U.S. OVERVIEW OF JAERI-US COLLABORATION
ON FUSION NEUTRONICS
AND
REMARKS ON ROLE OF NEUTRONICS
IN NEXT FUSION DEVICE

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16 June 1987

Introductory Remarks

- The Joint Effort has Made Remarkable Technical Progress

    - We gained much experience from Phase I

    - Phase II is clearly very successful. The uncertainty in TBR has substantially been reduced for the simple assembly

- The Collaboration Program is an Excellent Example of a Very Successful International Cooperation Arrangement

- The Importance and Complexity of the Tritium Self-Sufficiency Issue Are Now Better Recognized

- The Next Fusion Engineering Facility (ITER) has Key and Fundamental Issues Related to Neutronics and Self-Sufficiency Demonstrations

- Our Near-Term Effort Should Focus on the Following:

    - Proceeding with more prototypical experiments (geometrical complexity, penetrations, heterogenity, etc.)

    - Sophistication in interpretation of experimental results

    - Answering near-term questions related to ITER

Present U.S. Effort by Organization

UCLA

- Overall Coordination and Technical Direction

- Pre- and Post-Experiment Analysis

- Sensitivity/Uncertainty Analysis

- Generate Suitable Data Base in Collaboration with LANL and Others

- Identify Sources of Uncertainties; Recommend Actions for Improvements in Methods and Data

ANL

- Development of Measurement Techniques

- Direct Participation in Experiments and Performing Measurements

- Experimental Data Processing

- Material Fabrication and Preparation

ORNL

- Monte Carlo Analysis for Cavity (Flux Mapping)

- Source Characterization

LANL

- Data Processing and Library Preparation

Status of Technical Activities in the U.S. for the Collaboration Program

Phase I

- All Calculations and Analyses Completed

- Documentation Under Way; Joint Report to be Completed Soon

Phase II

- Extensive Analysis of All Three Experiments Have Been Performed

  - Reference
  - Beryllium Front
  - Beryllium Sandwich

- All the Foils from the August 1986 and Most of the Foils from February 1987 Have Been Processed

- Further Effort, Particularly in the Analysis Area, is Planned

Others

- Beryllium Shipped from ANL to FNS

- Proton Recoil Counter: Work Completed; Assembly Ready for Shipment

- Pre-Experiemnt Analysis for Phase II is in Progress

- Evolution of Alternative Breeder Materials in Progress

Phase I

Table 1: Range of the Calculated to Measured Values, C/E,
of Tritium Production Rate from ^{6}Li (T_6) and ^{7}Li (T_7)
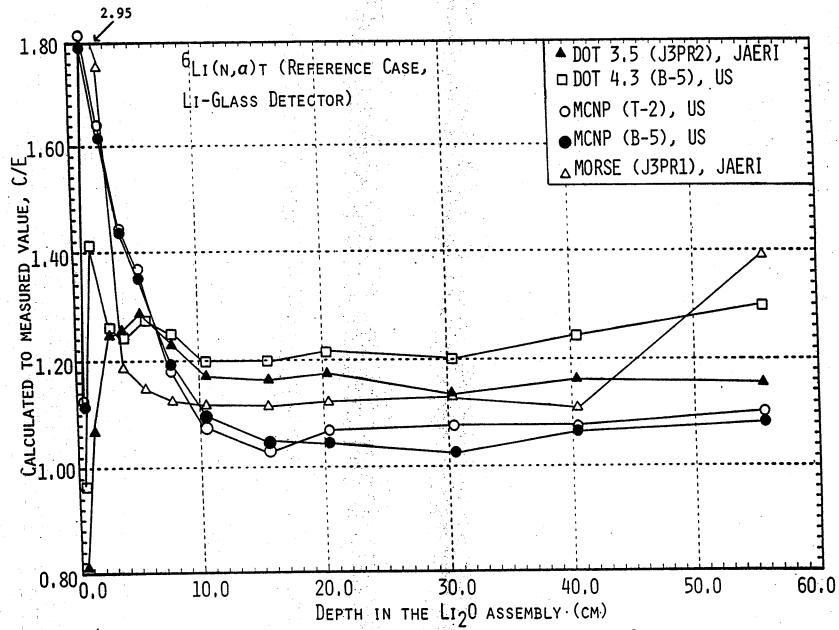as Obtained by the U.S. and JAERI based on deterministic Methods

Type of Experiment and Method Applied	T_6		T_7	
	U.S.	JAERI	U.S.	JAERI
(A) Reference Experiment	$(0.9, 1.4, 1.25)^a$	$(0.8, 1.3, 1.2)^a$	$\sim 1.2^d$	$\sim 1.05^d$
(B) First Wall Experiments	$(1.18, 1.25, 1.3)^a$	$(0.8, 1.15, 1.1)^a$	$(1.18, 1.2)^d$	$\sim 1.05^d$
(C) Beryllium-Sandwiched Experiment				
Li-glass method	$(0.9, 1.15, 1.2)^b$	$(0.65, 1.35, 1.1)^b$	$(1.2, 1.28)^d$	$(1.05-1.1)^d$
Li-metal method (U.S.)	$(5.6, 1.1)^c$	$(5.2, 0.9)^c$		
Li$_2$O-Pellet method (JAERI)	$(2.4, 1.25)^c$	$(2.3, 1.1)^c$		

(a) C/E values at the front surface, the first few centimeters, and at the back region of the Li$_2$O assembly, respectively

