Fusion Neutronics

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Key Neutronics Issues

- Tritium breeding
  - self sufficiency (breeding ratio)
  - tritium production profiles
- Nuclear Heating (neutron & γ- heating)
  - total
  - heating profiles
- Adequate shielding for components and personnel
- Radioactivity and decay heat

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%

Suggested IEA Activity for Neutronics

- Collaborative Program on:

  Neutronics Integral Experiments

  1. Radiation shielding (bulk and penetration)
  2. Tritium Breeding and nuclear heating
  3. Radioactivity and decay heat

- The Program requires only 2 configurations

  a. Shield b. Blanket

  Radioactivity, decay heat and nuclear heating can be measured in both configurations.

Objectives of Proposed Experiments

1. Validate methods and data for ITER - type devices.

2. Provide estimates of uncertainty and, hence, design safety factors.

Focus

- First wall/divertor, blanket, shield
- Program has a large part which is common to:

    - base blanket/shield

    - test modules

Utilization of Integral Experiments

- Use information obtained from experiments to assess prediction inaccuracy under the fusion facility conditions/environment and compare to target accuracies.

- Identify sources of discrepancies between analytical prediction and experimental measurements of integrated and/or local key parameters (e.g. TPR, heating rate, dose to personnel, radiation damage parameters, etc.) in prototypical test modules.

- Take actions to reduce these discrepancies:

  - Improve particular nuclear data sets in the current data files (e.g. ENDF, EFF, JENDL)

  - Improve capabilities of present transport codes for modeling

  - Derive safety factor for designers

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1. Shield Experiments

- Bulk Shield

- Penetration Shielding

Bulk Shielding Experiments

- Candidate Materials — SS304, S316, Fe, B_4C, Water, Boral, Pb, Borated-Polyethylene, Concrete, Tungsten
- Geometry — slab, pseudo-cylinder
- Thickness — varies from 10 cm to 80 cm max.
- Procedures
  - decide the combination of materials of high interest (e.g. SS/H_2O, SS/B_4C, W/H_2O, W/B_4C, etc.)
  - Perform experiments starting with thin slabs and proceeding to thick slabs
  - Perform necessary measurements at each step and make final decisions on the subsequent steps.

Bulk Shielding Experiments (continued)

- Perform independent analysis by participants and reach consensus on prediction accuracy during workshops

- **Measurements** (at each step)

  (1) Transmitted scalar neutron spectrum down to thermal energies

  (2) Angular dependence of transmitted neutron spectrum

  (3) Gamma rays spectrum behind shield

  (4) Scalar neutron spectrum at selected locations inside the shield.

- From these differential and integral measurements one can infer the accuracy of double differential and emission spectrum data of various materials.

- The prediction accuracies of the various spectrum-dependent responses (e.g. SC magnet damage parameters, dose to personnel, etc.) are derived from the prediction accuracy of neutron/gamma spectrum at various energies. (Prediction accuracy of response, e.g. kerma factors are also needed)

Bulk Shielding Experiments (continued)

- Recommended measuring techniques
  - Miniaturized NE 213 and Li-glass detectors for in-system scalar neutron spectrum measurement supplemented by in-system multi-foil activation measurements (MFA)
  - NE 213 spectroscopy for gamma spectrum measurements
  - Time-of-flight (TOF) spectrometry for the angular dependence as transmitted neutron spectrum
  - Proton-recoil counters to cover low-energy neutron spectrum

Shielding Experiments

Requirements on Facility

- Source intensities of ~1012 n/s are adequate. However, for foil activitation measurements at deep locations, higher (by an order of magnitude) intensities may be required to improve counting statistics.

- Need both steady state and pulsing capabilities:

  - Steady-state operation mode is important for MFA, in-system spectrometry

  - Pulsed mode operation is important for TOF spectrometry

Neutronics Facilities

Name	Country	Neutron Yield (n/s)	Source Tube Type	DC-Operation Mode	Pulsed Operation Mode
FNS	Japan (JAERI)	$5x10^{11}$-$5x10^{12}$	open	Yes	Yes
LOTUS	Switzerland (EPFL)	~ $5\ x10^{12}$	sealed	Yes	No
OKTAVIAN	Japan (U. of Osaka)	~ 10^{12}	open	Yes	Yes
Others	(France, Germany, UK, USA, etc.)				

Shielding Experiments

Facility Evaluation

- At present, FNS facility is most suited to perform the experiments (steady-state and pulsed mode, high yield 5×10^{11} - 5×10^{12} n/s, large space, presence of specialized equipment)

  - Target room #1 (large room)

    - TOF spectrometry
    - Negligible room return effect
    - DC or pulsed operation

  - Target room #2 (small room)

    - High intensity operation (10^{12} n/s) is ideal for in-system foil activation measurements

- The on-going collaborative program between USDOE and JAERI on fusion breeder neutronics utilizes room #2 to perform integral experiments where the incident neutron spectrum on a Li_2O assembly is simulated by a rectangular Li_2CO_3 enclosure (provided by the U.S.) This enclosure also permits drastic reduction of room-returned neutrons which in turn allows for better modeling.

Shielding Experiments (continued)

- For bulk shield experiments, the Li_2O assembly could be replaced by the selected shield assembly while retaining the existing Li_2CO_3 enclosure. This will reduce the overall cost involved.

- The experimental cavity in the wall between room #2 and room #1 could also be used for that purpose.

Suggestion on Facility

Use FNS at JAERI as the primary facility for IEA collaboration. Other facilities already being operated in Europe, Japan and USA can play a supporting role.

