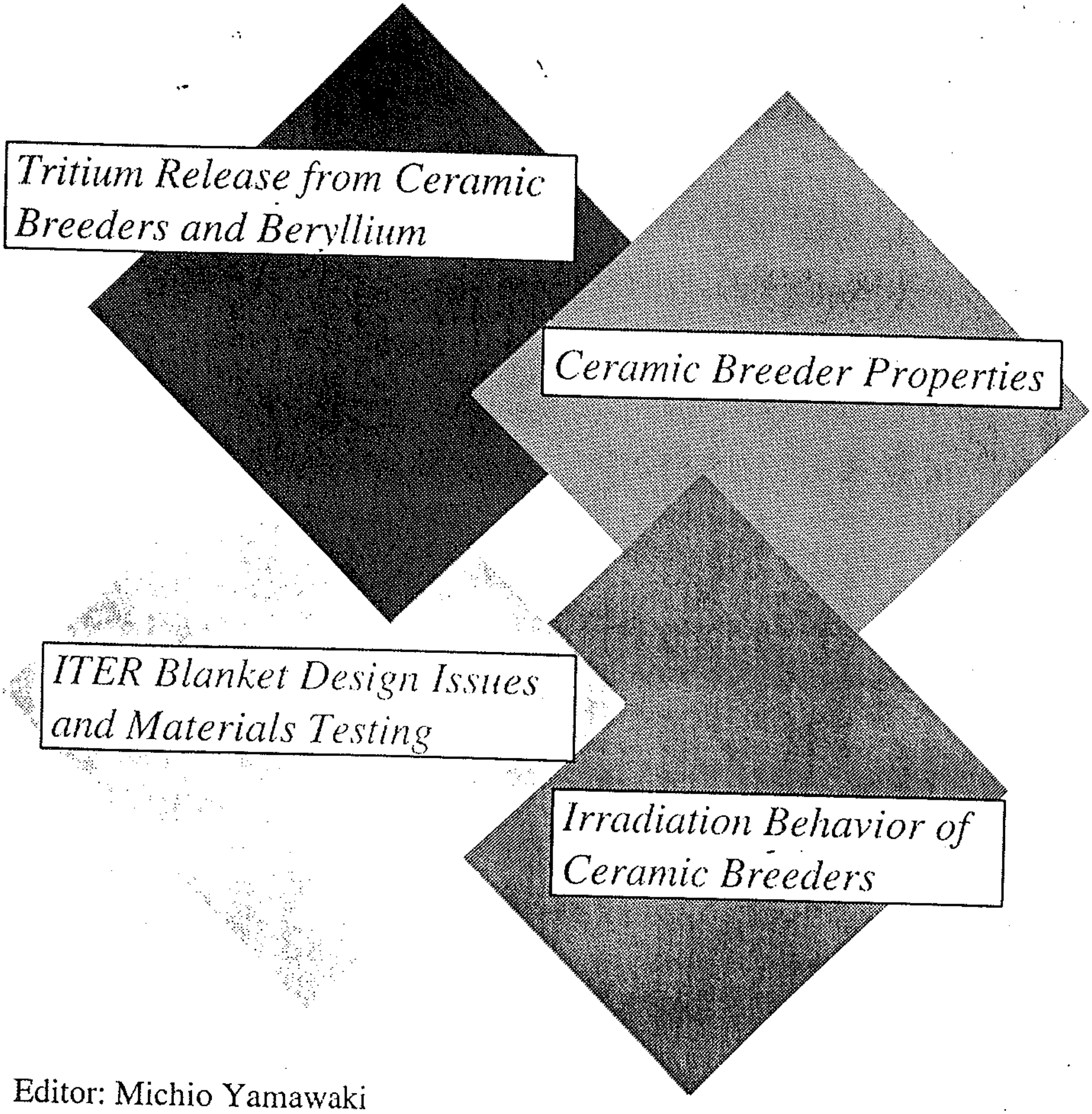

Tritium Release from Ceramic Breeders and Beryllium

Ceramic Breeder Properties

ITER Blanket Design Issues and Materials Testing

Irradiation Behavior of Ceramic Breeders

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Overview of UCLA Solid Breeder Blanket Activities

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Abstract

Research efforts on solid breeder blanket activities at UCLA have been focused on critical issues that are of high priority to ITER and testing of DEMO components in ITER. In this paper, recent R&D activities on DEMO solid breeder blanket design, solid breeder thermomechanics and thermal control, tritium modeling for tritium plant fuel cycle dynamics studies are presented. The efforts include experiments, modeling and design analysis.

1. Introduction

For many years, UCLA has been identified as one of the lead institution at US contributing to the resolution of the critical issues concerning solid breeder blanket design and R&D. Our activities center around blanket and test module designs, solid breeder thermomechanics and thermal control, tritium modeling for breeder materials and for beryllium, and tritium plant fuel cycle dynamics studies.

