Overview of FINESSE

Experiments and Facilities For Fusion Nuclear Technology

Mohamed A. Abdou
Professor
Mechanical, Aerospace and Nuclear Engineering Department
UCLA

Presentation To Japanese Fusion Experts,
Tokyo, July 1, 1985

OUTLINE

- Introduction
- FINESSE Process
- Issues
- Evaluation of Facilities
- Required New Facilities, Experiments
- Summary

FUSION NUCLEAR TECHNOLOGY

- Function
  - Fuel Production and Processing
  - Energy Extraction and Use
- Components
  - Blanket
  - PIC (First Wall, Limiter, etc.)
  - Shield
  - Tritium Processing

FUSION NUCLEAR TECHNOLOGY

Technical Disciplines

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

FINESSE

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

FINESSE

FINESSE ORGANIZATION

- Major Participation by Key U. S. Organizations:
  - UCLA, ANL, EG&G, HEDL, MDAC, TRW, GAC
  - LLNL, PPPL, LANL, SNL, ORNL
- Significant International Participation:
  - Canada, Europe, Japan
- Broad Participation by Fusion Community:
  - Advisory Committee
  - Domestic, International Workshops

FINESSE PRINCIPAL TECHNICAL TASKS

I. Identification of Issues

II. Quantifying Test Requirements
   - A. Survey of Testing Needs
   - B. Quantifying Test Requirements

III. Evaluation of Experience from Other Technologies
   - A. Fission
   - B. Aerospace

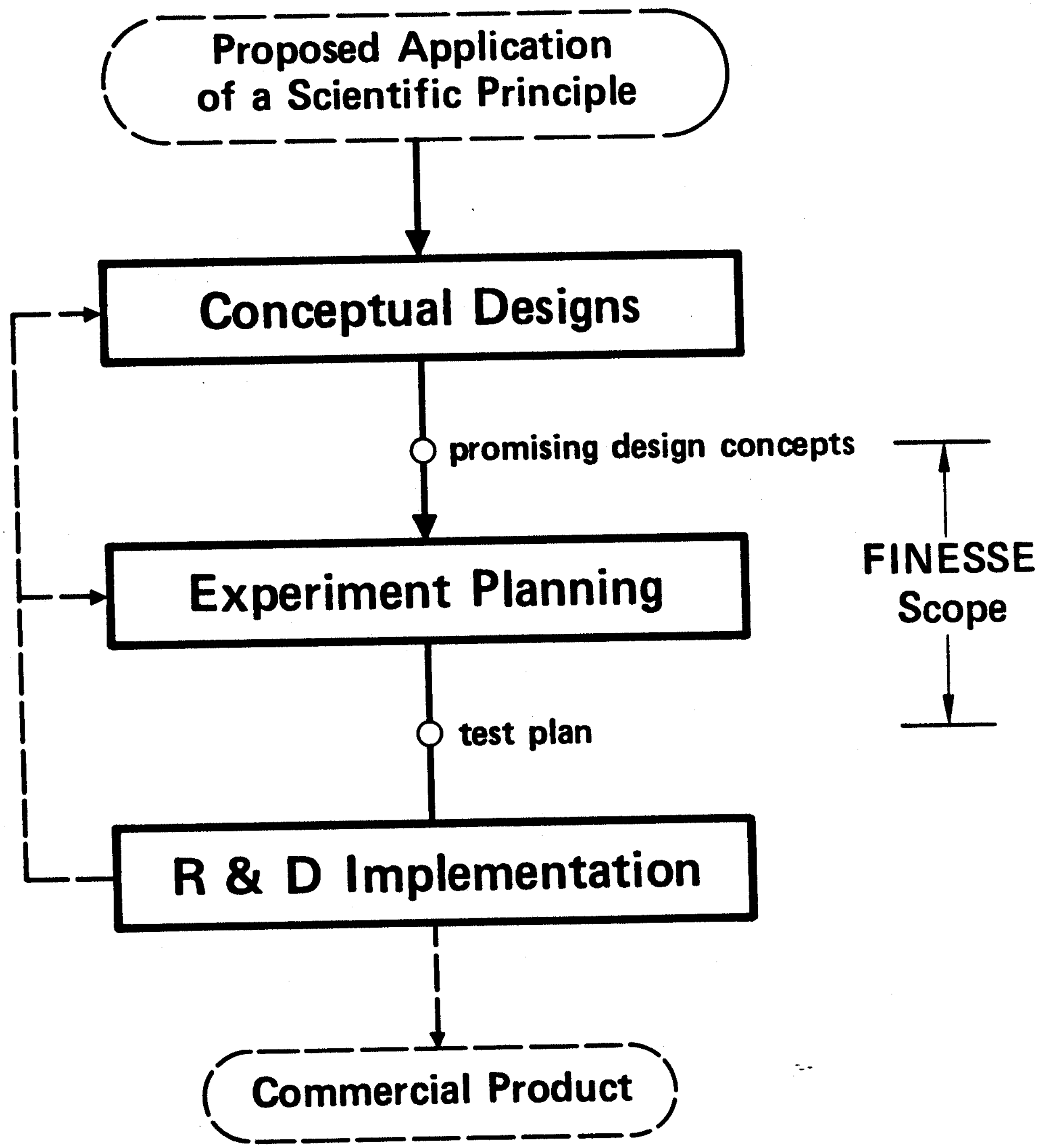
IV. Survey and Evaluation of Test Facilities
   - A. Non-Fusion Devices
   - B. Fusion Devices

V. Comparative Evaluation of Test Facilities, Scenarios

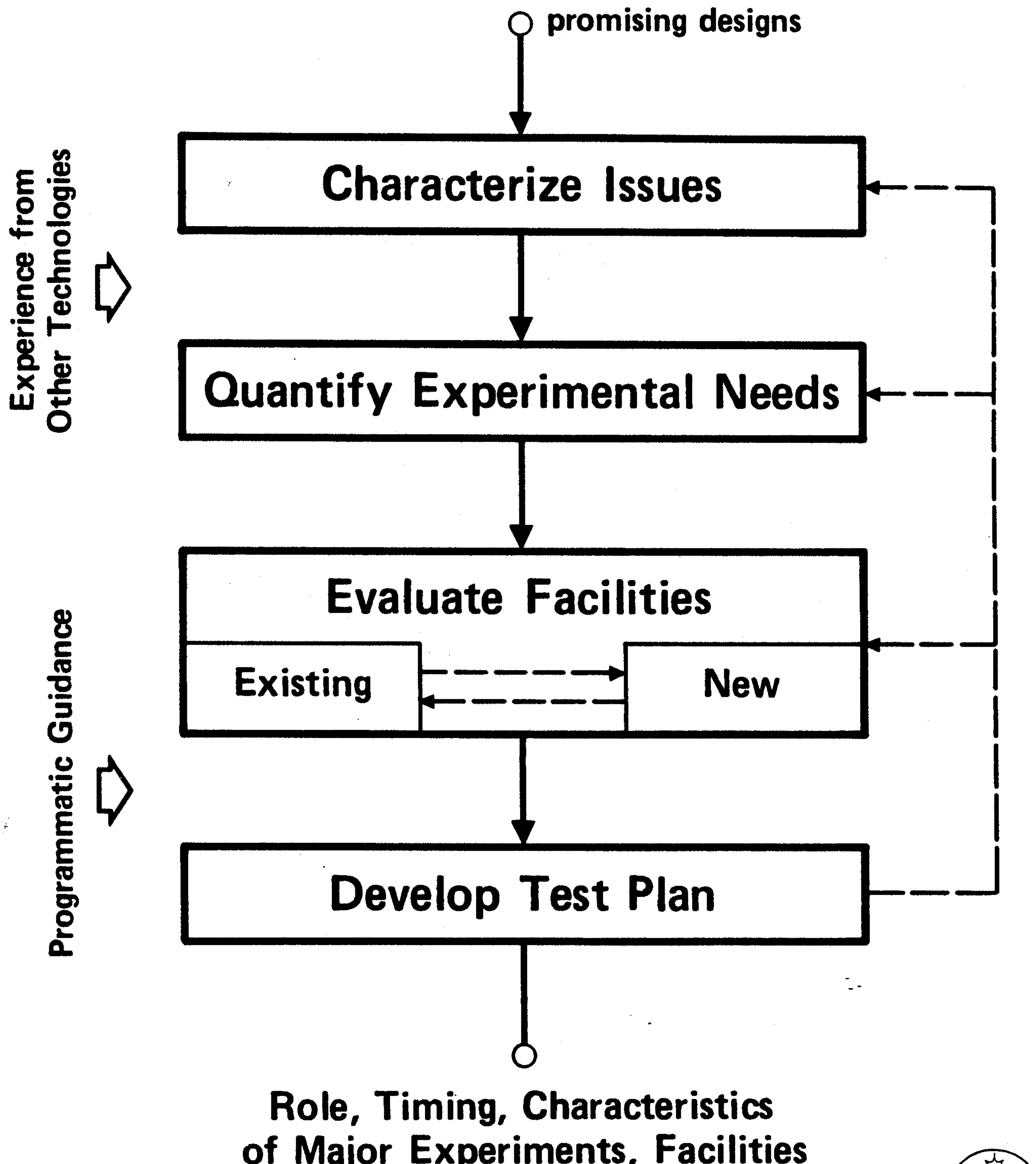
VI. Recommendations on Fusion Nuclear Technology Development Strategy

FINESSE PROCESS

EXPERIMENT PLANNING
Is a Key Element of Technology Development



FINESSE PROCESS For Experiment Planning



Characterize Issues

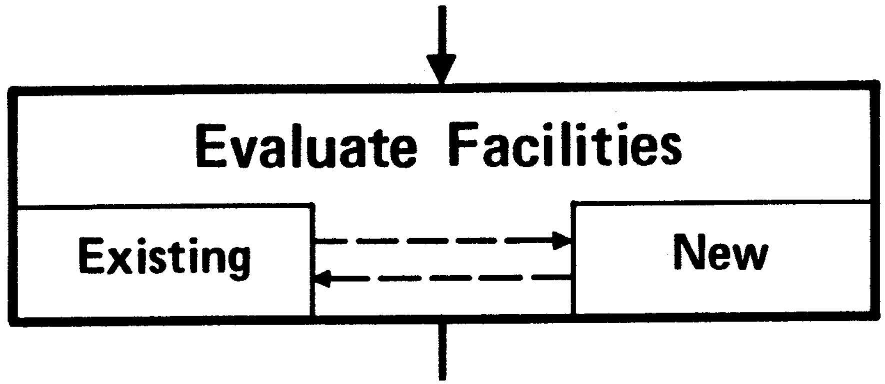
- Assess Accuracy and Completeness of Existing Data and Models
- Analyze Scientific/Engineering Phenomena to Determine (Anticipate) Behavior, Interactions and Governing Parameters in Fusion Reactor Environment
- Evaluate Effect of Uncertainties on Design Performance
- Compare Tolerable and Estimated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



- 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

FINESSE

ISSUES

FUSION NUCLEAR TECHNOLOGY ISSUES HAVE BEEN:

- Identified
- Characterized
- Prioritized

POTENTIAL IMPACT

Feasibility Issues

- May Close the Design Window
- May Result in Unacceptable Safety Risk
- May Result in Unacceptable Reliability, Availability or Lifetime

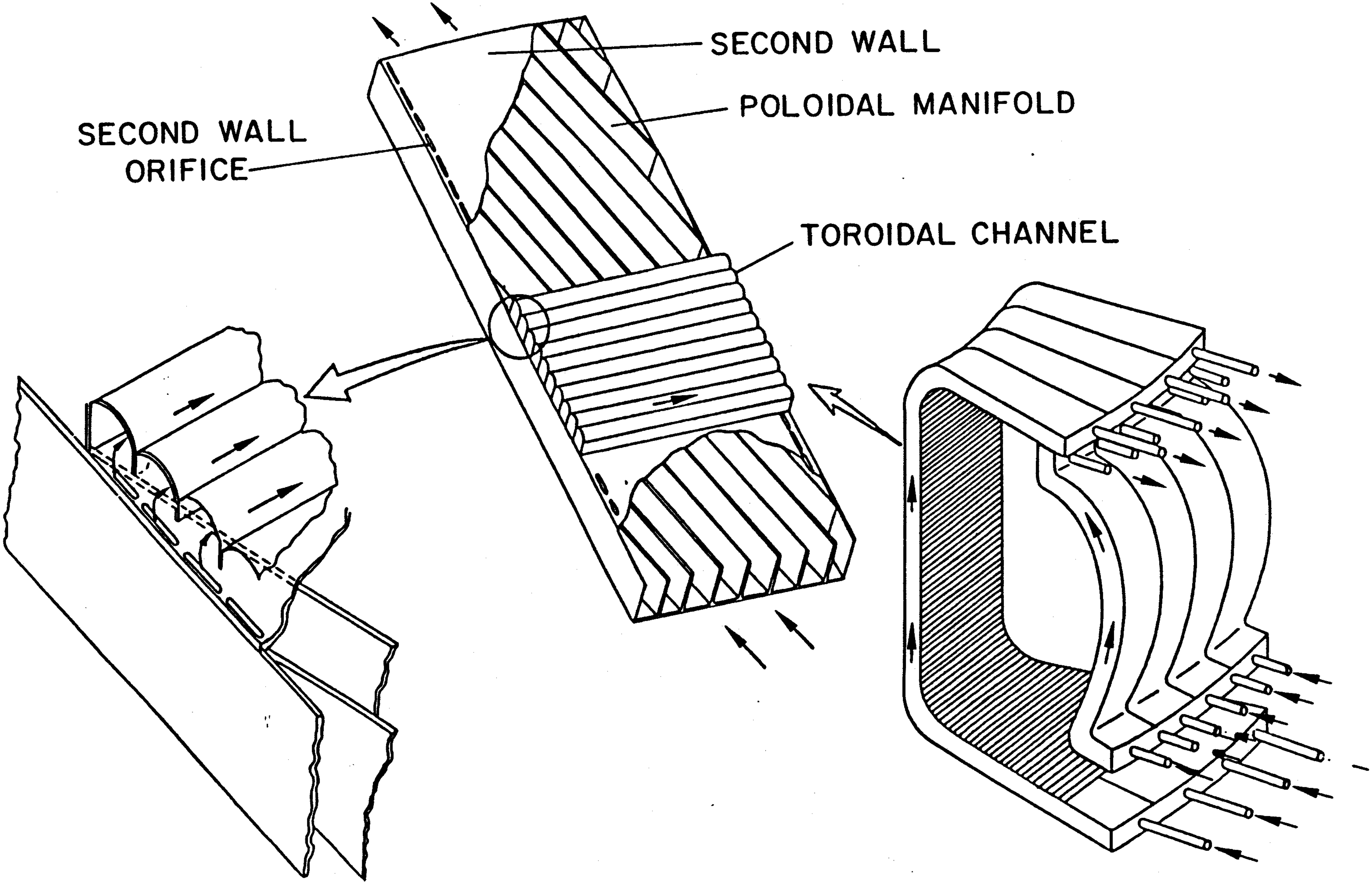
Attractiveness Issues

- Reduced System Performance
- Reduced Component Lifetime
- Increased System Cost
- Less Desirable Safety or Environmental Impact

FINESSE

Representative Parameters For Attractive Fusion Reactor

Neutron Wall Load	5 MW/m^2
Surface Heat Load	0.2-1.0 MW/m^2
Magnetic Field in Blanket	4-8 T
Plasma Pulse Length	2000 s — continuous
Reactor Availability	85%
Fluence	12-20 MW · y/m^2


SECOND WALL
POLOIDAL MANIFOLD
SECOND WALL
ORIFICE
TOROIDAL CHANNEL

MAJOR ISSUES FOR LIQUID METAL BLANKETS

- DT Fuel Self Sufficiency
- MHD Effects
  - Pressure Drop
  - Fluid Flow
  - Heat Transfer
- Compatibility, Corrosion
- Structural Response under Irradiation
- Tritium Extraction and Control
- Failure Modes

FINESSE

MHD PRESSURE DROP

- **The MHD Pressure Drop Depends on the Device Parameters and the Blanket Wall Thicknesses**

