U.S. Solid Breeder Blanket and Neutronics Experiments and Facilities

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Present U.S. Solid Breeder Experimental Activities

- Carried out mostly in collaboration with other countries

- Primary organizations: ANL, HEDL
  Support: ORNL, GA, UCLA

- Fabrication
  - BEATRIX/FUBR-1B
  - LBM

- Irradiation
  - Completed: TRIO, FUBR-1A
  - Active: FUBR-1B/BEATRIX
    - First Insertion: Fall 85 to Fall 86
    - Second Insertion: Spring 87 for ~2 yrs

- Material Characterization
  - Li_2O, $LiAlO_2$ (at ANL)

- Tritium Oxidation Experiments (ANL)

Solid Breeder Blanket

Issues	Ongoing Research
- Tritium self-sufficiency	a
- Tritium release and recovery	b
- Tritium permeation and processing	b
- Hydrogen thermodynamic/chemistry studies	b
- Compatibility with multiplier and structural materials	c
- Materials fabrication	c
- Breeder/multiplier chemical and mechanical integrity	c

a U.S./Japan neutronics experiment, Nuclear Technology Program

b Experimental program

c Low level of effort being maintained

Capabilities of Selected U.S. Fission Reactors

Reactor	Site	Neutron Flux $n/cm^2 \cdot s$	Experiment Size cm OD × cm	Comments
FFTF EBR-II	HEDL ANL-W	5×10^{15} (fast) 2×10^{15} (fast)	10×91 6×33	Operational; Suitable for T-Recovery Experiments
HFIR	ORNL	1.3×10^{15} (fast) 0.2×10^{15} (thermal)	3×51	Presently used (structural, other materials)
ORR		0.5×10^{15} (fast)	8×38	Scheduled for shutdown
Others	A number of reactors not presently utilized			

International Collaboration - BEATRIX

- Involves the exchange of materials and shared irradiation testing among partners - Belgium, Canada, England, France, West Germany, Italy, Japan, the Netherlands, and USA.

- Allows comparison of materials preparation and fabrication methods, irradiation techniques, and tritium extraction methods.

- Irradiation experiments are of two types: closed-capsule tests to evaluate lifetime and open-capsule tests to evaluate purge flow tritium recovery.

Closed-Capsule Tests

- Closed-capsule tests are being done in mixed-spectrum reactors (HFR, OSIRIS, and NRX) and in a hard-spectrum reactor (EBR-II)

Laboratory	Reactor	Experiment	Materials
Westinghouse/Hanford	EBR-II	FUBR-1B	(Li_2O, $LiAlO_2$, Li_2SiO_3, Li_4SiO_4, Li_2ZrO_3)
ECN/Petten	HFR	EXOTIC	(Li_2O, $LiAlO_2$, Li_2SiO_3)
CEA/Saclay	OSIRIS	ALICE	($LiAlO_2$)
KfK/Karlsruhe	OSIRIS	DELICE	(Li_2SiO_3, Li_4SiO_4)
AECL/Chalk River	NRX	CREATE	(Li_2O, $LiAlO_2$)

- The most detailed experiment is FUBR-1B because it involves five different materials supplied by six different partners in three different configurations

FUBR-1B/BEATRIX TEST MATRIX
(Second Insertion - May 1987 for about 2 years)

Capsule	Material	Source	Density (% TD)	Diameter (inch)	Goal (C)	Time Exposure (EFPD)
		S1 PINS				
S3T	$LiAlO_2$	WHC	80%	0.913	1150	900
S3B	$LiAlO_2$	WHC	80%	0.648	900	900
S4T	$LiAlO_2$	Saclay	74%	0.913	1120	600
S4B	Li_4SiO_4	Karlsruhe	89%	0.647	1000	600
S5T	Li_2ZrO_3	WHC	89%	0.913	1240	600
S5B	Li_2O	JAERI	90%	0.647	930	600
		B7A PINS				
B4T	Li_2O	WHC	80%	0.375	700	900
B4C	Li_2O	WHC	80%	0.375	900	900
B4B	Li_2O	WHC	80%	0.375	500	900
B5T	$LiAlO_2$	WHC	80%	0.375	700	900
B5C	$LiAlO_2$	WHC	80%	0.375	900	900
B5B	$LiAlO_2$	WHC	80%	0.375	500	900
B8T	Li_2O	JAERI	89%	0.375	700	600
B8C	Li_2O	JAERI	89%	0.375	900	600
B8B	Li_2O	JAERI	89%	0.375	500	600
B9T	Li_2O	Springfield	83%	0.372	700	600
B9C	Li_2O	JAERI	45%	0.410	700	600
B9B	Li_2O-sc	JAERI	100%	0.314	500	600
			100%	0.314		
B10T	$LiAlO_2$	Saclay	74%	0.375	700	600
B10C	$LiAlO_2$	Saclay	73%	0.375	900	600
B10B	$LiAlO_2$	Saclay	75%	0.375	500	600
B11T	Li_2SiO_3	Karlsruhe	81%	0.375	700	600
B11C	$LiAlO_2$	Casaccia	85%	0.375	700	600
B11B	Li_4SiO_4	Karlsruhe	92%	0.375	500	600
B12T	Li_2ZrO_3	Springfield	81%	0.370	700	600
B12C	$LiAlO_2$	Casaccia	81%	0.375	700	600
B12B	Li_4SiO_4	Karlsruhe	36%	0.410	500	600

B is bottom, C is center, and T is top capsule in each pin.

Open-Capsule Tests

- Purge flow tests are being performed in HFR, SILOE, and NRU

- Complementary data will be obtained on tritium release behavior under irradiation

Laboratory	Reactor	Experiment	Materials
ECN/Petten	HFR	EXOTIC	(Li_2SiO_3, $Li_2Si_2O_5$, Li_2ZrO_3, Li_4SiO_4)
CEA/Saclay	SILOE	LILA*	(γ-$LiAlO_2$, Li_2ZrO_3)
KfK/Karlsruhe	SILOE	LISA	(Li_2SiO_3, Li_4SiO_4)
JAERI/Tokai	JRR2	VOM-23H	(Li_4SiO_4, γ-$LiAlO_2$)
AECL/Chalk River	NRU	CRITIC**	(Li_2O)

* U.S. material provided by ANL (Li_2ZrO_3)

** U.S. collaboration through ANL

Hydrogen Studies at ANL

- Measure adsorption/desorption of H_2O and He from ceramic breeder in non-irradiated environment.

