He-Cooled Solid Breeder Blanket Design for ITER

A. R. Raffray
M. A. Abdou
(UCLA)

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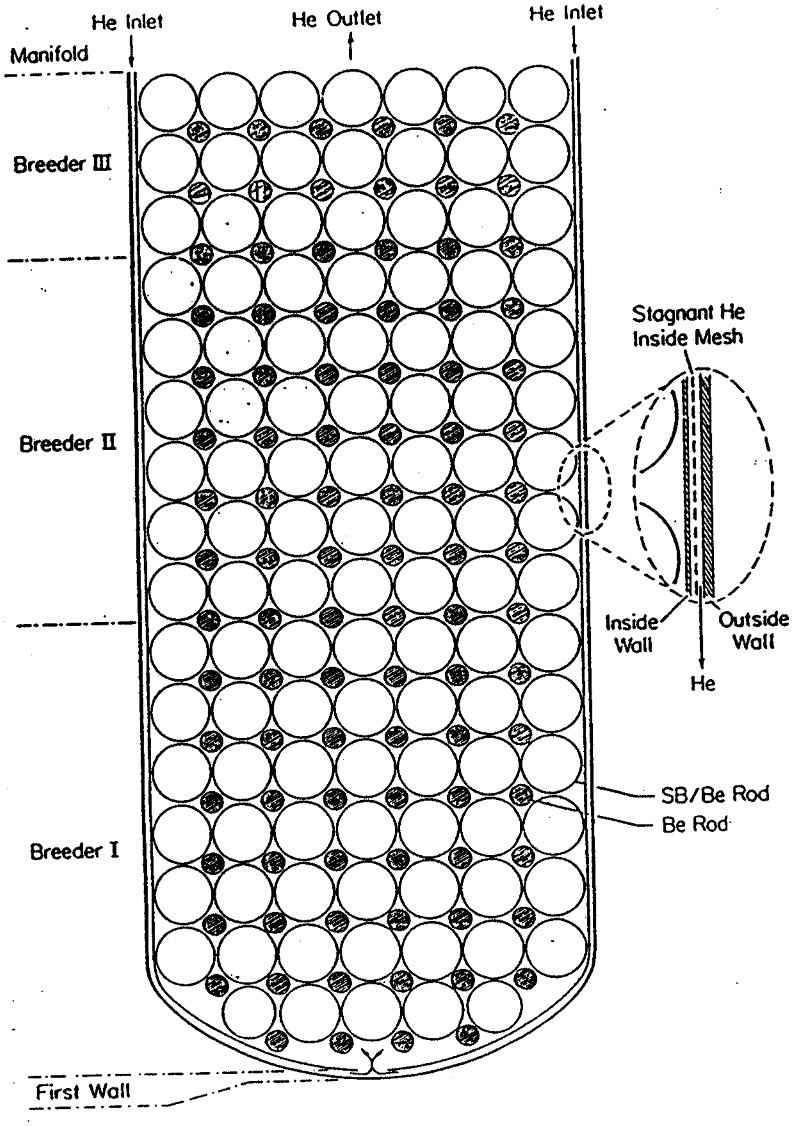
HELIUM-COOLED SOLID BREEDER BLANKET DESIGN FOR ITER

Key reasons for considering such a Blanket

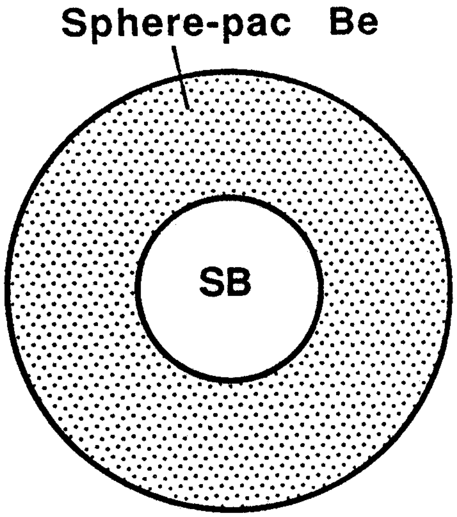
- Well-studied reactor-relevant materials and configurations (INTOR, BCSS, FINESSE, TOKOPS, and many others)
- Large Design Margin
  - If we know how to design for 5 MW/m^2 wall loading and 20 MW -yr/m^2 fluence, we should be able to design for 1 to 2 MW/m^2 wall loading and 3 MW-yr/m^2 fluence
  - Need to use only a part of SB temperature window
- Data base for solid breeder
  - Major progress over past few years from increasing number of Solid Breeder experiments
  - Data will be available from experiments in fission reactor for ITER type fluence
- R & D and testing benefit
  - Substantially reduces R & D required before and after ITER
  - Could reduce the risk for the next fusion device
- Design/Operation Flexibility

  He coolant - temperature virtually decoupled from pressure when compared to saturated liquid
  - can run He to optimize structure temperature (~ 300° C?)
  - can accommodate power variation (temperature of He and SB can be adjusted)
- Safety
  - Inert He Gas - no chemical reaction, no corrosion
  - Low activation SB material - Li_4SiO_4, Li_2O
  - He at moderate temperature and pressure