Radiation Streaming Experiments through Ducts

- Monte Carlo methods entail large prediction inaccuracies because of poor statistics for deep penetration problems.

- Discrete-ordinates based deterministic methods fail in calculating streaming through ducts due to discretization of angular variables (ray effect).

- Validation of both M.C. and deterministic methods by experiments is necessary to validate methods and data and to provide estimates of uncertainties.

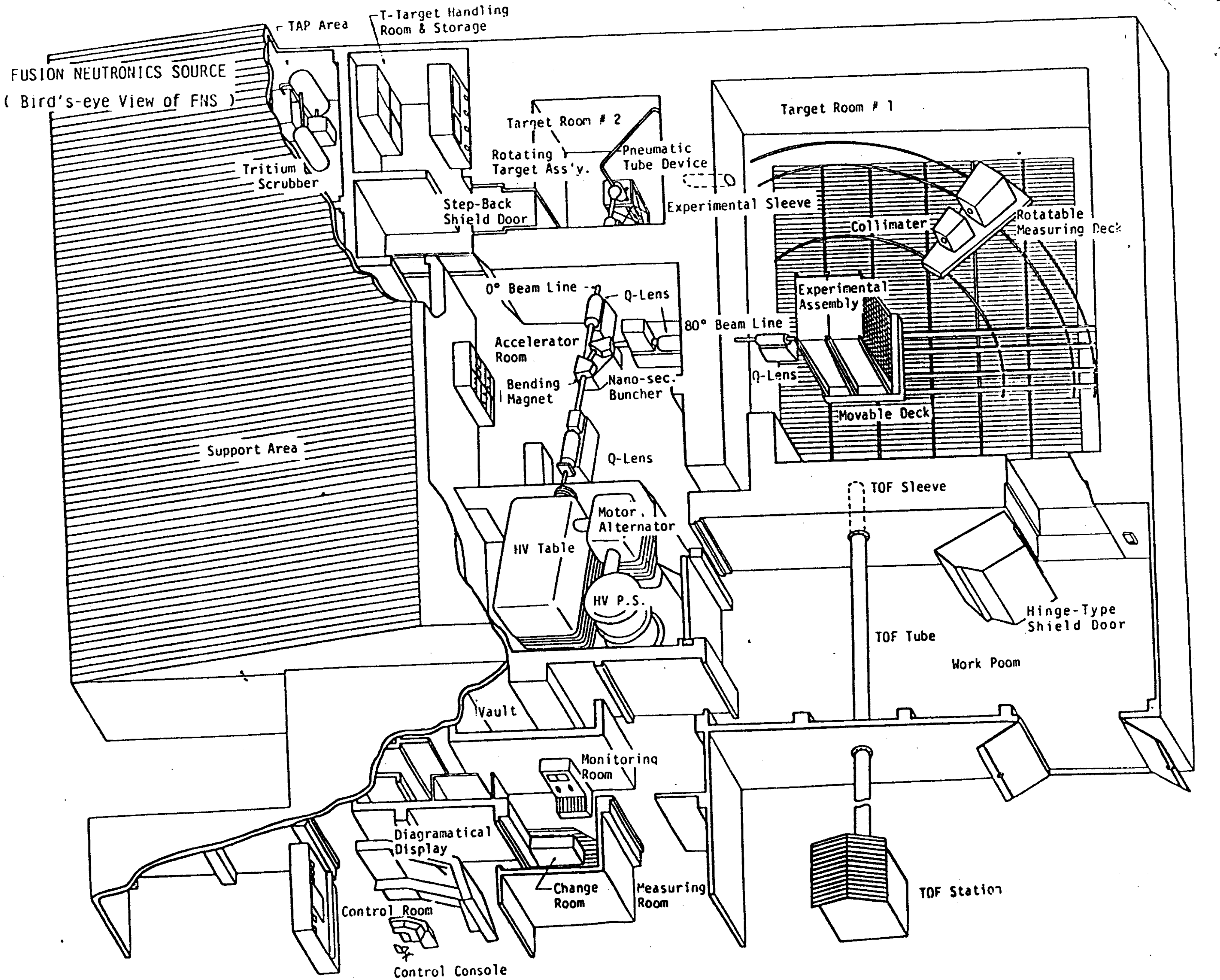
- Experiments on streaming through ducts in shielding or blanket materials should be planned for ducts of different sizes (L/D) and shapes.

