# FINESSE NUCLEAR TECHNOLOGY
# TESTING REQUIREMENTS

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TECHNICAL COMMITTEE AND WORKSHOP
ON
FUSION REACTOR DESIGN AND TECHNOLOGY
YALTA, USSR
26 MAY - 6 JUNE 1986

[redacted]

# A STUDY OF THE ISSUES, PHENOMENA AND EXPERIMENTAL FACILITES FOR FUSION NUCLEAR TECHNOLOGY

## Objectives

- Understand Issues
- Develop Scientific Basis for Engineering Scaling and Experimental Planning
- Identify Characteristics, Role and Timing of Major Facilities Required

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# FUSION NUCLEAR TECHNOLOGY

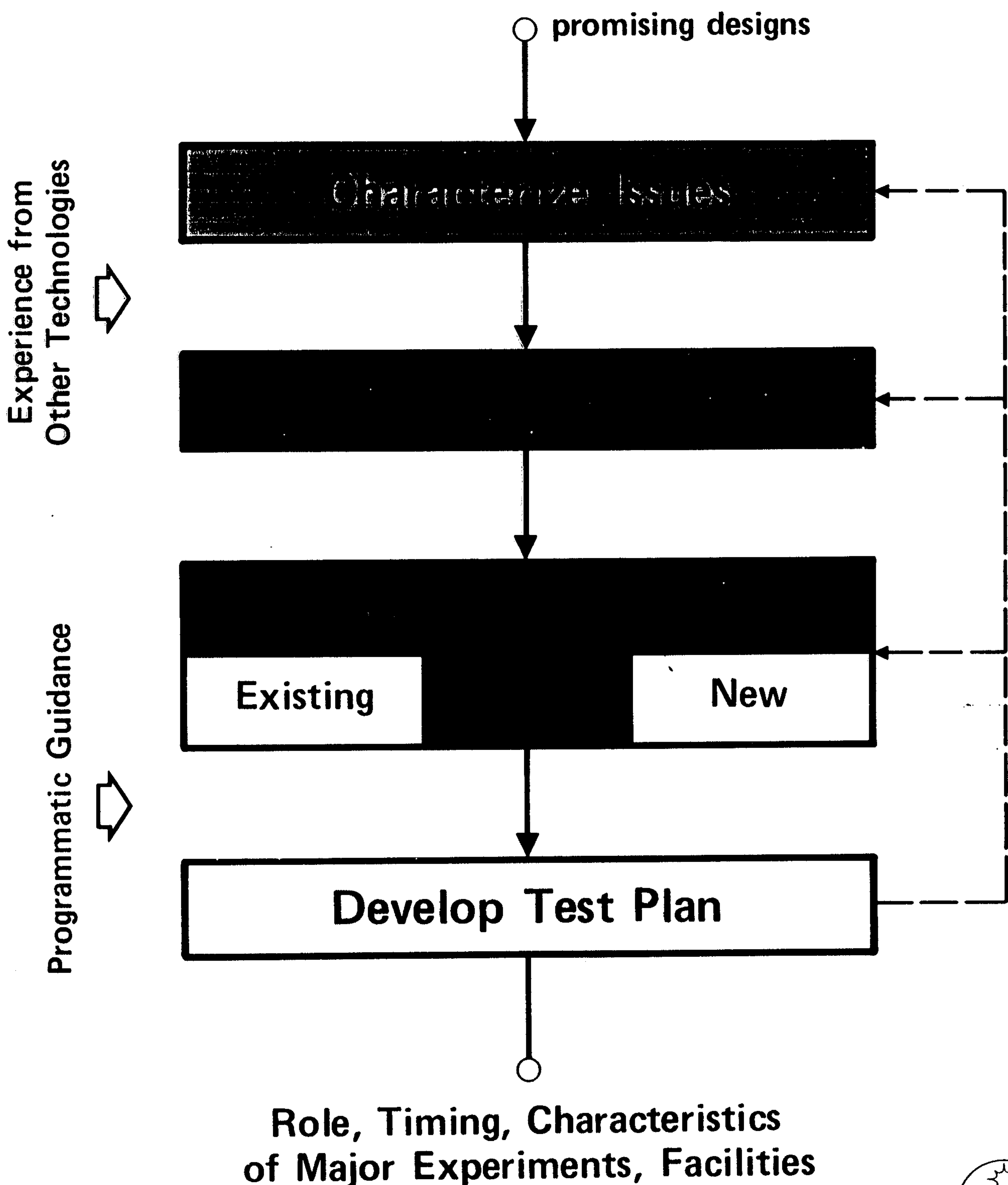
[redacted]

- Fuel Production and Processing
- Energy Extraction and Use

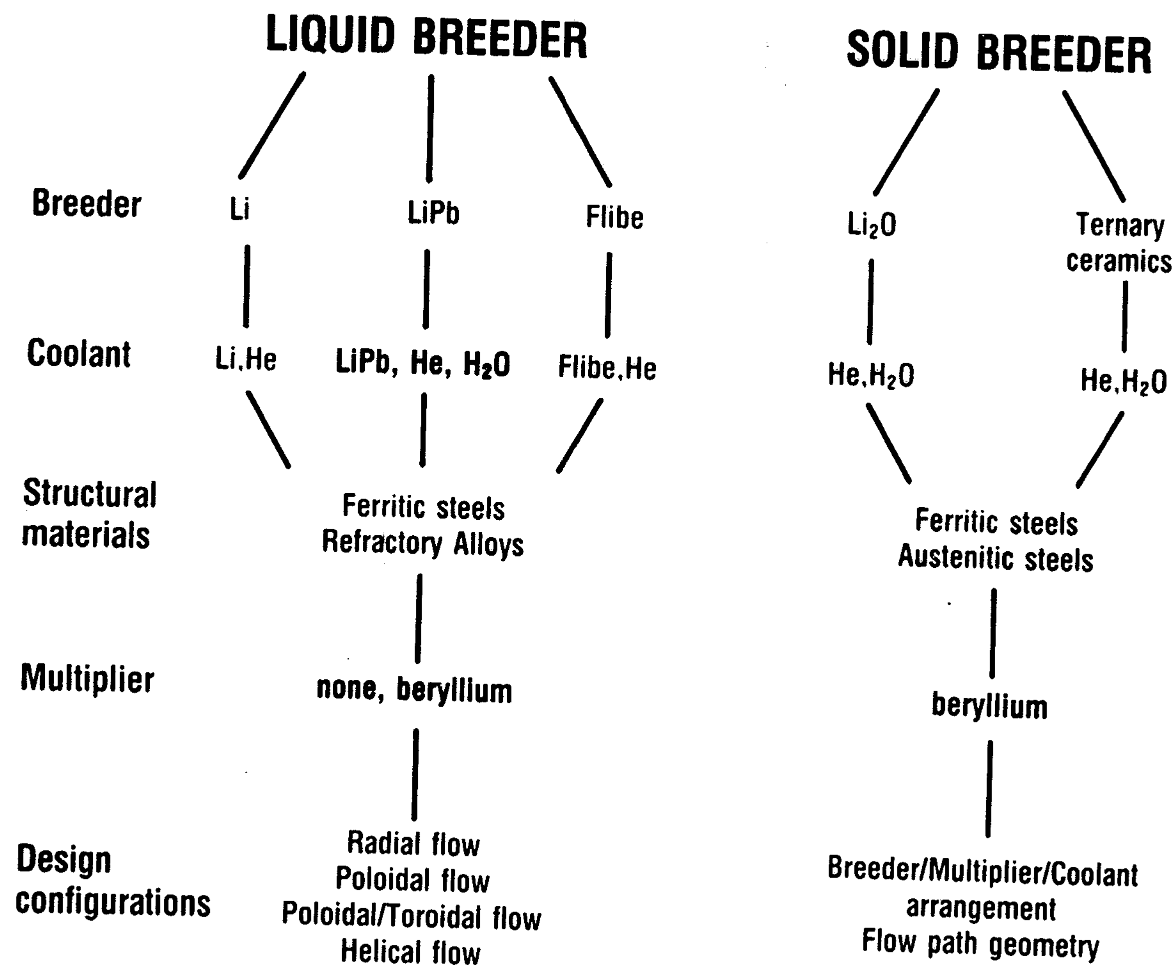
[redacted]

