U.S. Approach to Planning of FNT Research and Strategy for Resolving Key Technical Issues

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Fusion Nuclear Technology, Especially Blankets

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FNT Technical Planning in U.S.

Technical Planning

A technical process to identify the role, timing, and characteristics of major experiments and facilities and other R&D needs in a logically consistent and cost effective path to a practical product.

U.S. Activities

The U.S. fusion program has found technical planning to be extremely useful in guiding the R&D program. Comprehensive technical planning has been carried out for FNT:

- FINESSE
  - November 1983 to January 1987
  - Focused on FNT
  - Major Participation by U.S. Organizations; Study Led by UCLA
  - Significant International Participation from Canada, Europe and Japan

- TPA
  - Technical Planning Activity for Magnetic Fusion in 1985-1986
  - Involved Key U.S. Organizations; Led by ANL

Fusion Nuclear Technology

Function

- Fuel Production and Processing
- Energy Extraction and Use
- Radiation Protection of Components and Personnel

Components

- Blanket/First Wall
- Tritium Processing
- Radiation Shield
- Nuclear Elements of PIC

FUSION NUCLEAR TECHNOLOGY

Technical Disciplines

- Nuclear Physics
- Thermodynamics
- Fluid Mechanics
- Electromagnetics
- Chemistry
- Structural Mechanics
- Material Applications
- Nuclear, Mechanical, Chemical Engineering

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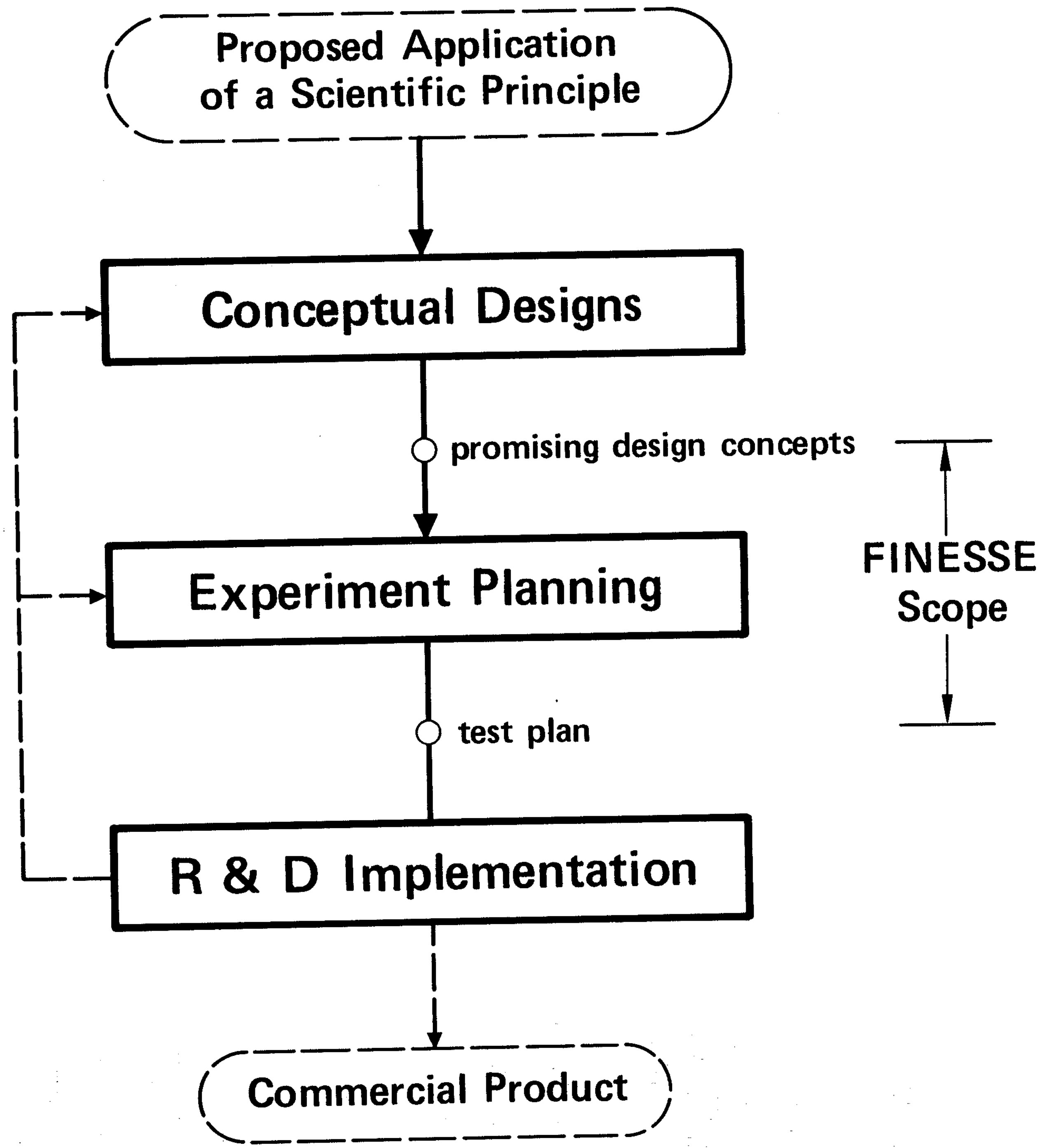
A STUDY OF THE ISSUES, PHENOMENA AND EXPERIMENTAL FACILITES FOR FUSION NUCLEAR TECHNOLOGY

