THE U.S./JAERI COLLABORATIVE PROGRAM ON FUSION NEUTRONICS

(highlights)

May 1989

Participants

	U. S.	JAERI
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* ORNL participated in Analysis for Phase I First Wall Experiments: R. Alsmiller, R. Santoro, J. Barens, and T. Gabriel

Objectives of the Program

1. Provide guidance in resolving key design feasibility issues related to fusion nuclear technology development

   - Tritium self-sufficiency
     (feasibility, economics, safety)

   - Total heat deposition and heating rate profiles
     (economics, safety)

   - Induced activation and afterheat levels
     (safety, environmental impact)

   - Shielding effectiveness
     (safety, economics)

Example:

* Evaluate the overall uncertainties (both experimental and analytical) in the achievable tritium breeding ratio due to uncertainties in various experimental techniques, uncertainties in nuclear data, calculational methods, and modeling

* Take action to reduce these uncertainties once the source of discrepancy between measurements and predictions is identified (e.g., improve particular data set, calculational method, recommend particular measuring techniques)

Objectives of the Program, cont'd

2. Screening of Various Blanket Concepts
   - Experimental examination of the potential of various breeders (in several configurations) to produce tritium)

3. Develop the Neutronics Technology Needed for the Next Fusion Experimental Reactor (e.g., ITER)
   - Develop various experimental measuring techniques for tritium production and heating rate measurements (e.g., local and zonal measurements for TPR)
   - Gain experience in how to plan, build, and perform neutronics testing in a well-characterized test assembly
   - Develop the required methodology and techniques to maximize information extracted from experiments and extrapolate results to commercial reactors (e.g., scaling for tritium self-sufficiency)

Chronological History of the U.S./JAERI Collaborative Program on Fusion Breeder Neutronics

Official collaboration started October 1984 to jointly perform and analyze several fusion integral experiments at the FNS facility (JAERI)

- Phase I Experiments
  Started October 1984 - Completed March 1986
  Characteristics:
  Open geometry with point source
  Li_2O assembly
  reference, first wall, and beryllium multiplier experiments

- Phase II Experiments
  Began August 1986 - Completed Dec. 1988
  Characteristics:
  Closed geometry with point source
  Li_2O assembly
  - Reference Experiment
  - Beryllium liner and multiplier experiments (with and without first wall)
  - Heterogeneity and coolant channel experiments
  - Short and long radioactivity buildup verification

- <u>Phase III Experiments</u>

  Planned for 1989/1990

  Will concentrate on:

  - Better simulations of fusion source conditions by periodic movement of the test assembly while holding the point source stationary, thus creating a line source

  - Measure tritium, heating, spectra

  - Activation and afterheat measurements

  - Shielding experiments

Measured Items and Measuring Techniques

- Neutron Spectrum
  - NE213 (above 1 MeV, JAERI)
  - Proton recoil counter (1 KeV - 1 MeV, U.S.)

  (both in-assembly and out-of-assembly measurements are performed)

  - TOF Measurements (JAERI)

- Foil Activation Measurements (spectral indices)
  - ^{197}Au(n,2n), ^{197}Au(n,γ), ^{58}Ni(n,2n), ^{58}Ni(n,p) ^{27}Al(n,α), ^{115}In(n,n'), ^{90}Zr(n,2n)

  (used for source characterization around the D-T neutron source and in-system)

- Tritium Production Rate (TPR)

  Local measurements:
  - T_6:
    - Li-glass scintillator (JAERI)
    - Li-metal detectors (U.S.)
    - Li_2O-pellet detectors (JAERI)
  - T_7:
    - NE213 indirect method (JAERI)
    - Li-metal detector (U.S.)
    - Li_2O-pellet detectors (JAERI)

  Zonal Measurements (Phase II)

  Liquid scintillation method in zones of size ~ 5 cm x 5 cm x 5 cm

Measurement Techniques Development

So far, neutron spectrum, foil activation, and tritium production measurements were performed. Technique development is underway for the following items:

- <u>Nuclear Heating</u>:

  - Calorimetry (total heating)

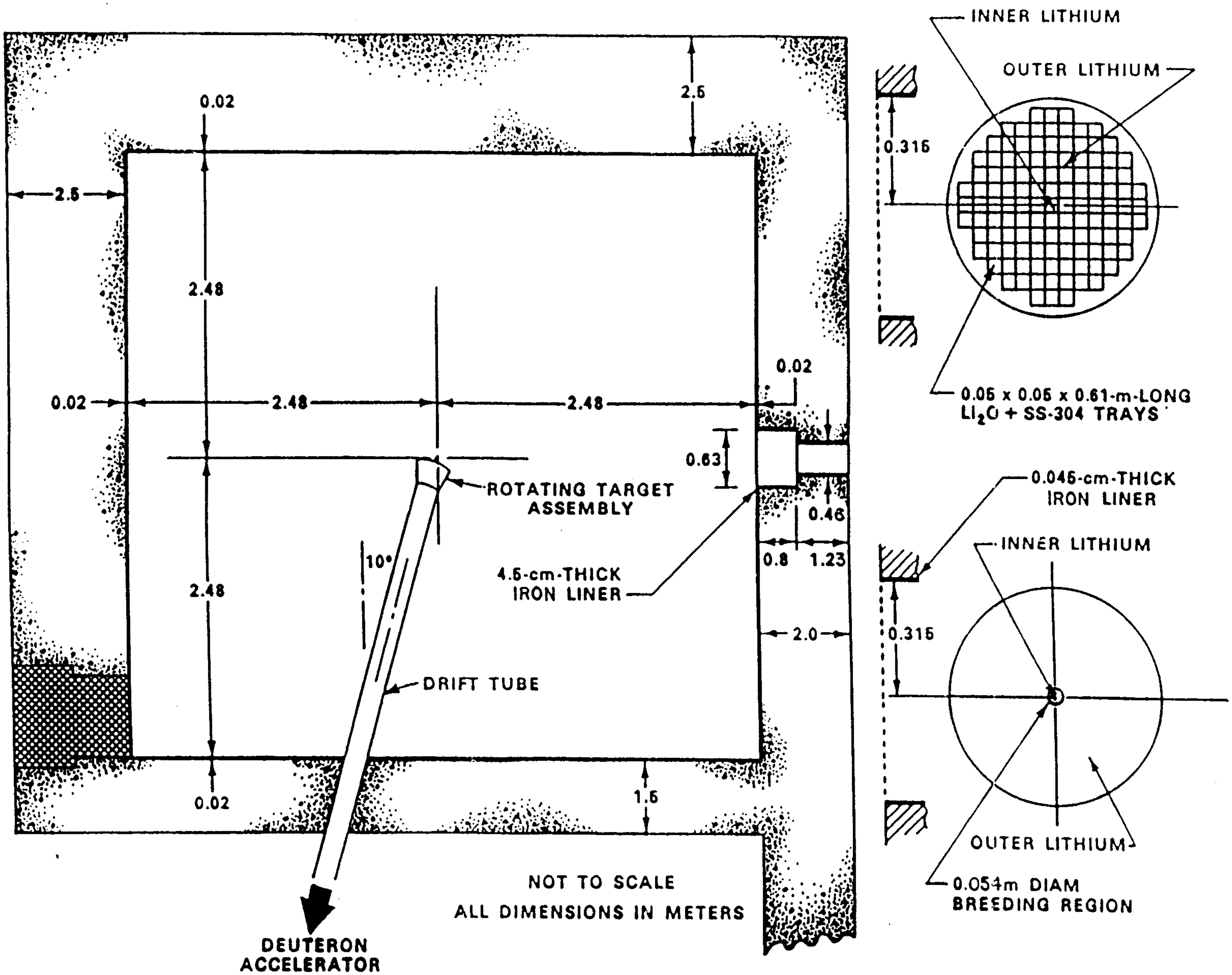
  - Ionization detectors

    Pair of ionization chambers, one with tissue equivalent wall (sensitive to both neutron and gammas) and the other with carbon wall (sensitive to gammas) could be employed

  - TLD Interpolation (gamma heating)

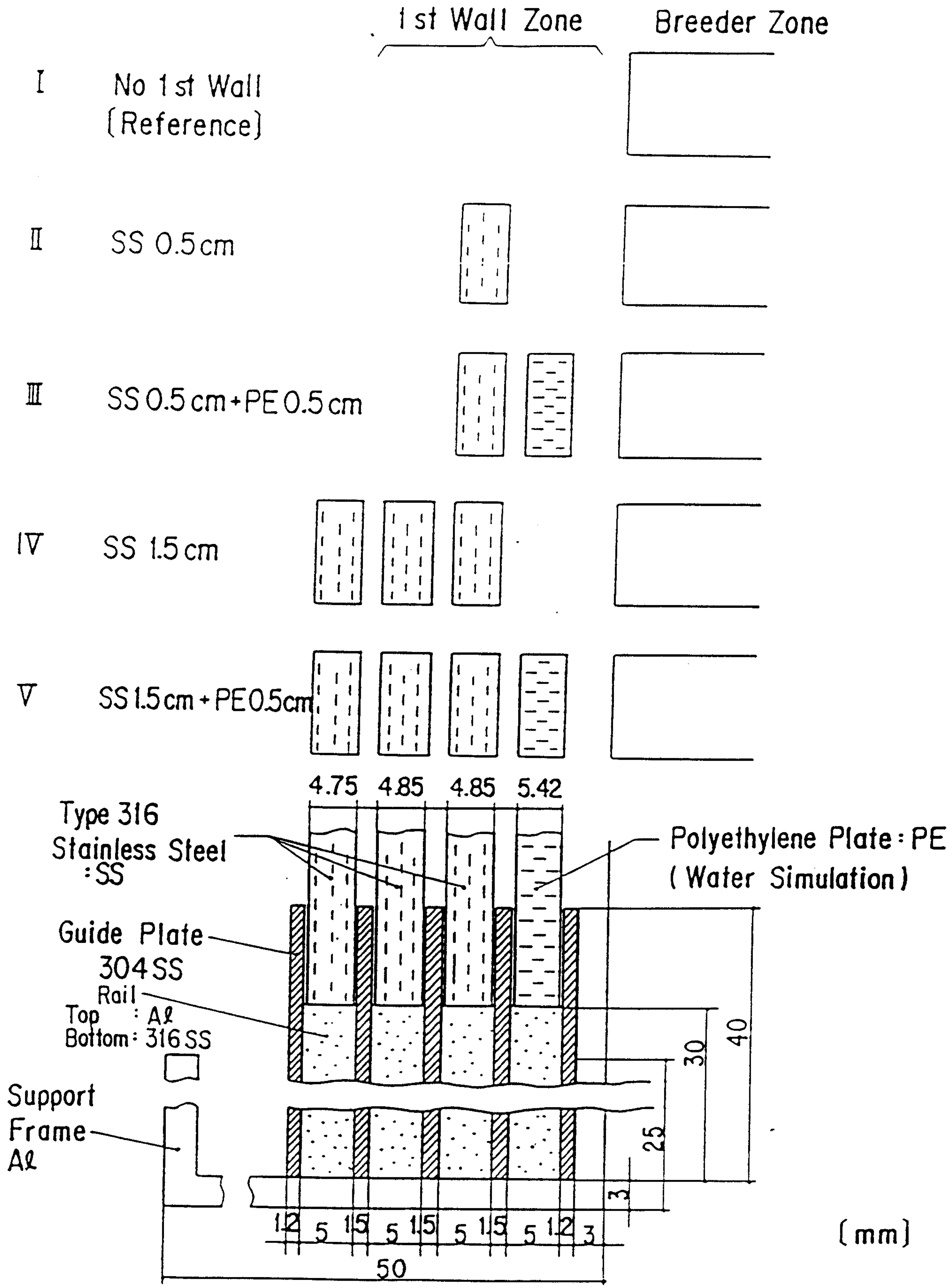
    TLD's: ^{7}LiF (Mg)
    Mg_2SiO_4 (Tb)
    Sr_2SiO_4 (Tb)
    Ba_2SiO_4 (Tb)

