Summary of the U.S. Activities on Fusion Neutronics

Mohamed Abdou
UCLA

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Neutronics R & D Needs

1. Method Development
    - Transport
    - Response Functions

2. Differential Data
    - Cross Sections
    - Secondary Energy & Angular Distributions

3. Integral Experiments
    - Benchmarks
    - Prototype

Suggested for IEA Activity

Integral Experiments

Reasons:

1) Urgent needs for next fusion facility (ITER,...)

2) International collaboration is both needed and effective

Accuracies

Key Issue	Target Accuracy	Present Accuracy
• Tritium Breeding & Nuclear Heating		
- TPR (local)	~ 10%	~ 30%
- TPR (global)	~ 5%	~ 15%
- Heating rate (local)	~ 20%	~ 50%
- Heating rate (global)	~ 10%	~ 25%
• Inboard Bulk Shield		
- Radiation damage parameters to SC magnet	~20-30%	100-200%
• Outboard and Penetration Shields		
- Radiation damage to SC Magnet	30-50%	200-300%
- Dose to Personnel	50-100%	200-300%
• Radioactivity and decay heat		
- FW structure	~10%	~ 50%
- Breeding material	~20%	~ 40%

U.S. activities on Fusion Neutronics

- OFE
  - The largest part of effort is devoted to the USDOE/JAERI collaboration (FNS experiments)
    - *An excellent Example for International Collaboration
    - *Primary organizations: UCLA, ANL
      support: LANL, ORNL, others

  Support also in the area of other integral experiments devoted to improving nuclear data (e.g. Manganese-bath Experiment at Idaho)

  - Data assessment/evaluation/retrieval (ENDF/B system)

*BNL	*LANL
*ORNL	*RSIC
*ANL	*LLNL

  - Modest effort on maintaining codes and data libraries
  - Broad-based <u>neutronics</u> design as part of system & design study (e.g. ITER)
- BES

  support to fusion in generating and evaluating basic nuclear data

The USDOE/JAERI Collaborative Program on Fusion Neutronics (overview)

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

- Phase III Experiments
  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

- <u>Neutron Spectrum</u>
  - 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
- <u>Foil Activation Measurements</u> (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)
- <u>Tritium Production Rate (TPR)</u>

  <u>Local measurements</u>:
  - 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)

  <u>Zonal Measurements</u> (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:

- Nuclear Heating:
    - 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: ^7LiF (Mg)

      Mg_2SiO_4 (Tb)

      Sr_2SiO_4 (Tb)

      Ba_2SiO_4 (Tb)

Phase II

Objectives of the workshop

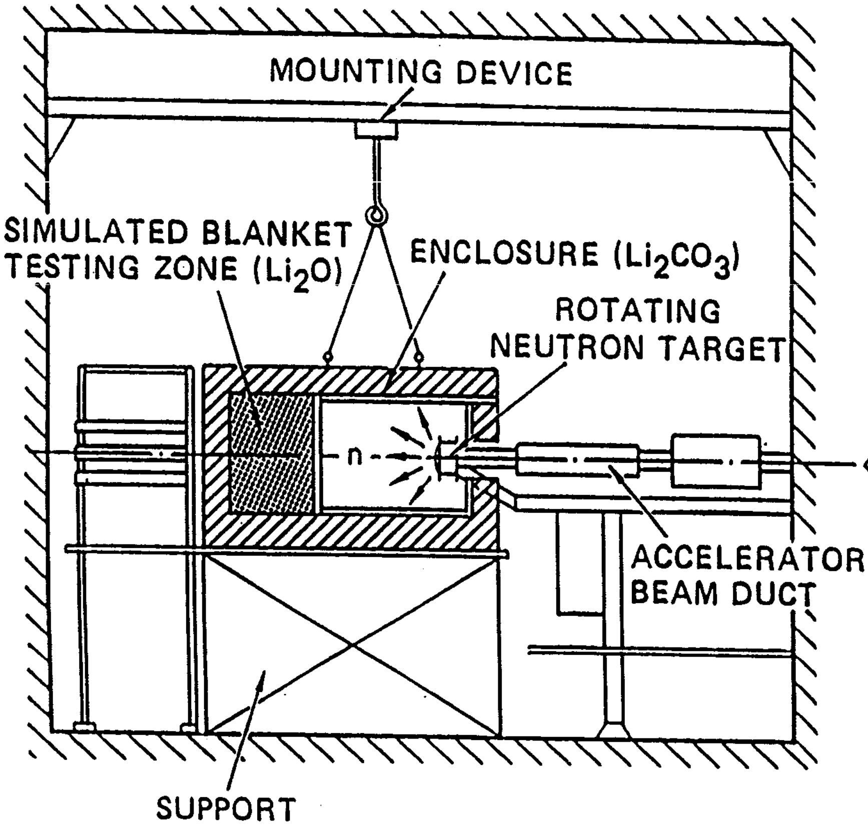
- Exchange information on recent activities pertaining to Fusion Neutronics
  - Basic nuclear data
  - Basic Integral Experiments
  - Blanket engineering Integral Experiments
  - Codes/methods development
  - Measuring Techniques development
  - Shielding Experiments