- Early 1986 to Fall 1987: γ-$LiAlO_2$

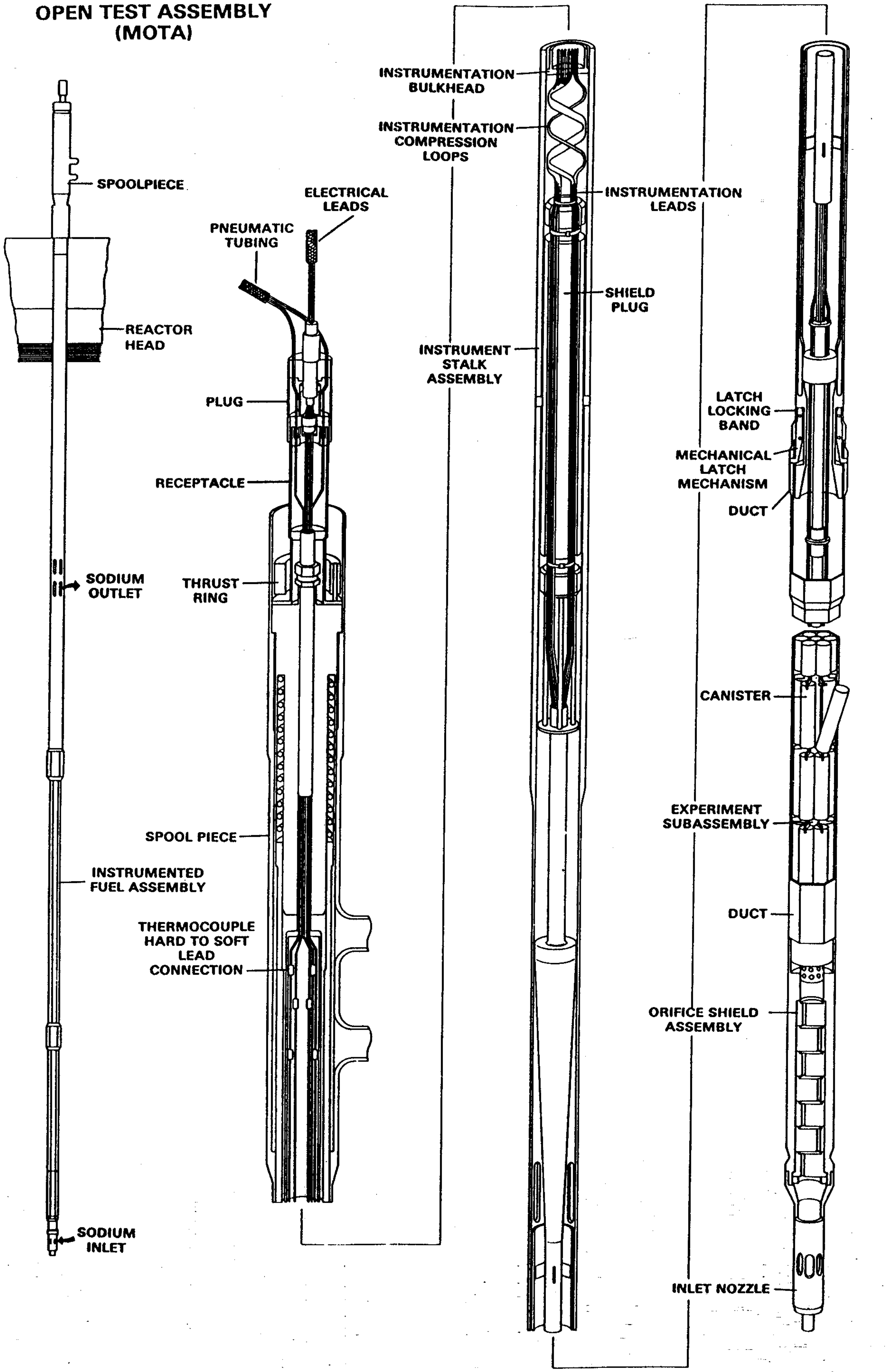
- Starting Fall 1987: Li_4SiO_4 or Li_2ZrO_3 depending on comparative analysis of the two candidate solid breeders
  - thermodynamic calculations at ANL
  - UCLA comparative study of solid breeders

MOTA Experiment
(Materials Open Test Assembly)

- Current operation in FFTF reactor (at HEDL) includes structural and high heat flux fusion material testing

- Plan is to start in-situ tritium recovery experiment in MOTA around 1990 with international collaboration

STRUCTURAL MATERIAL OPEN TEST ASSEMBLY (MOTA)



Tritium Oxidation
(Applicable to Solid Breeders and Liquid Breeders)

- The rate of tritium release is highly dependent on the form of the tritium
  - T_2O, Low Release
  - T_2, High Release

- Experimental data from TRIO showed a high fraction of release in the T_2 form

- It has been assumed in design studies that almost all the tritium is in the water vapor form

- The concerns raised with possible high levels of tritium release warranted an experiment aimed at assessing tritium oxidation rates for expected fusion conditions

Tritium Oxidation Experiment
(cont'd.)

Two competing reactions are possible at the steel surface:

- The combination of tritium atoms and oxygen to form water

- The combination of tritium atoms to form tritium gas

To determine the conditions which favor oxidation, an experimental matrix is being examined in which different parameters are varied:

- Oxygen concentration (<1 to 1000 ppm);

- Tritium atom concentration (10(-4) to 1 Pa)

- Temperature (350 to 550° C);