Objectives

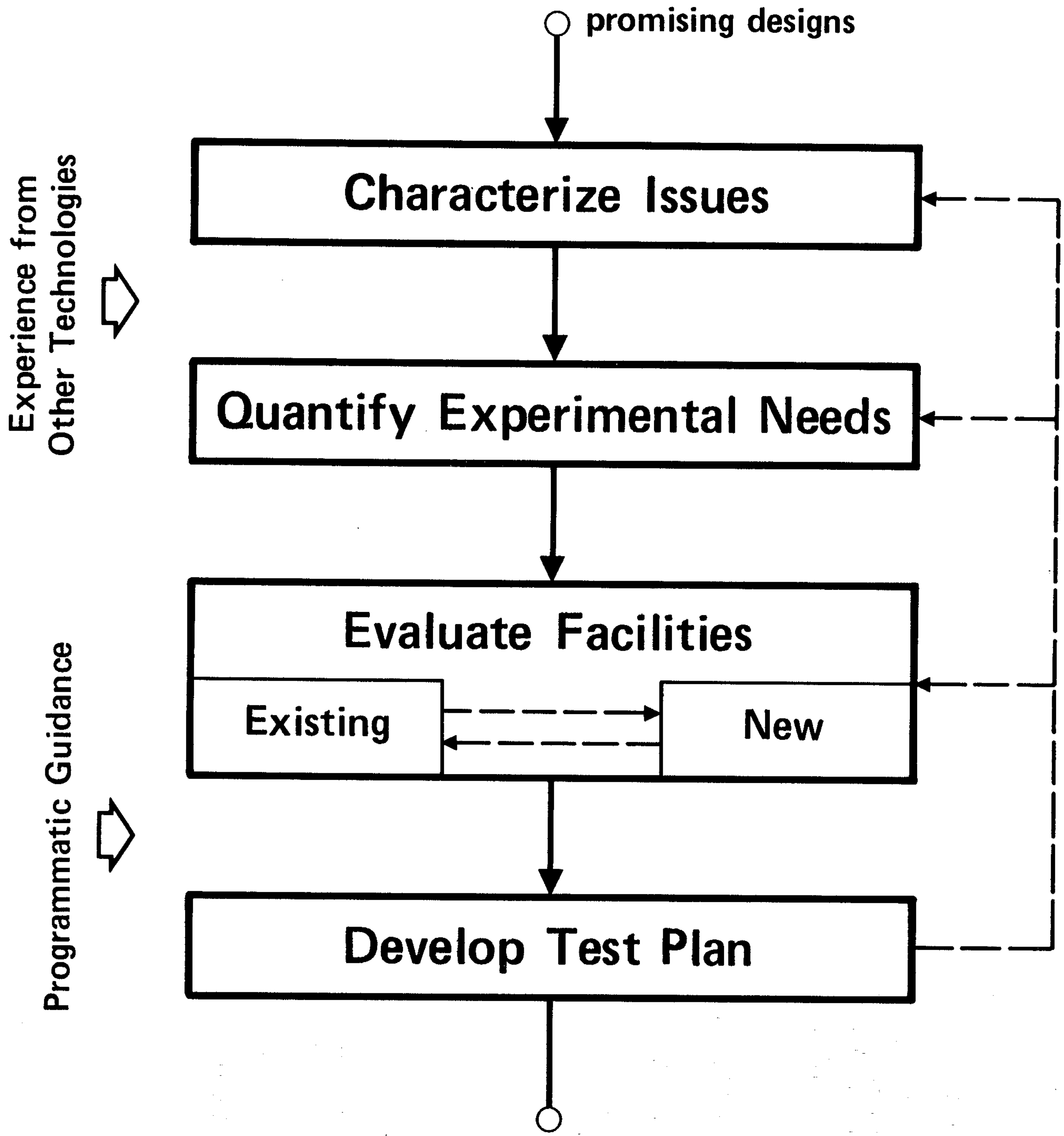
- Understand Issues
- Develop Scientific Basis for Engineering Scaling and Experimental Planning
- Identify Characteristics, Role and Timing of Major Facilities Required

EXPERIMENT PLANNING

Is a Key Element of Technology Development



FINESSE PROCESS For Experiment Planning



Role, Timing, Characteristics
of Major Experiments, Facilities

Characterize Issues

- Assess Accuracy and Completeness of Existing Data and Models
- Analyze Scientific/Engineering Phenomena to Determine (Anticipate) Behavior, Interactions and Governing Parameters in Fusion Reactor Environment
- Evaluate Effect of Uncertainties on Design Performance
- Compare Tolerable and Estimated Uncertainties

△ Quantified Understanding of Important Issues, Interactions, Parameters . . .

FINESSE

Quantify Experimental Needs

- Survey Needed Experiments
- Explore Engineering Scaling Options
  (Engineering Scaling is a Process to Develop Meaningful Tests at Experimental Conditions and Parameters Less Than Those in a Reactor)
- Evaluate Effects of Scaling on Usefulness of Experiments in Resolving Issues
- Develop Technical Test Criteria for Preserving Design-Relevant Behavior
- Identify Desired Experiments and Key Experimental Conditions

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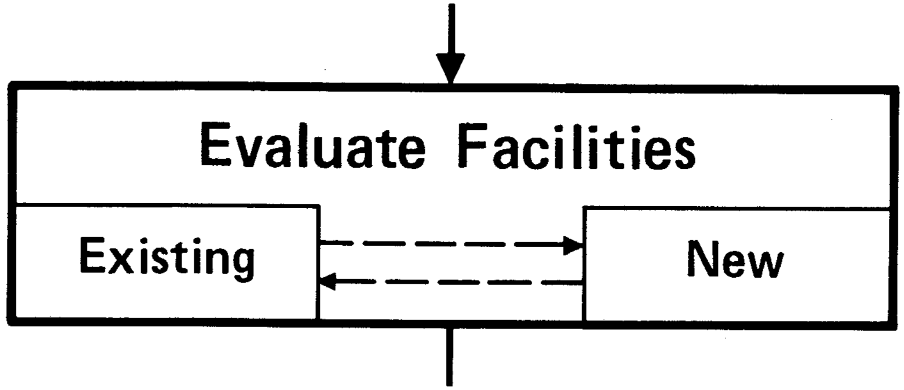
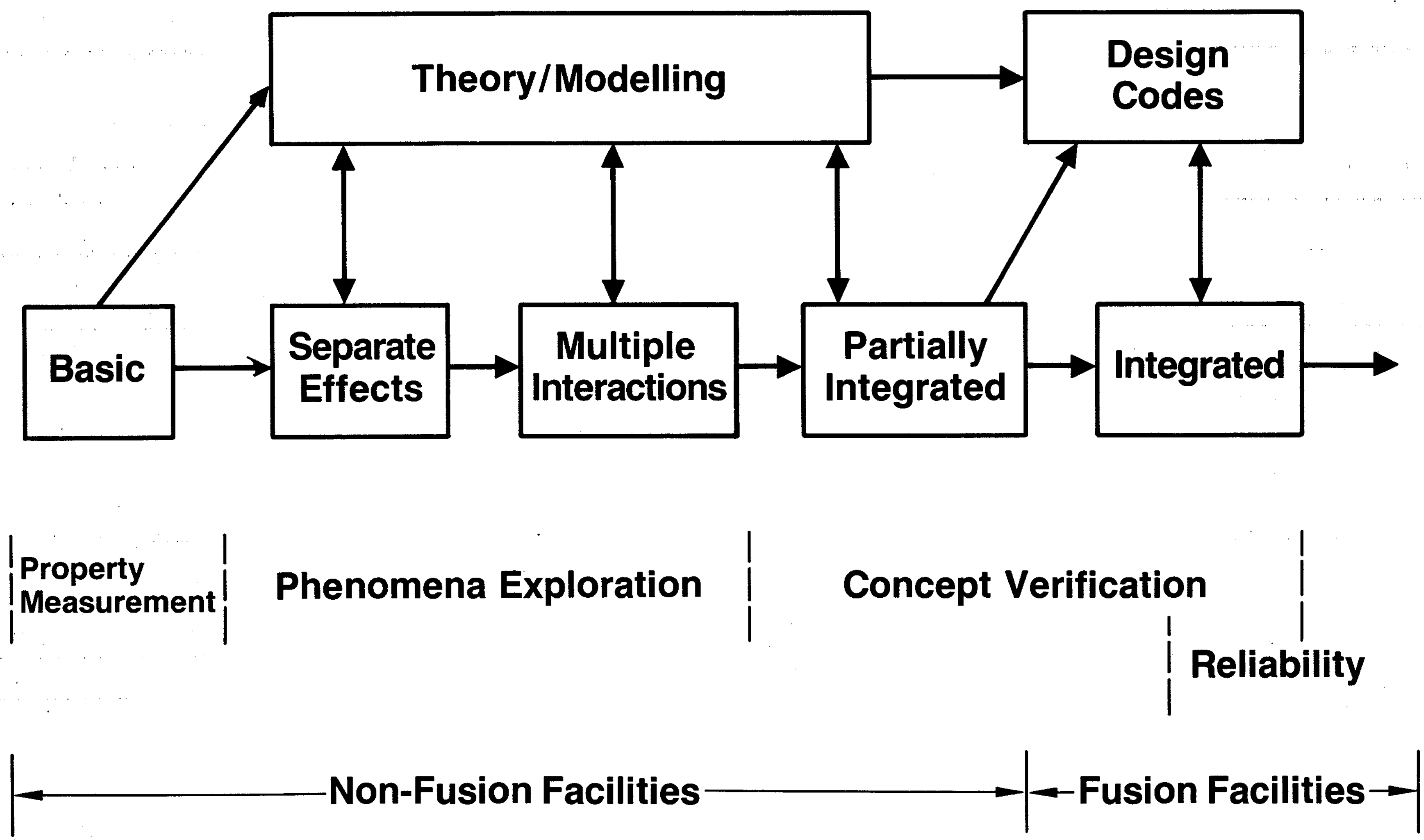