- Blanket
- PIC (First Wall, Limiter, etc.)
- Shield
- Tritium Processing

# FINESSE PROCESS For Experiment Planning



# Primary Options
# For Blanket Materials and Configurations



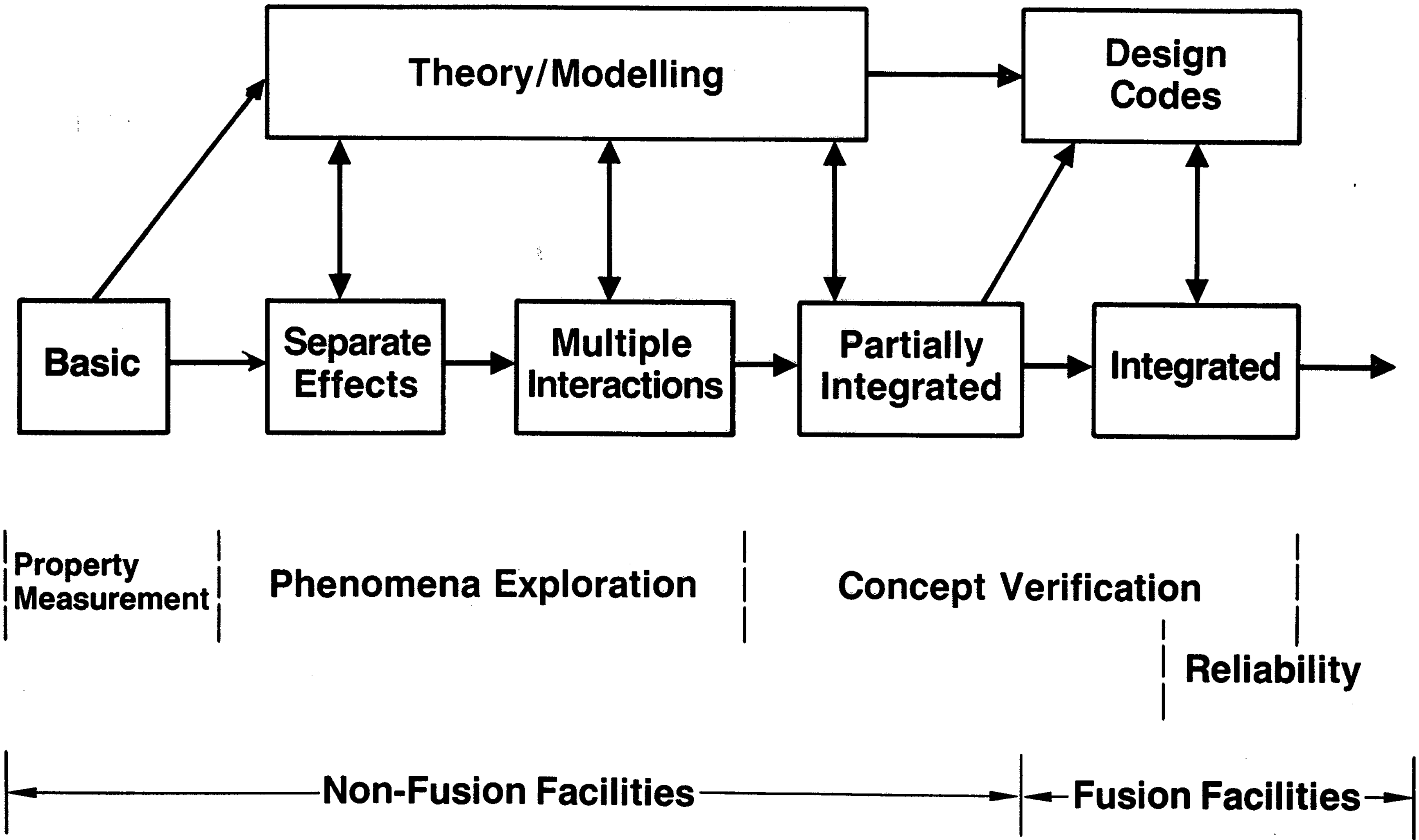

—Further experimental work is required prior to selection.

# Generic Liquid Metal Blanket Issues

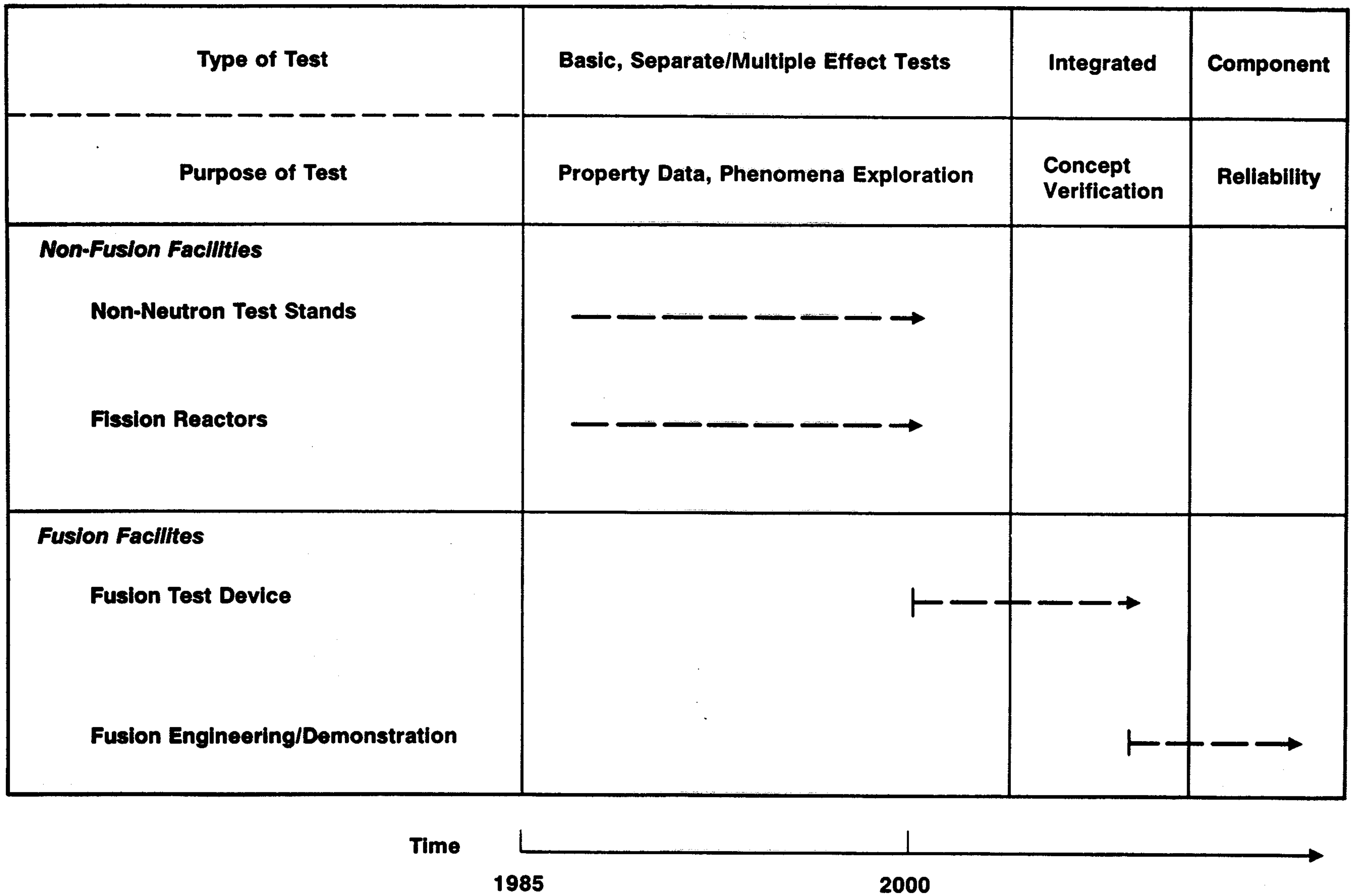
- Tritium Self-sufficency
- Magnetohydrodynamic (MHD) Effects
  —Fluid Flow (including pressure drop)
  —Heat Transfer
- Material Interactions (e.g., Corrosion)
- Structural Response in the Fusion Environment
  —Irradiation Effects on Material Properties
  —Response to Complex Loading Conditions
  —Failure Modes
- Tritium Recovery and Control

# Generic Solid Breeder Blanket Issues

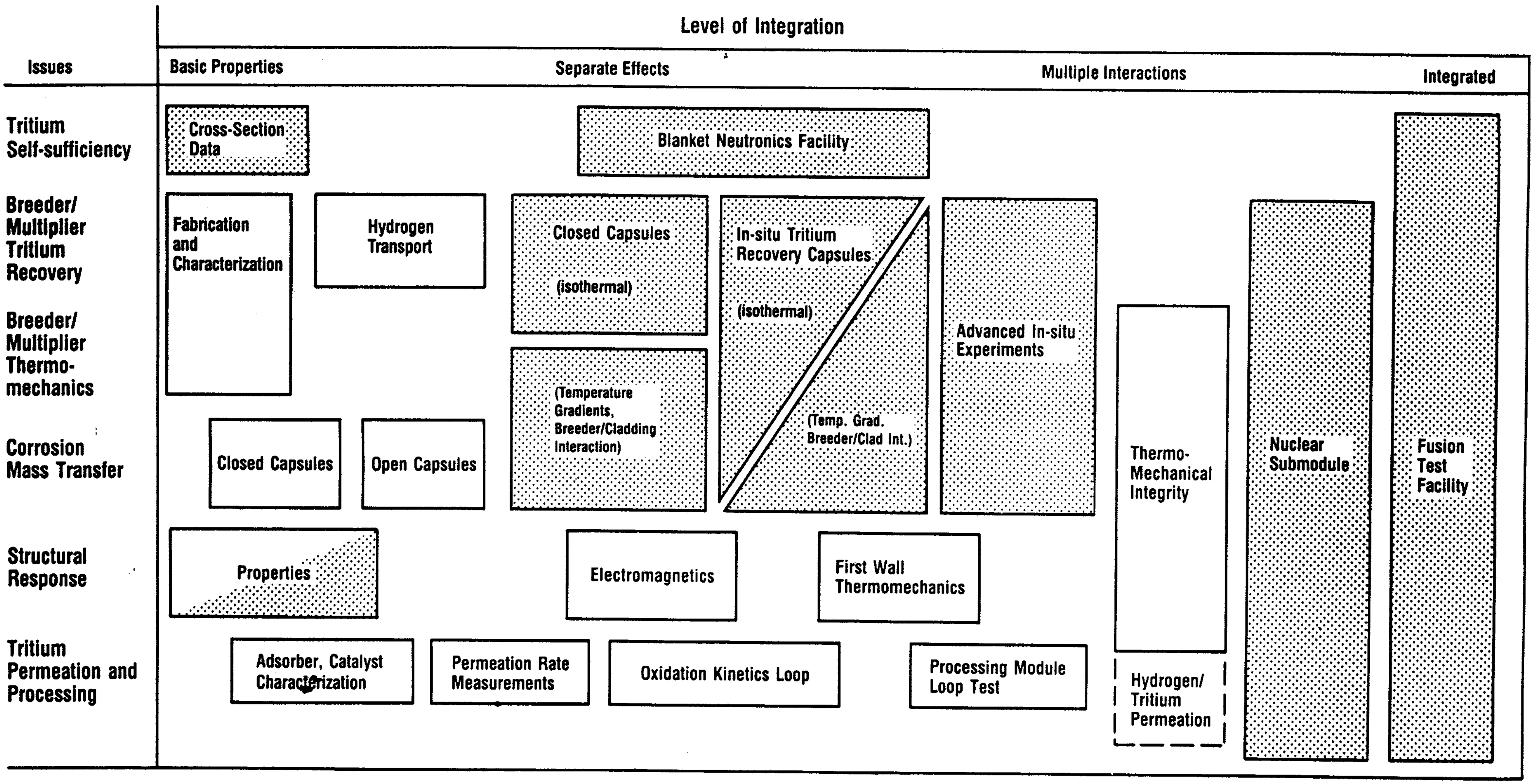
- Tritium Self-sufficiency
  —Achievable Breeding Ratio
  —Required Breeding Ratio
- Breeder/multiplier Tritium Inventory and Recovery
- Breeder/multiplier Thermomechanical Behavior
- Corrosion and Mass Transfer
- Structural Response and Failure Modes in Fusion Environment
- Tritium Permeation and Processing from Blanket