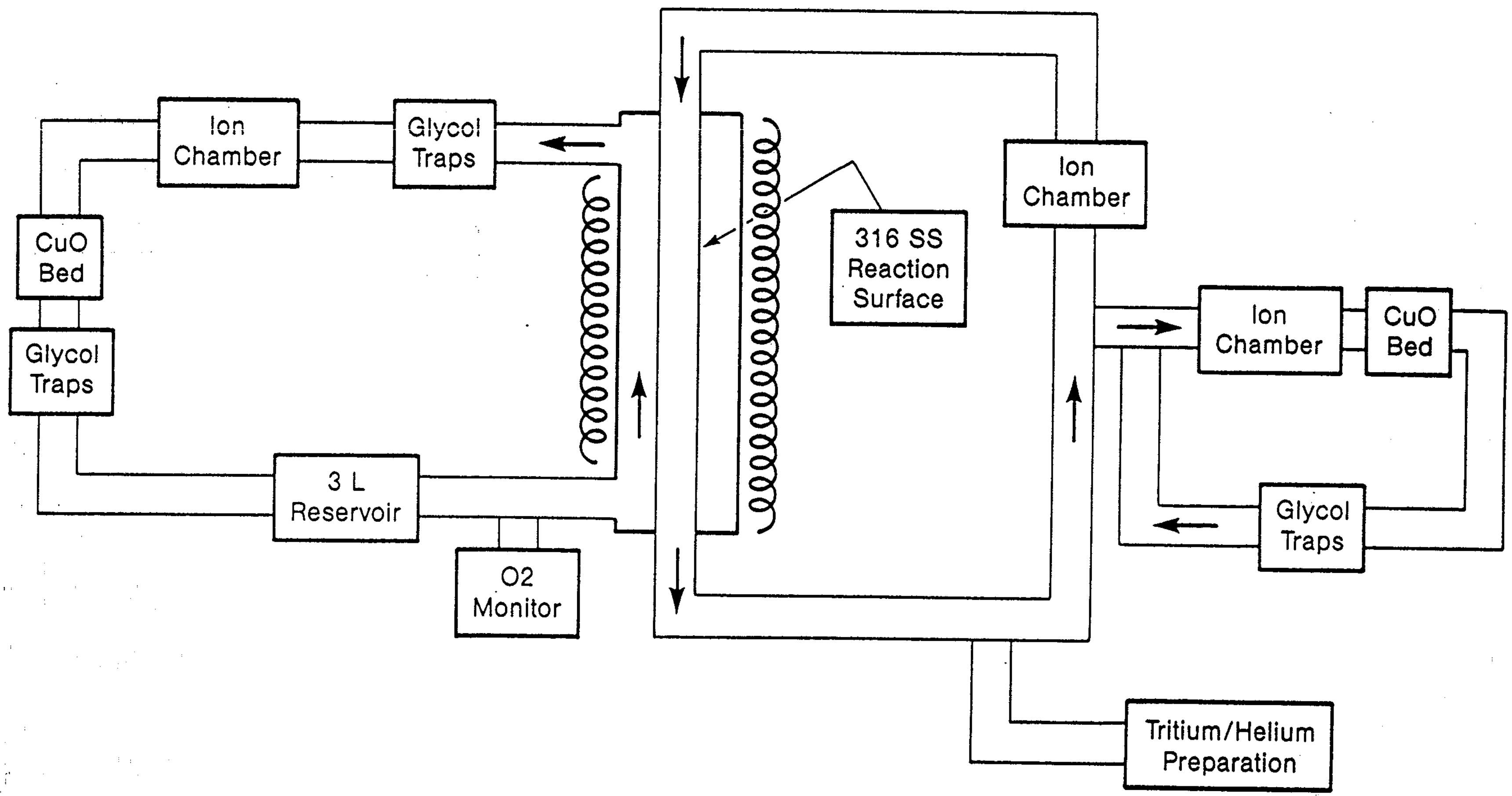
- Residence time (2 to 30 sec).

- Hydrogen concentration (0-50 ppm)

- Time (days)

Experimental Apparatus

Loop C Analytical Loop (O2/He Circulated)	Loop A Source Loop (T2/He Circulated)	Loop B Reference Loop (Tritium Calibrated)



Summary of Tritium Oxidation

- Significant dependence on oxygen was observed:
  - The ratio of HTO/HT is < 1 at oxygen concentrations < 1 ppm
  - The ratio of HTO/HT is > 10 at oxygen concentrations > 50 ppm

- Oxidation rate is a function of:
  - Temperature in the range 350-550° C
  - Residence time in the range 2 to 30 seconds

- Experiment started in 1986 and experimental matrix will be about 60% completed by the end of fiscal 1987

Comparative Study of Solid Breeders (1986)

Lead Organization: UCLA

Objectives

- Provide a consistent comparison of the effect of solid breeder material choice on blanket attractiveness
- Evaluate impact of uncertainties in solid breeder properties and behavior on blanket feasibility and attractiveness
- Provide guidance to the test program on the choice of experimental parameters and solid breeders

Materials and Configurations Considered

Without a Multiplier	Homogeneous Solid Breeder/Multiplier Mixture	With a Separate Be Multiplier Region
Li_2O	$LiAlO_2/Be$	Li_2O
Li_2ZrO_3	$LiAlO_2/BeO$	$LiAlO_2$
Li_8ZrO_6	Li_2O/Be	Li_5AlO_4
$Li_2Be_2O_3$	Li_2O/BeO	Li_2SiO_3
Li_7Pb_2		Li_4SiO_4
		Li_2ZrO_3
		Li_8ZrO_6
		Li_2TiO_3

Comparative Study of Solid Breeders

Performance Parameters

Neutronics:	Tritium Breeding Ratio, Energy Multiplication, Maximum Li Burnup
Thermomechanics:	Clad Stress and Deflection, Breeder Thermal Stress
Tritium:	Tritium Inventory and Permeation
Activation:	Waste Disposal Rating, Biological Hazard Potential, Recycling Hazard, Afterheat
Economics:	Material Cost, Net Thermal Efficiency, Power Leakage from Blanket

