BERYLLIUM RELATED
EXPERIMENTAL AND MODELING ACTIVITIES
AT UCLA
(1993)

UCLA GROUP

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UCLA ACTIVITIES IN THE BERYLLIUM AREA

THERMOMECHANICS

EXPERIMENTAL:

- PACKING EXPERIMENTS
- PARTICLE BED EFFECTIVE THERMAL CONDUCTIVITY
- PARTICLE BED/WALL INTERFACE CONDUCTANCE, h,
- EFFECT OF INTERNAL AND EXTERNAL LOAD ON K_{eff} AND h

MODELING:

- PARTICLE BED EFFECTIVE THERMAL CONDUCTIVITY
- PARTICLE BED/WALL INTERFACE CONDUCTANCE COEFFICIENT
- BERYLLIUM/STAINLESS STEEL INTERFACE CONDUCTANCE

TRITIUM TRANSPORT AND RELEASE

- MODELING OF TRITIUM TRANSPORT AND RELEASE FROM BERYLLIUM
- ANALYSIS OF THE AVAILABLE IRRADIATED BERYLLIUM DATA
- BENCHMARKING THE MODELS AGAINST THE EXPERIMENTAL DATA

ITER FIRST WALL/BUMPER LIMITER

- CONTRIBUTE TO THE DESIGN AND ANALYSIS OF THE ITER FWB/BUMPER LIMITER

NEUTRONICS

- BROAD RANGE OF EXPERIMENTS

Thermo-Mechanics Modeling at UCLA

Packed Bed Effective Thermal Conductivity

- 2-D model developed and calibrated: with extensive capabilities. (Gas pressure variation. high ks/kg, single-size and binary bed. porosity, contact area. roughness)
- Several simple. faster-to-run models based on the literature have also been coded: (modified Hall&Martin. Bauer&Schlunder. Kunii&Smith)

Packed Bed Wall Conductance

- Model developed and calibrated; provides lower and upper bound estimates based on porosity distribution at the wall and
- Simple lower-bound expression proposed for initial design calculations

- *Help in the understanding of thermomechanics behavior of ceramic breeders and Be in packed bed and sintered block forms.*
- *Provide tools for analysis of blanket performance under different conditions and for determination of thermal controllability of ceramic breeder blanket.*
- *Help determine range of blanket parameters and conditions over which uncertainties in the blanket performance are highest. The results can then be used to recommend most needed experiments.*
- *Provide tools for pre- and post- analyses of blanket partially -integrated and integrated experiments.*
- *Share modeling results with national and international organizations*

Contact Conductance

- Models based on Shlykov and Yovanovich have been coded
- Plan is to develop a semi-empirical model for Be/SS based on these models and our experimental results

Porous Flow

- Steady-state model based on modified Darcy's equation has been developed/ Velocity profile. Pressure drop
- Transient capability is being developed/ LOFA analysis

Tritium Modeling at UCLA

Ceramic Breeders

- Development of MISTRAL, a state of the art, comprehensive model for tritium transport in ceramic breeders
- Used for ITER blanket analysis in US and Europe
- Used for analysis of experimental data, BEATRIX-II, TEQUILA

Single Crystals

- MISTRAL-SC has been developed specifically for modeling tritium transport in ceramic breeder single crystals
- Focus is on better understanding and characterization of fundamental property data based on analysis of experimental results
- Applied to analysis of recent LiAlO2 results

- *Predict inventory in ITER blanket*
- *Predict inventory in reactor blankets*
- *Help understand time-dependent behavior*
  - *help define ITER operating requirements*
- *Pre- and post-analysis of experiments*
- *Collaboration with national and international organizations*
- *Excellent topics for Ph. D. students, which allows field to benefit*

Beryllium

- Tritium inventory in Be can be substantial over the blanket life
- Be is considered as a candidate plasma facing material
- Comprehensive model is being developed for better understanding of tritium behavior in Be

Tritium Fuel Cycle

- A model is being developed in cooperation with LANL for estimating time-dependent tritium inventories and major species concentrations based on detailed characterization of each subsystem in the ITER fuel cycle

Thermal Control Experiments at UCLA

Basic Properties

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

HTBX *(operational)*

Pebble Bed Heat Transfer
at High Temperature

Mechanical Response to Thermal Expansion
Effect of Mechanical Constraints on Heat Transfer

Separate Effects

HiTeC *(in planning)*

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

Multiple Effects

UNICEX *(under consruction)*

Solid Breeder Blanket Unit Cell

Thermomechanical Interactions
Breeder & Multiplier at Prototypic Conditions
Simulation of Bulk Heating
He or Water Coolant, He purge

Partially Integrated

INTERFACE CONDUCTANCE EXPERIMENT (ICE)

SCOPE:

PREDICTABILITY AND CONTROLLABILITY OF BE-STEEL INTERFACE THERMAL CONDUCTANCE COEFFICIENT IS ESSENTIAL TO THE FUSION BLANKET DESIGN BASED ON SOLID BREEDER DESIGN

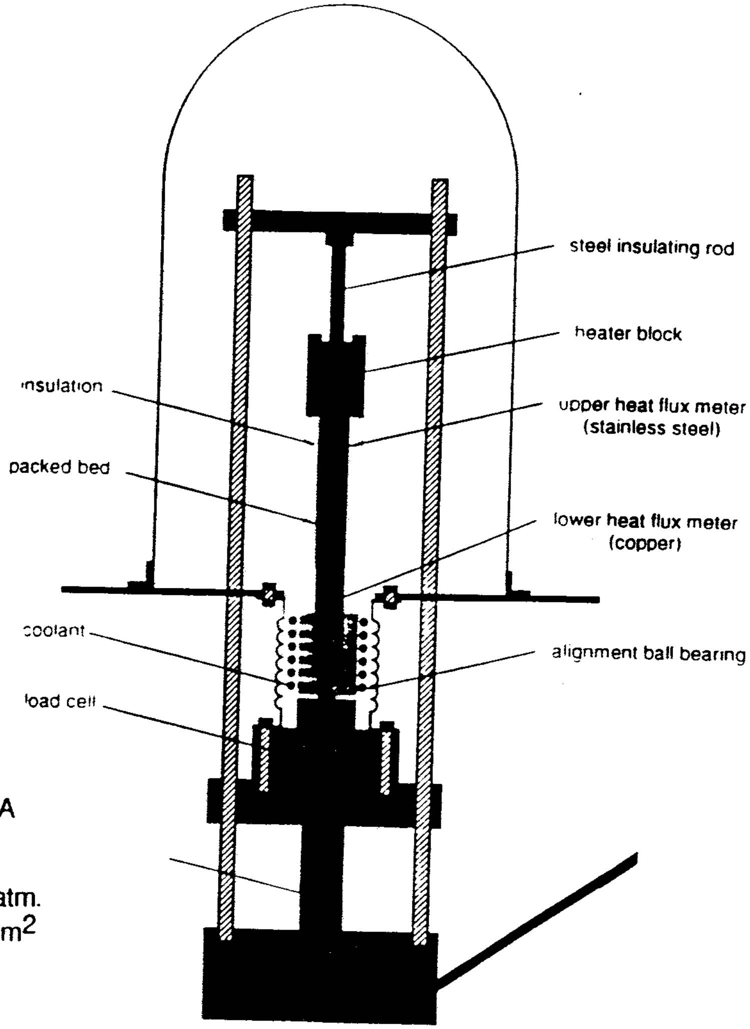
NO DATA EXIST FOR BE-STEEL INTERFACE THERMAL CONDUCTANCE COEFFICIENT

EXISTING MODELS AND DATA SHOW LARGE DISCREPENCIES, EVEN FOR STEEL INTERFACES

OBJECTIVES:

TO MEASURE THE INTERFACE THERMAL CONDUCTANCE COEFFICIENT AS A FUNCTION OF THE :

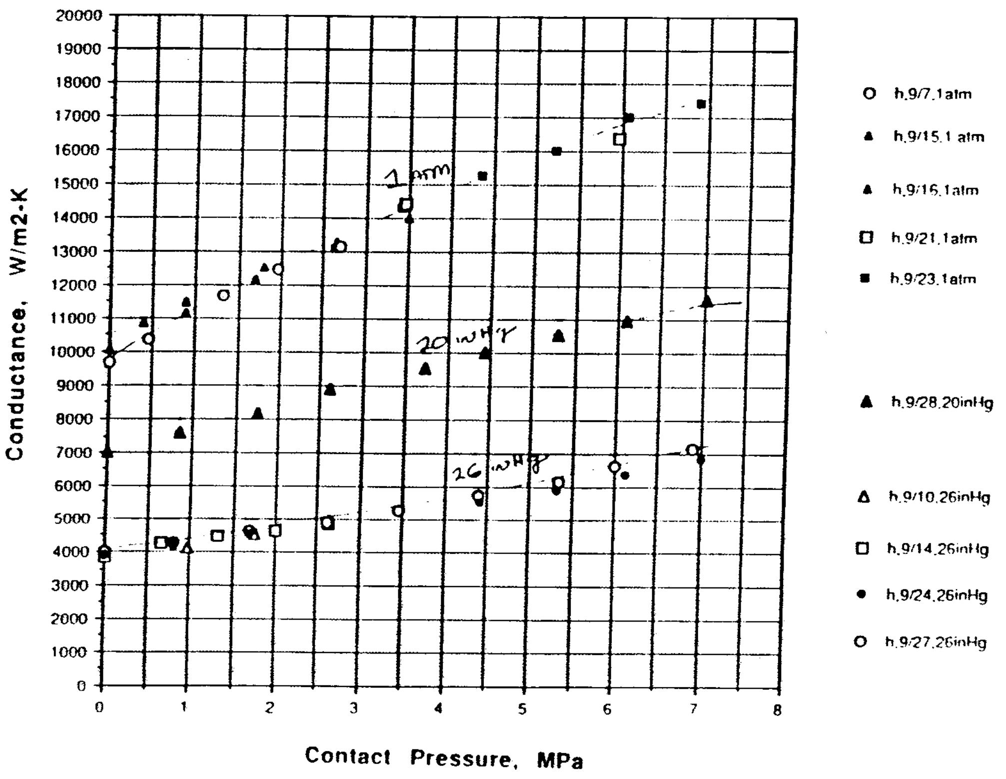
CONTACT PRESSURE	0-20 MPA
SURFACE ROUGHNESS	1-50 μ
COVER GAS COMPOSITION	N2, He
COVER GAS PRESSURE	1 Torr-1 atm.
HEAT FLUX	0-50 W/cm^2