- Define areas of common interest for collaboration
  - specific items/proposals
  - format and procedure
  - relationship to existing programs

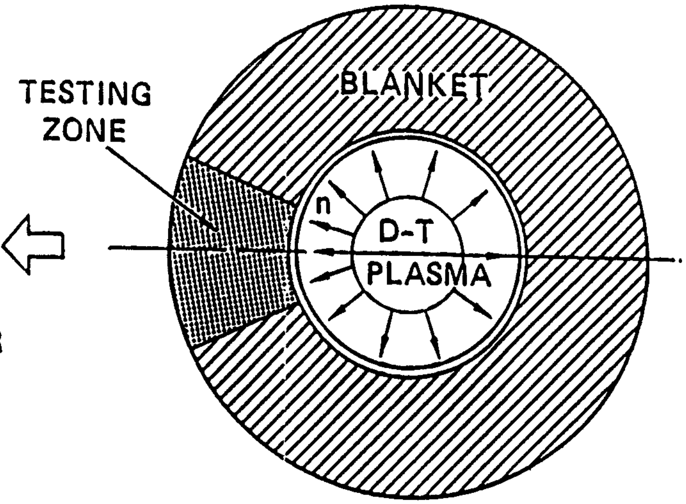
- Report on current activities of the USDOE/JAERI Collaboration Program on fusion Neutronics (recent activities and future plans)

- Discuss potential/plans for other International collaboration on fusion Neutronics
  e.g. (Japan/PRC/US)
  (IEA/Japan/US)
  (US-USSR)

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



SCHEMATIC OF REACTOR MODEL



OBSERVATIONS ON ANALYSIS OF PHASE II EXPERIMENTS

(1) Tritium Breeding

Local T_6

- No steep profiles for T_6 are found at front locations as in Phase I. Better prediction in Phase II.

- T_6 is overestimated by all codes and libraries (by ~ 15%) in Phase IIA. The overestimation still persists in Phase IIB in the U.S. calculations but JAERI's values show some local underestimation in Phase IIB due to the noticeable differences in beryllium data between LANL and JENDL-3PR1 evaluation

- Where beryllium is used as a front-layer multiplier, the local T_6 values just behind this layer are always underestimated.

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

Local T_7

- Generally overestimated by 10-20% in Phase IIB
- The C/E values obtained by the U.S. are larger than those obtained by JAERI.
- While T_7 is overestimated in the U.S. calculations for Phase IIA (by ~ 20%) it is underestimated (by ~10%) at deep locations in Phase IIB due to the overestimation in the Be (n, 2n) cross-section.

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

Zonal TPR

- Zonal TPR measurements from natural lithium using the liquid scintillation method were proven to be a successful technique. The C/E values at various zones in Phase IIA are 0.85 - 1.25 (15 - 25% prediction accuracy).

- Integrated TPR (indicative of TBR) has better prediction accuracy due to error cancellation. The C/E values are 0.97 - 1.07 (3 - 7% accuracy).

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

(2) Nuclear Data

- ^{7}Li (n, total) in JENDL-3PR1 is overestimated due to overestimation in (n, elastic), (n, γ) and (n, d) cross-sections while
- ^{7}Li (n,n' α)t in JENDL-3PR1 it is underestimated by 8-10%.
- The Fe(n, inelastic) and Fe(n, 2n) cross-sections are larger in JENDL-3PR1 than in ENDF/B-V by ~25% and ~15% at high energy (~14 MeV).
- ^{58}Ni(n, 2n) cross-section of ENDF/B-V is underestimated by 10-30%.
- The ^{9}Be(n, 2n) cross-section in JENDL-3 and ENDF/B-V are overestimated (by ~7%) at high energies.
- The low-energy component of the emission spectrum (below 0.5 MeV) from the ^{9}Be(n, 2n)

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

(2) Nuclear Data (cont'd)

- The Be emission spectrum in the intermediate energy range (2-10 MeV) seems to be overestimated.
- The angular distribution of the $^9Be(n, 2n)$ cross-section of JENDL3 is overestimated in the backward direction and underestimated in the forward direction.