Topics presented in this paper include: (1) a reference DEMO solid breeder blanket concept utilizing a BOT design with ferritic martensitic steel as structural material, helium as the coolant and Li_2TiO_3 as solid breeder material, (2) recent experimental data on solid-solid interface conductance and on the packed bed effective thermal conductivity and heat transfer coefficient; including planned activities in modeling and experiments and design innovation analysis for a partially-sintering mixed Be/ceramic bed, and (3) dynamics simulation studies on ITER fuel cycle subsystem designs and operation limits. UCLA is always open to expand current collaboration with the international solid breeder blanket community.

2. DEMO Solid Breeder Blanket Design

Although the leading candidate solid breeder blanket designs were identified during the BCSS study[1], the need of an economically competitive and environmentally friendly energy source has pushed the blanket to be operated at higher temperature regimes using low activation materials. This provokes re-evaluating the old design concepts. The need of revisiting DEMO solid breeder blanket design is further driven by the forthcoming blanket testing in ITER. Much greater detail will be required on the specific features of the DEMO solid breeder blanket in order to provide the level of detail required to design ITER test modules such that the testing results are DEMO relevant.

The reference solid breeder blanket design utilizes a breeder-out-of-tube (BOT) concept, with ferritic martensitic steel as the structural material, Li_2TiO_3 as solid breeder material, beryllium as the multiplier material and helium as the coolant. Table I summarizes the major parameters of this design concept. Li_2TiO_3 was chosen as the solid breeder because it offers low activation properties as well as excellent tritium release behavior. Both the solid breeder and the beryllium are in the form of sphere-packed beds. Ferritic martensitic steel is presently considered as the structural material due to difficulties involved in developing low activation structural material in the ITER testing time frame.

A complete outboard blanket segment is shown in Figure 1. Each of the outboard blanket segments is divided into an upper and a lower module. Nominal dimensions of the module are 3.7 m length poloidally, 1 m width toroidally and 54 cm depth measured radially away from the plasma. As shown in Figure 2, the interior of the blanket is all breeding zone: for outboard, the first 35 cm of the zone consists of alternating layers of Li_2TiO_3 breeder and Be neutron multiplier separated by radially oriented coolant-panels. Packing density for the breeder region is about 62% and about 72% for Be zone. The remaining 19 cm of the breeding zone is filled with sphere-pac breeder only. The shield is separated from the blanket, but can be incorporated readily into an integral part of the blanket module.

Table 1: Design Parameters for the Reference DEMO He-Cooled Solid Breeder Blanket

Parameter	Value
Total Blanket Power	2,500 MW
Li^6 Enrichment	40 at.%
Coolant Inlet Pressure/Pressure Drop	10MPa/0.47 MPa
Coolant Inlet/Outlet Temperature	250 / 420 °C
First Wall Structure Temp., Min./Max.	408 / 543 °C
Breeder Temperature, Min./Max.	320 / 930 °C
Maximum Be Temperature	660 °C
1-D TBR without ports	1.47
Tritium Purge He Pressure	0.2 MPa

The first wall is an integral part of the blanket module. The first wall and blanket are all poloidally cooled to minimize the number of coolant joint connections. Lateral and depth wise spacing of the tubes is graded in accordance with local nuclear heating rates, material thermal properties and allowable temperature limits of the surrounding materials. A coolant pressure of 10 MPa is chosen for helium in order to reduce the pressure drop and to have a compact design. The fractional pressure drop is about 5%.

3. Solid Breeder Blanket Thermomechanics and Thermal Control

Thermomechanical performance and control has been cited as a critical issue for all solid breeder blankets because maintaining the breeder temperature within allowable limits has several constraints: 1) a relatively low thermal conductivity and a stringent allowable temperature window, 2) uncertainties and heterogeneity due to manufacturing and operating conditions, 3) radiation-induced changes in properties and 4) requirements for power variation accommodation. The overall goals of the UCLA thermomechanic and thermal control activity are to: 1) develop innovative design solutions to tehrmomechanic/thermal control problem, 3) develop a better understanding of thermomechanical behavior, 4) further develop and verify predictive capabilities and 5) demonstrate acceptable performance parameters and design margins through experiments and modeling. The activities incorporate modeling, experimental studies and design analysis.

Experimental Studies and Modeling

Laboratory experiments were initiated in conjunction with the development of models for addressing solid breeder blanket thermal control and thermomechanical issues in 1988. Since then, the types of experiments have progressed from the basic properties and separate effects into the multiple effects tests as shown in Figure 3. Under the category of basic properties experiments, effective thermal conductivity and wall conductance of a packed bed were measured in the PBX facility while solid-solid interface conductance was measured as a function of gas pressure, contact pressure, surface roughness and heat flux in the ICE facility. As shown in Figure 4, the measured interface conductance of Be disk/stainless steel disk decreases as the surface heat flux increases because of the formation of an additional gap due to thermal deformation. The results also indicate that smoother surfaces encountered greater maximum values of interface conductance, but experienced large drops in interface conductance over a relatively small heat flux range[2]. These experiments were used to provide data for solid breeder blanket designs involving sphere-pac and sintered block configurations. In parallel, fundamental phenomenological modeling of interface conductance and bulk thermal conductivity of porous medium were developed[e.g., Ref. 3].