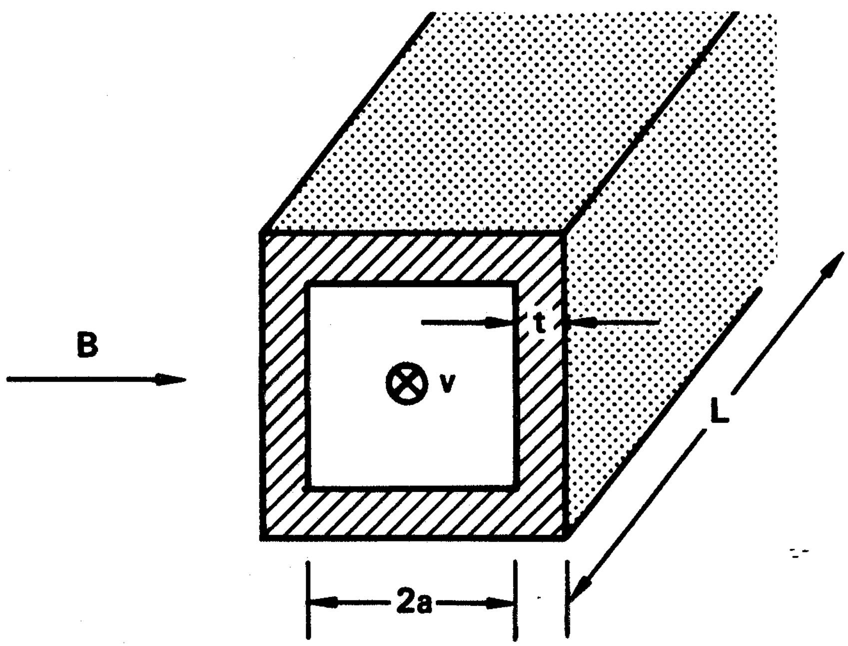
$$\Delta p \simeq \sigma_f v B^2 L \phi$$

$$\phi = \frac{\sigma_w t}{\sigma_f a}$$

- **But the Pressure Stress is Relatively Insensitive to the Wall Thickness**

$$\sigma = \frac{pa}{t} \sim \sigma_w v B^2 L$$

- **The Maximum Allowable Pressure Stress Limits the Flow Velocity. This Conflicts with Heat Transfer Requirements.**

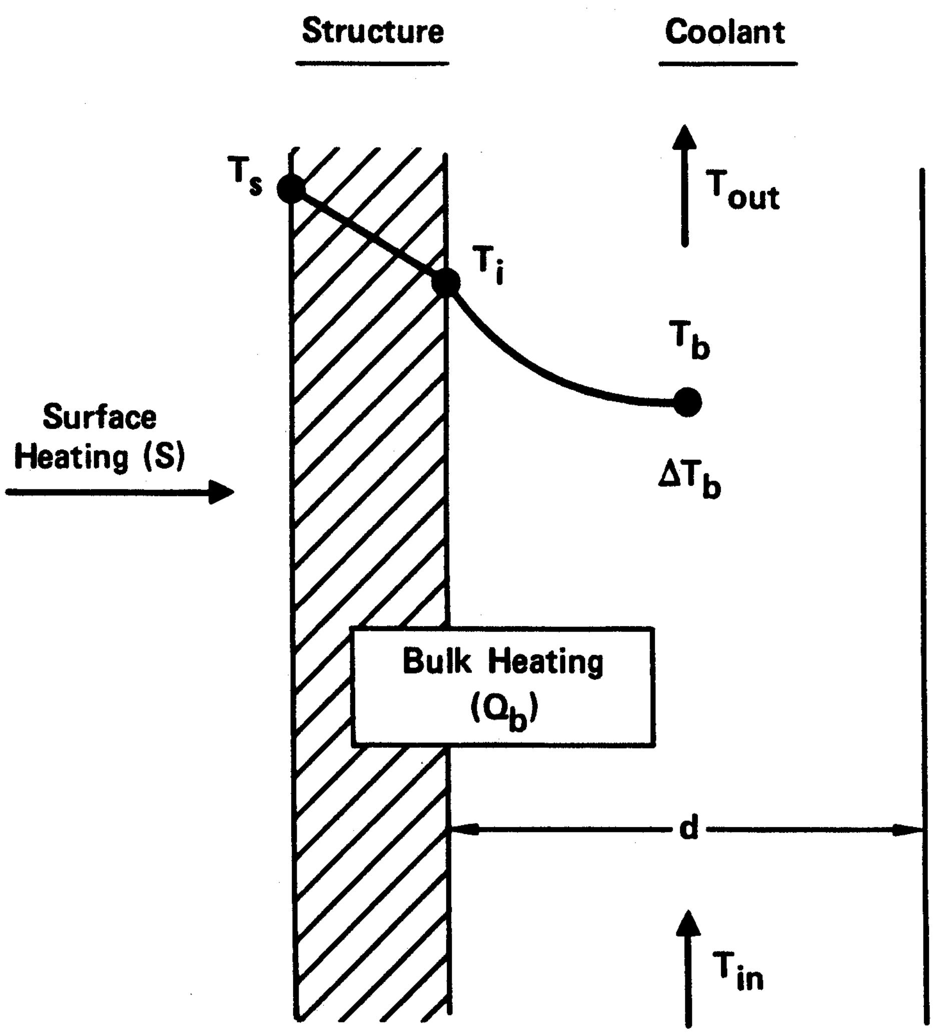


HEAT TRANSFER REQUIREMENTS

The Minimum Inlet Temperature and Maximum Structure and Interface Temperatures Place Upper Limits on $\Delta T_b = T_{out} - T_{in}$

This Translates to a Lower Limit on Flow Velocity.

$$\rho\, c_p\, v\, \Delta T_b = \frac{L}{d}\,(S + Q_b)$$



$$T_s = T_{in} + \Delta T_b + \Delta T_{film} + \Delta T_s \leqslant T_s^{max}$$

UNCERTAINTIES IN MHD PRESSURE DROP

MHD Flow in Conducting Structures Requires the Simultaneous Solution of Electromagnetic and Fluid Flow Equations in Complex Geometrical Configurations

Uncertainties Arise From:

- Complex Three-Dimensional Flow Effects (Internal Channel Geometry)

  Bends, Contractions, Manifolding, etc.

- Complex Magnetic Field Effects

  Sensitivity to Direction of Field

  Field Gradients

- Complex Structure Geometry Effects (External Channel Geometry)

  Multiple Channel Effects

  Leakage Currents

FINESSE

MHD FLUID FLOW PHENOMENA

The Magnetic Field Dominates the Velocity Profiles in a Liquid Metal Blanket, Resulting in

- Turbulence Supression

  Long Entry Lengths for Heat and Mass Transfer

  Reduced Heat and Mass Transfer in the Coolant

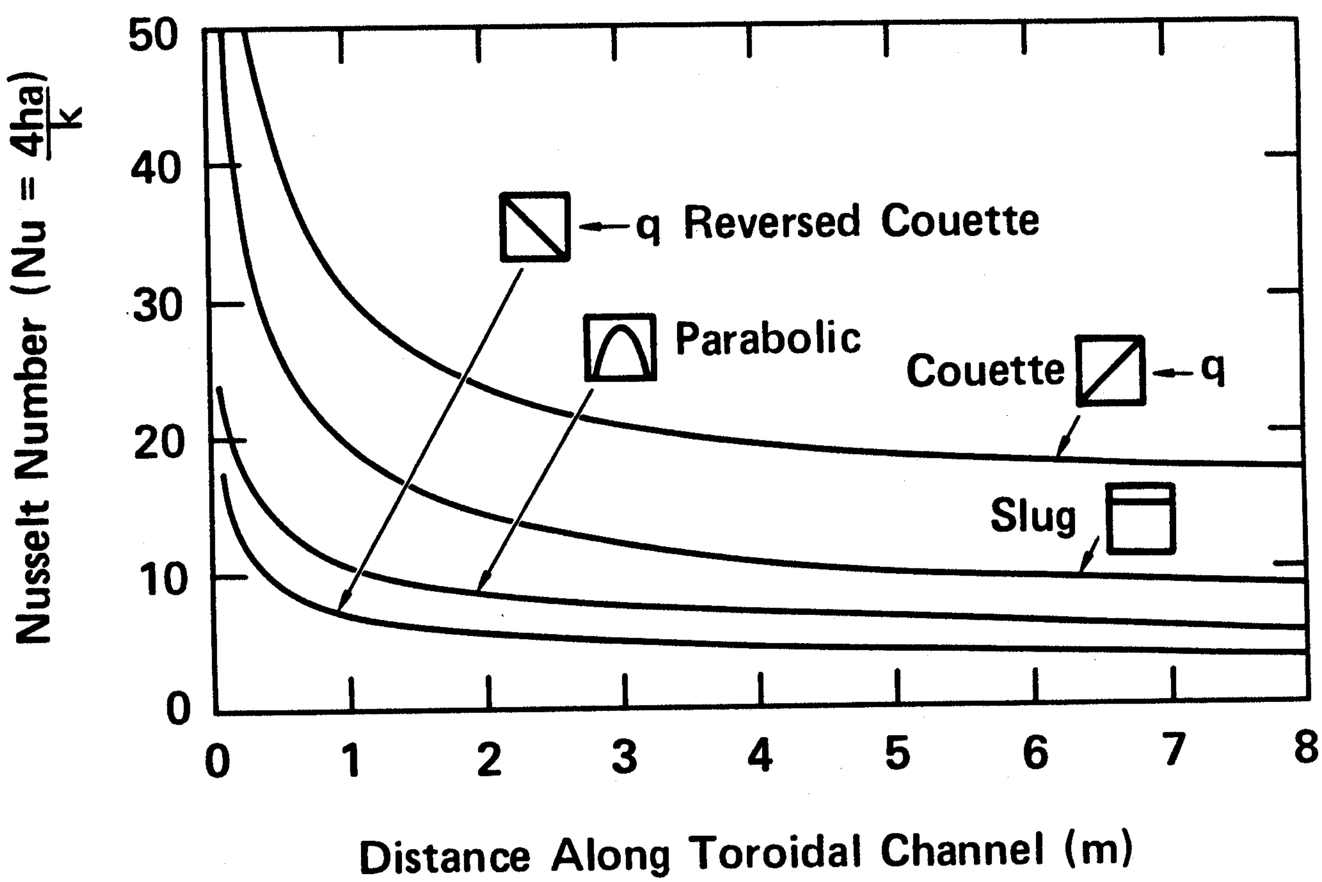
- Very Thin Boundary Layers

  Enhanced Corrosion

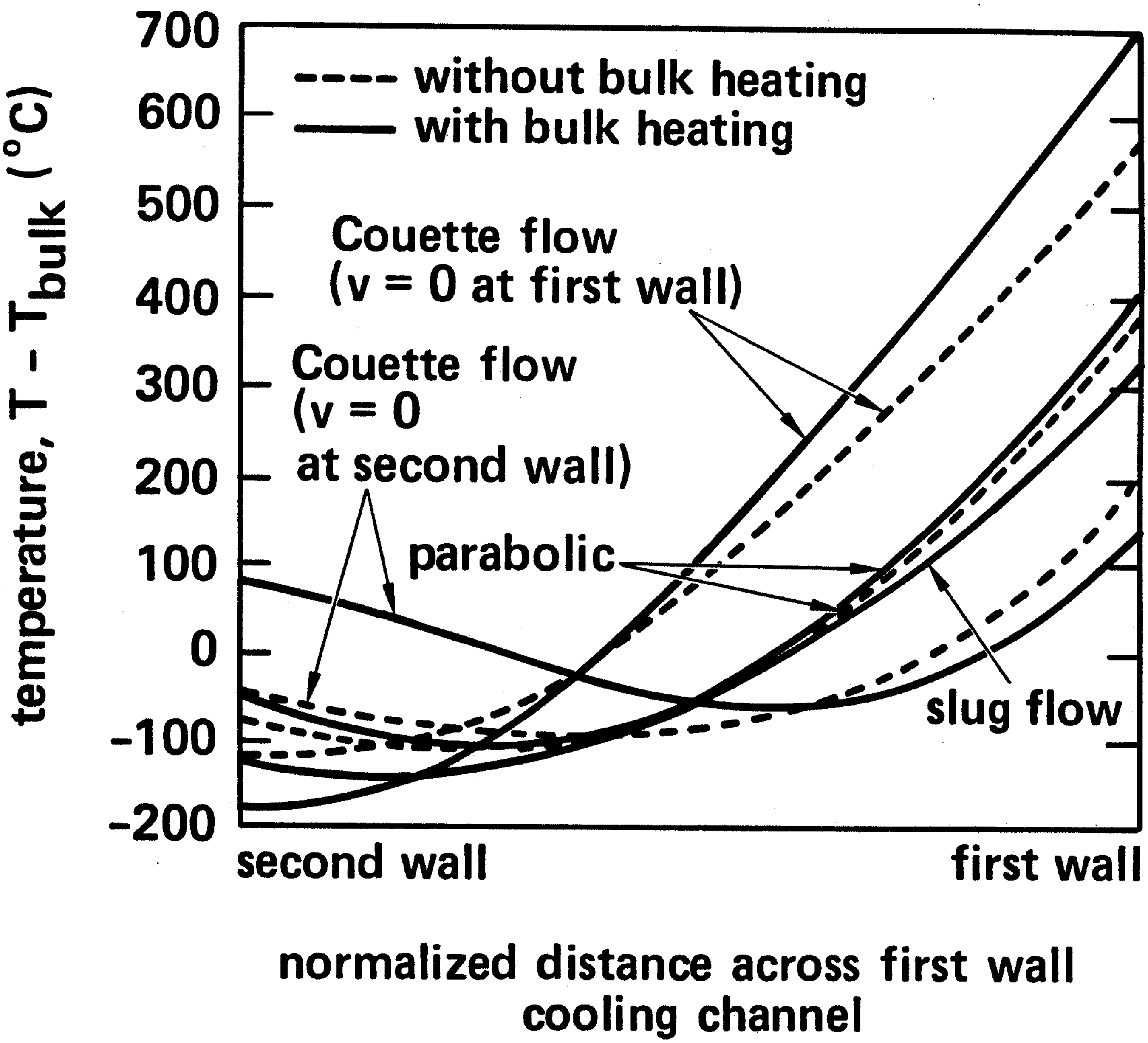
- High Velocity Fluid Jets

The Uncertainties in MHD Fluid Flow Are Similar to Those for MHD Pressure Drop i.e., Geometric Complexities in Flow, Magnetic Field, and Structure Geometry

In Laminar Flow, the Heat Transfer Coefficient Depends on the Velocity Profile and Varies Throughout the Entire Blanket



Temperature Profiles Depend Strongly on the Velocity Profile



FINESSE

LIQUID METAL CORROSION PHENOMENA

- Mass Transport in the Primary Coolant System
  - Plugging
  - Activated Material Transport
- Localized Wall Thinning
- Selective Dissolution (e.g. Ferrite Layer Formation in Stainless Steel)
- Embrittlement
  - Due to Liquid Metal (Especially LiPb)
  - Due to Impurities (Especially Vanadium)