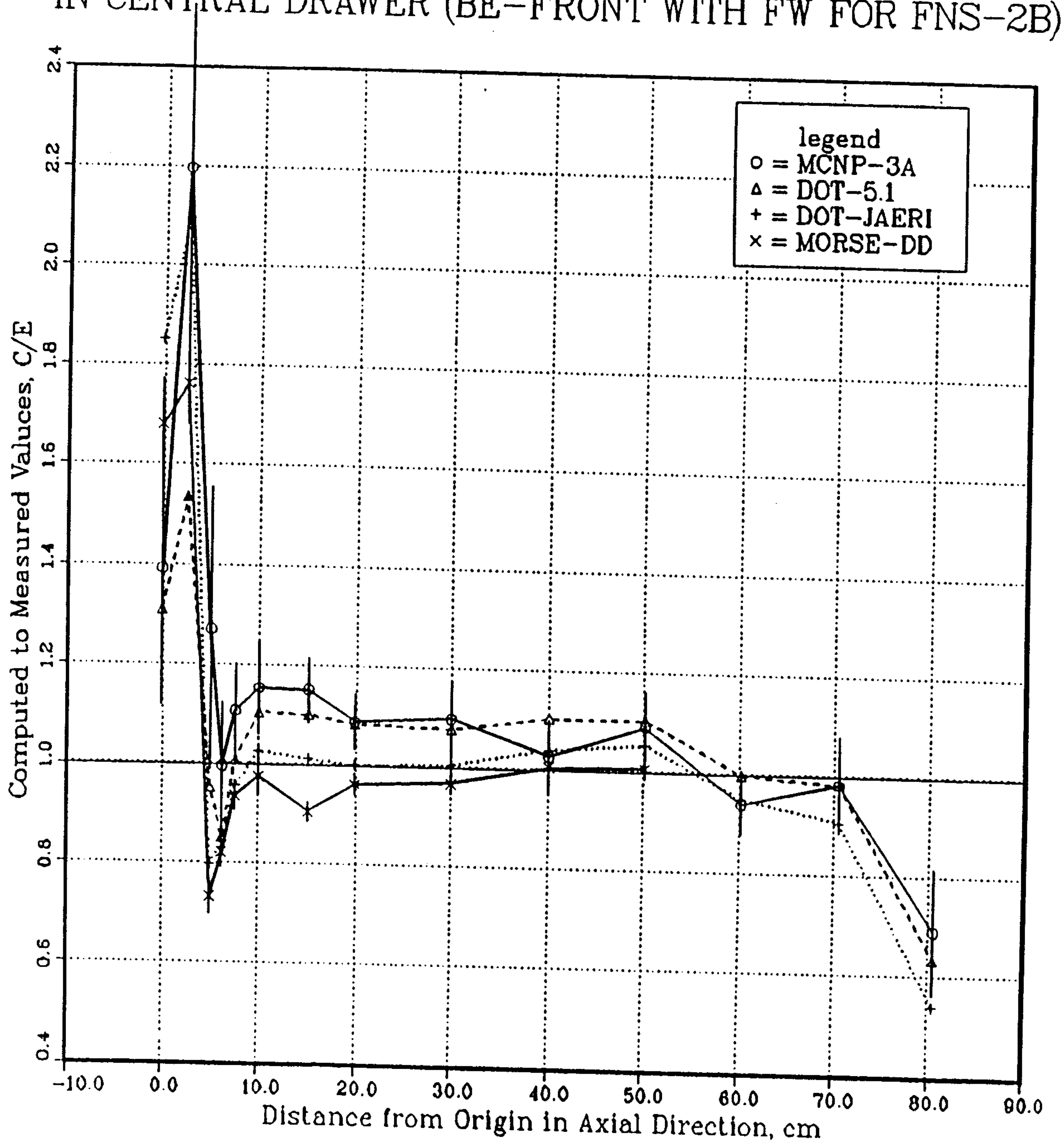
Remarks on Beryllium Data of ENDF/B-VI and Impact on T_6 and T_7 Profiles

- 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.