Our recent experimental efforts focused on separate and multiple effects on thermomechanical performance issues, in particular mechanical forces and clad/bed interaction with regard to the blanket thermal behavior. Representative experimental test articles/facilities under these categories are HPBX, HiTeC (Figure 5) and UNICEX. Experimental results show that the effective thermal conductivity of a metallic particle bed such as Be packed bed increases as the external applied load (e.g., coolant pressure) increases (Figure 6). This is because forces exerted on packed beds have an amplified effect causing an increase of the contact area between two particles. Besides the external forces, internally induced forces such as irradiation swelling will also produce a significant increase in the particle contact area and in the effective thermal conductivity. A theoretical model that would correlate applied loads to packed beds to the actual normal contact forces at particle contact points is currently under development. The ultimate goal is to study the evolution of the contact area with associated thermal properties as a function of operating conditions.

Design Innovation Analysis

An innovative concept involving partially sintering of a mixed Be and ceramic particle bed to help improve thermal performance of the solid breeder blanket design was introduced[5]. The intend of this work is to suggest a direction for improving thermal characteristics of solid breeder blankets for further investigation. Issues associated with the mixed bed design concept are: long term chemical compatibility between ceramic breeder and Be, tritium implantation in Be, formation of BeO on the surface of Be affecting tritium release and enclosure of small breeder pellets by Be.

By partially sintering the mixed bed prior to operation, the thermal conductivity of the bed can be increased by more than a factor of 4 to 5. Such a potential improvement in the effective thermal conductivity has led to investigate the sintering conditions required to achieve "partial sintering" of a mixed bed. Synonymous to partial sintering is "initial stage" of sintering. Sintering provides the interparticle bonding of otherwise loose particles. During the initial stages of sintering, particles form weld bonds at particle contacts without significant shrinkage of the bed, because only the pore shapes change while the pore sizes remain the same[5]. It is critical that the temperature and time requirements for the initial stages of sintering do not surpass compatibility allowables between Be, the breeder, and the structural materials.

During the initial stages of sintering, there are five alternate mechanisms contributing the sintering growth rate: surface diffusion, grain boundary diffusion, evaporation-condensation, lattice diffusion and plastic flow. The transport paths of sintering/neck growth rates are sensitive to the particle diameter and temperature (determining diffusivities for various processes). However, for Be at all temperatures, the lattice diffusion process is found to be the dominant mechanism for neck growth. To show that the required temperature and times for achieving the initial stage of sintering are within the allowables, sintering maps for the mixed bed are determined. The time required to achieve the initial stages of sintering (defined as neck size ratio, X/D, of < 0.3) as a function of operating temperature for particle sizes of 2 and 0.5 mm is shown in Figure 7. For the 2 mm Be particle bed the time to fully develop X/D =0.3 at 900°C has risen to about 1000 hours compared with 13 hours for 0.5 mm Be. If the maximum temperature is 700°C, then chossing Be particle diameter of 0.5 mm would result in sintering times of the order of 300 hours to achieve neck size ratio of 0.3. The estimated thermal conductivity of such a partially sintered mixed Be/ceramic breeder bed show an upper limiting value of about 25 W/m-K at 600°C. Detailed description of this work can be found in Ref. 5.

4. Tritium Transport and Fuel Cycle Modeling

Tritium modeling at UCLA began with the development of tritium transport computer codes for ceramic breeder and beryllium materials, including effects of temperature and chemistry transients[6,7]. Computer codes such as MISTRAL have been used extensively for time dependent ITER/DEMO blanket design tritium release and inventory calculations and for irradiation experimental data analyses. Recently, this activity has been extended to the development of a modular dynamic model for the fuel cycle in a fusion reactor, with ITER being used as the reference design[8]. The code attempts to track tritium flow rates and inventories in real time enabling design engineers to better understand transient system behavior and subsequently to minimize tritium inventories. In addition, DT fuel self-sufficiency can be assessed using this dynamics fuel cycle code to provide more accurate values for the required TBR and to examine the effects from fuel cycle design parameter changes on self-sufficiency.

