

**FUSION TECHNOLOGY DEVELOPMENT
NEEDS AND STRATEGY**

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THE INFORMATION PRESENTED HERE IS BASED ON INTERPRETATION OF RESULTS FROM FINESSE. THIS STUDY IS CARRIED OUT BY UCLA, ANL, EG&G IDAHO, HEDL, MDAC, AND TRW, WITH MAJOR SUPPORT FROM LLNL, PPPL, KfK (WEST GERMANY), CFFTP (CANADA), AND JAERI (JAPAN), AND THE UNIVERSITY OF TOKYO AND KYOTO UNIVERSITY (JAPAN).

NOTE

AT THE TIME OF THIS PRESENTATION, FINESSE HAS COMPLETED ONLY THE FIRST QUARTER OF ITS TWO-YEAR DURATION. HENCE, AVAILABLE RESULTS REQUIRE CONSIDERABLE ANALYSIS PRIOR TO DRAWING CONCLUSIONS. THESE RESULTS ARE OFFERED NOW ONLY FOR THE PURPOSE OF STIMULATING DISCUSSIONS OF THE FUSION NUCLEAR TECHNOLOGY ISSUES AND DEVELOPMENT NEEDS.



OUTLINE

- INTRODUCTION
- FINESSE
- ISSUES AND TESTING NEEDS
 - BLANKET/FIRST WALL
 - OTHER COMPONENTS
- NEED FOR NEUTRONS
- TEST FACILITIES
 - NON-FUSION FACILITIES
 - TEST STANDS, POINT SOURCES, FISSION REACTORS
 - FUSION FACILITIES (MIRRORS, TOKAMAKS)
- QUANTIFYING TEST REQUIREMENTS FOR FUSION FACILITIES
 - WALL LOAD
 - SURFACE HEAT LOAD
 - BURN CYCLE
 - TEST ELEMENT SIZE
 - FLUENCE
 - TEST ELEMENT AREA
- SCENARIOS FOR FUSION DEVELOPMENT
 - COMBINED PHYSICS AND TECHNOLOGY DEVICE
 - PARALLEL PHYSICS AND TECHNOLOGY DEVICES
 - SEQUENTIAL PHYSICS AND TECHNOLOGY DEVICES
- CONCLUSIONS



FUSION: WHERE ARE WE IN 1984?

PLASMA

- SUBSTANTIAL PROGRESS
- USES MOST OF WORLD RESOURCES

ENGINEERING/TECHNOLOGY

- PLASMA HEATING
 - SUBSTANTIAL PROGRESS
- MAGNETS
 - SIGNIFICANT PROGRESS
- NUCLEAR COMPONENTS
 - LEAST PROGRESS
 - MANY OF FUSION'S UNRESOLVED CRITICAL ISSUES



NUCLEAR COMPONENTS AND
COMPONENTS AFFECTED BY THE NUCLEAR ENVIRONMENT

- BLANKET
- SHIELD
- PLASMA INTERACTIVE AND HIGH HEAT FLUX SUBSYSTEMS:
 - FIRST WALL
 - IMPURITY CONTROL
 - RF ANTENNAS, LAUNCHERS AND WAVEGUIDES
- TRITIUM AND VACUUM SYSTEMS
- INSTRUMENTATION AND CONTROL
- MAGNETS
- REMOTE MAINTENANCE
- HEAT TRANSPORT AND POWER CONVERSION



WHY SHOULD RESEARCH BE CARRIED OUT NOW
ON BLANKET, MATERIALS AND NUCLEAR ISSUES?

- THE DEVELOPMENT OF A VIABLE FIRST WALL AND BLANKET CONCEPT REPRESENTS A MAJOR, UNRESOLVED FEASIBILITY ISSUE FOR FUSION
- THE SELECTION OF A FIRST WALL AND BLANKET CONCEPT CAN SIGNIFICANTLY IMPACT PLASMA ENGINEERING ISSUES AND VICE VERSA. EXAMPLES INCLUDE:
 - IMPURITY CONTROL OPTIONS
 - ACCESS AND MAINTENANCE
- OPERATION OF ANY FUSION DEVICE THAT BURNS TRITIUM FOR A SIGNIFICANT PERIOD OF TIME WILL REQUIRE CONSTRUCTION OF A TRITIUM-PRODUCING BLANKET
- THE PERCEPTION OF FUSION'S SAFETY AND ENVIRONMENTAL FEATURES IS LARGELY DETERMINED BY NUCLEAR/MATERIALS TECHNOLOGY CONSIDERATIONS
- FUSION ECONOMICS WILL GREATLY DEPEND ON THE PERFORMANCE OF THE NUCLEAR SYSTEM
- THE TIME SCALE FOR THE DEVELOPMENT OF NUCLEAR COMPONENTS IS LONG
- LESSONS LEARNED FROM OTHER TECHNOLOGY DEVELOPMENT STRONGLY SUGGEST WORKING ON LONG LEAD TIME ITEMS EARLY