(b) C/E values at the front surface of Li$_2$O layer, at the beryllium zone, and at the bulk of the Li$_2$O assembly, respectively
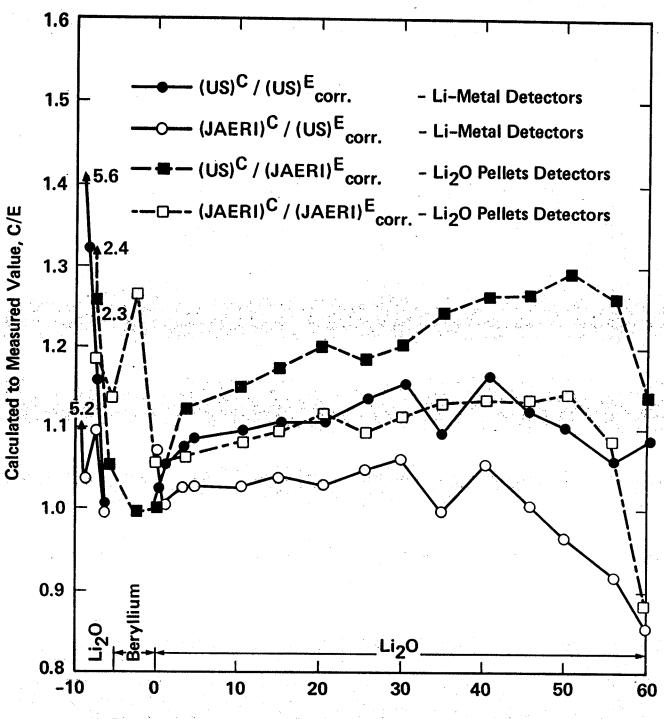
(c) The largest and lowest value of C/E, respectively

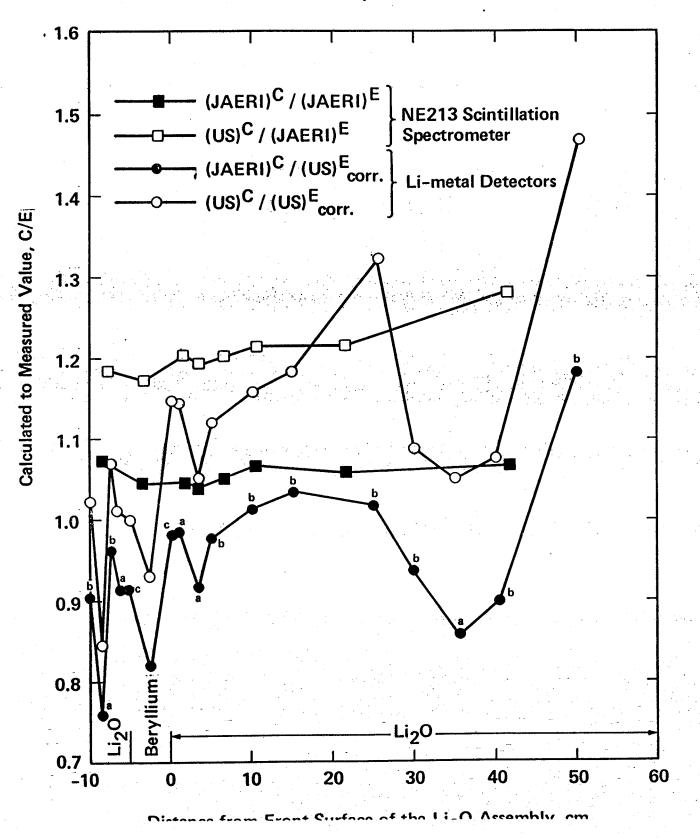(d) Obtained by the NE213 indirect method

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

PHASE 1

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

Tritium Production Rate from ^{7}Li, T_7, in the Beryllium-Sandwiched System
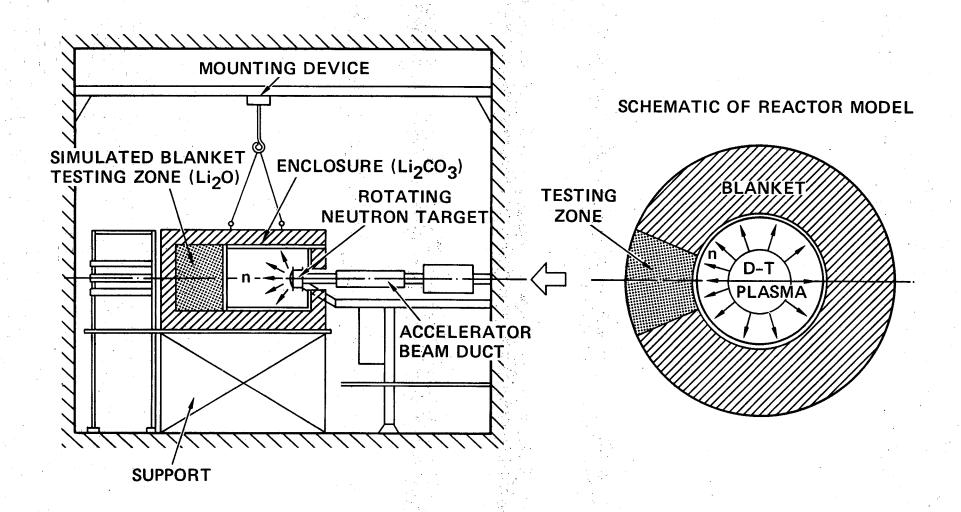
Summary Observations on Phase I Experiments

- Primary Characteristic: Open Geometry; Concrete Walls of Target Room #2 are Used as the Enclosure to the Rotating Target. The Li_2O Test Assembly is Embedded in the Wall at $80°$ to the D^+ Beam

- Large Discrepancies are Found in T_6 at the **Front** Locations of the Li_2O Assembly as Determined by Both Deterministic and Monte Carlo Methods **(C/E ~ 0.8-5)** Even After Correcting for Self-Shielding Effect. Possible Causes for These Discrepancies are:

    - Inaccuracy in predicting the angle/energy distribution of the low-energy room return component of incident neutrons due to:
      * complexity involved in modelling the neutron target structure and surrounding equipment
      * uncertainty in the atomic density of the concrete wall

    - Sensitivity of results to the interpolation scheme applied to calculated values of the **steep profile of T_6** near the front edge

    - Approximations used to derive the self-shielding factors and sensitivity of these factors to atomic densities of detectors

- At Deeper Locations in the Li_2O Assembly, the Calculated Values for T_6 are Larger than Measurement by ~ 30%. This Deviation is Lower for Experiments that have Front Zones of FW or Beryllium (deviation ~ 20-25%)

- The Calculated T_7 is consistently Larger than Experimental Values by ~ 20% (US) and 10% (JAERI). The $^7Li(n,n'\alpha)t$ Cross-Section Needs Re-Evaluation.