Dynamics Fuel Cycle Modeling

The general fusion fuel cycle flowsheet for use in TRUFFLES (TRitiUm Fusion Fuel cycLE dynamic Simulation) is illustrated in Figure 8. This flowsheet schematic is purposely made to be as general as possible in order for the modules representing the various options in the subsystem blocks to be incorporated as the design warrants. A major departure from previous models is the ability to specify design parameters and operating scenarios:

- The use of real unit design parameters in place of a general tritium residence time to define each subsystem.
- The inclusion of actual tokamak fusion reactor operating parameters and scenarios.
- The inclusion of the major impurities, hydrogen isotope and operational states and types.
- The inclusion of fuel cycle component operating modes and their associated scheduling.
- Flexibility of the modular approach in this model that is able to account for changes in fuel cycle design and modeling improvements.

The calculation of inventory is expressed as a function of inflows, operating state and component characteristics. The model is able to account for any number and type of impurity, for which typical impurties are: He, Q_2, AR, O_2, N_2, CQ_4, CO, CO_2, NQ_3, Q_2O. With regard to Q_2, this model tracks all six hydrogen isotope molecules, namely T_2, D_2, H_2, DT, HD, and HT. The output parameters of the model include: inventories of all molecular species in each subsystem, mole fractions of each species in the outflow from each subsystem and hydrogen isotopic ratios in the outflow.

Modeling of real time inventory in the blanket module is based on the following formulation in order to drastically reduce the amount of computer time needed to solve the large number of resulting differential and algebraic equations:

$$\frac{\partial I}{\partial t} = \dot{G} - \sum_{n} [(F_t^n - F_{t-\delta t}^n)\Delta I_0^n] \qquad \text{n= number of inventory packet= 1 --- N}$$

where F_t^n = fractional release during time t according to the controlling mechanism as a function of its operating temperature regime as given in Table 2, $\dot{G}$ = tritum generation rate at time t and ΔI_0^n = the initial tritium inventory at inventory packet n. The model makes use of frictional packets of inventory that are created at each time interval δt. These inventory packets, ΔI_t^n, are assumed to act independently from one another. It is further assumed that each inventory packet, ΔI_t^n, will undergo its own release according to the controlling mechanism with ΔI_0^n as the initial inventory. This modular is currently under development.

Table 2 Analytical Models for Calculating Tritium Release Fraction from a Slab Geometry

Controling Mechanism	Analytical Expression of Fractional Release
Diffusion Control	$F = 1 - \frac{8}{\pi^2} \sum_{n=1} \frac{1}{(2n+1)^2} e^{-D\beta_n^2 t}$; $\beta_n = (2n+1)\pi/2L$, n= 1--- $\propto$ [D: diffusivity]
Desoprtion Control (1st order)	$F = 1 - e^{-\frac{K_d}{I}t}$
Desorption Control (2nd order)	$F = 1 - \frac{1}{1 + \frac{2K_rC_o}{L}t}$
Diffusion/Desorption Control	$F = 1 - \frac{\frac{1/\alpha_n^2}{(\alpha_n^2 + h^2)L + h} e^{-D\alpha_n^2 t}}{\frac{1/\alpha_n^2}{(\alpha_n^2 + h^2)L + h}}$; α_n = root of [$\alpha\tan(\alpha L) = h$], h= K_d/D