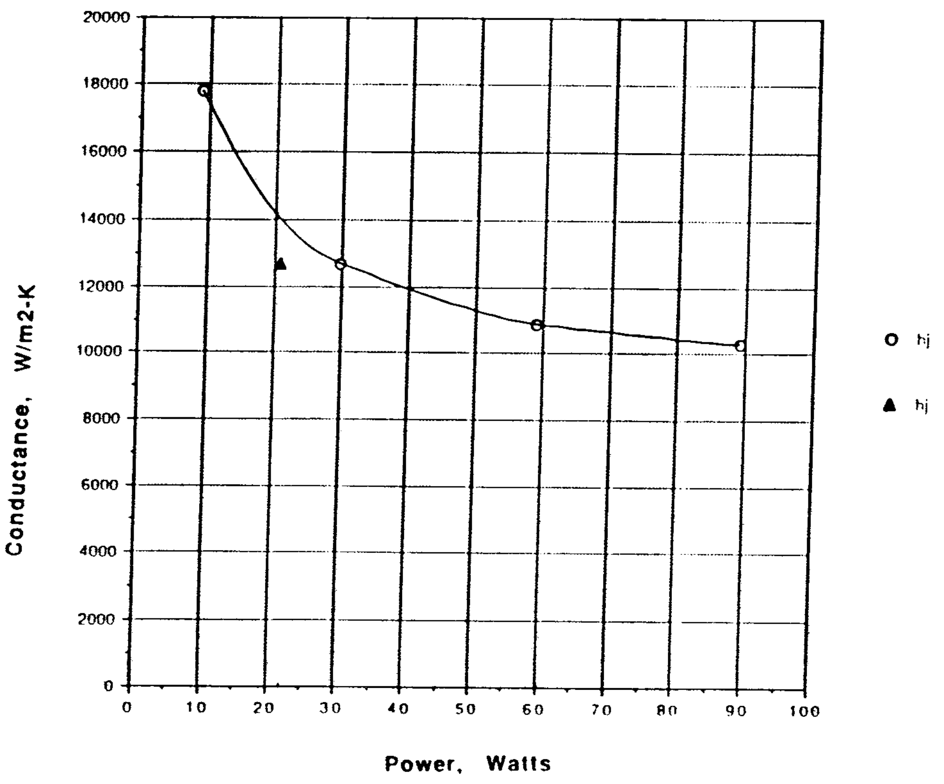
INTERFACE CONDUCTANCE EXPERIMENT

RECENT RESULTS ON BERYLLIUM /STAINLESS STEEL

INTERFACE THERMAL CONDUCTANCE COEFFICIENT



Heat Conductance vs Contact Pressure, Be#1/SS304, Helium Gas



Conductance vs Heater Power, Be#1/SS304, He@1 atm, Load = 70 lbs

PARTICLE BEDS THERMOMECHANICAL EXPERIMENTS

SCOPE:

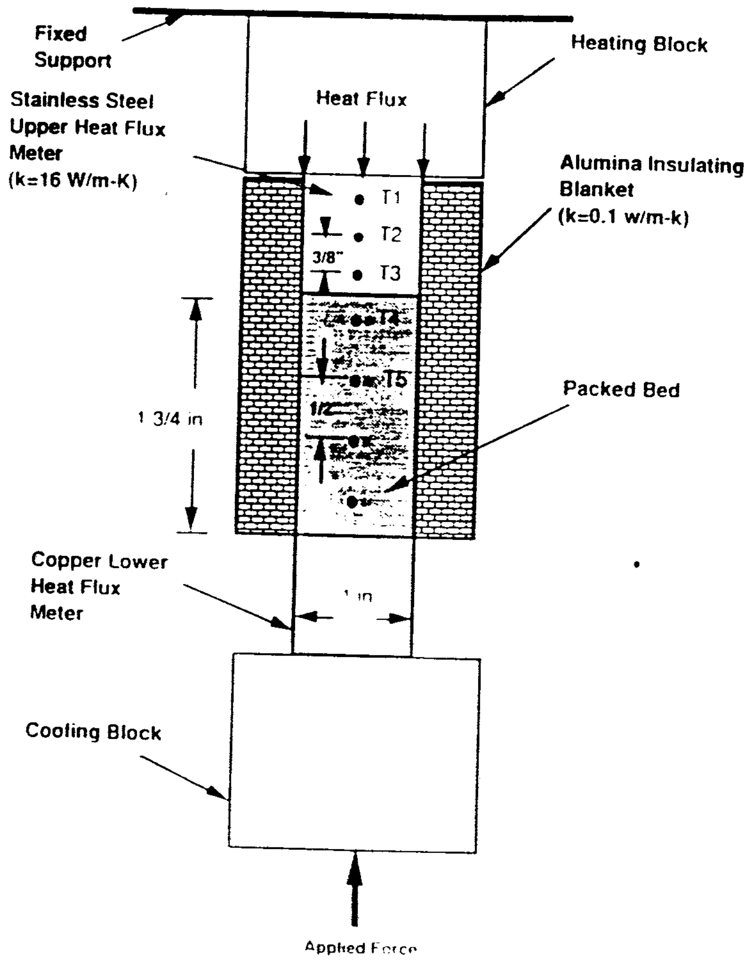
THERMOMECHANICAL EFFECTS IN PARTICLE BEDS ARE STRONGLY INTERDEPENDENT

UNDERSTANDING THE THERMOMECHANICAL EFFECTS IN PARTICLE BEDS IS CRITICAL TO THE DESIGN OF FUSION BLANKETS BASED ON SOLID BREEDERS AND MULTIPLIERS IN THIS FORM

OBJECTIVES:

TO QUANTIFY THE VARIATIONS IN THE PARTICLE BED THERMAL PROPERTIES (EFFECTIVE BED THERMAL CONDUCTIVITY AND BED/CLAD INTERFACE CONDUCTANCE COEFFICIENT) WITH THE APPLIED EXTERNAL LOAD

TO GENERATE A DATA BASE TO HELP THE DESIGN AND ANALYSIS OF THE MORE COMPLEX AND INTEGRATED THERMOMECHANICAL TESTS AND THE DESIGN OF BLANKETS BASED ON STATIONARY PARTICLE BED CONCEPT.



PARTICLE BEDS THERMOMECHANICAL EXPERIMENTS

RECENT RESULTS ON BERYLLIUM PARTICLE BED

Figure 12a . Effect of External Load on Beryllium Particle Bed Effective Thermal Conductivity

Particle Diameter= 2 mm, PF= 0.634, Average Bed Temperature= 33 C

Cover Gas= Air at 1 Atmosphere

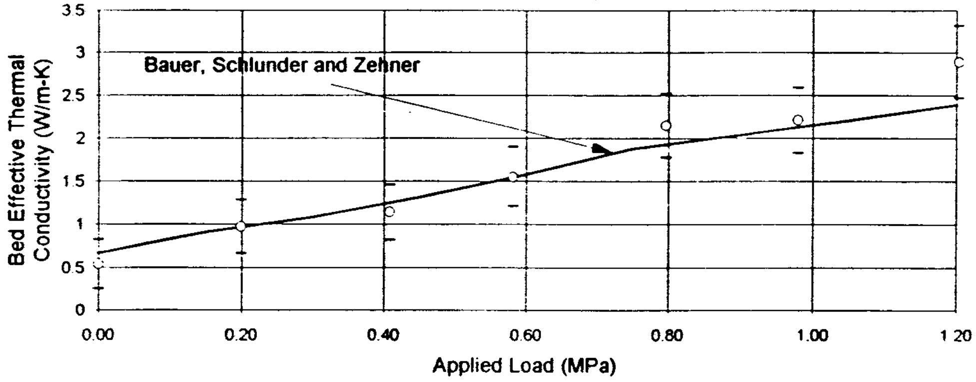


Figure 15a . Effect of External Load on Beryllium Particle Bed Effective Thermal Conductivity

Particle Diameter= 2 mm, PF= 0.634, Average Bed Temperature= 33 C

Cover Gas= Helium at 700 Torr

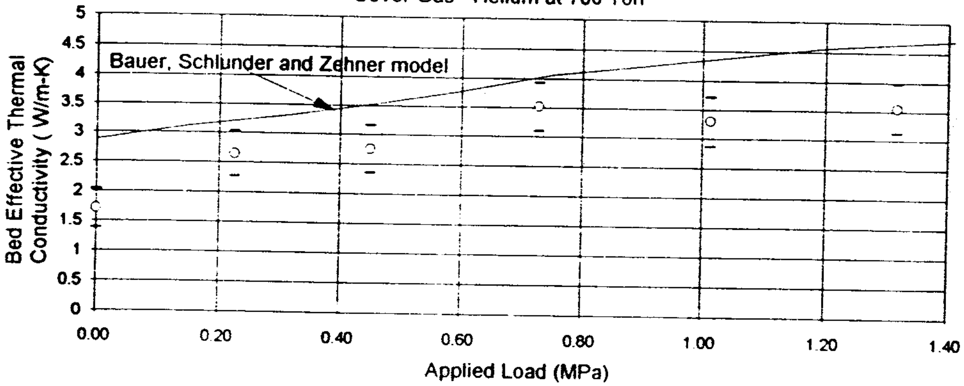


Figure 12b . Effect of External Load on Beryllium Particle Bed Effective Thermal Conductivity Ratio