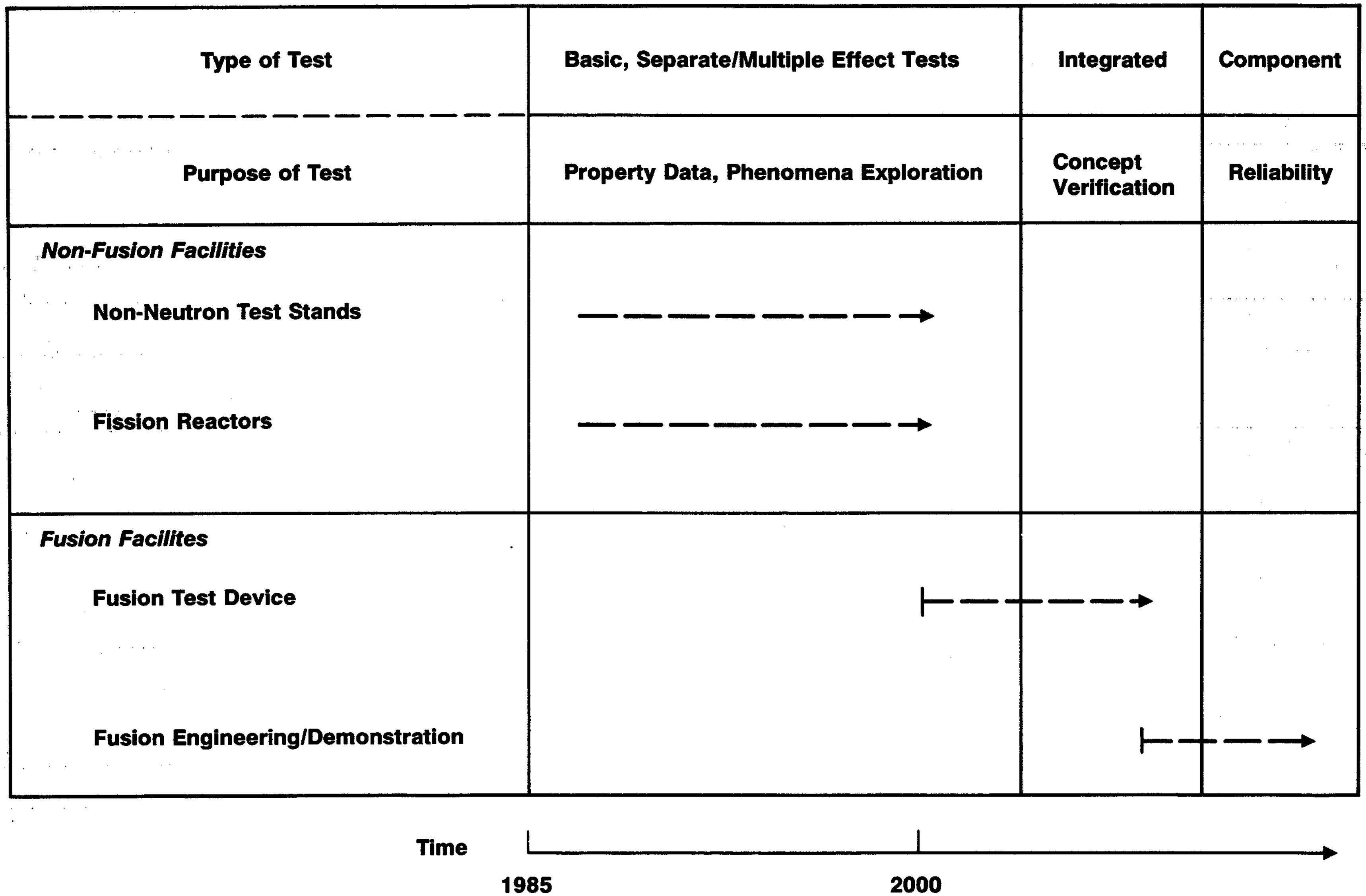
- Survey (Availability)
- Evaluate Capabalities and Limitations
- Define Meaningful Experiments (Experiment Conceptual Design a Tool)
- Estimate Costs