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Figure 1

U.S. DEMO He-Cooled Solid Breeder Reference Blanket

One Complete First-Wall/Blanket Segment

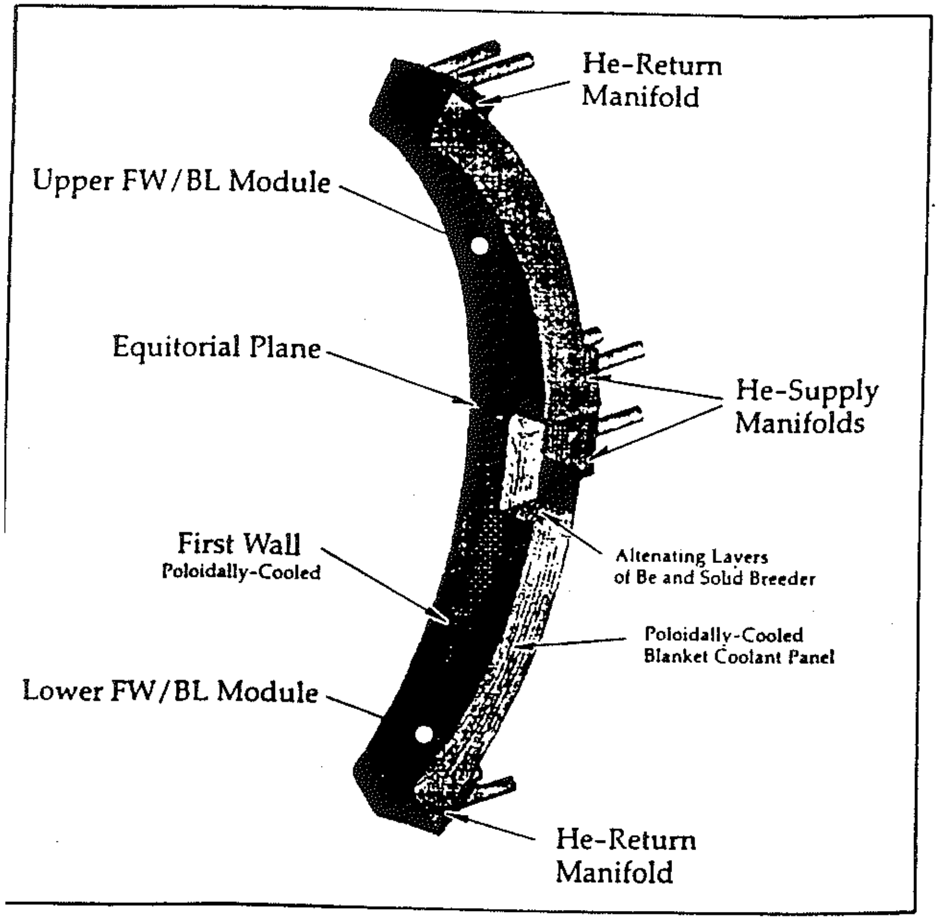


Figure 2

U.S. DEMO He-Cooled Solid Breeder Reference Blanket

Cutout View of the First Wall/Blanket/Upper Manifold

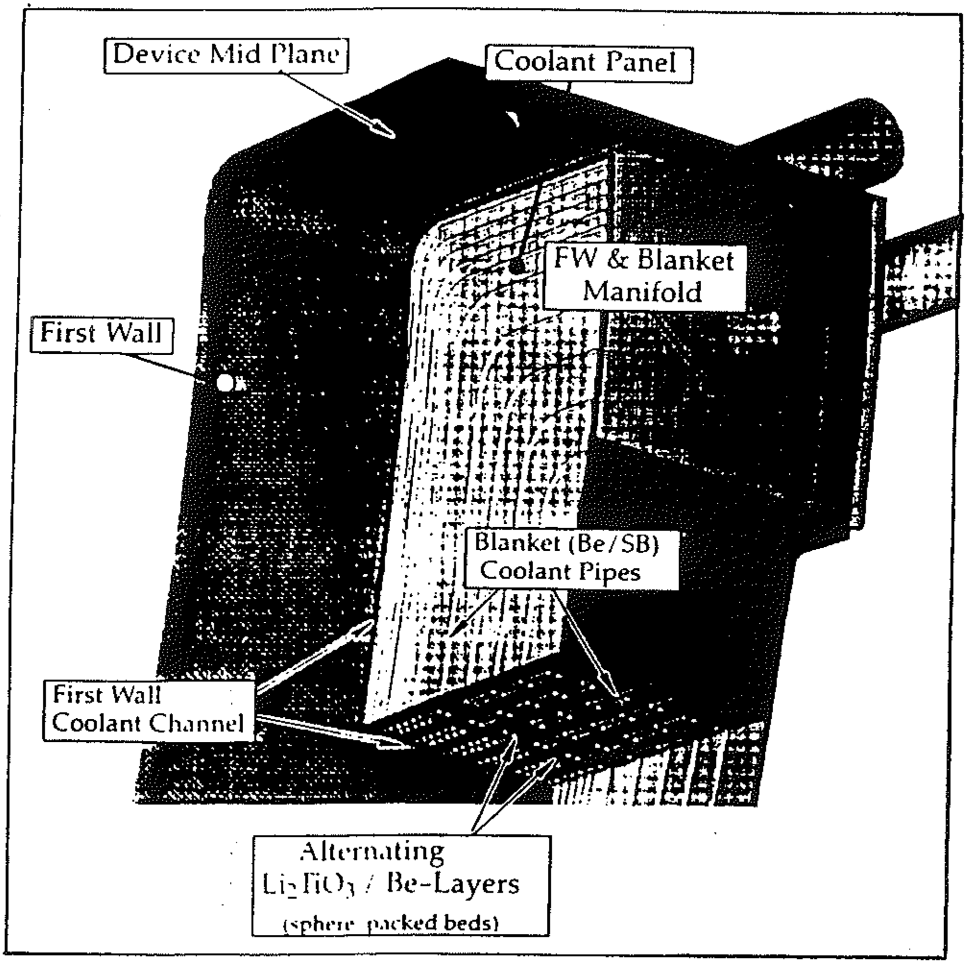
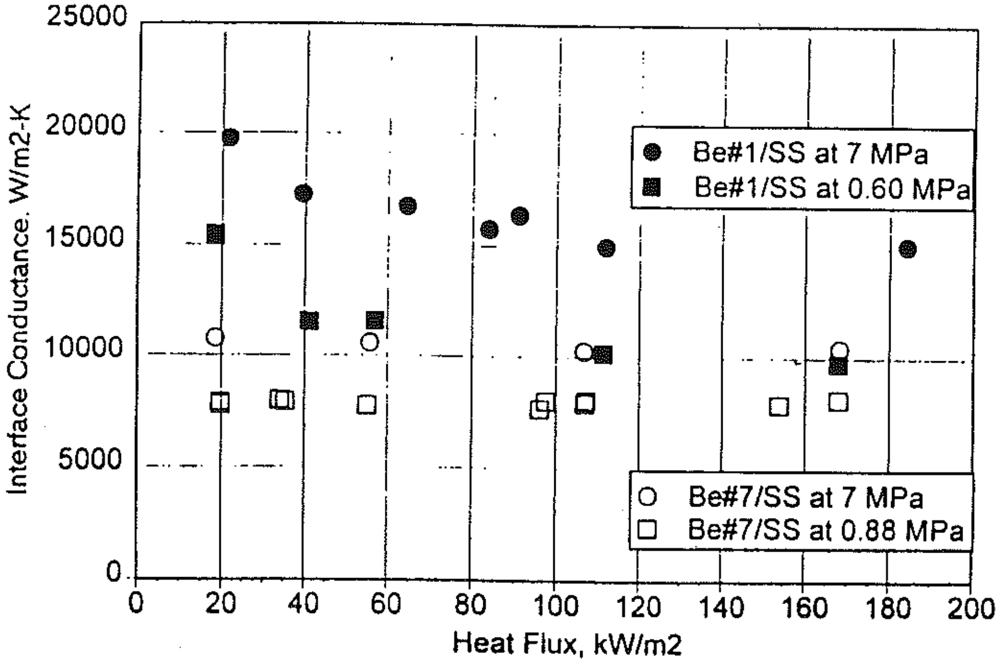