**THE WORLD FUSION COMMUNITY
MUST ACT IMMEDIATELY TO DEVELOP A STRATEGY
FOR SUCCESSFUL AND TIMELY RESOLUTION
OF THE FUSION NUCLEAR ISSUES**

- **MANY OF FUSION'S UNRESOLVED ISSUES ARE IN NUCLEAR TECHNOLOGY. THESE ISSUES RELATE TO:**
 - **FEASIBILITY (TECHNOLOGY COMMUNITY ACCEPTANCE)**
 - **ECONOMICS (UTILITY ACCEPTANCE)**
 - **SAFETY, ENVIRONMENT (PUBLIC ACCEPTANCE)**

- **RESOLVING THESE ISSUES IS CHALLENGING:**
 - **COSTLY (REQUIRES NEUTRONS IN TEST ENVIRONMENT)**
 - **REQUIRES LONG LEAD TIME**
 - **TEST FACILITIES REQUIREMENTS ARE COMPLEX**
 - * **NON-FUSION FACILITIES ARE USEFUL BUT NOT SUFFICIENT**
 - * **FUSION TEST FACILITIES NECESSARY?**
 - **COMBINED WITH OR SEPARATE FROM PHYSICS TESTING?**
 - **COST?**
 - **TIME SCHEDULE?**
 - **RISK?**



FINESSE
FUSION NUCLEAR TECHNOLOGY DEVELOPMENT STUDY

- OBJECTIVE:
 - INVESTIGATE THE TECHNICAL AND PROGRAMMATIC ISSUES IN THE DEVELOPMENT OF FUSION NUCLEAR COMPONENTS

- TWO-YEAR STUDY (STARTED IN NOVEMBER, 1983)

- MAJOR PARTICIPATION BY KEY U.S. ORGANIZATIONS:
 - UCLA, ANL, EG&G, HEDL, MDAC, TRW
 - LLNL, PPPL
 - COORDINATION WITH OTHER DOE AND EPRI PROGRAMS

- BROAD PARTICIPATION BY FUSION COMMUNITY: ADVISORY COMMITTEE, WORKSHOPS

- SIGNIFICANT INTERNATIONAL PARTICIPATION
 - GERMANY (KFK), JAPAN (JAERI, UNIVERSITIES), CANADA
 - IMPORTANCE:
 - * ALL WORLD PROGRAMS FACE THE SAME ISSUES
 - * INTERNATIONAL COOPERATION ON NT: VIABLE, ECONOMICAL



FINESSE PRINCIPAL TECHNICAL TASKS

- I. IDENTIFICATION OF ISSUES AND REQUIRED NUCLEAR TESTS

- II. QUANTIFYING TEST REQUIREMENTS
 - A. REQUIREMENTS ON TEST CONDITIONS (E.G., WALL LOAD, FLUENCE, SIZE, BURN CYCLE, FIELD, ETC.)
 - B. ISSUES OF ENGINEERING SCALING
 - C. NEED FOR NEUTRONS AND INTEGRATED TESTING
 - D. BENEFITS FUNCTION OF TEST FACILITY PARAMETERS

- III. EVALUATION OF EXPERIENCE FROM OTHER TECHNOLOGIES
 - A. FISSION
 - B. AEROSPACE

- IV. SURVEY, EVALUATION OF NEUTRON-PRODUCING TEST FACILITIES (COST AND RISK FUNCTION OF TEST FACILITY PARAMETERS)
 - A. NON-FUSION DEVICES
 - B. FUSION DEVICES

- V. COMPARATIVE EVALUATION OF TEST FACILITIES, SCENARIOS

- VI. RECOMMENDATIONS ON FUSION NUCLEAR TECHNOLOGY DEVELOPMENT STRATEGY



NUCLEAR TECHNOLOGY ISSUES

- **COMPREHENSIVE CHARACTERIZATION OF FUSION NUCLEAR ISSUES AND TESTING NEEDS IS UNDERWAY (FINESSE)**

- **OBSERVATIONS:**
 - **ISSUES ARE TOO MANY TO LIST IN A BRIEF PRESENTATION**

 - **TESTING REQUIREMENTS ARE COMPLEX**

- **THE FOLLOWING ARE ONLY EXAMPLES**



BLANKET/FIRST WALL

- MANY DESIGN OPTIONS PROPOSED
- ALL OPTIONS HAVE POTENTIALLY CRITICAL FLAWS
- DEMONSTRATING THE VIABILITY OF A BLANKET:
 - CANNOT BE ASSURED
 - REQUIRES EXTENSIVE TESTING:
 - SEPARATE/MULTIPLE EFFECTS TESTS IN NON-FUSION FACILITIES
 - INTERACTIVE AND INTEGRATED TESTS WITH NEUTRONS IN THE TEST ENVIRONMENT (FUSION FACILITIES APPEAR TO BE NECESSARY)