- Explore Innovative Testing Ideas
- Assess Feasibility of Obtaining Desired Information (e.g. I & C Limitations)
- Develop Preliminary
  - Conceptual Designs of Facilities
  - Cost Estimates
- Trade offs in Sequential and Parallel Experiments and Facilities
- Define Major Facilities

Develop Test Plan

- Define Test Program Scenarios Based on
  - Promising Design Concepts
  - Importance of Issues
  - Desired Experiments
  - Possible Test Facilities
- Compare Risk, Usefulness and Cost of Test Program Scenarios


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

FNT R&D Framework

- *Non-Fusion Testing (+ Model Development)*

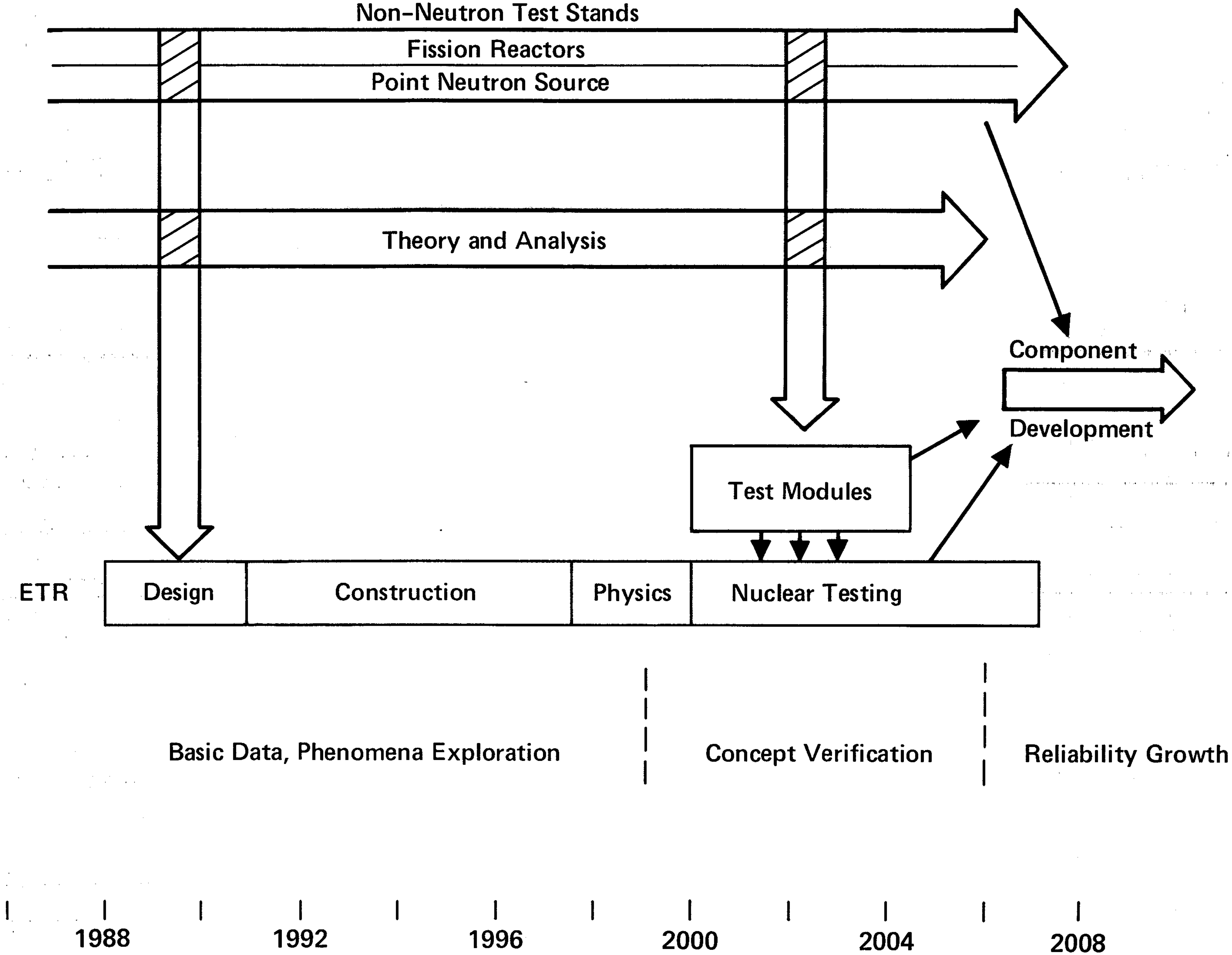
  Non-Neutron Test Stands
  Fission Reactors
  14 MeV Neutron Sources

  - Support Conceptual Design Screening and Evolution
  - Initial Validation of Theory and Models
  - Provide Data for Design, Construction and Operation of Test Elements and Modules in ITER