Experiments and Facilities

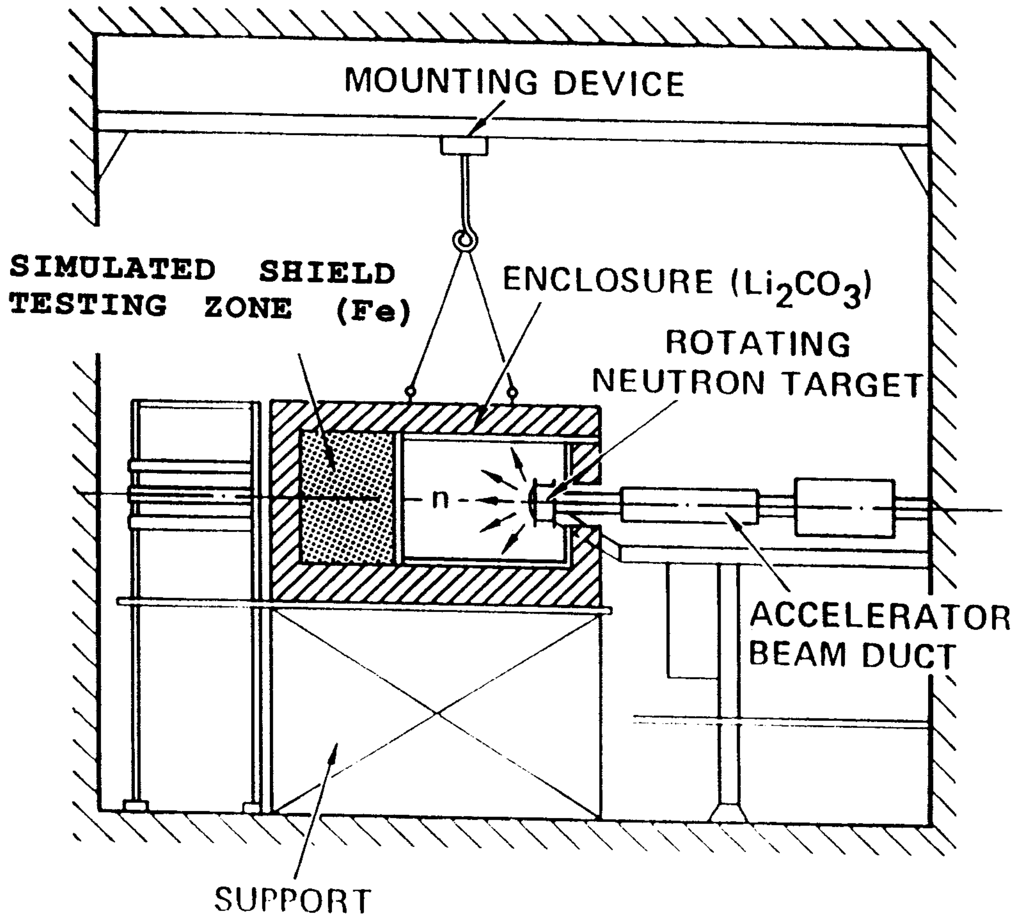
- Penetration experiments can be conveniently combined with some of the bulk shielding experiments and tritium breeding experiments.

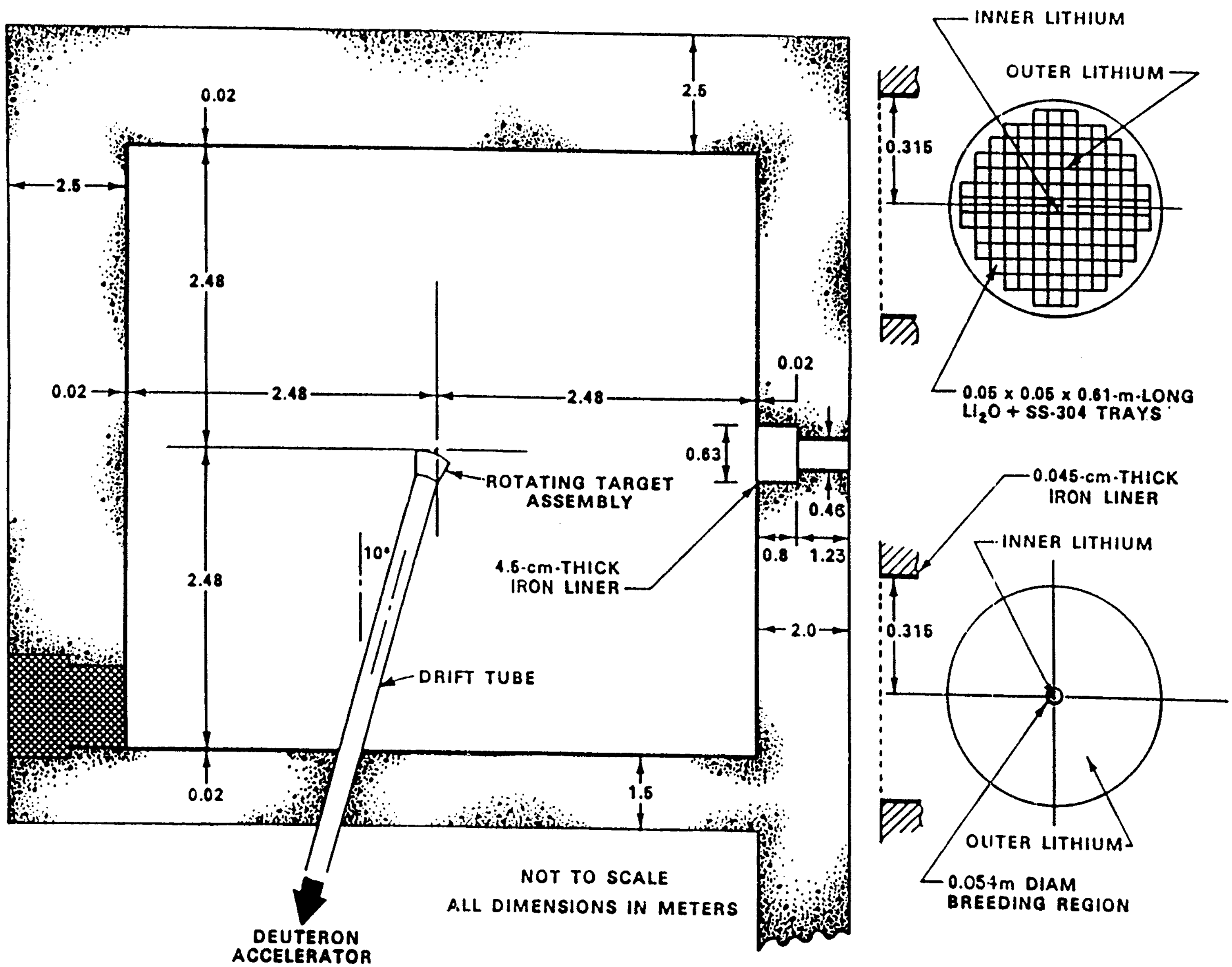
FUSION NEUTRONICS SOURCE

(Bird's-eye View of FNS)



