SOLID BREEDER IRRADIATION EXPERIMENTS

USA Input to IEA Specialists Meeting

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Presented by
Mohamed A. Abdou

This presentation was prepared by M. Abdou, A. R. Raffray and A. Ying (UCLA) with input from C. Johnson (ANL), G. Hollenberg (Battelle), R. Puigh (Hanford) and others

Major Solid Breeder Blanket Issues

Breeder/multiplier tritium inventory and recovery

Tritium self-sufficiency

Breeder/multiplier/structure mechanical interactions

Structural response to environmental conditions

Corrosion and mass transfer

Tritium permeation and processing from blanket

Failure modes and reliability

Solid Breeder Blanket Concepts
(Candidates for Test Modules in ITER)

Breeder Materials

Li_2O, Li_4SiO_4, Li_2ZrO_3, $LiAlO_2$

Multiplier

Beryllium

Breeder/Multiplier Form

Pebble bed or Sintered product

Coolant

Helium
Water

Purge

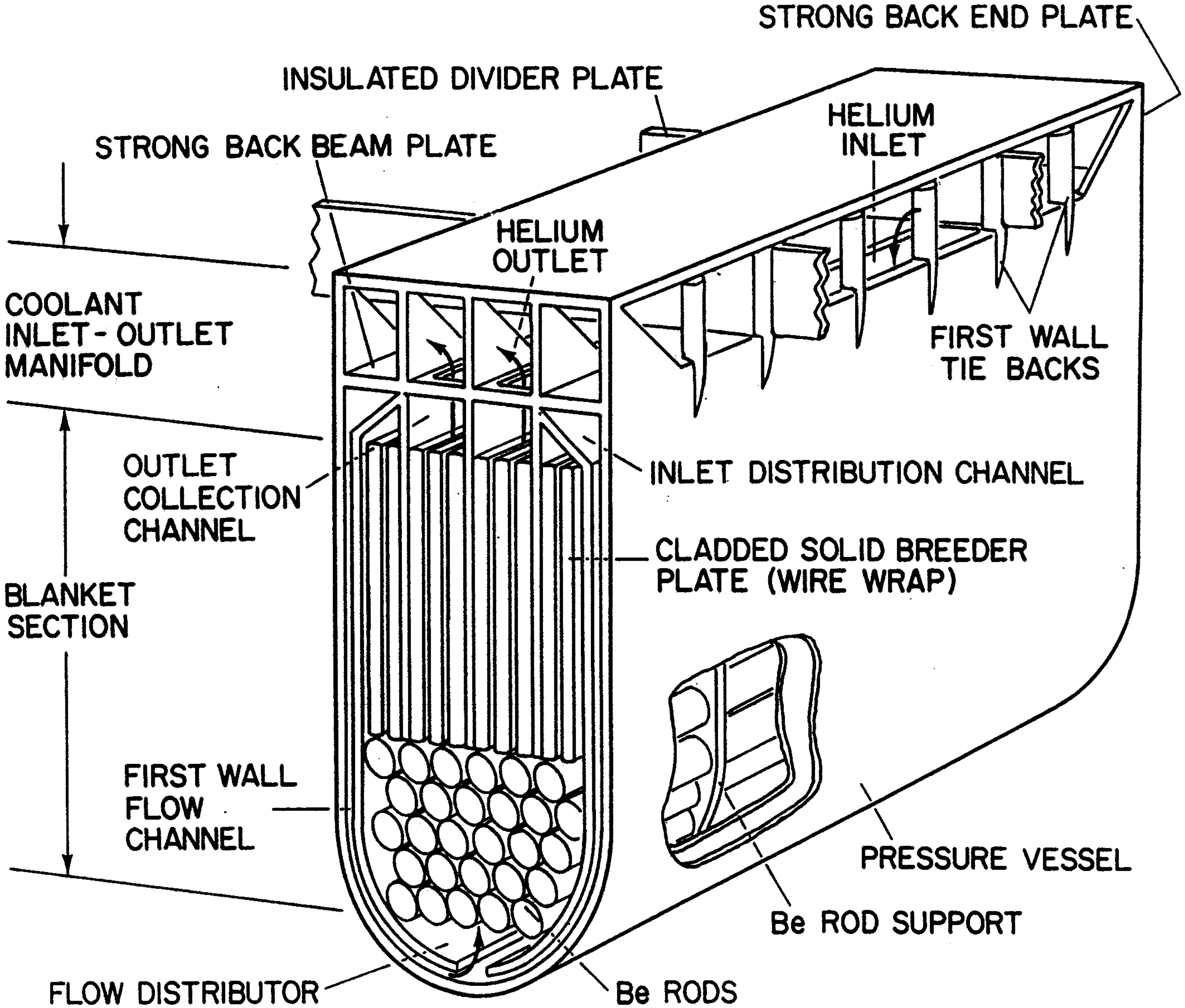
Helium + %H_2

Structure

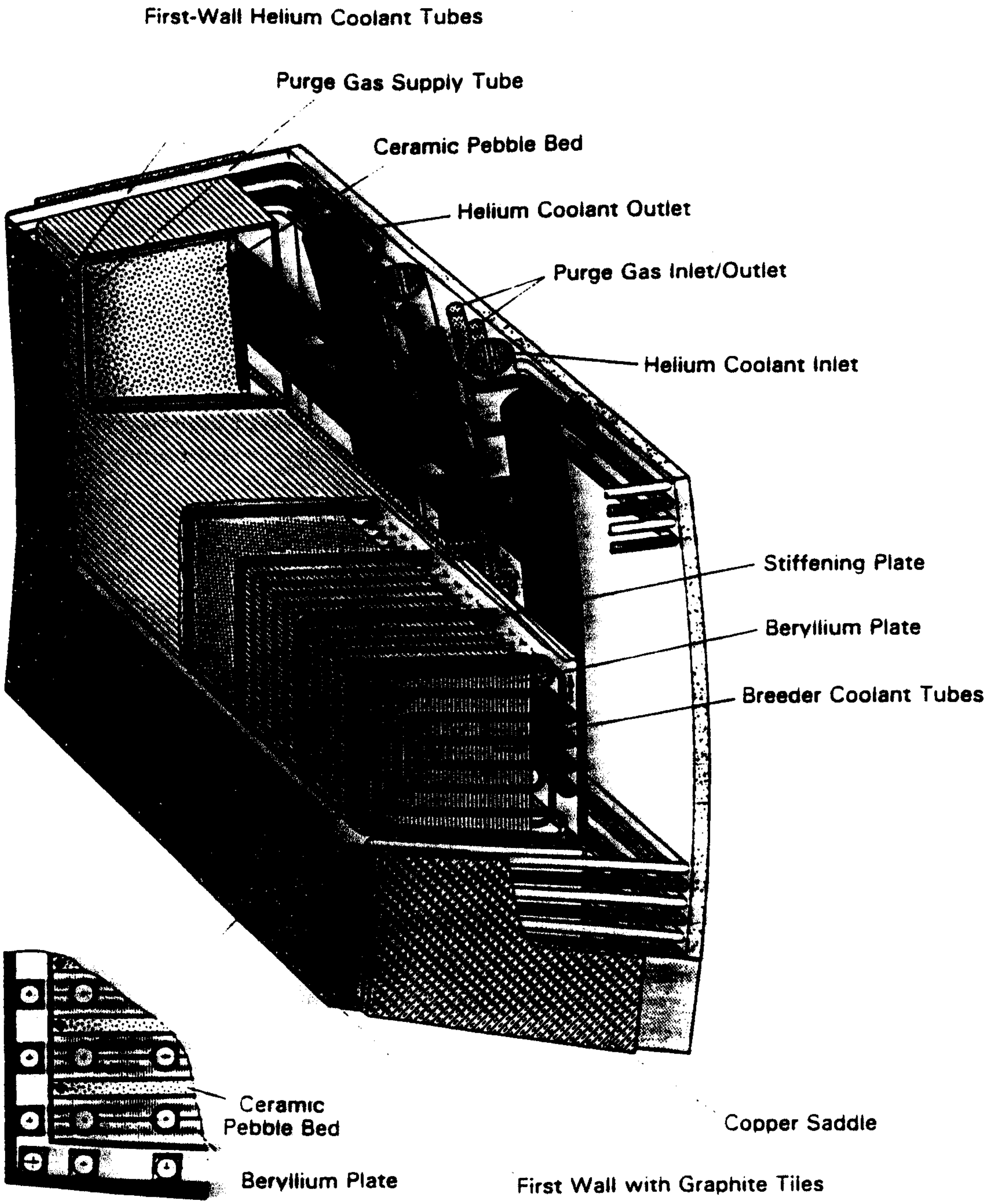
Ferritic Steel
Austenitic Steel

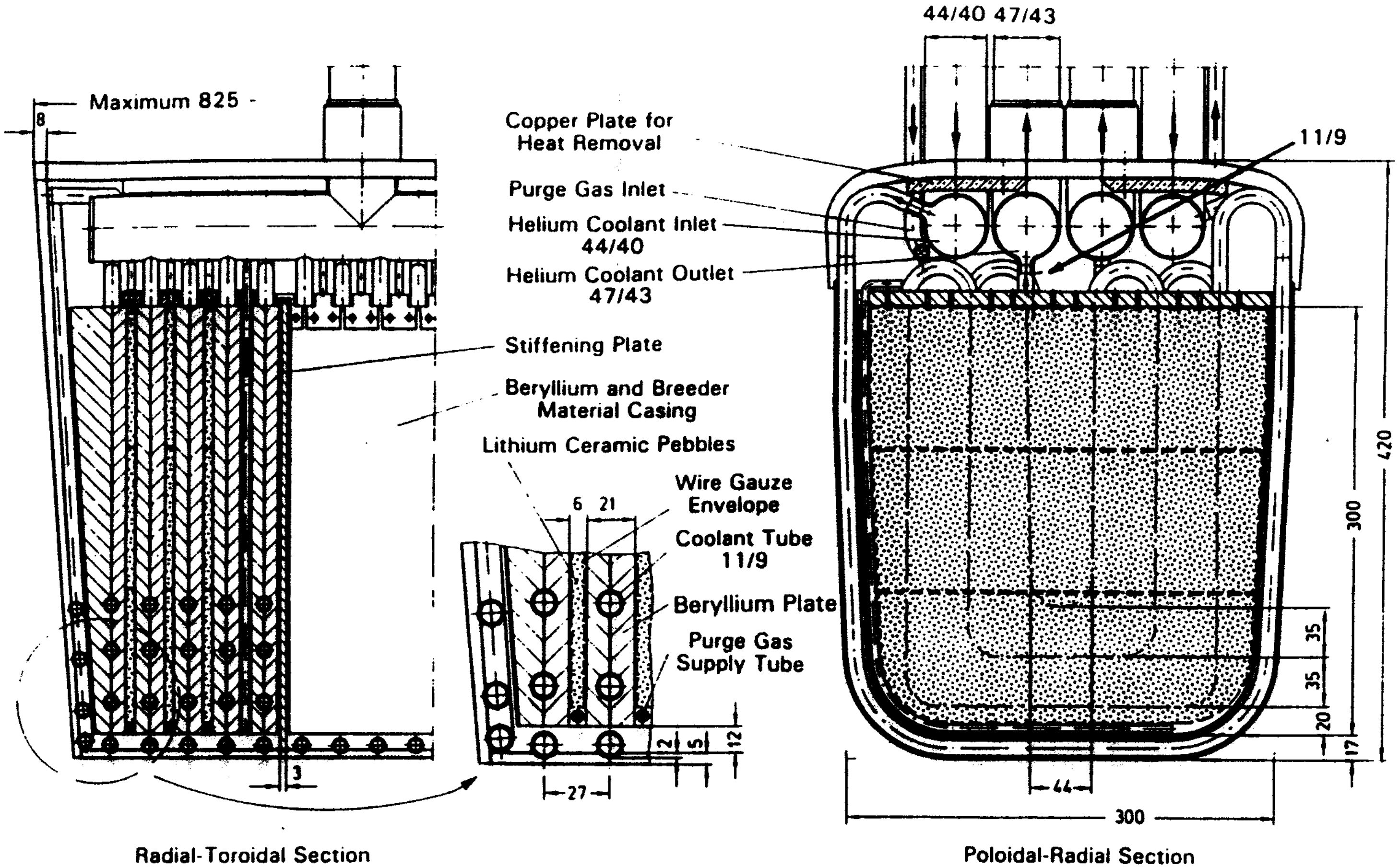
Configuration

- Beryllium mixed with breeder or separate
- BIT, BOT
- Different zones, coolant arrangements


STRONG BACK END PLATE
INSULATED DIVIDER PLATE
HELIUM INLET
STRONG BACK BEAM PLATE
HELIUM OUTLET
COOLANT INLET-OUTLET MANIFOLD
FIRST WALL TIE BACKS
OUTLET COLLECTION CHANNEL
INLET DISTRIBUTION CHANNEL
CLADDED SOLID BREEDER PLATE (WIRE WRAP)
BLANKET SECTION
FIRST WALL FLOW CHANNEL
PRESSURE VESSEL
Be ROD SUPPORT
FLOW DISTRIBUTOR
Be RODS

Isometric View of Outboard Blanket Canisters of Ceramic Breeder Blanket for NET (Dalle Donne et al.)





Radial-toroidal and Poloidal-radial cross section of the outboard canister of ceramic breeder blanket for NET (Dalle Donne et. al.,)

SOLID BREEDER MATERIAL IRRADIATION EXPERIMENTS

Experiment	Ceramic	Grain Size (µm)	Density (%TD)	Temperature (°C)	Li Burn-up (Max at %)	Reactor	Time Frame
Closed Capsule							
ORR (US)	Li_2O	<47	70	750, 850, 1000	0.05	ORR	- -
TULIP	Li_2O	50	87	600	3	EBR-II	84
FUBR-1A (US)	Li_2O	6	85	500, 700, 900	1.5	EBR-II	84/85
	$LiAlO_2$	<1	85, 95	500, 700, 900	3		84/85
	Li_4SiO_4	2	85	500, 700, 900	2		84/85
	Li_2ZrO_3	2	85	500, 700, 900	2		84/85
FUBR-1B (US)	Li_2O	<5	60, 80	500, 700, 900	5	EBR-II	85/89
	Li_2O	<5	80	500-700/1000			
	$LiAlO_2$	<5-10	80	500, 700, 900	9		85/89
	(sphere-pac)		80	500-700/1000			
	Li_4SiO_4	<5	80	400-500	9		85/89
	Li_8ZrO_6	<5	80	600-700	7		85/89
	Li_2ZrO_3	<5	85	520-620	7		85/89
ALICE (France)	$LiAlO_2$	0.35-13	71-84	400, 600	- -	OSIRIS	85/86