CRITICAL FEASIBILITY ISSUES: LIQUID METAL BREEDING BLANKET

- **CORROSION**
 - RADIOACTIVE MASS TRANSFER/DEPOSITION
 - TEMPERATURE LIMIT AT LIQUID METAL/STRUCTURE INTERFACE
- **MHD (CIRCULATING OR DURING B-FIELD TRANSIENTS)**
 - HIGH PRESSURE/STRESS ON STRUCTURE
 - LARGE PUMPING/RECIRCULATING POWER
- **SAFETY**
 - LITHIUM: REACTIVITY WITH AIR AND WATER
 - LI-Pb: TRITIUM PERMEATION/CONTAINMENT
 - REQUIRE NON-H₂O COOLANT FOR LIMITER/DIVERTOR/RF
- **HYDRAULICS**
 - WITH HIGH HEAT FLUX: HIGH T (INTERFACE)/T (MEAN)
 - SOLUTION: FLOW MIXING - INCREASES MHD
- **TRITIUM BREEDING**
 - WITH LITHIUM (IMPOSSIBLE TO ELIMINATE INBOARD BLANKET)
 - (LI-Pb HAS THE HIGHEST BREEDING POTENTIAL)



CRITICAL FEASIBILITY ISSUES: SOLID BREEDER BLANKETS

- TRITIUM BREEDING
- TRITIUM INVENTORY IN SOLID BREEDER
- DESIGN PRACTICABILITY
 - LOW K, HIGH POWER DENSITY, NARROW ΔT
 - THERMAL CONDUCTANCE AT BREEDER/STRUCTURE INTERFACE
 - BREEDER PHYSICAL INTEGRITY AND CONTAINMENT
 - ABILITY TO ACCOMMODATE POWER VARIATION
 - LIFETIME LIMITATIONS (HIGH BURNUP, ETC.)
- TRITIUM FORM (T_2 , T_2O), PERMEATION
- ISSUES RELATED TO SPECIFIC SOLID BREEDERS, E.G., Li_2O
REACTIVITY WITH H_2O TO FORM $LiOH$, Li_2O SWELLING
- ISSUES RELATED TO SPECIFIC COOLANT, E.G.:
 - H_2O : TRITIUM PERMEATION/REMOVAL
FAILURE RATE OF HIGH PRESSURE CONTAINMENT
 - He : LEAKAGE OF TRITIUM CONTAMINATED He
FIRST WALL COOLING
HIGH OPERATING TEMPERATURE
- ISSUES RELATED TO STRUCTURAL MATERIALS:
 - AUSTENITIC: HIGH THERMAL STRESS, RADIATION DAMAGE,
ACTIVATION
 - FERRITIC: WELD PROCEDURE, DBTT, FERROMAGNETIC EFFECTS,
ACTIVATION
 - VANADIUM: SPARSE DATA, WELD PROCEDURE, OXIDATION AT
HIGH TEMPERATURE, TRITIUM PERMEATION, NOT
COMPATIBLE WITH HELIUM OR WATER



TYPES OF TESTS IN TECHNOLOGY DEVELOPMENT

- BASIC TESTS (SPECIMEN)
 - BASIC DATA

- SEPARATE-EFFECT TESTS (SPECIMEN, ELEMENT)
 - SIMULATION OF ONE ENVIRONMENT CONDITION
 - PHENOMENOLOGICAL, VERIFY SINGLE-EFFECT PREDICTION CAPABILITY

- MULTIPLE/INTERACTIVE EFFECTS TESTS (ELEMENT, SUBMODULE)
 - SIMULATION OF INTERACTION AMONG 1) TWO OR MORE ENVIRONMENTAL CONDITIONS (E.G., B, T, ϕ) AND/OR 2) TWO OR MORE COMPONENT ELEMENTS (E.G., BREEDER/CLAD)
 - VERIFY PREDICTION CAPABILITY FOR SPECIFIC INTERACTIONS

- INTEGRATED TESTS (MODULE, VARIOUS SCALES)
 - ALL ENVIRONMENT ELEMENTS AND INTERACTIVE EFFECTS
 - DISCOVER "UNKNOWN"
 - FAILURES, FIXES
 - DATA BASE AND INITIAL VERIFICATION OF A DESIGN CONCEPT