Theory/Modelling
Design Codes
Basic
Separate Effects
Multiple Interactions
Partially Integrated
Integrated
Property Measurement
Phenomena Exploration
Concept Verification
Reliability
Non-Fusion Facilities
Fusion Facilities


Type of Test
Basic, Separate/Multiple Effect Tests
Integrated
Component
Purpose of Test
Property Data, Phenomena Exploration
Concept Verification
Reliability
Non-Fusion Facilities
Non-Neutron Test Stands
Fission Reactors
Fusion Facilites
Fusion Test Device
Fusion Engineering/Demonstration
Time
1985
2000

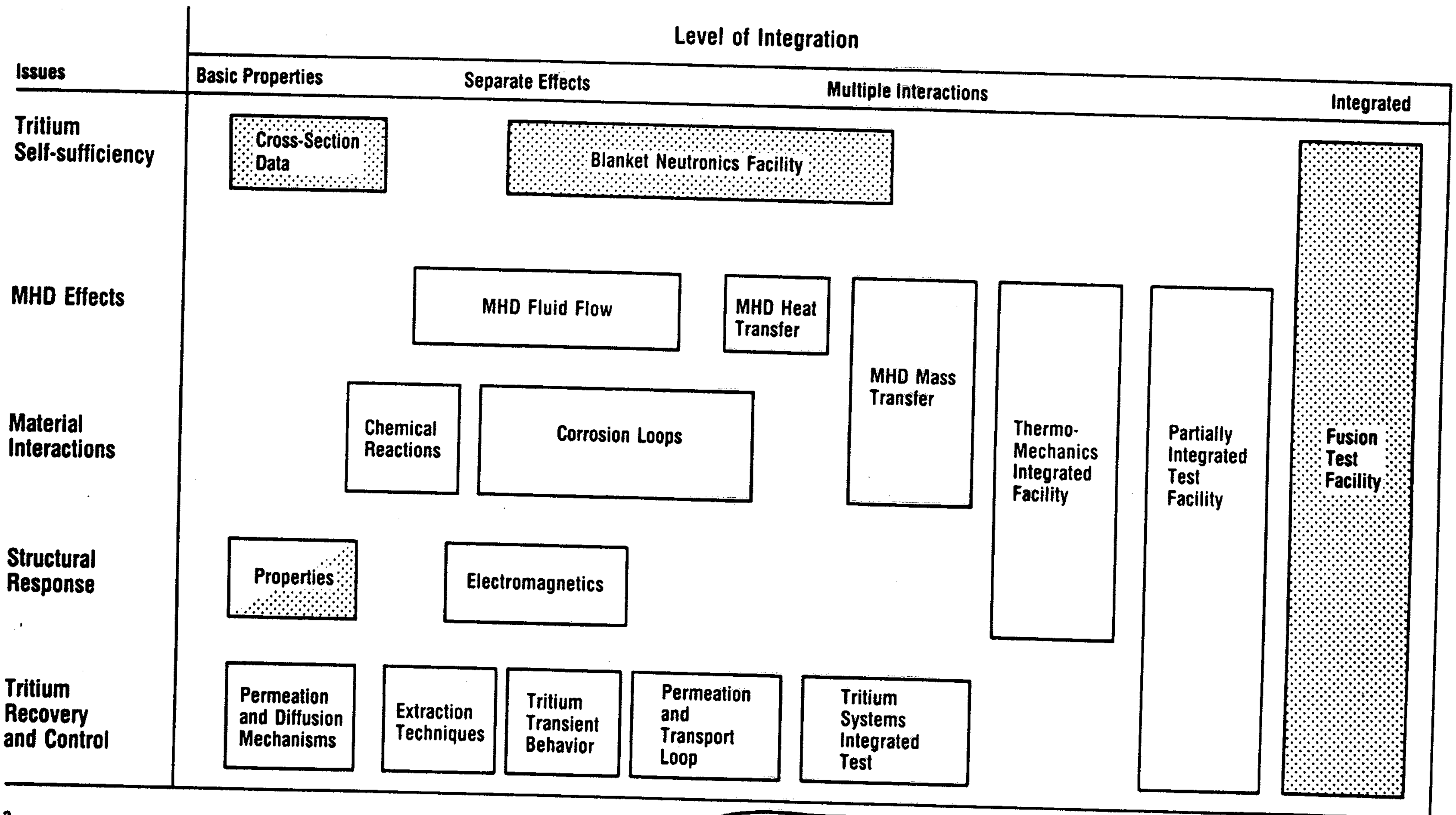
# TYPES OF EXPERIMENTS AND FACILITIES FOR SOLID BREEDER BLANKETS[a]




[a] Some Experiments and Facilities Exist

Neutron Test

# TYPES OF EXPERIMENTS AND FACILITIES FOR LIQUID METAL BLANKETS[a]




[a] Some experiments or facilities already exist

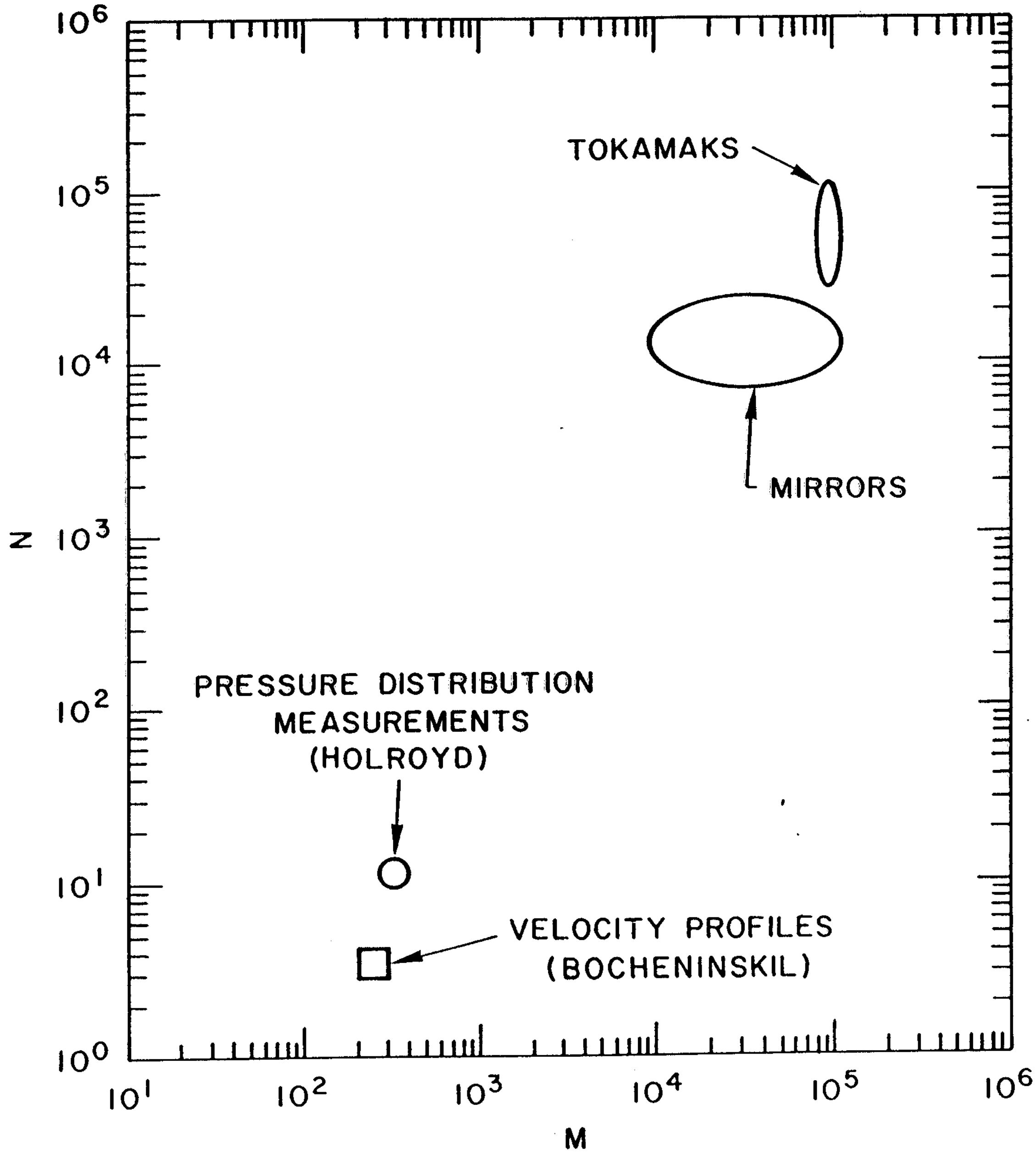



FIGURE 6. Hartmann number (M) and interaction parameter (N) ranges for existing data and reactor conditions

# Features and Objectives of Major Liquid Breeder Experiments

| | ALEX | Magnetic Transport Phenomena Facilities: LMF | Magnetic Transport Phenomena Facilities: MHDM | TMIF | PITF |
|---|---|---|---|---|---|
| Features of Experiments | • Simple Geometry of a channel<br>• NaK | • Basic elements of relevant geometry | • Basic elements of relevant geometry<br>• Relevant material combinations<br>• Transport loop<br>• Relevant T, ΔT, impurities, V<br>• Long operating time per experiment | • Actual materials and geometry<br>• Transport loop<br>• Relevant environmental and operating conditions | • Prototypic blanket module<br>• Transport loop<br>• Prototypic environmental and operating conditions |
| | • Measure velocity profile, electric potential, pressure drop | • Measure V and T profiles; pressure drop, temperature, electric potential | • Measure dissolution and deposition rates | • Measure integral quantities (ΔP, T, corrosion and deposition rates) | • Measure integral quantities |
| Objectives | • Develop and test velocity profile instrumentation in NaK environment<br>• Validate MHD in simple geometry (basic heat transfer data may be possible in upgrade | • Develop and test instrumentation<br>• Validate MHD heat transfer<br>• Design data (ΔP, T) for configuration screening<br>• Explore techniques to reduce ΔP and enhance heat transfer | • Develop and test instrumentation in relevant environment<br>• Design data on MHD heat and mass transfer<br>• Verify techniques to reduce corrosion and corrosion effects | • Design data for blanket test module<br>• Confirm and refine configurations | • Engineering design data<br>• Reliability data in non-fusion environment |