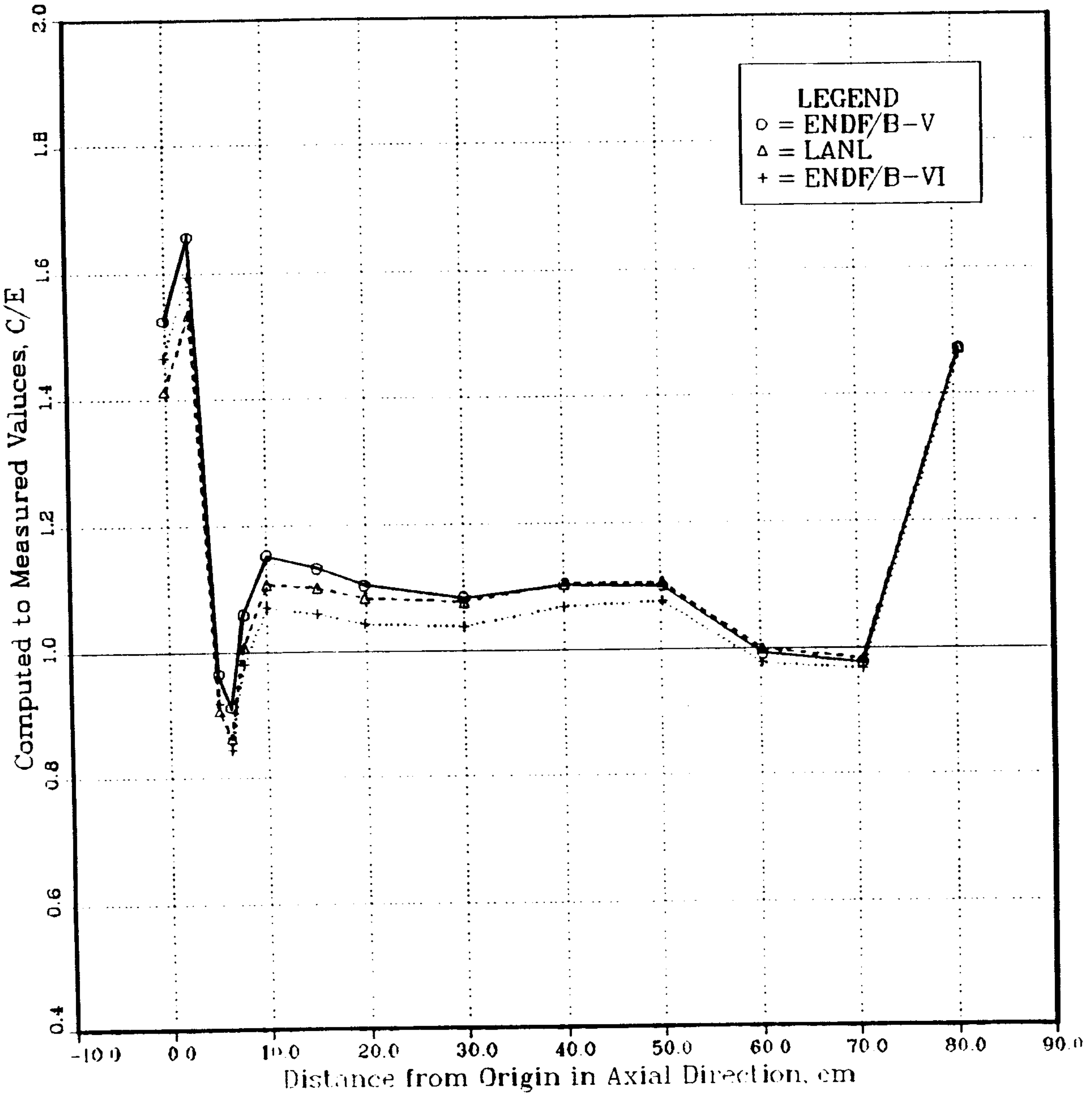
- Be (n, 2n) cross-section of ENDF/B-VI is 5-8% less at 14 MeV than the cross-section of ENDF/B-V and LANL evaluation.

- 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.

TRITIUM PRODUCTION RATE FROM LI-6 USING LI-GLASS DETECTOR
IN CENTRAL DRAWER (BE-FRONT WITH FW FOR FNS-2B)



TRITIUM PRODUCTION RATE FROM LI-6 MEASURED BY LI-GLASS
IN CENTRAL DRAWER OF PHASE-2B BE-FRONT W/ FW



Phase IIC Experiments

Multi-layers of Beryllium

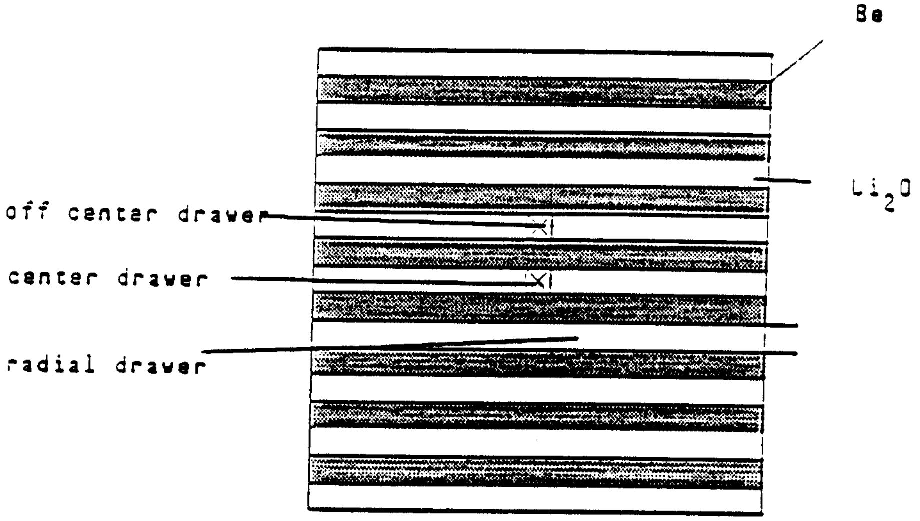
- multi-layers of beryllium inside the Li_2O assembly are considered in various configurations
- edge-one configuration was chosen based on its higher TPR performance