Figure 3

Thermal Control Experiments at UCLA

Basic Properties	*Separate Effects*	*Multiple Effects*	*Partially Integrated*
PBX *(operational)* Pebble Bed Heat Transfer at Low Temperature Gas Phase Control Effective Bulk Conductivity Wall Conductance Pressure Drop **ICE** *(operational)* Interface Conductance Be With Surface Roughness High Contact Pressure Variable Heat Flux Control of Gas Phase	**HiTeC** *(operational)* High Temperature Cyclic Heat Transfer in Prototypic Geometry Be or Ceramic Pebble Beds Independent Control of Temperature and Gradient Bulk Conductivity Wall Conductance Effect of Bed or Clad Deformations	**UNICEX** *(new test article in planning)* Solid Breeder Blanket Unit Cell Thermomechanical Interactions Breeder & Multiplier at Prototypic Conditions Simulation of Bulk Heating He or Water Coolant, He purge	
HTBX *(operational)* Pebble Bed Heat Transfer at High Temperature Mechanical Response to Thermal Expansion Effect of Mechanical Constraints on Heat Transfer			

Figure 4 **Be/SS Interface conductance as a function of Heat Flux for Different Surface Roughness**



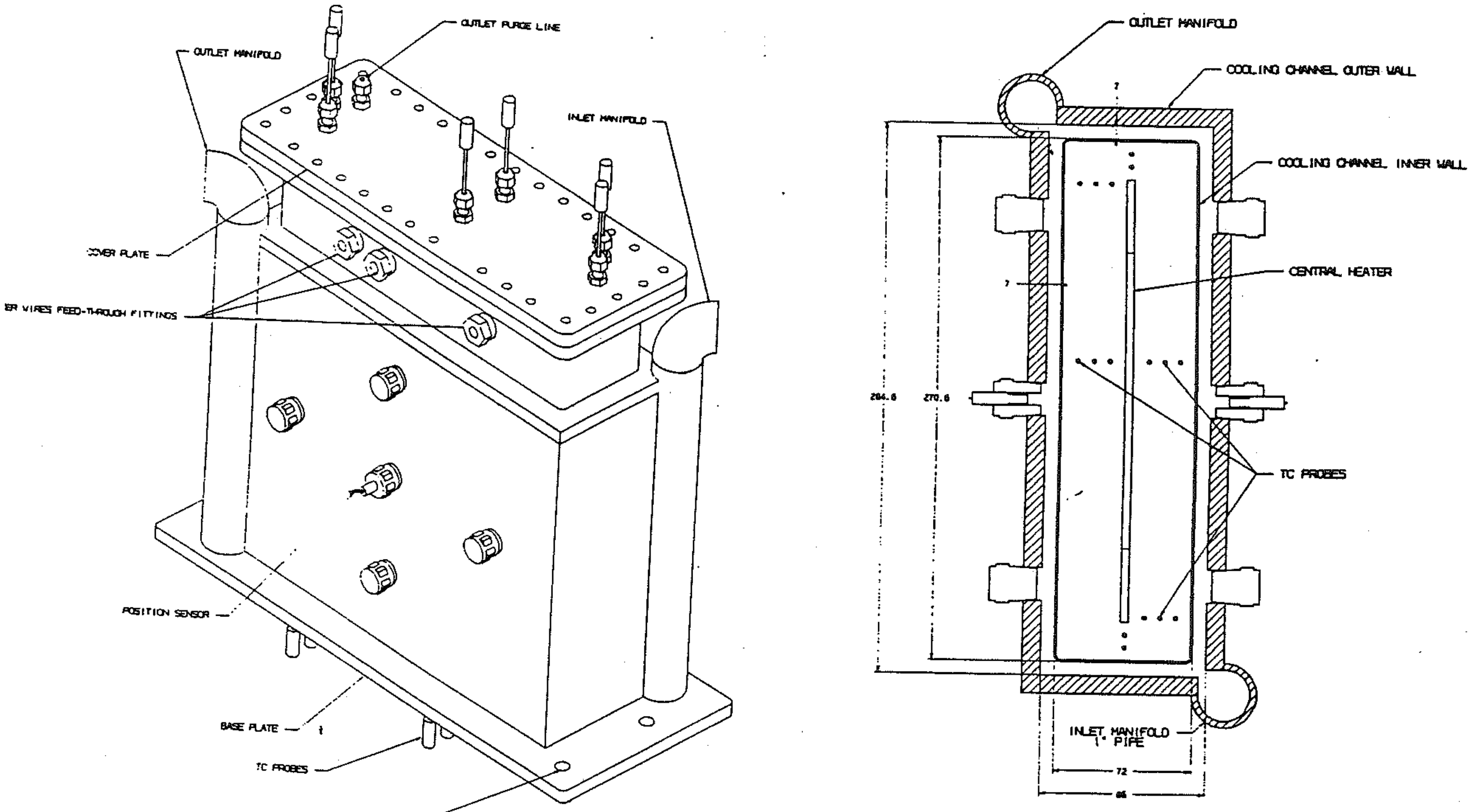


Figure 5 **HiTeC Test Article**

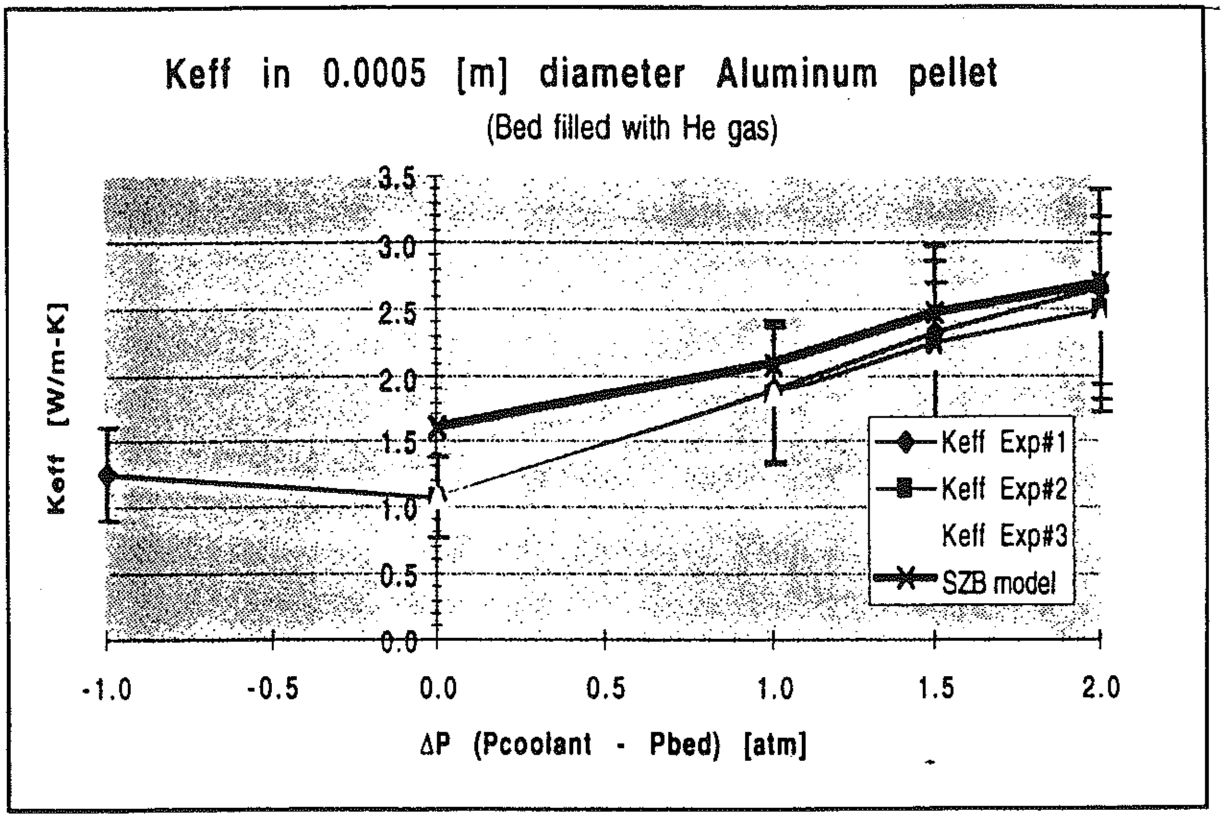


Figure 6 **Packed Bed Effective Thermal Conductivity as a function of External Pressure**