Table 8. Characteristics of Major Liquid Breeder Experiments

| Characteristic | ALEX[a] | Magnetic Transport Phenomena Facilities | | TMIF[d] | PITF[e] |
|---|---|---|---|---|---|
| | | LMF[b] | MHDM[c] | | |
| Fluid | NaK (100°C) | NaK | actual materials | actual materials | actual materials |
| Testing volume (m x m x m) | 1.83 x 0.76 x 0.15 (0.21 $m^3$) | 3 x 1 x 0.5 (1.5 $m^3$) | | 3 x 1 x 0.5 | 3 x 1 x 0.5 |
| Magnetic Field | 2 T | 4-6 T | | 4-6 T | 4-6 T |
| Configuration | simple geometry | elements of complex geometry | | submodule | prototypic |

[a]Exists (ANL)

[b]Liquid Metal Flow Facility

[c]MHD Mass Transfer Facility

[d]ThermoMechanical Integration Facility

[e]Partially Integrated Test Facility

# LIQUID BREEDER BLANKET TEST PLAN

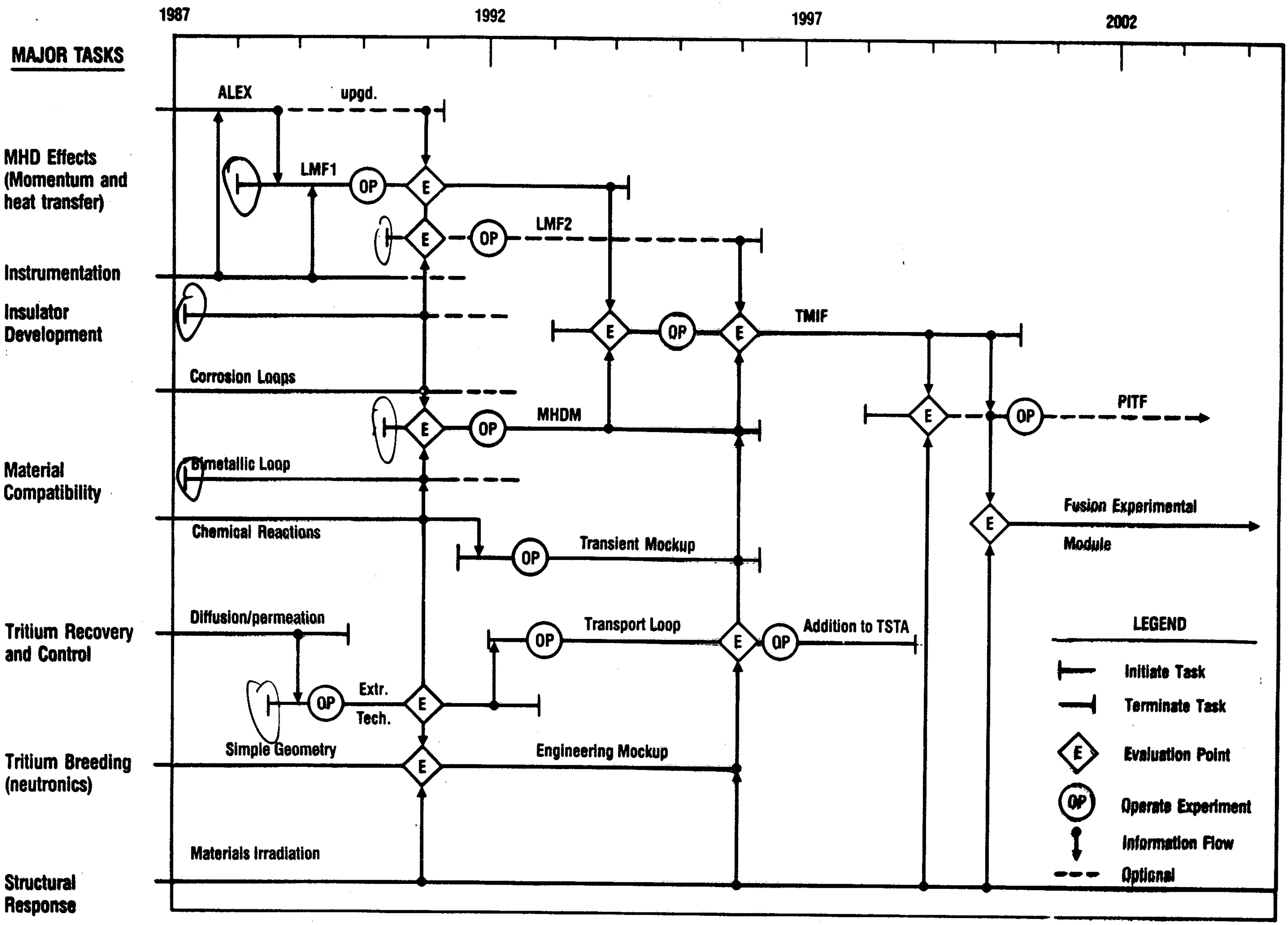


Table 2-7. Parameters for Major Integrated Non-fusion Irradiation Experiments

| | Advanced In-situ Tritium Recovery | Nuclear Submodule |
|---|---|---|
| Test geometry | Subassembly with multiple capsules | Blanket breeder section or unit cell |
| Material | Multiple | One per submodule |
| Temperature, °C | 350-1200°C | Reactor blanket profile |
| Temperature gradients, °C/cm | 100-1000 | 100-1000 |
| Breeder thickness, cm | 0.5-5 | 0.5-5 |
| Purge gas | Helium, plus $O_2$, $H_2$ and/or $H_2O$ | Helium, plus $O_2$, $H_2$ and/or $H_2O$ |
| Purge flow rate, $m^3/s$-g[a] | 0.01-0.1 | 0.01-0.1 |
| Burnup, at.% Li | 3-10 | 3-10 |
| Heat generation, $MW/m^3$ | 30-100 | 30-100 |
| Irradiation time, yrs | 1-3 | 1-3 |
| Tritium production, T/Li-yr | 0.01-0.5 | 0.01-0.5 |

[a]Normalized per gram of solid breeder material

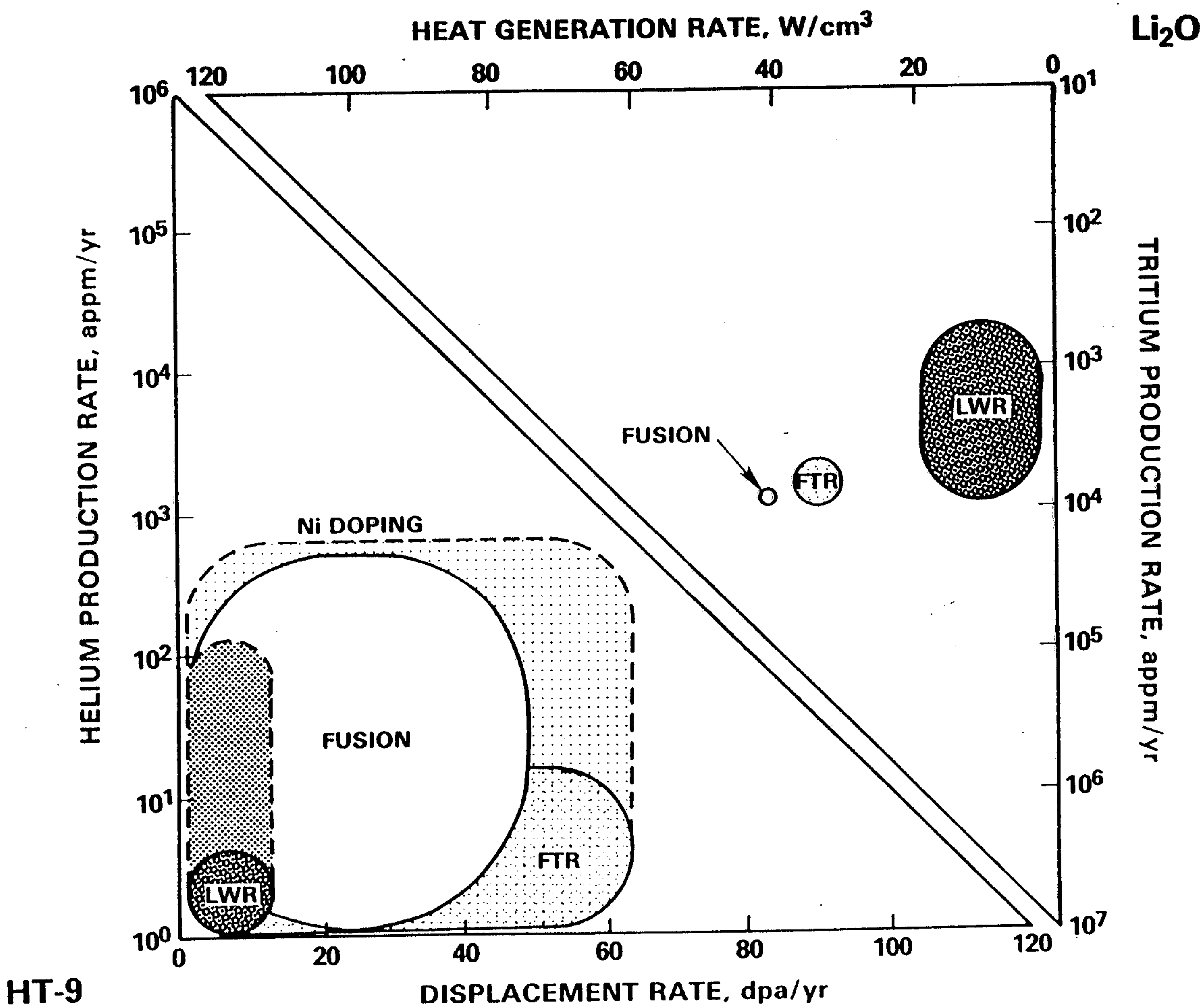
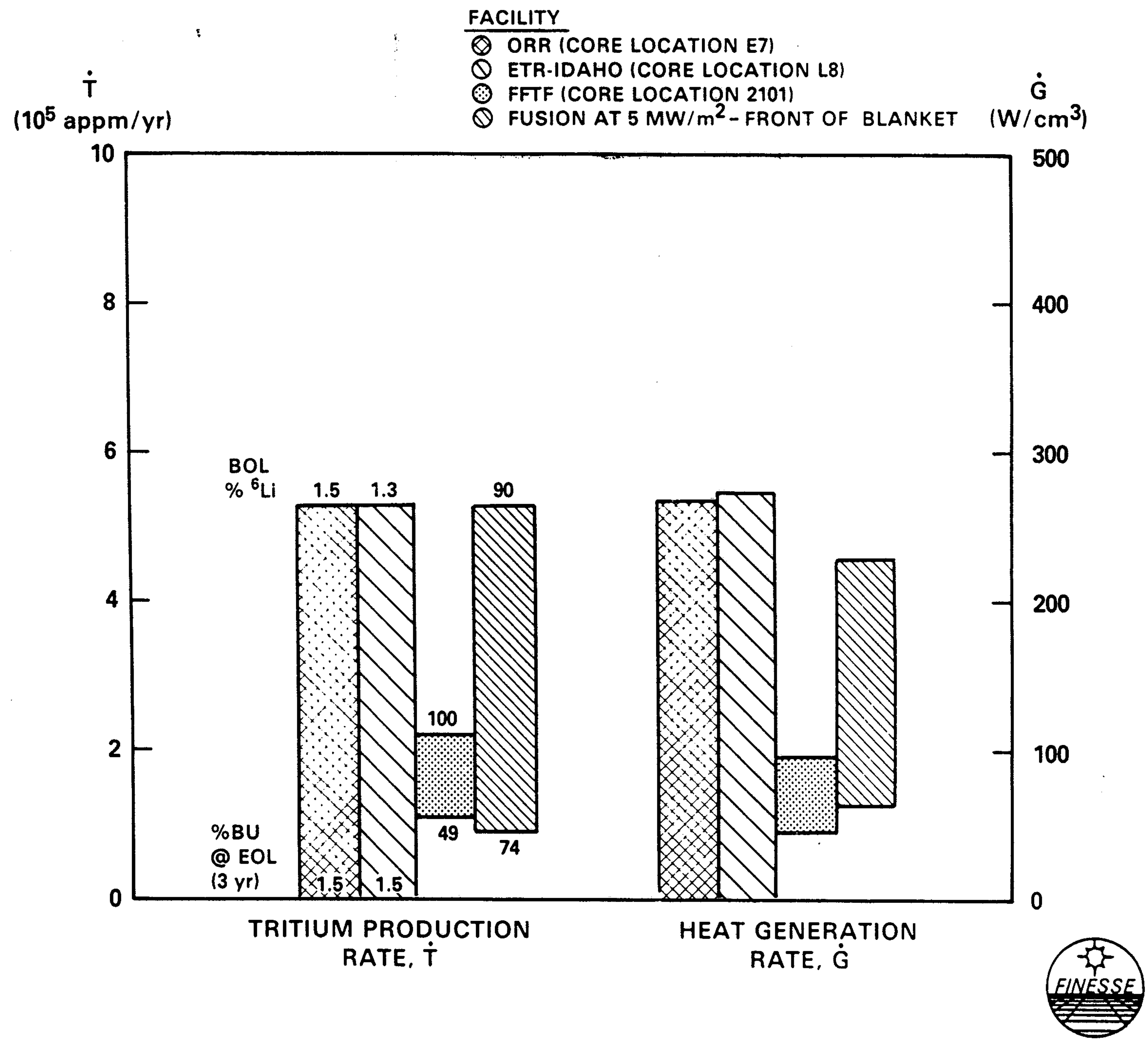