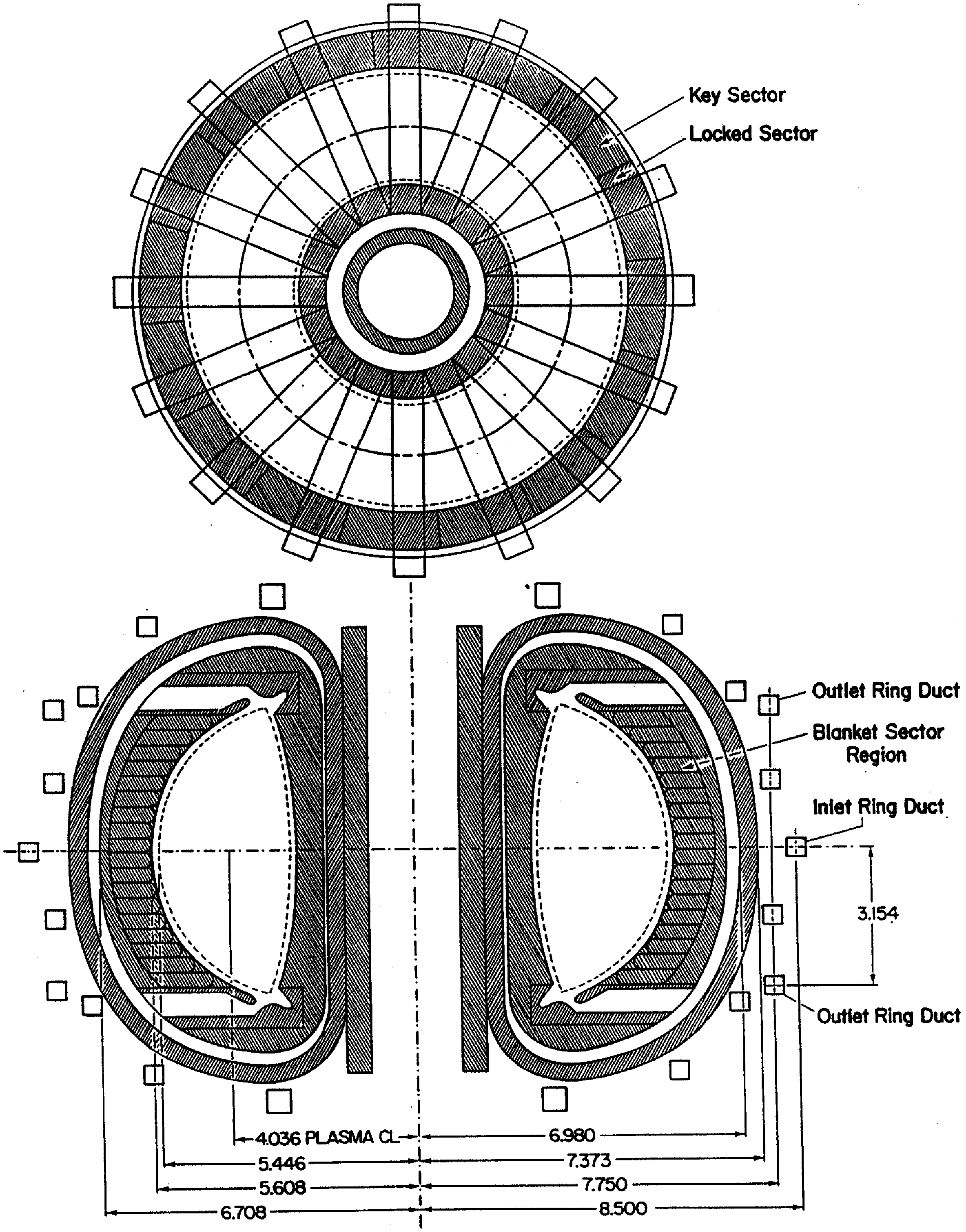
Helium-Cooled Solid Breeder Blanket Canister for ITER

Solid Breeder/Multiplier Rod Configuration



Advantages

- Be can be purged
- Effective barrier against permeation to the main helium flow
- Be sphere pac configuration provides more allowance for swelling and thermal expansion
- Larger rods (~ 4 cm)
  - Larger SB/Be volume fraction for better neutronics
  - Fewer rods

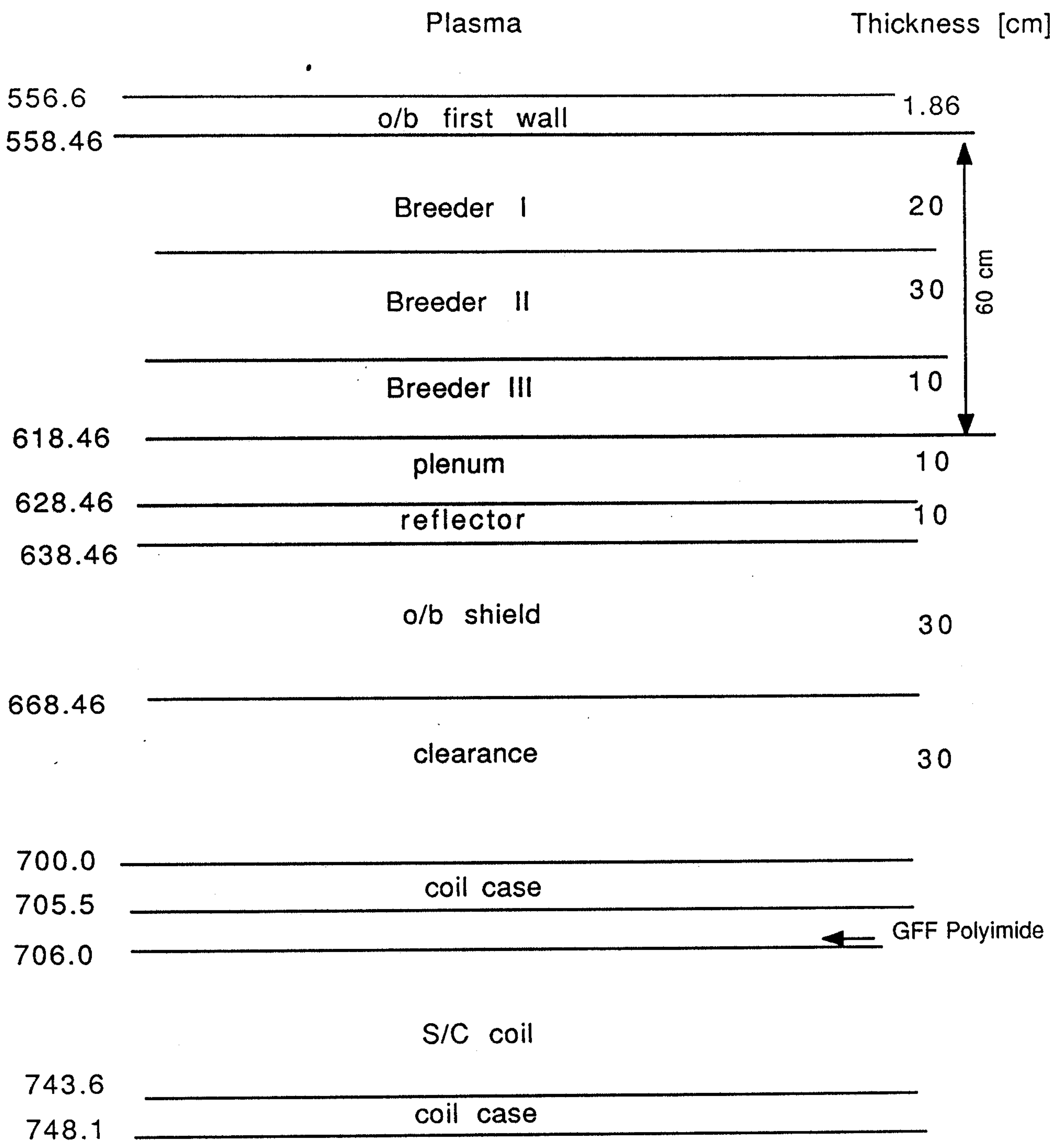


Plan View and Cross-Section of ITER showing Canister Layout

Helium-Cooled Solid Breeder Blanket Design for ITER

Issues raised at the last meeting have been addressed

- Tritium Breeding Ratio
  - 1.35 for 1-D toroidal model with ~~full coverage~~ blanket in outboard only
- Thermal-Hydraulics
  - Max. Helium velocity in FW/Canister = 62/31 m/s
  - Pressure drop and pumping power in helium circuit outside canister about the same as corresponding values for the canister itself
- Temporal and Spatial Heat generation variation
  - Can be accomodated
  - Predictability and reproduceability of gap conductivity are key factors which need to be addressed experimentally
- Helium leakage to the plasma
  - Estimate is substantially lower than production rate in plasma
- Availability
  - Both consequence and probability of failure must be considered
  - Robust design in this regard
- Tritium inventory in Be
  - Purge flow through Be sphere-pac
- Inboard Shield
  - Separate coolant circuit for all blanket concepts
  - Water coolant assumed for the calculations
  - Possible helium-cooled optimization once ITER skeleton agreed on internationally