- COMPONENT TESTS (FULL SCALE)
 - COMPONENT TESTED IN ACTUAL OPERATION
 - STAGES FOR DESIGN VERIFICATION AND RELIABILITY GROWTH
 - * TEST/DEVELOPMENTAL REACTORS
 - * PROTOTYPE
 - * NEAR-COMMERCIAL



EXAMPLES OF INTERACTIVE EFFECTS
REQUIRING SUBMODULE OR MODULE TESTS
(FOR SOLID BREEDER BLANKETS)

BREEDER/INTERFACE/CLAD INTERACTIONS

- DIMENSIONAL CHANGES (E.G., SWELLING) RESULT IN A) LOADS, POSSIBLE FAILURE OF CLAD, B) CHANGE IN INTERFACE THERMAL CONDUCTANCE AFFECTING TEMPERATURE
- LITHIUM BURNUP MAY LEAD TO BREEDER/CLAD CHEMICAL INTERACTION

FRONT/BACK OF BREEDER PLATES

- HE PURGE DISTRIBUTION: CRACKING, SINTERING, AND LiO TRANSPORT MAY CLOG NARROW PURGE CHANNELS AT HOT END AND CAUSE PREFERENTIAL PURGE FLOW THROUGH COLDER SECTION
- T GETTERING: COLDER BACK REGION MAY BE SINK FOR T FROM HOT FRONT EXITING THROUGH COLD REGION
- GENERAL MECHANICAL BEHAVIOR: ASPECT RATIO, DEAD LOAD WEIGHT
- SLUMPING/SETTLING: CRACKING AND SUBSEQUENT SETTLING MAY ENHANCE LOCAL BREEDER/CLAD INTERACTION, INCREASE LOCAL T AND HEAT PRODUCTION, AND/OR CHANGE BREEDER/CLAD SPACING; SUBSEQUENT BALLOONING OR BUCKLING OF CLAD POSSIBLE; THIS ISSUE SENSITIVE TO ORIENTATION RELATIVE TO GRAVITY, POSSIBLY TO HEIGHT OF COLUMN
- LiO TRANSPORT: TRANSPORT FROM HOT TO COLD REGIONS MAY BE WELL SPREAD OUT IN FULL-DEPTH MODULE, BUT ACCUMULATE AT BACK OR LEAVE IN A TOO-SMALL PLATE
- COOLANT DISTRIBUTION: GEOMETRY CHANGES AT FRONT CAN REDIRECT COOLANT AND CAUSE BACK OF CHANNEL TO HAVE HOT SPOTS
- CLAD STRAIN: AVERAGED OVER ENTIRE DEPTH IF SOME SLIPPAGE, OR LOCALIZED IF NO SLIPPAGE



EXAMPLES OF INTERACTIVE EFFECTS
REQUIRING SUBMODULE OR MODULE TESTS
(FOR SOLID BREEDER BLANKETS)
(CONTINUED)

PLATE/PLATE INTERACTIONS

- **FLOW-INDUCED VIBRATIONS: ENHANCED OR CORRELATED VORTEX SHEDDING; CHANNEL/CHANNEL FLOW OSCILLATIONS**
- **BREEDER INSTABILITY: LOCAL HOT SPOT INDUCED BREEDER INSTABILITY MAY BE AMPLIFIED BY ADJACENT CHANNEL**
- **FLOW DISTRIBUTION: MIXING IN PLENUM AND DISTRIBUTION BETWEEN PLATES SHOULD BE UNIFORM, BUT MAY NOT BE BECAUSE OF MISALIGNMENT OR SWELLING, OR SIMPLY DUE TO DESIGN GEOMETRY**
- **PURGE DISTRIBUTION: CLOGGING IN ONE PLATE MAY CAUSE PREFERENTIAL HELIUM FLOW THROUGH ADJACENT PLATES; END PLATE MAY HAVE EXIT CLOGGED FROM ACCUMULATED CORROSION/BREEDER MATERIALS FROM PRECEDING PLATES**
- **TRITIUM BACK PRESSURE: HIGH TRITIUM CONCENTRATION AT EXIT MAY INHIBIT ADJACENT PLATE TRITIUM RECOVERY**
- **SINGLE PLATE BOWING: PLATE/PLATE TEMPERATURE DIFFERENCES MAY CAUSE DIFFERENTIAL SWELLING; SOME PLATES MAY BOW MORE THAN OTHERS LEADING TO SHAPE, AND SO FLOW, ASYMMETRIES OR STRESSES**
- **WIRE-WRAP SPACERS: EFFECTIVENESS IN MAINTAINING CHANNEL SPACING, HOLDING OVERALL BREEDER REGION SHAPE, DAMPING VIBRATIONS; DEGREE OF FRETTING**