FIGURE 5. Simulation of $Li_2O$/He/HT-9 fusion blanket in fission reactors

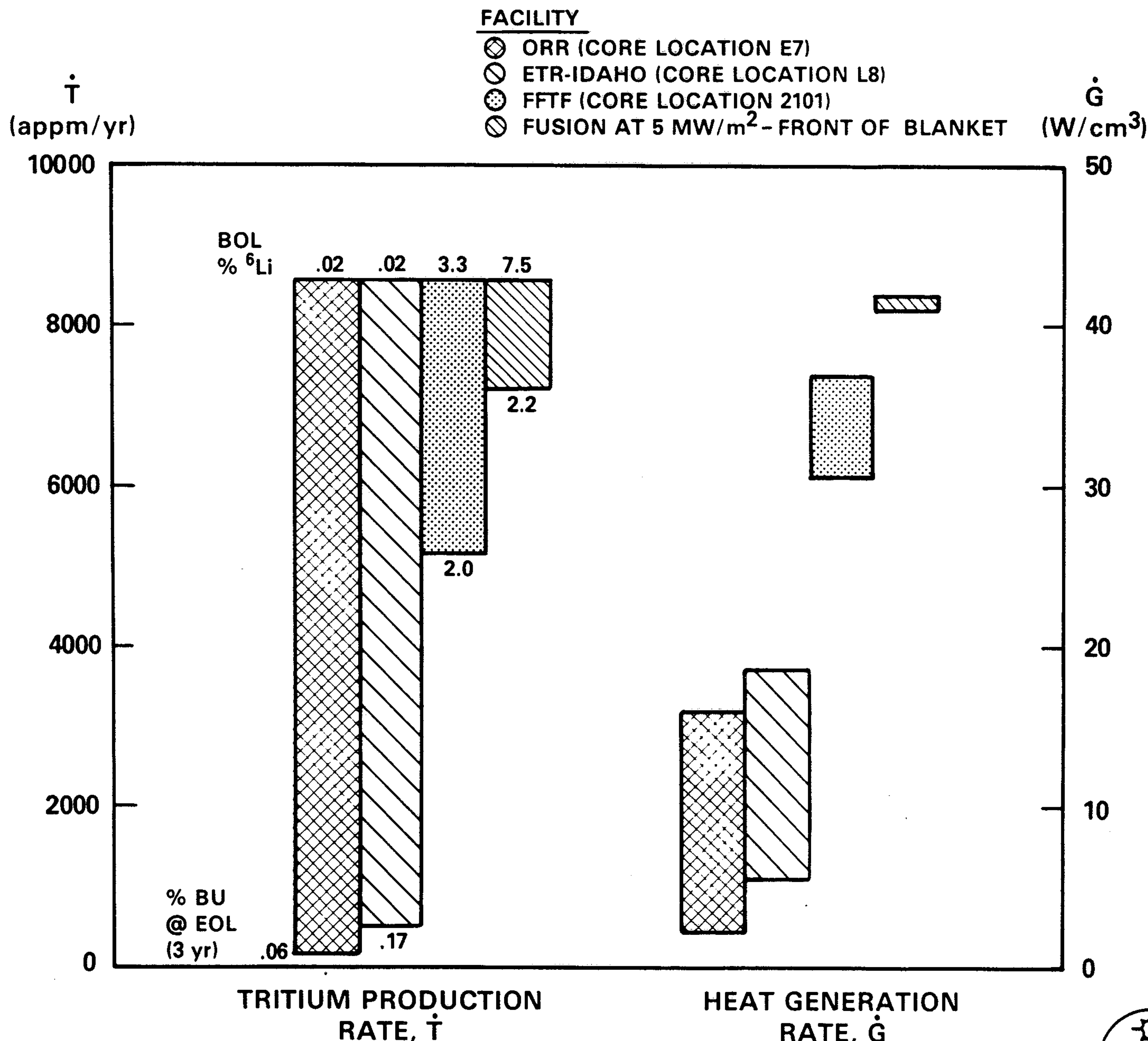
# FISSION/FUSION IRRADIATION COMPARISON FOR $LiAlO_2/H_2O$/HT-9/Be SYSTEM