Particle Diameter= 2 mm, PF= 0.634, Average Bed Temperature= 33 C

Cover Gas= Air at 1 Atmosphere

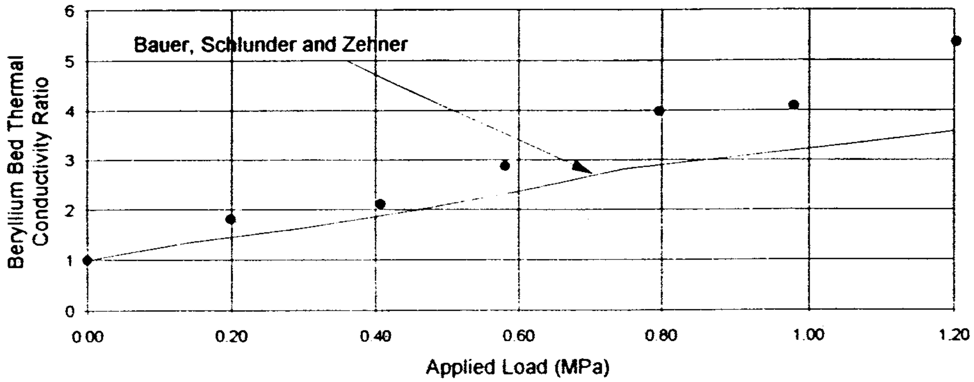
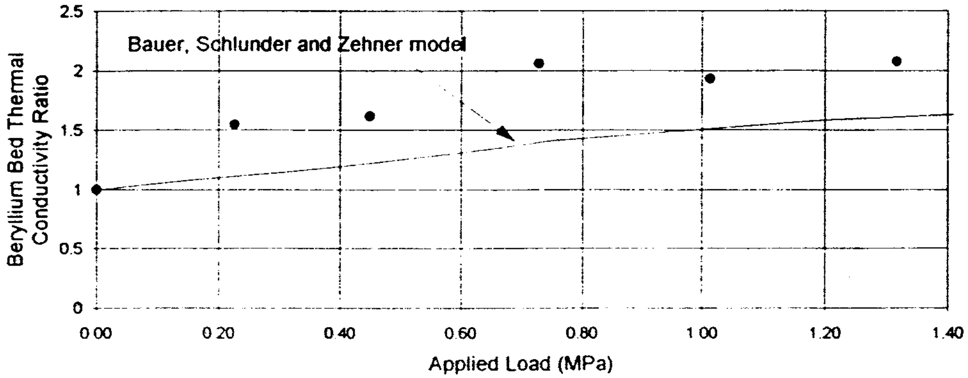


Figure 15b . Effect of External Load on Beryllium Particle Bed Effective Thermal Conductivity Ratio

Particle Diameter= 2 mm, PF= 0.634, Average Bed Temperature= 33 C

Cover Gas= Helium at 700 Torr



PARTICLE BEDS THERMOMECHANICAL EXPERIMENTS

CONCLUSIONS:

1. FOR METALLIC BEDS (ALUMINUM AND BERYLLIUM), THE BED EFFECTIVE THERMAL CONDUCTIVITY IS A STRONG FUNCTION OF THE EXTERNAL LOAD
    - WITH AIR AS COVER GAS,
        - Keff INCREASED BY A FACTOR OF 3-7 AS THE LOAD INCREASED FROM 0 TO 1.5 MPa
    - WITH HELIUM AS COVER GAS
        - Keff INCREASED BY A FACTOR OF 2-3 AS THE LOAD INCREASED FROM 0 TO 1.5 MPa

2. FOR CERAMIC BED (Li2ZrO3), CHANGES IN THE BED EFFECTIVE THERMAL CONDUCTIVITY WITH EXTERNAL LOAD WERE SAMALL AND WITHIN EXPERIMENTA UNCERTAINTIES

3. THE INCREASE IN INTERFACE THERMAL CONDUCTANCE SHOWED VARIATIONS WITH EXTERNAL LOAD SIMILAR TO THOSE OF THE THERMAL CONDUCTIVITY

PARTICLE BED EXPERIMENT (PBX)

SCOPE:

THERMAL PROPERTIES (EFFECTIVE THERMAL CONDUCTIVITY AND INTERFACE CONDUCTANCE COEFFICIENT) ARE FUNCTIONS OF THE COVER GAS COMPOSITION, COVER GAS PRESSURE, PARTICLE SIZE, BED POROSITY

THE VARIATION OF THERMAL PROPERTIES WITH THE COVER GAS COMPOSITION AND PRESSURE CAN BE USED AS AN ACTIVE CONTROL MECHANISM FOR CONTROLLING THE BED TEMPERATURE

OBJECTIVE:

TO MEASURE PARTICLE BEDS EFFECTIVE THERMAL CONDUCTIVITY AND INTERFACE THERMAL CONDUCTANCE COEFFICIENT AS A FUNCTION OF THE PARAMETERS INVOLVED

TO DEMONSTRATE THE POSSIBILITY OF ACTIVE THERMAL CONTROL IN SOLID BREEDERS

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THERMAL PROPERTIES (EFFECTIVE THERMAL CONDUCTIVITY AND INTERFACE CONDUCTANCE COEFFICIENT) ARE FUNCTIONS OF THE COVER GAS COMPOSITION, COVER GAS PRESSURE, PARTICLE SIZE, BED POROSITY

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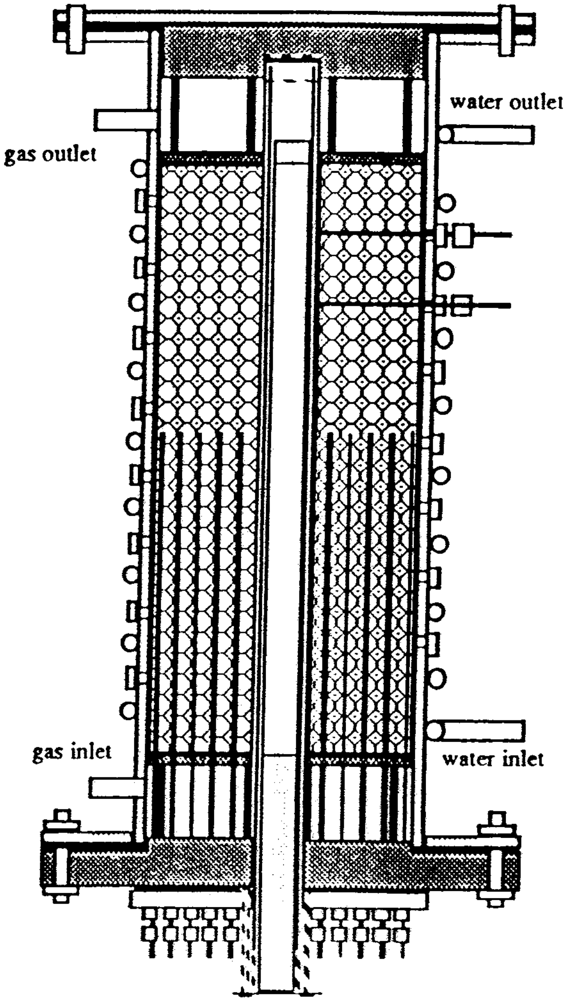
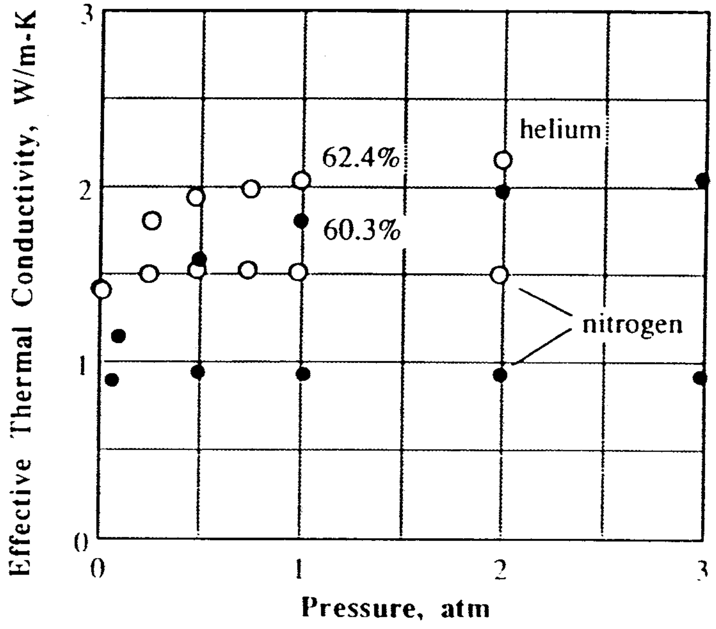


PARTICLE BED EXPERIMENT (PBX)

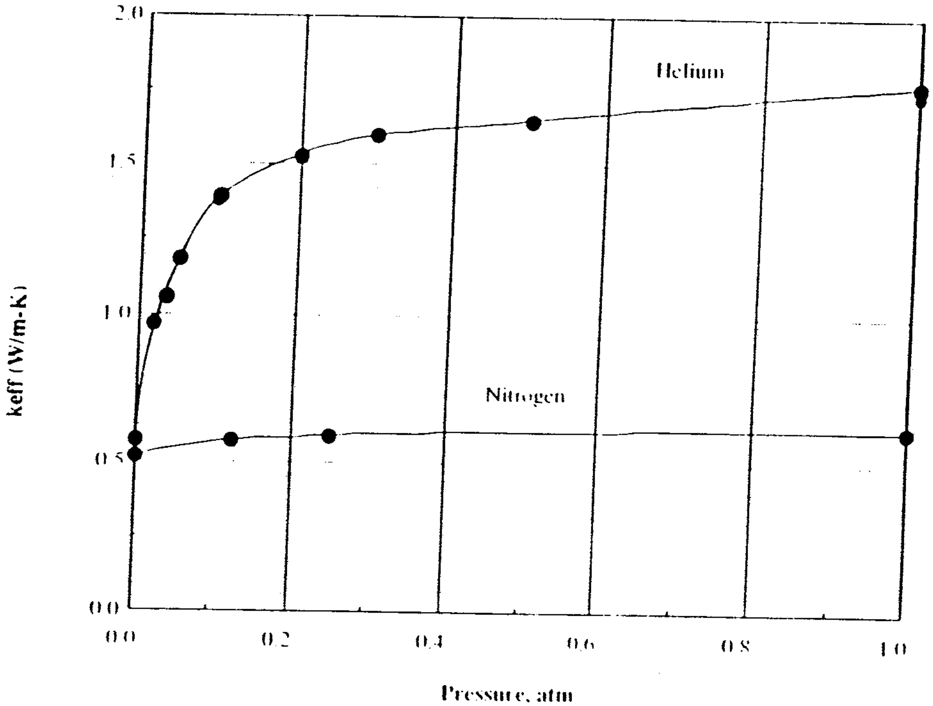
RESULTS ON METALLIC BED THERMAL CONDUCTIVITY

THE EFFECTIVE THERMAL CONDUCTIVITY OF METALLIC PACKED BEDS SHOWS SUBSTANTIAL VARIATION WITH GAS PRESSURE AND COMPOSITION- IN SOME CASES A S MUCH AS A FACTOR OF 4.