Table 1.2-6 Blanket Performance Summary

Solid Breeder	Effective TBR[a]	Power Mult.	$\dot{q}$ (W/cm^3)[b]	Peak Li Burnup (at.%)	Gross η_{th} (%)	Power Leakage (MW)	Blanket SB & M Cost ($M)	Breeder Total T Inventory (g)	Breeder Permeation Rate (g T/d)	Pumping Power Ratio (%)	Dose Rate at 1 m[c] (REM/hr-g)	Afterheat Time to Reach T_{max} (hr)
Cases Without a Multiplier												
Li_2O	1.08 (nat)	1.22	41.8	2.9	39.4	5.6	28	5.6	1.4	5.4	0.0029	183
Li_2ZrO_3	0.93 (29)	1.02	35.5	6.1	37.8	4.1	90	85.8	1.8	6.0	24.1	0.048
Li_8ZrO_6	0.98 (nat)	1.12	41.4	3.7	38.6	4.2	54	85.2	2.0	5.3	24.1	0.047
$Li_2Be_2O_3$	1.09 (nat)	1.31	47.6	5.4	39.7	3.4	135	552,000	2.4	4.1	0.031	56
Li_7Pb_2	1.22 (29)	1.18	33.7	5.0	39.1	14.9	110	1,590	2.9	5.6	2.64	0.024
Cases With a Homogeneous SB/M Mixture												
$LiAlO_2$/Be	1.51 (36)	1.51	43.9	46.8	41.4	7.1	104	230	2.2	3.1	1.86	5.4
$LiAlO_2$/BeO	1.09 (40)	1.36	43.5	35.3	40.3	6.1	96	76.5	1.3	3.6	1.27	20
Li_2O/Be	1.57 (nat)	1.52	45.9	19.5	41.2	4.7	73	8.1	2.3	3.1	0.0033	420
Li_2O/BeO	1.14 (14)	1.36	43.7	14.3	40.3	3.8	81	9.5	1.6	3.7	0.027	940
Cases With a Separate Be Multiplier Region												
Li_2O	1.24 (20)	1.42	81.6	15.8	40.7	1.2	68	43.9	1.2	3.5	0.0029	130
$LiAlO_2$	1.09 (62)	1.39	64.9	37.8	40.4	2.5	75	36.4	1.1	3.6	7.1	2.6
Li_5AlO_4	1.17 (30)	1.40	72.6	23.2	40.6	2.5	68	23	1.9	3.3	7.1	0.51
Li_2SiO_3	1.10 (50)	1.37	68.5	31.2	40.4	2.6	78	9.6	1.7	3.4	0.14	21
Li_4SiO_4	1.14 (33)	1.38	70.0	24.9	40.5	2.5	71	9.2	1.5	3.5	0.14	2.5
Li_2ZrO_3	1.17 (58)	1.27	67.1	31.8	39.7	2.4	97	47	1.3	3.9	24.1	0.041
Li_8ZrO_6	1.22 (26)	1.34	74.6	21.2	40.3	2.1	91	45.4	1.6	3.5	24.1	0.036
Li_2TiO_3	1.12 (51)	1.39	65.5	32.9	40.6	3.2	77	4.1	1.1	3.6	5.6	5

[a]% ^{6}Li enrichment corresponding to optimum TBR is shown in parentheses; (nat) is for natural lithium (7.25% ^{6}Li).
[b]At 0.5 cm from tip of breeder plate.
[c]After 3-year irradiation and 10-hour cooling.
For the separate multiplier cases, the dose rate for Be is 0.0034 REM/hr-g and is due entirely to impurities.
For the homogeneous SB/M mixture cases, the dose rate for the multiplier (0.0034 REM/hr-g for Be and ≈ 0.03 REM/hr-g for BeO) have been included in these figures.

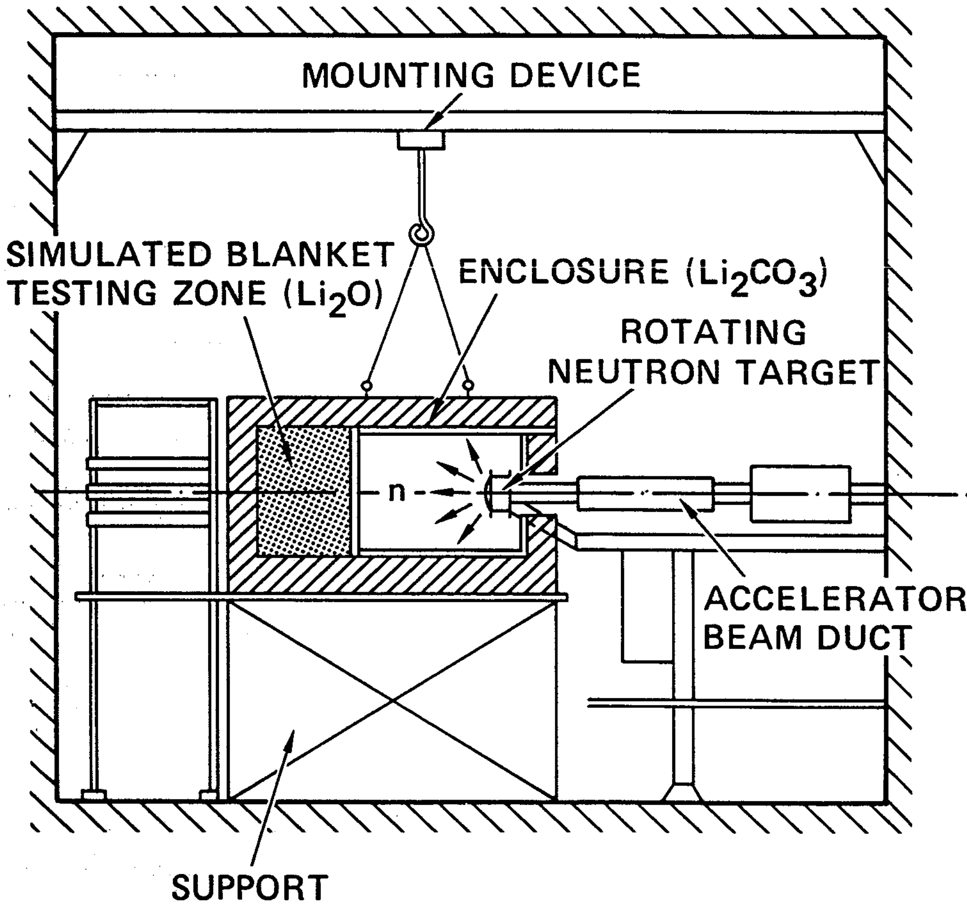
Summary of Experiments

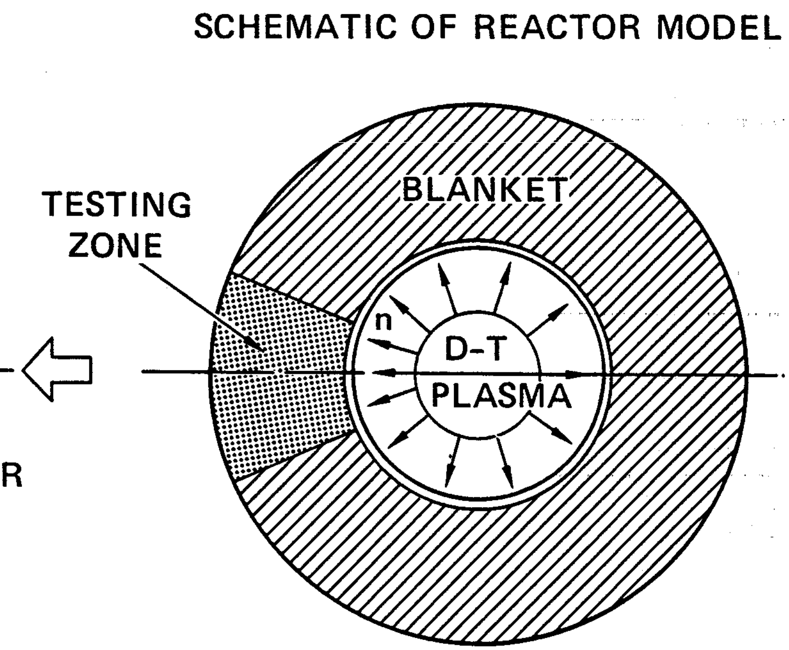
- *Phase I*
  - Late 1984 to March 1986
  - Open Geometry
    Li_2O assembly
    Be added later