DELICE (FRG)	Li_2SiO_3	- -	65, 85	400, 600, 700	<0.02	OSIRIS	85/86
	(Li_4SiO_4)		95				
ORDALIA (Italy)	$LiAlO_2$	0.4-2.0-10	80	600, 700	- -	OSIRIS	86/87
EXOTIC	Li_2SiO_3	- -	80	400, 600	- -	HFR	85/86
(Neth./UK/Belgium)	Li_2O	- -	- -		- -		85/86
	$LiAlO_2$	30	80		- -		85/86
	Li_2ZrO_3	- -	- -		- -		85/86
CREATE (Canada)	$LiAlO_2$	<1	80, 90	100	- -	NRU	85/86
BEATRIX-II	Li_2O		85, 100	390-425	4	FFTF	89/90
(IEA)	Li_2O/Be						
	Li_2ZrO_3/Be						
	$LiAlO_2$/Be						
	Li_4SiO_4/Be						

IN-SITU TRITIUM RECOVERY

Experiment	Ceramic	Grain Size (μm)	Density (%TD)	Temperature (°C)	Li Burn-up (Max at %)	Reactor	Time Frame
TRIO (US)	$LiAlO_2$	0.2 (50 μm particles, 0.9 cm thick annular pellet)	65	400...700	0.2	ORR	84/85
VOM-15H (Japan)	Li_2O	<10	86	480...760	0.24		84
VOM-21H (Japan)	Li_2O	- -	89-95	485-900	0.86	JRR-2	84/85
VOM-22H (Japan)	Li_2O	10 (0.5 cm spheres)	85	350-900	0.5	JRR-2	85/86
	$LiAlO_2$	4 (0.4 cm spheres)	77	430-900	1.7		
VOM-23H (Japan) (BEATRIX-I)	$LiAlO_2$	0.5 (0.4 cm dia. rods)	77	600-850	0.26	JRR-2	86
	Li_4SiO_4	14 (0.4 cm spheres)	90	500-900	0.28		
VOM 22/23 (Japan)	Li_2O	- - (1.1 cm pebbles)	- -	400-900	0.04		- -
	$LiAlO_2$	- - (1.1 cm pebbles)	- -	400-900	0.1		- -
VOM-31H (Japan)	Li_2O	Single Crystal (0.8 cm dia.)	100	400-900	(121 FPD)	JRR-2	88/89
		13 (pellet)	89.5	400-900	(121 FPD)		
LILA (France)	$LiAlO_2$	1-30 (1 cm dia. pellet)	78	375-600	<0.02	SILOE	86
LISA (FRG, France)	$LiAlO_2$	0.4	78	450-730	- -	SILOE	86
	Li_2SiO_3	30-80	86-93	450-730	- -		
	Li_4SiO_4	26 (1 cm diameter pellet)	94	450-730	- -		

IN-SITU TRITIUM RECOVERY

Experiment	Ceramic	Grain Size (µm)	Density (%TD)	Temperature (°C)	Li Burn-up (Max at %)	Reactor	Time Frame
EXOTIC (Neth./UK/Belgium) (I, II, III)	$LiAlO_2$	30, 8 (1.4 cm dia. pellet)	80, 95	400, 650	<0.4	HFR	86
	Li_2SiO_3	- - (1.4 cm dia. pellet)	50	400, 650	<0.4		86
	Li_2O	5	80	400, 650	<0.4		86/87
	Li_2ZrO_3	2	80	400, 650	<0.4		86/87
TEQUILA (Italy)	$LiAlO_2$	0.4-2.0-10 (1 cm dia. pellet)	80	500, 700	- -	SILOE	88/89
CRITIC (Canada)	Li_2O	60 (1 cm thick annular pellet)	90	400-900	0.15	NRU	86
EXOTIC IV	Li_2ZrO_3	.5	80, 85	350-680	<.4		86/87
	$Li_6Zr_2O_7$	.5	80	450-650	<.4		
	Li_8ZrO_6	.5	82	450-650	<.4		
BEATRIX-II Phase I (US, Japan, Canada)	Li_2O		85, 89	460-685	4	FFTF	89/90
			89	450-900	4		
MOZART (France, US, Japan)	$LiAlO_2$		81, 92.7	300-680	Natural	MELUSINE	87/88
	Li_2ZrO_3		80	300-680			
	Li_2O		80	300-500			
SIBELIUS	Li_2O/Be $LiAlO_2/Be$ Li_4SiO_4/Be Li_2ZrO_3/Be		85	550		SILOE	89/90
BEATRIX-II Phase II (US, Japan, Canada)	Li_2O		85	460-685	8	FFTF	90/91
	Li_2ZrO_3 or Li_4SiO_4		85	460-685	4		