THE POSSIBILITY OF ACTIVE TEMPERATURE CONTROL IN SOLID BREEDER BLANKETS HAS BEEN CLEARLY DEMONSTRATED



Variation of Conductivity with Pressure in 0.5-mm Al Bed with Helium or Nitrogen



Keff vs. Gas Pressure for 2-mm Be Bed with Helium and Nitrogen

PARAMETRIC ANALYSIS OF BERYLLIUM PARTICLE BED EFFECTIVE THERMAL CONDUCTIVITY

SCOPE:

1) Predictive models are needed for analysis of the blanket performance under different operating conditions.
2) Predictive models can be used to determine methods of actively controlling the thermal behavior of the blanket.

Objectives:

Find the most suitable model and reasonable parameters to predict the beryllium-gas packed bed thermal conductivity.

Models involved in the study:

1) The UCLA 2-D model,
2) The modified Hall and Martin model by UCLA,
3) The SZB model (Schlunder, Zehner, and Bauer),
4) The Kunii and Smith model.

Model Description

UCLA 2-D model

consider 2-D heat transfer, can model the surface roughness characteristics as well as porosity of the bed, particle-to-particle contact area, diameter of the particles.

Modified Hall and Martin model by UCLA

1-D heat transfer model with finite contact area, orthorhombic arrangement for the representation of the single size packed bed, capability of estimation for binary bed.

SZB model

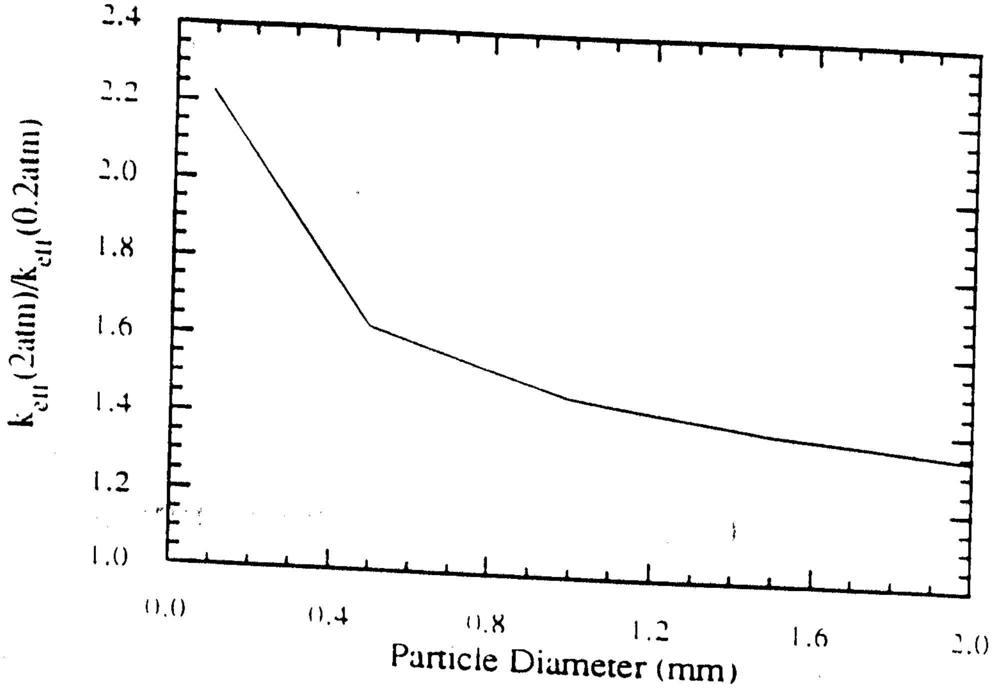
1-D heat transfer model, accounts for radiation, conduction, particle size distribution, bed porosity, contact area.

Kunii and Smith model

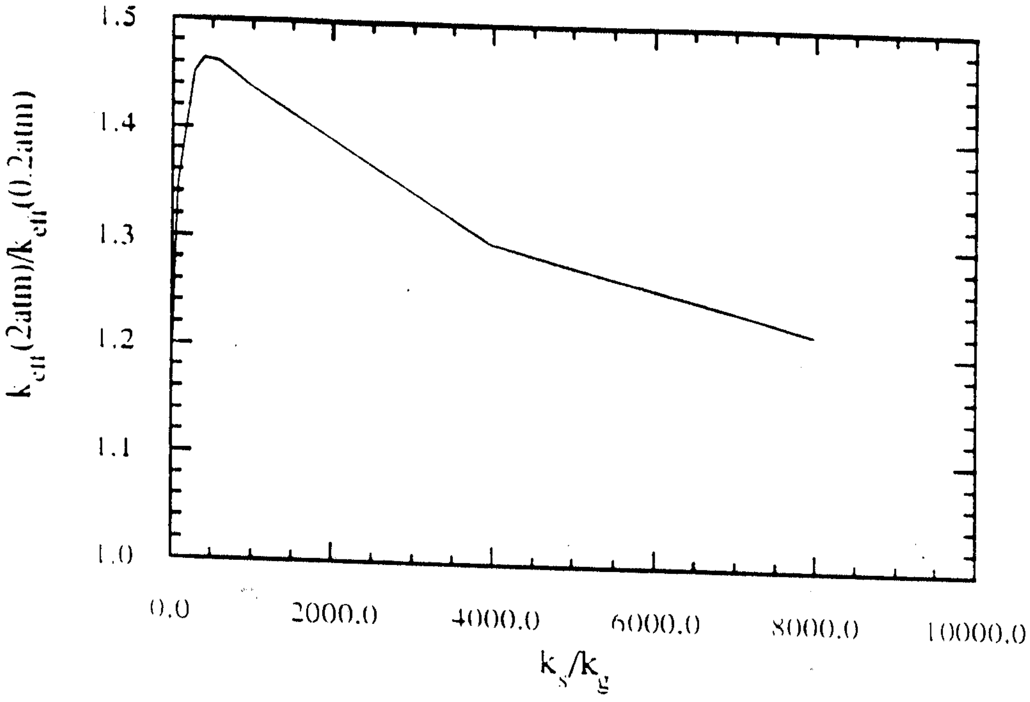
1-D heat transfer model, accounts for heat transfer through the fluid in the void by conduction and by radiation between adjacent voids, heat transfer through the contact surface of the solid particles, conduction through the stagnant fluid near the contact surface, radiation between surfaces of solid, conduction through the solid phase

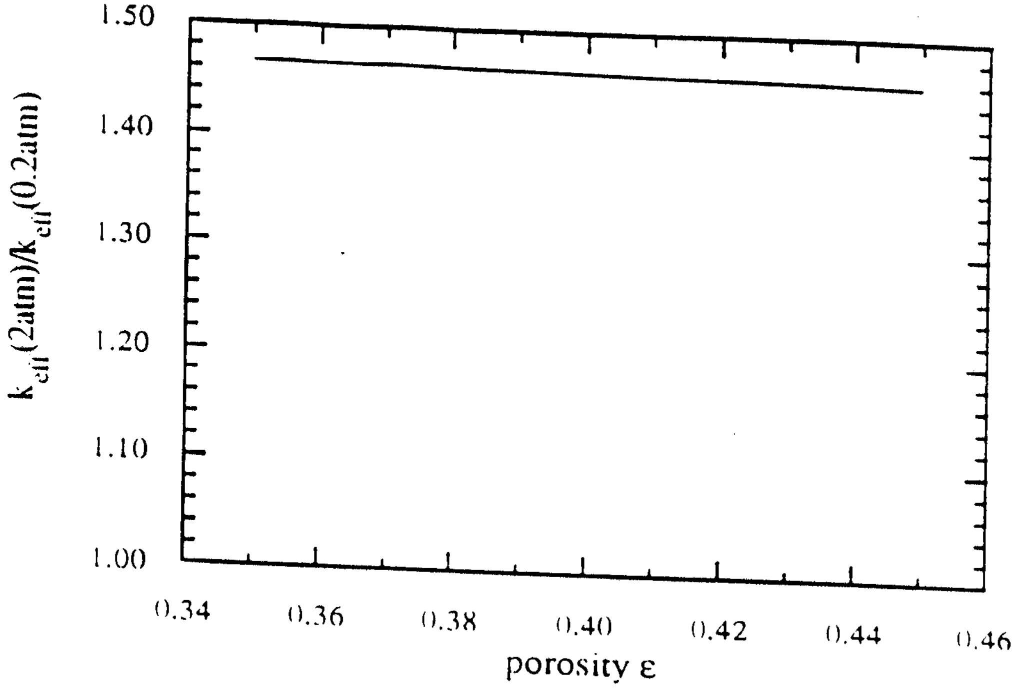
Parametric Analysis of Beryllium Bed Effective Thermal Conductivity (Using UCLA 2-D model)

