

**Solid Breeder Blanket
Thermal Control and Thermomechanics
Activities at UCLA**

- **UCLA Small-Scale Thermal Control Experiments and Modeling**
 - Particle Beds Heat Transfer and Fluid Flow
 - Contact Conductance
 - UNICEX Experiment for Interactive Effects

- **Requirements for Large Out-of-Pile Test Facility**

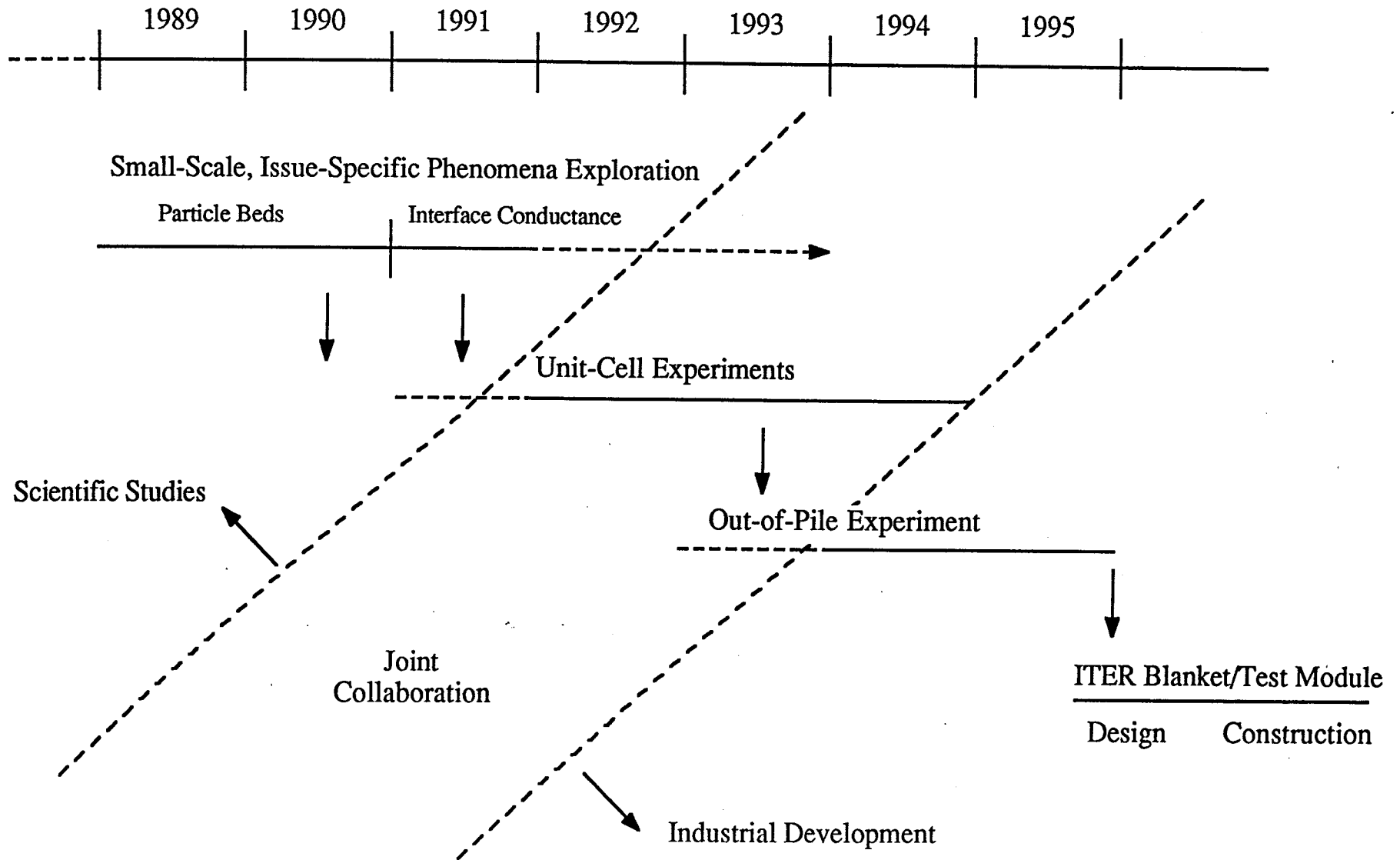
Thermal Control Issue for Solid Breeder Blankets

- Maintain breeder within allowable temperature window
 - uncertainties due to manufacturing and operational conditions
 - accommodate power variations
 - radiation-induced changes in behavior
- Particularly difficult with water-cooled blankets, in which coolant is colder than breeder
- Critical issue for ITER breeding blanket, where coolant is at low temperature

Goals of UCLA Program:

- Develop innovative design solutions to thermal control problem
- Develop modeling capability to accurately predict blanket behavior
- Generate data used for design
- Validate concepts through experiments and modeling

Test Plan for Solid Breeder Blanket Thermomechanics



Thermal Control Experiments and Modeling at UCLA

Objectives:

- Develop concepts for stable and predictable thermal resistance between blanket elements
(early design concepts employed thin He gaps, which are subject to large uncertainties and possible changes during operation)
- Develop active control mechanisms to accommodate uncertainties and operational flexibility:
 - Uncertainties in solid breeder temperature window remain – particularly in the fusion environment
 - Guidelines for operating power level changes in ITER specify $\pm 50\%$
 - Poloidal power variation in ITER is almost a factor of 2
- Establish the allowable range of operating conditions for the He purge

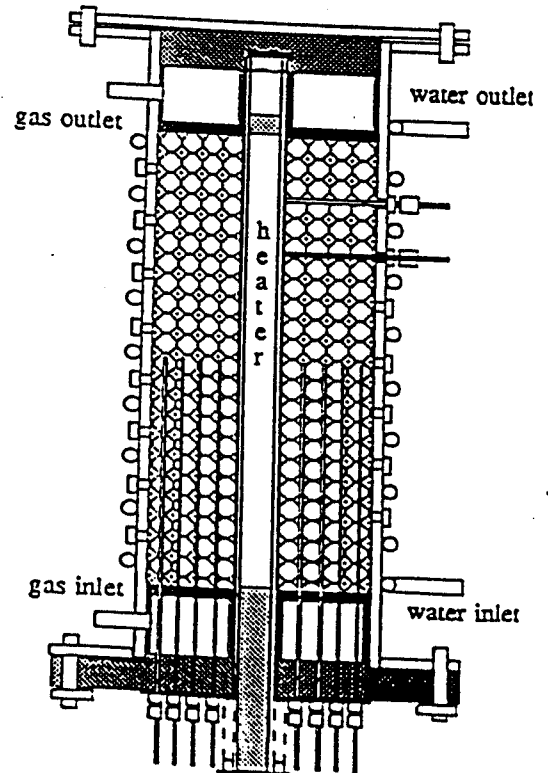
Particle Bed Experiment

Measurements include effect on conductivity of:

- Particle surface characteristics
- Bed packing and particle sizes
- Change in gas pressure
- Change in gas composition
- Gas flow rate

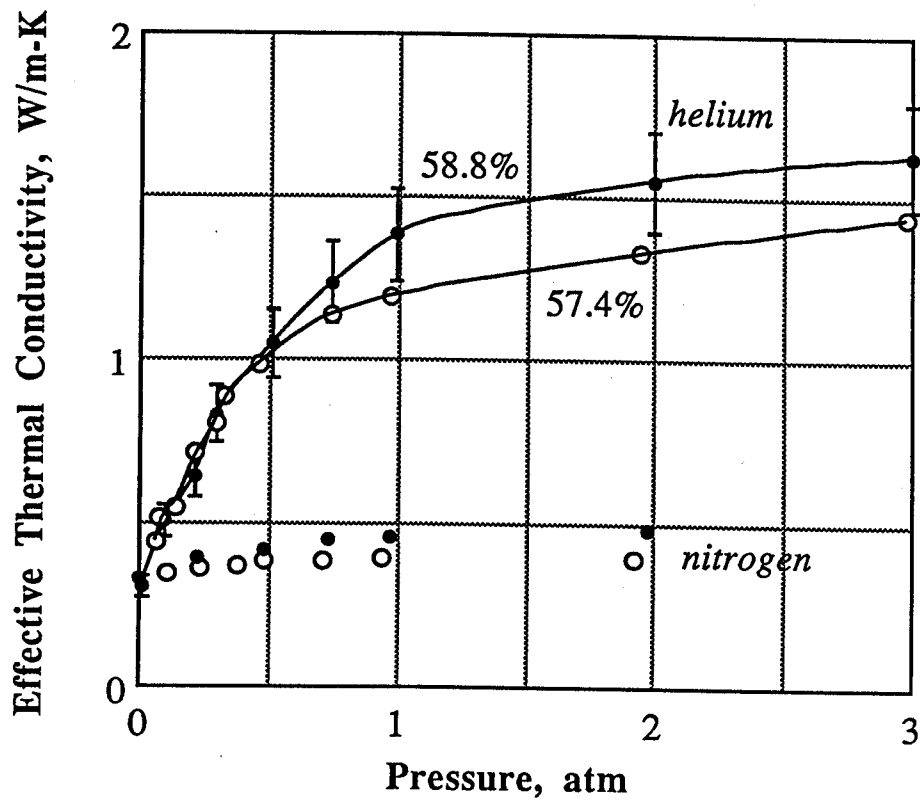
Initial Results:

Metallic particle beds were shown to provide predictable and controllable thermal resistance. Up to a factor of 2 change in conductivity was demonstrated by varying gas pressure and/or composition



Active, in-situ control of thermal conductivity is an innovative approach to resolve solid breeder thermal control issues

Variation of Conductivity with Pressure in 0.1-mm Al Bed with Helium or Nitrogen



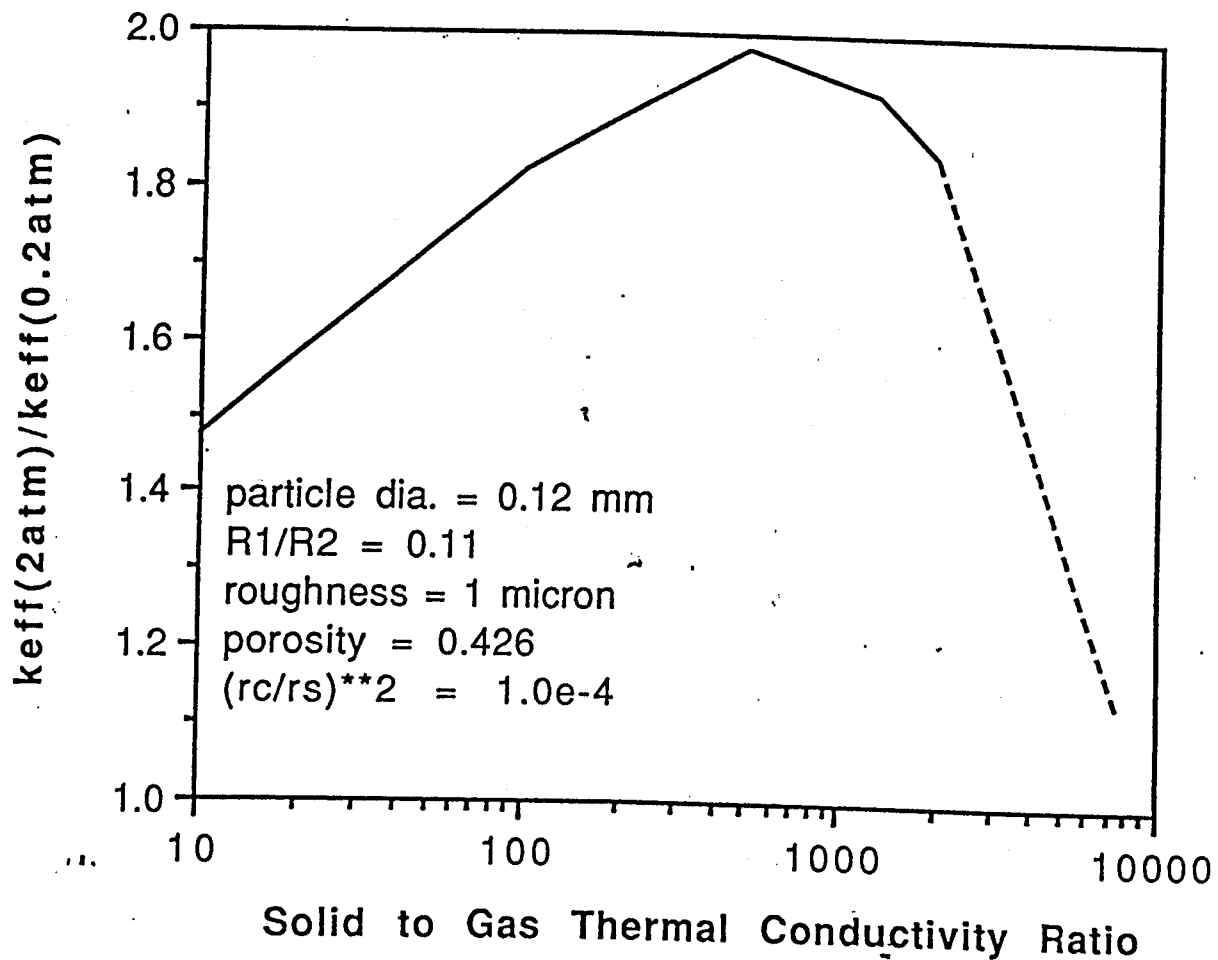
Results of UCLA experiments show substantial (factor of 2 or more) variation in thermal conductivity of Be particle beds can be achieved.