BEATRIX-II Experiment Status

Objective

Determine tritium release and thermal characteristics of Li_2O at high lithium atom burnup

Phase 1 Test - FFTF Cycle 11

- Scope Includes Two Vented Canisters - Li_2O (4% Li Burnup)

  ring specimen: tritium release vs. temperature, gas composition, and flow rate changes

  solid pellet specimen: integrated tritium release under temperature gradient

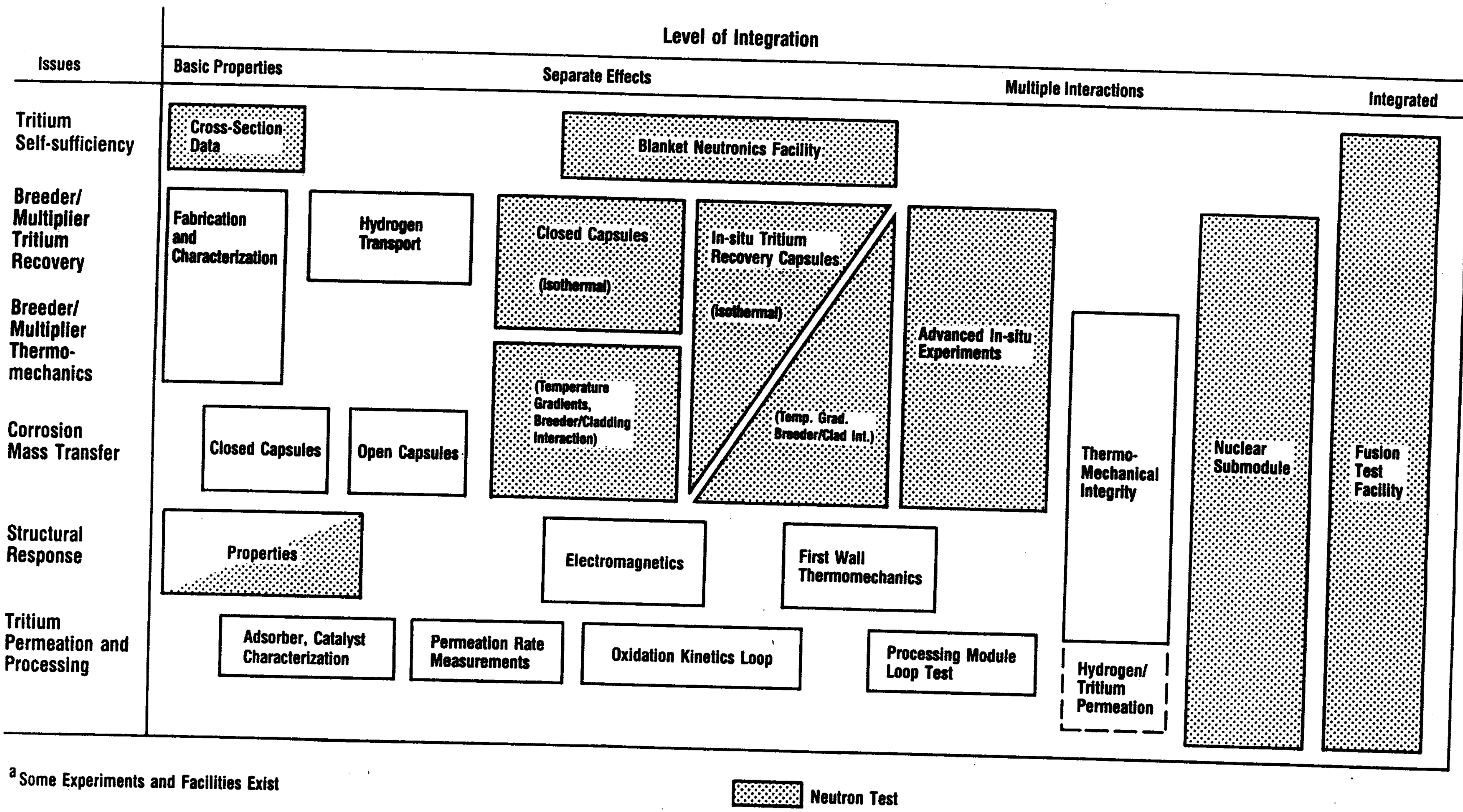
- Irradiation Vehicle Assembly Completed
- Tritium Handling System Physically Installed in FFTF
- Irradiation Scheduled to Begin June-July, 1989

Phase 2 Test

- Scope Proposed to IEA Executive Committee
  - Two Ring Geometry Vented Canisters:
    Li_2O (8% Li Burnup)
    Ternary Ceramic (Max. Li Burnup)
  - In-Situ Permeation Measurement
  - Closed Capsule Irradiation
    - Beryllium
    - Mechanical Interaction

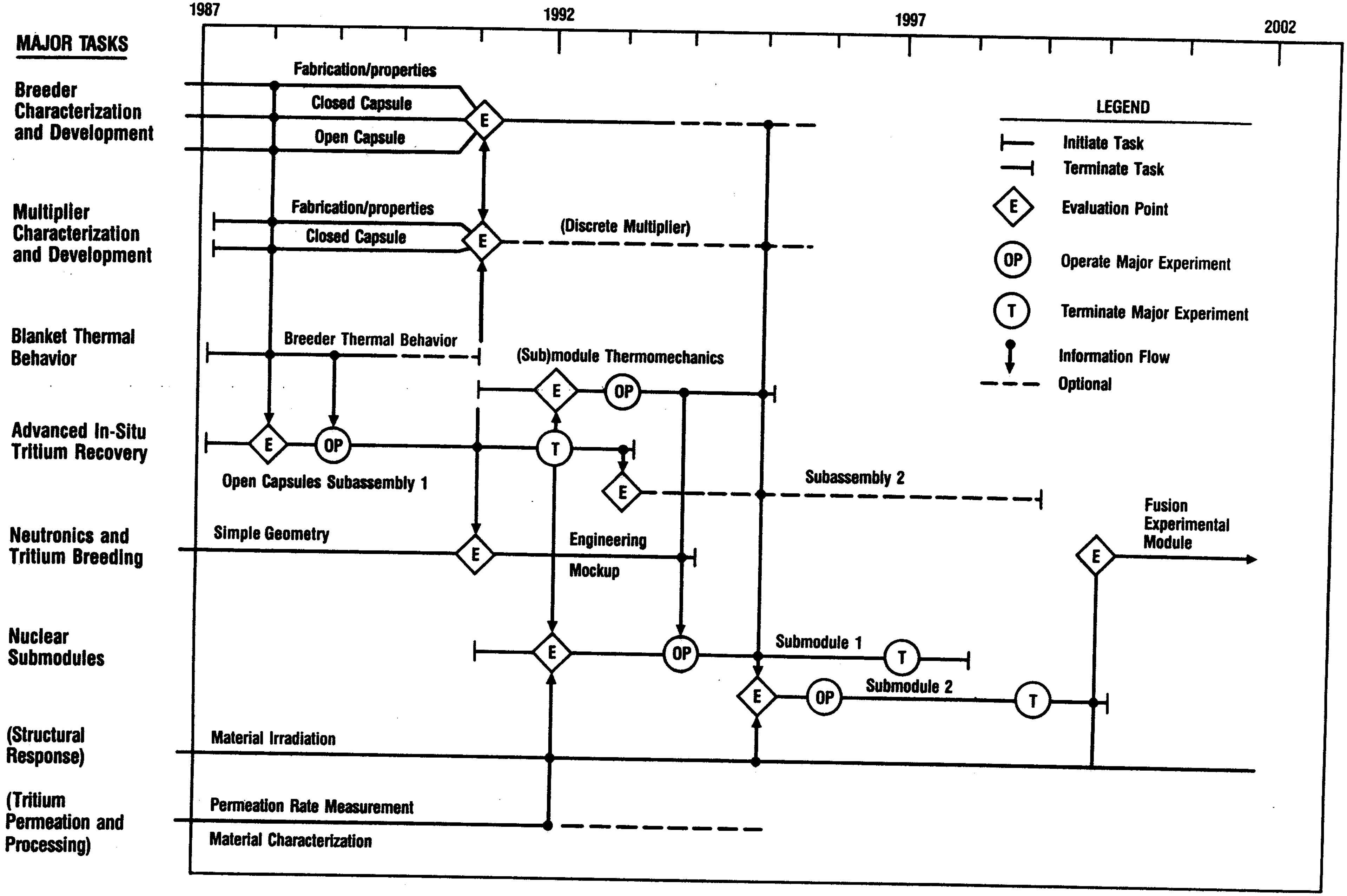
- Irradiation Scheduled to Begin Fall, 1990

TYPES OF EXPERIMENTS AND FACILITIES FOR SOLID BREEDER BLANKETS[a]



[a] Some Experiments and Facilities Exist

SOLID BREEDER BLANKET TEST PLAN



- What should the focus of IEA activity be?

  1) ITER Test Module

  2) ITER Base Blanket

  3) Both

- Adhoc group agreed previously that

  IEA Activity: R & D for ITER Test Program

  Validating R & D: R & D for ITER Base Blanket

- Is there a mechanism for international collaboration on ITER validating R & D?