## $LiAlO_2$ SOLID BREEDER

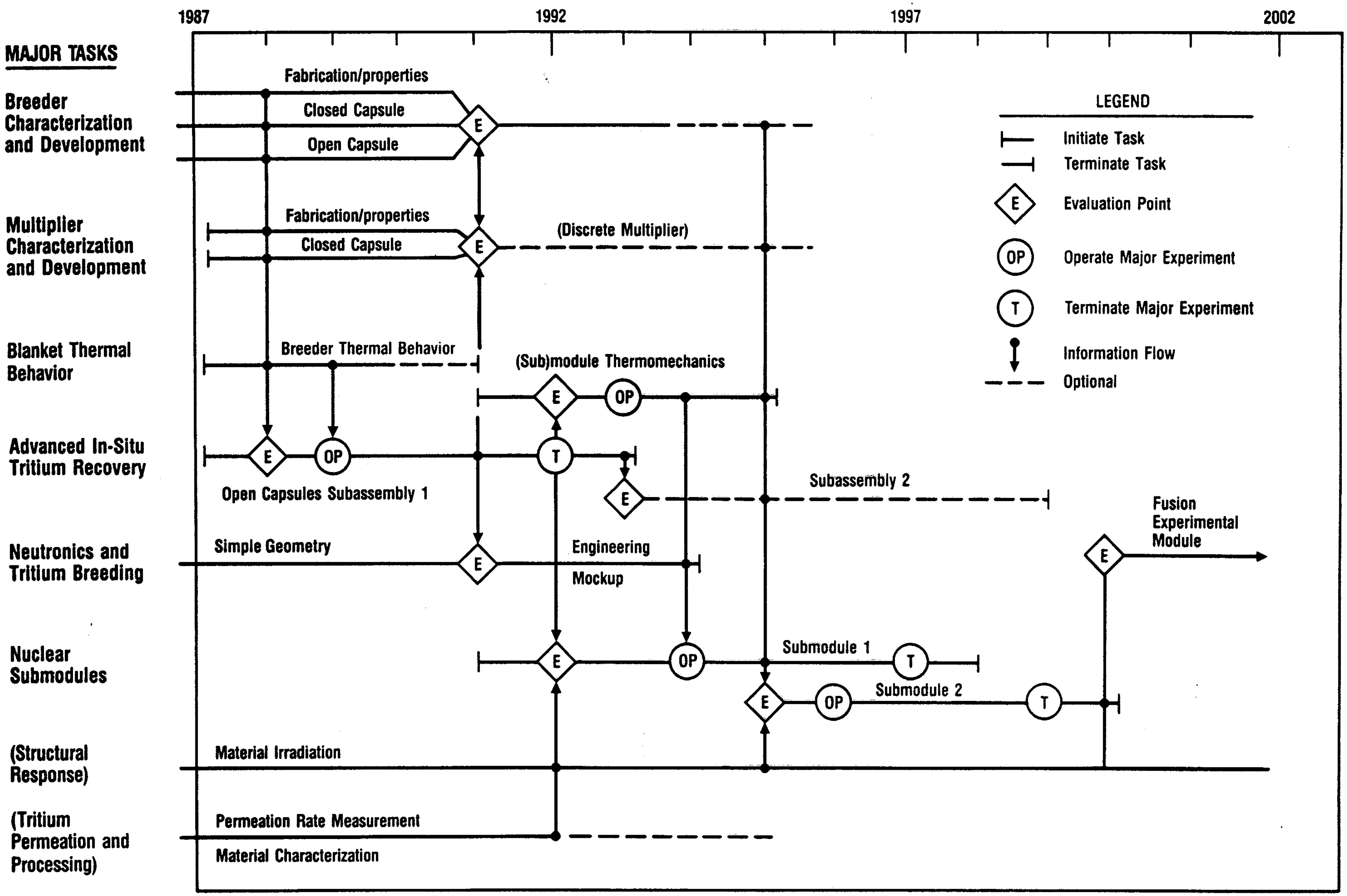


FISSION/FUSION IRRADIATION COMPARISON FOR $Li_2O$/He/HT-9 SYSTEM

# $Li_2O$ SOLID BREEDER



# SOLID BREEDER BLANKET TEST PLAN



# Representative Costs of Key Liquid Breeder Blanket Facilities[a]

| Item | Capital Cost (M$) | Operating Cost (M$/yr) | Duration (years) | Total Cost (M$) |
|---|---|---|---|---|
| Advanced liquid metal flow facility (LMF1) | 7-10 | 0.5 | 4-6 | 10-15 |
| Integral Parameter Experiment (LMF2) | 7-10 | 0.5 | 4-6 | 10-15 |
| MHD mass transfer facility (MHDM) | 8-12 | 1.0 | 6-8 | 15-20 |
| Corrosion Loops | 6-10 | 1.6 | 8-12 | 12-20 |
| Tritium extraction test (2) | 2-3 | 0.4 | 3-4 | 3-5 |
| Tritium transport loop test | 6-8 | 0.6 | 5-7 | 9-12 |
| Partially Integrated Test Facility (PITF) | estimate not available | | | |
| Thermomechanical Integrated Test Facility (TMIF) | 20-25 | 2.0-3.0 | 8-10 | 35-60 |
| Analysis and model development | 0 | 2.0-4.0 | 15 | 30-60 |

[a]In 1985 constant dollars

TABLE IV. RADIATION SHIELD ISSUES

Radiation protection criteria of sensitive components (superconducting magnets, vacuum equipment, plasma heating systems and control system)

Effectiveness of bulk shield

- composition, thickness of shield materials
- deep penetration of high energy neutrons (14 MeV) including cross-section windows

Effectiveness of penetration shielding

- streaming and partial shield
- modeling procedure

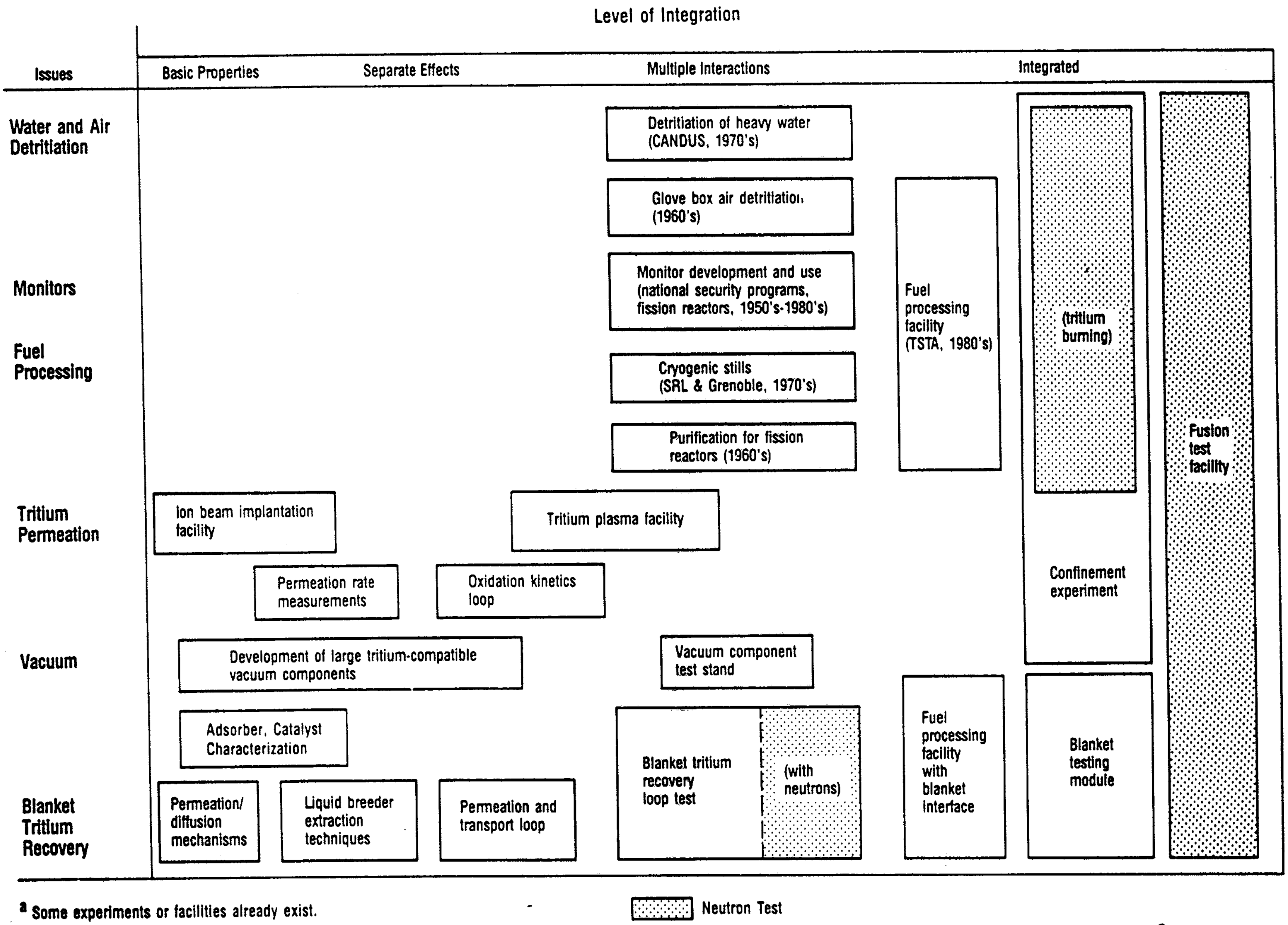
Occupational exposure

- induced activity and dose distribution
- radioactive corrosion materials
- remote maintenance system

Public exposure and waste management

- sky shine
- radioactive waste of shield materials

Shield compatibility with blanket heat transport system and magnet, including assembly/disassembly and magnetic field penetration




[a] Some experiments or facilities already exist.

FIGURE 9. Types of experiments and facilities for tritium processing and vacuum systems[a]

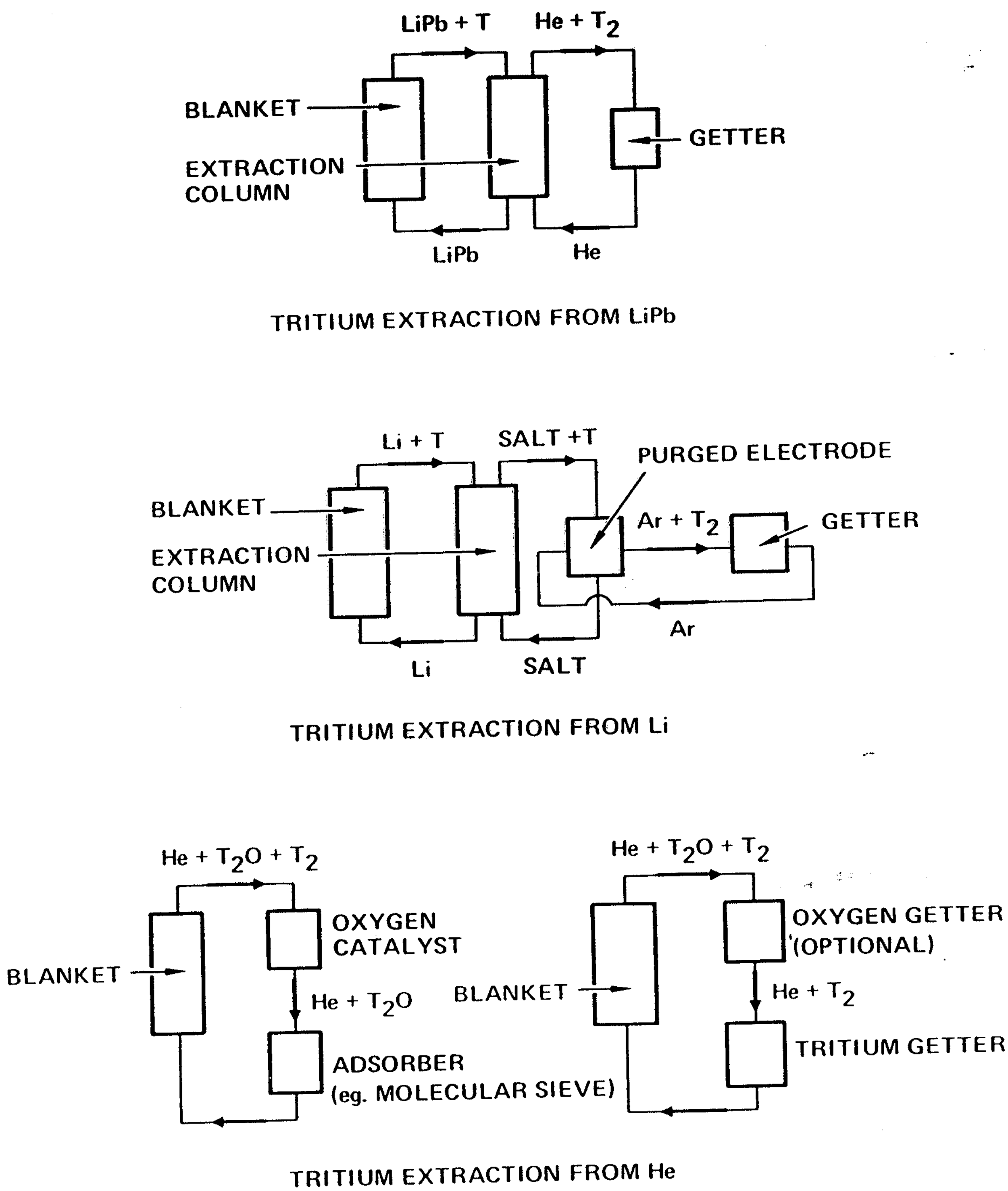



FIGURE 10. Schematic representation of tritium processing schemes

# ROLE OF FUSION DEVICES FOR NUCLEAR TESTING

- Confirm Data from Non-Fusion Facilities
- Complete Exploration of Phenomena
- Integrated Tests
  - Concept Verification
  - Engineering Data
- In the Long Term:
  - Component Development
  - Reliability Data