Phase I

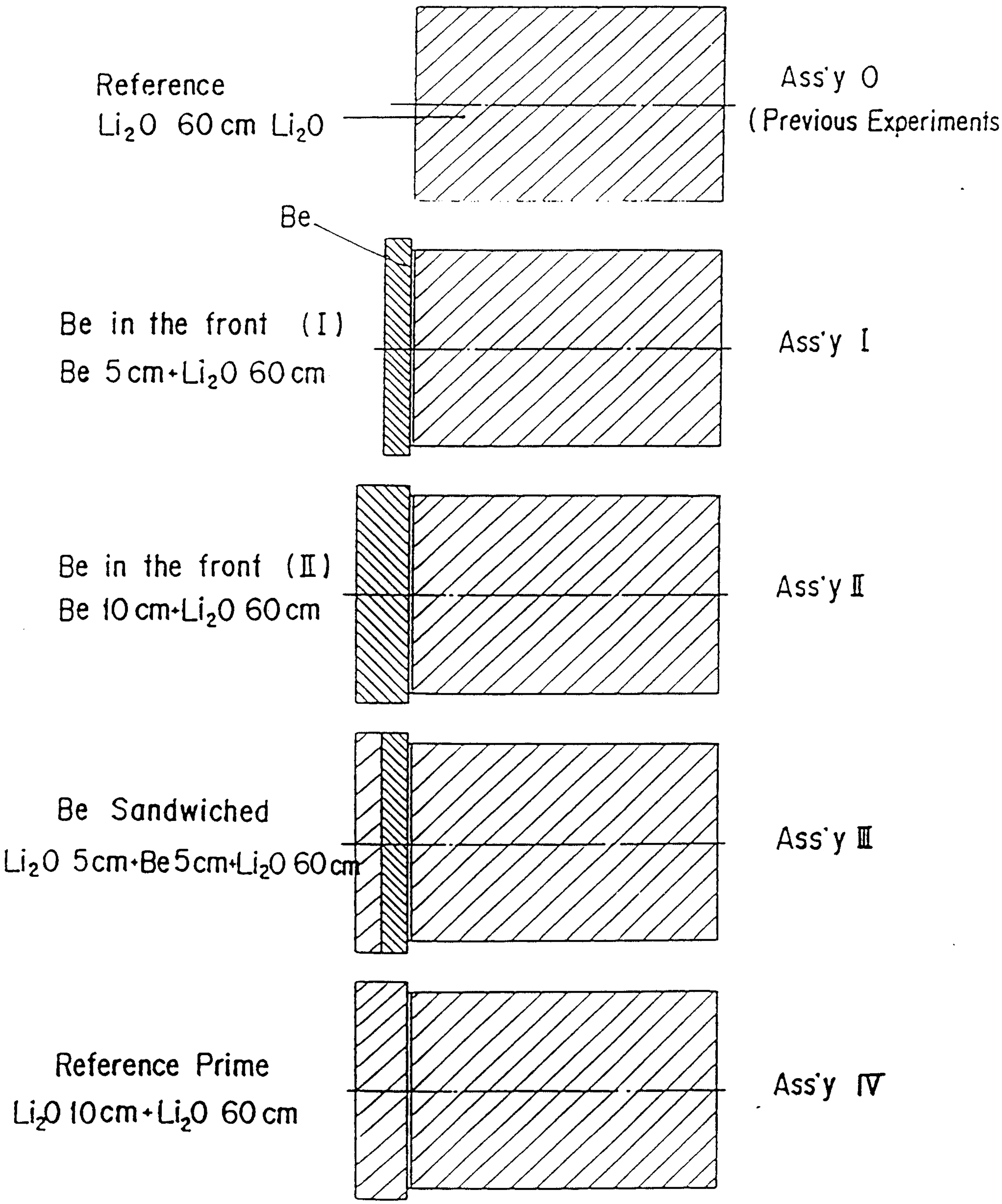


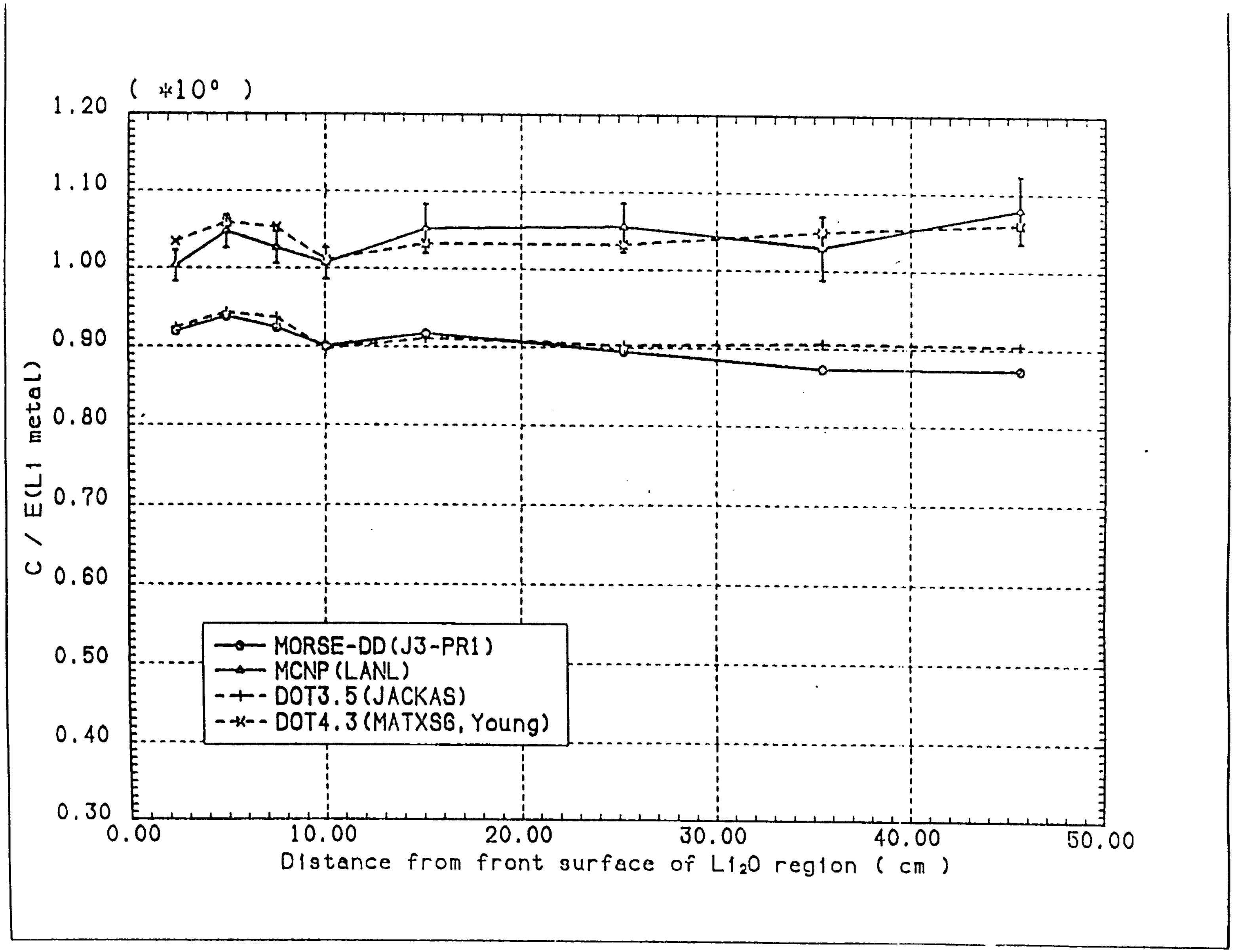
INNER LITHIUM
OUTER LITHIUM
0.315
0.05 x 0.05 x 0.61-m-LONG
Li_2O + SS-304 TRAYS
0.045-cm-THICK
IRON LINER
INNER LITHIUM
0.315
OUTER LITHIUM
0.054m DIAM
BREEDING REGION
2.5
0.02
2.5
2.48
0.02
2.48
2.48
0.02
0.63
ROTATING TARGET
ASSEMBLY
0.46
0.8
1.23
10°
4.5-cm-THICK
IRON LINER
2.48
2.0
DRIFT TUBE
0.02
1.5
NOT TO SCALE
ALL DIMENSIONS IN METERS
DEUTERON
ACCELERATOR