Thermal Control Modeling

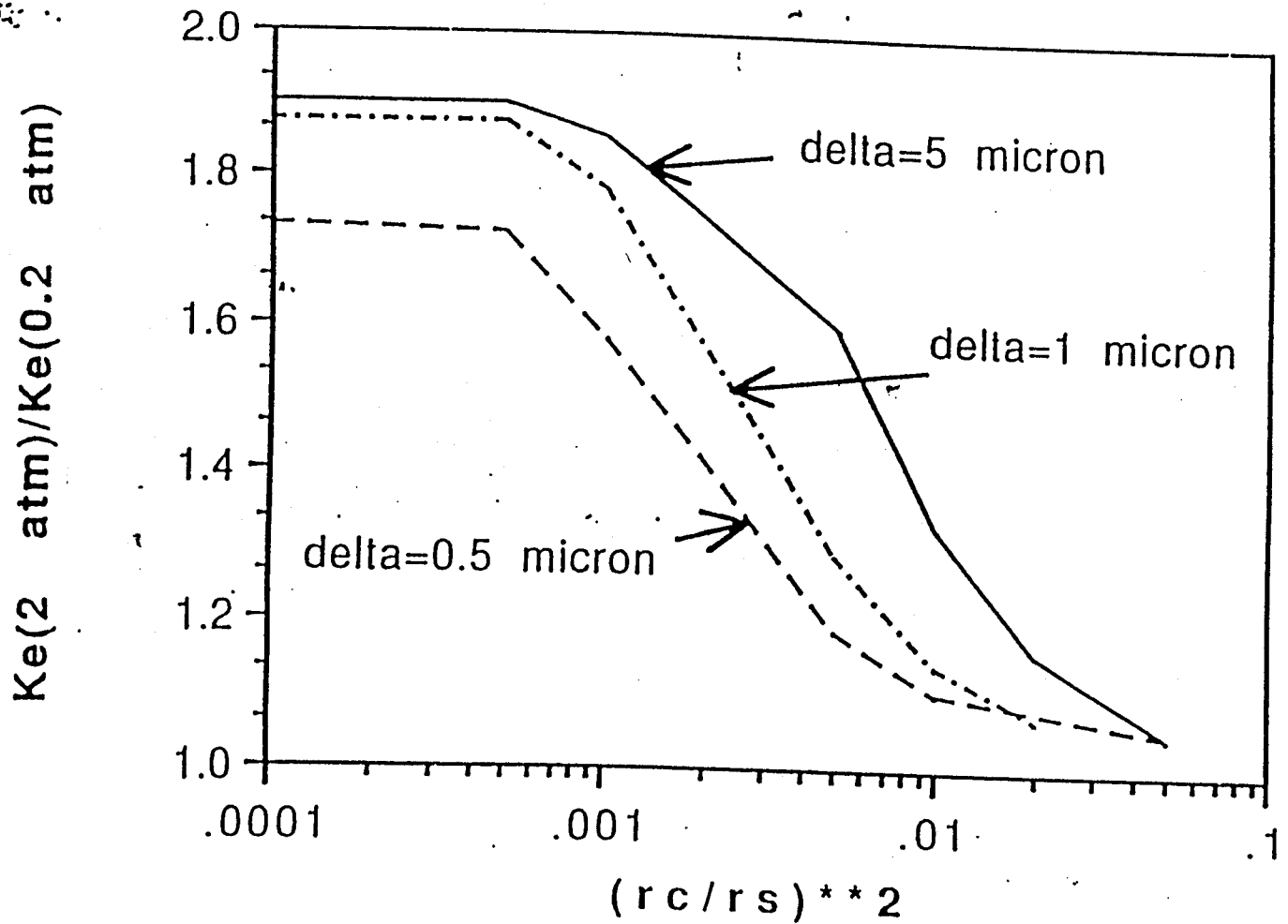
- **Packed Bed Thermal Conductivity**
 - Development of both 2-D and 1-D (simpler to use) model for single-size and binary beds with capability for accounting for pressure variation
 - Determination of controllability of k_{eff} through gas pressure variation as a function of k_s/k_g . Optimum control for k_s/k_g of about 500 (similar to that of Be/He)
 - Calculations of k_{eff} of Be and Li_2O single-size and binary beds over a range of temperatures and pressures. The results were made available to designers for ITER blanket analysis application
- **Interface Contact Conductance Characterization**
 - Analysis based on semi-empirical models of Shlykov et al., and Yovanovich et al.
 - Key parameters are surface characteristics, material hardness and contact pressure
 - Analysis suggested need for experimental determination of contact conductance using prototypic materials, from which an experimentally-based model can be developed for blanket analysis
- **Thermo-Fluid Model for Porous Flow**
 - Development of transient 2-D model using modified Darcy equation and energy equation for blanket and small-scale experiment analysis

Modeling is vital to interpret and extend available data,
and to explore regions of parameter space

Controllability in terms of $(k_{eff}(2atm)/k_{eff}(0.2atm))$ as a
function of k_s/k_g ratio for single-size powder bed



Models predict good controllability under a wide range of conditions, provided the contact area is not too large