- *Phase II*
  - August 1986 to October 1987
  - Closed Geometry
    Li_2O assembly/Li_2CO_3 container
    Be multiplier

- *Phase III*
  - Begins Late 1987
  - Important Engineering Features
  - New Important Material

EXPERIMENTAL SYSTEM FOR PHASE-2 OF US/JAERI PROGRAM
ON BLANKET NEUTRONICS





PHASE I

BLANKET TEST ASSEMBLIES INVESTIGATED

- REFERENCE SYSTEM

  SINGLE-REGION Li_2O BREEDER
  60 CM Li_2O

- FIRST WALLED SYSTEM

NO FIRST WALL	/60 CM Li_2O *
0.5 CM SS+	/60 CM Li_2O
0.5 CM SS/0.5 CM PE++	/60 CM Li_2O
1.5 CM SS	/60 CM Li_2O
1.5 CM SS/0.5 CM PE	/60 CM Li_2O

- BE NEUTRON MULTIPLIER SYSTEM

5 CM BE	/60 CM Li_2O
10 CM BE	/60 CM Li_2O
5 CM Li_2O/5 CM BE	/60 CM Li_2O **
10 CM Li_2O	/60 CM Li_2O

*: IDENTICAL WITH REFERENCE SYSTEM
**: BE SANDWICHED SYSTEM
+: TYPE 316 STAINLESS STEEL
++: POLYETHYLENE AS SIMULANT OF WATER

Measured Items and Methods Applied

TRITIUM PRODUCTION RATES

On-line Type (JAERI)

T6: Paired Li Glass Scintillation Counters

T7: Micro Spherical NE213 Spectrometer

- Indirect method -

Irradiation Type

T6
T7 : Li_2O Pellet/Liq. Scint.* (JAERI)
TN : Li Metal Foil/Liq. Scint. (ANL)

NEUTRON SPECTRUM

On-line Type

Fast Neutron: NE213 Spectrometer

0.5 MeV < E < 15 MeV (JAERI)

Slow Neutron: Proton Recoil Spectrometer**

5 keV < E < 2 MeV (ANL)

Irradiation Type (JAERI)

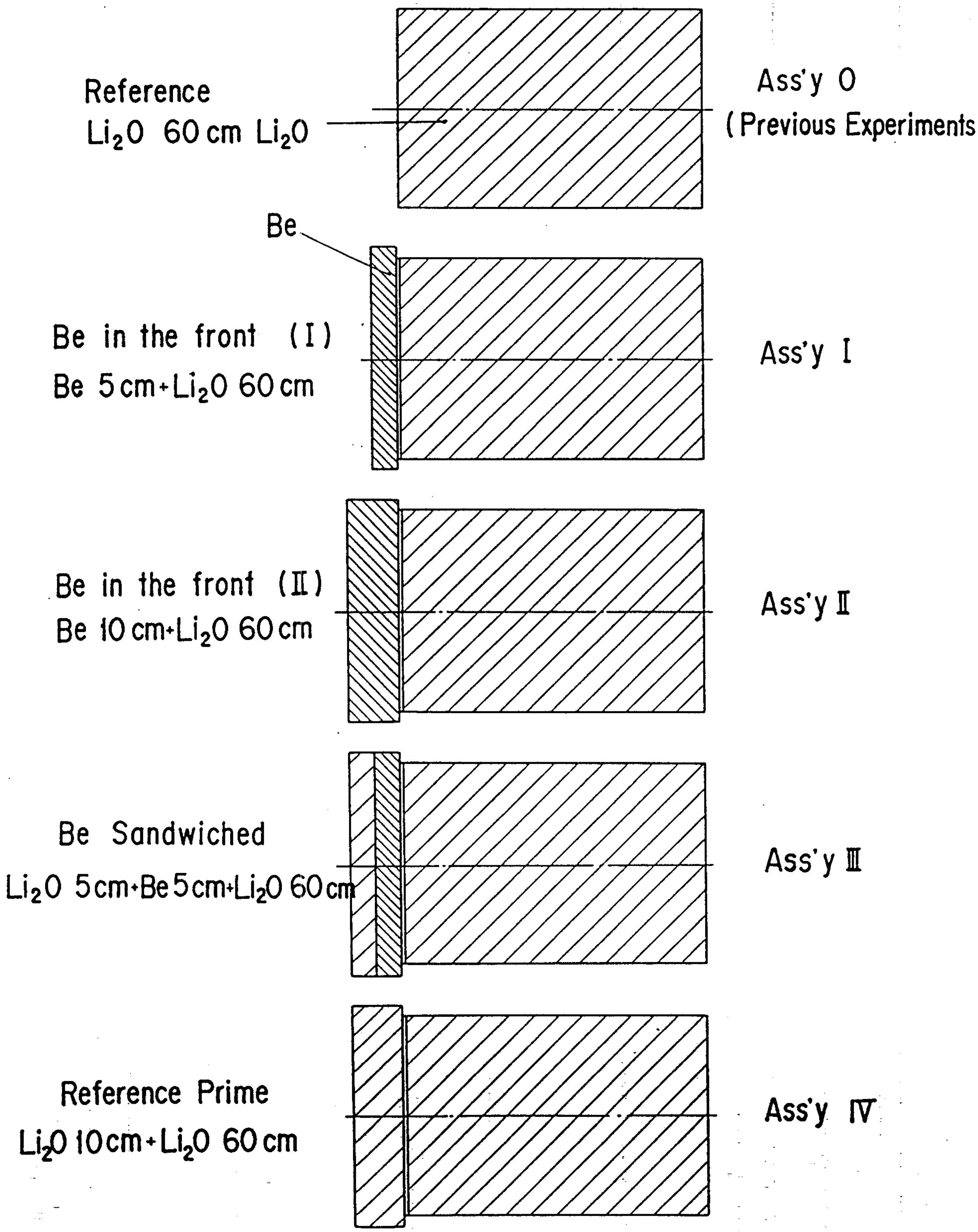
Activation Foils: Al, Au, Co, In, Nb, Ni