FINESSE

UNCERTAINTIES IN LIQUID METAL CORROSION

- New Materials

  The Basic Materials Interactions are Poorly Understood and Poorly Quantified

- Unique Environment

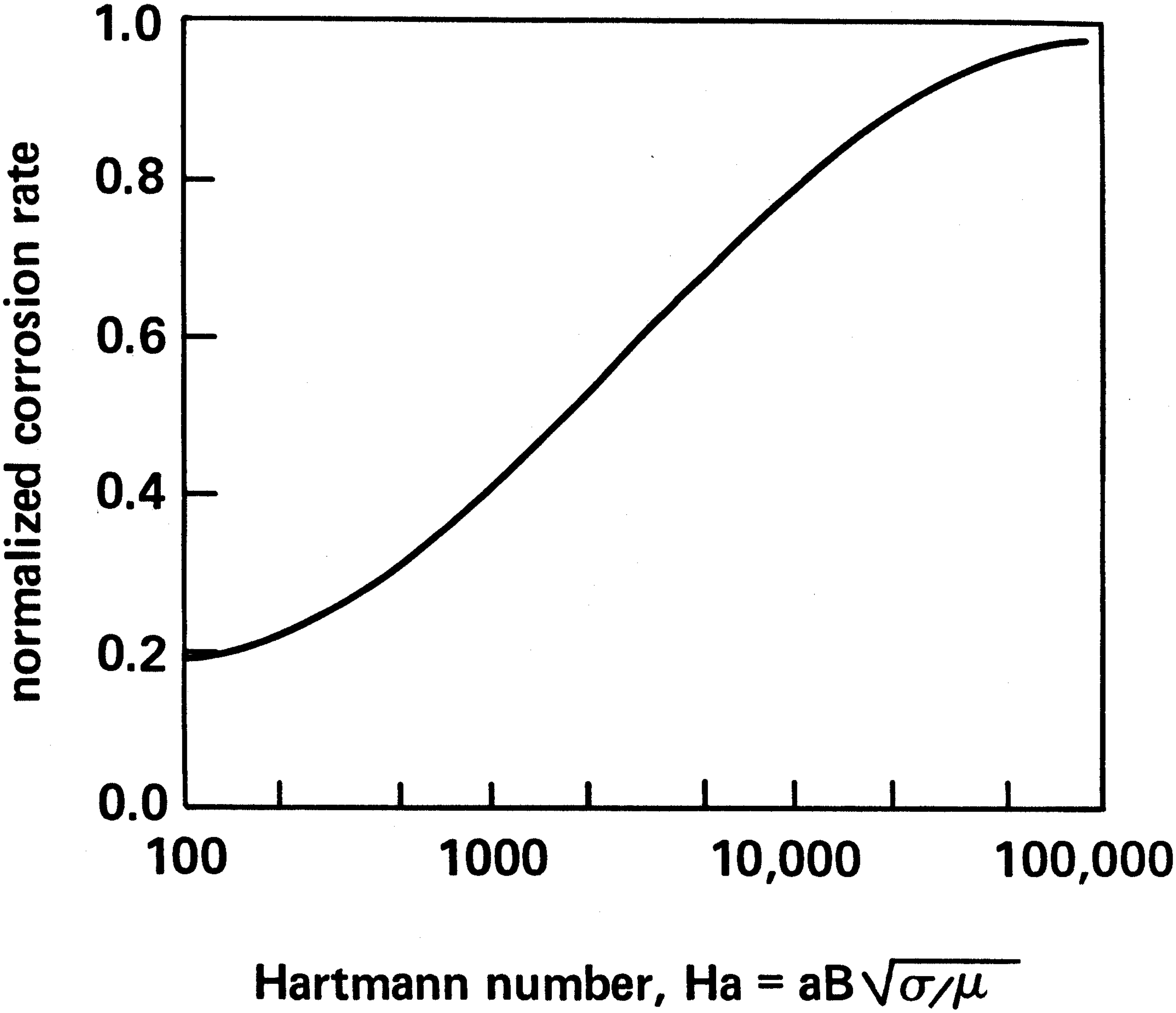
  MHD Effects (Coupled Heat, Mass, and Momentum Transport)

  Loop Effects

  Irradiation Effects

FINESSE

The Corrosion Rate is Strongly Influenced by MHD Velocity Profiles



DESIGN WINDOW ISSUES

Issue

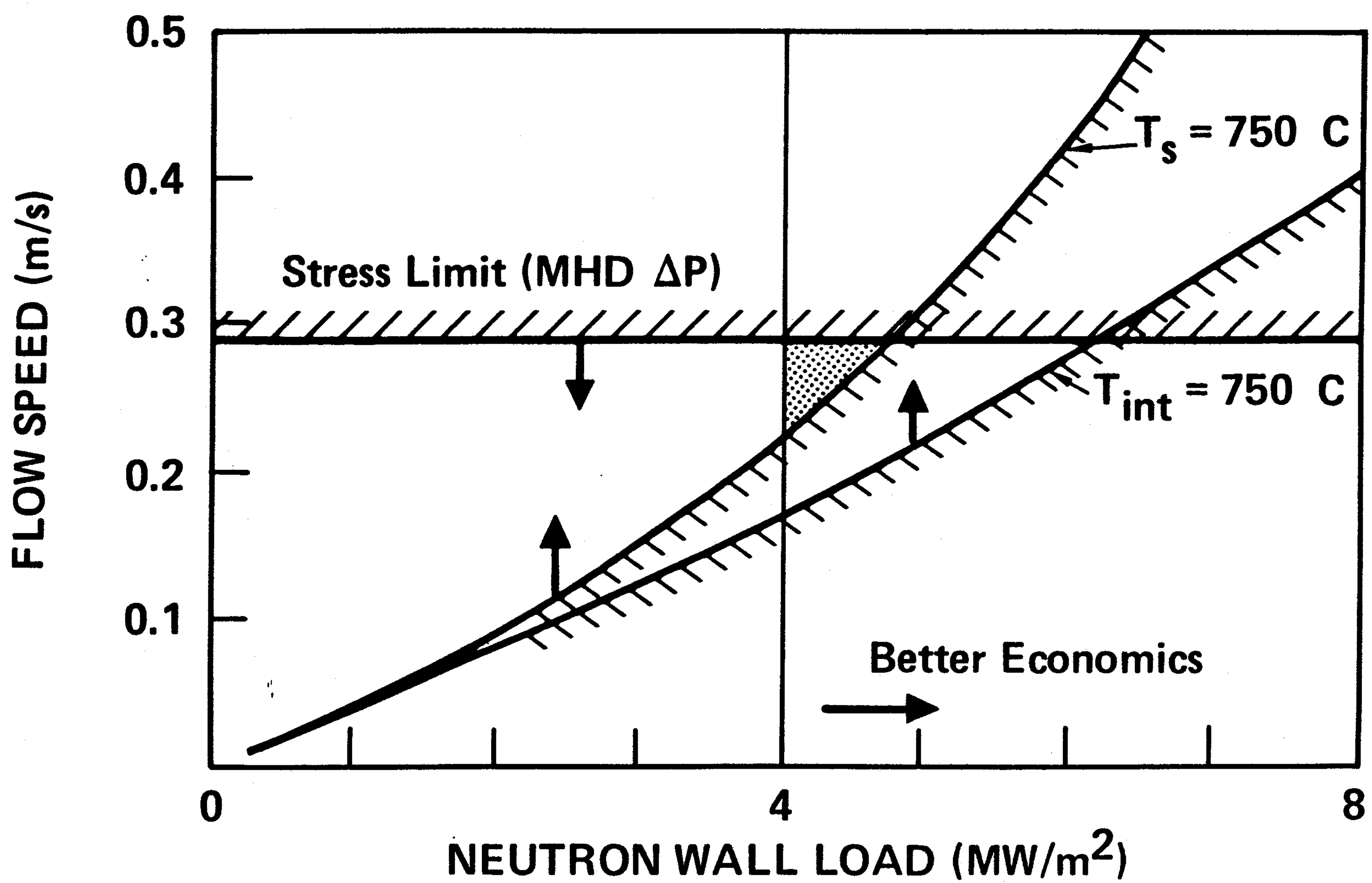
An Effect That Imposes a Limit on Design Window Represents an Issue

Important

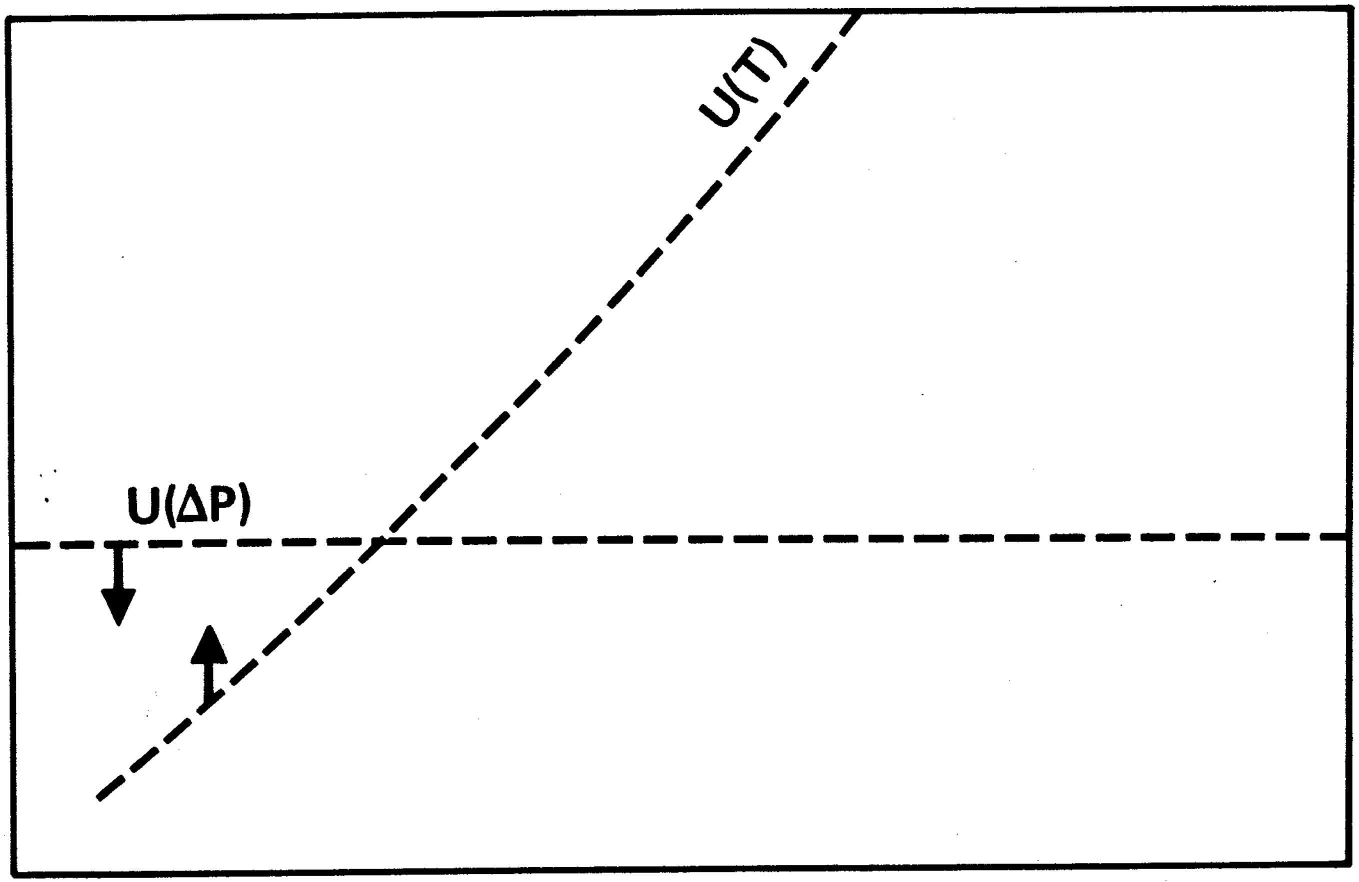
If Uncertainty in Defining the Limit is Wider Than Design Window, the Issue is Important

FINESSE

Design Window Is Narrow For Best Liquid Metal Blanket (Li/V)



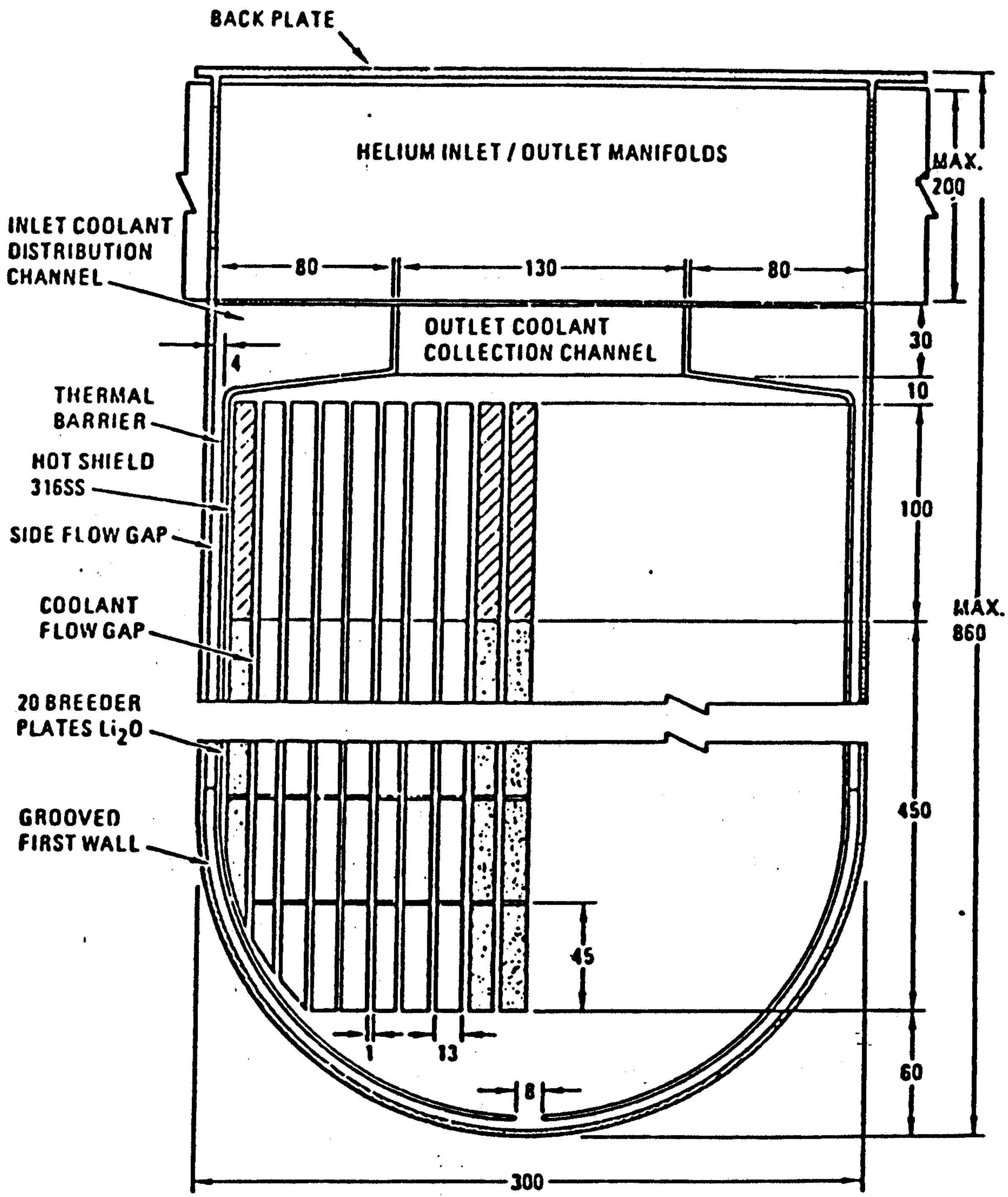
FINESSE



U(T): Any of:
T_s = 650 C
T_{int} = 550 C
h_m = 0.7h

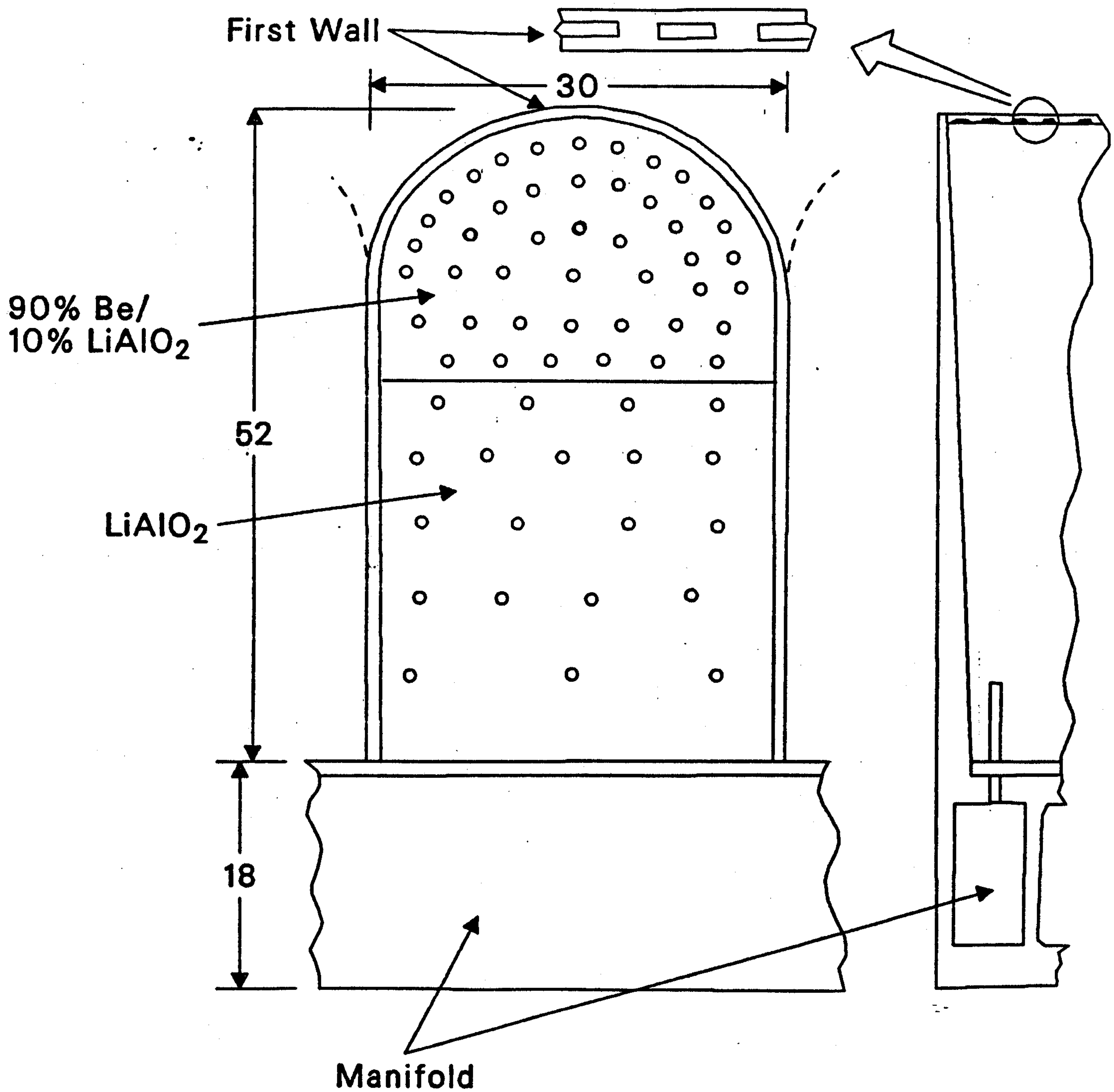
Uncertainties in MHD, Corrosion, Heat Transfer,
Radiation Effects Represent Major Issues