- It appears useful for the IEA activity to also consider the interests of the base blanket whenever it can be integrated into the R& D for the test program.

- There are many common issues between ITER solid breeder base blanket and solid breeder test modules.

Type of Experiment Proposed for IEA Activity

Integrated Submodule Experiment in Fission Reactor

- Maximum possible simulation within limitations of existing fission reactors
- Experimental assembly includes breeder, multiplier, clad, coolant, purge, etc. in configuration that reproduces at least a unit cell

Conditions to be Simulated

- ITER- like conditions
- Emphasis on test module and, where there is overlap, base blanket?

Issues to be Addressed by Submodule Experiment

A. Performance Issues

1) Integrated Tritium Retention, Release and Recovery

2) Integrated Material Interactions

   breeder/structure, breeder/multiplier, multiplier/structure

3) Thermal Performance

   for breeder, multiplier, conductance gap, and interfaces

4) Tritium Permeation and Tritium Processing of the Purge Stream

5) (If possible) Overall Structural Response of the Blanket Submodule

Issues to be Addressed by Submodule Experiment (Continued)

B. Special Issues/Variables

a) effect of burnup/fluence on performance (e.g. on tritium release, thermal performance)

b) lower and upper ends of temperature range for solid breeder tritium release

Examples of issues:

- at lower end: effect of slower T diffusion on T inventory
- at higher temp. end: sintering and LiOT mass transfer

c) ability to control temperature difference between coolant and breeder

d) ability to accomodate power variation

e) transient, off-normal behavior

Key Questions on Submodule

1. How many submodules?

   One or more

2. Fission Reactor Facility

   Thermal or Fast

3. Technical Details of Submodule

   Materials, Configuration, etc.

4. Schedule

5. Cost

Slab Vs. Core

Two Types:

- Slab-type module at the core side
- Submodule (section of a module) inside the core

- **Slab Tests**
  - Not possible in many reactors
  - Limited to < $1 MW/m^2$ simulation
  - Modification to fission reactors is expensive.

- **Core Submodule Tests**
  - Higher flux, higher fluence achievable in more reactors
  - Limitation on size

Recommended : Core Submodule Test

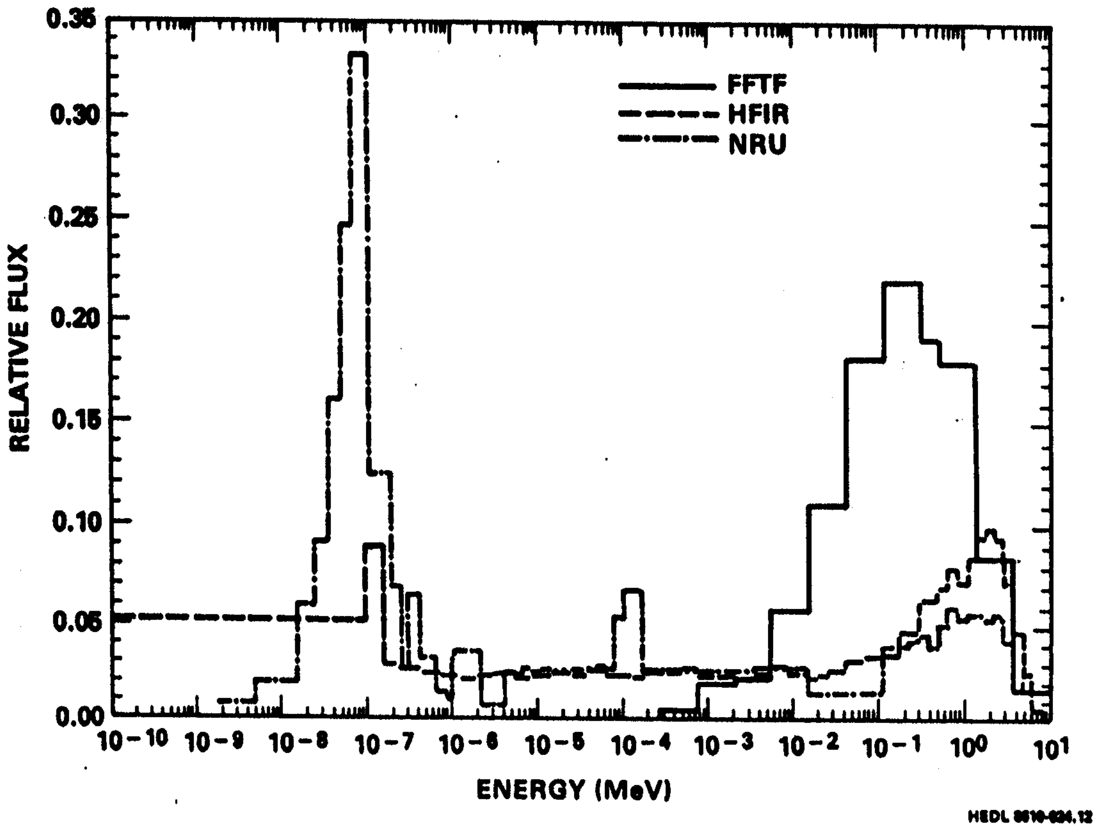
Evaluation and Selection of Fission Reactor Facility

- Instrumentation, Experimental Control
- Availability of Space for Test
- Effect on Core Reactivity
- Thermal Environment
- Neutron Spectrum/Neutron Flux
  - Heat Generation Rate
  - Tritium Production Rate
  - Fluence
- Time-Dependent Variation

  How simulated heat generation and tritium production profiles change during irradiation

CAPABILITIES OF SELECTED TEST REACTORS

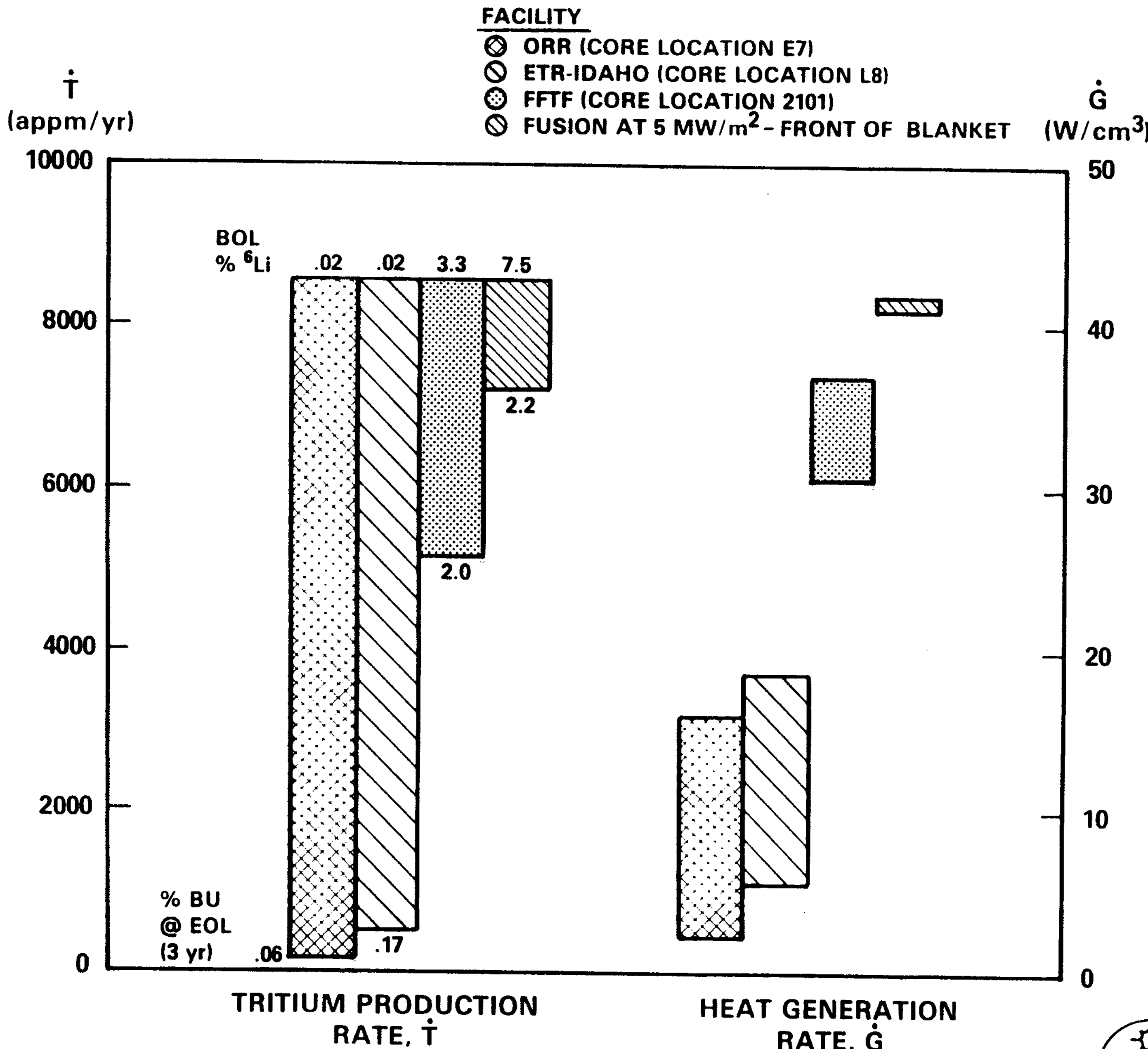
Reactor	Location	Power (MW)	Exp. Neutron Flux ($n/cm^2/sec$)	Exp. Size (cm)	Test Position Exp. Vol (l)	Notes	Core Side Facility Dim.
FFTF	U.S.	300	5.0×10^{15}F	6.35 x 91 10.2 x 91	2.9 8.5	2 Closed Loops 6 Instrumented Numerous Non-Instrumented	None
HFIR	U.S.	85	1.3×10^{15}F, 2.4×10^{15}Th	1.6 x 51	- -	Target Region	
			4.3×10^{14}F, 1.3×10^{15}Th	4.6 x 51	- -	Removable Be Position	Outside Core Region
			1.6×10^{13}F, 5.2×10^{14}Th	3.8 x 51	- -	Vertical Exp. Facility	Outside Core Region
			1.1×10^{13}F, 4.4×10^{14}Th	7 x 51	- -	Vertical Exp. Facility	Outside Core Region
			1.5×10^{12}F, 2×10^{14}Th	9.8 x 51	- -	Engineering Facility	Outside Core Region
NRU	Canada	200	1×10^{14}Th	12 x 300	33.9	In-Situ Tritium Recovery Experiments	Possible 240 x 240cm 6×10^{13} $n/cm^2/sec$
BR-2	Belgium	60	1×10^{15}Th 6×10^{14}F	20 x 96	30	1 loop, 4 open, many posit.	None
KNK	W. Germany	60	2×10^{15}F 2×10^{14}Th	10 x 60	4.7	Several Temp. Controlled Position; I instrumented position	None
JMTR	Japan	50	3×10^{14}Th 3×10^{14}F	6 x 60	2.6		OWL-2 Loop 11.8 cm (OD) x 7.5cm 5×10^{12} $n/cm^2/sec$ F 5×10^{13} $n/cm^2/sec$ Th
SILOE	France	35	4×10^{14}Th 4×10^{14}F	8 x 60	3.0	Insitu Tritium Recovery Exp.	possible 40 x 63 cm