Configurations for the Experiments on First Wall Effect

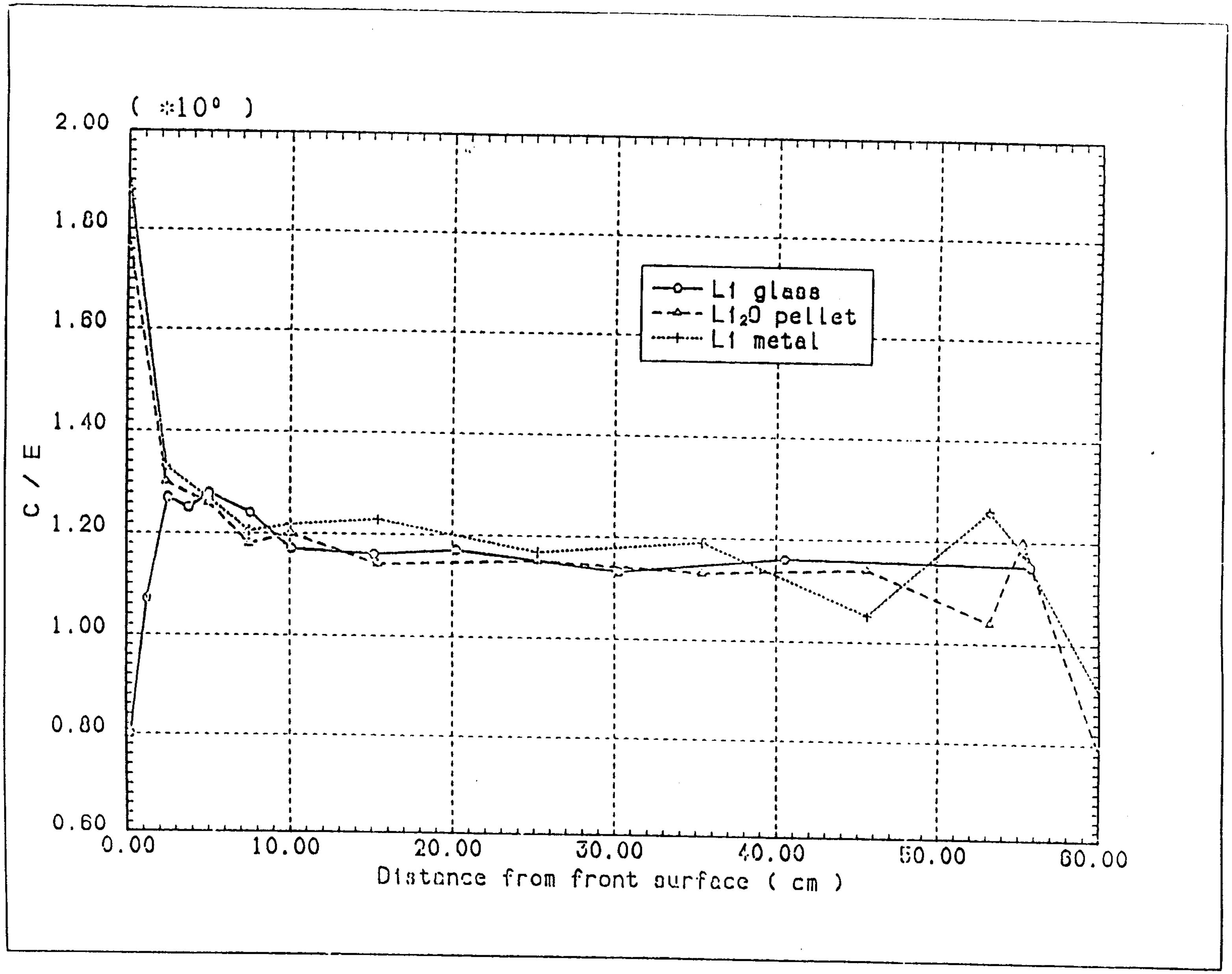


Assemblies for the Experiments on Neutron Multiplier Effect

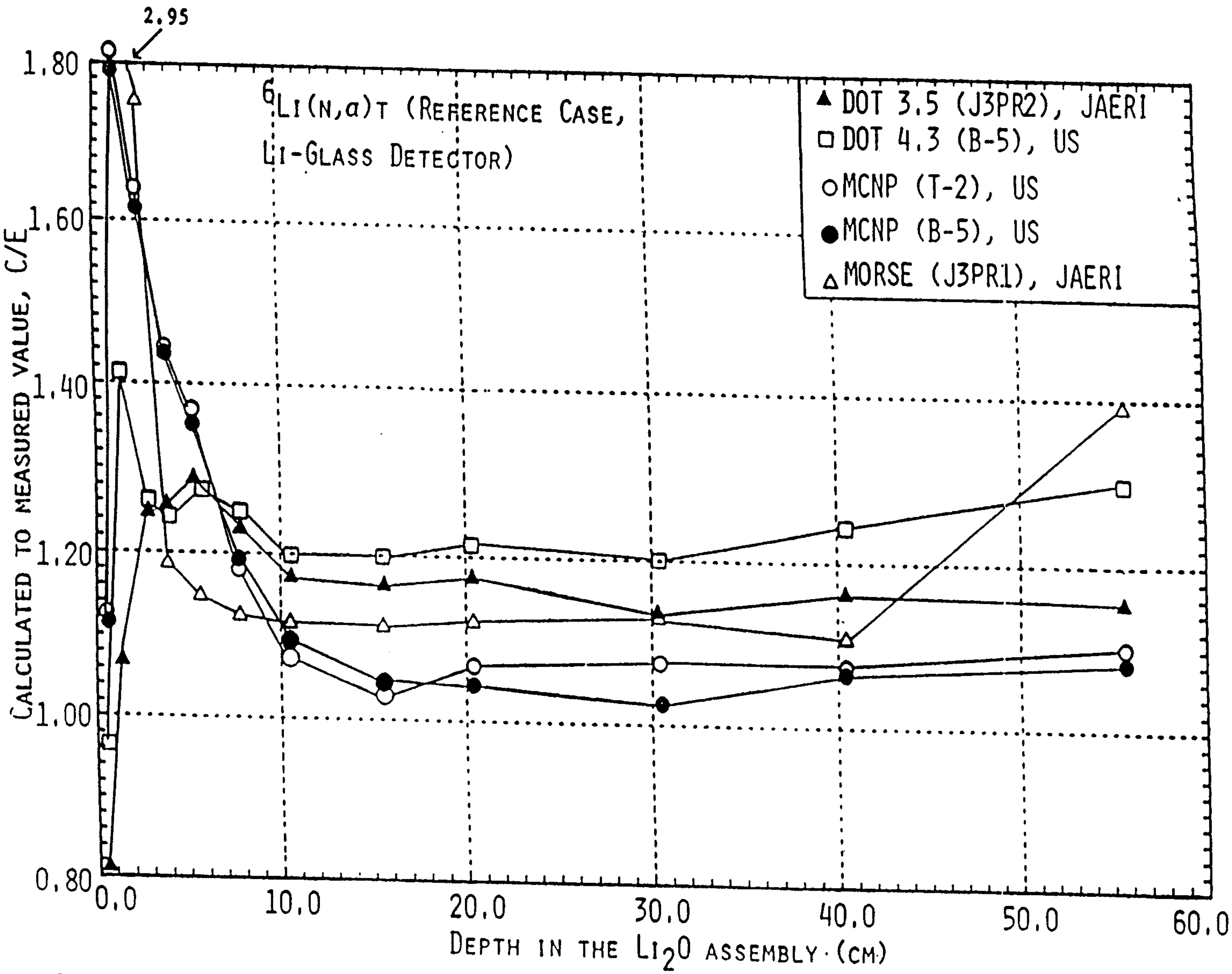




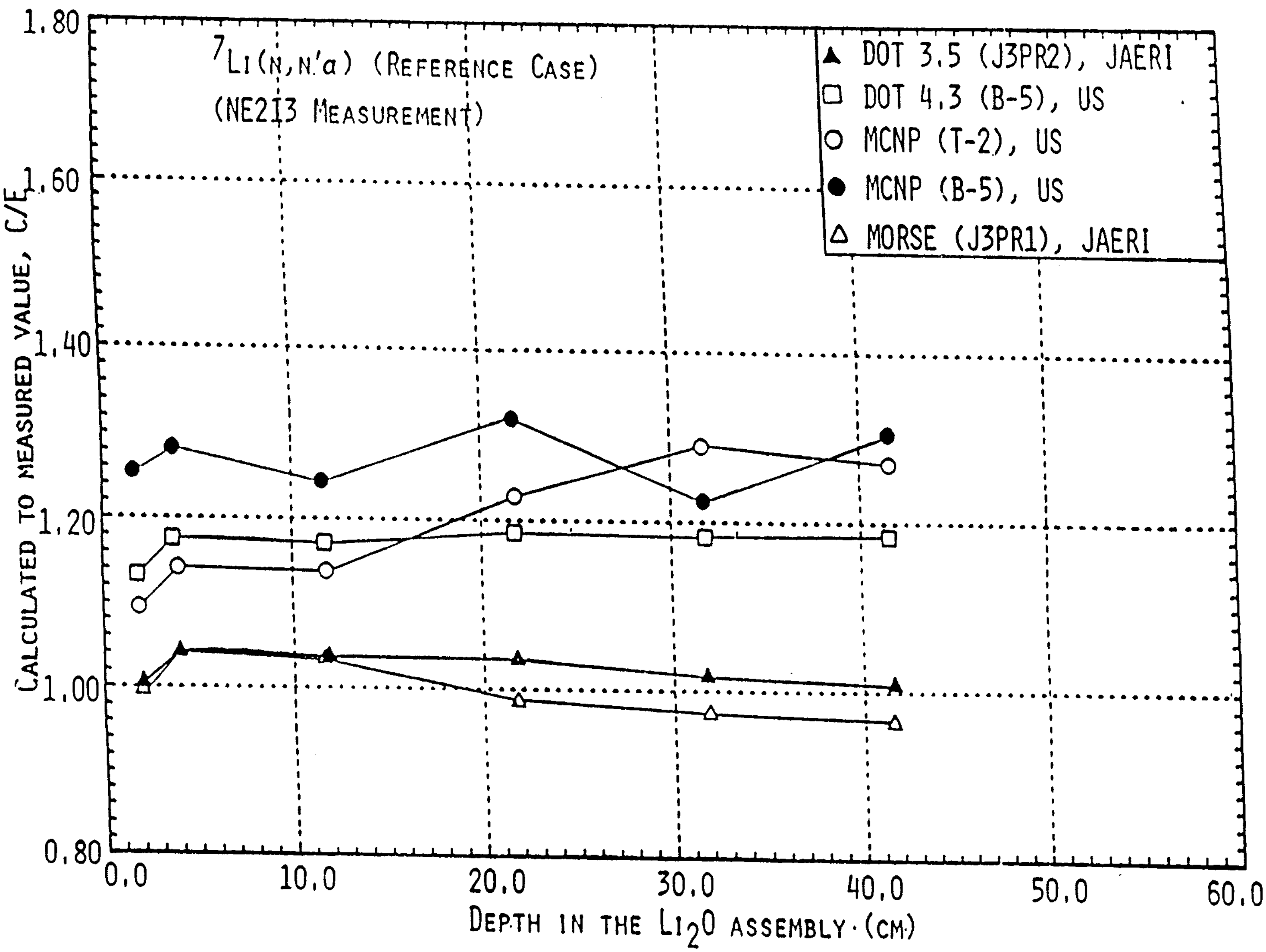
C/E Valus for Tritium Production Rate from ^{7}Li Along the Central Axis of the Test Assembly



C/E Values for Tritium Production Rate from ^6Li Along the Central Axis of the Test Assembly

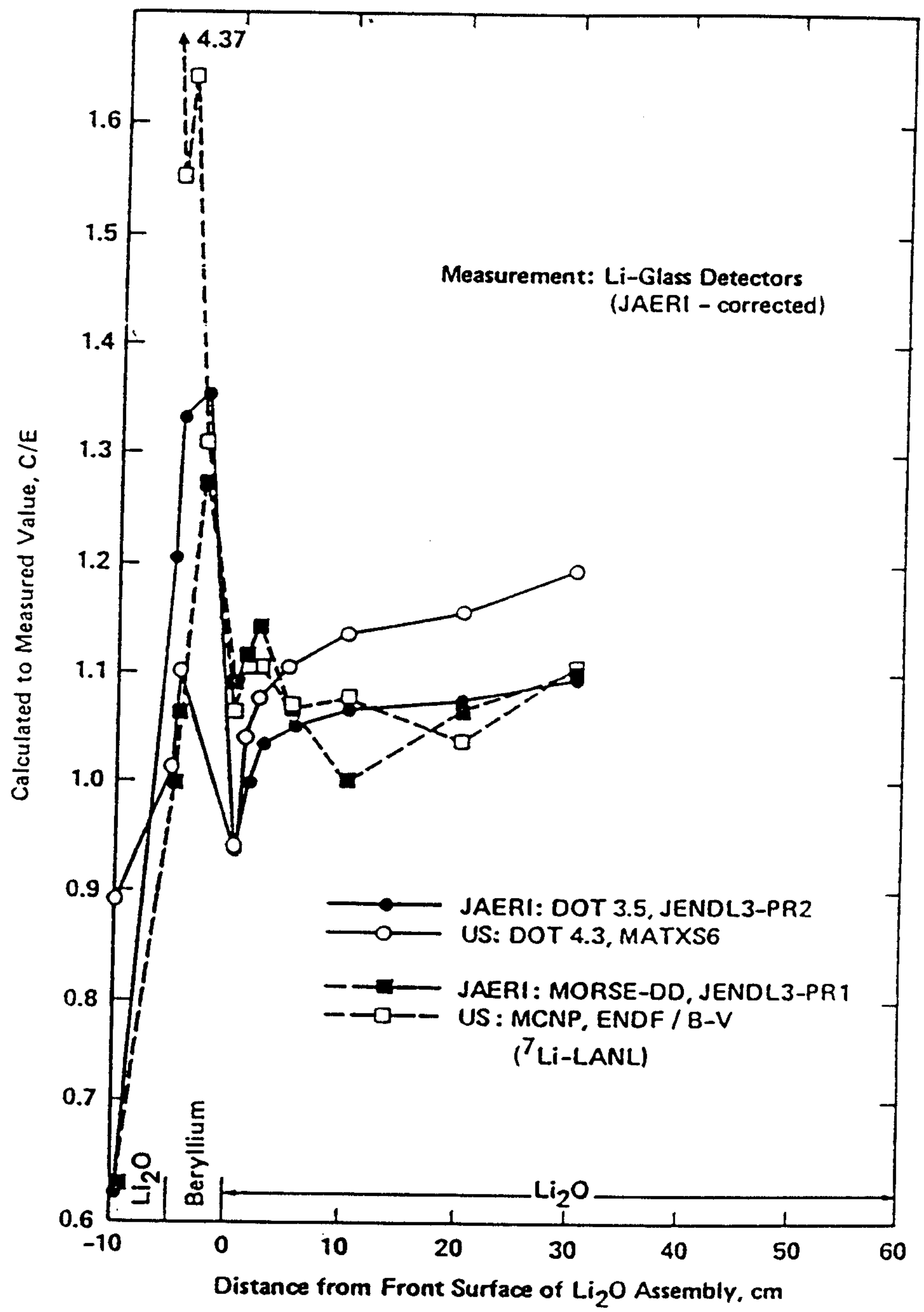


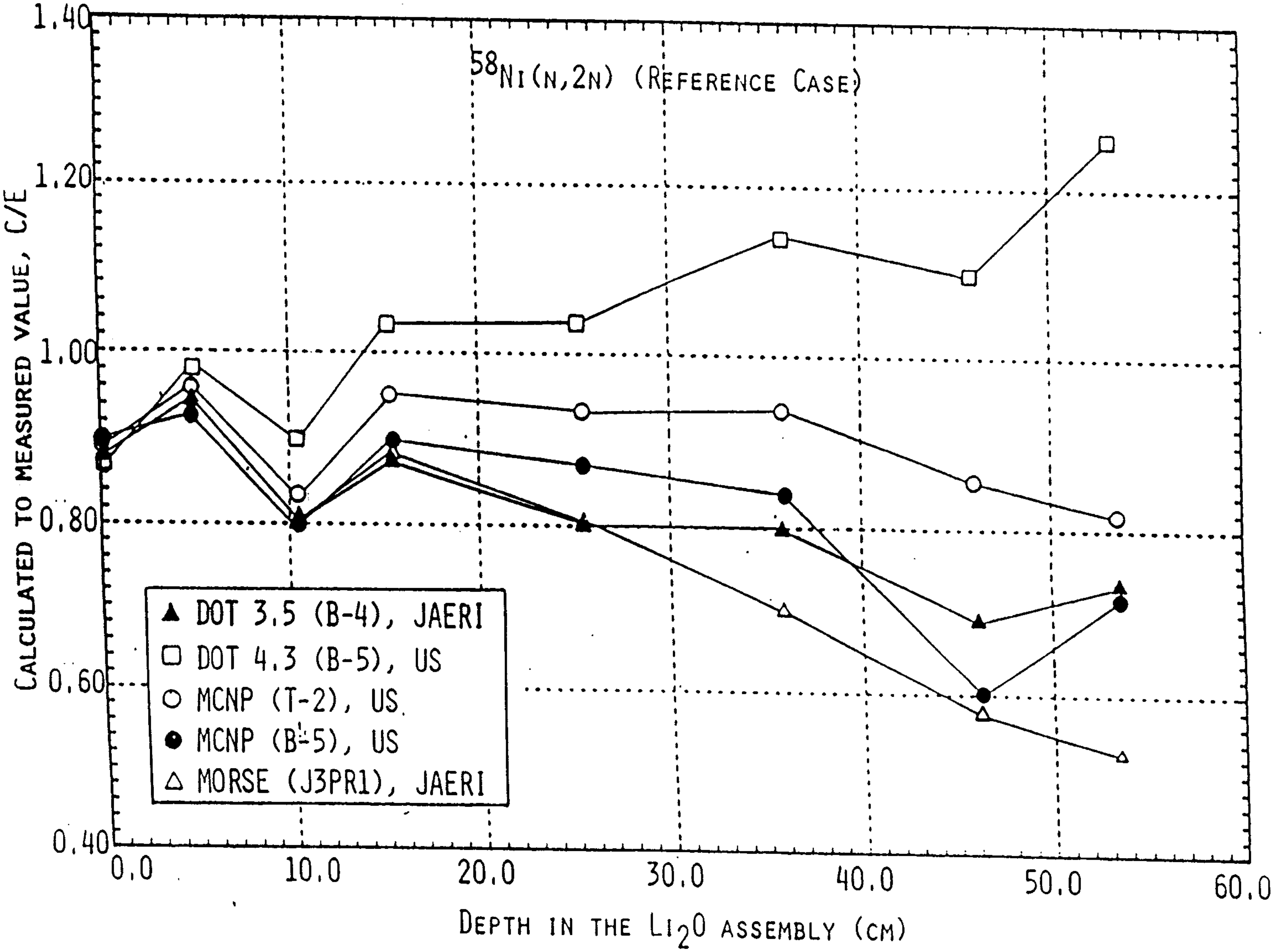
CALCULATED TO MEASURED VALUE OF TRITIUM PRODUCTION RATE FROM ^{6}LI IN THE REFERENCE ASSEMBLY (SELF-SHIELDING EFFECT IS CORRECTED USING DOT-JACKAS)