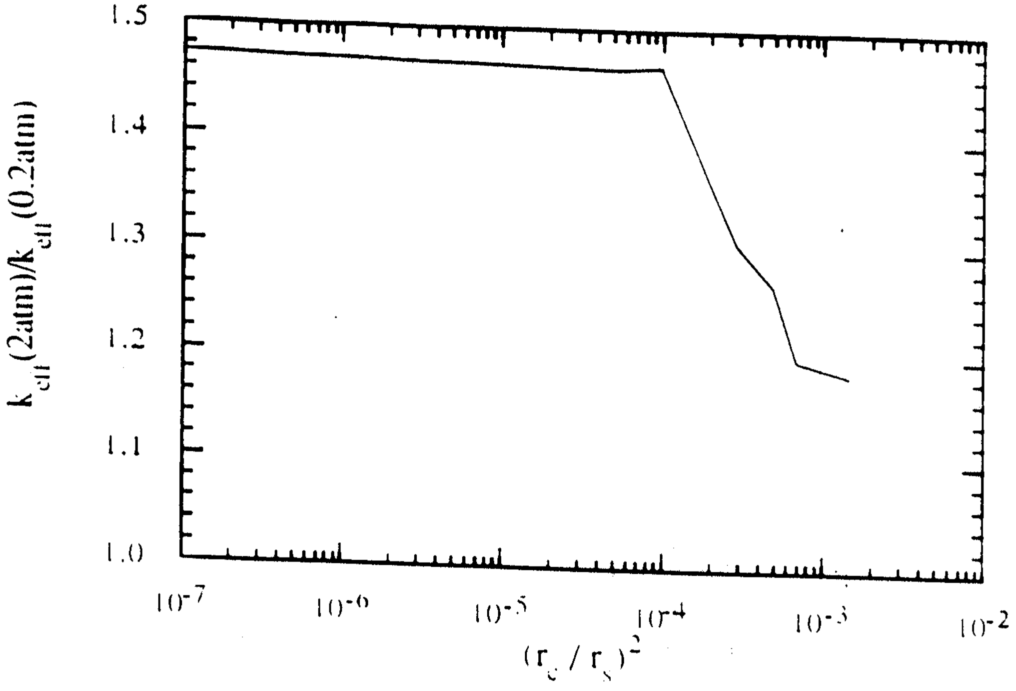
Effect of particle size



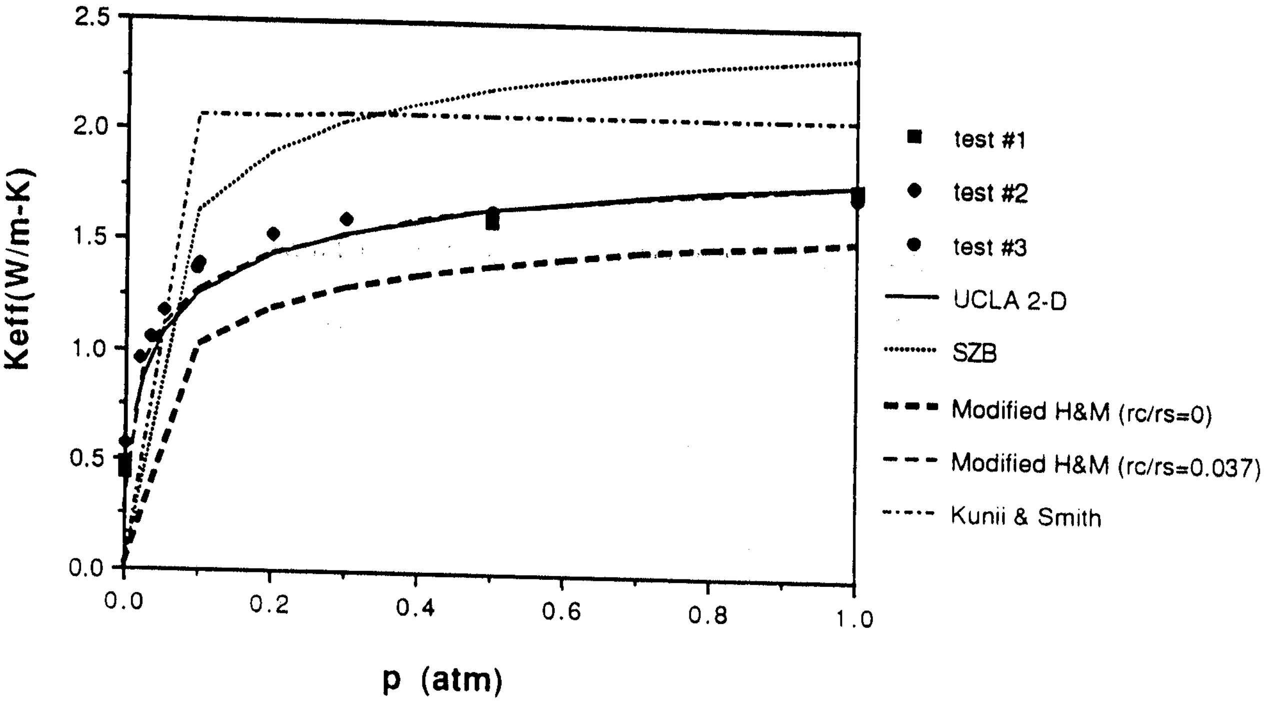
Effect of solid-to-gas conductivity ratio



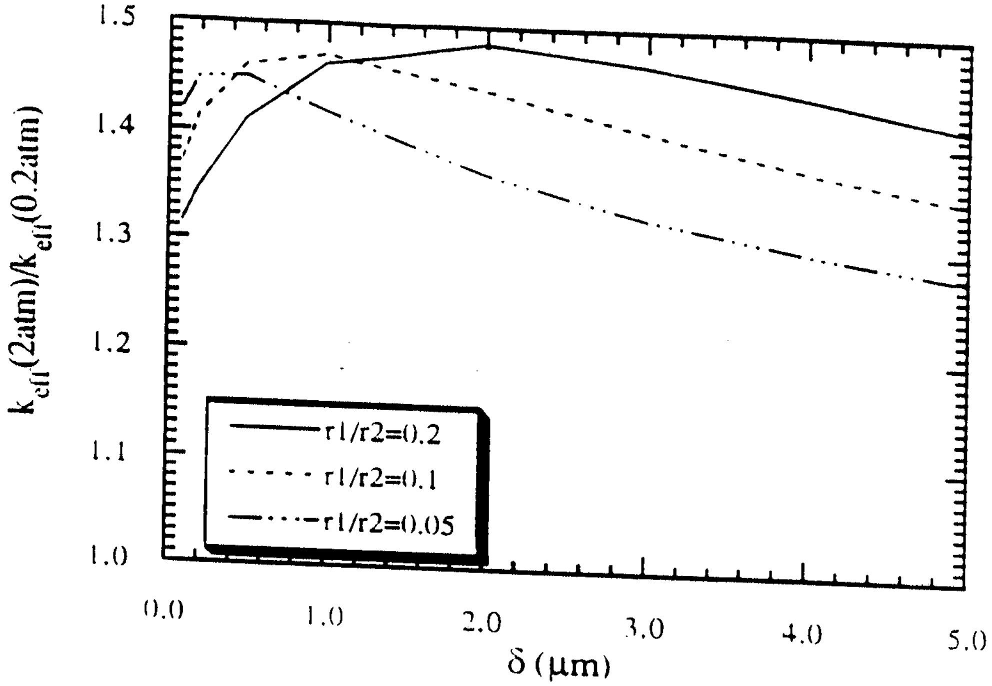

Effect of porosity


Effect of particle-to-particle contact area

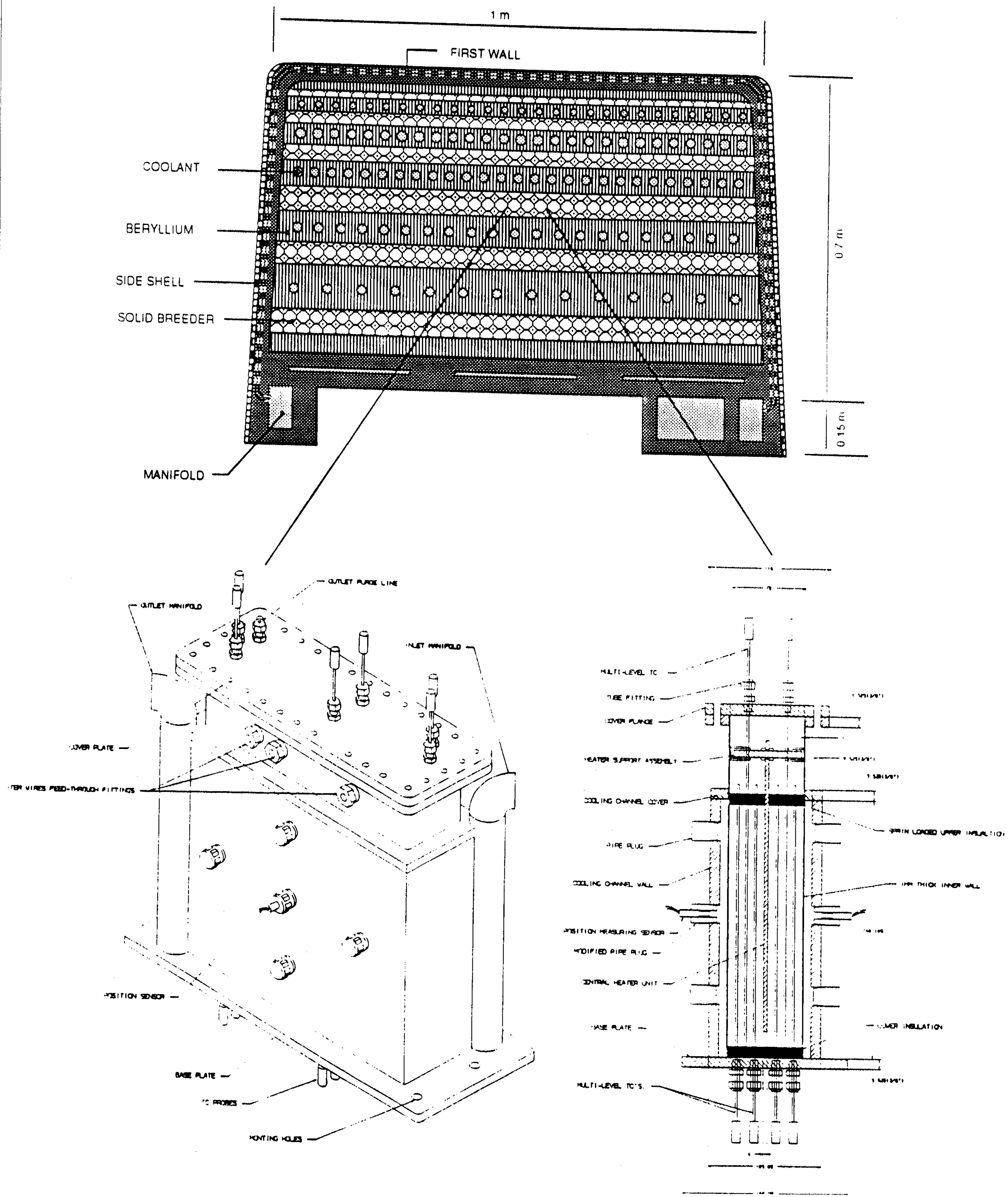
Comparison of Prediction from Different Models and Experiments (Be/He bed with packing factor of 0.60)