BLANKET MODULE CROSS SECTION (AN EXAMPLE)



ALL DIMENSIONS IN mm

REFERENCE DESIGN CONFIGURATION FOR $LiAlO_2/H_2O/FS/Be$ CONCEPT - TOKAMAK



MAJOR ISSUES FOR SOLID BREEDER BLANKETS

- DT Fuel Self Sufficiency
- Tritium Recovery, Inventory
- Breeder Temperature Window and Control
- Irradiation Effects: Structure, Breeder, Multiplier
- Thermal/Mechanical Interaction:
  Breeder/Structure/Multiplier/Coolant
- Tritium Permeation (T_2, T_2O)
- Failure Modes

FINESSE

DT FUEL SELF SUFFICIENCY

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

  Achievable TBR > Required TBR

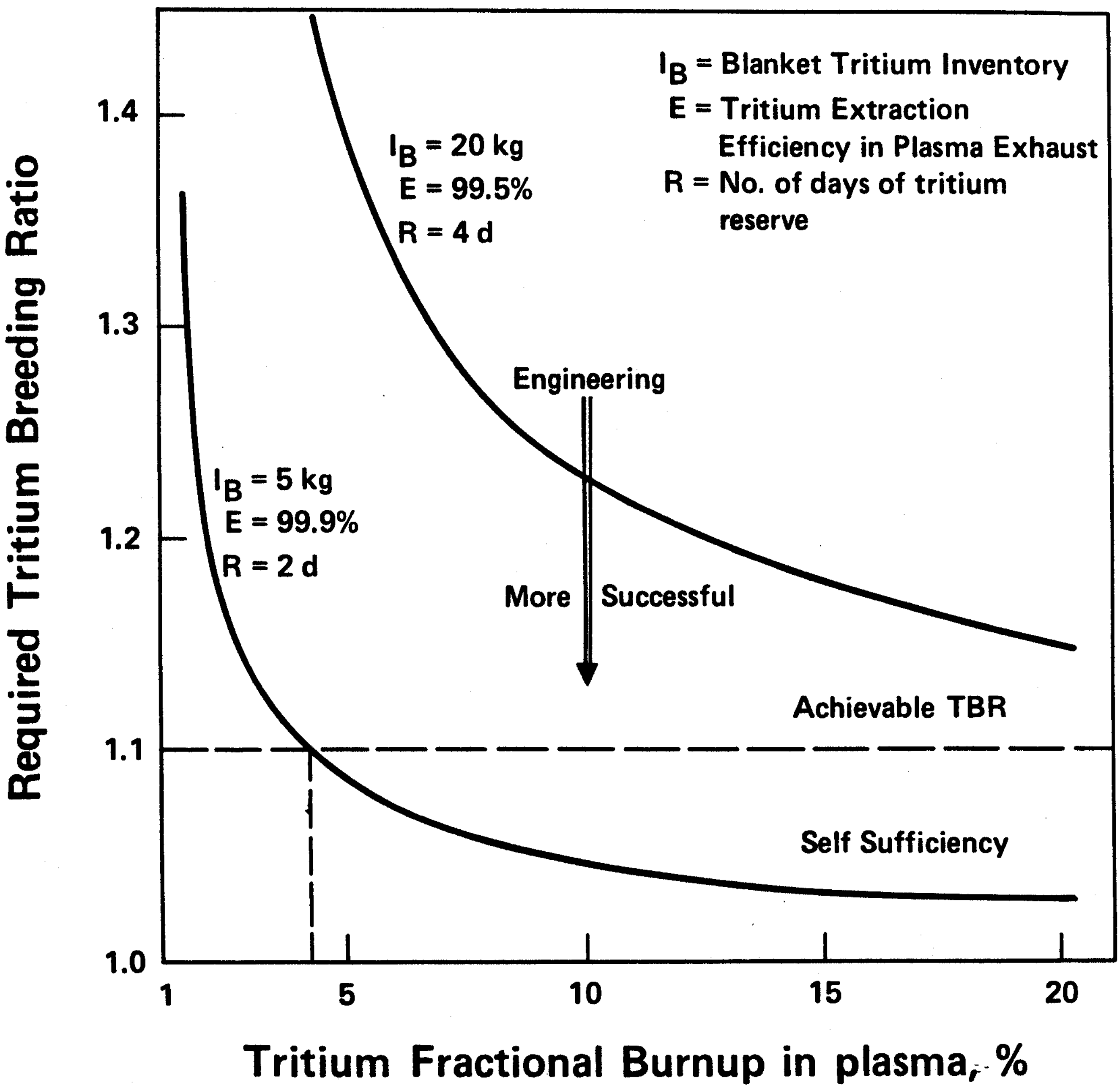
- Achievable TBR Analysis Shows:
  - TBR Strong Function of Reactor System, Blanket Concept
  - Best Blanket Concepts: TBR ~1.05 - 1.2

    Present Uncertainties: ~20%

- Required TBR Analysis Shows:
  - Strong Function of Several Physics, Engineering Parameters

FINESSE

Attaining DT Fuel Self Sufficiency Requires Success in Physics and Engineering



TRITIUM INVENTORY AND RECOVERY UNCERTAINTIES

Thermal Effects

- Tritium Diffusivity
- Sintering and Grain Growth
- LiOT Mass Transfer (in Li_2O)
- Breeder Temperature Profile
- Porosity Redistribution

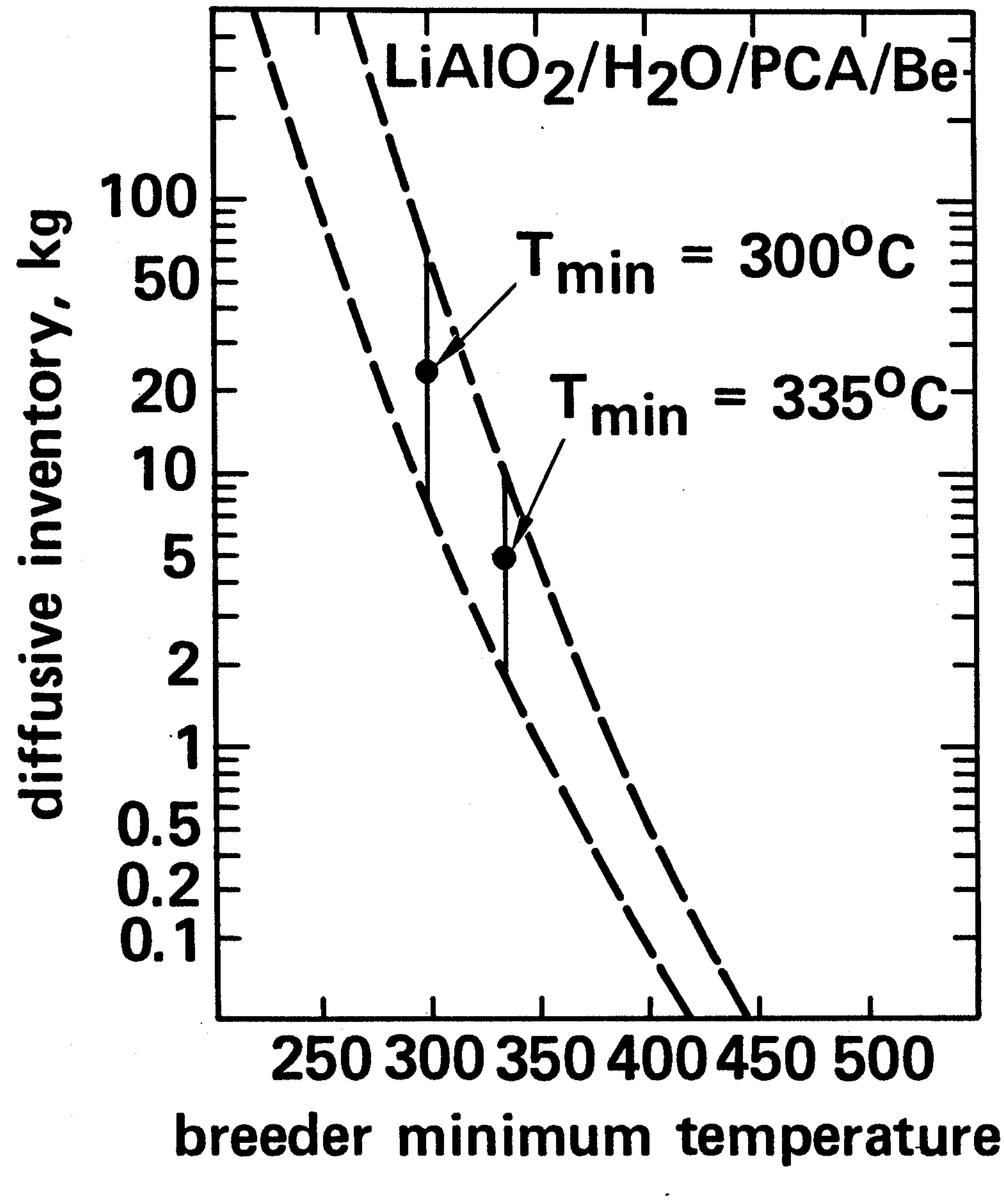
Chemistry Effects

- Tritium Solubility
- Oxidation State of Breeder
    - Thermodynamics
    - Purge gas
    - Metal cladding
    - Beryllium
- Fabrication Impurities and Burn-up Products

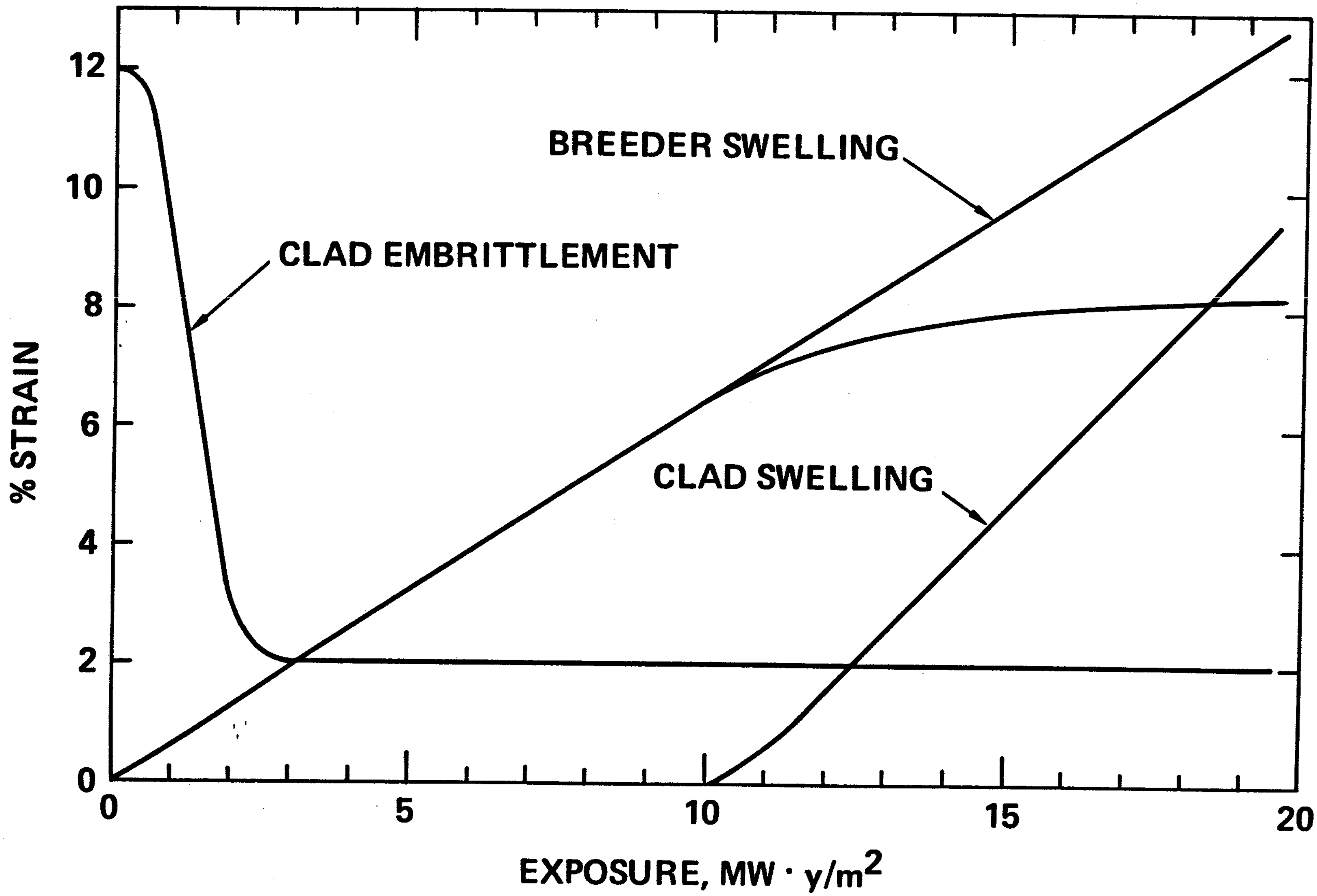
Radiation Effects

- Radiation Trapping
- Creep, Swelling, Sintering and Cracking Effects on Porosity and Purge Channels
- Burn-up Effects on Thermal and Mechanical Properties

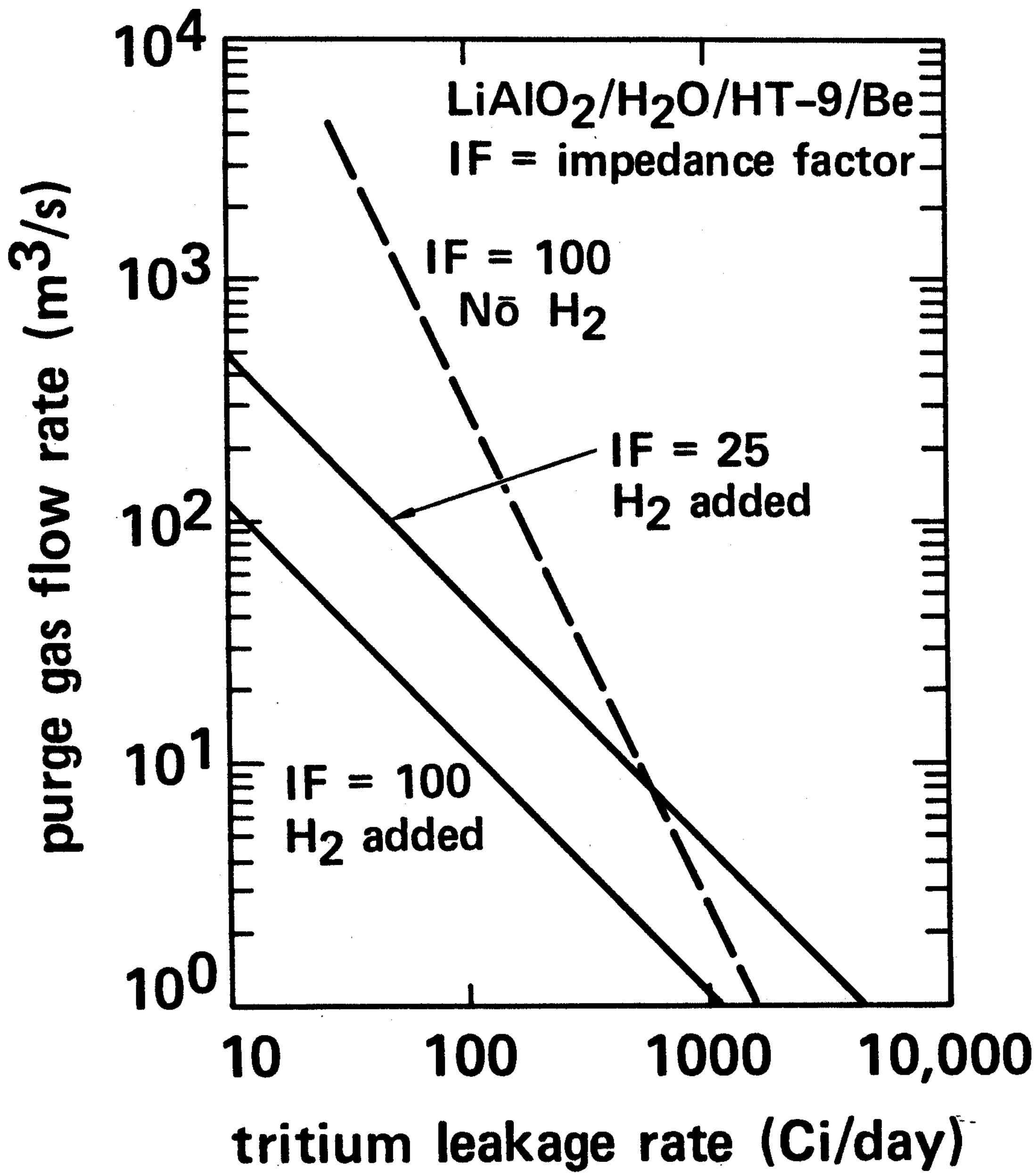
Uncertainties in tritium diffusion rate and breeder temperature affect blanket inventory.