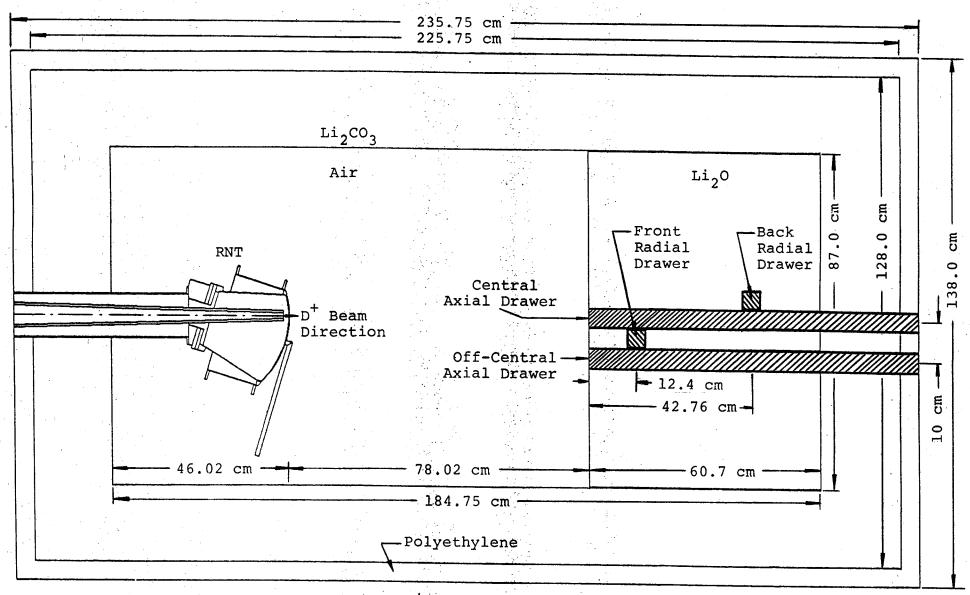# Summary Observation from 3-D Analysis for Phase I

- Using same model, two calculations using Li_7 nuclear cross-section from ENDF/B-V version 1 and from Young's re-evaluation were performed. At bulk locations, except for T_7 and $^{58}Ni(n,2n)^{57}Ni$, the C/E values from version 1 are lower and closer to unity than those from Young's. For T_6, deviations in C/E are about 5% and 10%, respectively.

- Calculated T_7 using ENDF/B-V version 1 for Li_7 is consistently higher than that using Young's re-evaluation by ~ 15%. Comparing to direct measured values (Li-foil case) in the reference case, the deviation in C/E for T_7 from unity in the calculation using Young's is about 5%.

- In the Be-sandwiched case, the Be nuclear cross-sections from ENDF/B-V were used. Compared to the 2-D calculation which used LANL's evaluation at locations within and near the Be layer, the ENDF/B-V data gives much higher neutron multiplication. Nuclear data of Be in ENDF/B-V needs to be re-examined.

- Due to different self-shielding correction techniques, C/E distributions of either T_6 or T_7 are not consistent among different measurements. T_6 C/E varies from 0.9 to 1.15 and 0.98 to 1.5 for T_7.

Phase II

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

CROSS-SECTIONAL VIEW OF FNS PHASE II CONFIGURATION

Axial direction: parallel to the D$^+$ Beam direction
Radial direction: perpendicular to the page

Status of Experimental Results (ANL)

- August 1986 Run

  - All foils processed

  - Initial counting completed

  - Data reduced and preliminary results sent to participants

  - Low count samples have been re-run to obtain better statistics

  - Data reduction of re-run sampels is in progress

- February 1987 Run

  - All foils, except for 12 ^{6}Li foils, have been processed

  - Counting completed on processed foils

  - Data reduced and preliminary results sent to participants

  - Foil processing and counting of remaining samples will be completed in July 1987

<u>Proton Recoil Counter (ANL)</u>

- Status

  - Detector assembly completed

  - Electronics are completed

  - Calibration completed

  - Assembly being prepared for shipment

- Hardware Components

  - Detector/pre-amp assembly

  - Interfacing to FNS power supplies

  - Analog amplifiers for use with data acquisition at FNS

- Characteristics

  - 1 KeV - 400 KeV detection range

  - 4% energy resolution

- Possible Future Effort

  - Detector with range up to 2 MeV

Beryllium

- Stock of Beryllium Blocks Located at ANL

  - Cleaned

  - Sorted

  - Packed

- Total Amount Shipped to FNS

  - 642 pieces

  - 390.5 kg

- Some Blocks Have Been Activated in Previous Irradiations

  - High activation limited to a few number of blocks

  - If necessary, they can be replaced from ANL stock

- Attachment Method to Li_2Co_3 Enclosure Needs to be Identified

Phase II: Flux Mapping (ORNL)

- Calculated Results Using MORSE Have Been Obtained for Comparison with Much of the Activation Data Obtained During the Phase II Experiments

- The Method of Calculation is Similar to That Used in the ORNL Phase I Calculations. The Activation Cross Sections are from the ORACT Library.