A PROPOSED SET-UP FOR SHIELD EXPERIMENTS AT FUSION NEUTRONICS FACILITY OF JAERI





0.02
2.5
2.5
2.48
0.02
2.48
2.48
0.02
0.63
ROTATING TARGET ASSEMBLY
0.46
10°
2.48
4.5-cm-THICK IRON LINER
0.8
1.23
2.0
DRIFT TUBE
0.02
1.5
NOT TO SCALE
ALL DIMENSIONS IN METERS
DEUTERON ACCELERATOR
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

Tritium Breeding and Nuclear Heating Experiments

- At present, the materials considered in various integral experiments for tritium production verification are limited to Li, Li_2O, Li_2CO_3

- We need to consider:

  - Alternative solid breeder material

    e.g. $Li_4 SiO_4$
    Li_2ZrO_3

  - Alternative liquid breeder material

    e.g. $Li_{17}Pb_{83}$

- There is also a definite need to consider more prototypical geometries.

- None of the existing programs are focusing on nuclear heating verification (modest effort has started jointly under USDOE/JAERI collaborative program on Fusion Neutronics)

Tritium Breeding and Nuclear Heating Experiments (continued)

- Nuclear heating verification is not only necessary from the neutronic point of view but also it will provide the uncertainties associated with the source terms needed for the non-neutronics' tests (e.g. tritium recovery tests, thermo-mechanical tests) planned in the next experimental reactor (e.g. ITER)

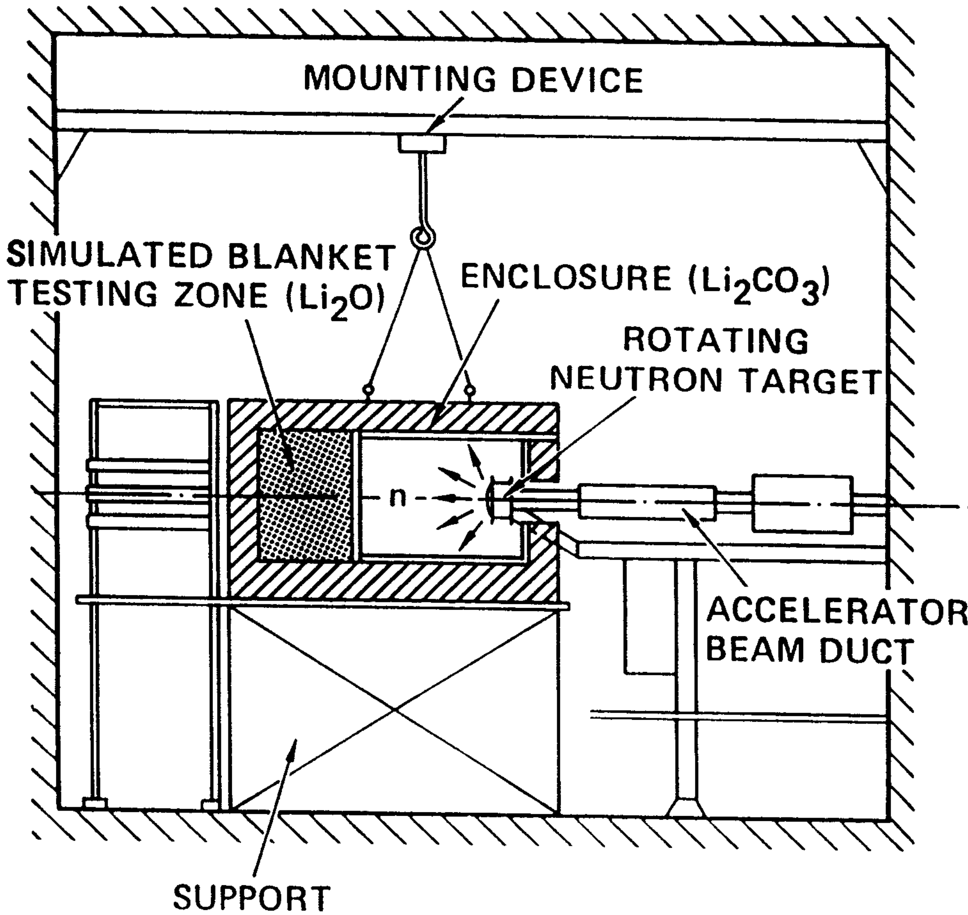
- We also need to advance and develop the experimental techniques needed to measure both neutron and gamma components of nuclear heating in structural as well as breeder materials.