CLAD/BREEDER MECHANICAL INTERACTION
(ESTIMATES FOR Li_2O/HT-9/He)



Uncertainties in surface barrier effectiveness may lead to substantial tritium permeation rates



MAJOR ISSUES FOR PLASMA INTERACTIVE COMPONENTS
(First Wall, Limiter, Divertor, etc.)

- Erosion and Redeposition Mechanisms and Rates under Various Plasma Edge Conditions
- Thermomechanical Loading and Response
- Electromagnetic Loading and Response

MAJOR ISSUES FOR TRITIUM PROCESSING SYSTEM

- Plasma Exhaust Processing: Impurity Removal from Fuel
  - Extraction Efficiency
  - Reliability
- Coolant: Tritium Permeation and Processing
- Cryopumps Performance, Lifetime
- Reactor Room Air Detritiation Efficiency, Reliability
- Tritium Monitoring, Accountablility

FINESSE

MAJOR ISSUES FOR RADIATION SHIELDING:

- Accuracy of Prediction
- Data on Radiation Protection Requirements

MAJOR ISSUES FOR INSTRUMENTATION AND CONTROL

- Accuracy, Decalibration in Fusion Environment
- Lifetime under Irradiation

IMPLICATIONS OF FUSION NUCLEAR ISSUES

- Fusion Environment is Unique
- New Phenomena Expected Due to Interactions:
  - Environmental Conditions
    Neutrons, Magnetic Field, Heating, Tritium, etc.
  - Subsystems and Components
- New Phenomena Result in Critical Issues:
  - Feasibility
  - Attractiveness
- Need New Knowledge
  - Carefully Planned Experiments

FINESSE

EVALUATION OF FACILITIES

TYPES OF EXPERIMENTS (TESTS)

- BASIC Tests

  Basic Property Measurements

- SEPARATE EFFECT Tests

  Explore Simple Phenomena

- MULTIPLE EFFECT/INTERACTION Tests

  Explore Complex Phenomena

  Multiple Environmental Conditions

  Multiple Interactions among Physical Elements

- INTEGRATED Tests

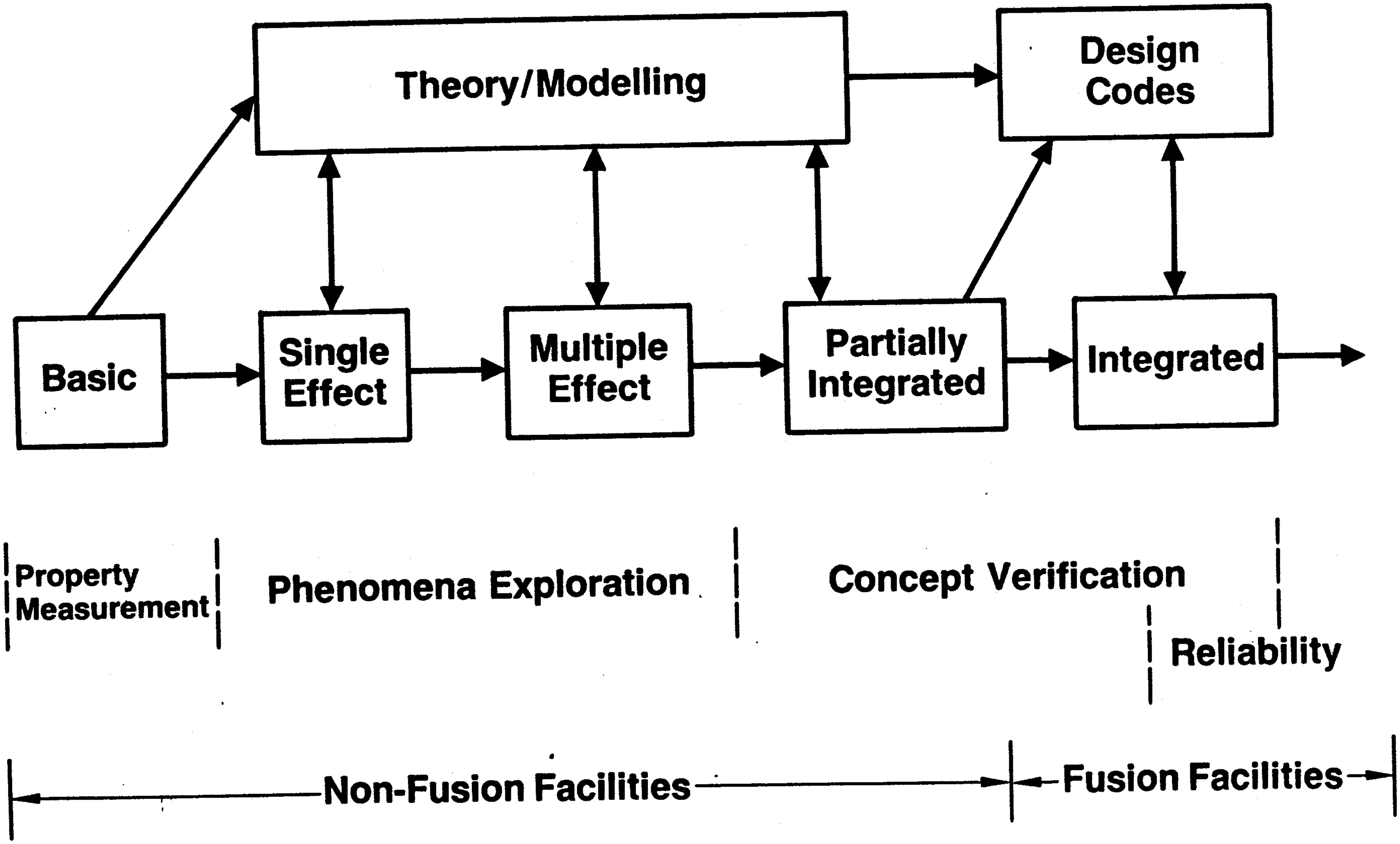
  Concept Verification, Engineering Data

  All Environmental Conditions, Physical Elements

- COMPONENT Tests

  Full-Size Component under Prototypical Conditions

FINESSE


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

FACILITIES FOR NUCLEAR EXPERIMENTS

- Non-Neutron Test Stands
- Neutron-Producing Facilities:
  - Point Neutron Sources
  - Fission Reactors
  - Fusion Devices

FINESSE

NON-NEUTRON TEST STANDS

- Can Play an Important Role:
  - Particularly for Fluid Flow/ Electromagnetic Issues
  - When Radiation Effects and Extensive Bulk Heating are Not Dominant Issues
- More Useful for Liquid Metal Blankets;
  Limited Value for Solid Breeder Blankets
- New Facilities are Required

FINESSE

NEUTRONS ARE NECESSARY FOR MANY KEY EXPERIMENTS

- A Key Element of the Fusion Environment
    - Produce Large Single and Interactive Effects/Changes
    - Cause Numerous Critical Feasibility Issues
- Only Practical Method to Provide in Experiments:
    - Bulk Heating
    - Radiation Effects
    - Specific Reactions

FINESSE

NEUTRON–PRODUCING FACILITIES

- Accelerator–Based "Point" Sources
- Fission Reactors
- Fusion Devices

FINESSE

POINT NEUTRON SOURCES CAPABILITIES

Facility	Status	Peak Flux* $n/cm^2 \cdot s$	Testing Volume cm^3
RTNS–II	In Use	5×10^{12}	0.1
LAMPF A–6	Operational	1×10^{13}	20000
FMIT	Design Completed Project Deferred	1×10^{15}	10

*Fusion First Wall Flux at 5 MW/m^2:

2×10^{15} $n/cm^2 \cdot s$

FINESSE

POINT NEUTRON SOURCES CONCLUSIONS

- Existing Sources Very Limited in Flux and Volume
  - Best Suited for:

    Neutronics Studies

    Limited Miniature Specimen Irradiation
- FMIT Can Provide High Fluence
  - Fission Reactor Testing Still Required
  - Fusion Reactor Testing Still Required

FINESSE

FISSION REACTOR UTILIZATION

Incentive for Use

Only Source Available Now to Provide:

- "Bulk Heating" in Significant Volume (Unit Cell) Experiments
- Significant Fluence

Limitations

- Different Spectrum
- Limitations on Simulating Fusion Environment (Electromagnetics, Surface Heat Flux, etc.)
- Limits on Temperature
- Small Test Size (<15 cm)

FISSION REACTOR UTILIZATION

- Fission Reactors Can, Should Be Used to Address Many Important FNT Issues
- Suitable, Necessary for Solid Breeders
- Not as Useful for Liquid Metals
- Characteristics and Timing of Major Solid Breeder Experiments in Fission Reactors Are Being Developed

FINESSE

TESTING IN FUSION DEVICES

Purpose of FINESSE Effort

- Understand Role of Fusion Devices
- Quantify Requirements of Nuclear Testing on Parameters and Features of Fusion Testing Devices

  e.g., Wall Load, Fluence, Test Area

  Develop Engineering Scaling

  Effort Generic to All Device Types

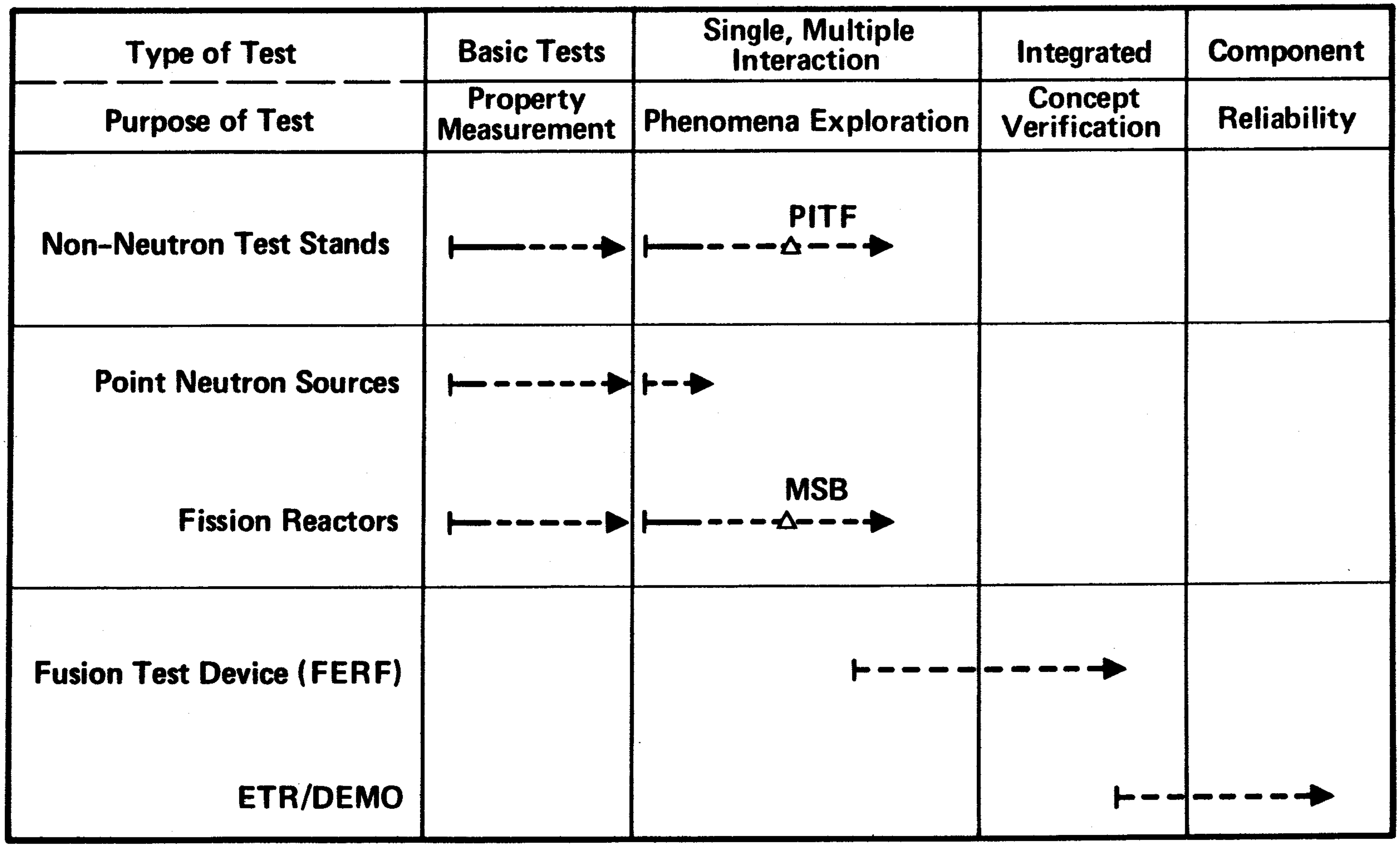
- Understand Impact of Nuclear Testing on Cost, Performance (e.g., availability) of Various Types of Fusion Devices

  e.g., On Combined Physics/Technology Facility

  On Technology-Dedicated Device

FINESSE

Role of Facilities For Fusion Nuclear Technology



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

SPECIFIC FEATURES OF FUSION TEST DEVICES NOT AVAILABLE IN NON–FUSION FACILITIES

1. Simulation of All Environmental Conditions
   - Neutrons
   - Plasma Particles
   - Vacuum
   - Electromagnetics
   - Tritium
2. Correct Neutron Spectrum
3. Large Volume of Test Element/Module

   Some Test Require ~1 m x 1 m x 0.5 m
4. Large Total Volume, Surface Area of Test Matrix

   Needed: $>5\ m^2$

FINESSE

FUSION NUCLEAR TECHNOLOGY TESTING REQUIREMENTS 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, $m^2 \times m$	0.5 x 0.3	1 x 0.5
Total Test Area, m^2	5	10

FINESSE

OBSERVATIONS ON TRITIUM CONSUMPTION 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

FINESSE

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)

FINESSE

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

  20 – 50 MW

  5 – 10 m^2

  2 – 10 MW · y/m^2

- Several Ideas for FERF Evaluated

  Potential Problems Include:

  - Physics Feasibility
  - Engineering Feasibility
  - Cost
  - Timing

FINESSE

Table 1: Performance Comparison of FERF Concepts

	TOKAMAKS					TANDEM MIRRORS			
	INTOR	LITE		BEAN	SPHERICAL TORUS	TDF	MFTF-α+T	REVERSE FIELD PINCH	
Plasma operating mode (a)	I	D	I	I	I	D	D	D	D
Fusion power, MW	620	150	310	185	39	36	17	22	110
Neutron wall loading, MW/m^2	1.3	1.0	2.0	1.3	1.0	2.1	2.0	1.0	5.0
Surface heat flux, MW/m^2	0.1			0.3	0.1	0.5	0.1		
First wall radius, m	1.2	0.81		0.90	0.59	0.30	0.25	0.33	
First wall area, m^2	380			129	90	8	4		
Total test area, m^2	40	16		16	10	3.8	1.6	9.7	
Test port area/depth, m^2/m	2/1			1.5/0.8	1.6/0.8	0.5/0.8	0.3/0.8		
Cycles/year	44,000	25,000		13,000	39	39	9	39	
Pulse length, s	200	500		1000	SS	SS	SS	SS	
Device duty cycle, %	80	90		90	100	100	100	100	
Run duration, h (b)	100	100		100	100	100	100	100	
Ultimate availability, % (b)	35	45		45	45	45	10	45	
Neutron fluence, MW-yr/m^2 (c)	3.6	3.6	7.2	4.7	3.6	7.6	1.6	3.6	18
Fluence x surface area, MW-yr	160	65	130	79	40	33	2.9	39	200
Magnetic field on-axis, T	5			3-6	3	4.5	5		

(a) D-Driven, I-Ignited.