Preliminary results at a variety of locations and for many of the activations have been obtained and compared with the experimental data. The C/E for many, but not all, of the positions and activations considered are less than +10%.

STATUS OF DISCRETE ORDINATES AND MONTE CARLO ANALYSIS FOR PHASE II EXPERIMENTS (UCLA)

| Experiment	Reference 2-D DOT	Reference 3-D MCNP	5-cm Be 2-D DOT	5-cm Be 3-D MCNP	Be-Sandwiched 2-D DOT	Be-Sandwiched 3-D MCNP
Axial Drawers						
• T_6 (Li-Glass)	√	√	x	√	x	√
• Spectra (NE213)	*	*	x	*	x	*
• Integrated Spectra	*	*	x	*	x	*
• T_7 (Indirect)	√	√	x	√	x	√
• Li-Foil						
T_6	√	√	-	-	x	√
T_7	√	√	-	-	x	√
T_N	*	*	-	-	x	*
• Li-Pellet						
T_6	*	*	-	-	x	*
T_7	*	*	-	-	x	*
T_N	*	*	-	-	x	*
• Reaction Rates	√	√	-	-	x	√
• Zonal TPR	√	√	-	-	x	x
• TLD	x	x	-	-	x	x
Radial Drawers						
• T_6: Li-glass	√	√	x	√	x	√
• Spectra (NE213)	*	*	x	x	x	√
• Integrated Spectra	*	*	x	*	x	√
• T_7 (Indirect)	√	√	x	√	x	√
• Reaction Rate	√	x	-	-	x	x
Flux Mapping						
• Reaction Rate	x	√a	-	-	-	-
• Spectra (NE213)	x	x	-	-	-	-
• Integrated Spectra	x	x	-	-	-	-

aOnly on front surface of Li_2O assembly
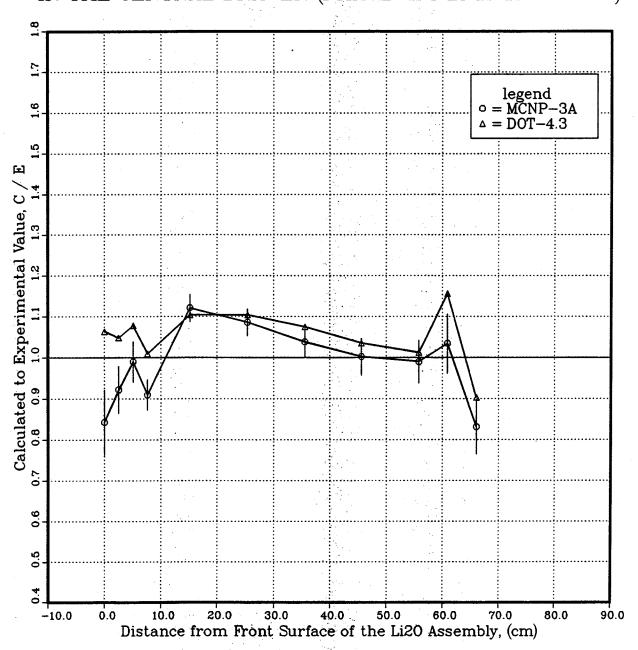
Legend: √ = C/E comparison was made
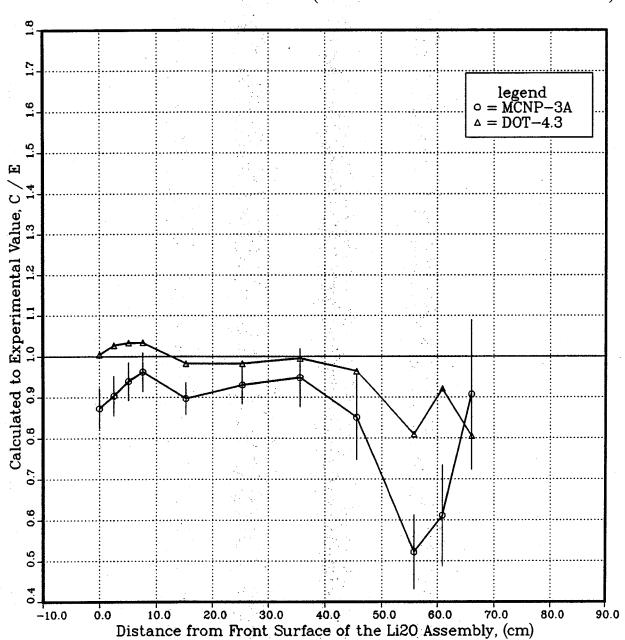* = Calculated values obtained; no comparison to experimental data
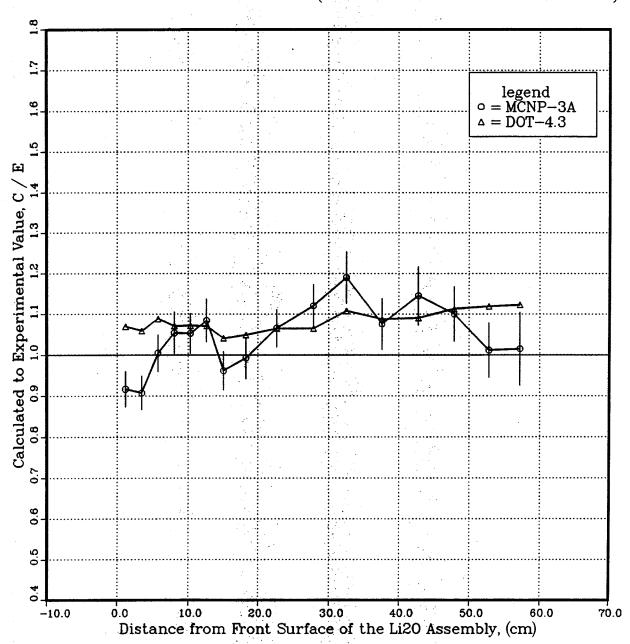x = No calculation
- = No calculation; no measurements