Spectral Indices: Ti, Zn, Zr

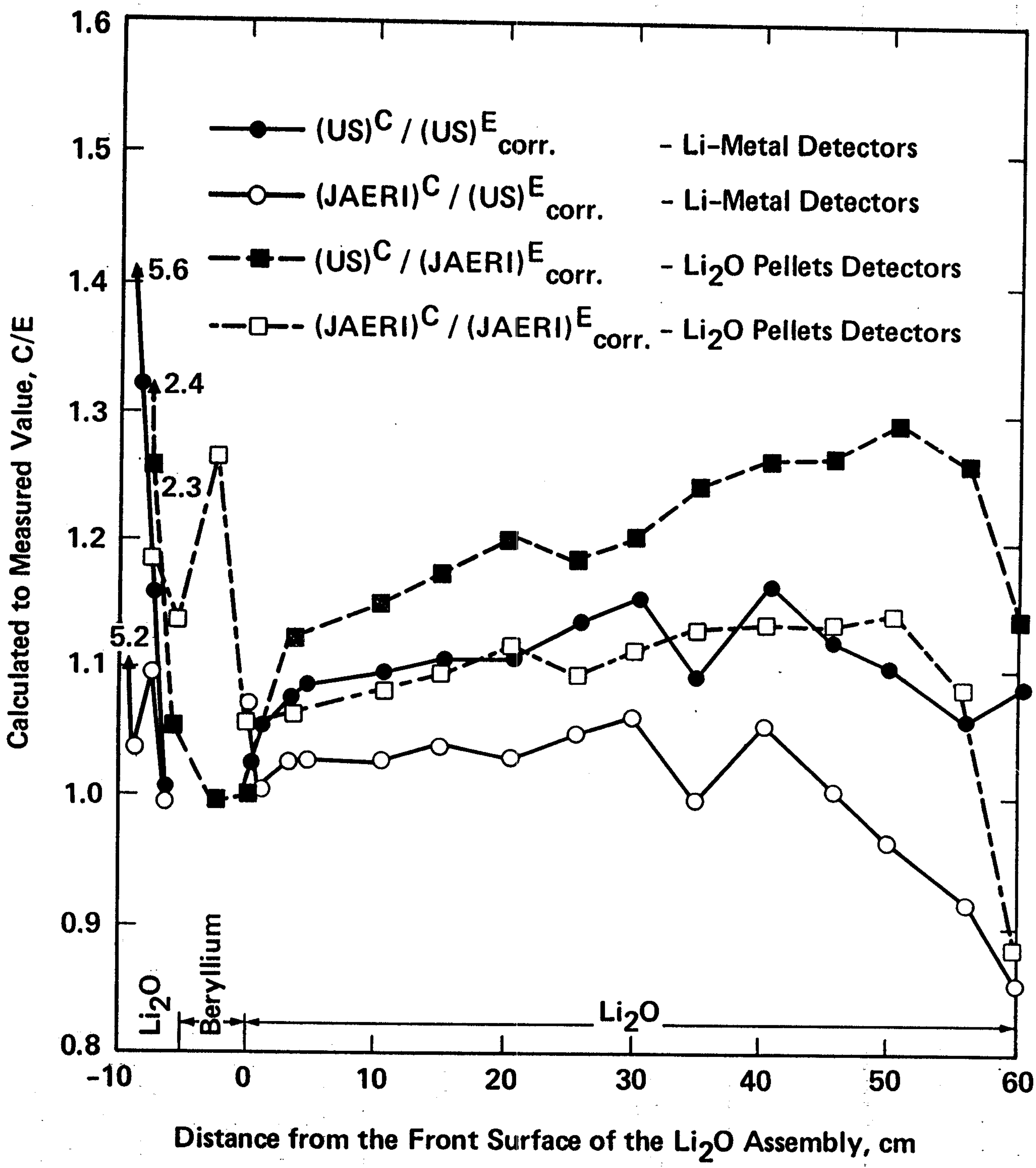
* Liquid Scintillation Counting Method

** Input Source Spectrum only

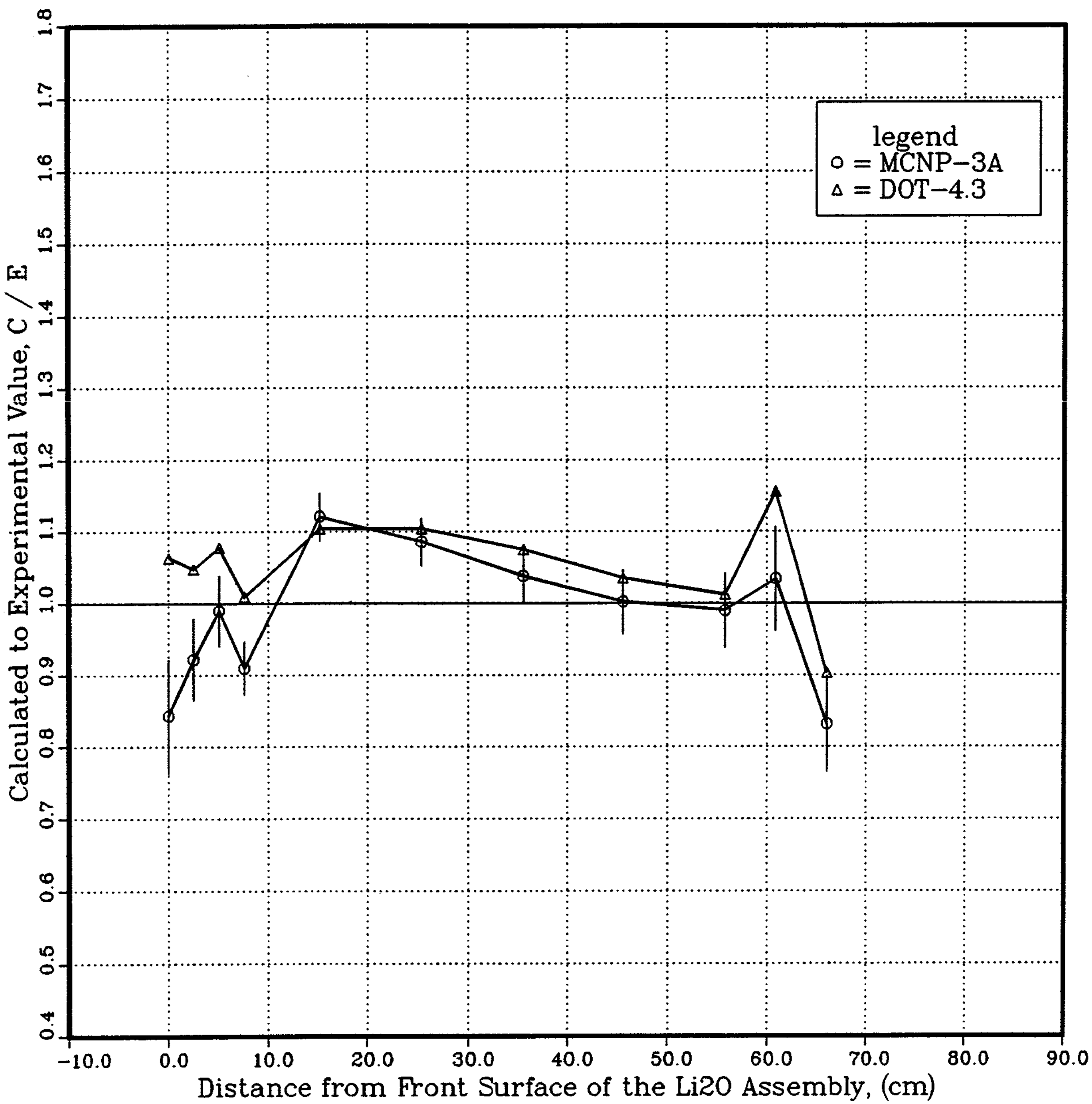
Assemblies for the Experiments on Neutron Multiplier Effect