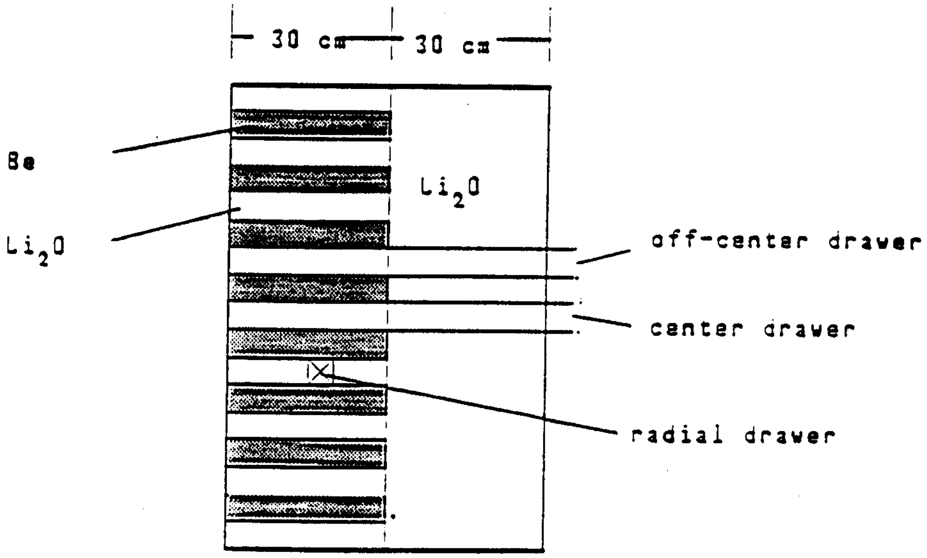
Heterogeneity and Coolant Channel Effect

- 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%

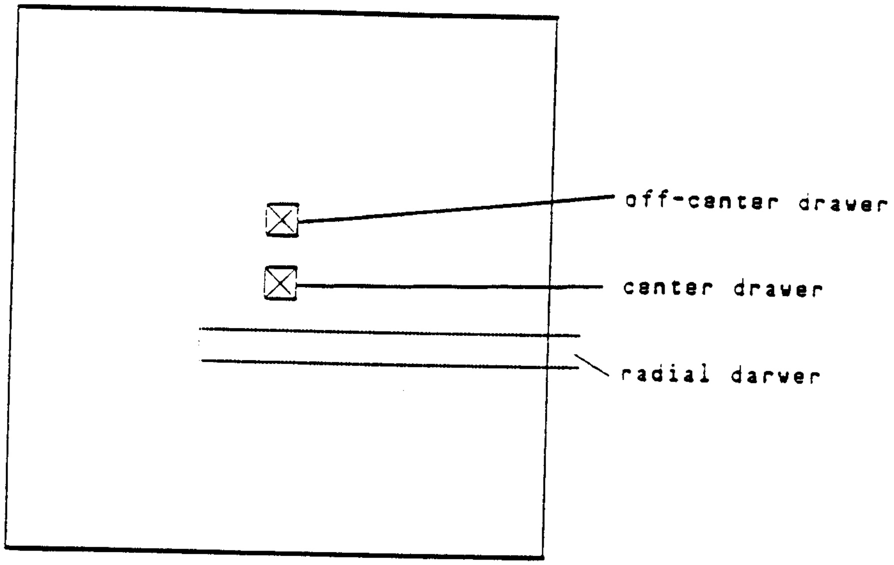
Phase IIC was completed during the experimental period Oct. 15 - Dec. 15, 1988. Activation and decay gammas were measured for various cooling time after irradiation during this phase in several foils made of Fe, Ni, Cr, etc. Comparison of predictions to measurements are underway.