Comparison of neutron flux spectra for the FFTF, NRU and HFIR reactors normalized to their total flux

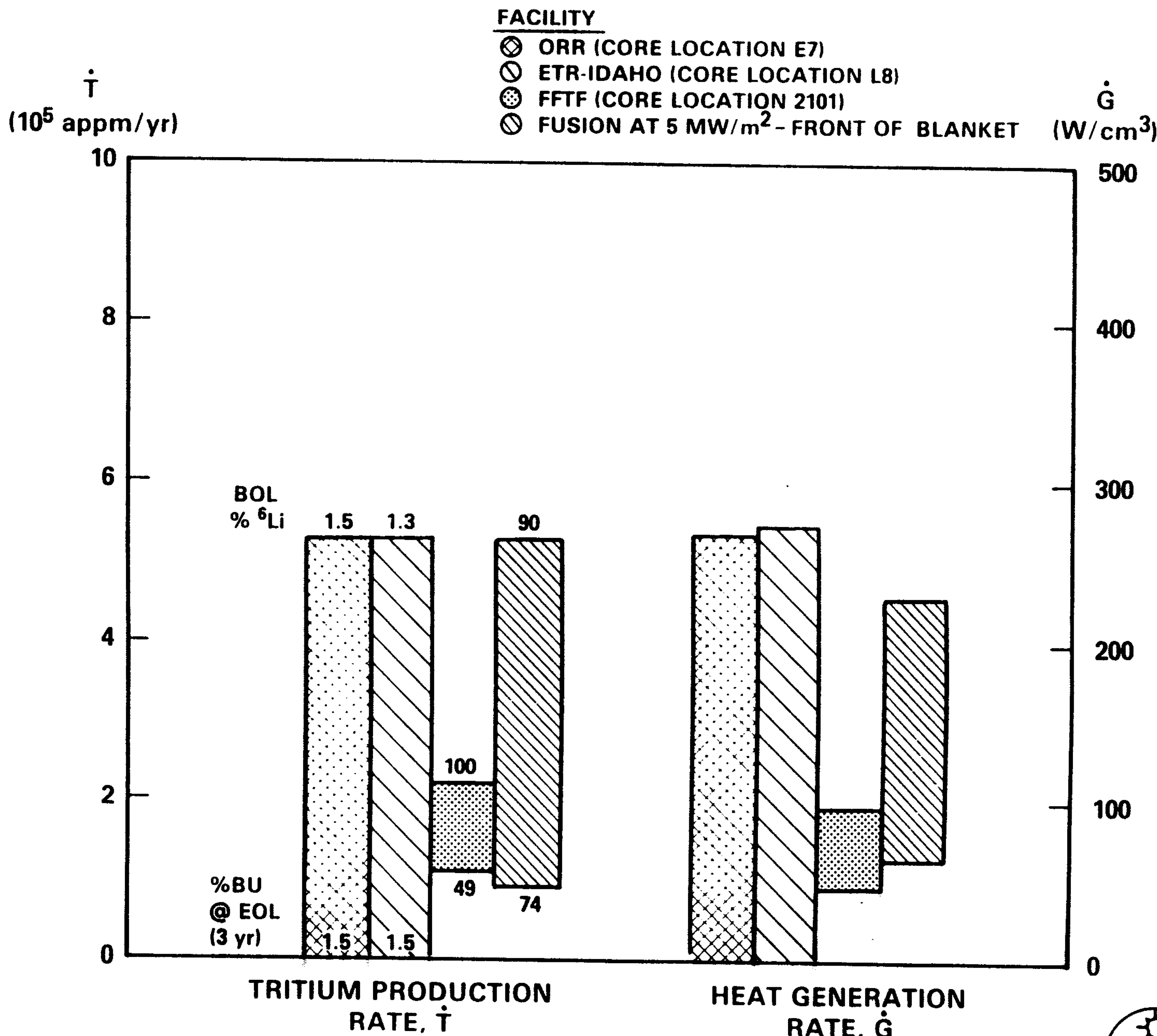
FISSION/FUSION IRRADIATION COMPARISON FOR Li_2O/He/HT-9 SYSTEM

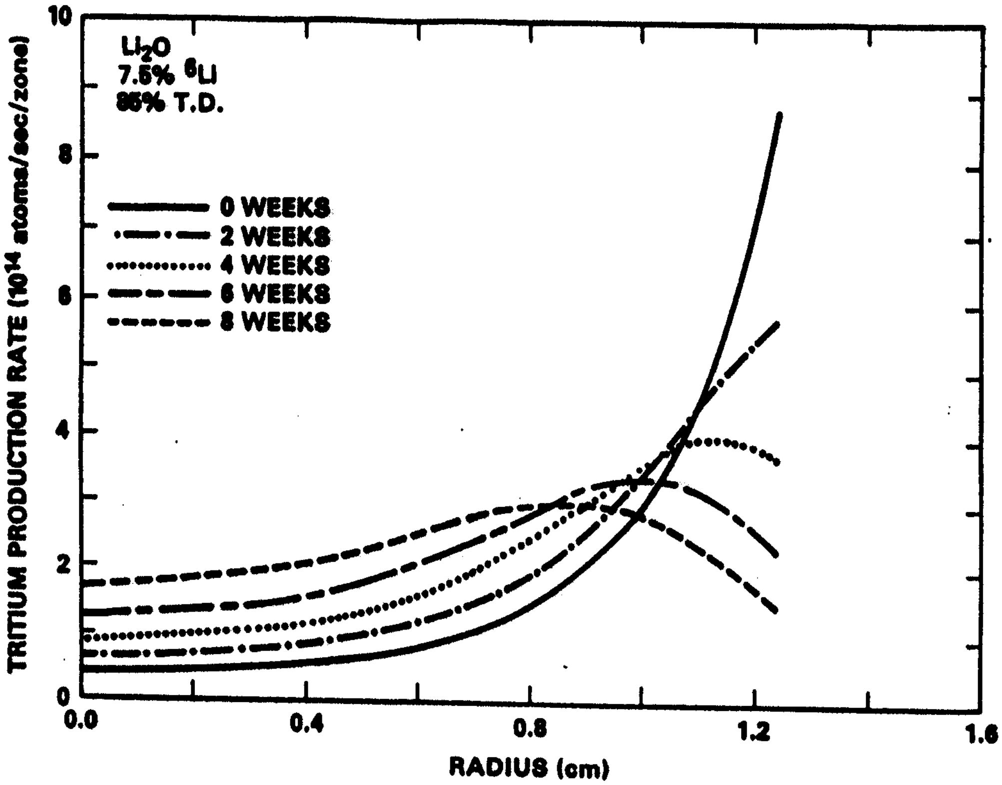
Li_2O SOLID BREEDER



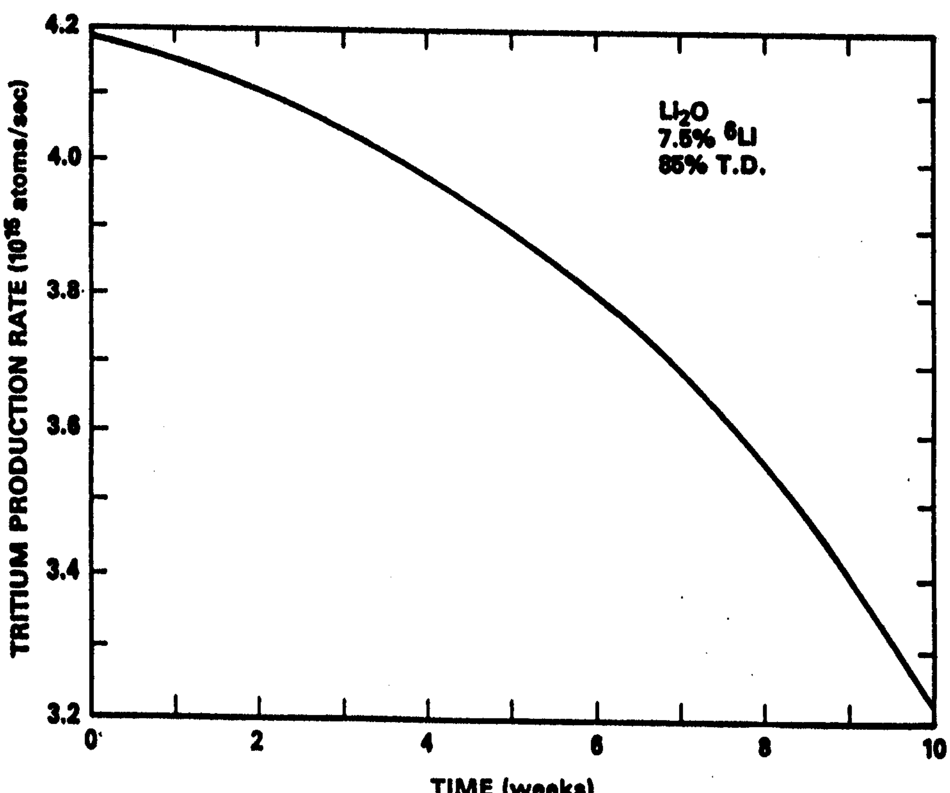
FISSION/FUSION IRRADIATION COMPARISON FOR $LiAlO_2/H_2O$/HT-9/Be SYSTEM

$LiAlO_2$ SOLID BREEDER

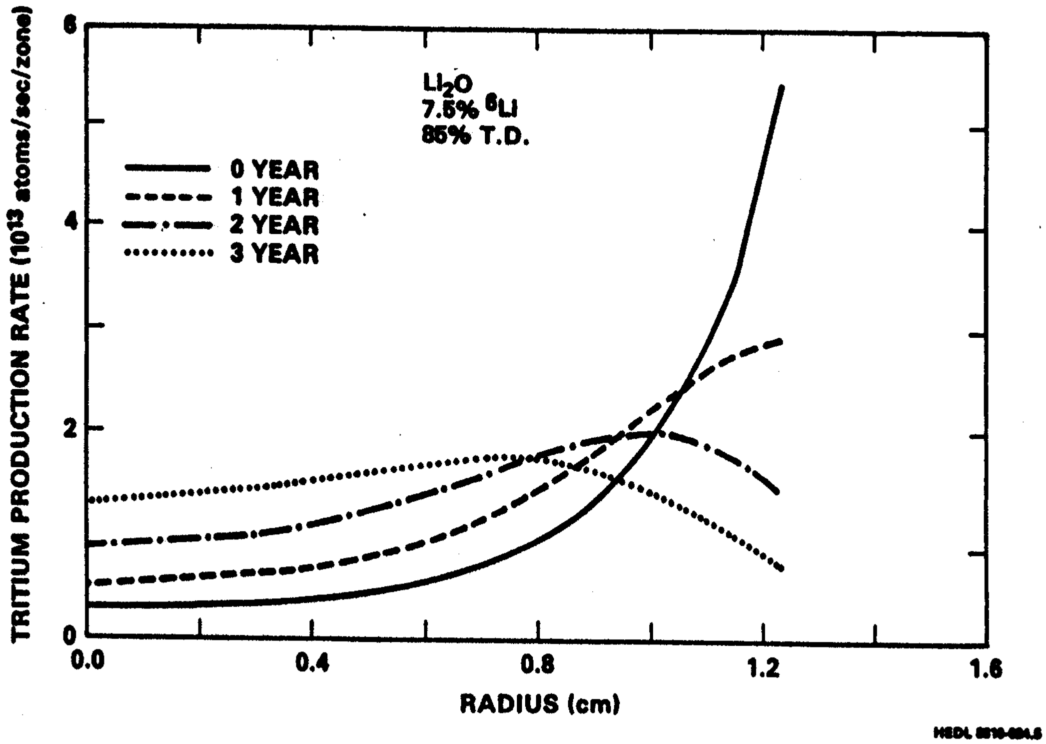




Time evaluation of tritium production rates in the HFIR reactor



Decrease in total tritium production as a function of test time in the HFIR reactor



Time Evaluation of tritium production rates in the NRU reactor

Thermal and Fast Reactor Performance Summary

- Temperature
  - Lower temperature must be > 400°C in fast reactors
  - Lower temperature possible in thermal reactors
- Use of water coolant in experiment is difficult in fast reactors
- Beginning-of-life simulation of tritium production rates and heat generation rates is possible in both thermal and fast reactors by adjusting ^{6}Li enrichment.
- Self shielding effects are serious concern for thermal reactors. They result in large and rapid changes in T-production and heat generation rate profiles.
- Thermal reactors are limited (because of self shielding) to:
  - size of breeder experiment < 1 cm thick
  - low fluence (weeks to months)
  - ^{6}Li enrichment (generally < 3%)

2 Submodules are Proposed

- Issues and conditions that need to be resolved cannot be simulated in one submodule. Several experiments are required in different fission reactors. For example, low temperature effects cannot be obtained in fast reactors while thermal reactors have fluence limitations and poor lifetime tritium profile reproduction.

- Cost constraints would argue for a minimum number of submodules. We propose two submodules for collaboration (in addition to other work going on).