$K_s/K_g=1275$
porosity=0.426
diameter= 0.119 mm
 $R_1/R_2=0.11$

Sintered Block Interface Conductance Experiments

Motivation

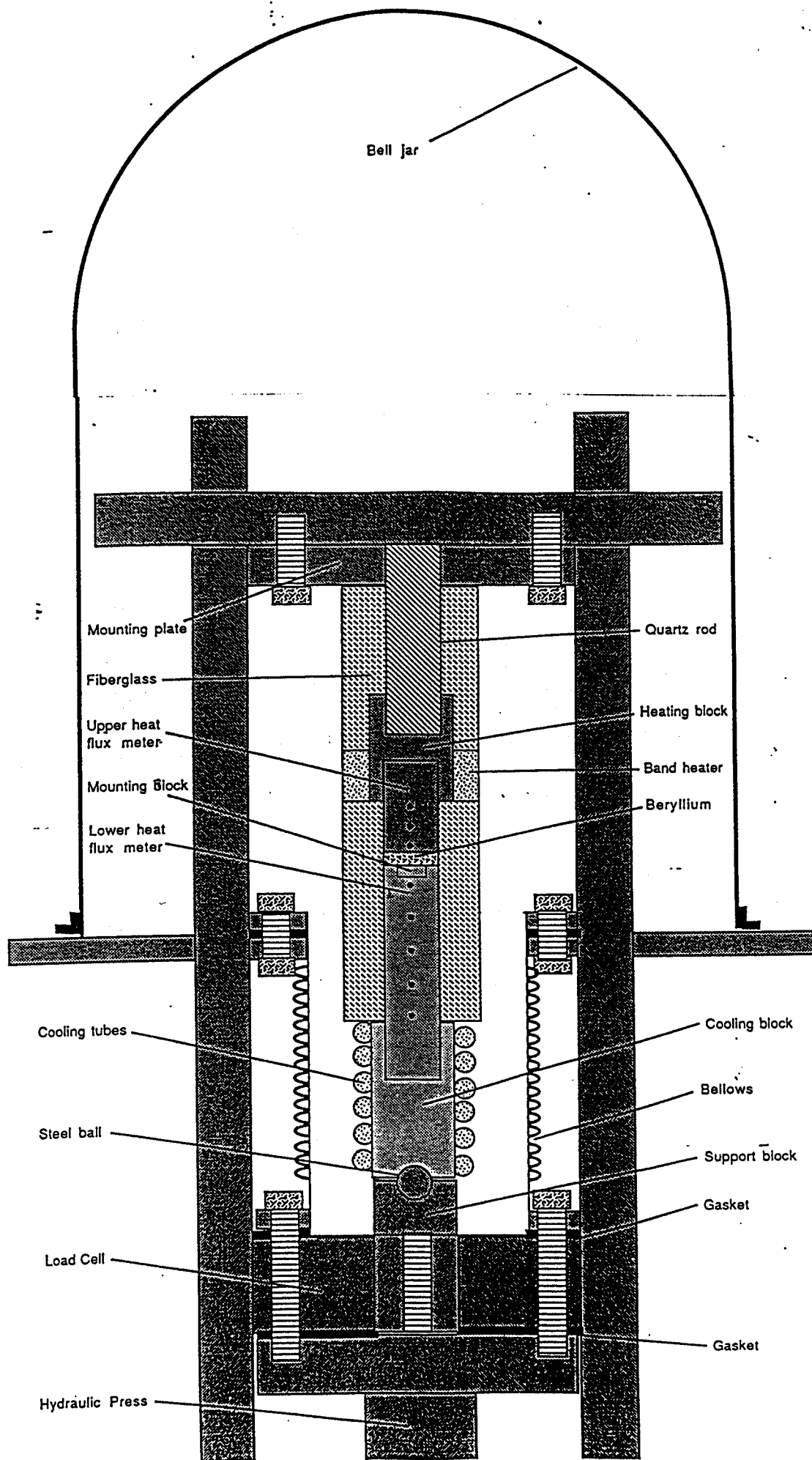
Changes at interfaces due to environmental factors (such as thermal gradients, mechanical stresses, etc.) could result in significant degradation of the normally high interface conductance in some solid breeder blanket designs

Objectives

- Examine the thermal conductance at interfaces between sintered blocks of breeder, multiplier and clad.
- Examine the effect of environmental factors and assess the possible implications for the use of sintered Be and breeder in ITER.
- The temperature jump at the interface will be measured as a function of the contact pressure, surface roughness, cover gas pressure, and heat flux (using prototypical temperature gradients, heat fluxes, and contact pressures)

Schedule

- Preliminary design and test plan developed; parts are being ordered
- Initial testing will be done at low temperature with simple instrumentation
- Several different specimens will be measured, starting with Be blocks (chosen to match the Be forms under consideration for use in ITER)
- High-temperature operation is planned for a later stage of operation



Bell Jar

Mounting plate

Fiberglass

Upper heat flux meter

Mounting block

Lower heat flux meter

Cooling tubes

Steel ball

Load Cell

Hydraulic Press

Quartz rod

Heating block

Band heater

Beryllium

Cooling block

Bellows

Support block

Gasket

Gasket

Operating Parameter Ranges for the Interface Conductance Experiments

Contact conductance	h	$200 \leq h \leq 20,000 \text{ W/m}^2\text{-K}$
Heat flux	q	$5\sim 20 \text{ W/cm}^2$
Surface roughness	δ	$10 \leq \delta \leq 50 \mu$
Cover gas composition		N_2, He
Cover gas pressure	p	$10^{-4} \text{ Torr} \leq p \leq 3 \text{ atm}$
Contact pressure	P_c	$0\text{--}50 \text{ MPa}$

Unit Cell Experiments and Analysis

Thermomechanical Testing Needs for the ITER Blanket

Thermal control of the solid breeder and thermomechanical interactions at interfaces are key issues for the ITER solid breeder blanket.

The ITER R&D plan provides for a large-scale fully-integrated out-of-pile prototypical test facility.

To bridge the gap between laboratory-scale property measurements and full-size blanket mockups, small-scale integrated tests of blanket unit cells are needed.

Small-scale, focussed experiments have several important features:

- Small-scale experiments can be better-instrumented to provide more complete information on the behavior of the test articles. The results could be correlated with larger tests, and also with in-reactor tests, to provide better understanding of blanket behavior;
- Experience gained from constructing and instrumenting these tests would greatly help in the design, operation, and measurement techniques used in the larger tests;
- Small-scale tests can be performed faster and cheaper, and thus the integrated operation of alternate configurations and material combinations can be tested;
- Results from unit cell tests, if performed in a timely manner, can be used to select configurations and material combinations to be tested in the larger out-of-reactor tests.