^{7}Li(n,n'α) (Reference Case)
(NE213 Measurement)
DOT 3.5 (J3PR2), JAERI
DOT 4.3 (B-5), US
MCNP (T-2), US
MCNP (B-5), US
MORSE (J3PR1), JAERI
Calculated to measured value, C/E
1.80
1.60
1.40
1.20
1.00
0.80
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Depth in the Li_2O assembly (cm)

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





58Ni(n,2n) (Reference Case)
Calculated to measured value, C/E
Depth in the Li2O assembly (cm)
1.40
1.20
1.00
0.80
0.60
0.40
0.0
10.0
20.0
30.0
40.0
50.0
60.0
DOT 3.5 (B-4), JAERI
DOT 4.3 (B-5), US
MCNP (T-2), US
MCNP (B-5), US
MORSE (J3PR1), JAERI

OBSERVATIONS ON ANALYSIS OF PHASE I EXPERIMENTS

$\underline{T_6}$:

• Both deterministic and Monte Carlo calculations show large discrepancies in T_6 at front locations as compared to measurements (C/E ~ 0.8-5) in all systems considered, even after corrections for self-shielding effect are made. The discrepancies are due to the large uncertainty in predicting the incident low-energy component of the input source. Possible causes are:

* Modeling
  - Modeling the geometrically complicated target and room walls
  - Source separation model used in Monte Carlo calculation
  - Isotropic source assumption and cylindrical modeling used in 2-D calculation

* Data Processing
  - Interpolation scheme used to extrapolate calculated values to measuring locations near front surfaces (e.g., Lagrangian, log-linear). The T_6 profiles are very steep at these locations

  - Approximations used to derive the self-shielding correction factors. Derived factors are sensitive to the uncertainty in the atomic densities of detectors used

OBSERVATIONS ON ANALYSIS OF PHASE I EXPERIMENTS (cont'd.)

- Uncertainties in determining exact locations of detectors, particularly at zone boundaries (e.g., between Be and Li_2O zone) where T_6 profiles are steep

* *Atomic densities of concrete are uncertain*

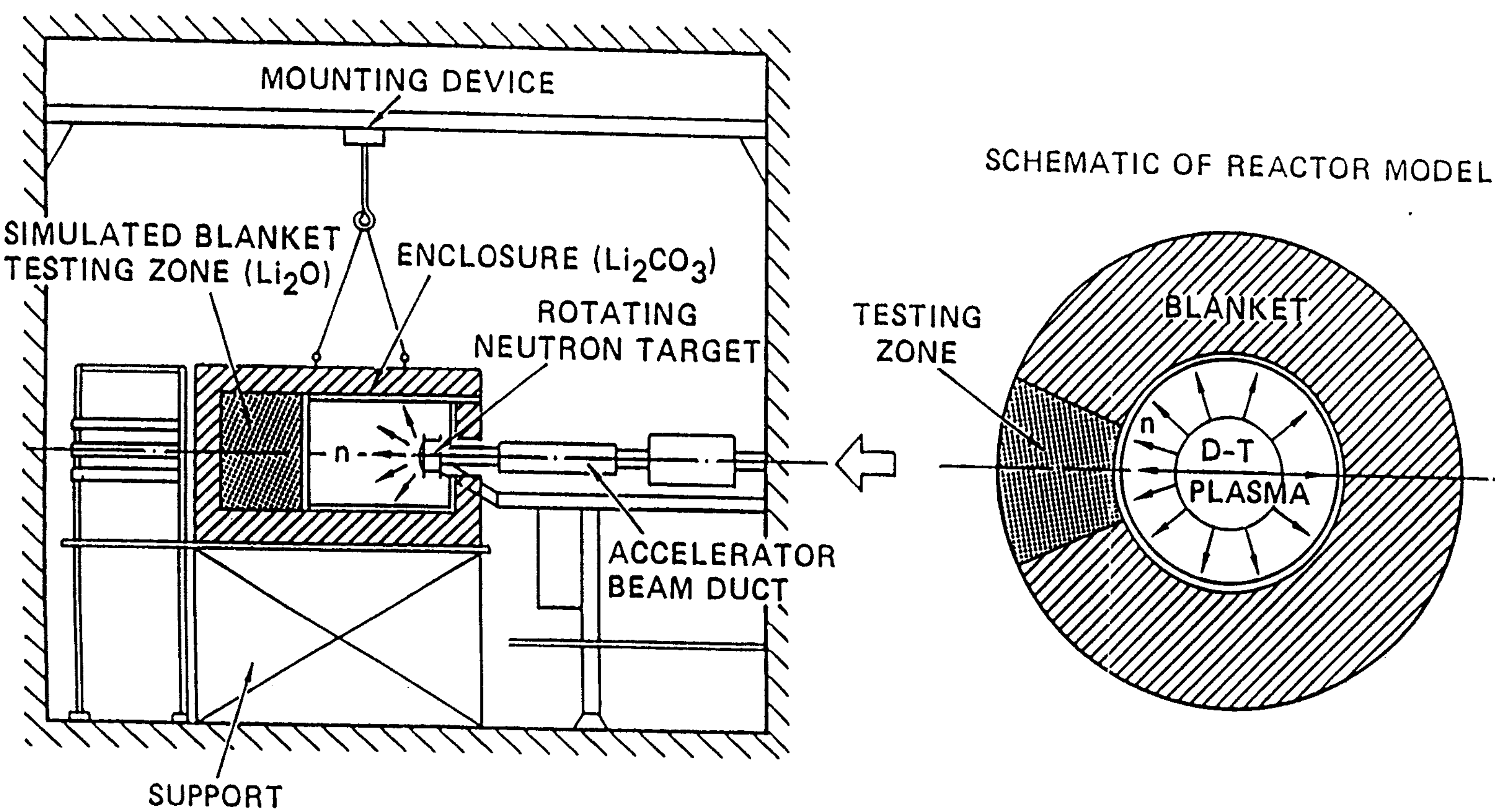
* At bulk region inside the Li_2O assembly, calculations for T_6 are larger by 30-35% than measurements. U.S. values are 10-15% larger than JAERI's. Including front zones (e.g., FW or beryllium), lessens the derivation (20-25%)

T_7:

* T_7 profiles are consistently larger than experimental values by 25% (U.S.) and 15% (JAERI). Serious effort is needed to improve ^7Li data [elastic, total, $(n,n'\alpha)$]. Sensitivity analysis showed that T_6 is most sensitive to ^7Li data particularly at middle locations. T_7 is most sensitive to ^{16}O data

Phase II

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



System Considered in Phase IIA

- Reference Li_2O assembly
- 5 cm Be + Li_2O assembly
  (Be-front system)
- 5 cm Li_2 + 5 cm Be + Li_2O assembly
  (Be-sandwiched system)

Systems Considered in Phase IIB

(in all systems, a 5 cm Be-liner covers the Li_2CO_3 inner surface)

- Reference Li_2O assembly
- 5 cm Be front system
  - With 0.5 cm FW
  - Without FW