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# FUSION NUCLEAR TECHNOLOGY
[redacted]
# ON FUSION FACILITY PARAMETERS

| Fusion Device Parameter | Minimum | Substantial Benefits |
|---|---|---|
| Neutron Wall Load, $MW/m^2$ | 1 | 2 - 3 |
| Surface Heat Load, $MW/m^2$ | 0.2 | 0.5 |
| Plasma Burn Time, s | 500 | 1000 |
| Plasma Dwell Time, s | 100 | |
| Magnetic Field, T | 1 | 2 - 3 |
| Continuous Operating Time | Days | Weeks |
| Availability, % | 20 | 50 |
| Fluence, $MW \cdot y/m^2$ | 1 - 2 | 2 - 6 |
| Test Port Size, $m^2$ x m | 0.5 x 0.3 | 1 x 0.5 |
| Total Test Area, $m^2$ | 5 | 10 |

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# OBSERVATIONS ON [redacted] [redacted] IN FUSION DEVICES

1. Tokamak Ignition Requires:
   - Fusion Power: 200-500 MW
   - Total DT Burn Time: $\sim 2 \times 10^5$ s
   - Tritium Consumption: ~0.2 kg
2. Fusion Nuclear Testing Requires:
   - Fusion Power: ~20 MW
   - Total DT Burn Time: Several Years
   - Tritium Consumption: ~5 kg
3. Combining 1 and 2 in One Device Requires:
   - Tritium Consumption: ~200 kg

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# SUMMARY OF TRITIUM SUPPLY

| | | |
|---|---|---|
| • ATMOSPHERE | 1 MG | NOT RECOVERABLE |
| • SPECIAL APPLICATIONS | | NO ASSESSMENT |
| • CANDU | | |
| PLANNED ONTARIO HYDRO | | 2.5 KG/YR |
| DOUBLE THROUGHPUT | | 0.2 KG/YR (DOUBLE THE COST) |
| • ENHANCED PRODUCTION | | 1 KG/YR (POST 1995) |
| • $^3$HE CONVERSION (N,P) | | 1 KG/YR (POST 1995) |

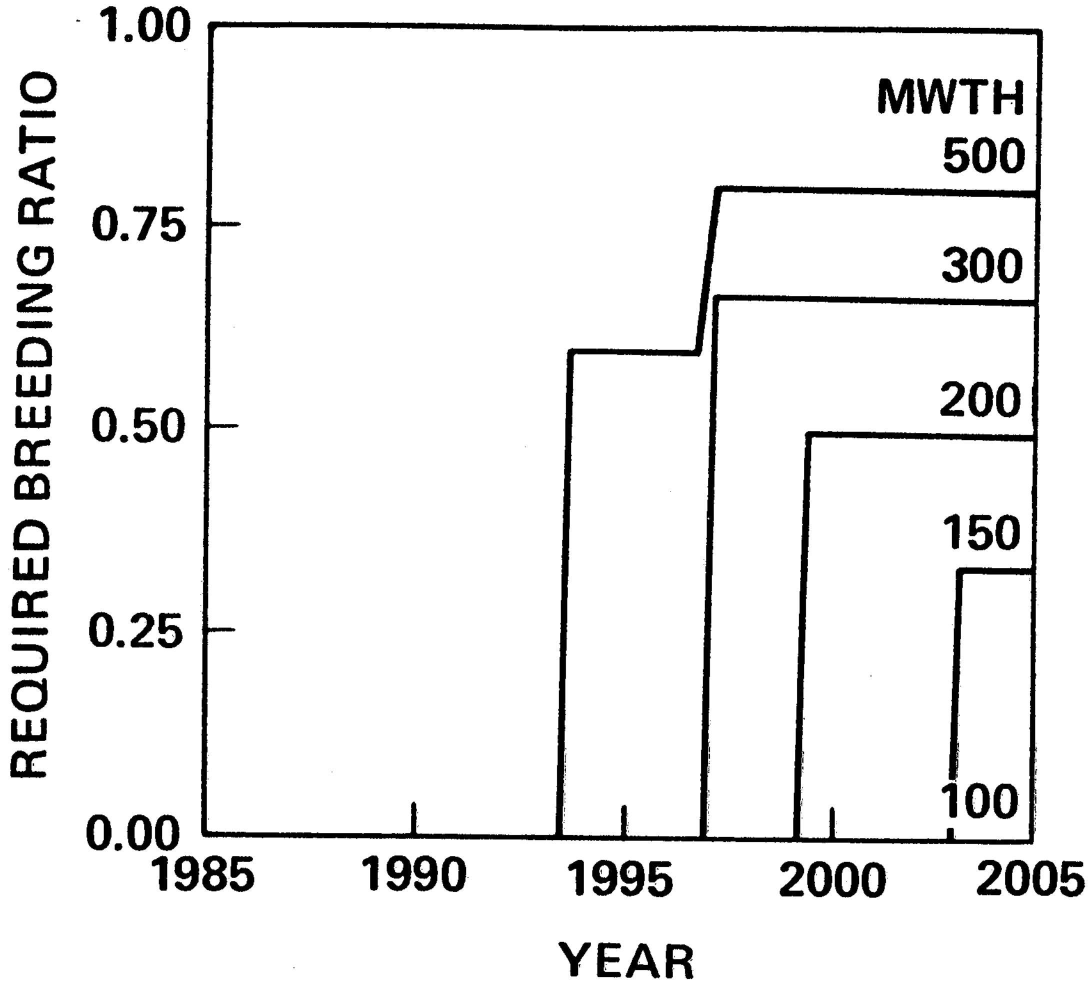


Figure 2.7.1-1 Tritium breeding ratio needs for 2.8 kg/yr tritium supply rate (starting 1988) with startup of fusion device delayed until 1995.

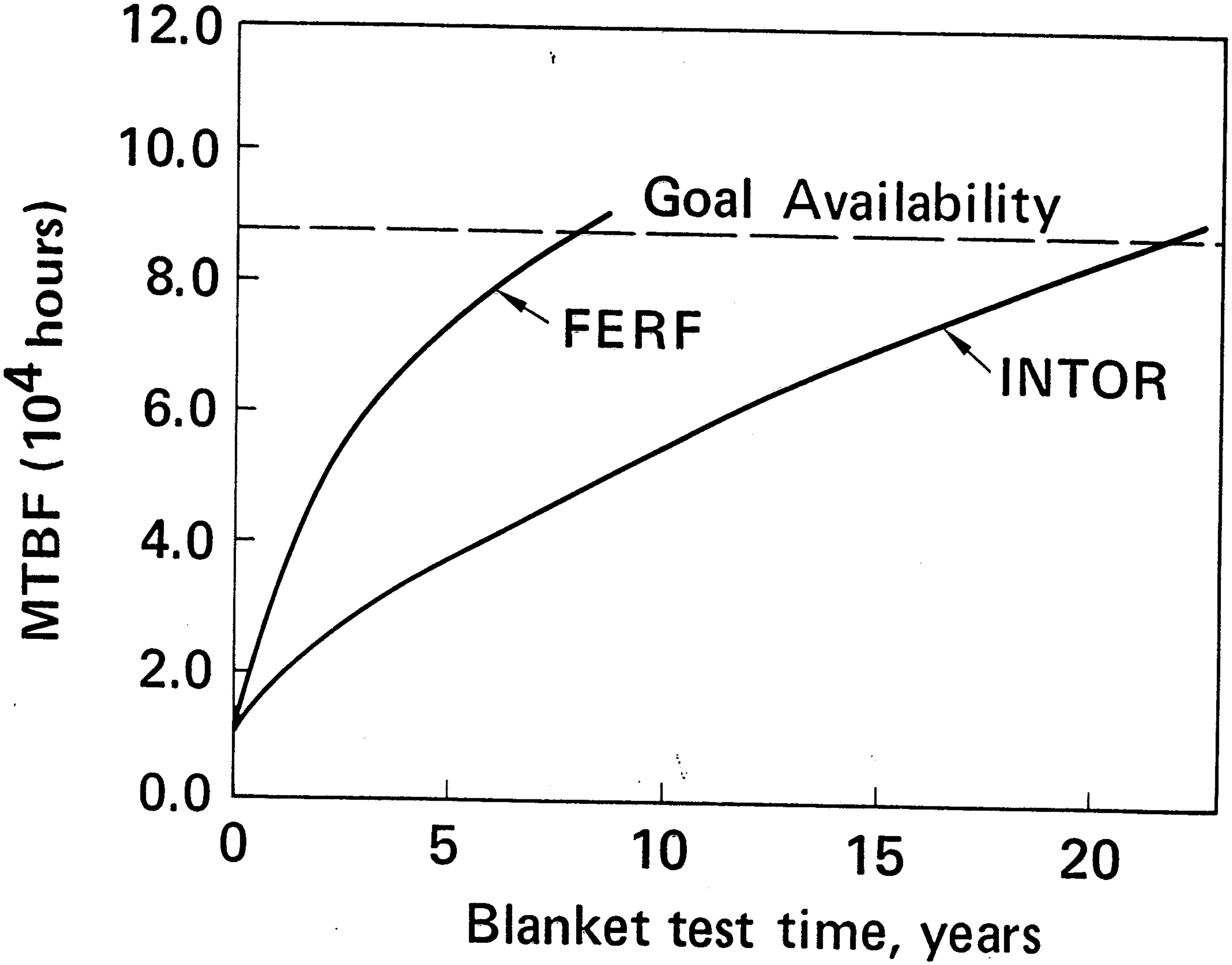


FIGURE 11. Nuclear component reliability growth in high availability (FERF) versus low availability (INTOR) test device