- 2 submodules would enable a larger number of options to be addressed, e.g. 2 different breeding materials, material forms, configurations, etc.

Examples of Focus for the 2 Proposed Submodules

Submodule 1

- Include lower end of temperature range for solid breeder tritium release
- Low Fluence
- Thermal Reactor (High flux with spectra tailoring)

  (Water and helium cooling of submodule possible)

Submodule 2

- High Fluence
- Include higher end of temperature range for solid breeder tritium release
- Fast Reactor

  (Only helium cooling of submodule possible)

Solid Breeder Submodule Irradiation Experiment

Open issues for each submodule

- Solid Breeder Material and Form
  - Choose one from each of two groups that are chemically similar

    Group 1: Li_2O, Li_4SiO_4

    Group 2: Li_2ZrO_3, $LiAlO_2$
  - Form: sphere pac or sintered product
- ^6Li Enrichment
- Multiplier Form
  - mix with breeder or separate region
  - sphere pac or sintered product
- Configuration (tubes, plates)
- Operating Conditions

  Breeder temperature

  Coolant temperature and pressure
- Type of Fission Reactor
- Submodule Dimensions

Typical Parameters for Solid Breeder Test Modules In ITER-Type Devices

Breeder	Li_2O, Li_2ZrO_3, Li_4SiO_4, $LiAlO_2$	
Density	0.8-0.85	
^6Li enrichment	~60%	
Multiplier	Be (except possibly for Li_2O)	
Breeder & Multiplier Form	Pebble bed, sintered product	
Coolant	Helium	Water
Pressure	5-6 MPa	10-12MPa
Temperature	250-550°C	260-320°C
Breeder Temperature	300°C-1000°C(breeder dependent)	
Temperature Control	Packed bed or gas gap plus coolant flow rate and temp.	
Purge	low pressure He (+~ 0.1%H2)	
Breeder, Max. Heat Generation (for P_{nw} = 1MW/M^2)	15-50 w/cm^3	
Tritium production (for P_{nw} = 1MW/m^2)	2 x 10^{12} - 5 x 10^{12} T/cm^{3}s	

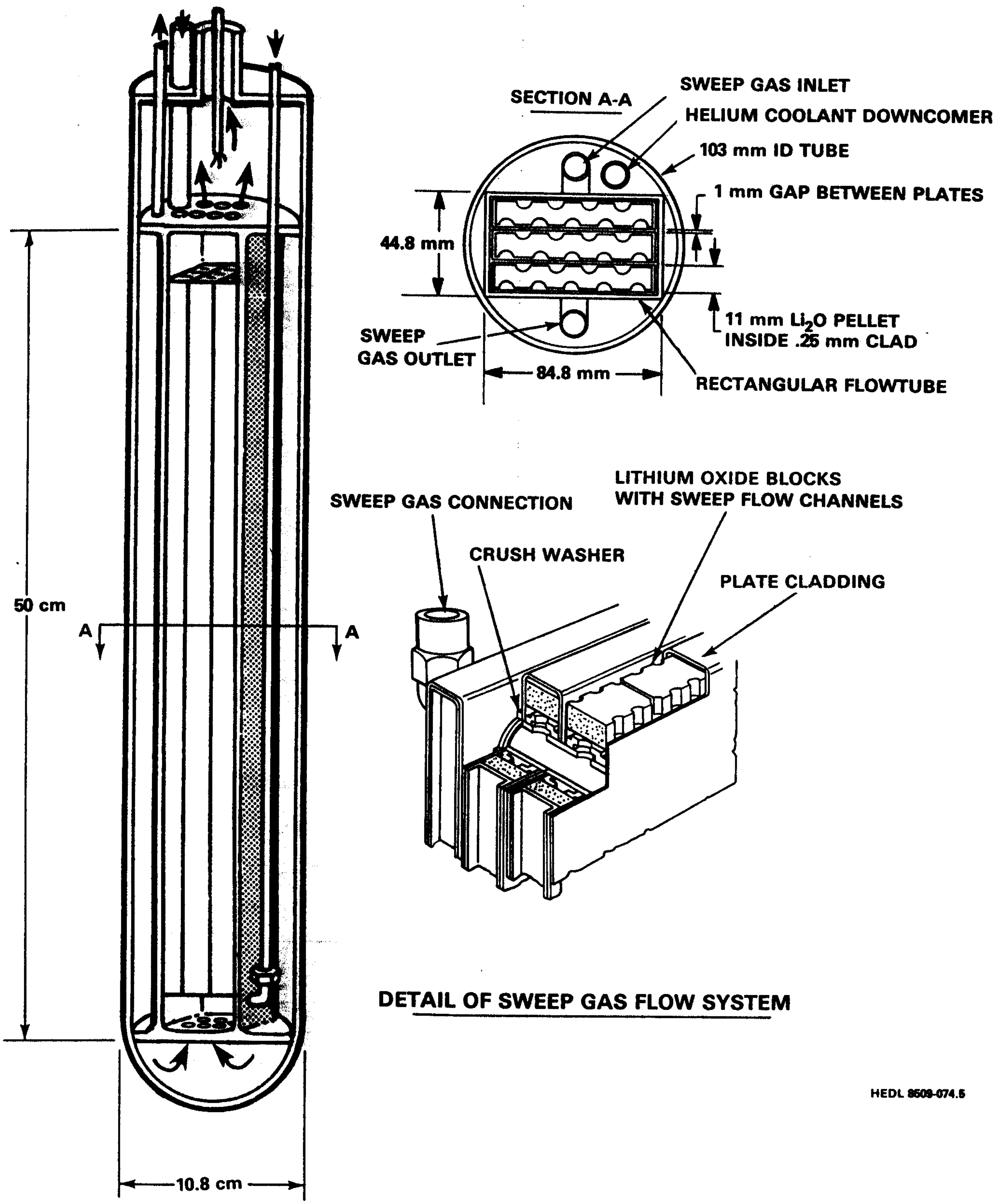
Example of Solid Breeder Base Blanket for ITER-Type Devices