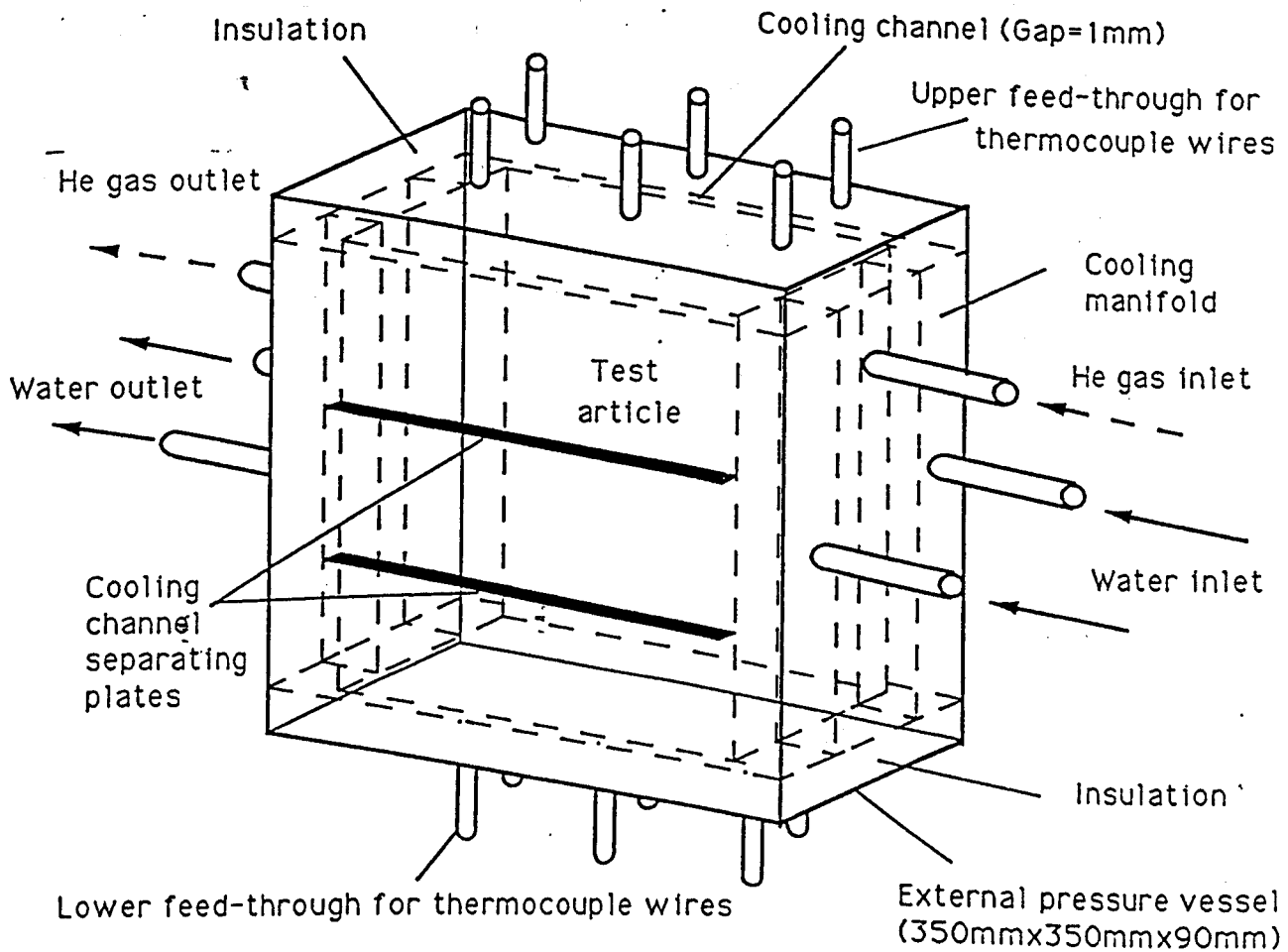
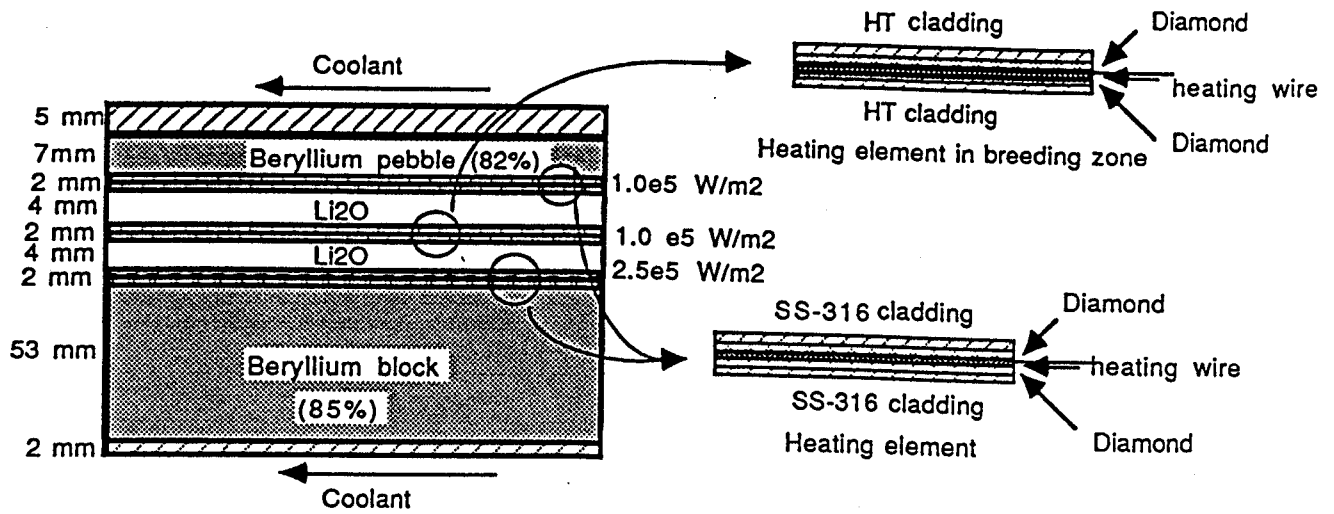
Since the larger out-of-pile experiments are already in the planning stage, it is important to initiate unit cell experiments very soon.