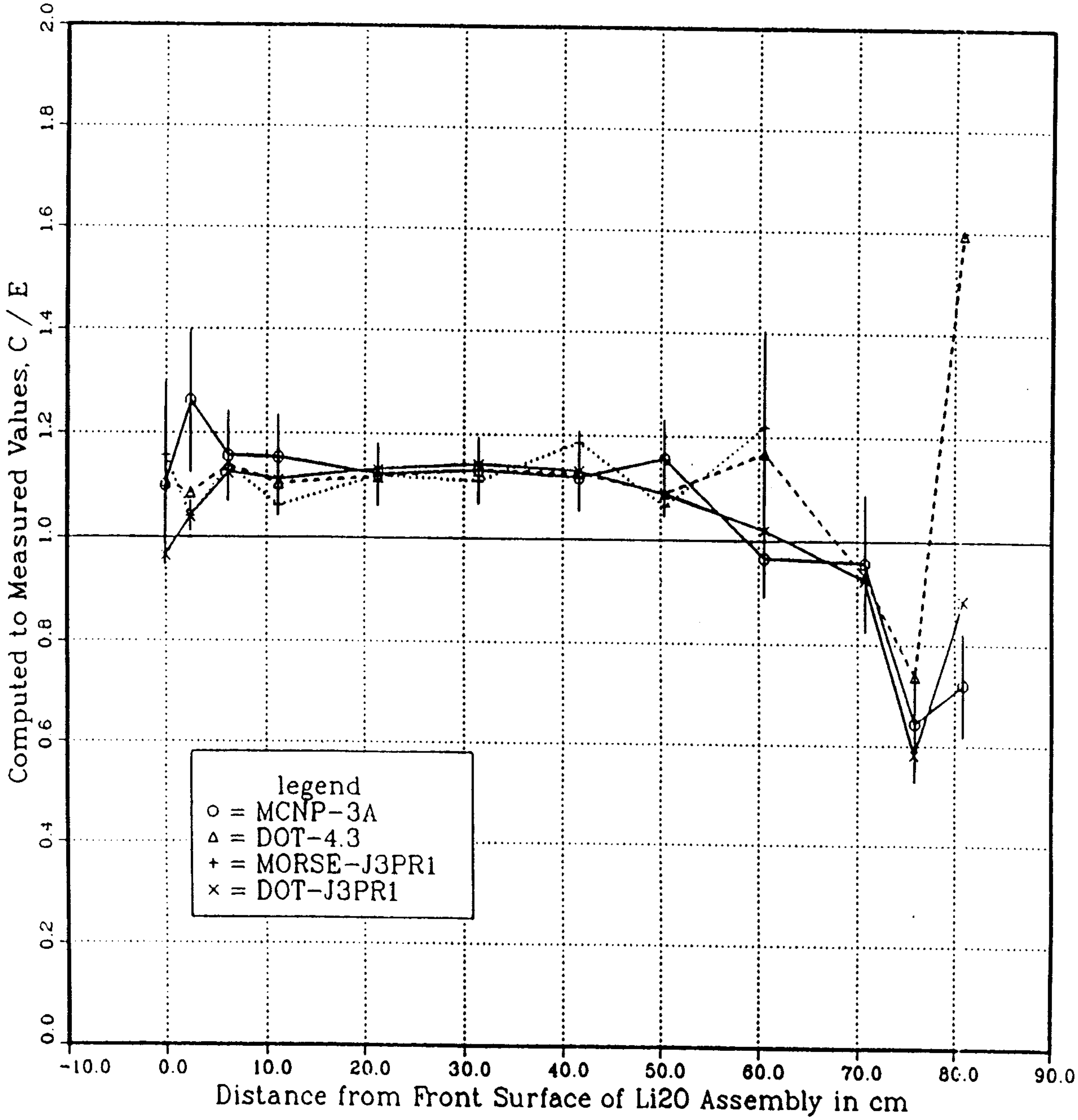
Systems Considered for Phase IIC

- Edge-on Be layers system
- Heterogeneity and coolant channels system

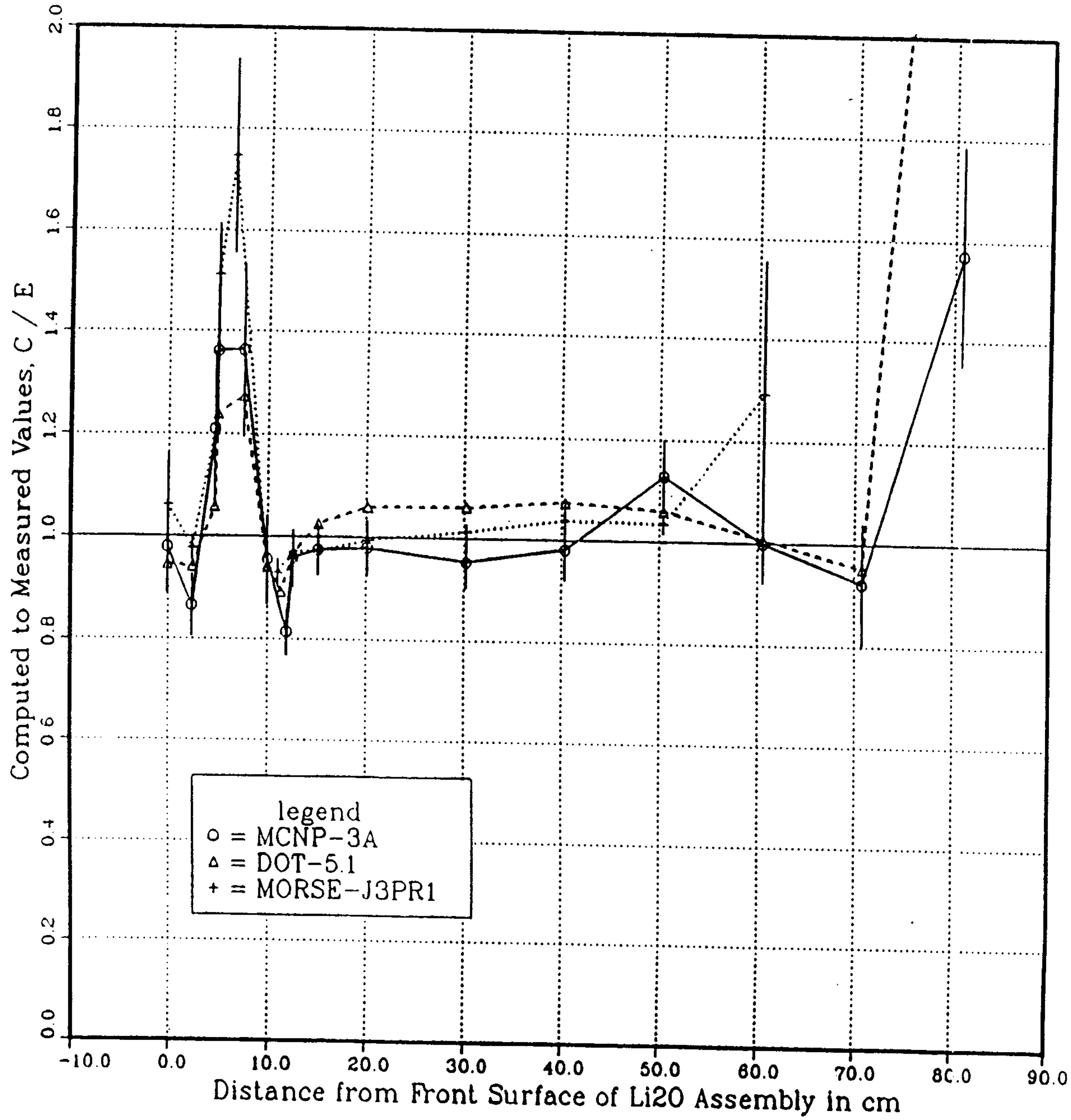
Analysis

	JAERI	U.S.
• Monte Carlo Codes	MORSE-DD	MCNP
• Discrete Ordinates Codes	DOT-DD DOT3.5	DOT4.3 DOT5.1
• Nuclear Data File	JENDL-3PR1	ENDF/B-V (LANL: ^{7}Li, ^{9}Be)
• Cross-Section Libraries	DDL/J3P1(125-g)	MATXS6(80-g) RMCCS/BMCCS

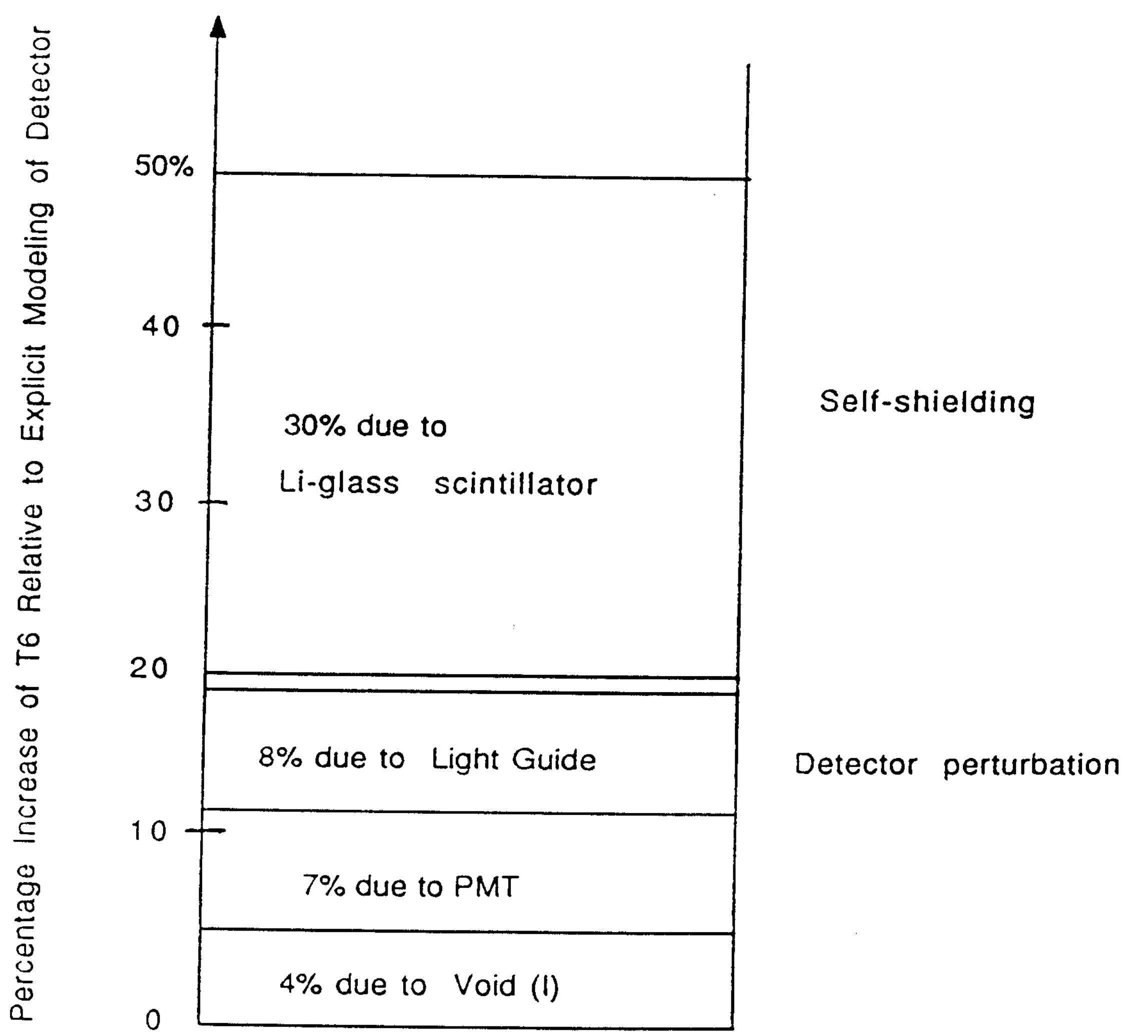
TRITIUM PRODUCTION RATE FROM LI-6,T6,USING LI-GLASS DETECTOR IN CENTRAL DRAWER (REFERENCE CASE OF FNS PHASE-2



TRITIUM PRODUCTION RATE FROM LI-6,T6,USING LI-GLASS DETECTOR IN CENTRAL DRAWER (BE-SAND. CASE OF FNS P-2A)



Impact of Detector Materials on T_6 in Beryllium Zone



OBSERVATIONS ON ANALYSIS OF PHASE II EXPERIMENTS

Local T_6:

- No steep profiles for T_6 are found at front locations as in Phase I. Better prediction in Phase II. Deviation from measured values is improved (~20%)

- T_6 is overestimated by all codes and libraries applied at all locations along the central axis where Li-glass detectors are used (C/E =1.1-1.2). Better agreement with Li-metal measurement (C/E = 1.0-1.2). Overestimation still persists even in the Be experiments

- Large C/E values were found inside the Be zone (C/E ≈ 1.5). The discrepancy is attributed to:

  - Flux perturbation by Li-glass components (~20%)
  - Self-shielding effect (~30%)

  The geometrical details of the detectors should be considered in the calculational model inside zones that have soft spectrum

- Discrepancies were also found between JAERI and the U.S. calculations inside the Be zone and at the boundaries. The secondary energy/angle distributions for the Be(n,2n) reactions need to be re-evaluated

OBSERVATIONS ON ANALYSIS OF PHASE II EXPERIMENTS, (cont'd.)

Local T_7:

- Predictions still overpredict T_7 and the C/E values obtained by the U.S. are larger than those obtained by JAERI

C/E	= 1 - 1.2	U.S., Reference System
	= 0.8-1.1	JAERI, Reference System

- There is a decreasing trend in the C/E curve in JAERI's calculation at deep locations. The C/E values fall below unity after 20-30 cm depth in the Li_2O assembly

- Direct comparison between JENDL-3PR1 and Young's evaluation for ^{7}Li showed:

  - ^{7}Li(n,n'a)t cross-section in JENDL-3PR1 is underestimated by 8-10%

  - Overestimation in the ^{7}Li(n, elastic), ^{7}Li(n,γ) and ^{7}Li(n,d) in JENDL-3PR1. This leads to descending slope in JAERI's calculations

  - It was also shown that oxygen and iron data in JENDL-3PR1 overmoderate neutron energies through (n,elastic) (n,inelastic) scattering in comparison to ENDF/B-V data

Integrated Zonal TPR from Natural Lithium in the Reference and the Be-Sandwiched System

a. Increase in the tritium breeding potential

Method	Reference		Be-sandwiched	
MCNP(U.S.)	2.442-28	(1.0)	2.644-28	(1.083)
DOT (U.S.)	2.657-28	(1.0)	2.832-28	(1.066)
MORSE (JAERI)	2.541-28	(1.0)	2.727-28	(1.073)
Measurement	2.477-28	(1.0)	2.732-28	(1.103)

b. C/E values

Method	Reference	Be-sandwiched
MCNP (U.S.)	0.986	0.968
DOT (U.S.)	1.073	1.037
MORSE (JAERI)	1.026	0.998

Zonal T_6 and T_7:

- Zonal TPR measurements from natural lithium using liquid scintillation method was proven to be a successful technique. The C/E values at various zones are 0.85-2.5 (15-25% accuracy)

- Integrated TPR (indicative of TBR) has better predictive accuracy with this technique due to error cancellation. The C/E values in this case are 0.99 - 1.07 (1-7% accuracy) as predicted by various codes and libraries

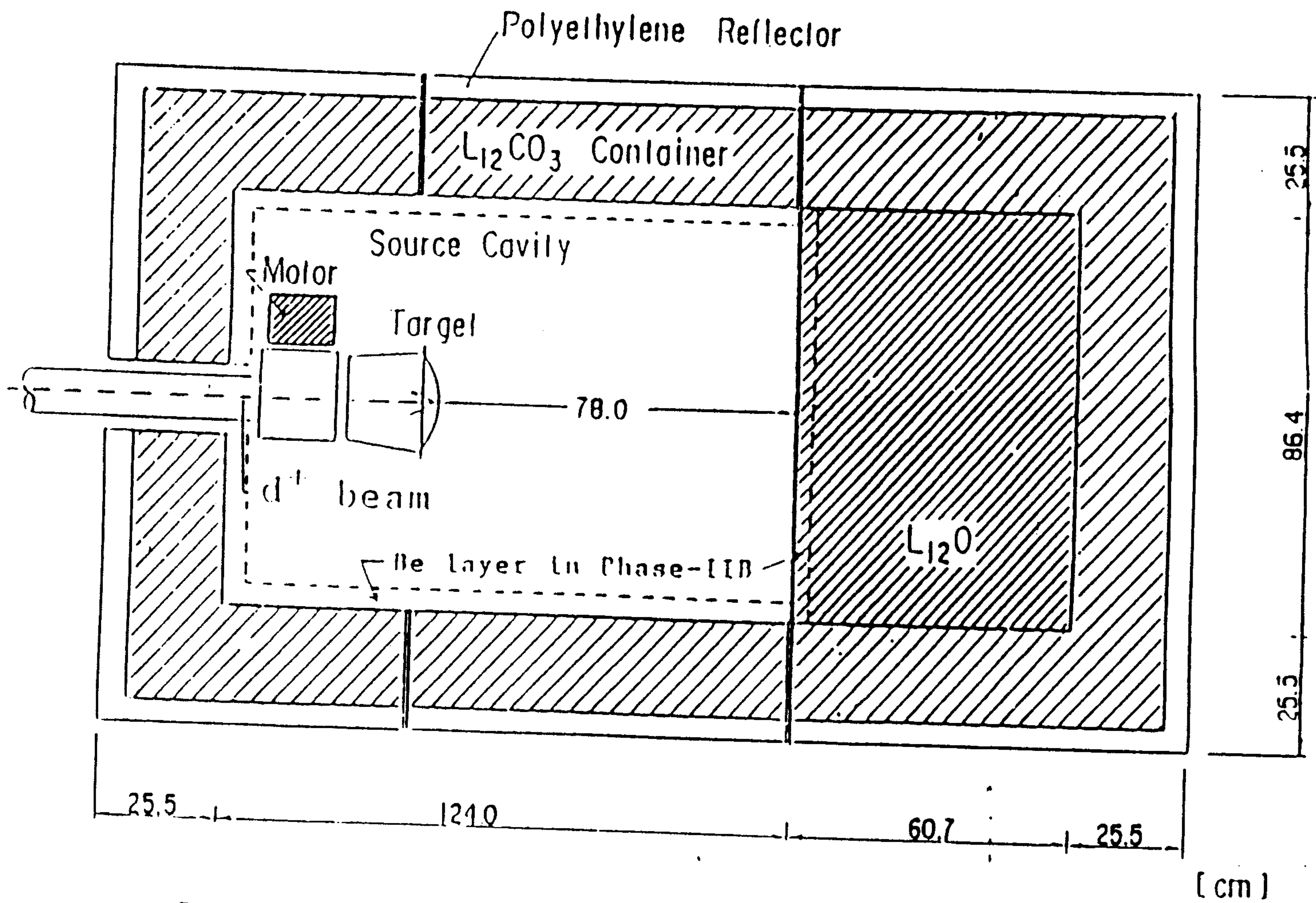


Fig. 1 Experimental system configuration for the JAERI/USDOE collaborative program on fusion blanket neutronics.