Outboard Blanket and Shield Configuration

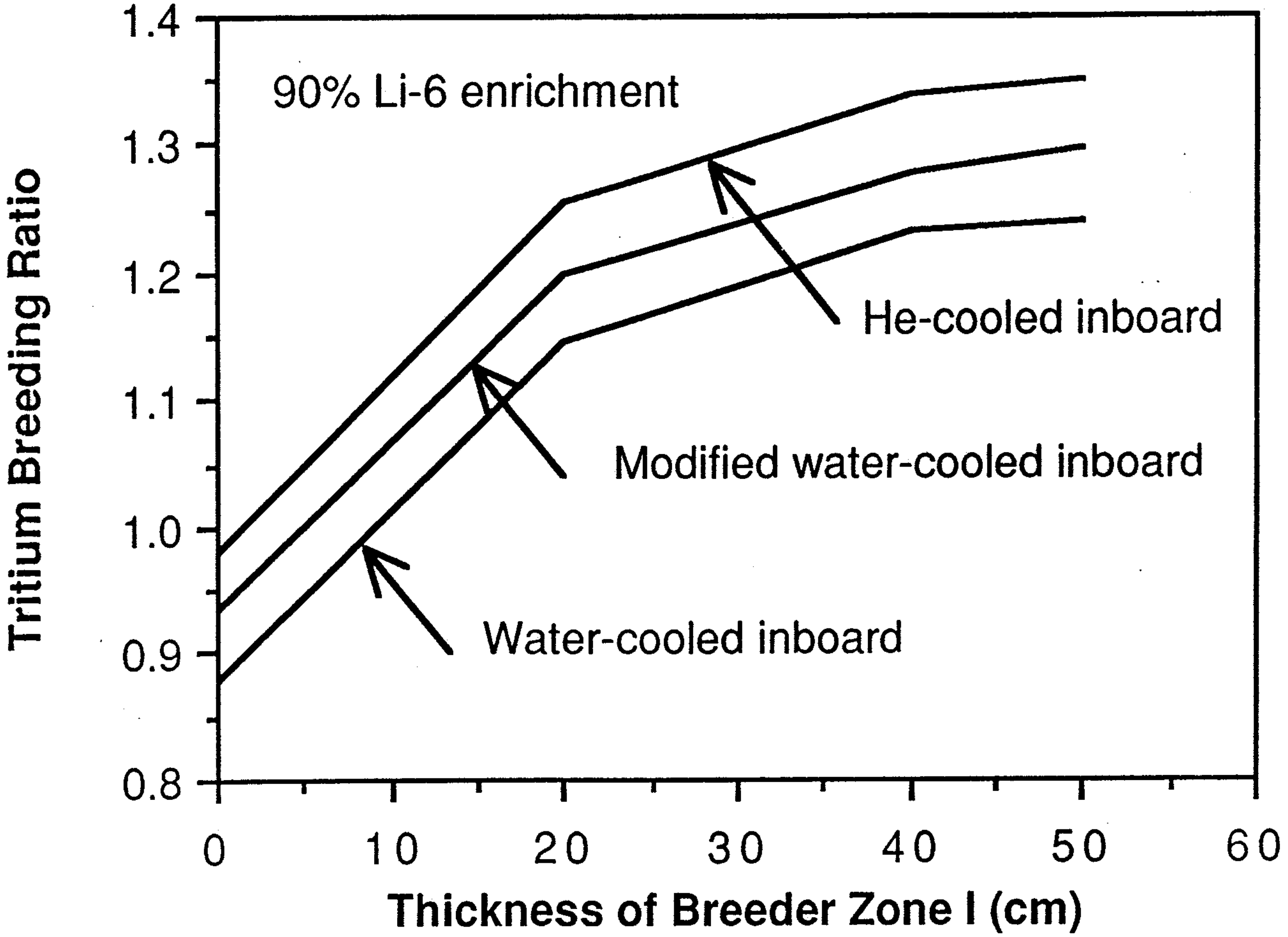
Material Compositions (Outboard)

Zone	% Volume fraction
o/b first wall	35.27 % PCA 64.70% He
breeder	Li_4SiO_4, Be, PCA, He (see Table I)
plenum	9.4% PCA 30.6% He
reflector	85% C 5% PCA 10% He
o/b shield	50% B_4C 40% PCA 10% He