(b) Consistent estimate.

(c) Assuming total equal to 9 years at ultimate availability.

Table 2: Cost Comparison of FERF Concepts

	TOKAMAKS					TANDEM MIRRORS			
	INTOR	LITE		BEAN	SPHERICAL TORUS	TDF	MFTF-α+T	REVERSE FIELD PINCH	
Tritium consumption, kg/yr	6.0[a]	3.7	7.7	4.6	1.0	0.9	0.1	0.5	2.7
Electrical consumption, MWe	300	320	372	185	120	250	150	100	120
Total capital cost, M$[b]	3000	1000	1250	1000	750	1250	500	750	900
Annual operating costs:									
Electricity, M$/yr[c]	46	63	73	36	20	49	7	20	24
Tritium supply, M$/yr[d]	90	55	115	69	15	14	1.5	7.5	40
Operation, M$/yr[b]	100	75	75	75	75	75	50	75	75
Total, M$/yr	226	193	263	180	110	138	59	96	103
Total cumulative cost, M$[e]	5000	2700	3600	2600	1700	2500	1000	1600	1900

(a) Assuming TBR=0.5.

(b) Rough scaling based upon TDF, INTOR, and MFTF-α+T estimates.

(c) 0.05 $/kWe-h.

(d) 15,000 $/g.

(e) Assuming total equal to 9 years at ultimate availability.

Table 3a: Risk Comparison of FERF Concepts[a]

	TOKAMAKS				TANDEM MIRRORS		
	INTOR	LITE	BEAN	SPHERI-CAL TORUS	TDF	MFTF-α+T	REVERSE FIELD PINCH
Physics Risk							
Confinement	L	L	H	M	L	M	H
Exhaust and impurity control	M	M	M	M	L	M	H
Fuelling	L	L	L	L	L	L	M
Heating	L	L	M	M	L	L	M
Burn length	L	L	L	H	L	L	H
Plasma control	L	L	M	M	L	L	H
Technology Risk							
Magnets and shielding	L	H	H	H	M	M	M
Exhaust and impurity control	M	M	M	M	M	M	H
Heating	L	L	L	M	M	M	M
Tritium	H	M	M	L	L	L	L
Burn length	L	L	M	M	L	L	H
Maintainability	M	M	M	M	M	M	M
Balance of plant	L	L	L	H	L	L	L

(a) Low (L), Moderate (M), or High (H) risk, based on extrapolating from devices presently operating or under construction.

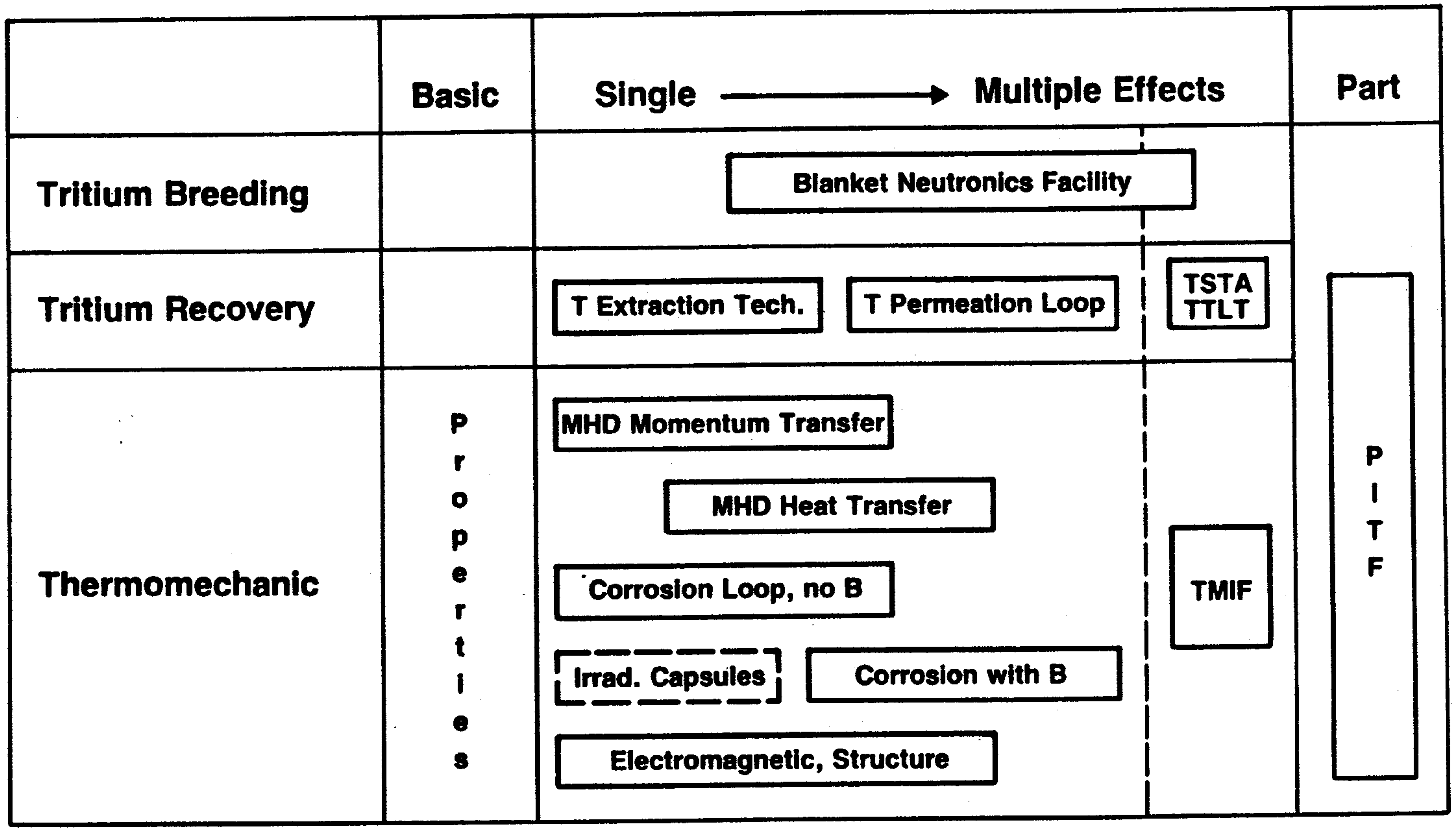
Table 4: Key Attributes of FERF Concepts

		TOKAMAKS				TANDEM MIRRORS		
	FERF THRESHOLD	INTOR	LITE	BEAN	SPHERICAL TORUS	TDF	MFTF-α+T	REVERSE FIELD PINCH
Neutron wall load, MW/m^2	1.0	1.3	1.0-2.0	1.3	1.0	2.1	2.0	1.0-5.0
Fluence x Area/Year, MW/yr	1.0	18.	7.2-14.	8.8	4.5	3.6	0.33	4.4-22.
Pulse length, s	500	200	500	1000	360,000	360,000	360,000	360,000
Tokamak physics relevance	L	H	H	H	M	L	L	M
Tokamak tech. relevance	M	H	H	H	H	M	M	M
Reactor physics relevance	L	H	H	H	M	M	H	H
Reactor tech. relevance	M	H	M	M	M	H	H	M
Physics risk	M	M	L-M	H	H	M	M	H
Technology risk	M	H	M	M	M	M	M	H
Total capital cost, M$	500	3000	1000-1250	1000	750	1250	500	750-900
Total cumulative cost, M$	1000	5000	2700-3600	2600	1700	2500	1000	1600-1900

(a) H High, M Moderate, L Low.

REQUIRED NEW FACILITIES, EXPERIMENTS

Liquid Metal Blanket Experiments, Facilities



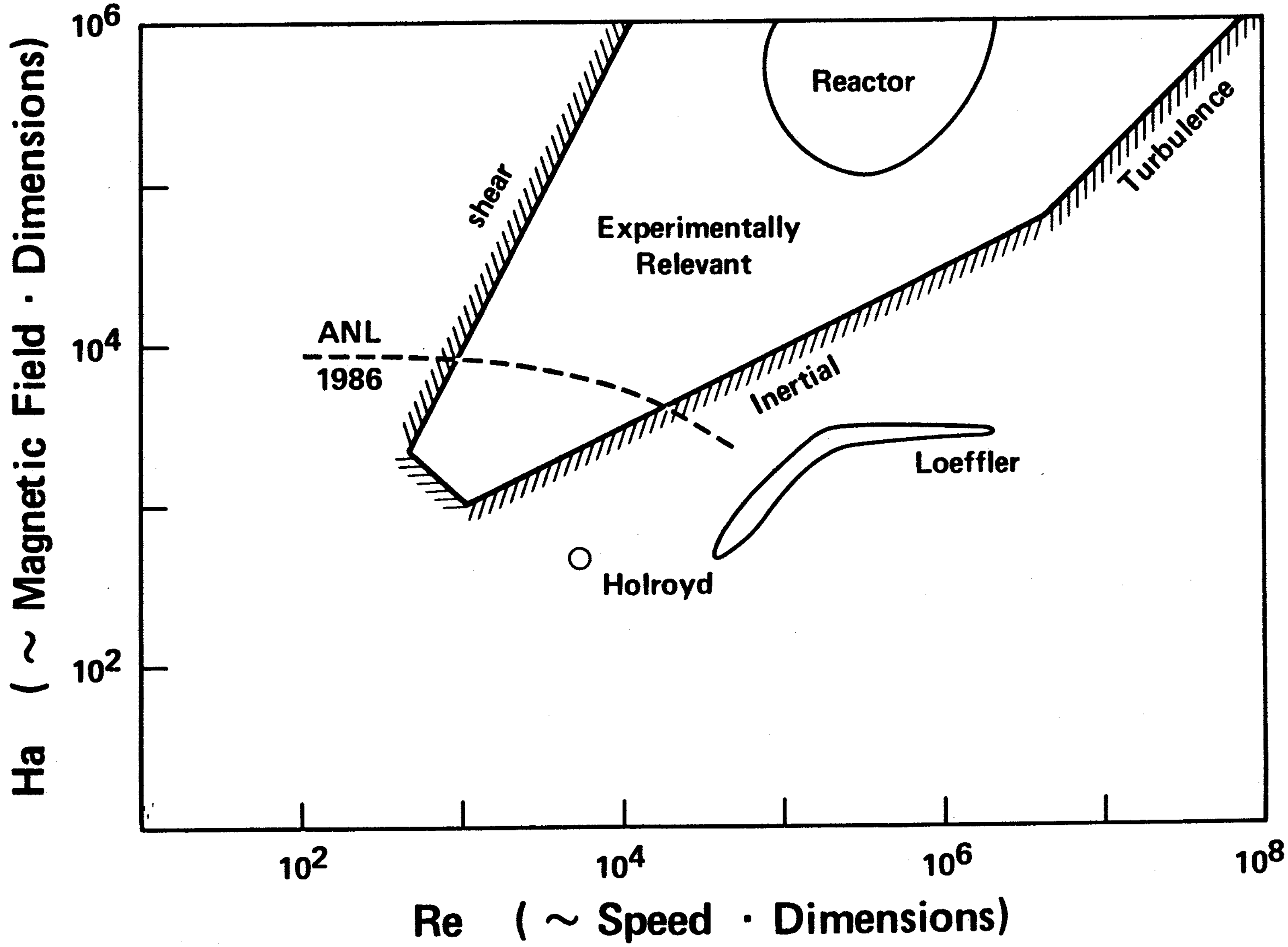
Important Test Conditions For Liquid Metal Blanket Thermomechanics Facilities

Testing Condition	Momentum Transfer	Heat Transfer	Mass Transfer
Magnetic Field	X	X	X
Velocity Profile	X	X	X
Geometry	X	X	X
Temperature Gradient	—	X	X
Temperature Level	—	—	X
Impurity Level	—	—	X
Material	—	—	X
Outer B Field Geometry	—	—	X
Long Time	—	—	X

X = Important

— = Not Important

Liquid Metal Blanket MHD Experiments Needs



Requirements For Liquid Metal Heat Transfer Experiments

• Correct Velocity Distribution	
• Turbulence Suppressed	$Re \ll 60\ Ha$
• Natural Convection Suppressed	$\rho g \beta \Delta T / V \sigma B^2 \ll 1$
• Entrance Length for Fluid Flow	$L \phi^{1/2} / a \gg 1$
• Negligible Axial Conduction	
• FW Temperature Distribution	$k \Delta T_W / Qt \simeq 1$
• Thermal Entrance Length	$\alpha L / Va^2 \sim 10^{-2}$

Preliminary Parameters For LM Heat Transfer Facility

	HT Facility	Reactor
Geometry	○ □	○ □
Axial Length, m	2-3	3-5
Radius, cm	5-20	5-50
Wall Thickness (t), mm	5-10	2-5
Magnetic Field (B), T	2-3	4-7
Surface Heat Flux (Q), MW/m^2	0.3-0.7	0.3-1
Velocity (V), m/s	0.1-0.5	0.1-1
Structural Material	Steel	HT-9, V
Coolant	Lithium	Lithium

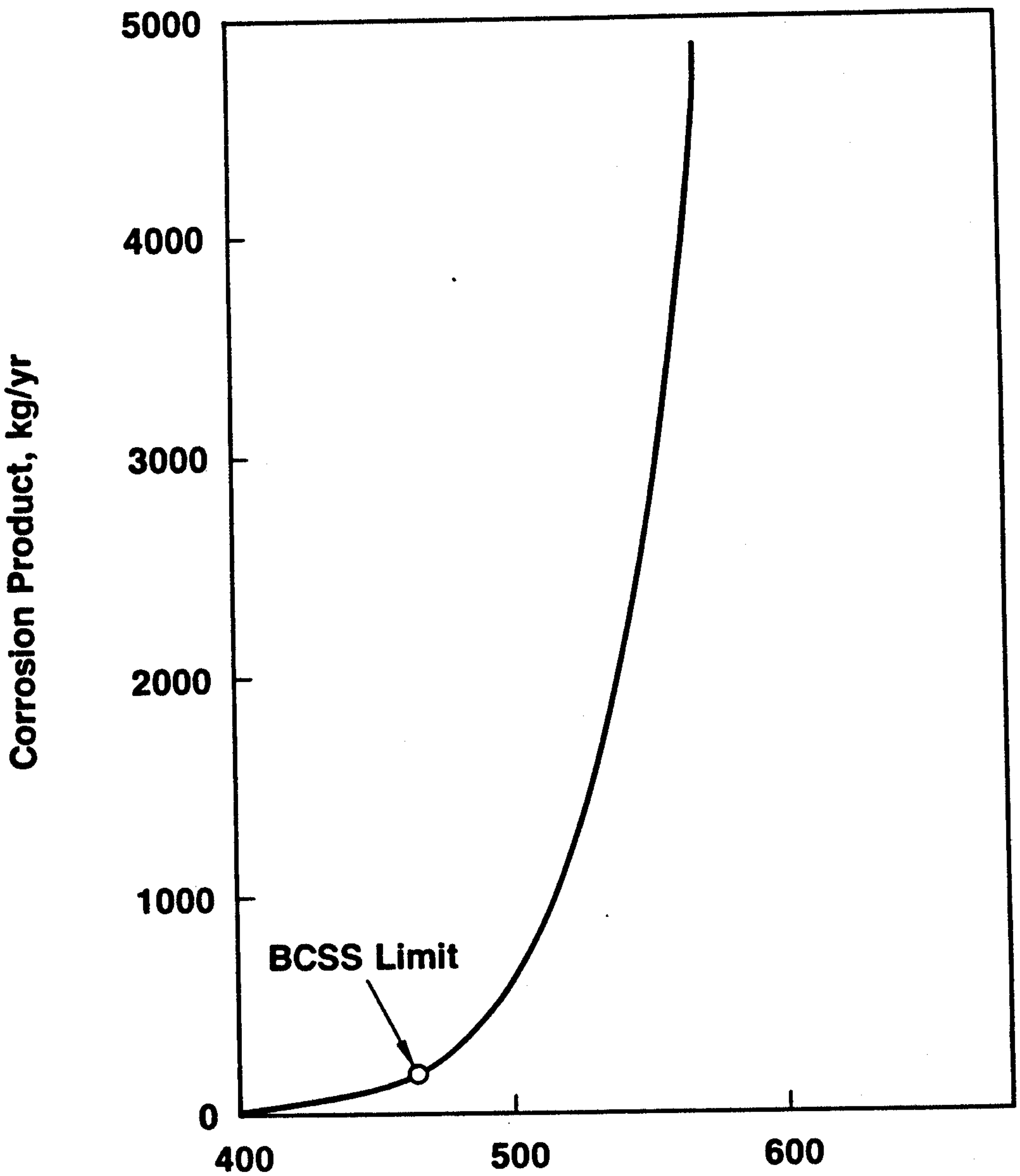
Important Test Conditions For Liquid Metal Blanket Corrosion Experiments