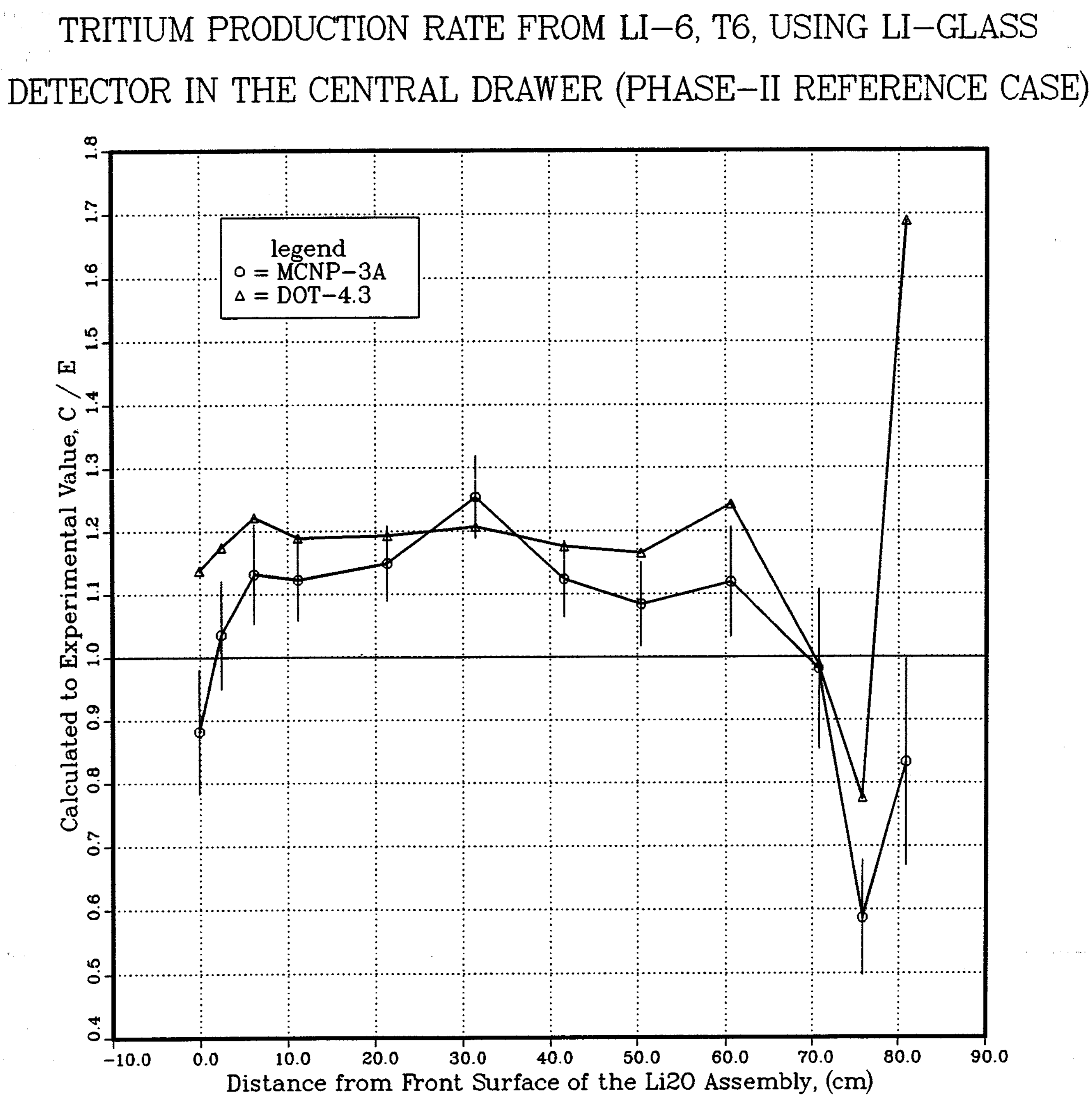


Tritium Production Rate From ^6Li, T_6, in the Beryllium-Sandwiched System

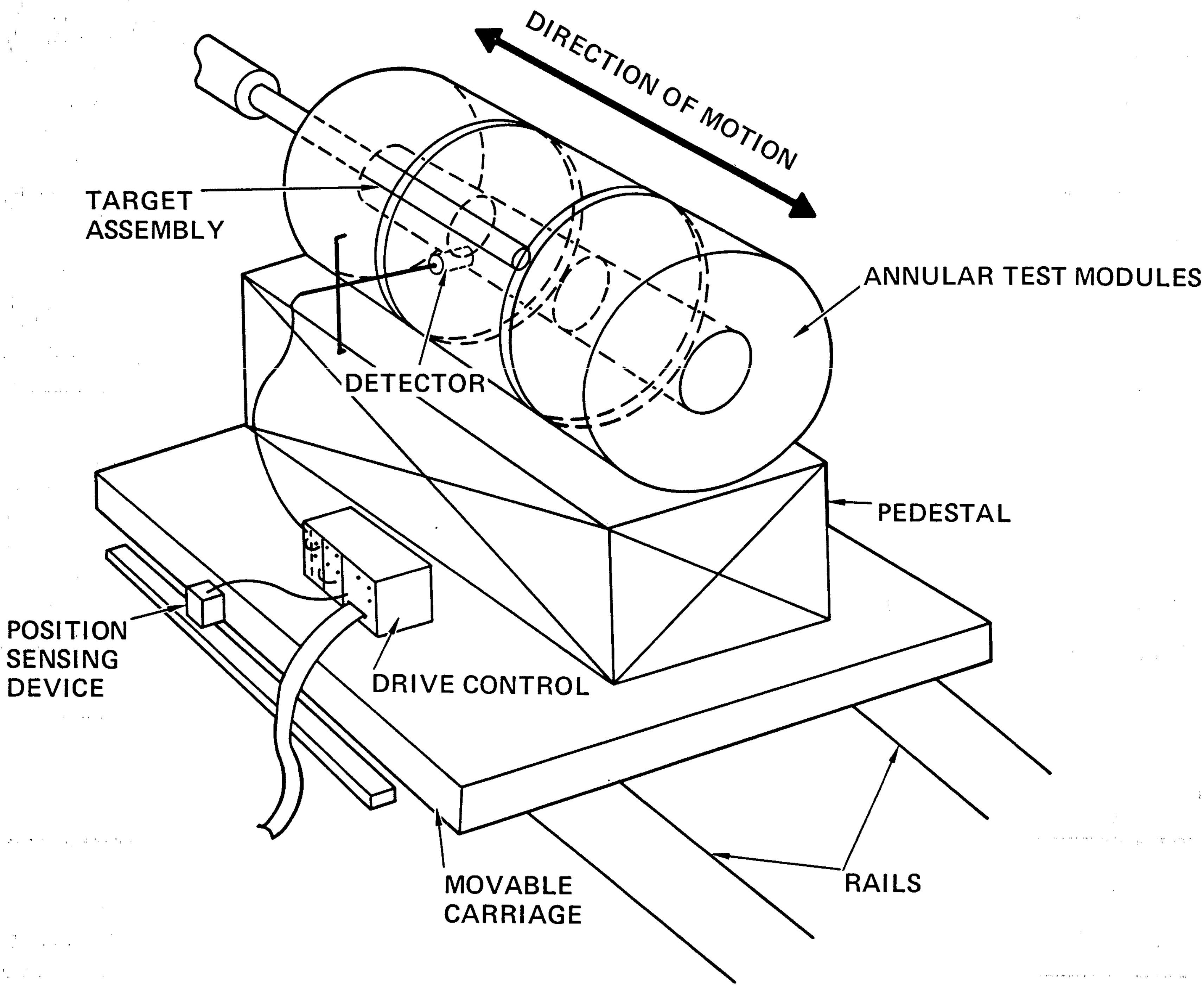


TRITIUM PRODUCTION RATES FROM LI-6, USING FOILS IN THE CENTRAL DRAWER (PHASE-II REFERENCE CASE)




TRITIUM PRODUCTION RATE FROM LI-6, T6, USING LI-GLASS
DETECTOR IN THE CENTRAL DRAWER (PHASE-II REFERENCE CASE)
legend
○ = MCNP-3A
△ = DOT-4.3
Calculated to Experimental Value, C / E
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Distance from Front Surface of the Li2O Assembly, (cm)

ADVANCED LINE SOURCE FOR TRITIUM BREEDING EXPERIMENTS



	Approx. Level of Effort (man years/year)
• Solid Breeder	~ 6.0
- Experiments (irradiation, characterization)	
- Including Part of Modelling	
• Oxidation Kinetics	~ 2.3
• Neutronics	~ 4.5
- Experiments	
- Pre- and Post-Experiment Analysis	

Comparative Study of Solid Breeders

Results and Conclusions

- A neutron multiplier is needed for all solid breeders, except possibly for Li_2O
- Cases with a homogeneous mixture of Be and solid breeder have superior neutronics performance to those with separate Be and solid breeder regions
- Be is superior to BeO based on improvement of tritium breeding and energy production, and lower tritium diffusive inventory in multiplier
- Li_2O is the most attractive solid breeder with or without a multiplier
- Li_4SiO_4 and Li_2SiO_3 (to a lesser extent) appear to be the most attractive ternary ceramics
- $Li_2Be_2O_3$ and Li_7Pb_2 are not particularly attractive; $Li_2Be_2O_3$ has a large tritium diffusive inventory (assuming BeO-like tritium diffusion) and a marginal tritium breeding ratio; and Li_7Pb_2 has a low energy multiplication, relatively high tritium inventory and a limited operating temperature range

Comparative Study of Solid Breeders

Recommendations for Test Program

Materials:

- Li_2O without a multiplier