Breeder	Li_2O
Density	0.8-0.85
6Li enrichment	~60%
Multiplier	Be
Breeder & Multiplier Form	sintered block or packed bed
Coolant	Water
Pressure	0.1-1 MPa
Temperature	40°C-100°C
Breeder Temperature	400°C-800°C
Temperature Control	Packed bed or gas gap
Purge	He + H_2
Breeder, Max. Heat Generation (for P_{nw} = 1MW/M^2)	15-40 w/cm^3
Tritium production (for P_{nw} = 1MW/m^2)	2 - 5 $x10^{12}$ T/cm^3s

Examples of Parameters For Submodule Irradiation Experiment

Breeder material	Li_2O	Li_4SiO_4
Breeder form	Sintered	Pebble
Breeder temperature		
Maximum	800°C	850°C
Minimum	400°C	350°C
Temperature gradient	~200°C	~200°C
Breeder density	80%	90%(80% packing)
Tritium generation rate (T/cm^3sec)	2-16 $\times 10^{12}$	2-16 $\times 10^{12}$
Structure	316 SS or FS	316 SS or FS
Coolant	helium	water(or helium)
Coolant temp. range	360/500 °C	50/150 °C
Coolant pressure	5- 6 MPa	0.3-5 MPa
Multiplier	option	beryllium
Sweep gas	helium	helium
Additives	H_2	H_2
Sweep gas pressure	0.1 MPa	0.1 MPa
Outer containment dimension	~100 mm dia	~100 mm x 100 mm
Temperature control method	He gas gap	He gas gap/particle bed

NUCLEAR SUBMODULE



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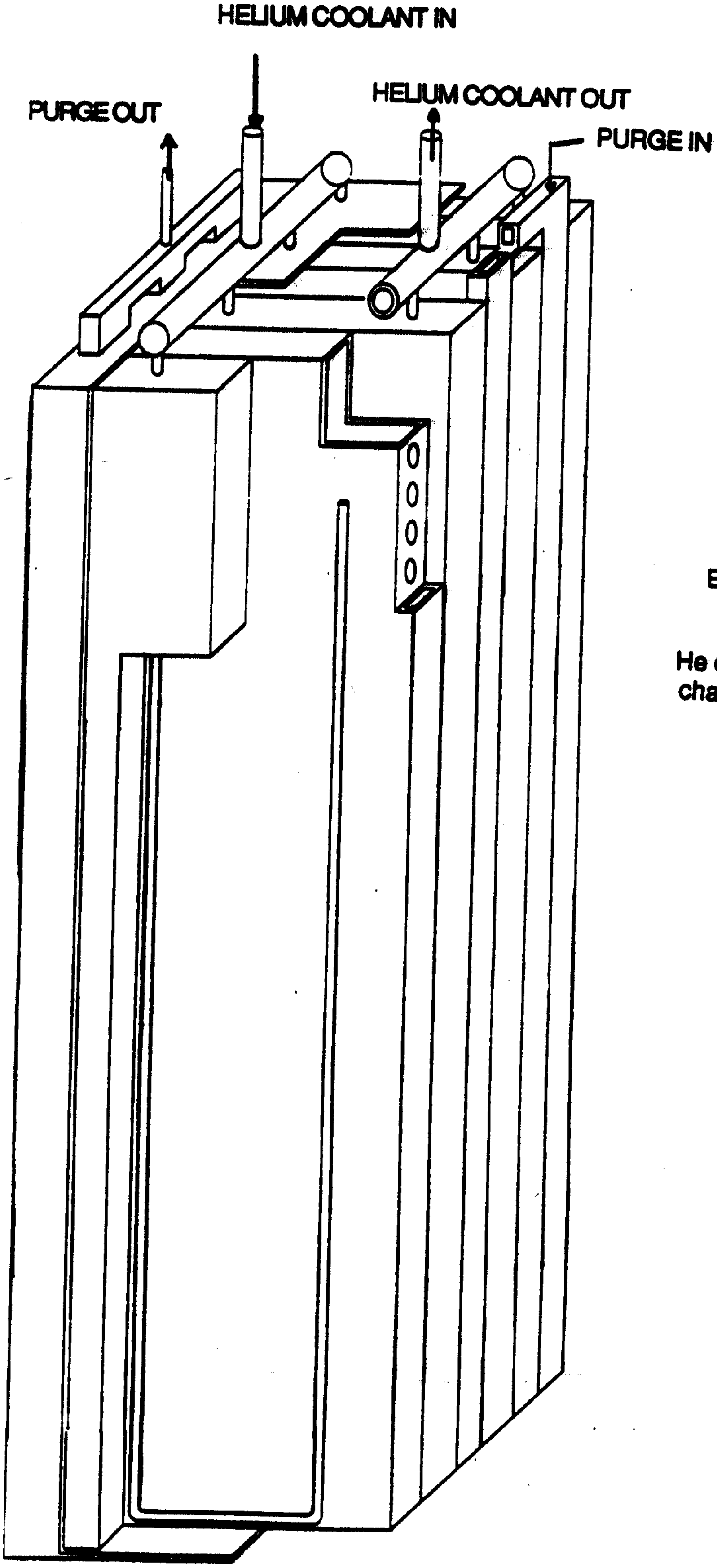
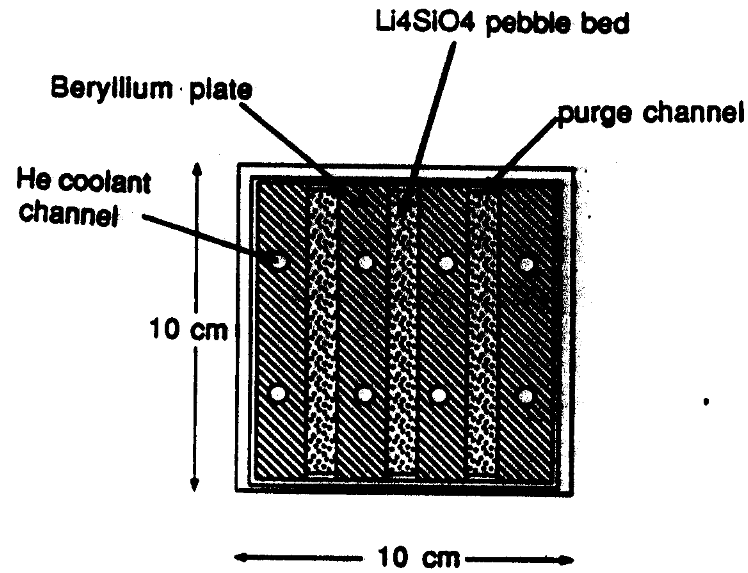
EXAMPLE OF SUBMODULE DESIGN
(Li_4SiO_4 PEBBLE BED/BE/HE/PCA)