  Promising techniques are:

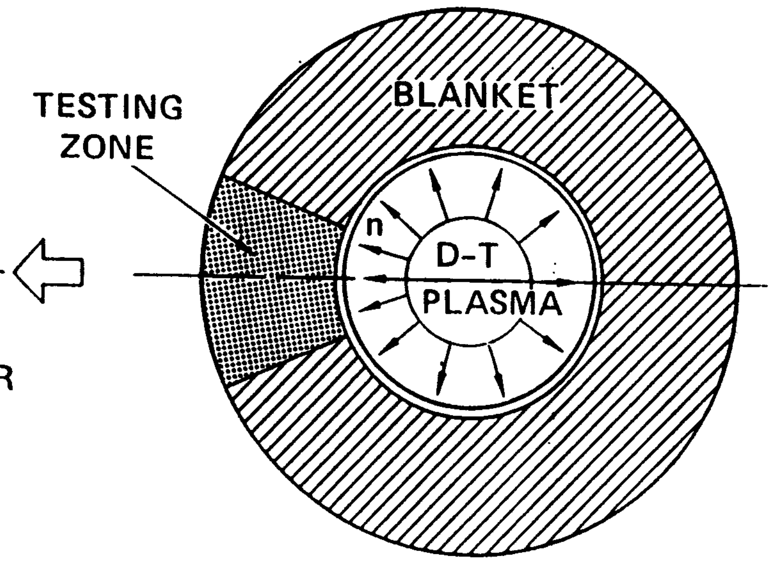
  - Detector pairs selectively sensitive to neutron and gamma heating