EXAMPLES OF INTERACTIVE EFFECTS
REQUIRING SUBMODULE OR MODULE TESTS
(FOR SOLID BREEDER BLANKETS)
(CONTINUED)

FIRST WALL/BREEDER PLATES

- PLATE/FIRST WALL CONTACT: POSSIBLY HIGH LOCAL TEMPERATURES; CONDUCTIVE HEAT TRANSFER LEADING TO HEAT EXCHANGER EFFECT AND HIGHER FIRST WALL TEMPERATURE
- FIRST WALL BACKPLATE RUPTURE: NON-UNIFORM FLOW DISTRIBUTION IN BREEDER PLATES; LACK OF COOLING OF FIRST WALL

FIRST WALL CHANNEL/CHANNEL

- FLOW-INDUCED VIBRATIONS OR FLOW OSCILLATIONS: BUFFETING OR VIBRATION OF UPPER STRUCTURE; OSCILLATING HEAT TRANSFER AT TIP OF MODULE (STAGNATION POINT); CORRELATION LENGTH FOR VORTEX SHEDDING TYPICALLY 2-5 DIAMETERS BUT MAY SYNCHRONIZE OVER LARGER DISTANCES NEAR RESONANCE CONDITIONS



EXAMPLES OF INTERACTIVE EFFECTS
REQUIRING SUBMODULE OR MODULE TESTS
(FOR SOLID BREEDER BLANKETS)
(CONTINUED)

MODULE

- **TRITIUM BREEDING: DEPENDS ON EXACT MATERIAL AND GEOMETRICAL ARRANGEMENTS AND CHARACTERISTICS; HIGH LITHIUM BURNUP IN PARTS OF MODULE AFFECTS OVERALL BREEDING**

MODULE/MODULE

- **EXPANSION: STRESSES FROM AXIAL AND RADIAL EXPANSION LIMITED BY ADJACENT MODULES; ANY GAP WOULD BE SOURCE OF NEUTRON STREAMING AND ENHANCED LOCAL HEATING**
- **RUPTURE: EFFECT OF RUPTURED MODULE ON NEIGHBORS**
- **DEFORMATION: CREEP/STRESS RELAXATION CHANGING DIMENSIONS AND MAKING MAINTENANCE DIFFICULT**



EXAMPLES OF INTERACTIVE EFFECTS
REQUIRING SEVERAL ENVIRONMENTAL CONDITIONS
(AND SUBMODULE AND MODULE TESTS)
(FOR LIQUID METAL BLANKETS)

- HEAT TRANSFER COEFFICIENT DEPENDS ON BULK (NUCLEAR) HEATING
- STRESS-CORROSION CRACKING FAILURE MODE DEPENDS ON TEMPERATURE, STRESS FIELD, FLOW PROFILES, IMPURITY LEVELS, AND RADIATION ENVIRONMENT
- CORROSION MASS TRANSFER DEPENDENCE ON MHD FLOW PROFILES AND TEMPERATURE DISTRIBUTIONS
- CORROSION MASS TRANSFER RATE DEPENDENCE ON ENTRY LENGTHS: MASS TRANSFER, HEAT TRANSFER, AND MOMENTUM TRANSFER ENTRY LENGTHS ARE ALL RELEVANT
- THERMAL STRESS DEPENDENCE ON MHD TEMPERATURE PROFILES
- PRESSURE STRESS DEPENDENCE ON MHD PRESSURE DROP
- MHD PRESSURE DROP DEPENDENCE ON TEMPERATURE GRADIENTS, ADJACENT CHANNELS, GEOMETRY, MAGNETIC FIELD (B , \dot{B}), HEATING, ETC.
- MATERIALS RESPONSE TO STRESS DEPENDENCE ON RADIATION, TEMPERATURE FIELD, AND CYCLIC BEHAVIOR



TESTING REQUIREMENTS FOR FAILURE MODES

FAILURE MODE	MATERIAL TESTING	COMPONENT TESTING	NEUTRON ENVIRONMENT
1. CRACK AROUND DISCONTINUITY/WELD	N	Y	Y
2. CRACK ON SHUTDOWN (WITH COOLING)	N	Y	Y
3. BREEDER DISINTEGRATES/CRACKS	Y	N	Y
4. FIRST WALL/BREEDER/STRUCTURE SWELLING AND CREEP LEADING TO EXCESSIVE DEFORMATION OR FIRST WALL/COOLANT TUBE FAILURE	N	Y	Y
5. CRACK DURING OPERATION (FIRST WALL/BREEDER/STRUCTURE)	N	Y	N
6. ENVIRONMENTALLY ASSISTED CRACKING	Y	N	N
7. CRACK ON START-UP (FIRST WALL/BREEDER/STRUCTURE)	Y	N	Y
8. EXCESSIVE TRITIUM PERMEATION OF COOLANT TUBES	Y	N	Y
9. FIRST WALL/BREEDER/STRUCTURE MELTING	Y	N	Y
10. MANIFOLD TUBE BREAKS	N	Y	N
11. INSUFFICIENT TRITIUM DIFFUSION THROUGH BREEDER	Y	N	Y