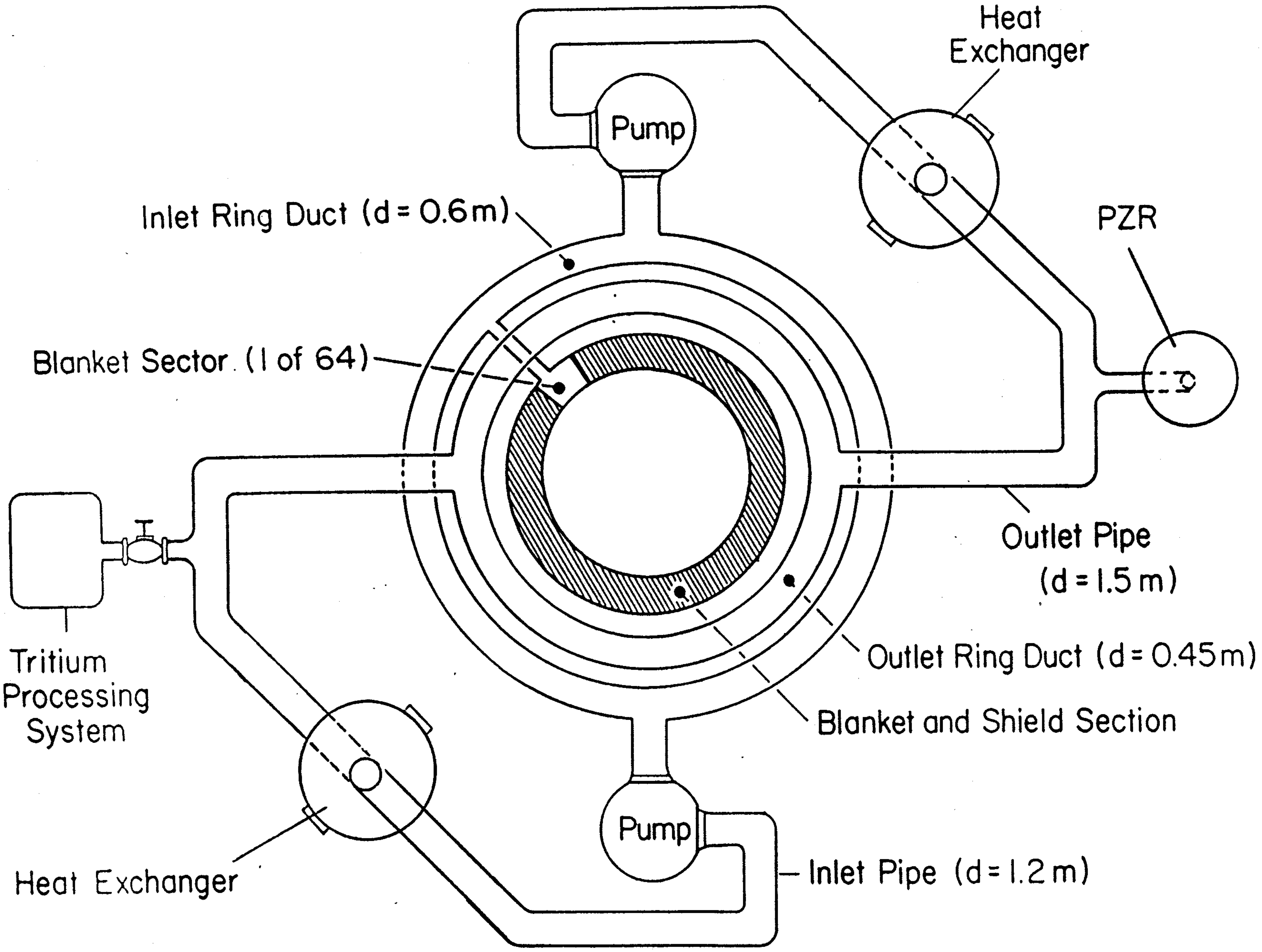
Material Compositions in Breeder Zones Used for Neutronics Calculations

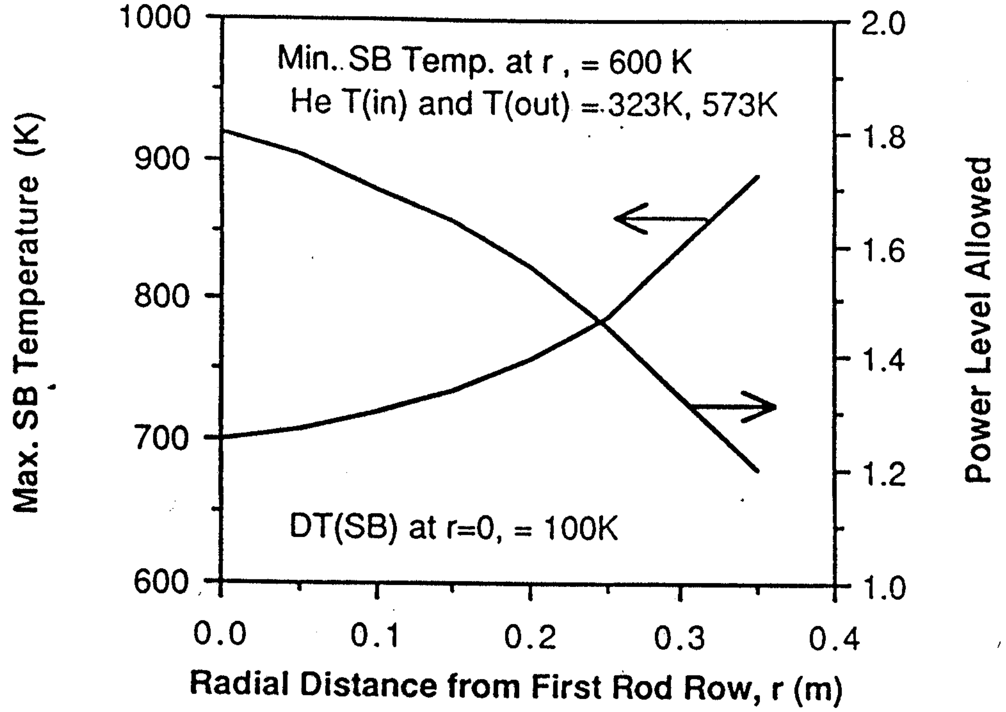
Zone	% Volume Fraction
Breeder I	7.2% Li_4SiO_4 (80% TD) 45.3% Be (90% TD) 9.2% PCA 38.3% He
Breeder II	37.6% Li_4SiO_4 (80% TD) 14.4% Be (90% TD) 16.1% PCA 31.9% He
Breeder III	51.0% Li_4SiO_4 (80% TD) 20.6% PCA 28.4% He