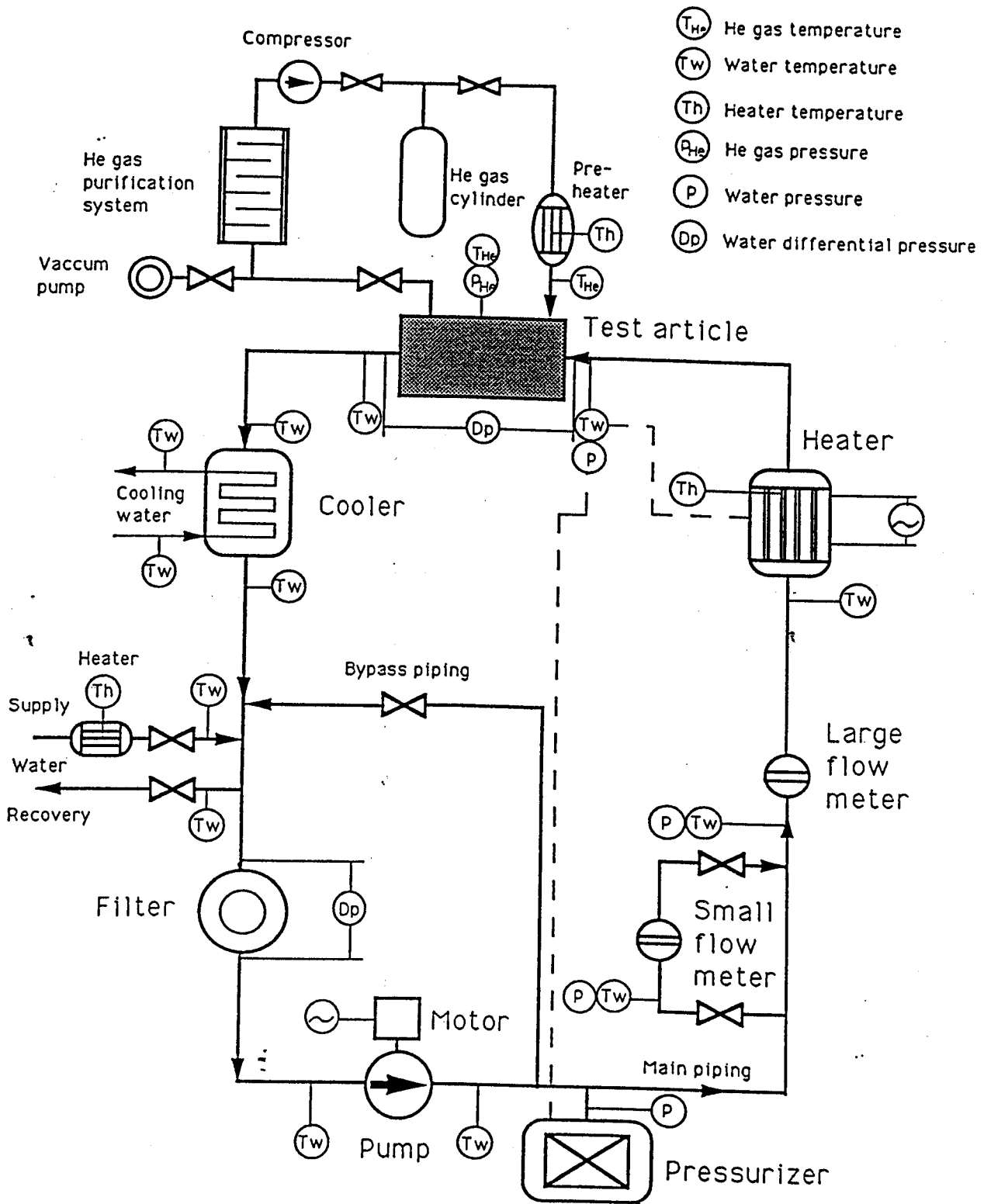
Design Options

Configuration	radially-layered, BIT-poloidal, BIT-toroidal
Breeder material	Li_2O , Li_2ZrO_3 , LiAlO_2
Multiplier material	Be
Cladding material	austenitic (316 solution annealed) stainless steel
Breeder & multiplier form	sintered blocks, particle beds
Coolant/breeder interface	He gap, Be blocks, Be particle bed

Final designs for testing will be consistent with the U.S. and international design concepts, which are still evolving

Example Test Article Design Based on US Layered Concept





Flow diagram of a unit cell blanket facility

Stages of Measurement

1. Steady-state measurements

Verify the predictability, uniformity, and controllability of temperature profiles under normal operation

2. Low-cycle measurements.

Verify the thermal behavior in ITER under a range of burn and dwell times

3. Off-normal measurements

Examine response to off-normal conditions, including: 1. purge heat removal and temperature profiles under loss-of-flow (LOFA) and loss of coolant (LOCA) conditions, simulating afterheat as the heat source, 2. adiabatic time constants for temperature rise with LOCA or LOFA, and 3. some over-power transients not attempted in Stages 1 and 2.

4. High-cycle measurements.

Accelerated life testing to observe the effect of mechanical deformations resulting from thermal ratchetting, cracking, or other cycle-induced behaviors