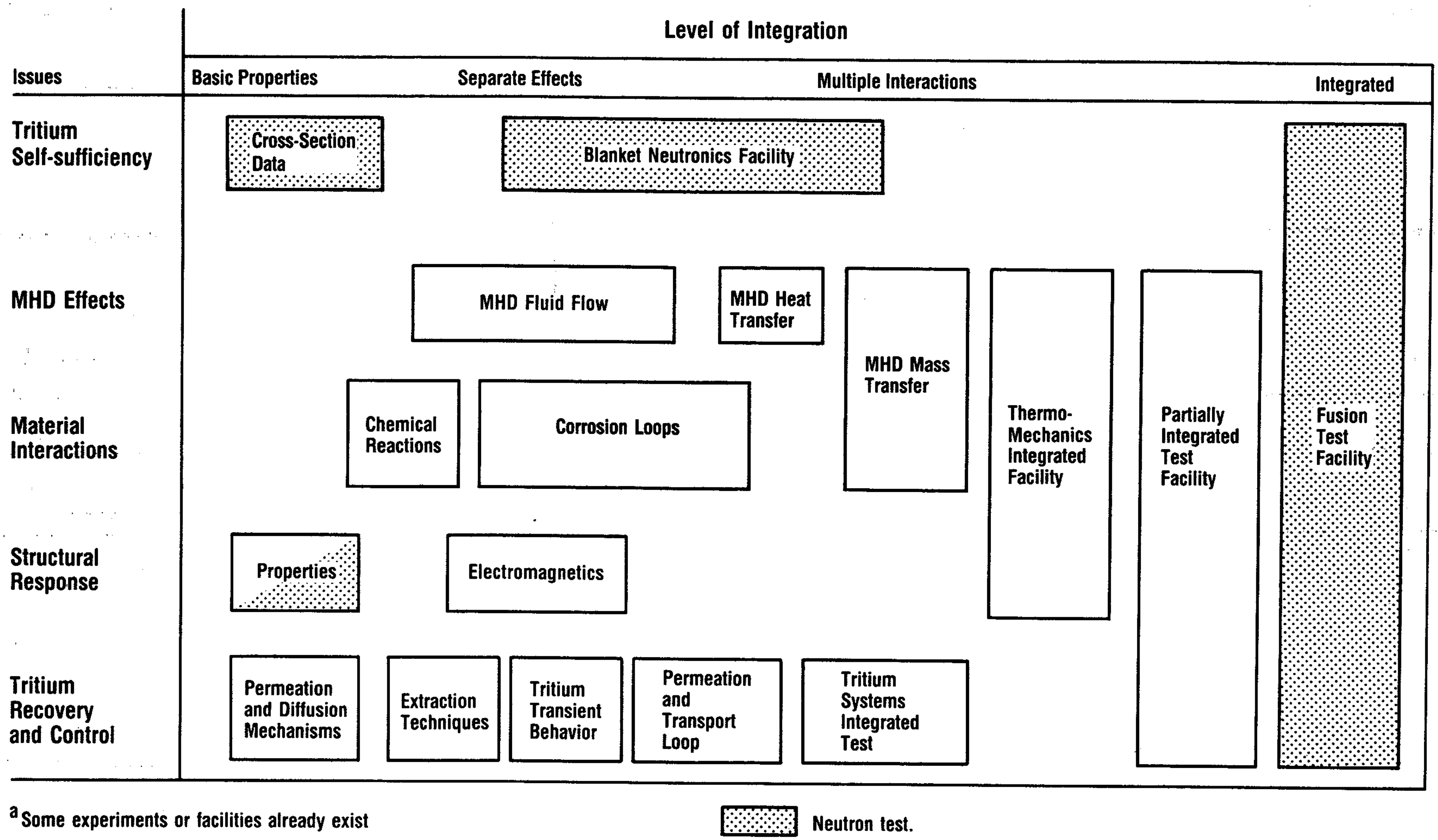
- *Fusion Testing*

  - Verify Theory/Models, Design Codes
  - Definitive Data for Concept Selection
  - Demonstrate Performance Level Extrapolatable to Reactor
  - Demonstrate Adequate Level of Reliability

Framework For Fusion Nuclear Technology Development

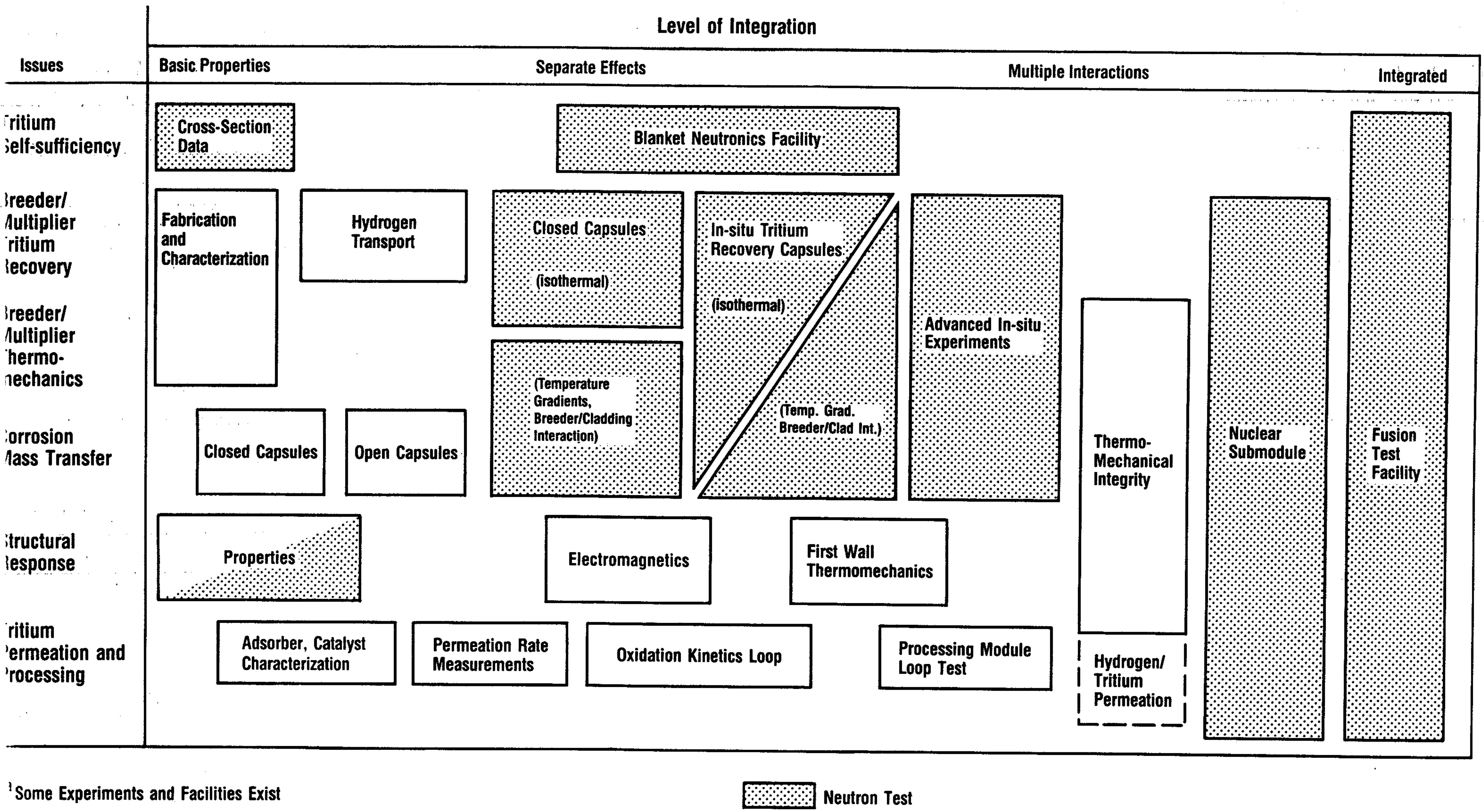


TYPES OF EXPERIMENTS AND FACILITIES FOR LIQUID METAL BLANKETS[a]