  - Absolute measurements through calorimetry

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



SCHEMATIC OF REACTOR MODEL



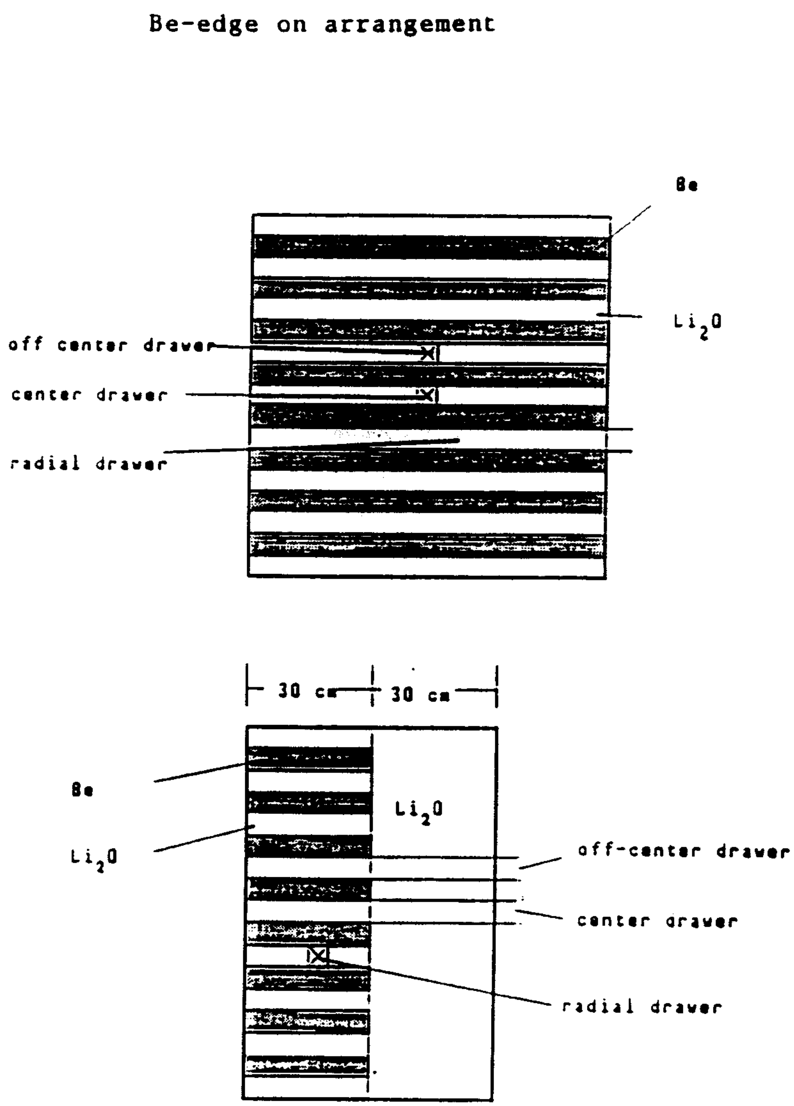


Fig. 5a Arrangements for Phase IIC: Be-edge-on arrangement

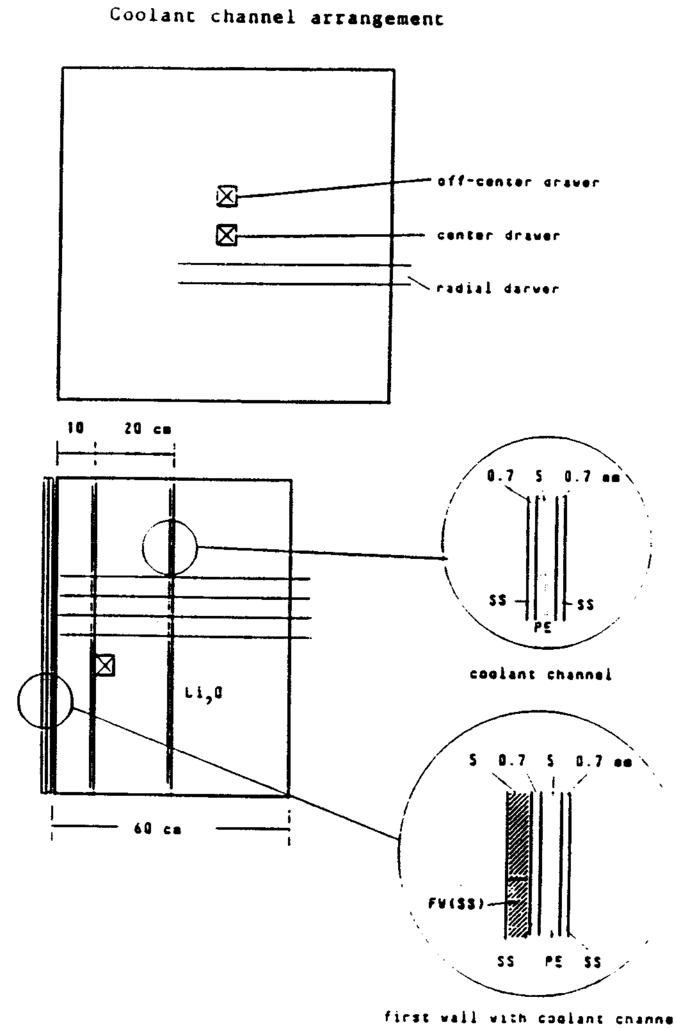
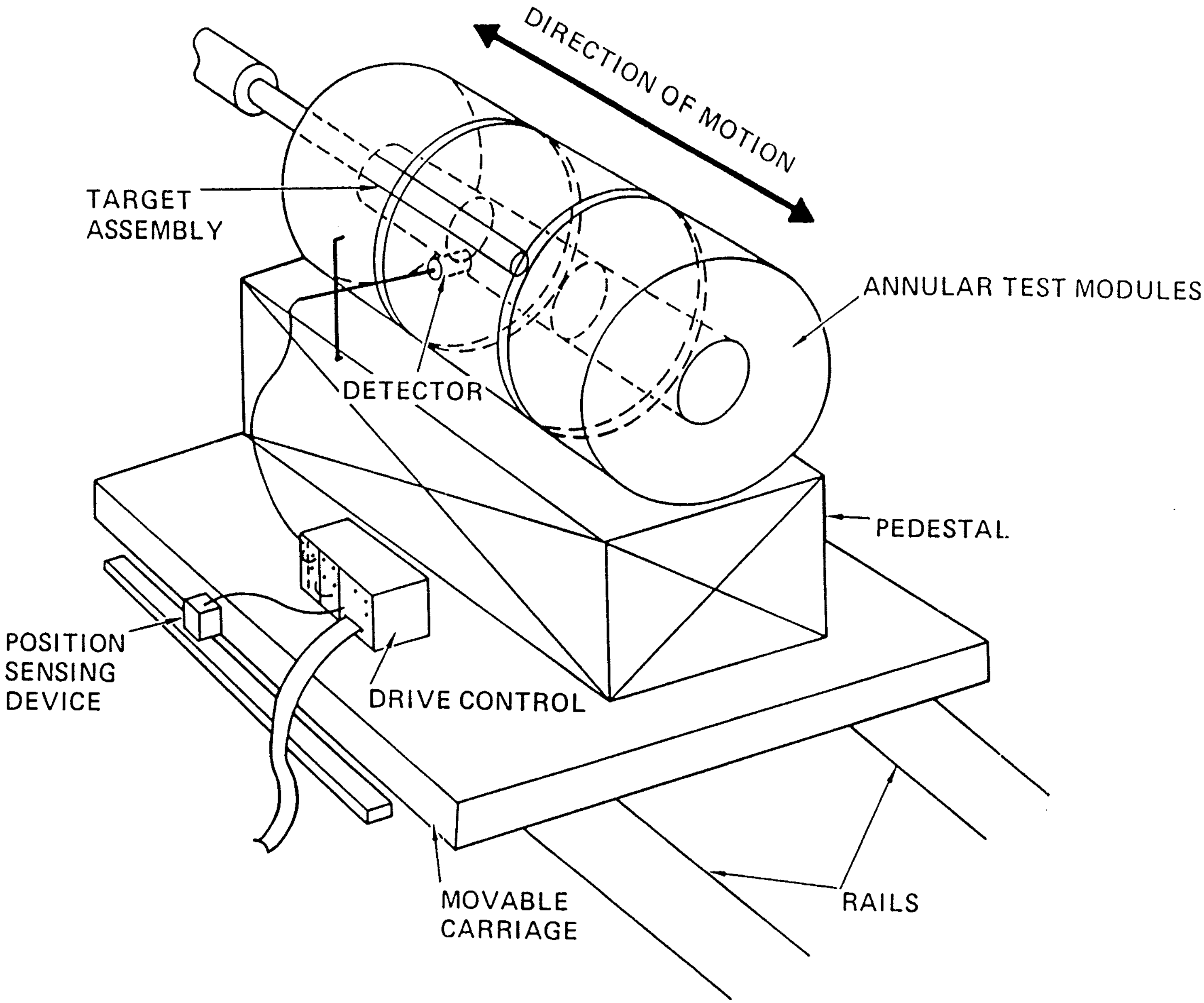


Fig. 5b Arrangements for Phase IIC: (b) Coolant Channel Arrangement



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

Radioactivity and Decay Heat Experiments

Status

- The uncertainties in the activation and decay data for potential structural materials for fusion applications are currently large. This leads to large difficulties and uncertainties in:

  - designing emergency and post-shutdown cooling systems

  - classification of materials for waste disposal recycling, passive safety, etc.