INITIAL STAGE SINTERING MAP OF 0.5 AND 2-MM DIAMETER BE BEDS FOR NECK SIZE RATIOS OF X/D = 0.3.

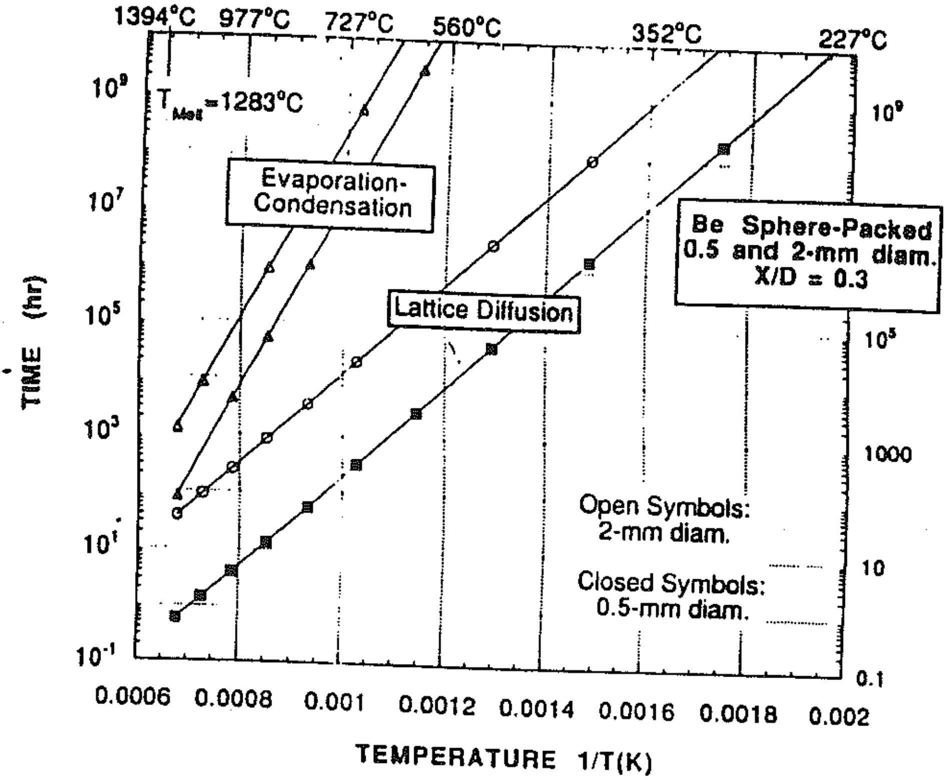


Figure 7

TRUFFLES Flowsheet

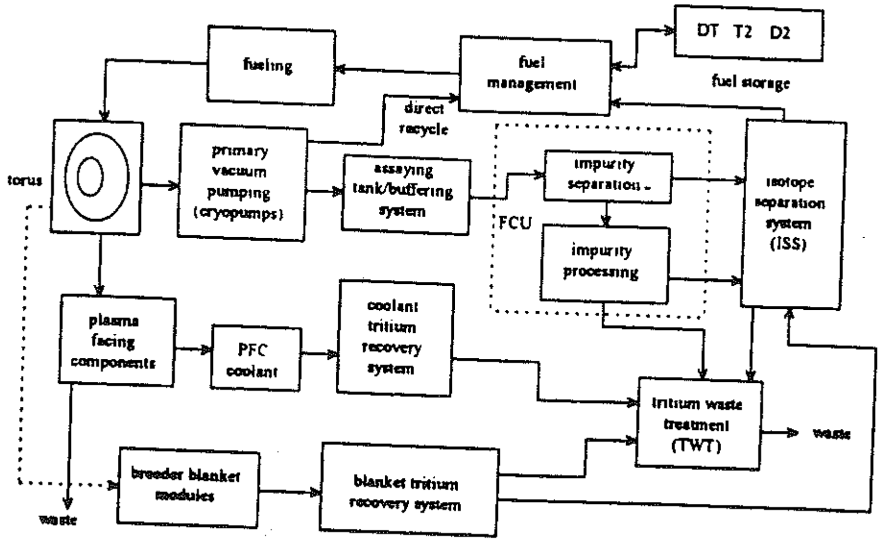


Figure 8 Flowsh