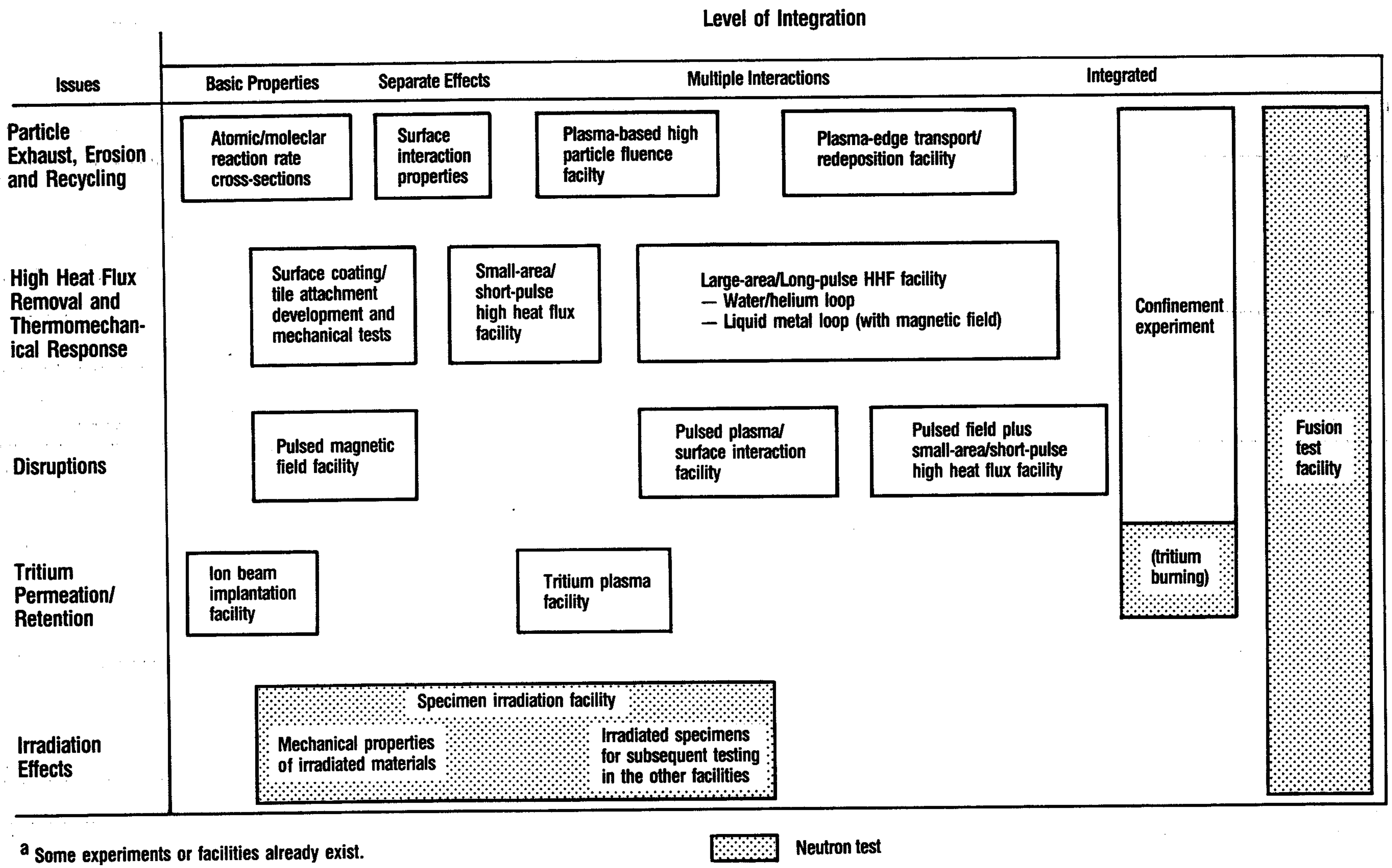
[a] Some experiments or facilities already exist

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



[a] Some Experiments and Facilities Exist

TYPES OF EXPERIMENTS AND FACILITIES FOR PLASMA INTERACTIVE COMPONENTS[a]



[a] Some experiments or facilities already exist.

Examples of Shielding Experiments

Issues	Basic	Single Effect	Partial Integrated Effect
Bulk Shield	Cross section of main nuclides (σ_t, $\sigma_e(E,\mu)$, resonance and window)	Attenuation in stainless steel, lead, tungsten, concrete, copper (10~100 cm)	Optimization of bulk shield (SUS + B_4C + Pb + coolant)
Pene-tration	$\sigma_e(E,\mu)$	Straight duct (L/D effect, source scanning) Bent duct (shape, angle) Slit (step, width)	• Penetration shield • NBI port, RF port with structure • Divertor/limiter duct and exhaust • Coolant channels • Interaction of streaming holes
Induced activity and dose rate	$\sigma_{n,x}$, decay data, gamma production, $P(E_n \rightarrow E_\gamma)$	Specimen irradiation Response function	• γ dose through bulk shield and penetration • Shutdown dose distribution in D-T burning device • γ dose from corrosion product • Sky shine
Design criteria	Damage rate	Specimen irradiation Response function	Property text
Data and method	Differential data base, evaluation and processing	Integral test of data base and benchmarks for method improvement	• Modeling of complex geometry • Interactive effect • Sensitivity study and optimization • Cost effective design method • Semi-empirical approximations

Major Tasks for Liquid Breeder Blankets

- MHD Effects
  —Momentum and Heat Transfer Facilities (LMF1, LMF2)
  —Instrumentation Development
  —Insulator Development

- Material Compatibility
  —Corrosion Loops
  —MHD Mass Transfer Facility (MHDM)

- Tritium Recovery and Control
  —Tritium Extraction Tests
  —Tritium Transport Loop