Testing Condition	Local Attack	Dissolution	Deposition
Magnetic Field	—	X?	XX
Velocity Profile	—	X	X
Geometry	—	X	X
Temperature Gradient	X	X	—
Temperature Level	XX	XX	XX
Impurity Level[a]	XX	XX	XX
Material[a]	XX	XX	XX
Outer B Field Geometry	—	—	XX
Long Time	X	X	X

XX Very Important X Important — Not Important

[a] Switching from V to steel outside blanket is a key concern

Corrosion Is Strongly Temperature Dependent



Providing Bulk Heating For Liquid Metal Thermomechanics

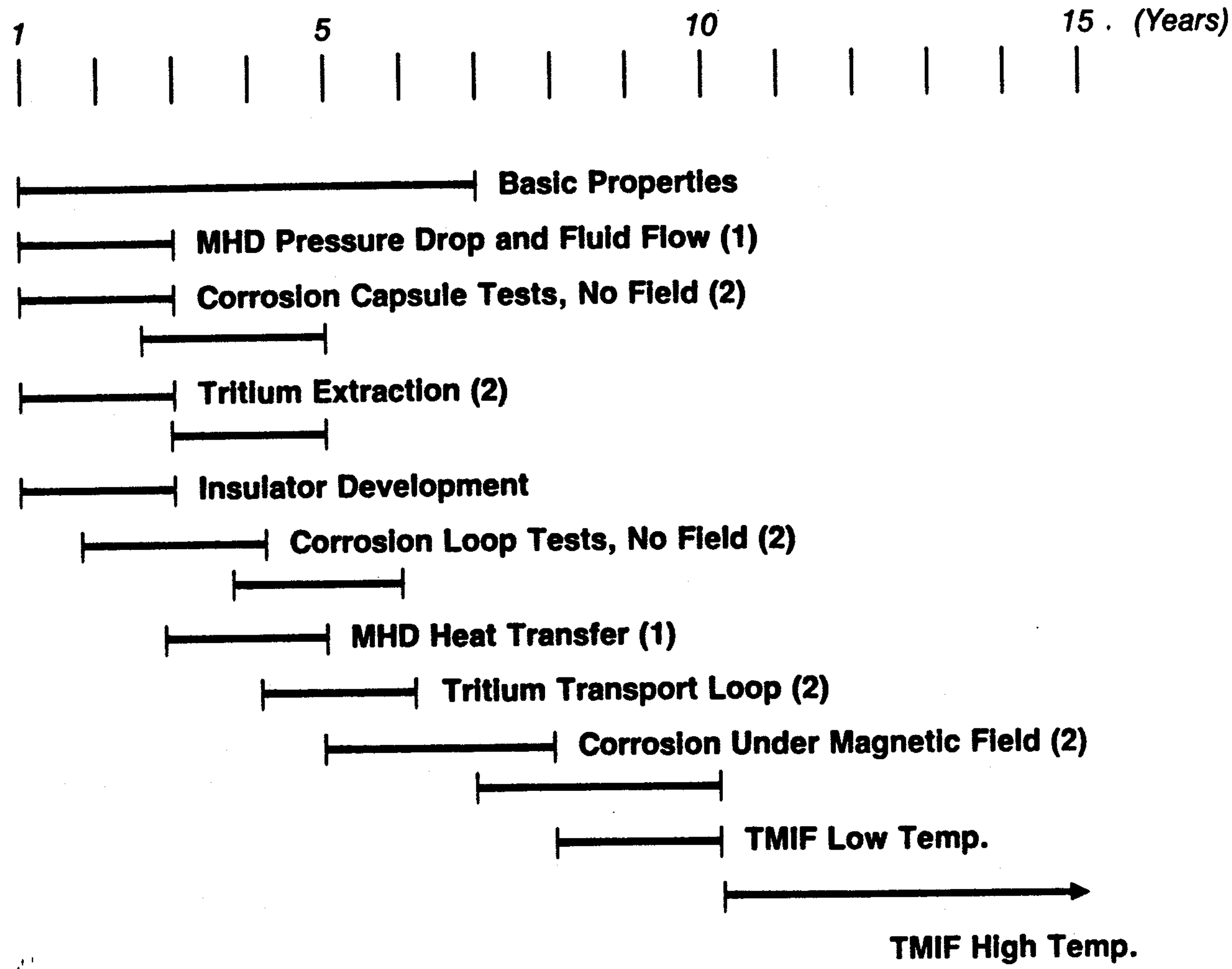
Experiments in Non-Fusion Facilities May NOT Be Practical

Method	Problems
Neutrons	Unaffordable
Thermal Inertia	Use $\rho C_p \Delta T$ Disrupt Velocity Profile
Inductive Heating	Disrupt Current Profile
RF Heating	Not Feasible for LM

Preliminary Parameters For Liquid Metal Blanket Thermomechanics Integration Facility (TMIF)

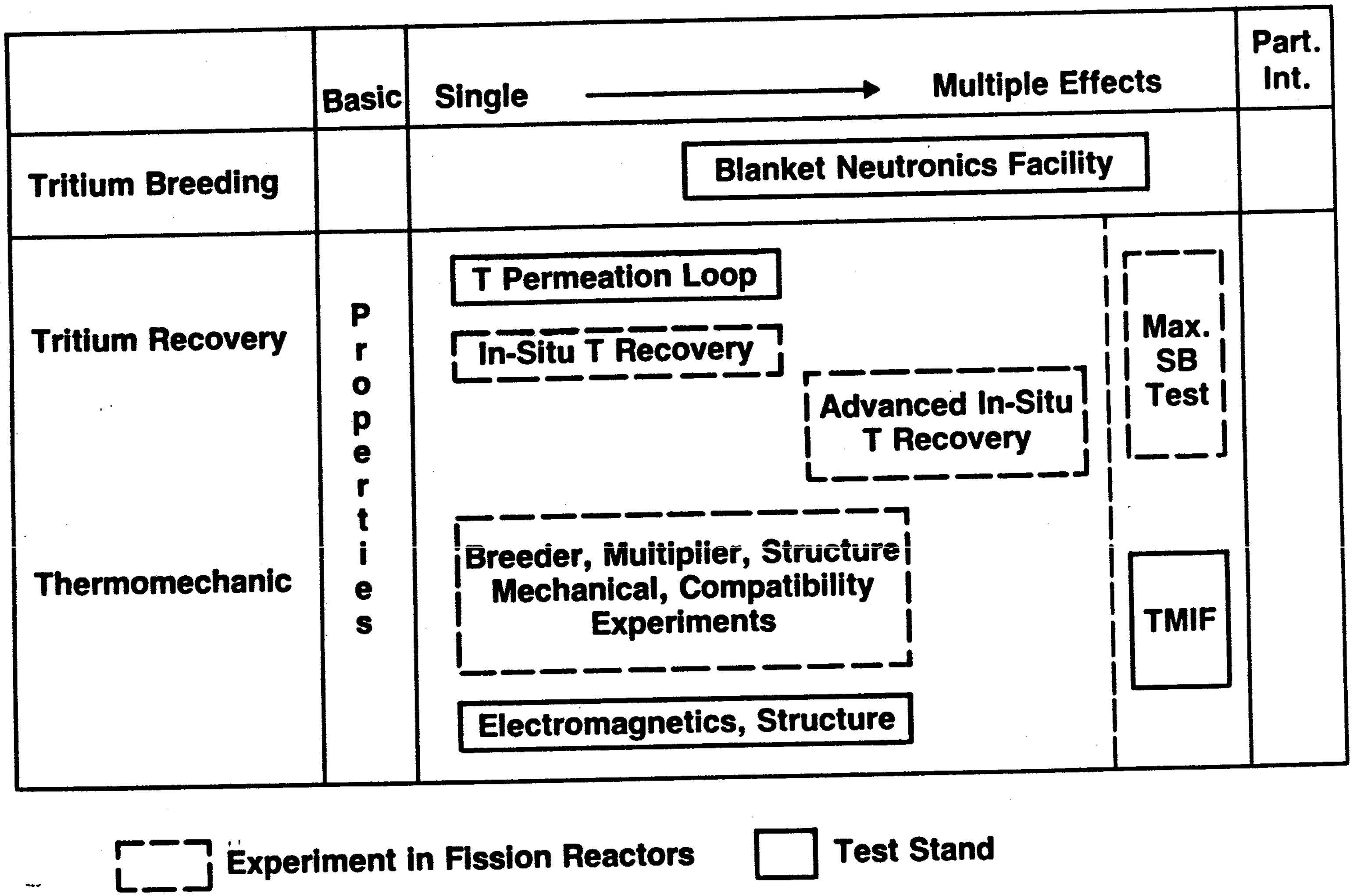
Parameter	Representative Value
Length	300 cm
Bore	20 cm x 50 cm
Velocity	10 – 20 cm/s
Volumetric Flow Rate	20 liter/s
Magnetic Field	3 Tesla
Surface Heat Flux	20 – 50 W/cm^2
Power	2 MW
Estimated Capital Cost	$30 million
Estimated Operating Cost	$8 million/yr

Example of Liquid Metal Test Sequence



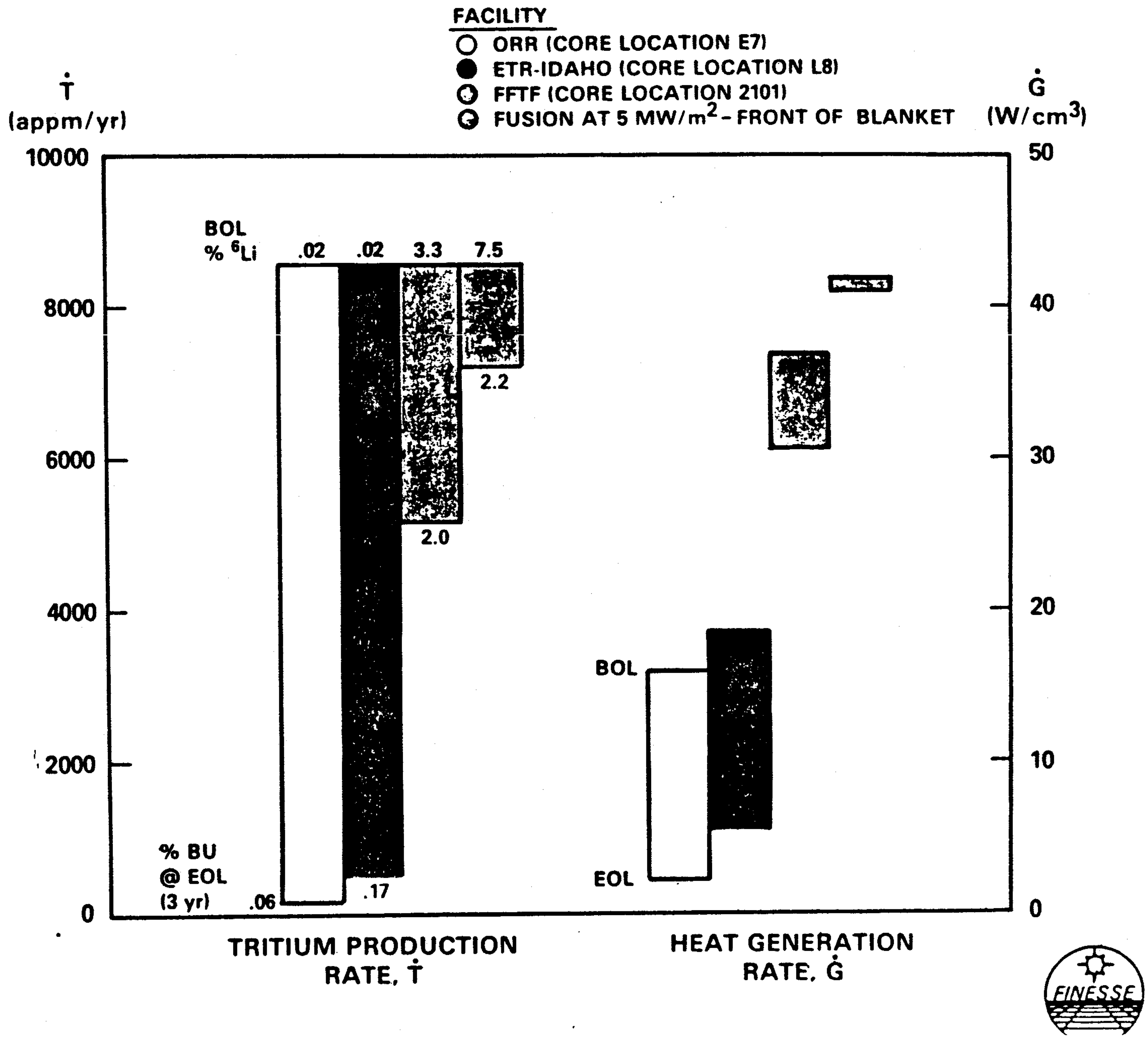
Assumptions: **1.5 Designs, 2 Material Combinations**
15 year period with no fusion facility