Phase II B

Effect of Beryllium Liner on T_6 Profiles in Phase IIB

- Upon including the Be liner, T_6 in the reference system increases appreciably in the first 10 cm but less increase is observed at deeper locations

- In addition to increasing neutron population through ^{9}Be (n,2n) reactions, the incident spectrum is softer than in Phase IIA (leads to larger T_6)

- Including the Be liner tends also to increase T_6 behind the Be layer in the Be-front system. However, the increase is less pronounced than in the reference system

- Remarkable increase in T_6 occurs inside the Be layer due to the softer incident spectrum in Phase IIB. The discrepancy between calculations and measurements in this layer is due mainly to the self-shielding effect and flux perturbation by the detector components

Characteristics of T_6 Profiles in Phase IIB

- At front locations in the reference system, the C/E values calculated by the U.S. are lower than that of JAERI
- The C/E values obtained by JAERI inside the Be layer in the Be-front system are larger than that of the U.S.
  - In Young's evaluation for the ^9Be (n,2n) reactions at high energy, the emission spectrum has a low-energy component (E_n < 0.5 MeV) in comparison to JENDL-3PR1 evaluation
- The C/E values obtained by JAERI are larger at the front surface of the Be layer and lower just behind it
  - Takahashi showed that the angular distribution of the ^9Be(n,2n) cross-section of JENDL3 at 14 MeV is overestimated in the backward direction and under-estimated at the forward direction
- The C/E values fall below unity just behind the front Be layer, then rise sharply after 3-5 cm to reach more or less steady values, and then decrease toward back locations

The Above Observations are Supported by:

- Oyama and Maekawa's experiment where it was shown that the emerged spectrum from a 5 cm-thick slab is:

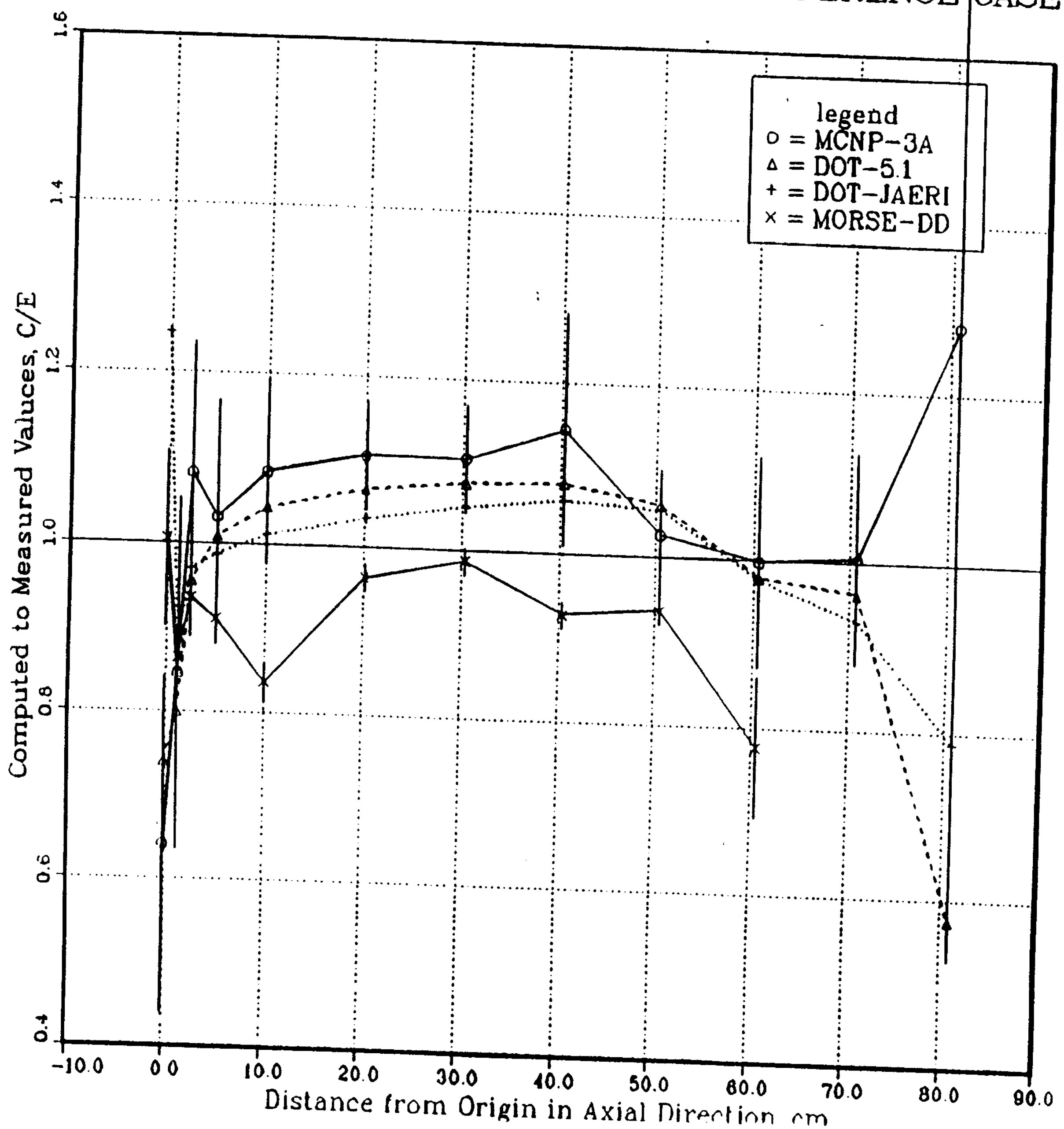
  * underestimated by Young's and ENDL-3PR1 data by ~10-30% in the energy range 0.1 MeV < E < 0.5 MeV

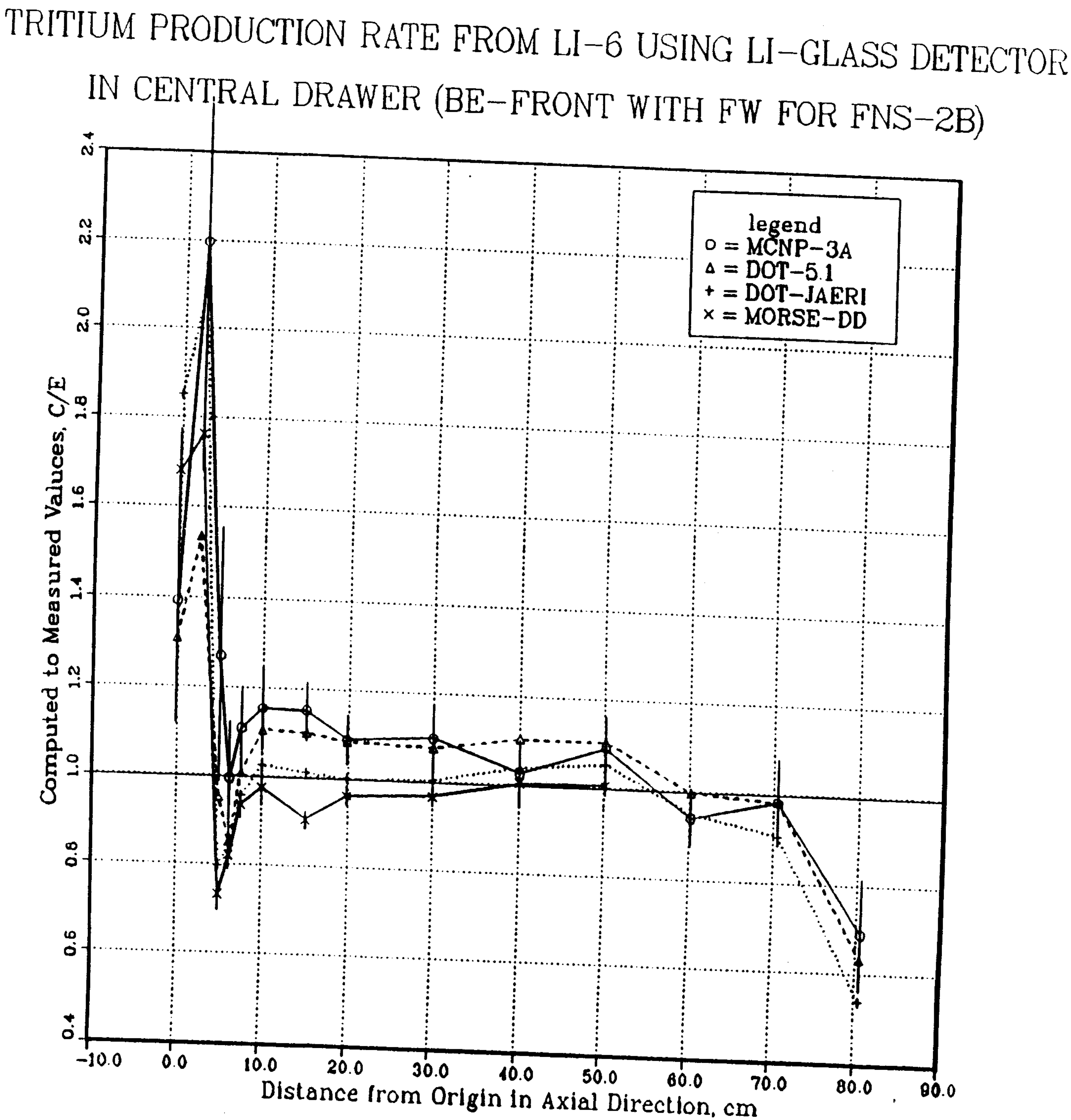
  * overestimated by Young's data (by 10-20%) in the energy range 2-10% MeV but under-estimated (by 20-40%) with JENDL-3PR1 data in this energy range

  * underestimated by 20-30% with both evaluations in the energy range E > 10 MeV

- Comparison between calculated and measured spectrum in the energy range 2-10 MeV at the entrance of the Li_2O assembly in Phase IIB (with Be liner) where calculations overpredict spectrum in this energy range

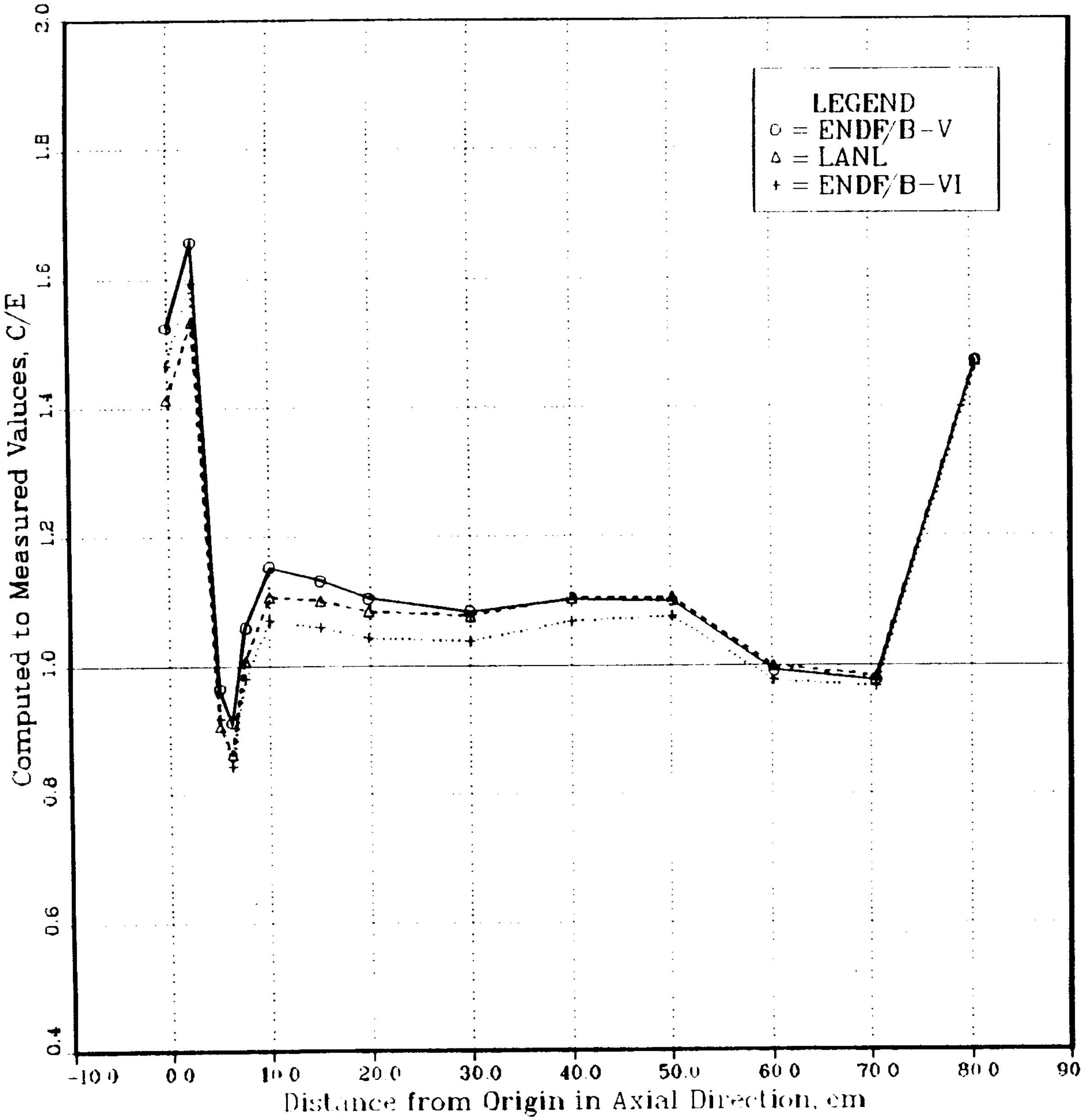
TRITIUM PRODUCTION RATE FROM LI-6 MEASURED BY LI-GLASS
IN CENTRAL DRAWER OF PHASE-2B REFERENCE CASE