- Li_2O, Li_4SiO_4 and Li_2SiO_3 with Be ($LiAlO_2$ should also be considered because of chemical stability considerations)

Configurations:

- Homogeneous mixtures of beryllium and solid breeder should be included in the test matrix in addition to the separate breeder and multiplier configuration
- Sphere-pac form is more attractive than sintered block form

Properties: Experimental effort should be pursued to reduce the large uncertainties in tritium-related properties. These properties are important for designs as well as breeder comparisons

Test Conditions:

- Better definition of burnup limits is required
- Tests should also include temperature gradients to determine the importance of cracking and/or breeder mass transfer

Present U.S. Neutronics Activities

- Almost all activities are part of international agreements

- US—Japan cooperation
  —Facility: FNS at JAERI, Japan (14 MeV neutron source, neutronics mockup facility)
  —US organizations: UCLA, ANL, ORNL
  —Focus: Tritium breeding, nuclear heating with candidate materials and representative configurations

- LBM at LOTUS
  —Test module constructed by GA
  —Neutronics experiments at LOTUS in Switzerland

- Activities on data and method improvements

U.S./JAERI Collaboration Program on Fusion Neutronics

Joint Effort (Annex II) to perform and analyze integral neutronics experiments

Facility

- Fusion Neutron Source (FNS) at JAERI, Japan
- FNS was constructed with capabilities specifically suited for fusion

Objectives

1. Contribute to resolving tritium self-sufficiency issue
   - Evaluate uncertainty in state-of-the-art tritium breeding estimates by comparing calculations and experiments
   - Identify and improve deficiencies in nuclear data, calculations and modelling
2. Develop the neutronics technology necessary for the next fusion device (components and testing modules), e.g., experimental measurement techniques for neutron spectra