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**NEUTRONS ARE NECESSARY FOR MEANINGFUL
INTERACTIVE AND INTEGRATED TESTING**

- **NEUTRONS REPRESENT THE ONE INGREDIENT IN THE FUSION ENVIRONMENT THAT:**
 - **IS MOST HARSH**
 - **PRODUCES LARGEST SINGLE AND INTERACTIVE EFFECTS/CHANGES**
 - **CAUSES NUMEROUS CRITICAL FEASIBILITY ISSUES**
 - **IS LEAST UNDERSTOOD**

- **THERE ARE NO SUBSTITUTES FOR NEUTRONS:**
 - **HEATING (CORRECTNESS OF SIMULATION, ECONOMICS)**
 - **RADIATION EFFECTS (MUST)**
 - **SPECIFIC REACTIONS (MUST)**



IMPORTANCE OF NEUTRONS FOR BLANKET/FIRST WALL TESTS

HEATING

- TEMPERATURE DISTRIBUTION IN BREEDER, MULTIPLIER, STRUCTURE AND INTERFACES
 - THERMAL STRESSES
 - THERMALLY ACTIVATED RESTRUCTURING
 - TRITIUM RECOVERY
 - OTHERS
 - "UNKNOWN"
- EXAMPLES OF UNEXPECTED EFFECTS:
 - HEAT TRANSFER COEFFICIENT IN LIQUID METALS DEPENDS ON BULK HEATING

SPECIFIC REACTIONS

- TRITIUM
- HELIUM
- ATOMIC DISPLACEMENTS
- TRANSMUTATIONS
- TRITIUM RECOVERY IN THE PRESENCE OF OTHER NEUTRON EFFECTS
- TRITIUM PERMEATION AND CONTAINMENT
- HELIUM BUBBLE FORMATION RATE, EFFECTS IN LIQUID METALS
- ACTIVATION AND CORROSION PRODUCTS TRANSPORT
- TRITIUM AND HELIUM HOLDUP AND EFFECTS IN ALL ELEMENTS
- LIOT TRANSPORT (IN Li_2O)



IMPORTANCE OF NEUTRONS
FOR BLANKET/FIRST WALL TESTS
(CONTINUED)

MATERIALS DAMAGE

- RADIATION-INDUCED CHANGES IN BASIC PROPERTIES (E.G., THERMOPHYSICAL) IN SOLID BREEDERS, MULTIPLIERS AND STRUCTURE
- RADIATION-INDUCED DIMENSIONAL CHANGES IN SOLID BREEDERS, MULTIPLIERS AND STRUCTURE (SWELLING, CREEP, ETC.)
- RADIATION-INDUCED EMBRITTLEMENT IN STRUCTURE
- NUMEROUS RADIATION EFFECTS IN SOLID BREEDERS CRITICAL TO TRITIUM RELEASE/RETENTION
- RADIATION EFFECTS IN STRUCTURE INFLUENCING TRITIUM PERMEATION/INVENTORY
- RADIATION-INDUCED SENSITIVITY OF STRESS-CORROSION
- RADIATION EFFECTS IN WELDS, JOINTS
- RADIATION DAMAGE TO INSTRUMENTATION
- MANY OTHER KNOWN EFFECTS
- UNKNOWNNS



IMPORTANCE OF NEUTRONS FOR OTHER (NON-BLANKET) COMPONENTS TESTS

SHIELDING

- MANDATORY FOR RADIATION TRANSPORT/STREAMING TESTS

IMPURITY CONTROL AND EXHAUST

- NEUTRON ENVIRONMENT AT PLATES AS HARSH AS THE FIRST WALL
- RADIOACTIVE EROSION PRODUCTS TRANSPORT
- RADIATION EFFECTS IN CRYOPUMPS

AUXILIARY HEATING

- ANTENNA, WAVEGUIDES, ETC.: MANY RADIATION EFFECTS AS THE FIRST WALL
- ADDITIONAL EFFECTS IN SUPPLEMENTARY SUBSYSTEMS, E.G., CRYOPANELS, COAXIAL CABLES