TRITIUM PRODUCTION RATE FROM LI-6 USING LI-GLASS DETECTOR
IN CENTRAL DRAWER (BE-FRONT WITH FW FOR FNS-2B)
legend
o = MCNP-3A
Δ = DOT-5.1
+ = DOT-JAERI
× = MORSE-DD
Computed to Measured Values, C/E
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
-10.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
90.0
Distance from Origin in Axial Direction, cm

TRITIUM PRODUCTION RATE FROM LI-6 MEASURED BY LI-GLASS

IN CENTRAL DRAWER OF PHASE-2B BE-FRONT W/ FW



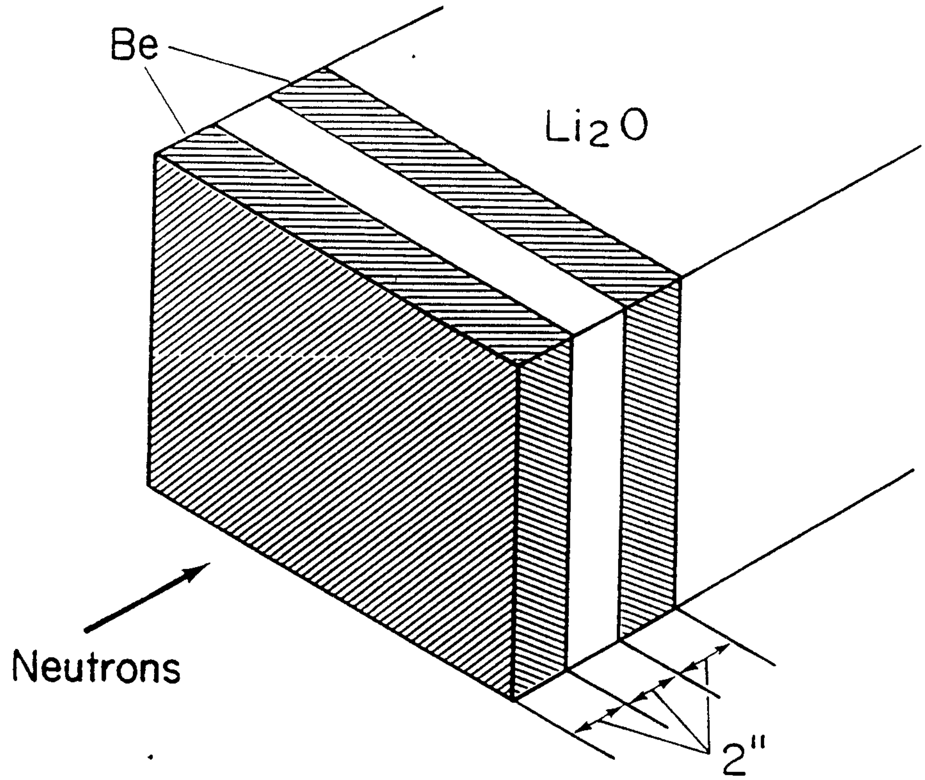
Remarks on Beryllium Data of ENDF/B-VI and Impact on T_6 and T_7 Profiles

- Better agreement with measurements of T_6 and tritium production from natural lithium is obtained by ENDF/B-VI beryllium data as compared to Be data of LANL and Be data of ENDF/B-V.

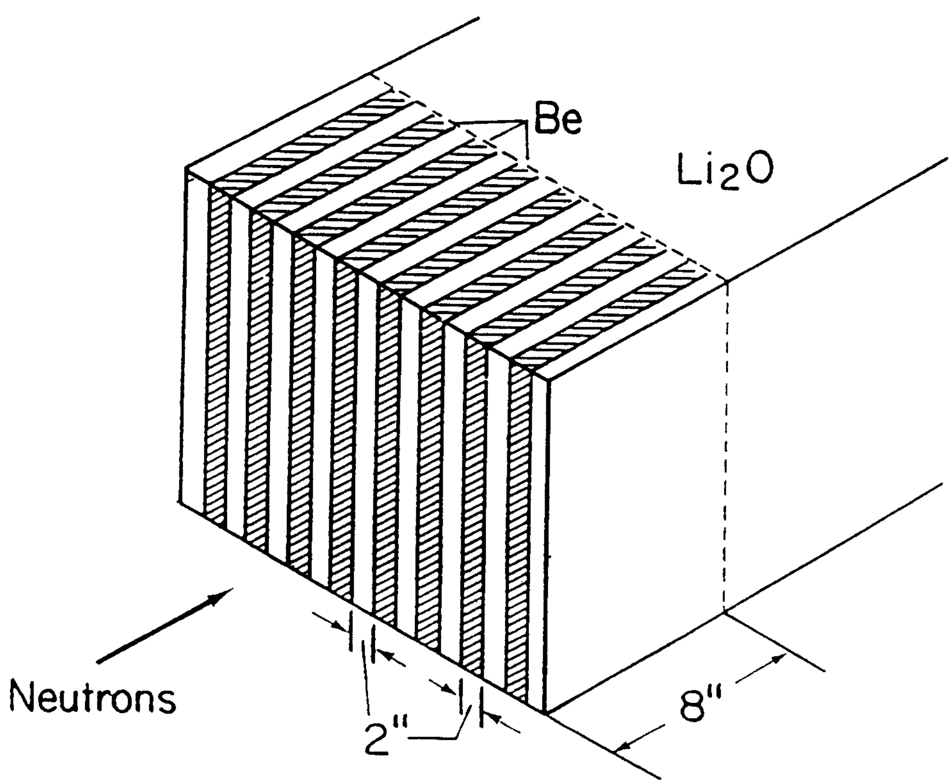
- Be (n, 2n) cross-section of ENDF/B-VI is 5-8% less at 14 MeV than the cross-section of ENDF/B-V and LANL evaluation.

- Be (n, 2n) cross-section in ENDF/B-V and LANL overestimates the SED of the emitted neutrons in the energy range 10-14 MeV.