- Tritium Breeding

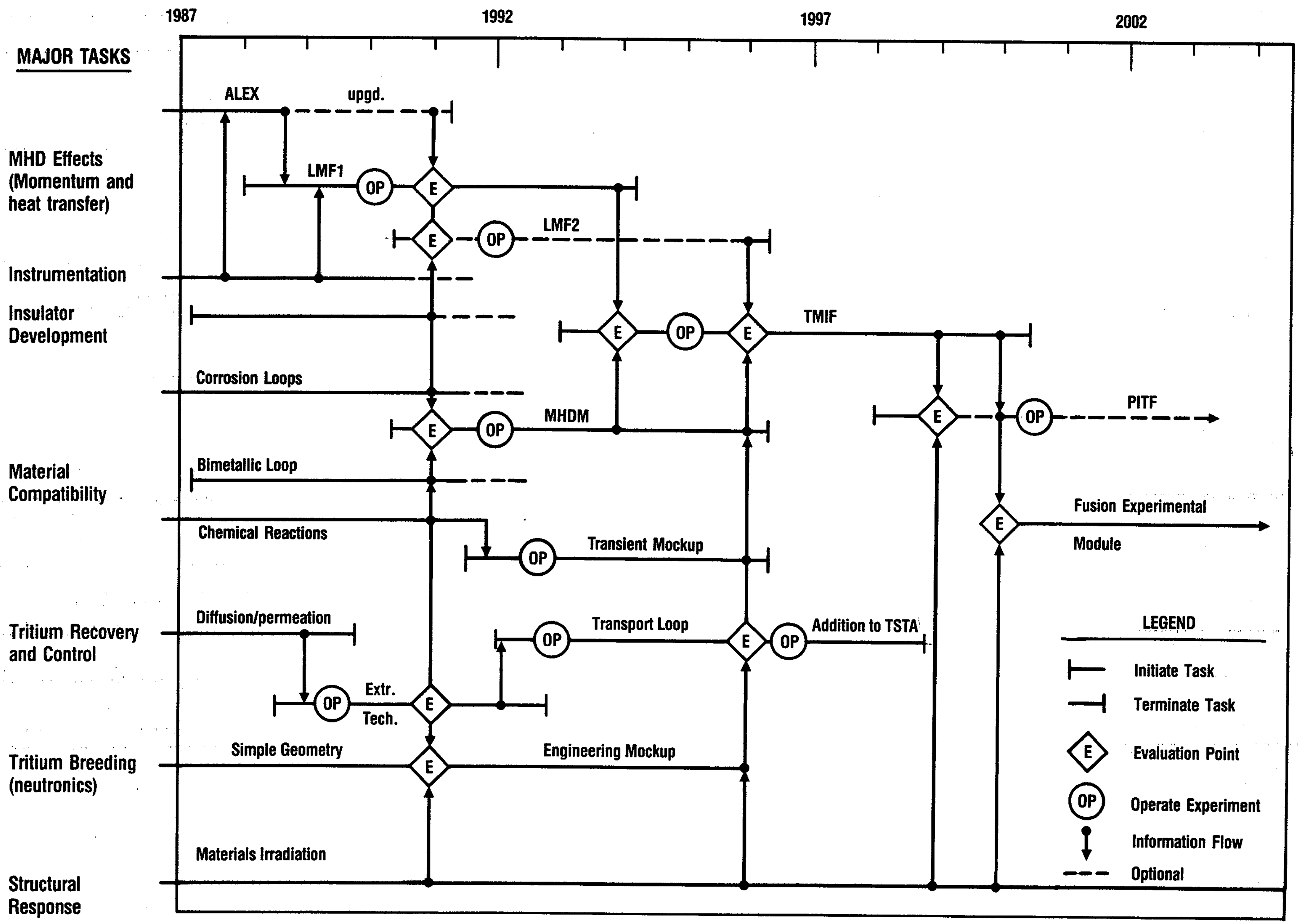
- Structural Response and Failure Modes

- Thermomechanics Integration Facility (TMIF)

- Partially Integrated Test Facility (PITF)

- Analysis and Model Development

LIQUID BREEDER BLANKET TEST PLAN



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 • NaK	• Basic elements of relevant geometry	• Basic elements of relevant geometry • Relevant material combinations • Transport loop • Relevant T, ΔT, impurities, V • Long operating time per experiment	• Actual materials and geometry • Transport loop • Relevant environmental and operating conditions	• Prototypic blanket module • Transport loop • 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 • Validate MHD in simple geometry (basic heat transfer data may be possible in upgrade	• Develop and test instrumentation • Validate MHD heat transfer • Design data (ΔP, T) for configuration screening • Explore techniques to reduce ΔP and enhance heat transfer	• Develop and test instrumentation in relevant environment • Design data on MHD heat and mass transfer • Verify techniques to reduce corrosion and corrosion effects	• Design data for blanket test module • Confirm and refine configurations	• Engineering design data • Reliability data in non-fusion environment

Table 8. Characteristics of Major Liquid Breeder Experiments

Characteristic	ALEX[a]	Magnetic Transport Phenomena Facilities: LMF[b]	Magnetic Transport Phenomena Facilities: MHDM[c]	TMIF[d]	PITF[e]
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

Major Tasks for Solid Breeder Blankets

- Solid breeder material development and characterization
  —Tritium retention and release
  —Thermophysical and thermomechanical properties
  —Fabrication and recycling techniques.

- Multiplier material development and characterization
  —Swelling in beryllium
  —Tritium retention and release.
  —Irradiation creep and mechanical properties

- Blanket thermal behavior
  —Corrosion, mass transfer and chemical interaction kinetics
  —Breeder/multiplier temperature profile and thermomechanical effects of breeder/cladding interaction
  —Non-neutron blanket (sub)module thermomechanical integrity

- Neutronics and tritium breeding
  —Simple geometry mockups
  —Engineering mockups

- Advanced in-situ tritium recovery
  —Two or more instrumented and purged assemblies with multiple capsules