- The adequacy of present data in various activitation libraries

  e.g. REAC 2, ACTL (US)
  THIDA (Japan)
  JACT88 (ECN, Harwell)

  has not been tested.

- Most of the data have been produced through nuclear models. Key pieces of data are known to be missing or incorrrect.

Radioactivity and Decay Heat Experiments

- Effort to improve induced activation and decay heat data (cross section measurements and modelling) is needed but not sufficient. It will take a very long time and effort and will not be sufficient for the next 20 years.

Suggested Program of Collaboration

- A most effective approach is to perform integral experiments on radioactivity and after heat in simulated fusion environment, in conjunction with other blanket and shield experiments.

  - **Advantages**

    - many materials, either elemental or alloys can be directly measured (specimens are ~ 1cm in diameter, 1 mm thick)

    - specimens can be placed at various locations at the first wall, blanket and shield

    - minimum cost and effort (facilities are operated anyway for some blanket or shield measurements)

    - most relevant, most reliable (direct measurements in prototypical conditions)

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 x 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.

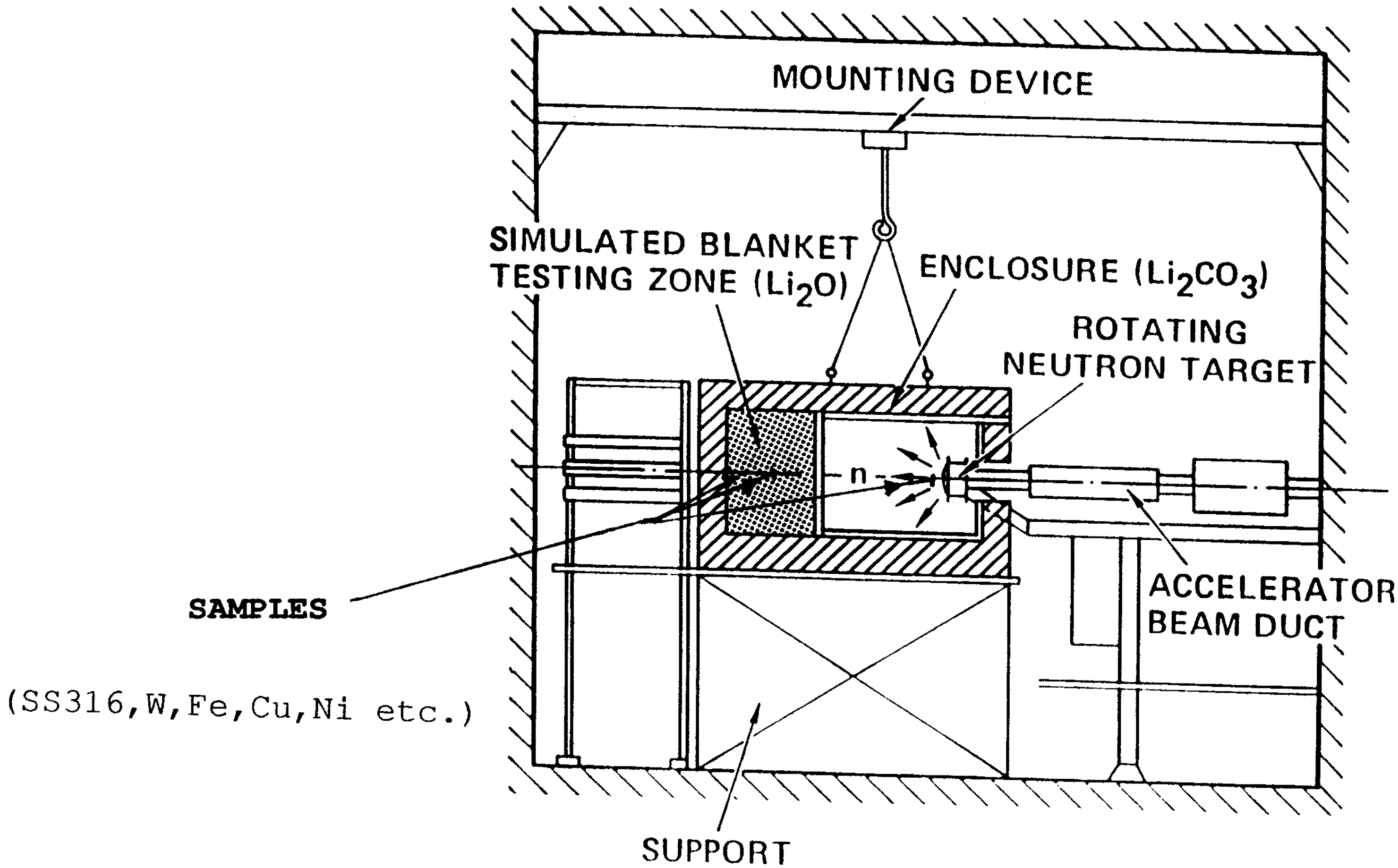
- Half lives: 2.24 m (^{28}Al) to 5.27 y (^{60}Co)

- 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)



<u>Schedule</u>

- Start 1990
- Total period 5 years
- Experiments per year:

  <u>2 experimental periods per year</u>

  - Each period is 2 months
  - One period focus on shield configuration
  - Second period focus on blanket configuration