TBR vs. Breeder Zone I Thickness

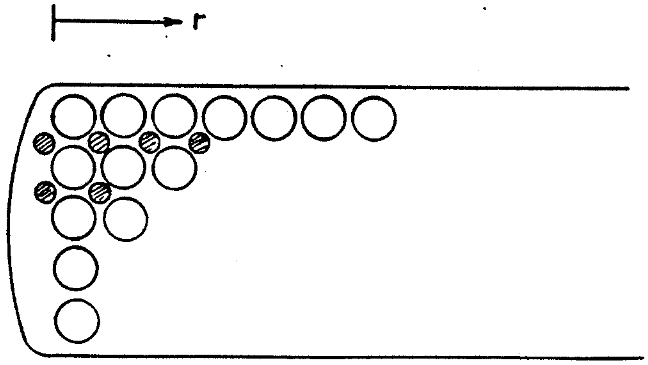


Layout of Proposed Helium Main Coolant Flow System

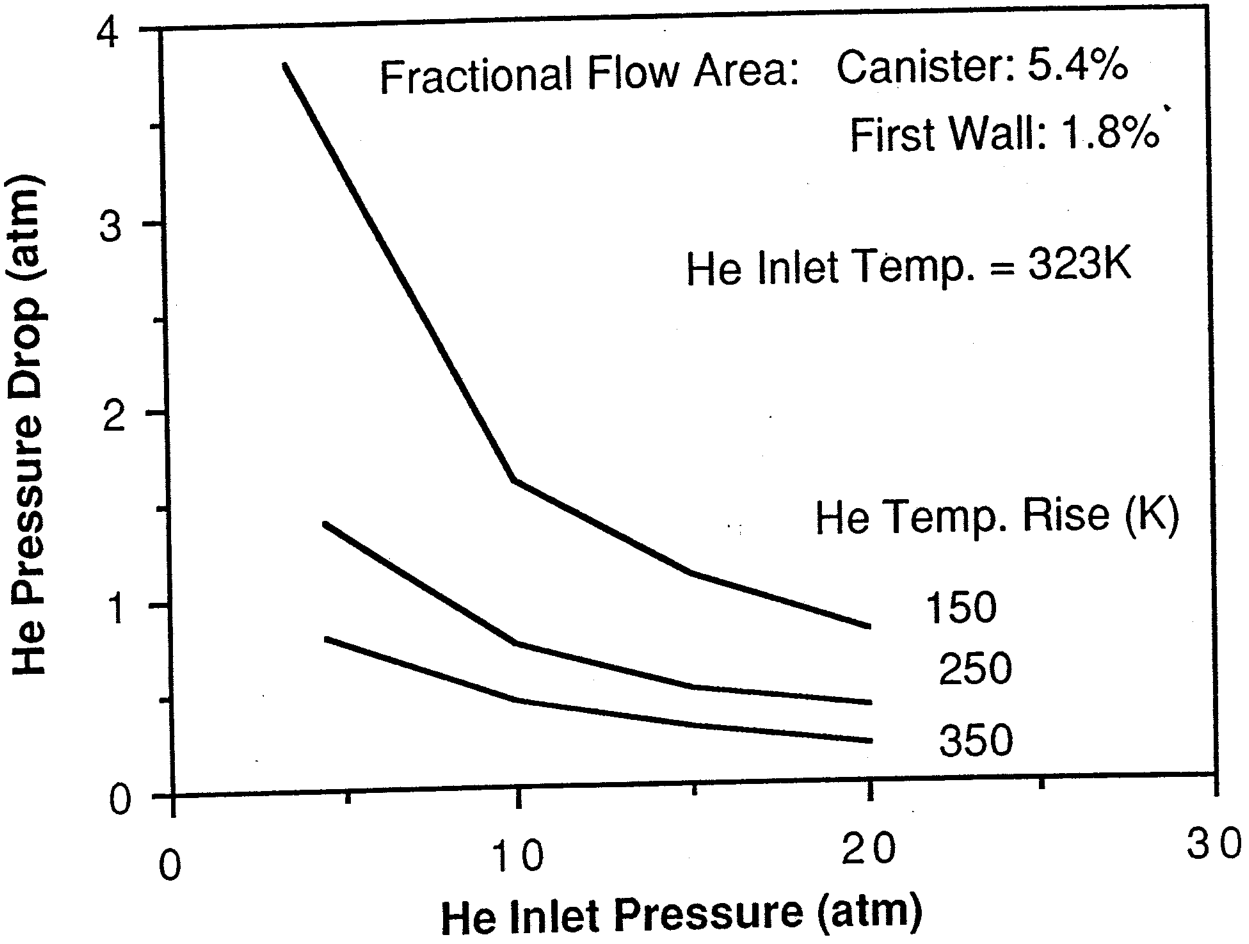




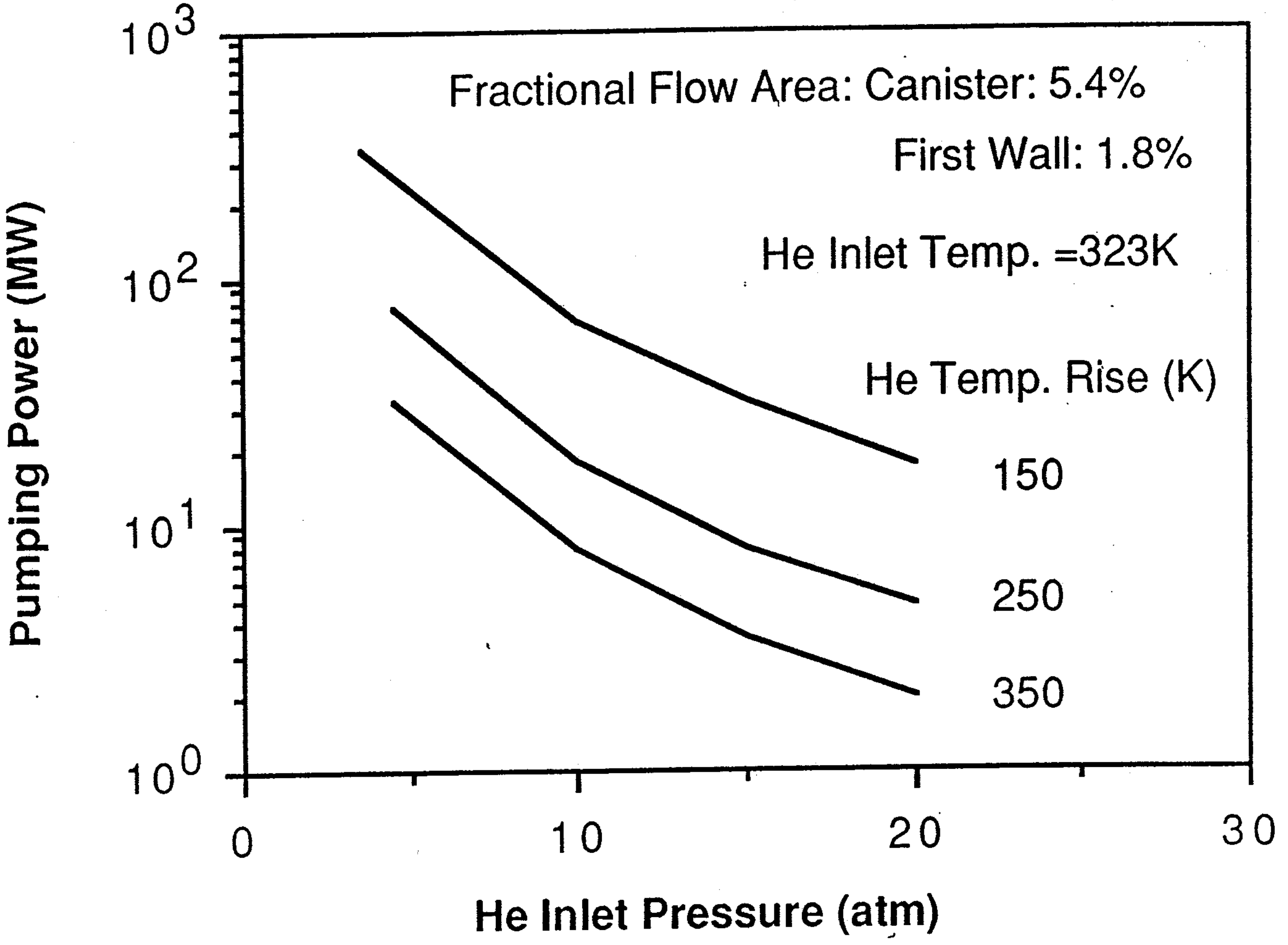
Max. SB Temp. and Power Level Allowed



Canister He Pres. Drop vs. Inlet Pressure



Canister Pumping Power vs. He Inlet Pres.