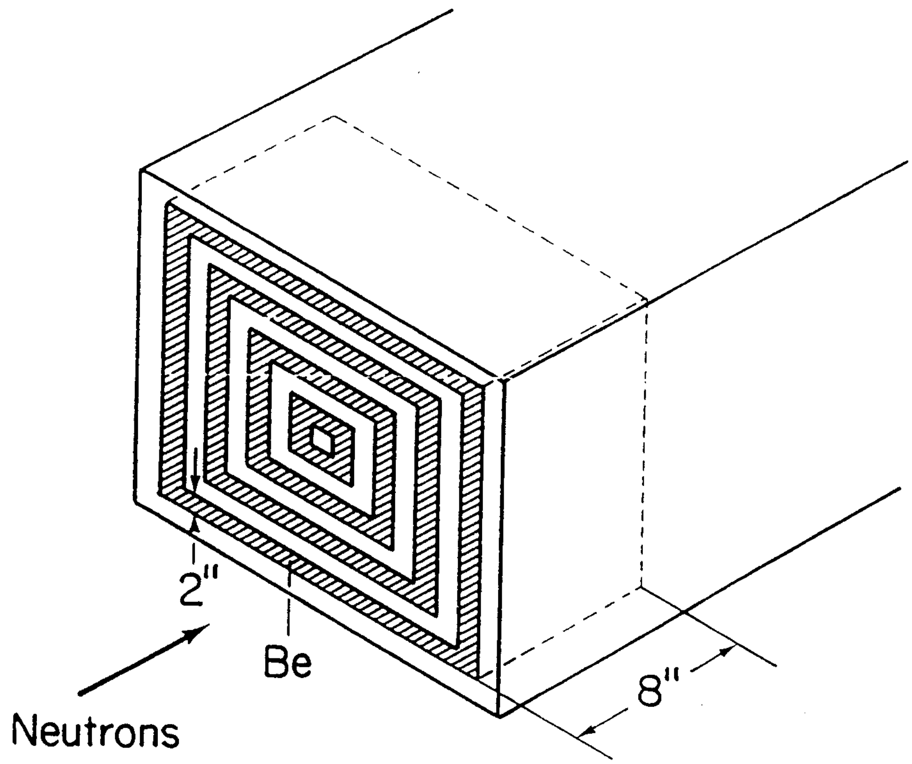
Multi - Layer Arrangement



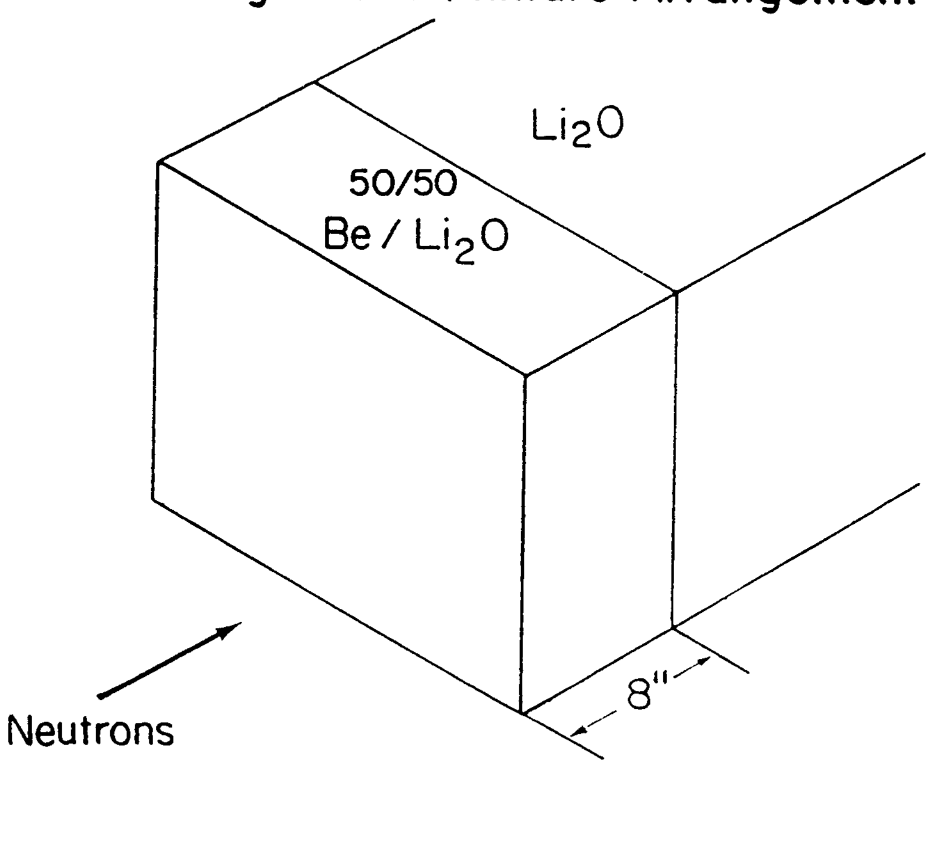
Edge - On Arrangement

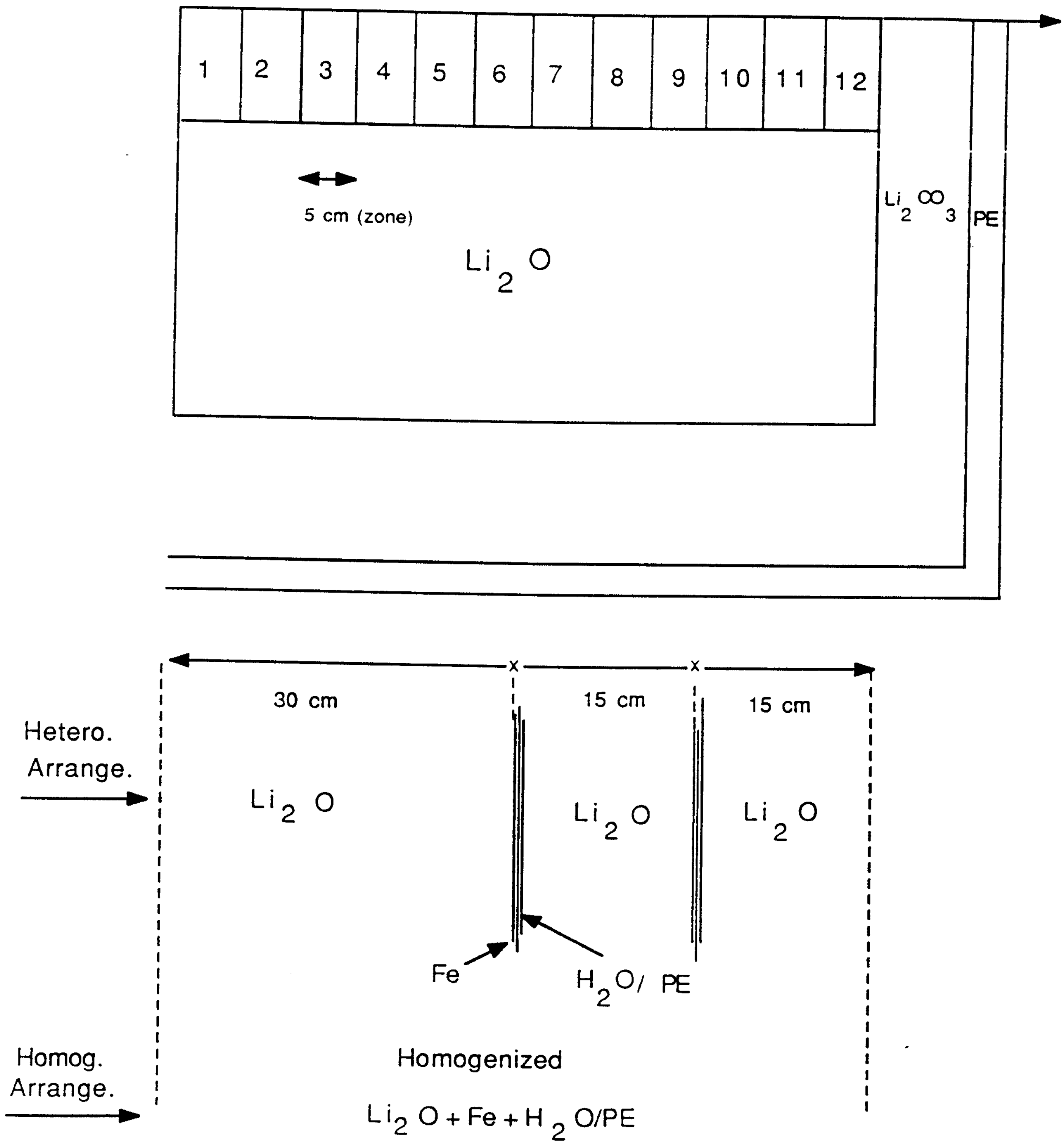


Be - Ring Arrangement



Homogeneous Mixture Arrangement





1
2
3
4
5
6
7
8
9
10
11
12
5 cm (zone)
Li_2O
Li_2CO_3
PE
30 cm
15 cm
15 cm
Hetero. Arrange.
Li_2O
Li_2O
Li_2O
Fe
H_2O/ PE
Homog. Arrange.
Homogenized
$Li_2O + Fe + H_2O$/PE

Radioactivity and Decay heat Experiments Testing the New Approach

- The new approach of integral radioactivity measurements has been tested in a moderate effort as a joint UCLA-JAERI activity.

- Measurements of Decay γ-ray Spectra (December, 1988)

  - Neutron Source: D-T neutron generating Fusion Neutronics facility of JAERI, Japan

  - Simulated Blanket: Li_2O test assembly inside a Li_2CO_3 enclosure (Phase IIC experiments)

  - Neutron Intensity: 2×10^{12} n/s for 9 and 10 hours

  - Material samples: Fe, Cr, Ni, Mo, SS316, V, W, MnCu alloy, Ti, Co, Zr, Nb, Al, Si, Ta, In, Mg, Au $YBa_2Cu_3O_7$, $ErBa_2Cu_3O_7$ (high temperature superconductors). Samples irradiated at two locations with different neutron energy spectra.

Radioactivity and Decay heat Experiments (continued)

- Typical dimensions:
  Fe: 5 mm dia. x 1 mm th.
  Zr: 12.7 mm dia x 0.127 mm th.

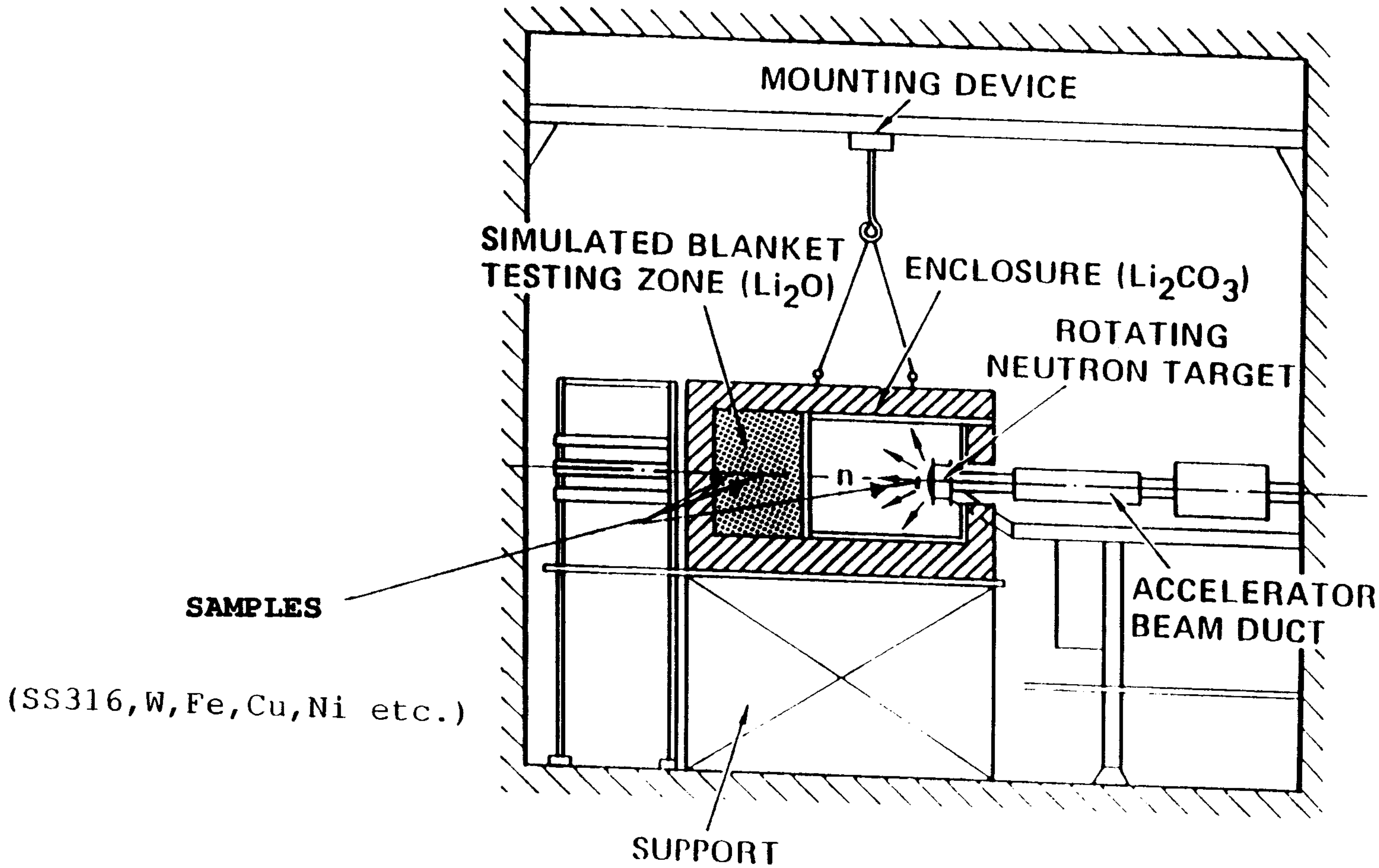
- Half lives: 2.24 m (^{28}Al) to 5.27 y (^{60}Co)

- γ-energy range: 60 KeV - 3 MeV

- Measuring equipment:
  γ-spectroscopy by four Intrinsic Germanium Dectectors linked to Canberra 8088 MCA's

- Strategy of measurements:
  measure γ-spectra at multiple cooling times for each sample

SET-UP FOR RADIOACTIVITY/AFTERHEAT UCLA EXPERIMENTS AT FNS (USDOE/JAERI PROGRAM)



Phase III Experiments

Characteristics:

- Test assembly is moved back and forth with the point D-T neutron source at the middle cavity to create a line source

- The angular and energy distributions of incident neutrons will be appreciably different from those of a point source. Better simulation to plasma source conditions in the toroidal direction will be achieved

- Test module has rectangular cross-section of a thickness ~50 cm. The inner cavity cross-section is also rectangular with ~1 m^2 area

Phase IIC Experiments

Multi-layers of Beryllium

- multi-layers of beryllium inside the Li_2O assembly are considered in various configurations

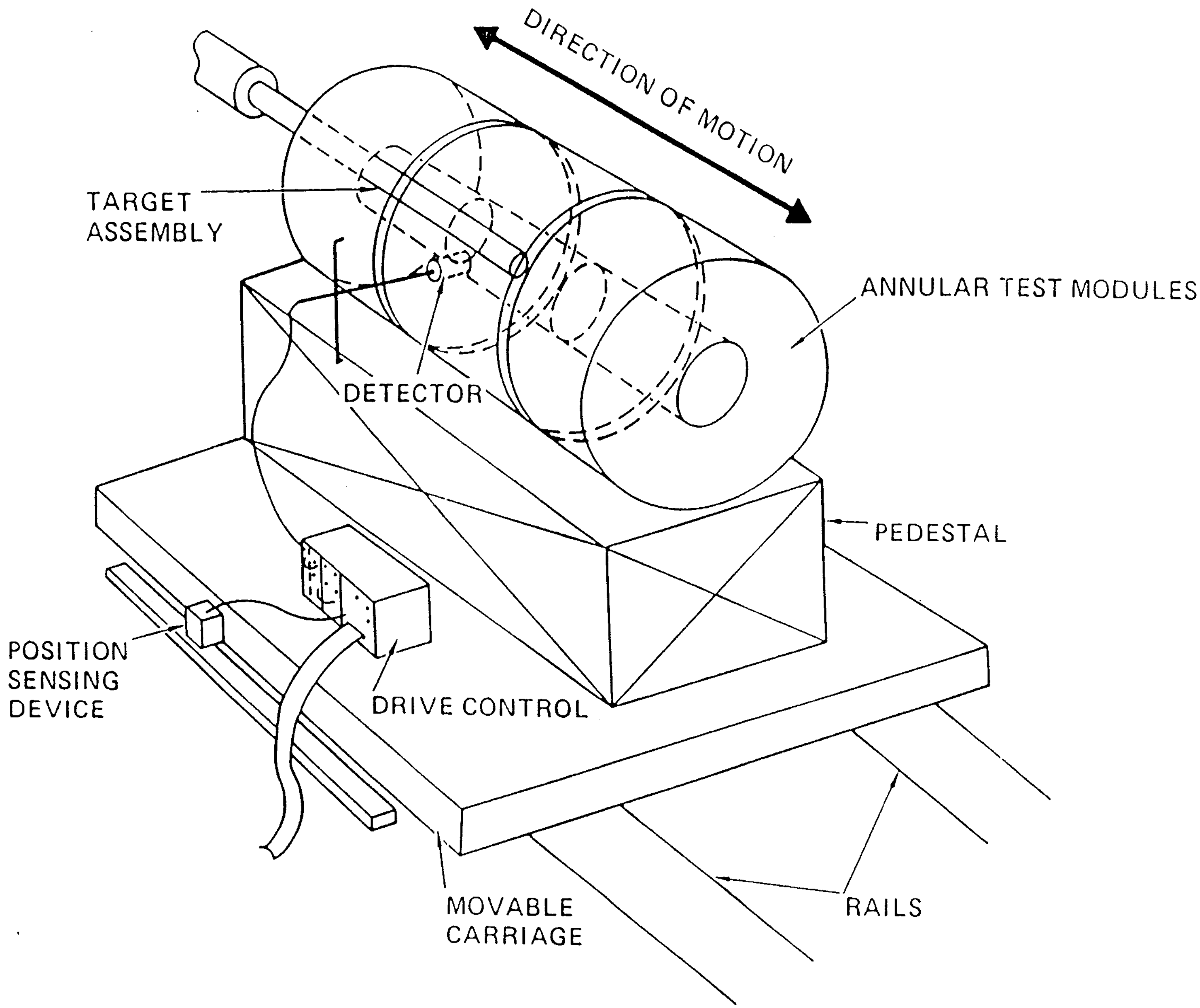
- edge-one configuration was chosen based on its higher TPR performance

Heterogeneity and Coolant Channel Effect

- Pre-analysis indicates appreciable changes in TPR around heterogeneity/coolant channels

  - 30-40% increase in T_6
  - about 50% decrease in T_7
  - net increase in TPR around heterogeneity by ~12%

Phase IIC was completed during the experimental period Oct. 15 - Dec. 15, 1988. Activation and decay gammas were measured for various cooling time after irradiation during this phase in several foils made of Fe, Ni, Cr, etc. Comparison of predictions to measurements are underway.


DIRECTION OF MOTION
TARGET ASSEMBLY
ANNULAR TEST MODULES
DETECTOR
PEDESTAL
POSITION SENSING DEVICE
DRIVE CONTROL
MOVABLE CARRIAGE
RAILS