SUPERCONDUCTING MAGNETS

- DEGRADATION OF MECHANICAL AND DIELECTRIC PROPERTIES OF INSULATORS
- INCREASE IN ELECTRICAL RESISTIVITY OF STABILIZER
- REDUCTION IN CRITICAL CURRENT DENSITY OF SUPERCONDUCTOR

INSTRUMENTATION AND CONTROL

- RADIATION EFFECTS, HEATING IMPEDING PROPER FUNCTIONING



NEUTRON-PRODUCING FACILITIES

- ACCELERATOR-BASED "POINT" SOURCES
- FISSION REACTORS
- FUSION REACTORS

POINT NEUTRON SOURCES

- NECESSARY/USEFUL FOR SPECIFIC PURPOSES
 - RADIATION EFFECTS IN CAPSULES (FLUENCE)
 - NEUTRONICS (TRITIUM BREEDING, SHIELDING)
- NOT SUITABLE FOR MULTIPLE-EFFECT/INTEGRATED TESTS

FISSION REACTORS

- LARGER (BUT LIMITED) VOLUME THAN POINT SOURCES
- SUITABLE FOR CAPSULE AND SOME SUBELEMENT TESTS
- ARE BEING USED AND WE NEED TO CONTINUE TO USE THEM
- BUT, THEY CANNOT SUBSTITUTE FOR FUSION TESTING
 - LIMITATIONS ON VOLUME
 - LIMITATIONS ON SIMULATING ENVIRONMENT ELEMENTS (E.G., ELECTROMAGNETIC)
 - LIMITATIONS ON SIMULATING ENVIRONMENTAL PARAMETERS (E.G., POWER DENSITY, SPATIAL/TIME DEPENDENCE, ETC.)
 - SPECTRAL DIFFERENCES FROM FUSION NEUTRONS



IN-CORE TEST LOCATIONS IN EXISTING FISSION REACTORS

MAXIMUM FLUX $n \cdot cm^{-2} \cdot s^{-1}$	MAXIMUM SIZE				
	5 cm	7.5 cm	10 cm	12.5 cm	15 cm
$5 \times 10^{12} - 5 \times 10^{13}$	13 (23)	13 (23)	3 (13)	1 (1)	1 (1)
$5 \times 10^{13} - 5 \times 10^{14}$	118 (223)	93 (115)	17 (36)	5 (17)	1 (10)
$5 \times 10^{14} - 5 \times 10^{15}$	9 (29)	9 (26)	9 (26)	9 (26)	0 (16)
7.5×10^{15}	40 (40)	4 (4)	4 (4)	1 (1)	0 (0)

SLAB-TYPE TEST LOCATIONS IN EXISTING FISSION REACTORS

MAXIMUM FLUX $n \cdot cm^{-2} \cdot s^{-1}$	MAXIMUM SIZE				
	25 cm	50 cm	75 cm	100 cm	150 cm
$5 \times 10^{13} - 5 \times 10^{14}$	7 (11)	1 (4)	0 (2)	0 (1)	0 (1)

NOTES

- NUMBERS IN TABLES REFER TO NUMBER OF AVAILABLE TEST LOCATIONS IN U.S. REACTORS. THE NUMBERS IN PARENTHESES REFER TO THE NUMBER OF TEST LOCATIONS IN U.S. AND FOREIGN REACTORS.
- NEUTRON FLUX AT THE FIRST WALL OF A FUSION REACTOR IS $\sim 4 \times 10^{14} n \cdot cm^{-2} \cdot s^{-1}$ FOR $1 MW/m^2$. THE FISSION REACTOR FLUX CONTAINS A LARGE THERMAL NEUTRON COMPONENT.



**TYPICAL NEUTRON FLUX AT FIRST WALL
(Li₂O/HT-9/He, TOKAMAK^A)**

ENERGY RANGE (MEV)	FLUX ^B (cm ⁻² ·s ⁻¹)	FRACTION
13.5-14.9	8.472×10^{13}	0.215
10.0-14.9	9.489×10^{13}	0.240
4.5-14.9	1.154×10^{14}	0.292
1.35-14.9	1.570×10^{14}	0.398
0.166-14.9	2.588×10^{14}	0.655
TOTAL	3.948×10^{14}	1.0

^APLASMA RADIUS = 253 CM
 VACUUM GAP = 20 CM
 FIRST WALL RADIUS = 275 CM

^BNORMALIZED TO 1 MW/M² WALL LOADING
 (NEUTRON CURRENT = 4.426×10^{13} N/SEC·CM²)

^CGAMMA RAY TOTAL FLUX = 1.777×10^{14} (γ/SEC·CM²)