TRITIUM PRODUCTION RATES FROM LI−6, USING FOILS IN THE CENTRAL DRAWER (PHASE−II REFERENCE CASE)
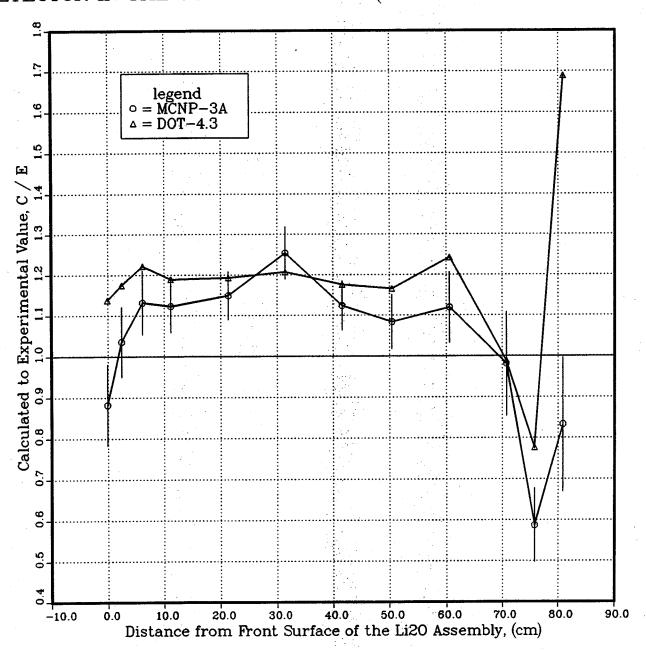
legend
o = MCNP−3A
Δ = DOT−4.3

Calculated to Experimental Value, C / E

Distance from Front Surface of the Li2O Assembly, (cm)

TRITIUM PRODUCTION RATES FROM LI−7, USING FOILS
IN THE CENTRAL DRAWER (PHASE−II REFERENCE CASE)
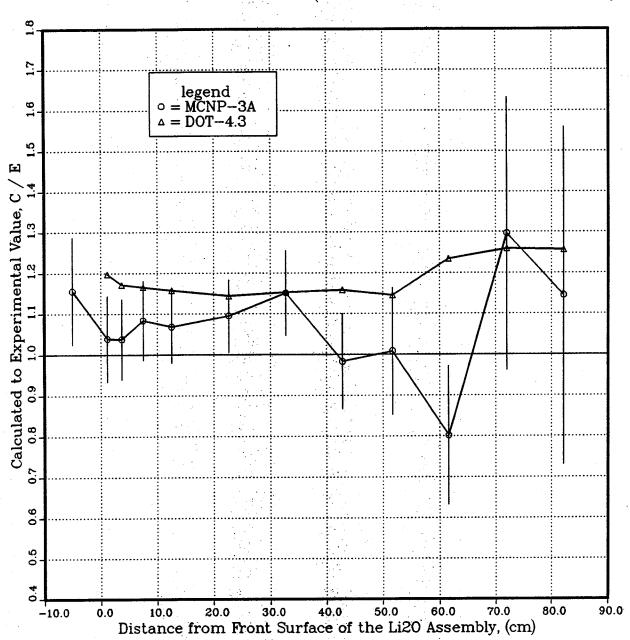
TRITIUM PRODUCTION RATE FROM NATURAL LITHIUM, ZONAL TPR
IN THE CENTRAL DRAWER (PHASE–II REFERENCE CASE)

legend
o = MCNP–3A
Δ = DOT–4.3

Calculated to Experimental Value, C / E

Distance from Front Surface of the Li2O Assembly, (cm)

TRITIUM PRODUCTION RATE FROM LI−6, T6, USING LI−GLASS
DETECTOR IN THE CENTRAL DRAWER (PHASE−II REFERENCE CASE)

legend
o = MCNP−3A
△ = DOT−4.3

Calculated to Experimental Value, C / E

Distance from Front Surface of the Li2O Assembly, (cm)

TRITIUM PRODUCTION RATE FROM LI-7, USING NE-213 DETECTOR
IN THE CENTRAL DRAWER (PHASE-II REFERENCE CASE)

Legend:
o = MCNP-3A
△ = DOT-4.3

Y-axis: Calculated to Experimental Value, C / E

X-axis: Distance from Front Surface of the Li2O Assembly, (cm)

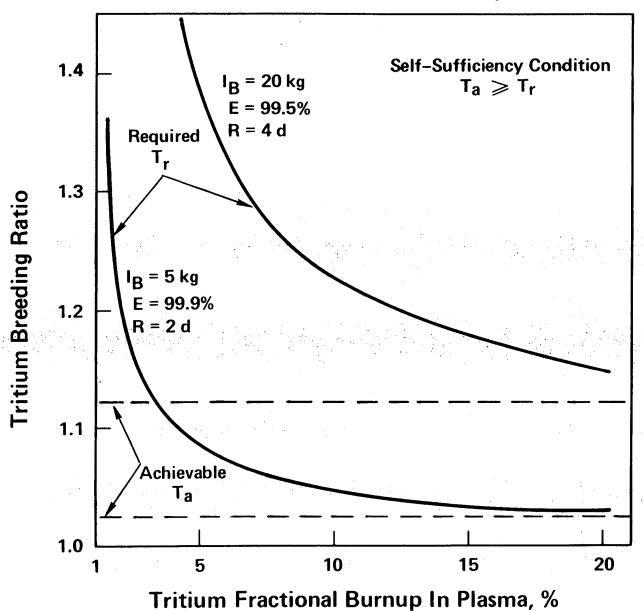## Summary of FNS Phase II Calculated to Experimental Values (C/E) for T_6 and T_7 in the First 10 cm of Test Assembly