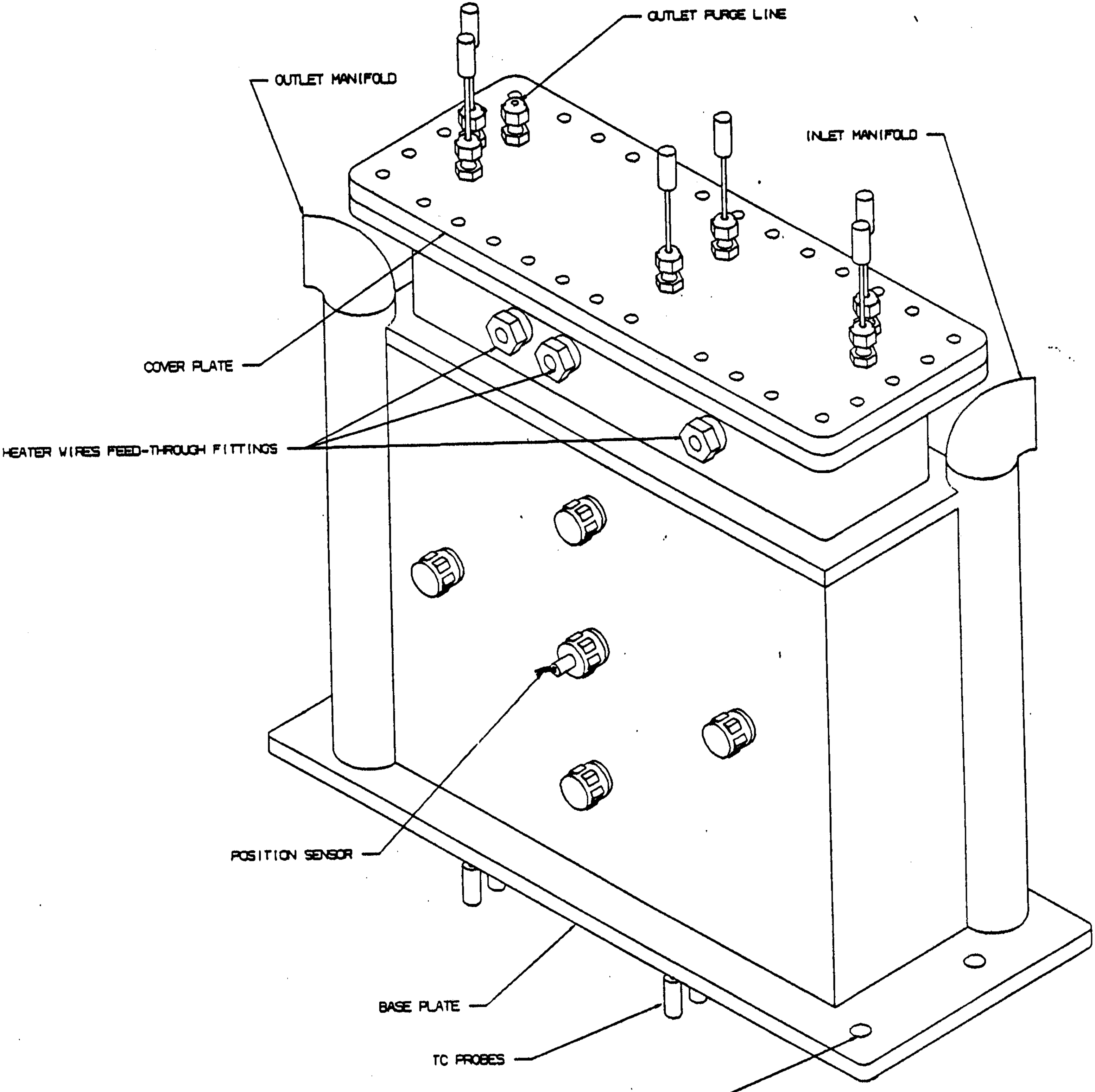


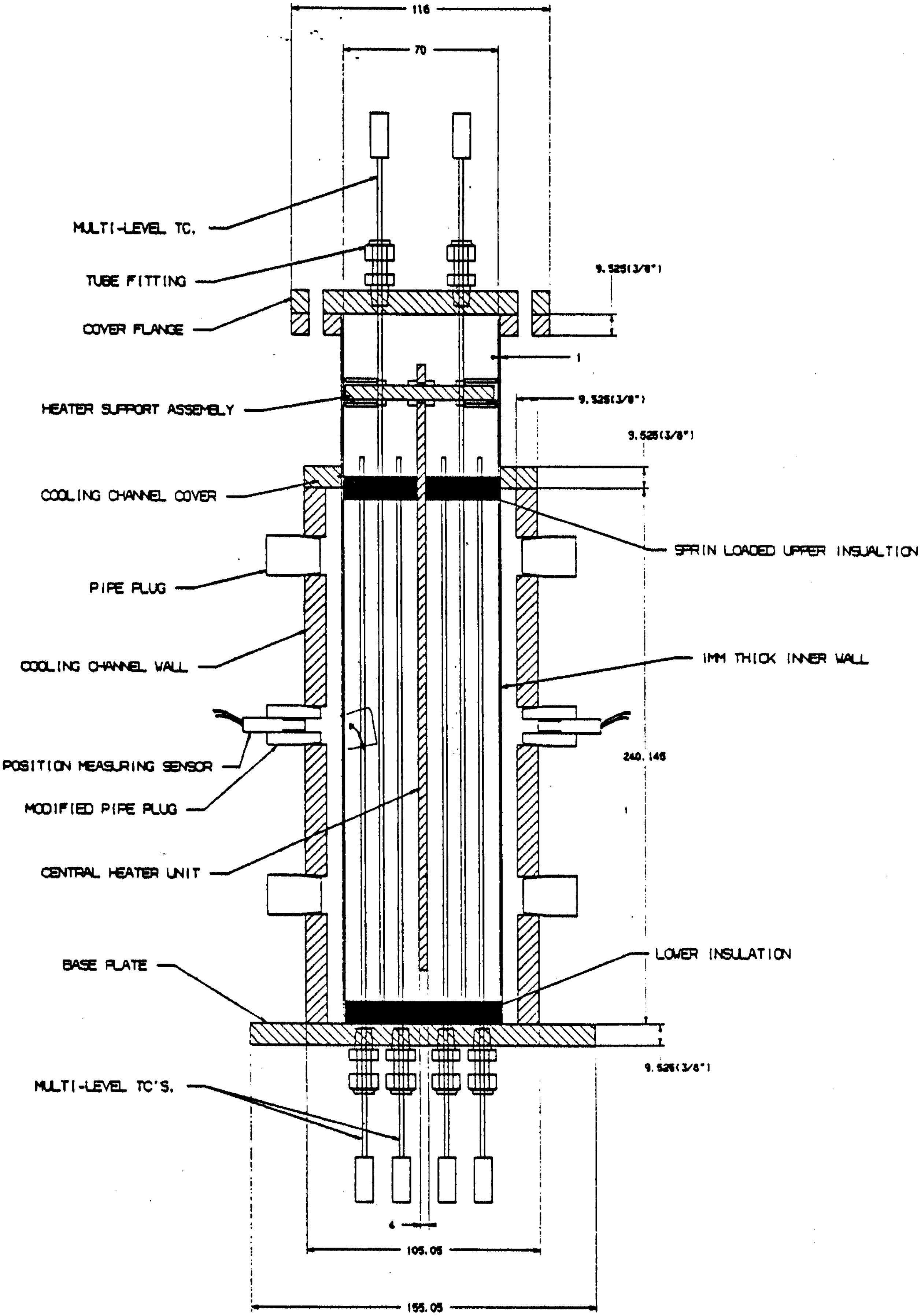
Effect of roughness height



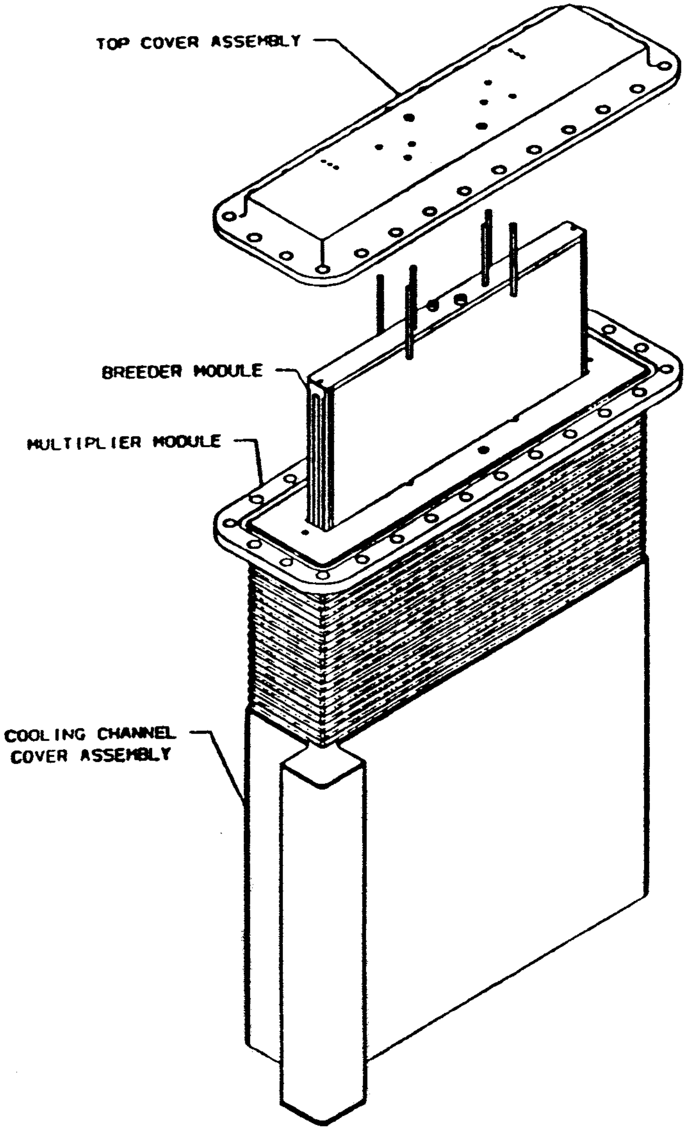
LAYERED SOLID BREEDER BLANKET AND HiTeC MOCKUP




OUTLET PURGE LINE
OUTLET MANIFOLD
INLET MANIFOLD
COVER PLATE
HEATER WIRES FEED-THROUGH FITTINGS
POSITION SENSOR
BASE PLATE
TC PROBES
MONTING HOLES


116
70
MULTI-LEVEL TC.
TUBE FITTING
COVER FLANGE
9.525(3/8")
1
HEATER SUPPORT ASSEMBLY
9.525(3/8")
9.525(3/8")
COOLING CHANNEL COVER
SPRIN LOADED UPPER INSUALTION
PIPE PLUG
COOLING CHANNEL WALL
1MM THICK INNER WALL
POSITION MEASURING SENSOR
240.146
MODIFIED PIPE PLUG
CENTRAL HEATER UNIT
BASE PLATE
LOWER INSULATION
9.525(3/8")
MULTI-LEVEL TC'S.
4
105.05
155.05