Predictions of Helium Leakage to Plasma Under Normal Operations Based on HTGR Observations

*Leakage rate per meter of weld at differential pressure of 1 atm	3.28×10^{-7} cm^3/sec
Leakage rate per meter of weld at differential pressure of 15 atm	2.187×10^{-9} g/sec
Total weld length of blanket exposed to plasma face	4682 m
Helium generation rate for ITER	1.667×10^{-3} g/sec
Leakage rate in terms of helium generation rate	0.8%

* Leakage rate observed from linear welding and non-destructive inspection procedures employed on Fort St. Vrain (Ref: IEEE Power Engineering Safety, Nuclear Plant Safety, "Gas Cooled ReactorPlant Safety", G.L. Wessman).

The He-Cooled Solid Breeder Rod Design is very "Robust" against Failures

- The rod design provides multiple barriers against contamination. (Also, there is a positive pressure difference into the purge system).

- The coolant is inert. Consequences of failure are not usually catastrophic. (Contamination is the more likely failure mode rather than acute failure).

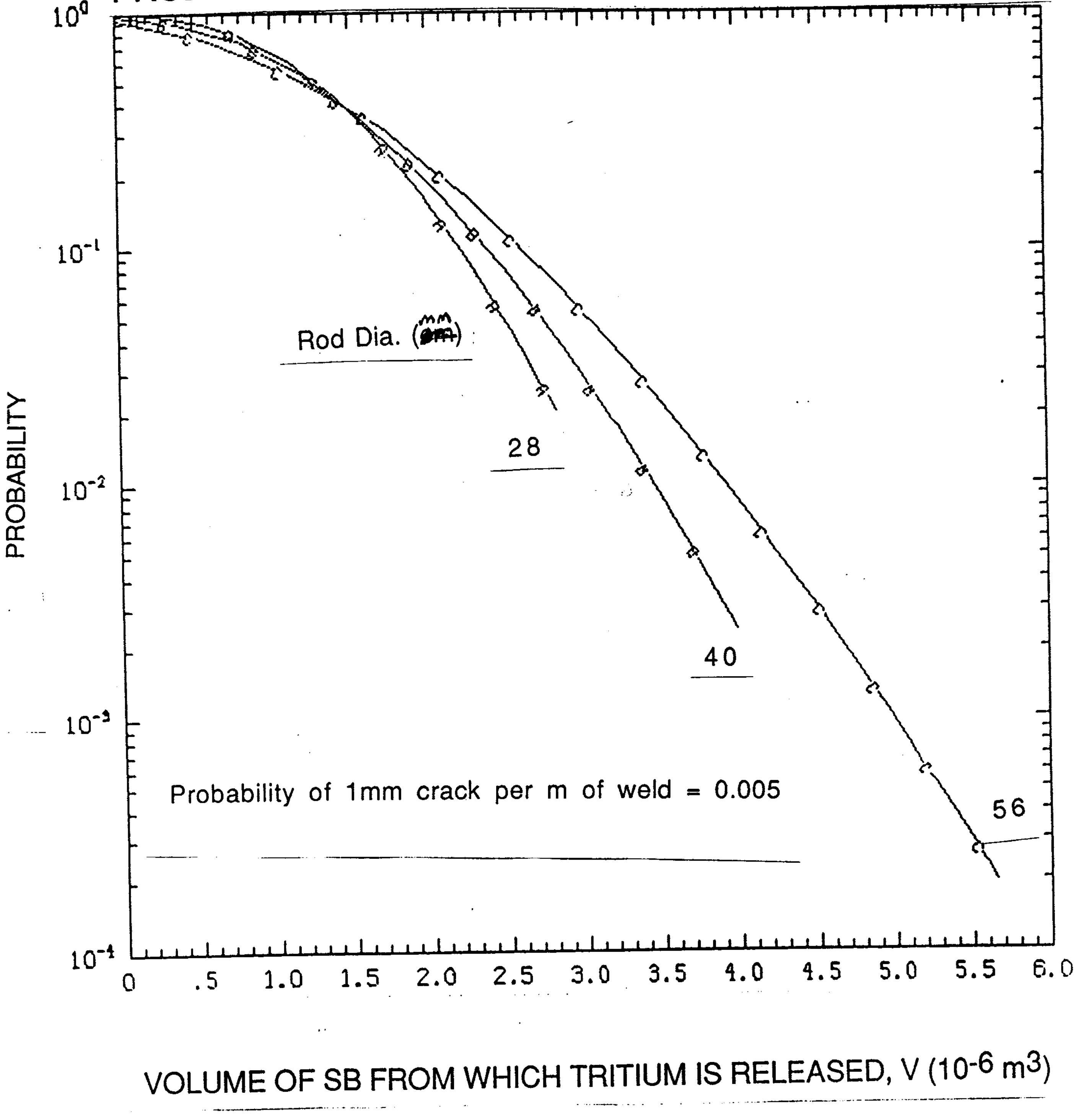
- The rod design "dilutes" the source term. Each rod produces only about 1g of tritium over the lifetime of the reactor. (cf. 200g inventory limit in H_20.) For non-fatal failures, increasing the number of rods can actually <u>decrease</u> the probability of exceeding contamination limits.