	T_6		T_7		Zonal T_N	
	Max.	Min.	Max.	Min.	Max.	Min.
Reference Case						
DOT 4.3	1.22	1.01	1.20	1.0	1.09	1.06
MCNP 3A	1.13(.07)*	0.84(.09)	1.16(.11)	0.87(.06)	1.05(.05)	0.92(.05)
Be-front Case						
MCNP 3A						
-0.13 cm to 5 cm	0.87(.14)	0.47(.20)	1.11(.10)	1.09(.12)	--	--
5 cm to 10 cm	1.06(.08)	1.01(.11)	1.04(.10)		--	--
Be-sandwiched Case						
MCNP 3A						
-0.13 cm to 5 cm	1.29(.29)	0.95(.11)	1.02(.10)	0.97(.10)	--	--
5 cm to 10 cm	1.48(.15)	1.01(.10)	1.11(.10)	1.07(.09)	--	--

*Relative error

Tritium Fuel Self Sufficiency

Self–Sufficiency Condition
$T_a \geqslant T_r$

$I_B = 20$ kg
$E = 99.5\%$
$R = 4$ d

Required
T_r

$I_B = 5$ kg
$E = 99.9\%$
$R = 2$ d

Achievable
T_a

Tritium Breeding Ratio (y-axis: 1.0, 1.1, 1.2, 1.3, 1.4)
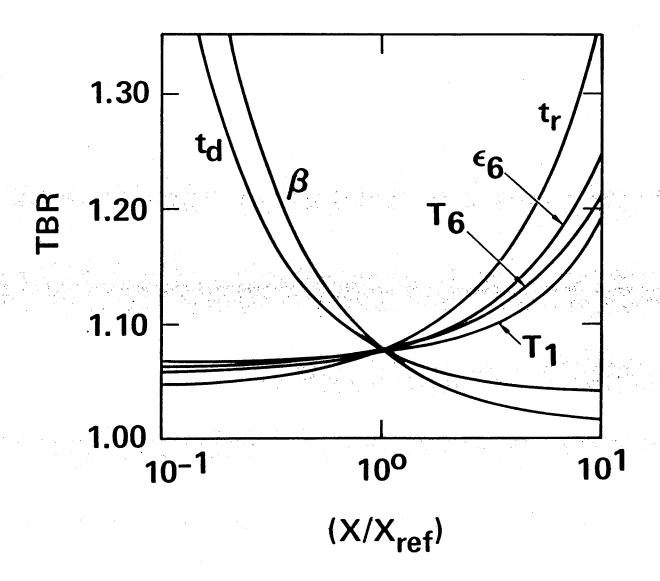
Tritium Fractional Burnup In Plasma, % (x-axis: 1, 5, 10, 15, 20)

Critical areas :

- Tritium burnup in plasma
- Neutronics data, methods, modelling
- Tritium inventory in blankets
- Tritium processing

Dependence of Required TBR
on Plasma, Engineering Parameters

Reference Case (X_{ref})

β = 5% t_d = 5y

T_1 = 10d T_6 = 1d

t_r = 2d ϵ_6 = 0.1%

Role of Neutronics R&D in ITER

Develop the Neutronics Technology Necessary to
Successfully:

- Design the basic device (radiation fluxes, shield,
   penetration, heating rates, tritium production rates,
   activation, etc.)

- Perform convincing tritium self-sufficiency tests

- Provide neutronics parameters for other component
   tests (e.g., tritium recovery tests for blanket need
   accurate spatial tritium production rates)

Usefulness of Integral Experiments and Analysis of Joint JAERI-US Program to ITER

- "Invaluable Experience" in How to Plan Good, Meaningful Experiments

    Prerequisite for complex experiments in ITER

- Key Input to Improving the Data and Method Base

- Screening Blanket Concepts (materi als and configuration)

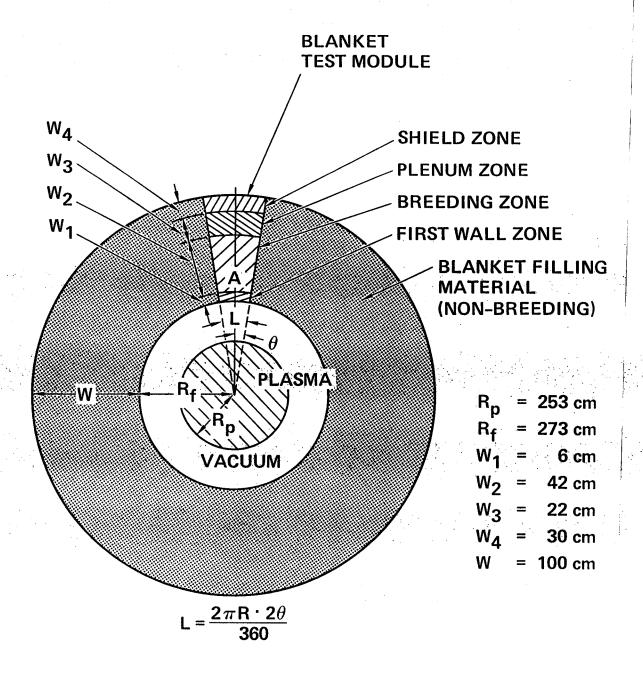- Develop Experimental Measurements Techniques

    Needed for use on ITER

- Develop Analysis Methodology to Interpret and Extrapolate Results

    Crucial for use of information from ITER that will definitely require extrapolation (particularly in self-sufficiency tests)

Example of Suggested Additional Experiments in the Joint Program of Immediate Interest to ITER

- Can we show experimentally that results from a "limited-size" test module are extrapolatable to reactor conditions with error smaller than available TBR margin?