# OBSERVATIONS ON NUCLEAR TESTING IN FUSION DEVICES

- Relatively Long Time (Several Years) Needed for Nuclear Testing Introduces Tritium Supply Problems in First Generation DT Facilities if Facility Fusion Power is Large (Hundreds of Megawatts)

- A Near Full–Scale Tritium Breeding Blanket in a Fusion Device Without Prior Fusion Testing Introduces Important Issues (e.g., Reliability, Cost)

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# OBSERVATIONS ON
# NUCLEAR TESTING IN FUSION DEVICES

- Cost of Providing Fusion Testing for Nuclear Technology Can Be Substantially Reduced if a Low Fusion Power Device Option Can Be Developed, e.g.,

    FERF: Fusion Engineering Research Facility

    [redacted]

    5 – 10 $m^2$

    2 – 10 MW · $y/m^2$

- Several Ideas for FERF Evaluated

    Potential Problems Include:

    - Physics Feasibility
    - Engineering Feasibility
    - Cost
    - Timing

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TABLE IX. SUMMARY CHARACTERISTICS OF FUSION ENGINEERING RESEARCH FACILITIES

| | Tokamaks | | | | Spherical Torus FERF | Tandem Mirrors | | Reverse Field Pinch |
|---|---|---|---|---|---|---|---|---|
| | INTOR | LITE FERF | BEAN FERF | DTFC-IDT | | TDF | MFTF-α+T | |
| Neutron wall load, $MW/m^2$ | 1.3 | 1.0-2.0 | 1.3 | 2.0 | 1.0 | 2.1 | 2.0 | 1.0-5.0 |
| Fluence x Area/Year, MW-yr/yr | 14 | 2.9 | 5.8 | 3.2 | 1.4 | 3.8 | 1.8 | 1.6-7.9 |
| Pulse length, s | 200 | 500-1000 | 1000 | 520 | 360,000 | 360,000 | 360,000 | 360,000 |
| Physics risk[a] | 2 | 1 | 7 | 3 | 8 | 2 | 2 | 10 |
| Technology risk[a] | 5 | 4 | 5 | 6 | 8 | 3 | 3 | 7 |
| Tritium consumption, kg/yr | 5.8[e] | 2.0 | 4.1 | 2.2 | 0.97 | 0.90 | 0.42 | 0.55-2.8 |
| Total capital cost, M$ | 2800 | 900 | 1200 | 1200 | 700 | 1200 | 600 | 700-800 |
| Annual operating cost, M$ | 251 | 112 | 155 | 169 | 74 | 123 | 56 | 68-117 |
| Total cumulative cost[b], M$ | 5500 | 2000 | 2800 | 2900 | 1500 | 2500 | 1200 | 1400-2000 |
| Total cost/useful neutron[c] | 4 | 7 | 5 | 9 | 11 | 6 | 7 | 9-2 |
| Useful neutrons/cost/"risk"[d] | 4 | 3 | 2 | 1 | 1 | 3 | 3 | 1-2 |

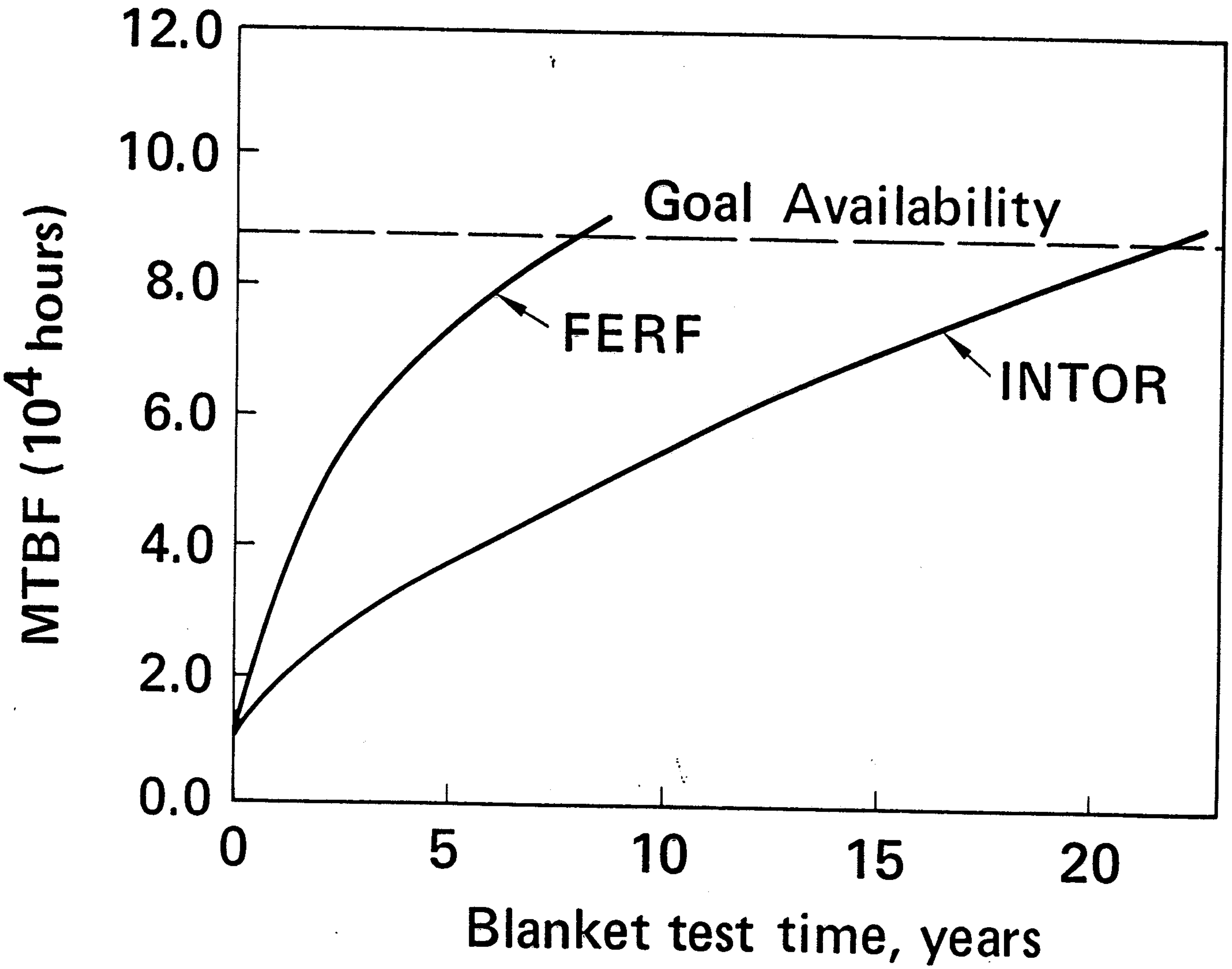
[a]Larger values indicate higher risk; based on judgement of the required subsystem extrapolation.

[b]Assuming 3 years non-tritium/low-availability operation plus 9 years full-availability operation.

[c](Total cost)/(Annual fluence*area) rounded to nearest leading digit.

[d](Annual fluence*area)/(Total cost)(Physics+Technology Risk) rounded to nearest leading digit.

[e]Assuming TBR = 0.6.

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[e]Assuming TBR = 0.6.

TABLE VIII. PERFORMANCE COMPARISON OF FUSION ENGINEERING RESEARCH FACILITIES

| | Tokamaks | | | | Spherical Torus FERF | Tandem Mirrors | | Reverse Field Pinch |
|---|---|---|---|---|---|---|---|---|
| | INTOR | LITE FERF | BEAN FERF | DTFC-IDT | | TDF | MFTF-α+T | |
| Fusion power, MW | 620 | 90 | 185 | 100 | 39 | 36 | 17 | 22-110 |
| Electrical consumption, MWe | 200 | 210-270 | 185 | 427 | 120 | 250 | 104 | 126-180 |
| Neutron wall loading, $MW/m^2$ | 1.3 | 1.0-2.0 | 1.3 | 2.0 | 1.0 | 2.1 | 2.0 | 1.0-5.0 |
| Surface heat flux, $MW/m^2$ | 0.1 | 0.1 | 0.2 | 0.9 | 0.1 | 0.3 | 0.1 | 3.5-4.4 |
| First wall radius, m | 1.2 | 0.8 | 0.75 | 0.59 | 0.59 | 0.3 | 0.25 | 0.3 |
| First wall area, $m^2$ | 380 | 72 | 110 | 40 | 31 | 8 | 4 | 18 |
| Accessible test area[a], $m^2$ | 38 | 7.2 | 11 | 4.0 | 3.1 | 4 | 2 | 3.5 |
| Test port area/depth, $m^2/m$ | 2/1 | 1/1 | 1.5/0.8 | 1.2/1 | 1.6/0.8 | 1.6/0.8 | 0.8/0.8 | 1/0.3 |
| Pulse length[b], s | 200 | 500-1000 | 1000 | 520 | SS | SS | SS | SS |
| Duty cycle (%) | 80 | 90 | 90 | 90 | 100 | 100 | 100 | 100 |
| Ultimate availability[a] % | 35 | 45 | 45 | 45 | 45 | 45 | 45 | 45 |
| Neutron fluence[c], $MW\text{-}yr/m^2$ | 3.3 | 4.0 | 4.7 | 7.3 | 4.0 | 8.5 | 8.1 | 4.0-20 |
| External field on-axis, T | 5.5 | 5.5 | 3-6 | 8 | 3 | 4.5 | 4.5 | 7-9 |

[a]Consistent estimate.

[b]Designs of tokamak devices, e.g., INTOR, with a plasma current drive for steady state (SS) operation were not explored here.

[c]Assuming total equal to 9 years at ultimate availability.