UNICEX – Solid Breeder Unit Cell Thermomechanics

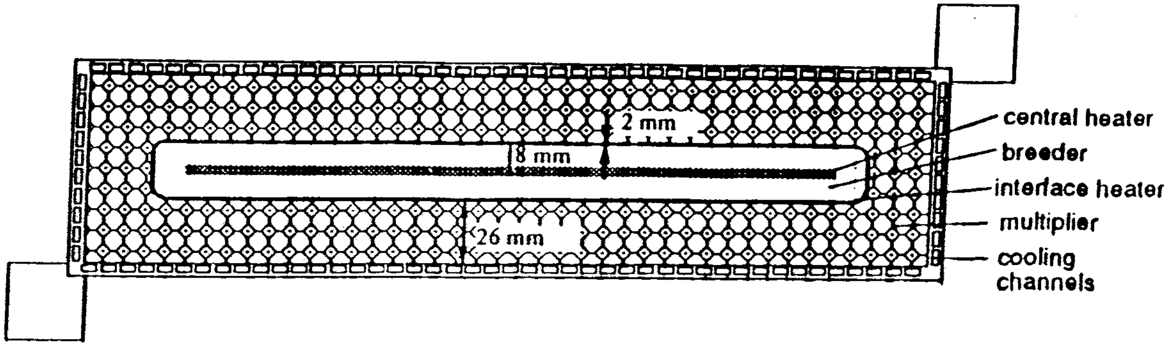


Purpose

- Demonstrate thermal control
- Generate empirical data
- Improve models and basic understanding

Key Features

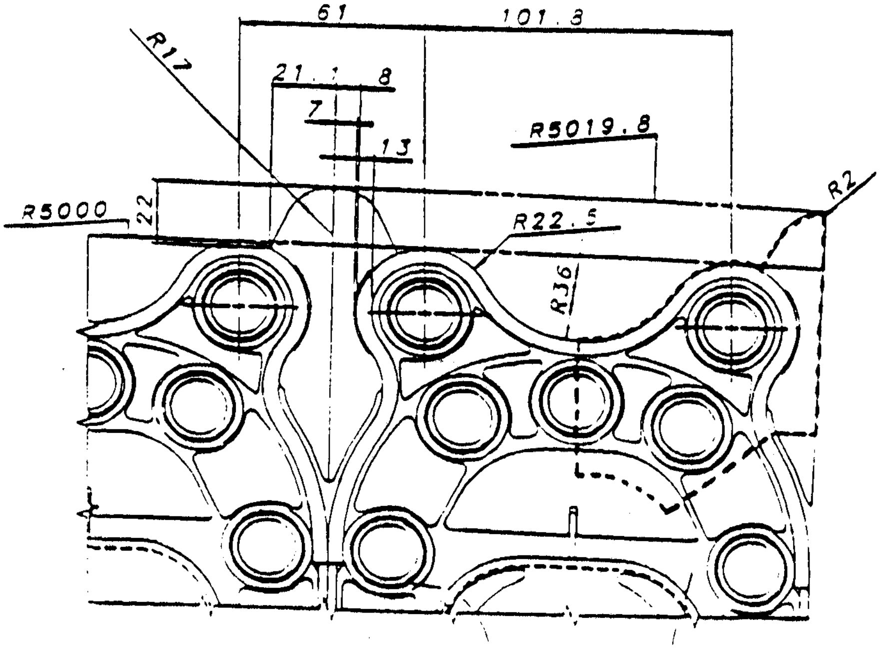
- Prototypical materials
  Li_2ZrO_3 bed
  Be binary bed
- He & water coolants
- Breeder and multiplier purges
- Plate heaters at center and interfaces

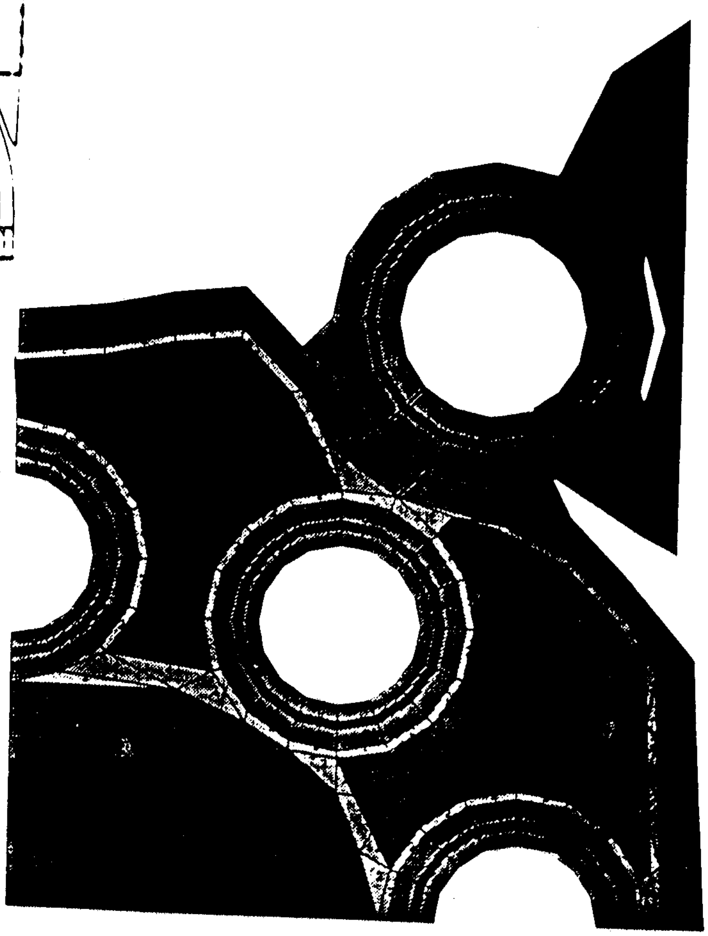


UCLA Contributions to ITER Design

– First Wall and Blanket Analysis –

- FEM Thermal and Structural Analysis of the Near-Wall Region
  - Internally-cooled and externally-cooled limiter
  - Spot-brazed and non-brazed limiter
- Bumper Limiter Thermal Contact Resistance with First Wall





Outline

§ Background

§ Description of a New Model, BETTY

§ Analysis of Experimental Data

§ Summary of Tritium Diffusion and Desorption Coefficients in Be/BeO

§ Summary of Analysis

Modeling of Tritium Release from Beryllium

Background

§ Only Limited Data are Available on Tritium Release from Irradiated Be

§ Recent Data (Baldwin) Indicated that:
  - Most of the Tritium Generated is Retained in the Bulk at Low Temp.
  - For High Density Be Samples, a Burst-Type Release is Observed at High Temperature

§ Analysis and Interpretation of These Data Would Help in Understand Tritium Release Mechanisms for Be

§ Existing Analytical Models cannot Reproduce Adequately the Experimental Data for Be and Lack the Capability of Accounting for Important Phenomena such as the Effects of the BeO Layer, As-fabricated Porosity and Irradiation-Induced Helium Bubbles

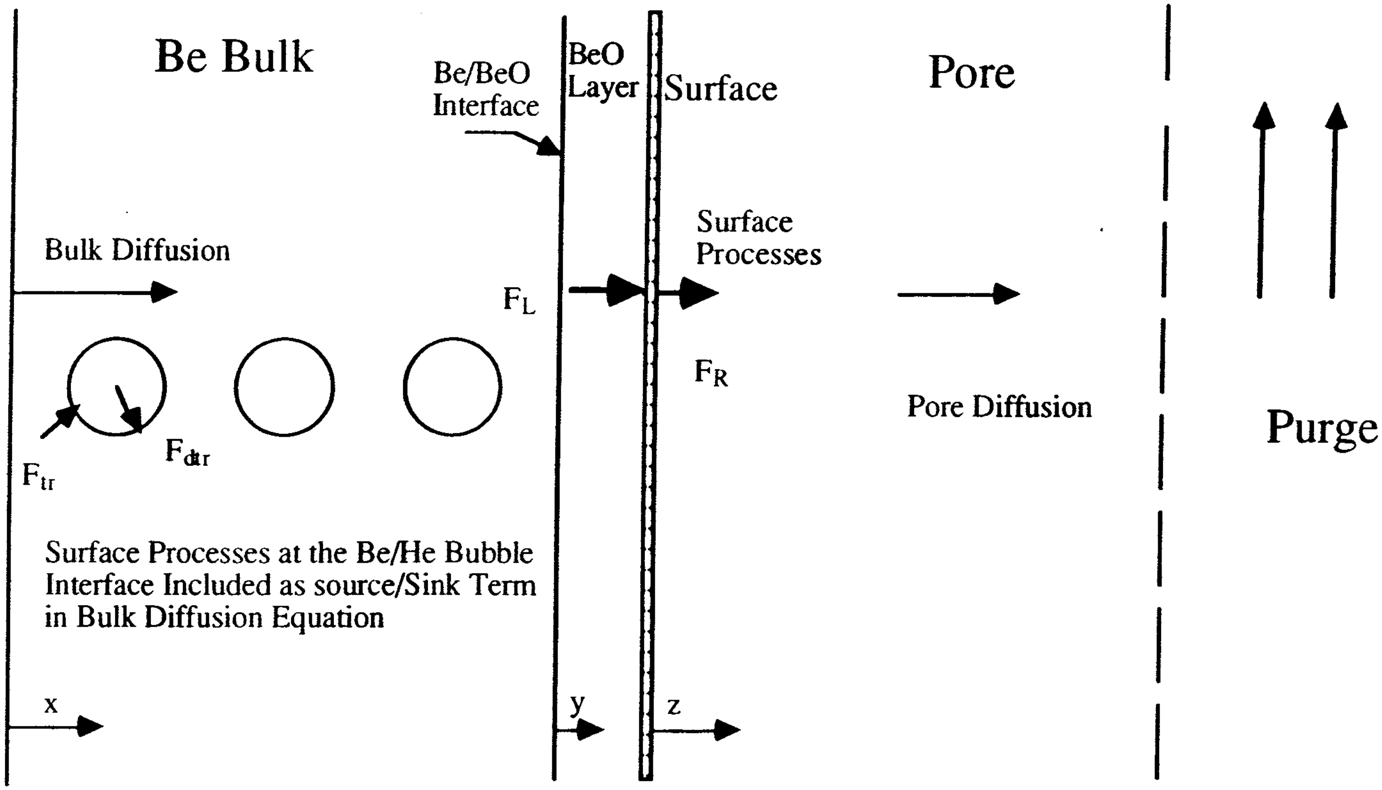
BETTY : Model Development at UCLA

- § A More Comprehensive Model is Being Developed, which Includes Tritium Diffusion in Be and BeO Region, Second Order Desorption and Diffusion through Interconnected Porosity