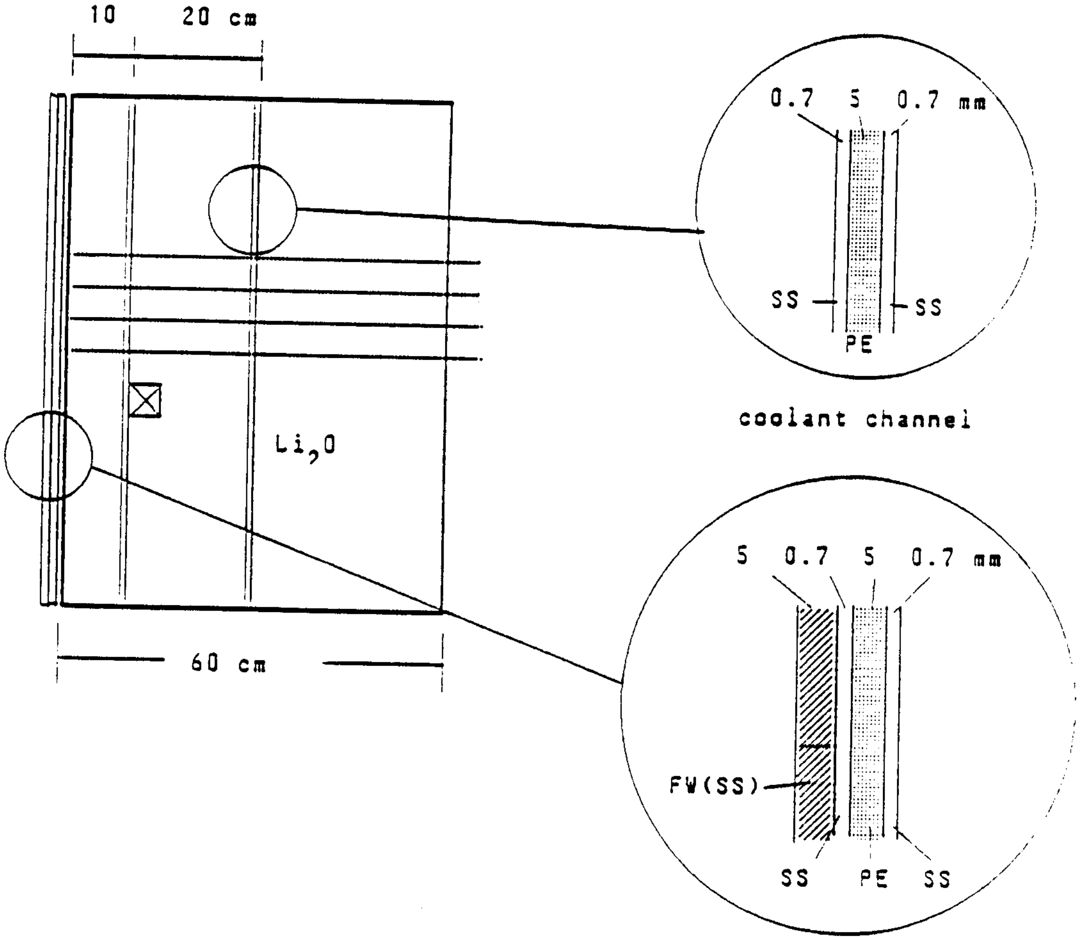
Be-edge on arrangement





Coolant channel arrangement

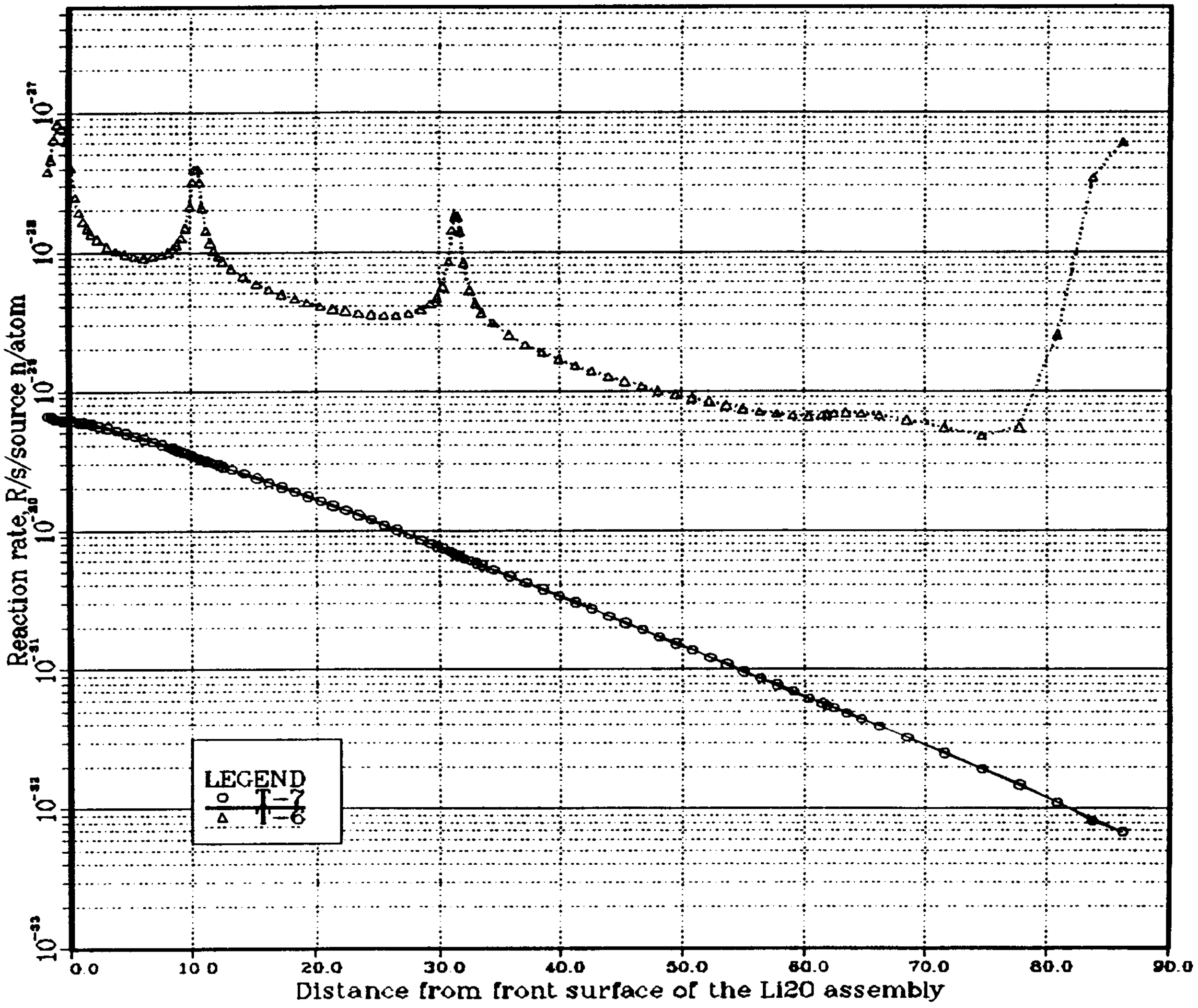




coolant channel

first wall with coolant channel

REACTION RATE ALONG THE CENTRAL AXIS OF THE TEST ASSEMBLY



Radioactivity and Decay Afterheat in Fusion Blankets

- Source: n and charged particle product induced radioactivity

- Primary agents
  - β's accompanied by γ's from b decay
  - γ's from isomeric states of stable nuclei
  - α's from α-decay
  - conversion electrons

  (all these agents heat through secondary electrons)

- Additional agents
  - photoelectrons by γ's through (γ,n) reactions
  - neutrons by α's through (α,n) reactions

Importance of Radioactivity/Decay Heat

- Required for
  - Assessment of after-shutdown cooling
  - Maintenance/handling purposes
  - Shield design
  - Waste Management

- The concerns related to radioactivity/decay heat have led to the work on the development of Low Activation Materials.

Why Measurements?

- Most of the available neutron activation cross section data is evaluated and little tested over the full energy range

- Even a number of neutron dosimetric reaction cross sections need to be improved, e.g., $^{19}F(n,2n)^{18}F$, $^{23}Na(n,g)^{24}Na$, $^{24}Mg(n,p)^{24}Na$, $^{59}Co(n,g)^{60}Co$, $^{47}Ti(n,p)^{47}Sc$, $^{63}Cu(n,2n)^{62}Cu$, $^{90}Zr(n,2n)^{89}Zr$ etc. (The reported error being as large as 30% in few cases.)

- Experimental Measurements allow