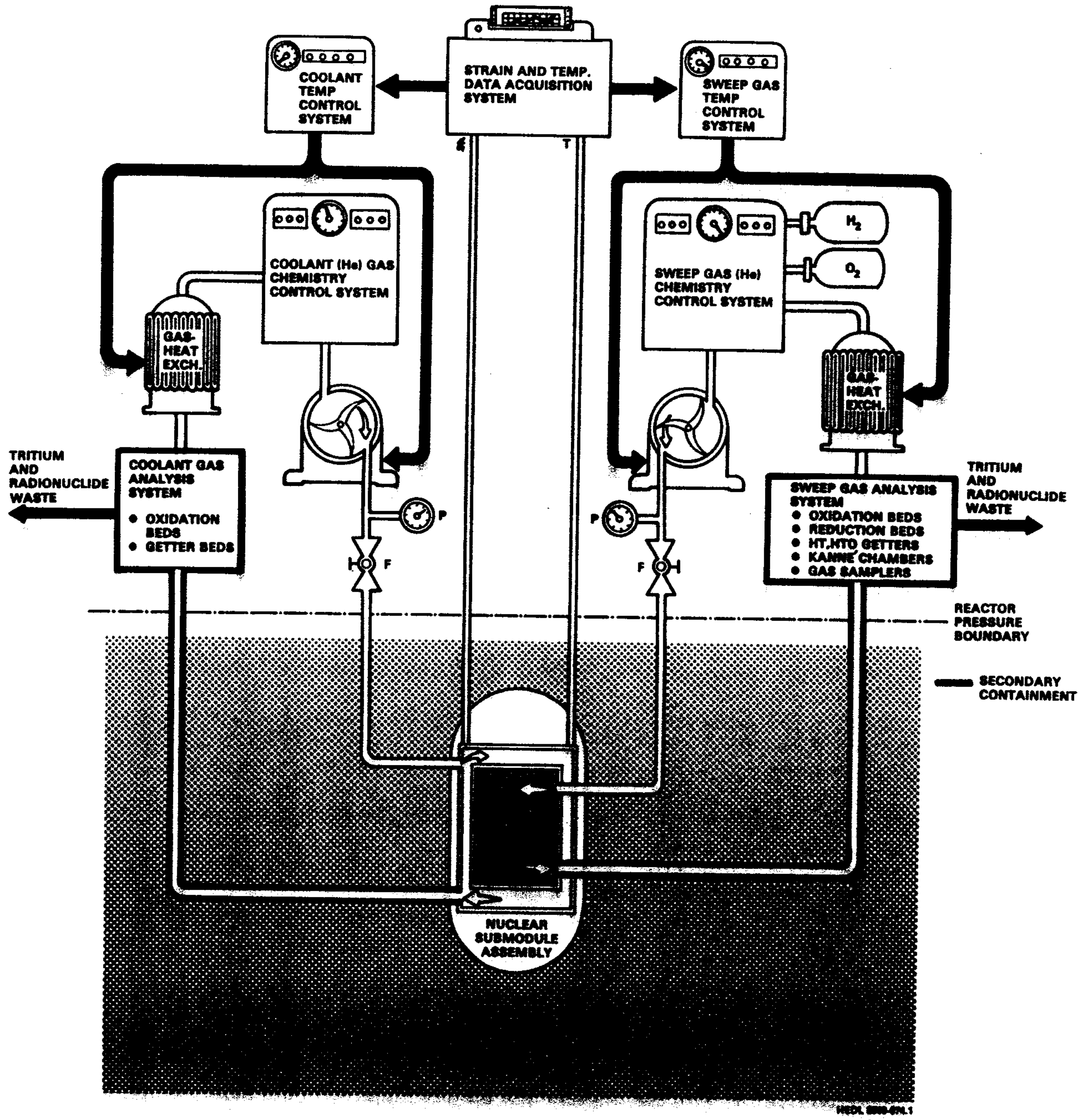


Schematic view



Cross section view

INSTRUMENTATION SCHEMATIC FOR THE NUCLEAR SUBMODULE ASSEMBLY TEST



Relationship to Tritium Processing/Recovery (BBI) Task

- Integrated solid breeder experiments in fission reactors will
  - require tritium processing system (significant cost item)
  - prototypical purge stream with actual impurities, and time-dependent effects of irradiation
- Part of the testing in the tritium processing/ recovery (BBI) task can be done in connection with the solid breeder submodule experiments.

Examples of Experimental Measurements

- During irradiation:

  integrated tritium release in purge gas

  purge gas chemistry

  purge gas pressure drop

  purge gas flow rate, control

  neutron flux/neutron spectrum

  interface temperature

  temperatures in breeder, multiplier

  coolant flow rate and temperature

  breeder/structure deformation

- Post irradiation:

  tritium distribution in breeder, multiplier and structure

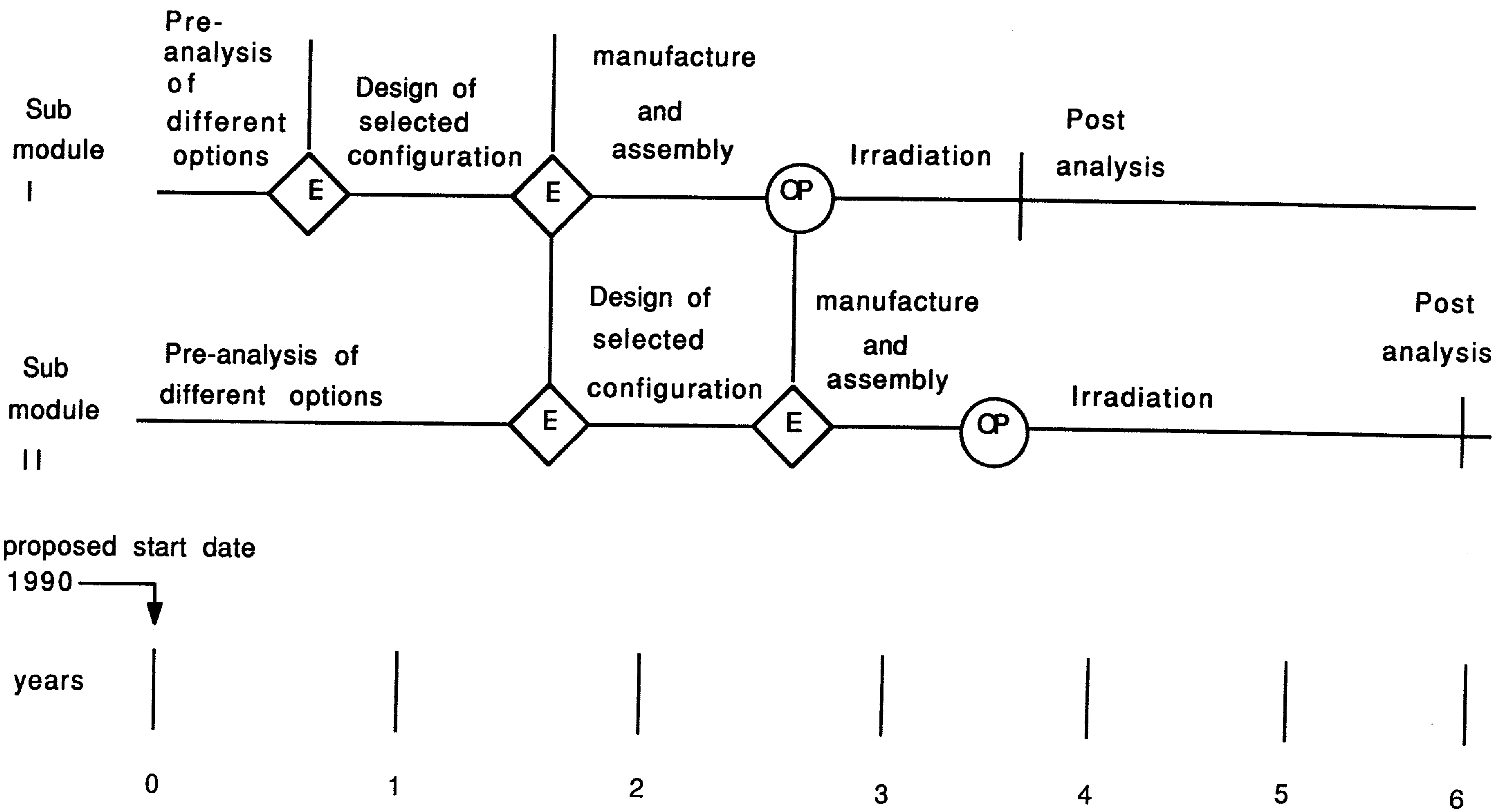
  structural, thermomechanical behavior

  integrity of material

Example Schedule

SOLID BREEDER SUBMODULE TEST PROGRAM

On-going side experiments already planned



Cost Estimates

Single Submodule

Design/Construction	$ 7-10 million
Cost of Neutrons per year	$ 1 - 2 million
Post-test Examination and Analysis	$ 2 - 3 million
Total Cost for One Submodule	$ 12 - 17 million

This assumes:

Design Time:	1 year
Construction Time:	1 year
Test Time:	0.5 - 2 yr (thermal reactor submodule) 2 - 3 yr (fast reactor submodule)
Post Analysis Time:	1 year

Total Program Cost for 2 Submodules:

$ 25 M to $ 30 M

Summary: Solid Breeder Irradiation

- Recent results on solid breeder blankets are encouraging.
- Solid breeder irradiation experiments are appropriate for IEA collaborative activity.
- Specific suggestions made by USA. More detailed discussions and other suggestions are encouraged.

Proposed Effort

- Perform 2 submodule irradiation experiments in fission reactors. Each submodule is an integrated test of a solid breeder blanket submodule (to simulate ITER conditions).
- First submodule in thermal reactor (mixed spectrum, high flux, spectral tailoring) with focus on lower end of breeder temperature, low fluence and water cooling
- Second submodule in fast reactor with focus on high fluence, high lithium burnup, higher temperature end
- Coordination with tritium processing/recovery task needed
- Program duration: 7 years
  - Design and Construction: 2 years
  - Irradiation: 0.5 to 2 yrs. for thermal, 3 yrs. for fast
  - Post Analysis: 1 year
- Total cost (over 7 yrs; 2 submodules) $25M - $30M.
  For single submodule: $8M- $10M for construction, $2M for cost of neutrons and $3M for PIE .