Steady State Tritium Inventory in Li_4SiO_4 for Helium-Cooled Solid Breeder ITER Blanket

DIFFUSION	0.4g
SOLUBILITY	1g
ADSORPTION	0.1g
TOTAL	1.5g

(Estimated uncertainty in total tritium inventory is ± a factor of 100)

PROBABILITY OF RELEASING TRITIUM FROM MORE THAN V

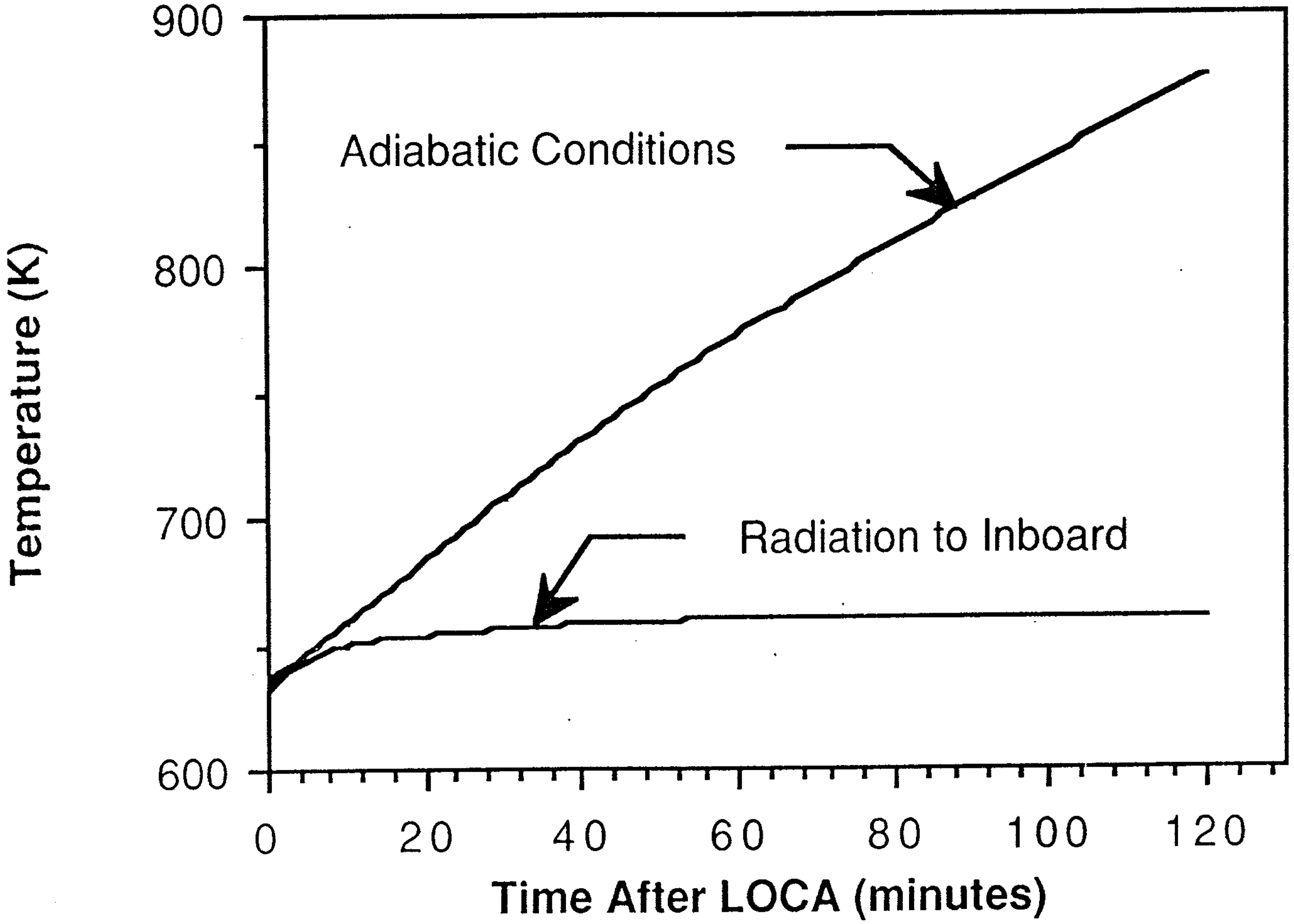


Predictions of Helium Leakage to Plasma for Different Equivalent Crack Diameters

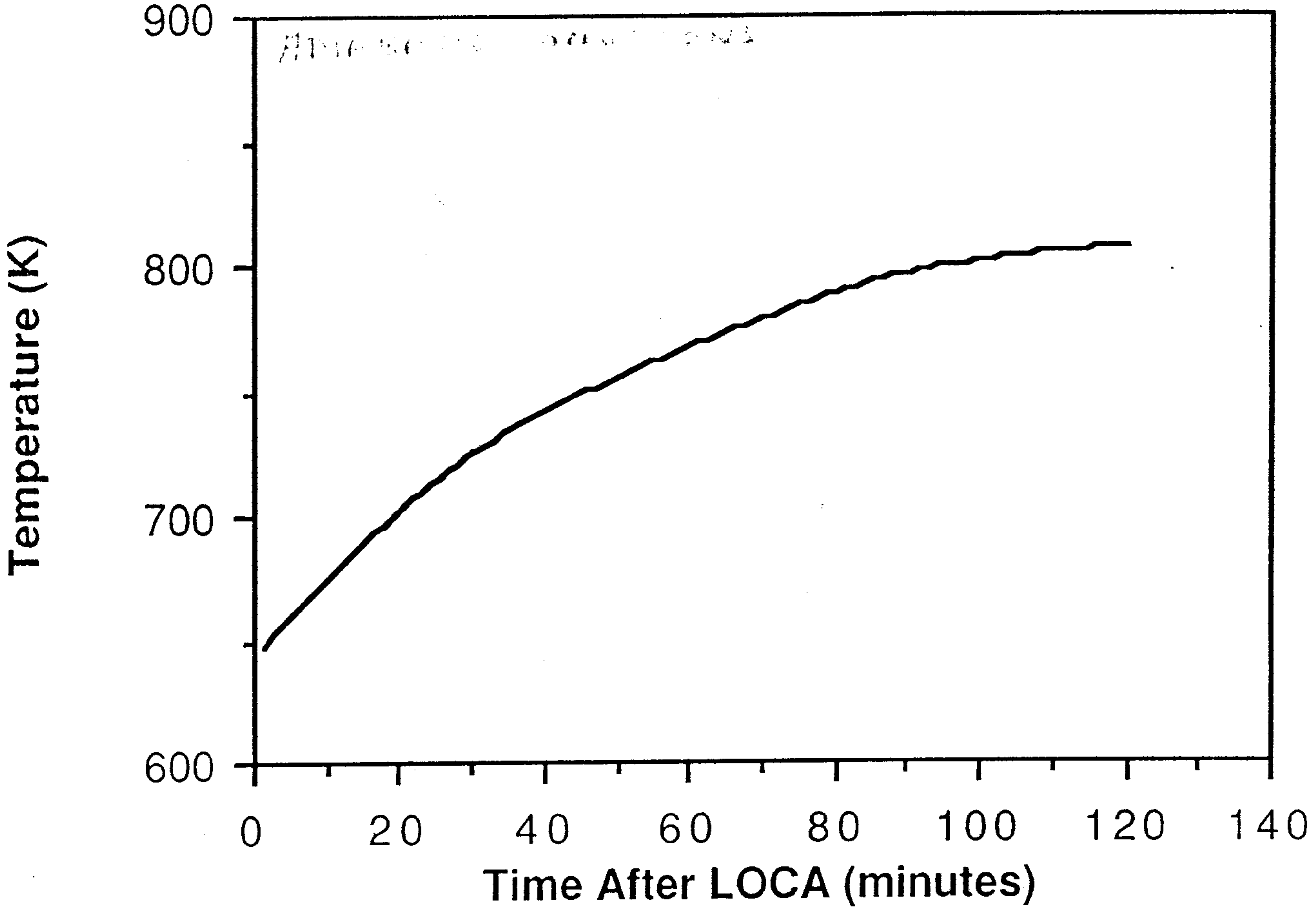
For blanket pressure > 7.3 atm

Leak (or crack) Diameter (cm)	Leak Flow Rate (g/sec)	Fraction in terms of Helium Generation Rate
0.05	1.62×10^{-5}	0.0097
0.1	6.46×10^{-5}	0.039
0.2	2.59×10^{-4}	0.16
0.3	5.82×10^{-4}	0.35
0.4	1.03×10^{-3}	0.62
0.5	1.62×10^{-3}	0.97
0.6	2.33×10^{-3}	1.40
0.8	4.14×10^{-3}	2.48
1.0	6.46×10^{-3}	3.88

First Wall Temperature After LOCA



Solid Breeder Temperature After LOCA



Concluding Remarks

He-Cooled Solid Breeder Blanket is a very attractive candidate for ITER

- It can meet all absolute requirements

- Significant safety advantages
  - Inert helium gas and low activation Li_4SiO_4
  - Minimization of tritium leakage to main flow under normal conditions
  - Robustness in ability to withstand failure e.g. rod failure is not catastrophic
  - Possibility of passive LOCA accommodation

- Large design margin and flexibility to allow for power variation
  - Large SB temperature window
  - Pressure virtually decoupled from temperature for helium gas

- Reactor-Relevant materials and configuration
  - Reduces R & D requirement after ITER
  - Could also reduce the risk for the next fusion device

- Well-studied material and configuration with expanding data base
  - Tritium has been produced and purged from different solid breeders
  - Reduces R & D requirement before ITER

Preliminary List of Major Parameters for Helium Cooled Solid Breeder ITER Blanket Design (outboard only)

Materials

Coolant:	Helium
Breeder:	Li_4SiO_4
^{6}Li Enrichment:	60%
Neutron Multiplier:	Be
Structure:	PCA, 25% CW
Reflector:	Carbon
Shield	Stainless steel

Configuration & Dimension

Breeder/Multiplier rods in canister

Canister:	Length	1.1 to 1.3m
	Width	0.33m
	Number	480
Rod:	Diameter	0.041m
	Spacing Between Rods	0.002m
	Number per Canister	106
First Wall:	Thickness	0.003m
	Channel Width	0.003m
	Second Wall Thickness	0.002m

Design Parameters

Coolant:	Inlet/Outlet Temperature	50°C/300°C
	Inlet/Outlet Pressure	1.5MPa/1.4MPa
Breeder:	Minimum/Maximum Temperature	325°/475°C
Structure:	Maximum First Wall Temperature	275°C
	Minimum/Maximum Temperature at	
	Coolant Interface	50°C/300°C