Solid Breeder Blanket Experiments, Facilities



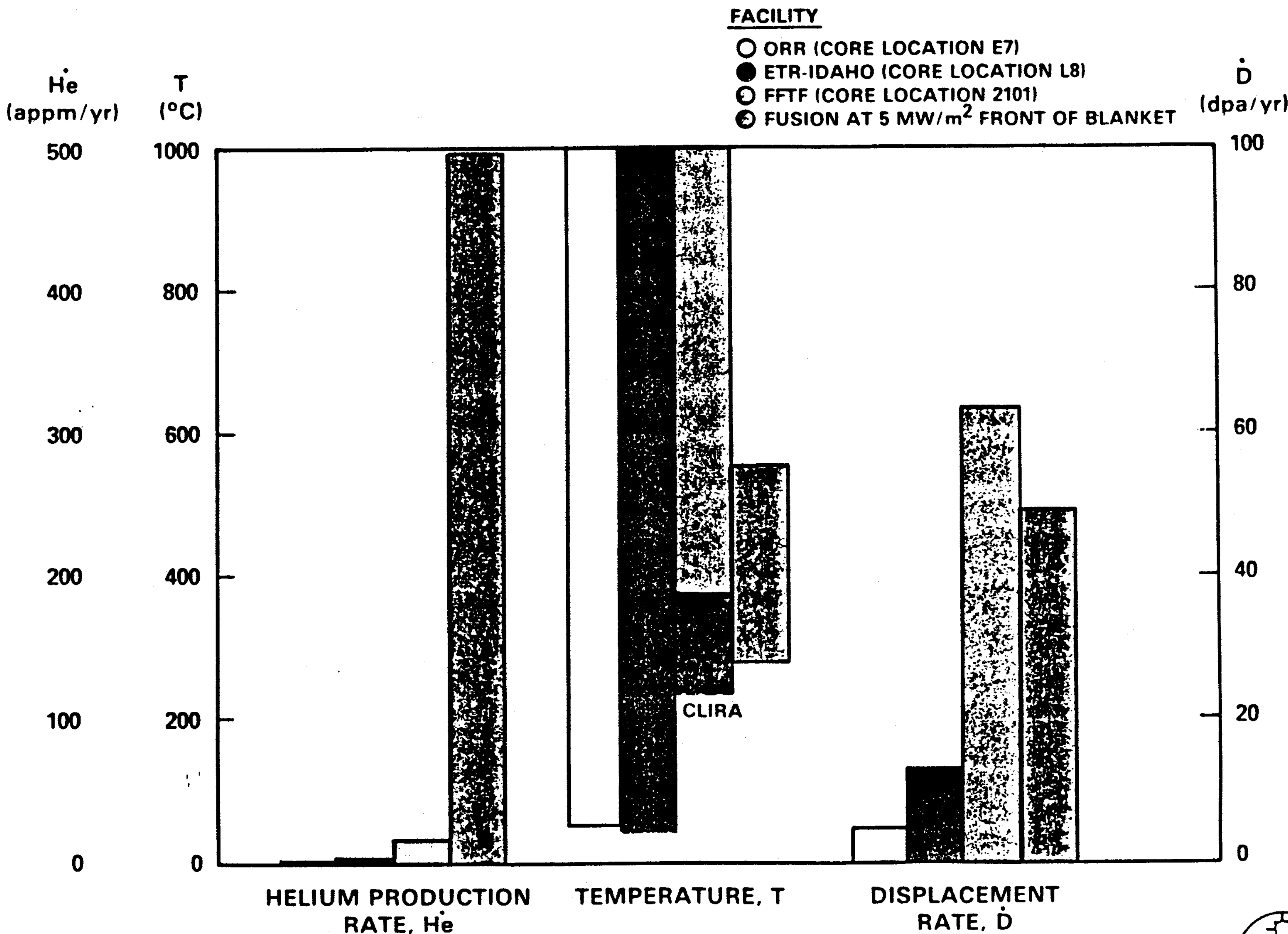
FISSION/FUSION IRRADIATION COMPARISON FOR Li_2O/He/HT-9 SYSTEM

Li_2O SOLID BREEDER

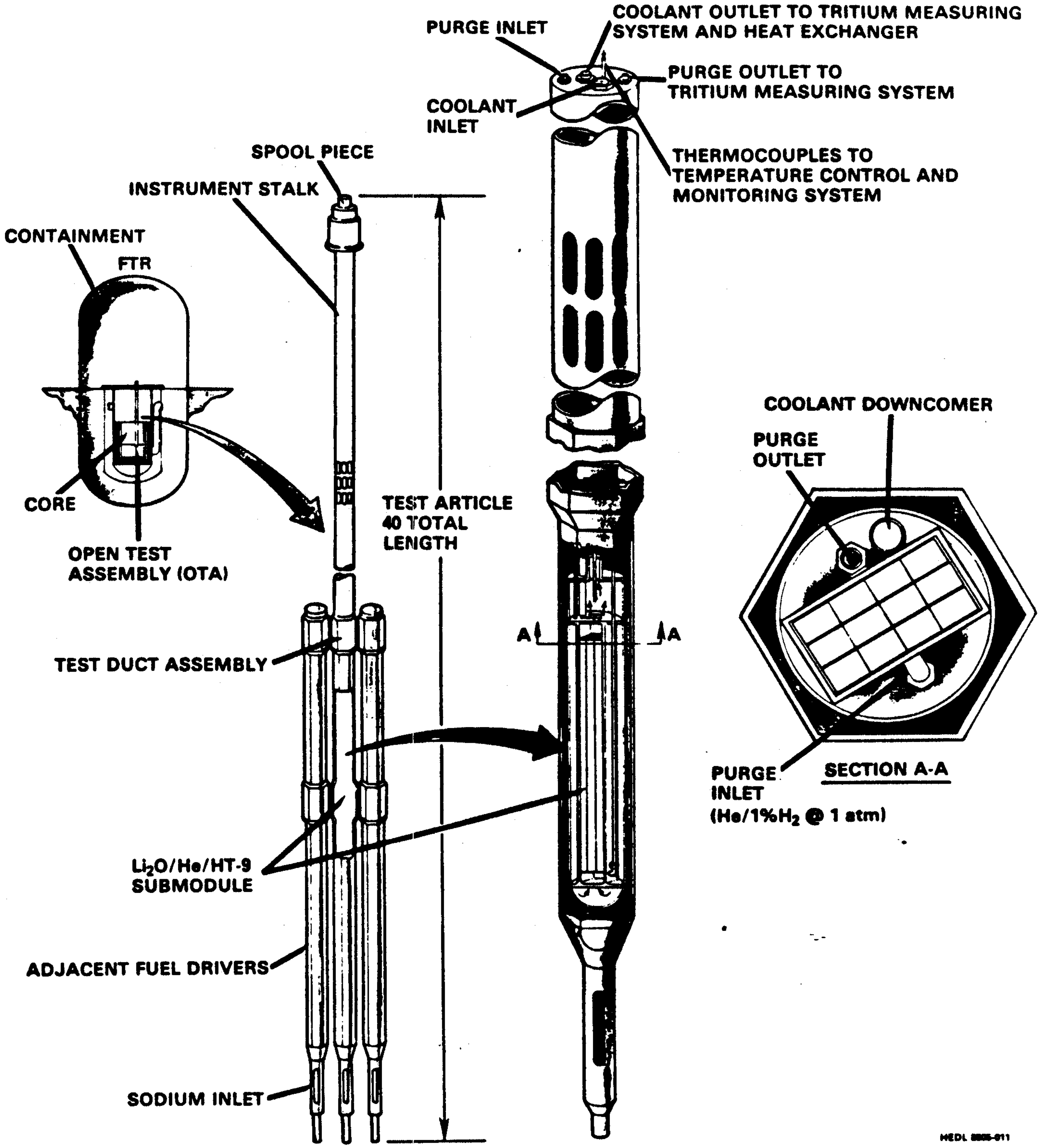


FISSION/FUSION IRRADIATION COMPARISON FOR Li_2O/He/HT-9 SYSTEM

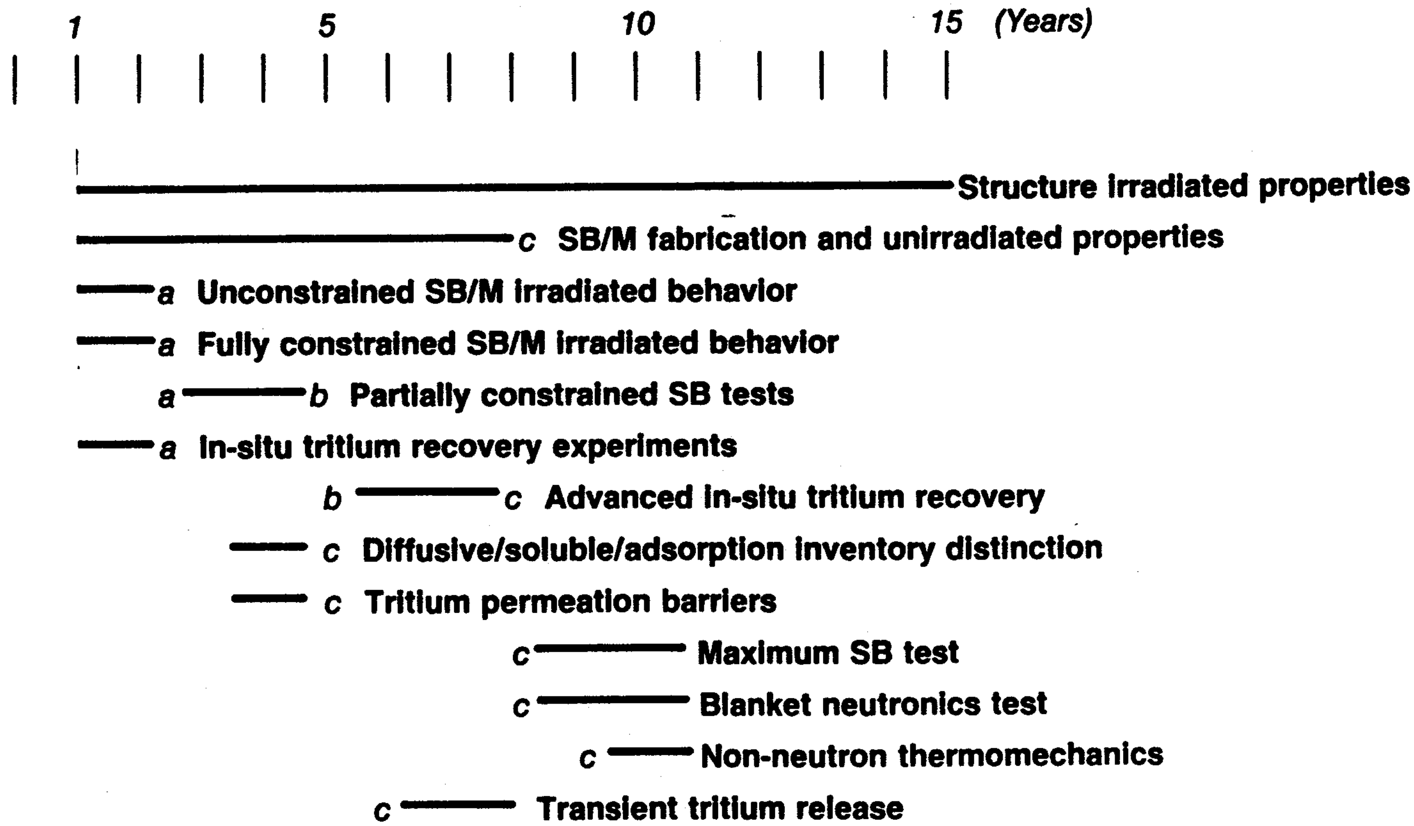
HT-9 STRUCTURE



HELIUM COOLED Li2O / HT-9
FUSION BREEDER MATERIAL INTERACTION TEST

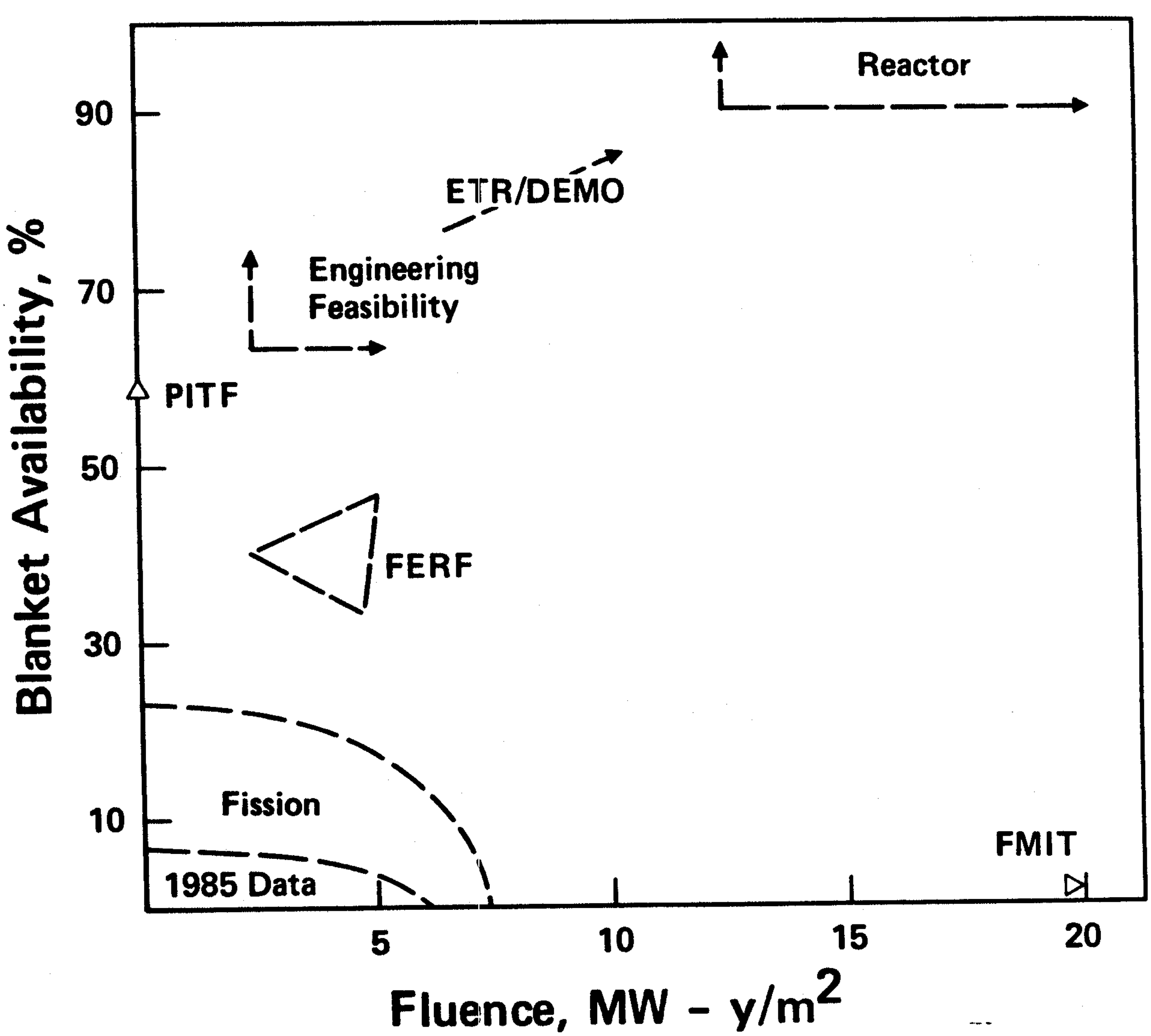


Example of Solid Breeder Test Sequence



a Select SB/M material and morphology
b Select SB/M/S configuration
c Select blanket configuration

Obtaining Availability and Fluence Data For Blanket Is Most Difficult



SUMMARY OBSERVATIONS

- Fusion Nuclear Technology Poses Critical Issues:

  Feasibility

  Attractiveness (Safety, Economics)

- Resolving These Issues Requires:

  New Knowledge

  Experiments, Theory

- Will Involve High Cost, Long Lead Time

- A Technical Process of Studying Issues, Quantifying Testing Needs and Evaluating Experimental Facilities is Very Useful in Providing Decision Makers with Technical Input for Effective R & D Planning

FINESSE

SUMMARY OBSERVATIONS (CONTINUED)

- From Now to 1990's (or until a DT Fusion Device Becomes Available), Testing is Possible Only in Non–Fusion Facilities:

  Non–Neutron Test Stands

  Fission Reactors

  Point Neutron Sources

- Non–Fusion Facilities Can Address Many of Fusion Nuclear Technology Issues

- A Number of Non–Neutron Test Stands Can Be Constructed at a Reasonable Cost to Address Many FNT Issues, e.g., Liquid Metal Blanket Issues

- Many Important Experiments Can Be Performed in Fission Reactors, e.g., Unit Cell for Solid Breeders

SUMMARY OBSERVATIONS (CONTINUED)

- First Generation DT Fusion Devices, When They Become Available, Will Provide the Earliest Opportunity for FNT Integrated Tests
    - Critical for Concept Verification
- Effective FNT Integrated Tests Impose Quantifiable Requirements on Fusion Device Parameters (e.g., Wall Load, Plasma Burn Time)
- FNT Testing Needs Can Be Satisfied with Relatively Low Fusion Power (< 50 MW), But Requires Relatively Long Testing Time (Several Years)

FINESSE

SUMMARY OBSERVATIONS (CONTINUED)

Number of Blanket Options (Breeder/Coolant/Structure/Multiplier) Greatly Affects R & D Cost

- However, Present Uncertainties with All Options Appear Too Large to Permit Selection of Only One Option
- More Experimental Data Will Permit Reducing Number of Options
- The Degree of Risk in Selecting One Option Prior to Testing in Fusion Devices Will Become Clearer after Obtaining More Data from Testing in Non–Fusion Facilities

FINESSE

In Summary

- Fusion Nuclear Technology Is Very Important
- Much Work Needs To Be Done
- International Cooperation Can Play a Key Role
- FINESSE Welcomes Working with ALL to:
  - Define FNT R&D Needs
  - Define Technical Areas of Common Interest