Quantities to be Measured

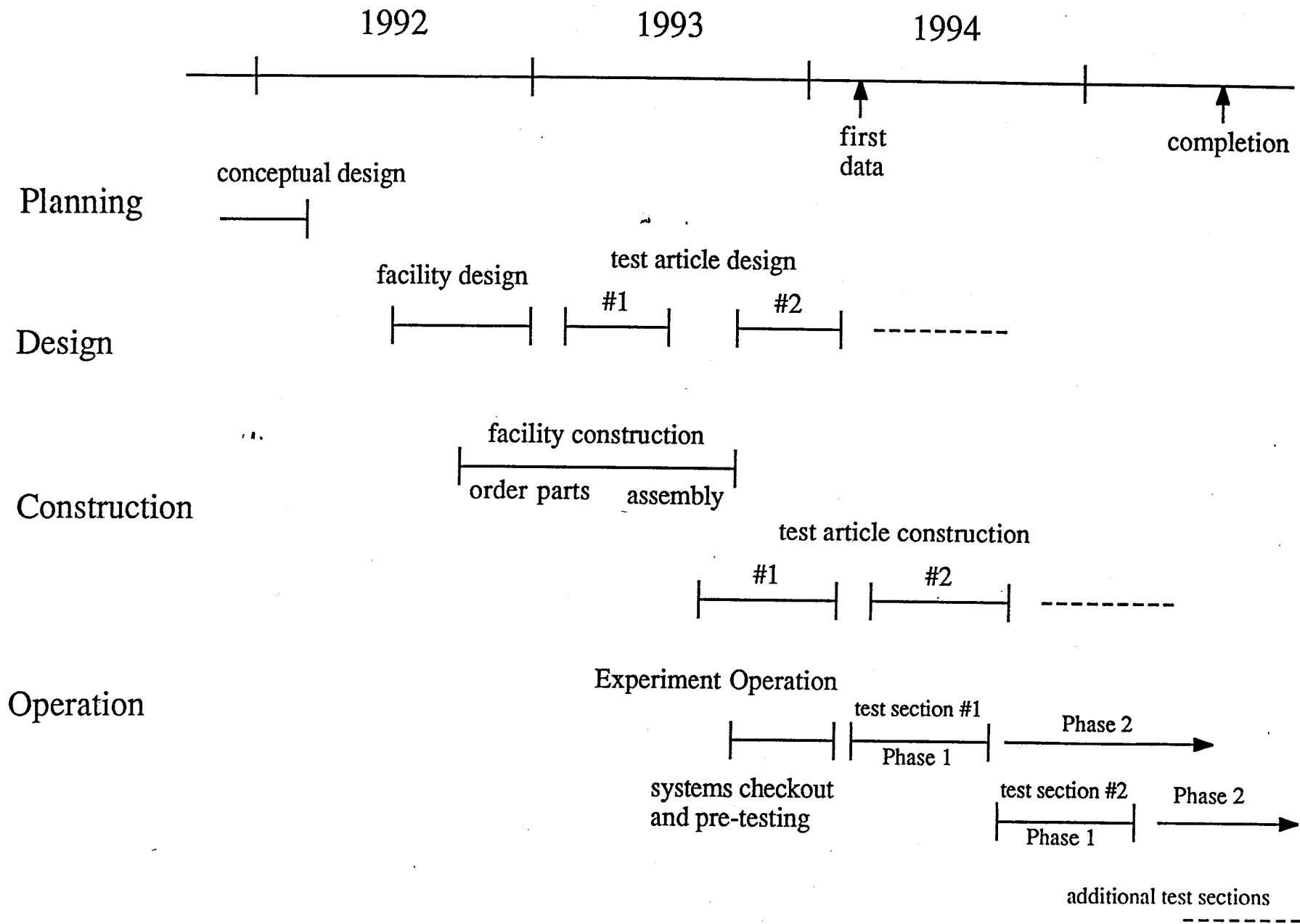
Inside the Test Articles:

- Temperature profile through breeder (5–10 locations)
- Temperature profile through multiplier (5–10 locations)
- Temperature of cladding (several locations)
- Heat flux at interface
- Stress in cladding at several locations

Outside the Test Articles:

- Coolant – flow rate, inlet/outlet pressure, inlet/outlet temperature
 - Purge – flow rate, inlet/outlet pressure, inlet/outlet temperature
 - Total power to heaters
-

Test Schedule for Unit Cell Solid Breeder Thermal Hydraulic Experiments



Publications by the UCLA Solid Breeder
Thermal Control Group
1989-1991

Articles

M. S. Tillack, A. R. Raffray, A. Y. Ying, M. A. Abdou, and P. Huemer, "Experimental Studies of Active Temperature Control in Solid Breeder Blankets," ISFNT-2, June 1991, to be published in Fusion Eng. & Design.

A. R. Raffray, A. Ying, Z. Gorbis, M. S. Tillack, and M. A. Abdou, "Thermal Control of Solid Breeder Blankets", ISFNT-2, June 1991, to be published in Fusion Eng. & Design.

Z. R. Gorbis, A. R. Raffray and M. A. Abdou, "Study of Effective Solid-to-Solid Contact Thermal Resistance and its Application to Solid Breeder Blanket Design for ITER", Fusion Technology, Volume 19, Number 3, Part 2B, pp. 1519-1524, May 1991.

P. Adnani, I. Catton, A. R. Raffray and M. A. Abdou, "Effective Thermal Conductivity of Binary Mixtures at High Solid-to-Gas Conductivity Ratios", submitted for publication in the Journal of Heat Transfer, May 1990.

Z. R. Gorbis, A. R. Raffray, M. S. Tillack, and M. A. Abdou, "Thermal Resistance Gaps for Solid Breeder Blankets Using Packed Beds," Fusion Technology, 15(2), Part 2, pp. 695-698, March 1989.

A. R. Raffray, et al., "Helium-Cooled Solid Breeder Blanket for ITER," Fusion Technology, 15(2), Part 2, pp. 858-863, March 1989.

M. A. Abdou, et al., "A Helium-Cooled Solid Breeder Concept for the Tritium-Producing Blanket of the International Thermonuclear Experimental Reactor," Fusion Technology 15(2), Part 1, March 1989, pp. 166-182.

Reports and Conferences

M. S. Tillack, A. Y. Ying, A. R. Raffray, and M. A. Abdou, "Experiments for Prediction and Control of Thermal Conductance Gap for ITER Ceramic Breeder Blanket Design," UCLA-FNT-027, September 1989.

Z. R. Gorbis, "Zone Model for Packed Bed Effective Thermal Conductivity," UCLA-FNT-028, October 1989.

P. Adnani, A. R. Raffray, M. A. Abdou, and I. Catton, "Model of Effective Thermal Conductivity for a Packed Bed," UCLA-FNT-29, November 1989.

C. E. Tickle, "Measurements of the Thermal Conductivity of Metal-Gas Particle Beds for Solid Breeder Blankets," UCLA-FNT-34, 1990.

Z. R. Gorbis, A. R. Raffray, A. Badawi, and M. A. Abdou, "Parametric Analysis of Packed Bed Effective Thermal Conductivity Using Zone Model," UCLA-FNT-38, January 1990.

Craig Tickle, "Progress Report: Packing Experiments for the Gap Conductance Experiment," UCLA-IFNT-4, June 12, 1989.

Craig Tickle, "Progress Report: Gap Conductance Heat Transfer Experiments," UCLA-IFNT-5, June 22, 1989.

A. Ying and M. S. Tillack, "Experience in the Design, Construction, and Operation of a Particle Bed Thermal Conductivity Experiment," UCLA-IFNT-6, August 1989.

A. R. Raffray, et al., "Model for Determining the Effective Thermal Conductivity of Particle Beds with High Solid-to-Gas Thermal Conductivity Ratios," 13th Symposium on Fusion Engineering, Knoxville TN, October 1989.

M. S. Tillack, et al., "Experimental Study of the Effective Thermal Conductivity of a Packed Bed as a Temperature Control Mechanism for ITER Ceramic Breeder Blanket Designs," 13th Symposium on Fusion Engineering, Knoxville TN, October 1989.

Dissertations

Craig E. Tickle, "Measurements of the Thermal Conductivity of Metal-Gas Particle Beds for Solid Breeder Blankets," UCLA M.S. Dissertaion, 1990.