- § Geometry is Based on Sample Density
  - For High Density Samples :
    - : Slab Geometry for Diffusion and Desorption to the Purge

  - For Porous Samples
    - : Cylindrical Geometry for Radial Bulk Diffusion, Desorption to the Pores and Axial Diffusion through Interconnected Porosity
    - : This Geometry is Also Applicable to High Density Samples under Burst Release Conditions due to the Interconnected He Bubbles and Closed Porosity

Schematic of New Model, BETTY



§ Initial Version has Only Desorption at the Surface and no Trapping in the He Bubbles

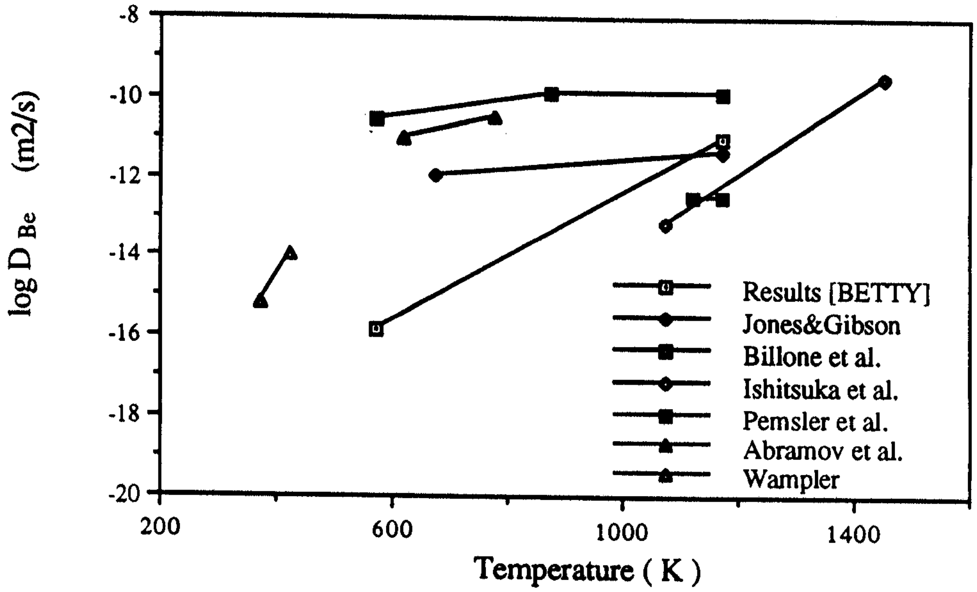
Strategy for the Analysis

1. Diffusion and Desorption Coefficients in Be
   - Based on the Burst Release Cases for the High Density Samples (Free of Oxygen)

2. Analysis of BeO Layer
   - Determination of BeO Layer Thickness Based on BeO Content of Samples and Known Property Data

3. Tritium Diffusion and Desorption Coefficients for BeO
   - Based on the Estimated BeO Layer Thickness of Each Sample

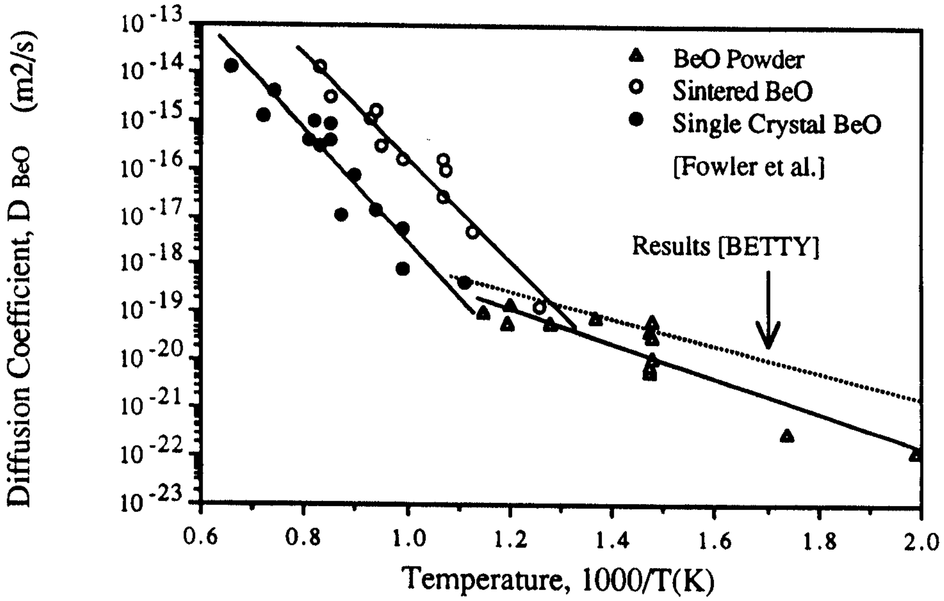
Comparison of Tritium Diffusion Coefficients in Beryllium



§ The Estimated Tritium Diffusion Coefficients for Be Tends to Be toward the Lower End of the Range

§ $D_{Be}(T)$ $(m^2/s) = 4.56 \times 10^{-7} \bullet \exp(-104.6\ (kJ/mol)/RT)$

Comparison of Tritium Diffusion Coefficients in BeO

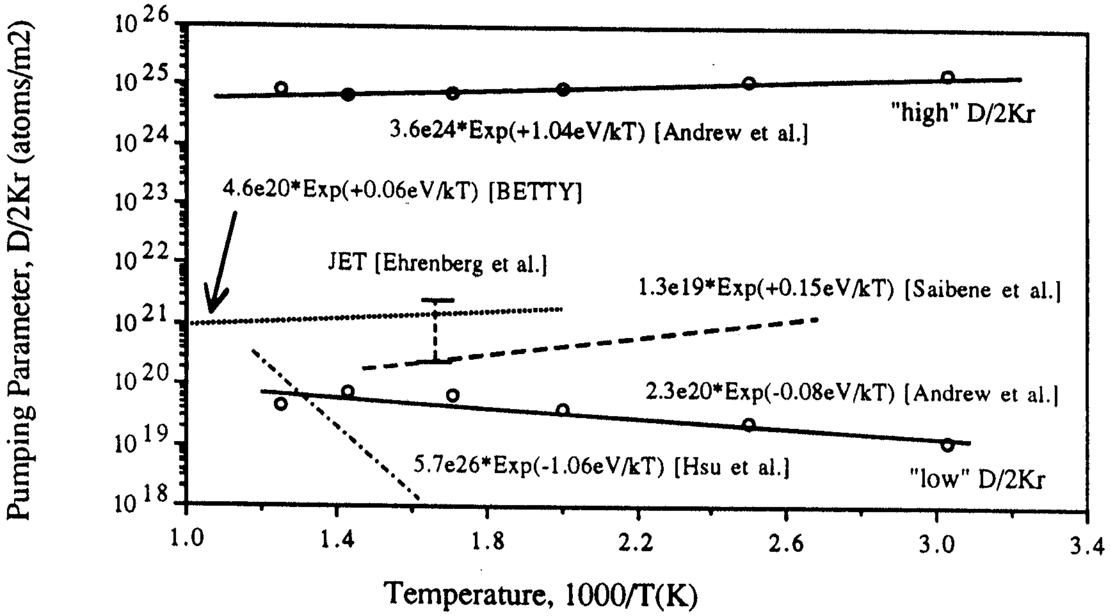


§ The Estimated Tritium Diffusion Coefficient for BeO is Much Closer to Values for BeO Powder at Temperature of 300 - 600 °C than to Extrapolated Single Crystal Values

§ It is Possible that Diffusion Follows a Different Arrhenius Function with Temperature at T < 600 °C than at T > 650 °C

§ $D_{BeO}(T)$ (m^2/s) = $6.28 \times 10^{-16} \bullet \exp(-53.4(kJ/mol)/RT)$

Comparison of Tritium Pumping Parameter in Beryllium



§ The Desorption Coefficients in Combination with Diffusion Coefficients are Compared to Other Experimentally Determined Values of Pumping Parameter $\frac{D}{2\,K_r}$

§ The Estimated Pumping Parameter for Tritium/Be is within the Range of Previous Experimental Values for Deuterium/Be

§ $\frac{D}{2\,K_r}(T)\ (\text{atoms/m}^2) = 4.6 \times 10^{20} \bullet \exp(+\,0.06\ \text{eV/kT})$

Summary of Analysis

§ To Help Understand and Interpret the Data, a New Model, BETTY, was Developed. The Initial Version Includes Diffusion in the Be and BeO Layer, Second Order Desorption, and Diffusion through Interconnected Porosity and/or Irradiation-Induced Helium Bubbles.

§ A Strategy was Developed in Order to Analyze the Several Types of Experimental Data for High Density and Porous Be Samples and to Estimate Diffusion and Desorption Coefficients for Be and BeO over the Experimental Temperature Range by Reproducing the Release Results.

§ Large Variations Exist in the Estimated "Effective" Diffusion Coefficient for Hydrogen in Be from Previous Experiments Probably Due to Other Mechanisms not Accounted in the Analysis.

§ The Estimated Tritium Diffusion Coefficient for BeO in the Low Temperature Range (< 650 °C) is Closer to the Powder BeO Data than To the Extrapolated Value from the High Temperature Single Crystal Data.

Summary of Analysis (cont.)

§ The Estimated Tritium Pumping Parameter ($D/2K_r$) for Be is within the Experimental Values.

§ The Analysis Presented here Attempted to Include the Effect of Major Mechanisms Dictating Tritium Behavior in Beryllium. Until More Detailed Data and Analysis Become Available, It is Suggested that the Diffusion and Second Order Desorption Coefficients Estimated here be Used for Blanket Analysis with Beryllium Operating under Similar Conditions.

§ Future Work Includes Extending BETTY's Capability to Better Account for Surface Processes and to Account for the Trapping Effect of He Bubbles on Tritium Behavior. As Experimental Data Become Increasingly Available, this Would Provide a Better Tool for Experiment Analysis as Well as for Blanket Analysis Applications.