  - testing of evaluated activation cross section data over larger energy range
  - improvement of often used dosimetric cross section data (reduction of variance)
  - improved cross section data for radioactivity, decay heat and dose calculating codes

Measurements of Decay γ Spectra from Radioactive Isotopes
(December 1988)

- Materials
  - Selection dictated particularly by considerations for ITER blanket and shield

  - Samples of Fe, Cr, Ni, Mo, SS316, MNCu alloy, V, Ti, Co, Al, Si, Zr, Nb, W, Au, In, Mg, Ta were retained along with a specimen each of two high temperature Tc = 90 K superconductors: $YBa_2Cu_3O_7$, $ErBa_2Cu_3O_7$ (on substrate of yttria stablilized zirconia)

- Typical Dimensions
  - Fe, V, Cr, Ni, Mo, SS316: 5mm dia. x 1 mm th.
  - Si: 2 mm x 2 mm x 0.4 mm thickness
  - Al, Zr, W, In, Ta : 12.7 mm dia.
- Facility: FNS, JAERI
- Simulated Blanket: Li_2O test assembly with 'coolant' channels in Phase IIC experimental phase

- Counting Equipment: 4 Intrinsic Germanium Detectors linked to Canberra MCA's

(measurements, continued)

- Irradiation spots
  - 10 cm from target
  - 5 cm inside Li_2O (82 cm from target)

- Neutron Intensity: ~ 2×10^{12} n/s (starting value)

- Irradiation Strategy
  - 30 minutes' starting irradiation for radioactive isotopes of half lives ≤ 5.3y (^{60}Co)

- Irradiation chronology
  - December 2, 1988: short and long irradiation at 10cm from target
  - December 9, 1988: at 5 cm inside Li_2O
  - December 14, 1988: multiple calibration runs