- Series of experiments with

    - Various sizes of experimental assembly

    - Different boundary conditions (e.g., materials surrounding test module)

BLANKET TEST MODULE TRITIUM PRODUCTION

$$L = \frac{2\pi R \cdot 2\theta}{360}$$

R_p = 253 cm
R_f = 273 cm
W_1 = 6 cm
W_2 = 42 cm
W_3 = 22 cm
W_4 = 30 cm
W = 100 cm

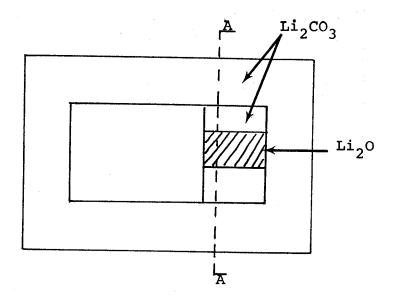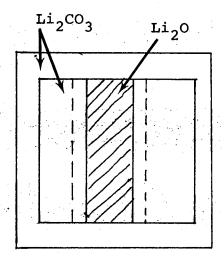|	
FIRST WALL ZONE:	PCA, 6.6% DENSE, BALANCE HELIUM
BREEDING ZONE:	6% PCA, 85% Li_2O (DENSITY FACTOR 0.8) BALANCE HELIUM
PLENUM ZONE:	PCA, 10% DENSE, BALANCE HELIUM
SHIELD ZONE:	100% STAINLESS STEEL
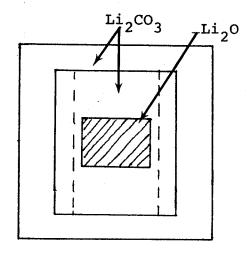
Li$_2$CO$_3$

A

A

Li$_2$O

Li$_2$CO$_3$ Li$_2$O
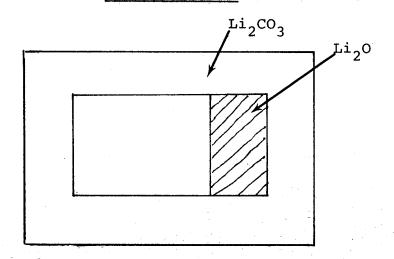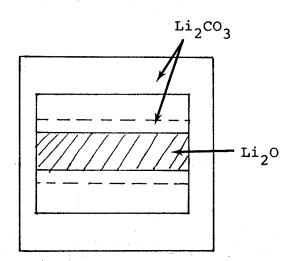
IMPACT OF VARYING THE SURFACE AREA
EXPOSED TO NUCLEAR FIELD ON THE TPR
PROFILES AND INTEGRATED TBR VALUES