	Breeder Interface	325°C/475°C
	Multiplier Interface	150°C/475°C

Tritium Breeding Ratio:

1-D Poloidal Model with 100% coverage	1.6
1-D Toroidal Model with ~~100% coverage~~ breeding in outboard only	1.3

Maximum Nuclear Heating Rates (based on 1-D, homogenized-region calculations)

Breeder	16w/cm^3
Coolant	0
Multiplier	16w/cm^3
Structure (First Wall)	9w/cm^3

Energy per Fusion Neutron:	19.7 Mev

First Wall/Blanket Description:

Total Thickness	1.1m
Manifold Thickness	0.1m
Coolant Total Pressure Drop	0.1 MPa
Coolant Pumping Power	18 MW
Coolant Velocity (Max/Ave):	
First Wall	62/47 m/s
Canister	31/20 m/s
Coolant Flow Rate	1.1 x 10^6 kg/h

Tritium Removal

Method: Proven method for tritium processing from helium

Steady-state Blanket Inventory:	Diffusion:	0.4g
	Solubility:	1g
	Surface Adsorption:	0.1g

Purge Gas Parameters:

Gas Material	Helium
Inlet/Outlet Temperature	~ 400°C
Pressure	1 MPa
Mass Flow Rate	590 kg/h
Average tritium production period	0.5g/FPY

Heat Transport System

Helium Side

Pressure Drop	0.1 MPa
Pumping Power	2.2 MW

Water Side

Maximum Pressure	0.1 MPa
Inlet/Outlet Temperature	20°C/40°C
Tritium Barriers	Oxide layer probably

LOCA

Method to Accommodate	Initial calculations indicate passive method but needs verification

Maximum Material Temperature

Structure	725°C
Breeder	725°C
Multiplier	725°C

Power Variation Capability

Method
Passive for power increase
He flow rate reduction for power decrease

Minimum/Maximum Charge from Average Conditions 50%:50% at least

Compositions and Dimensions for Neutronics Calculations

Region	Thickness (m)	Structure	Volume Fraction Breeder (80% TD)	Multiplier (90% TD)	Helium
First Wall	0.02	0.4			0.6
First Breeder	0.20	0.09	0.07	0.46	0.38
Second Breeder	0.3	0.16	0.37	0.14	0.32
Third Breeder	0.1	0.21	0.51		0.28
Shield	0.4	Composition to be optimized			

Nuclear Responses in the TF Coils (@ 2.5 FPY)

Maximum Fast Neutron Fluence in the Superconductor	$2.8 \times 10^{18} n/cm^2$
Maximum Atomic Displacement in Copper Stabilizer	8.63×10^{-4} dpa
Maximum Dose to Electrical Insulator Polyimide	3.55×10^9 rad
Maximum Nuclear Heating in the Superconductor	$1.36 \times 10^{-3} w/cm^3$
Nuclear Heating in the Superconductor at Midplane	$0.26 \times 10^{-3} w/cm^3$
Maximum Nuclear Heating in the Magnet Case at Midplane	4.72×10^{-3} w/cm^3

Max. Local After Heat (w/cm^3)

	First Wall	Breeder
1 h after Shutdown	0.1474	0.04947
1 Day after Shutdown	0.1437	0.0482
1 Month after Shutdown	0.1206	0.0404

Mass of Materials

Breeder	6.5×10^4 Kg
Multiplier	3.6×10^4 Kg
Structure	1.4×10^5 Kg
Shield	3.4×10^5 Kg