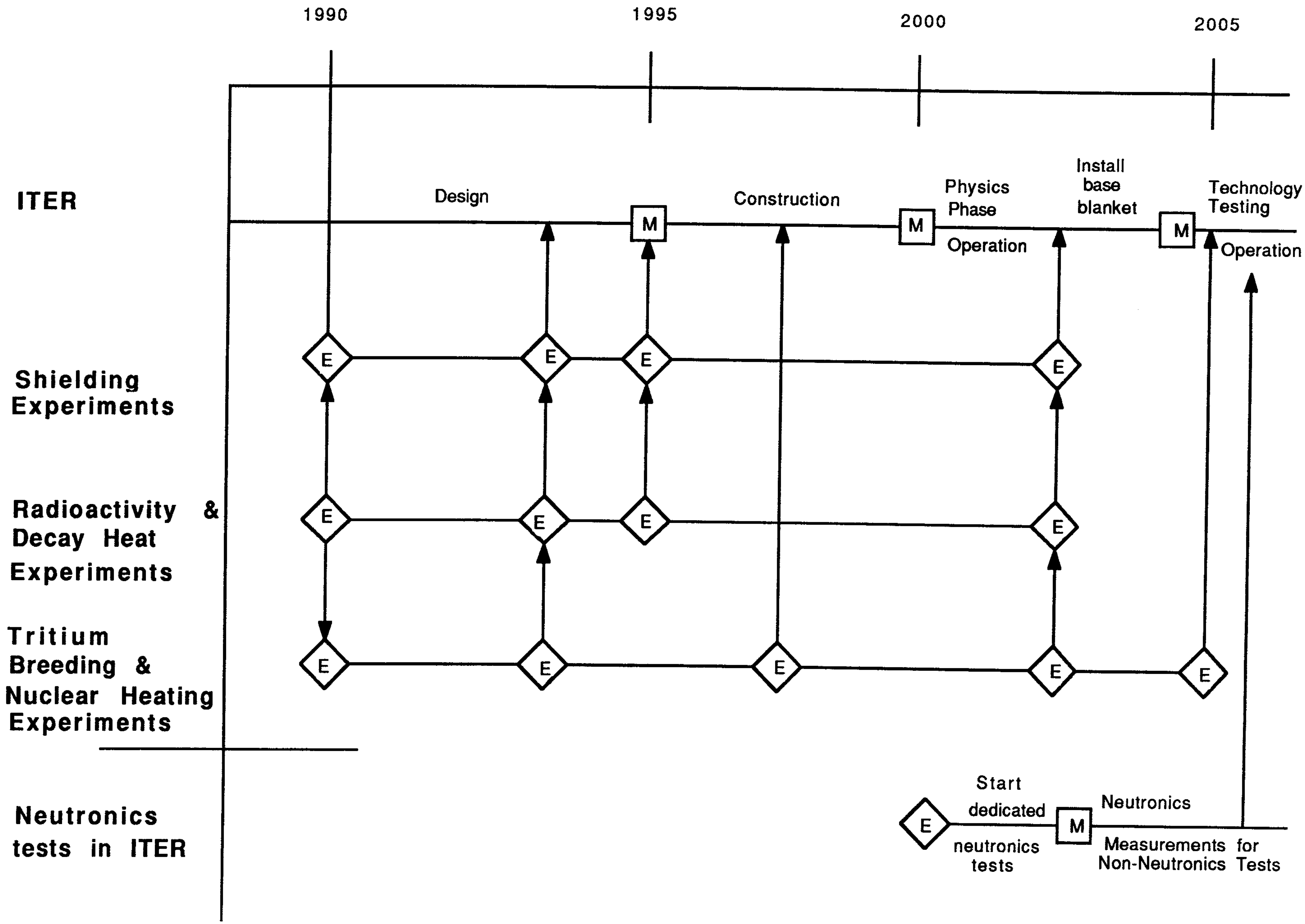
  In both periods, measurements will also be made on:

  - nuclear heating
  - radioactivity/decay heat

- In each period, 2 assemblies can be setup for 2 different experiments
- In a 5 year period:

  10 experiments for shielding
  10 experiments for blanket

Neutronics Integral Experiments Plan



Estimates of Cost and Manpower

(5 year, 2 experimental periods per year)

- Manpower ($2.5M/yr)
  - 8 man-year/year experimentalists
  - 8 man-year/year analysts
  - technicians for facility operation
- Instrumentation $1.8M
  (cost of hardware for operation & R & D)
  - Neutron Spectroscopy $0.6M
  - Gamma Spectroscopy $0.5M
  - α,β Spectroscopy $0.3M
  - Nuclear Heating $0.4M
- Materials for Experimental Assemblies $2.1M
  - Breeder $0.8M
  - Shield $0.8M
  - Foils $0.2M
  - Construction $0.3M
- Facility
  - Target (1000 hr x 500 $/hr) $0.5M
  - Other costs ?

Summary

- Tritium breeding, nuclear heating, shielding and radioactivity/decay heat are major issues.
- Integral experiments are required to resolve these issues and to provide critical input to ITER basic device and test program
- Proposed for IEA activity
  - Integral experiments for two configurations
    1. Blanket
       Measurements: Tritium Breeding, Nuclear Heating, Radioactivity/Decay heat)
    2. Shield
       Measurements: Radiation attenuation, Nuclear Heating, Radioactivity/Decay heat
- Duration: 5 year (starting 1990)
  Each year: 2 experimental periods (2 months each) one for blanket, one for shield
- FNS Facility at JAERI offers attractive features as a primary facility. Other facilities in EC, Japan and USA can play a support role.
- Material and Instrumentation cost over 5 year is $4M
- Manpower cost (experimentalists and analysts): 16 man-year/yr