- Nuclear submodule experiments
  —Two or more nuclear submodule assemblies

SOLID BREEDER BLANKET TEST PLAN

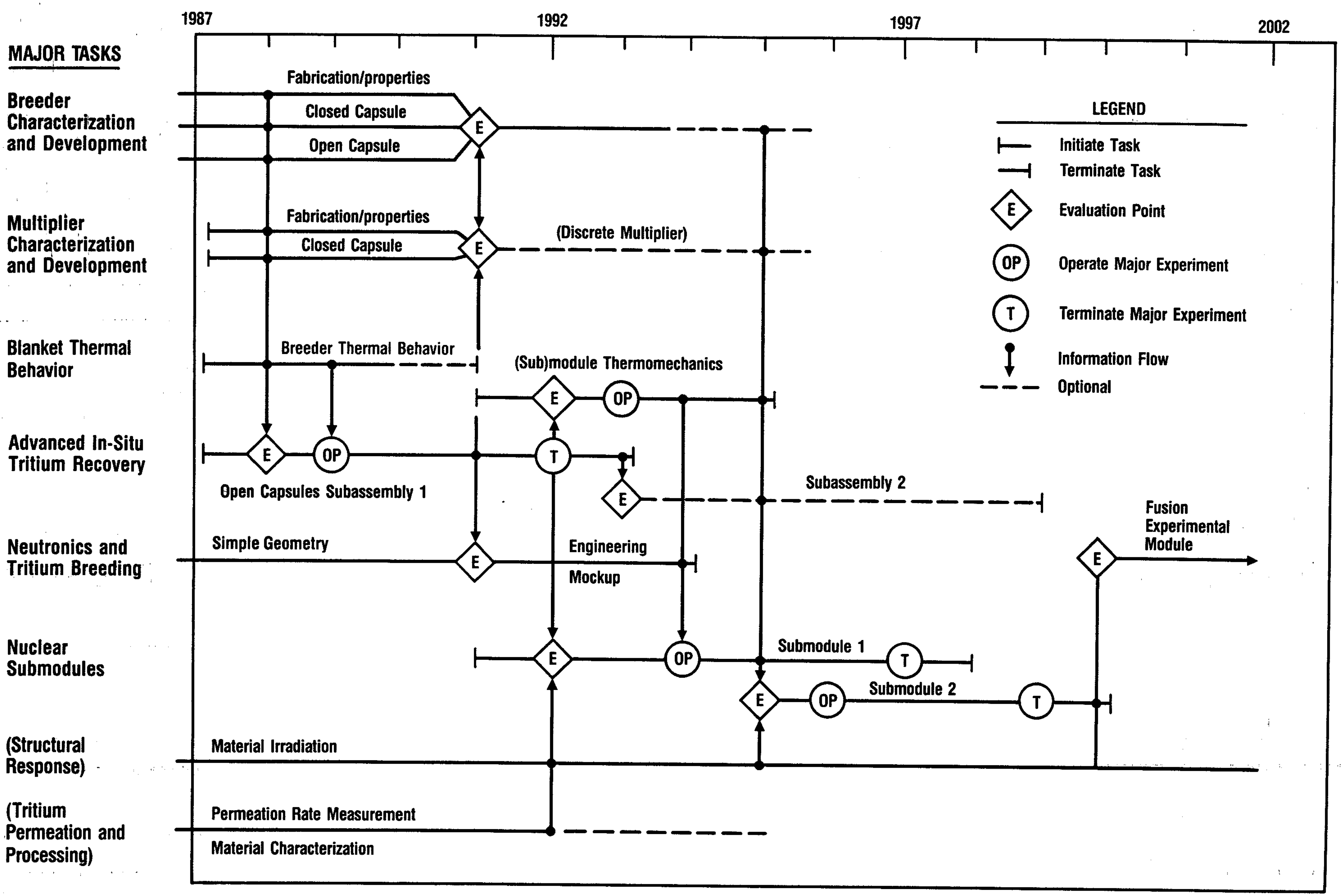


Table 2-7. Parameters for Major Integrated Non-fusion Irradiation Experiments

	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, $m^3/s\text{-}g$[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

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

Representative Costs of Major Solid Breeder Tasks[a]

Task	Capital cost (M$)	Operating cost (M$/yr)	Duration (years)	Total cost (M$)
Solid Breeder Characterization and Development (Fabrication, properties, closed/open capsule irradiations)	5-7	5-8	5	30-50
Multiplier Characterization and Development (Fabrication, properties, closed capsule irradiations)	1-2	1-2	5	6-12
Blanket Thermal Behavior				
A. Breeder thermal behavior	0.8-1.5	0.8-1.5	3-5	3-8
B. Non-neutron (sub)module thermomechanics	3-8	0.8	4	5-10
Neutronics and Tritium Breeding				
A. Simple geometry	3-6	0.8-1.5	5	7-14
B. Engineering mockup	4-7	0.8-1.5	3	6-12
Advanced In-Situ Recovery (Two sequential subassemblies with multiple open capsules)	3-5 each	0.8 each	6 each	12-16
Nuclear submodules (Two parallel submodules)	5-7 each	1-1.5 each	7 each	20-30
Analysis and Model Development	0	2-3	15	30-45

[a]1985 constant dollars (neutron charges not included)

FNT Testing Requirements for Major Features of Next Fusion Engineering Facility (e.g., ITER)

- *Major Parameters of Device*
  - Device Cost Drivers
  - Major Impact on Test Usefulness

- *Engineering Design of Device*

  e.g.,

  - Access to Place, Remove Test Elements
  - Provision for Ancillary Equipment
  - Accommodation of Failures in Test Elements

FNT Testing Requirements Have Been Investigated and Quantified

FNT RECOMMENDED PARAMETERS

Parameters	ETR		Reference Reactor
	Minimum	Recommended	
Neutron Wall Load, MW/m^2	1	2-3	5
Surface Heat Load, MW/m^2	0.2	0.5	1
Plasma Burn Time, s	>500	steady[a]	steady
Magnetic Field[b], T	3	5	7
Continuous Operating Time	days	weeks	months
Availability, %	20	30-50	70
Fluence[b], $MW\text{-}y/m^2$	1-2	3-6	15-20
Test Port Size, m^2 x m	0.5 x 0.3	1 x 0.5	
Total Test Area, m^2	5	10-20	

[a]See text

[b]At test article (device lifetime fluence is larger)

Reference Publications from FINESSE

Major Reports

M.A. Abdou, et al., "FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research and Development," Interim Report, UCLA-ENG-84-30 (October 1984).

M.A. Abdou, et al., "Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology (FINESSE Phase I Report)," UCLA-ENG-85-39 (December 1985).

M.A. Abdou, et al., "Modelling, Analysis and Experiments for Fusion Nuclear Technology: FINESSE Progress Report (3)," UCLA-ENG-86-44 (January 1987).

Summary Journal Publications

M.A. Abdou, et al., "A Study of the Issues and Experiments for Fusion Nuclear Technology," Fusion Technology, 1985.

M.A. Abdou, et al., "Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology," Nuclear Fusion, 1987.

M.A. Abdou, et al., "Modeling, Analysis and Experiments for Fusion Nuclear Technology," to be published in Fusion Engineering and Design

Others

Specialized Papers in Major Journals and Fusion Conferences

Concluding Remarks

- Comprehensive Technical Planning of Fusion Nuclear Technology Has Been Carried Out in the U.S.

- Technical Planning is Found to be a Very Useful Tool in Identifying the Role, Timing and Characteristics of Required Major R&D Items (experiments and facilities)

- International Cooperation Emerges as an Important Mechanism for Maximizing Progress in Fusion Nuclear Technology

  - *Opportunity:* Many areas of FNT R&D are of common interest to all countries (conclusion from International Workshop at UCLA, March 1985, and IAEA Workshop in Yalta, May 1986)

  - *Necessity:* Substantial resources are required to resolve FNT issues

  - *Effectiveness:* Many small-scale and user type facilities permit effective and equitable cost/benefit sharing programs