Li$_2$CO$_3$ Li$_2$O
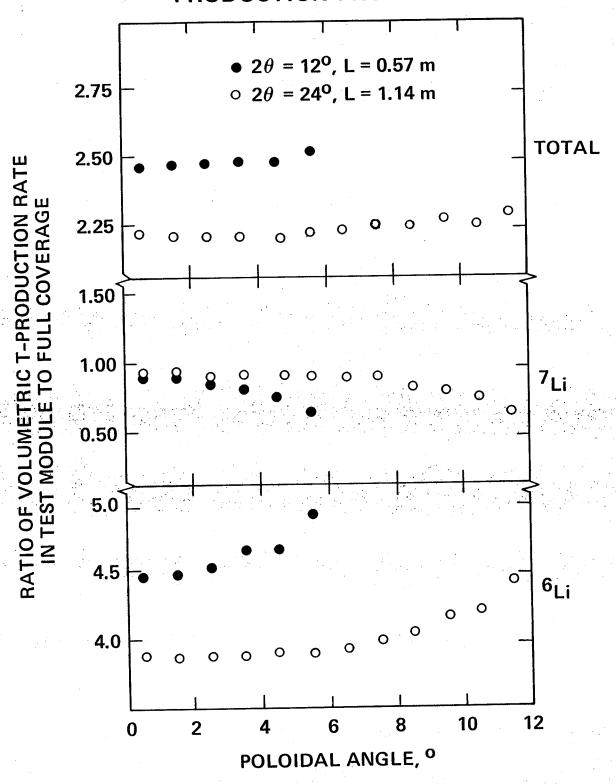
Reference Case

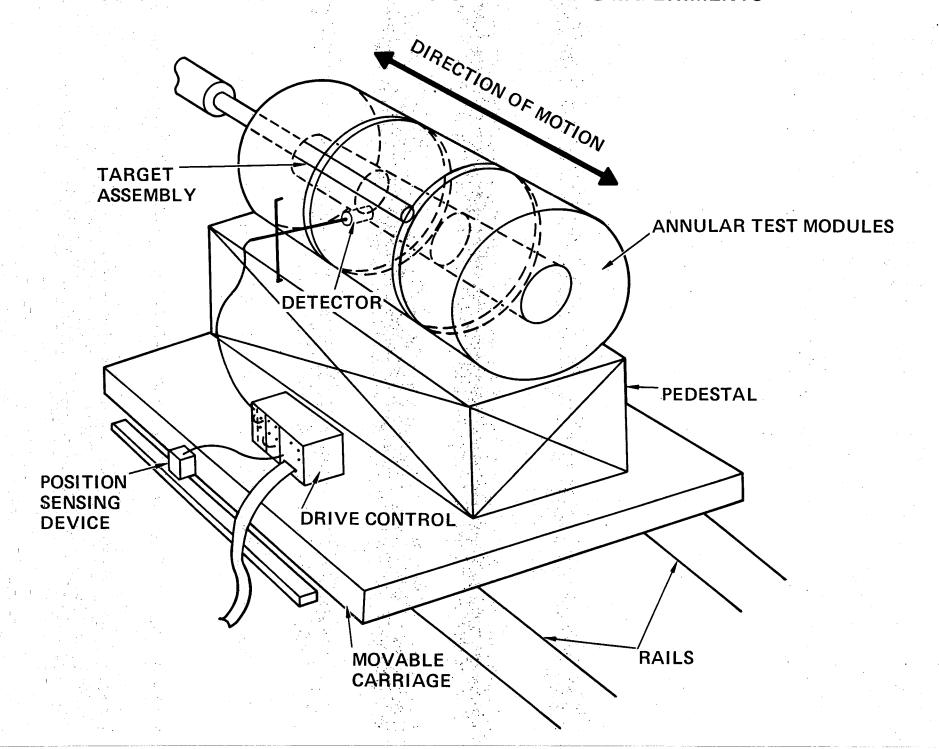Li$_2$CO$_3$

Li$_2$O

Li$_2$CO$_3$

Li$_2$O

LIMITING BLANKET TEST MODULE SIZE SUBSTANTIALLY CHANGES TRITIUM PRODUCTION PROFILES

Alternate Breeder Material

- Initial Assessment of Fabrication Being Performed

- Candidate materials

    - Lithium aluminate

    - Lithium silicate

- Future Fabrication Work Likely to be Performed at ANL Rather Than Commercial Vendors

    - Reduced volume compared with Li_2Co_3

    - Closer control of fabrication processes

- Costs and Schedule Depend Upon Experimental Needs

    - Purity

    - Dimensional accuracy needs

    - Density

    - Coating/cladding requirements

ADVANCED LINE SOURCE FOR TRITIUM BREEDING EXPERIMENTS

DIRECTION OF MOTION

TARGET ASSEMBLY

ANNULAR TEST MODULES

DETECTOR

PEDESTAL

POSITION SENSING DEVICE

DRIVE CONTROL

RAILS

MOVABLE CARRIAGE

Preliminary Observations on Phase II Results

- Primary Characteristics: Li_2Co_3 container is used as an enclosure to the rotating target and the Li_2O assembly. The D^+ beam is at $0°$ C to the Li_2O assembly.

- No Steep Profiles for T_6 are Found at Front Locations in Test Assembly. _Deviation from Measured Values is Improved_ ($\sim 20\%$) in Comparison to Phase I Experiments

- At Front Locations T_6 is Sensitive to the Reflected Neutron Component from the Li_2Co_3 Side Walls. More Neutrons are Emitted from Target to These Walls than to the $0°$ Direction.

- In 3-D Monte Carlo Analysis: C/E for T_6, T_7 and Reaction Rates at the Front is Found to be Always Less Than Unity Except for T_7 from NE-213 (and ^{58}Ni (n,p)

- The 2-D Model gives Larger Low-Energy Neutrons at Front Locations in the Li_2O Assembly than the 3-D Model. This is Due to Approximating the Rectangular Side Walls by Circular Geometry.

Preliminary Observations on Phase II Results
(continued)

- C/E Values for T_6 in the Li_2O Bulk Locations is ~ 1.1-1.2

- Deviation in Calculated T_7 from Experimental Values is Generally ~ 15-20%

- In general, Larger Deviations from Experimental Values of T_6 and T_7 are Found in the Li_2Co_3 Zone. Better Evaluation of the Impurity Level and Atomic Densities are Needed.

- The Value of C/E is Large Inside the Be Layer in the Be-Sandwich Case. Problem Needs Resolution.

- Computed and Measured Values for TPR by Foils in the Be-Sandwich Case are in Serious Disagreement (C/E ~ 0.3). Problem Needs Resolution.

Tritium Fuel Self-Sufficiency

- Critical Requirement for Renewable Energy Source
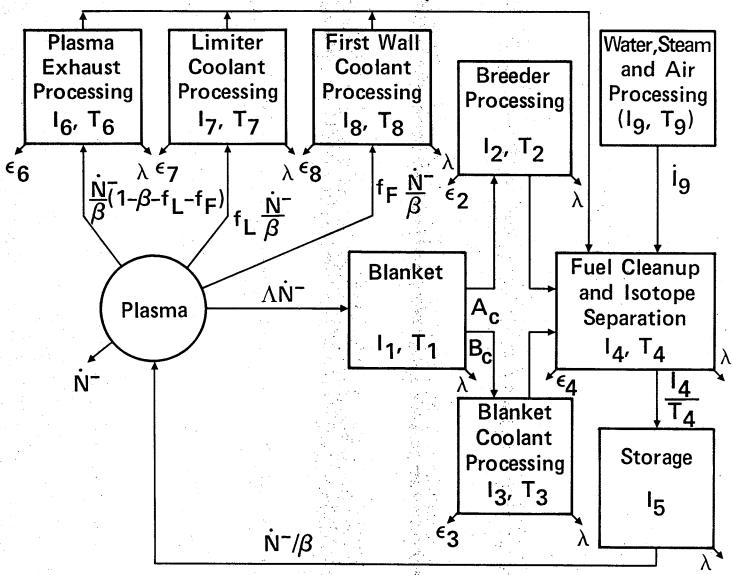
- Self-Sufficiency Condition:

    Achievable TBR > Required TBR

- Analysis Shows:

    - T_A and T_R depend on many system parameters

    - Present uncertainties are large

Key Questions

- What can we do in ITER to demonstrate (at least partially, e.g., through synthesis) tritium self-sufficiency?

- What can we do now in Neutronics Integral Experiments to provide input to ITER?

Schematic model of the fuel cycle for a DT fusion reactor used in the present work

L = tritium breeding ratio

$\dot{N}^-$ = tritium burn rate in the plasma

I_i = tritium inventory in compartment i

T_i = tritium mean residence time in compartment i

ε_i = nonradioactive loss of tritium in compartment i

λ = tritium decay constant

β = tritium fractional burnup in the plasma

f_i = tritium fractional leakage in compartment i

$\dot{I}_9$ = constant flow rate of tritium recovered from waste, steam, and air processing units