Parham Adnani, "Effective Thermal Conductivity of Binary Mixtures at High Solid-to-Gas Conductivity Ratios", UCLA Ph.D. Dissertation, May 1990.

ITER R&D Task BKT-1.2.3

The goal is to develop fabrication technology and demonstrate thermal-hydraulic and mechanical performance under ITER-relevant conditions, in the absence of neutrons (and tritium).

Main Issues for Integrated Out-of-Reactor Performance of the Blanket

- thermal control in breeder and multiplier
- mechanical interactions and their effect on heat transfer
- time-dependent behavior
- off-normal events
- thermomechanically-induced changes in material behavior
- mass transfer

Out-of-Pile Test Facility

Design and construct an integrated facility for mid-scale and full-scale models

Mid-scale:

Perform thermomechanical, safety and integrity tests for blanket internal functions, including tests of purge flow and control.

Approximate size: 0.5×0.5×0.4 m

Full-scale:

Demonstrate integrated performance of full-scale blanket models with the first wall under full power simulation and transient conditions.

Approximate size: 1×1×5 m

NOTE:

The request for expression of interest says nothing about the test articles, which could be more complex and costly than the facility

ITER Out-of-Pile Test Facility

Test Requirements

- Surface and bulk heating
0.1–1 MW/m², 10–20 MW/m³ (peak at the front)
- Primary system for heat removal
water @ 1–2 MPa and “low temperature” (<100°C)
- Cyclic operation (400–2000 s duration) over 1000’s of cycles
- Purge system (He@1–3 atm)
 - can be used for thermal control
 - used during off-normal events for heat removal
- Low vacuum (1000 Pa ?)
- Backup gas system with 0.5 MW power @ 250–300°C (simulate bake-out?)
composition, pressure, flow path?
- Operating temperatures inside module:
 - structure, coolant 60–100°C (water-cooled)
 - breeder, purge 350–1000
 - multiplier 100–750
- Ability to handle test module failures
- Instrumentation:
 - internal temperatures
 - internal stresses
 - coolant and purge conditions
(flow rate, pressure, inlet/outlet temperatures, etc.)
 - post-test examination

Methods of Supplying Internal Heating

Several methods have been proposed for simulating nuclear bulk heating

- Discrete Resistance
- Direct Resistance Heating
- Microwaves
- Induction Heating

Each method has some problems and cannot exactly simulate nuclear heating

Much more analysis is required to select the best method and determine how valid the simulation will be

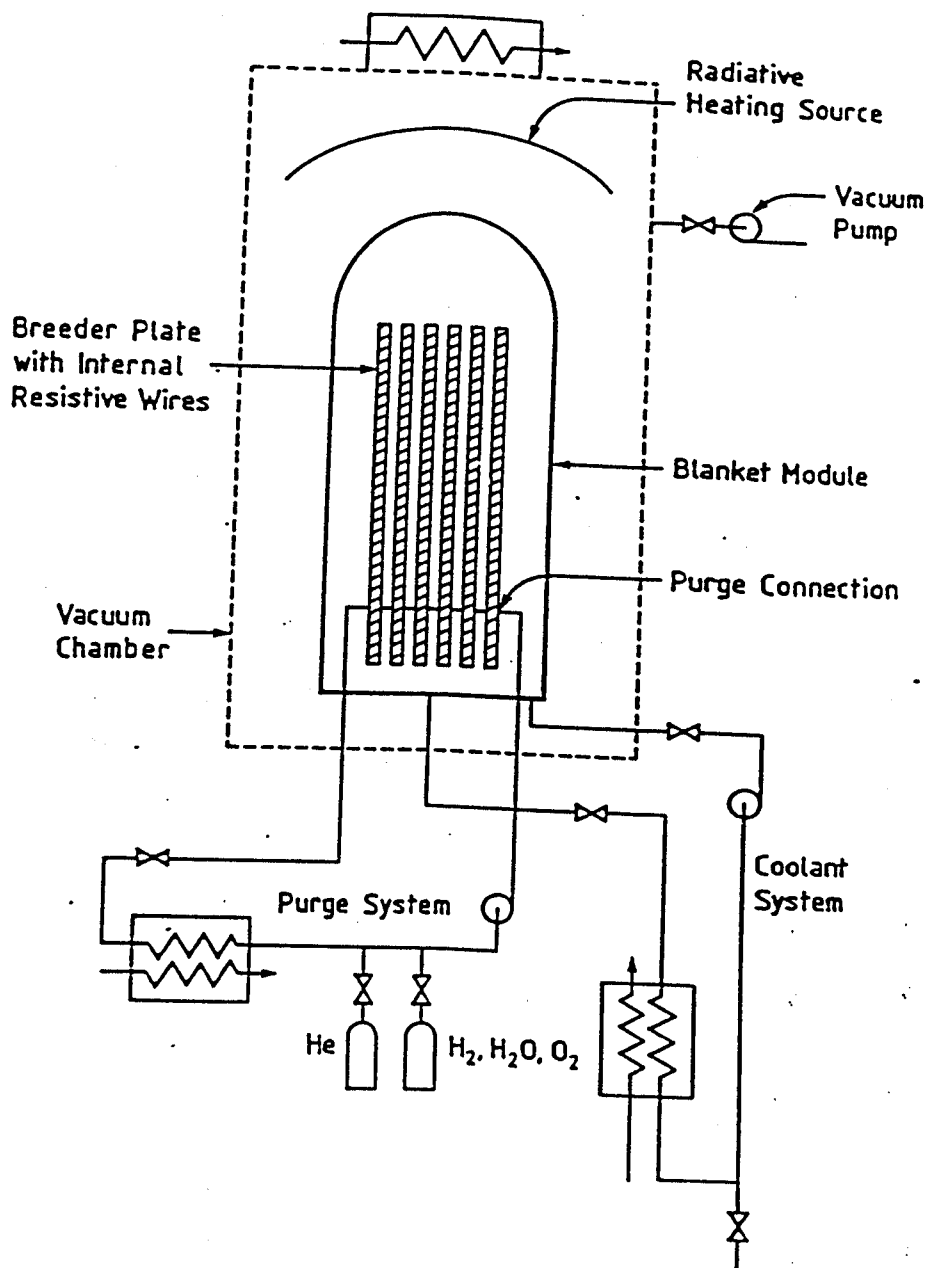


Figure 4.5.1-4. Block diagram of non-nuclear Thermomechanical Integrity Test Facility.