Phase III Experiments

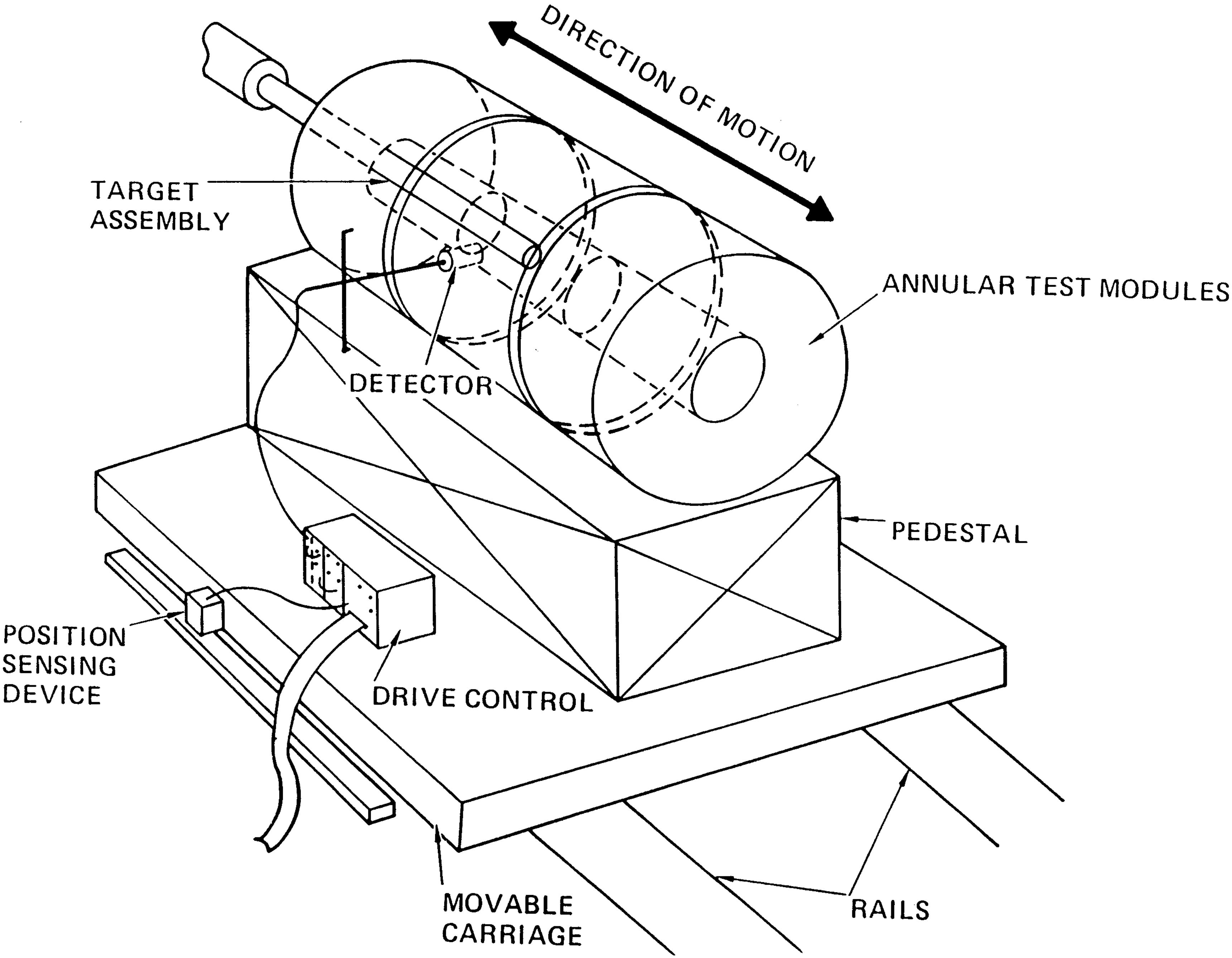
Characteristics:

- 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 ~ 50cm. The inner cavity cross-section is also rectangular with ~1 m^2 area

Concerns:

- lower fluence is obtained by a moving point source in comparison to stationary source
- the adequacy of present deterministic codes in representing a line source
- approximating a line source by superposition of results from limited number of point sources adds another source of uncertainty

ADVANCED LINE SOURCE FOR TRITIUM BREEDING EXPERIMENTS



CONCLUDING REMARKS

- Remarkable technical progress has been made.

- The collaborative program on neutronics is an excellent example of an almost "ideal" international collaboration.

- Areas of Emphasis to be considered in Future Work

  - Key Neutronics Parameters
    Nuclear Heating, Activation, etc.

  - Better Simulation of Source Geometry

  - More Prototypical Experimental Configuration

  - Other Materials (e.g., lithium silicate)

  - ITER-Related Priority Items

- Present Limitations on Program

  - Constraints on Resources

  - Limitations on Available Facility Time (FNS)