FUSION AND FISSION NEUTRON SPECTRUM

ENERGY (MeV)	FRACTION OF FLUX	
	FUSION	FISSION
> 10	0.24	~ 0
> 4.5	0.29	0.013
> 1.35	0.40	0.16
> 0.166	0.65	0.48
> 0	1.0	1.0

FIRST WALL DAMAGE INDICATOR AT 1 MW·Y/M ² EXPOSURE		FIRST WALL FLUX (CM ⁻² ·S ⁻¹)	REQUIRED FLUX (CM ⁻² ·S ⁻¹) IN FISSION REACTOR
DPA	11	4 x 10 ¹⁴	1.1 x 10 ¹⁵
He	203	4 x 10 ¹⁴	1.3 x 10 ¹⁷

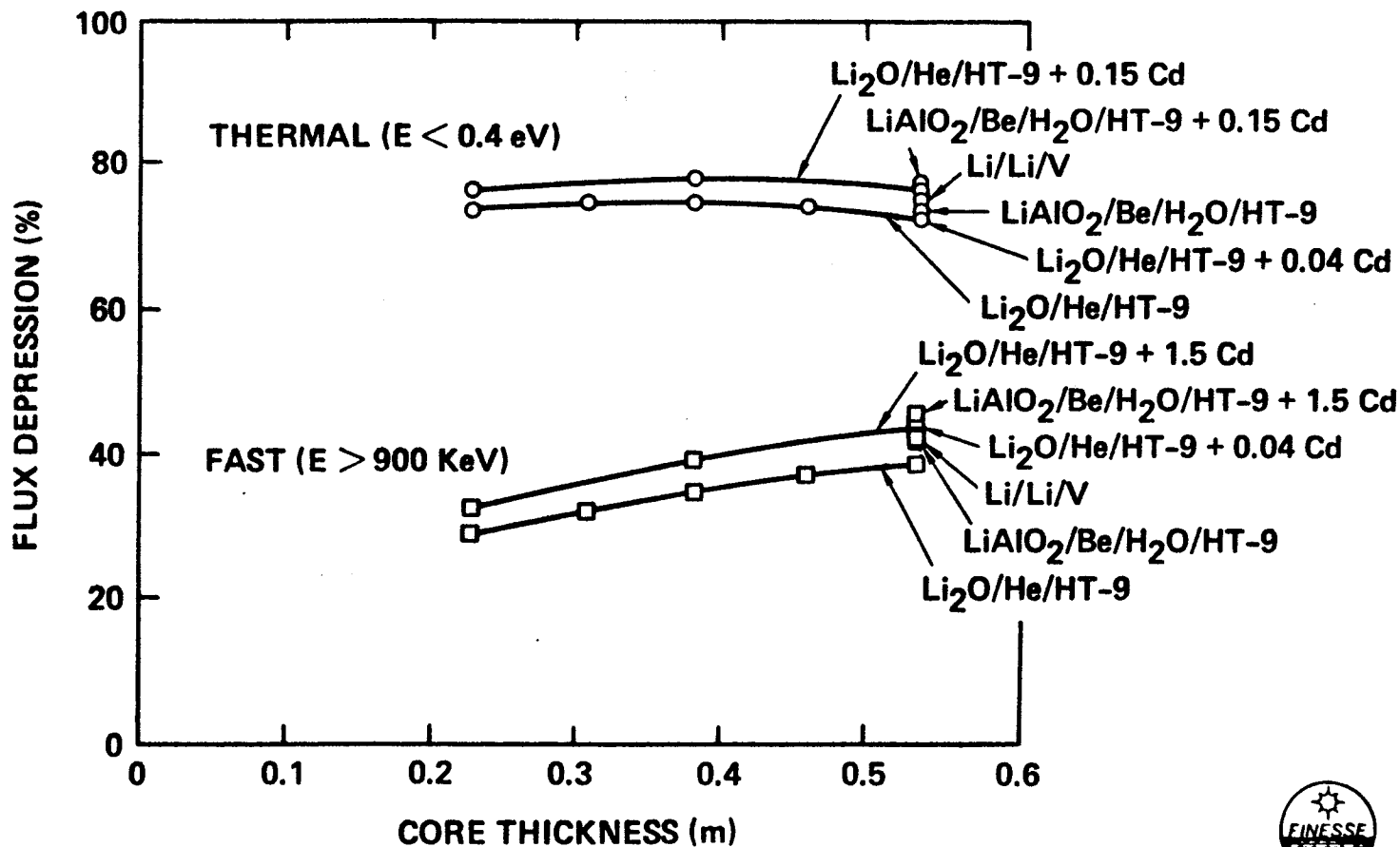


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FISSION REACTORS

FLUX DEPRESSION vs. CORE THICKNESS

$$\text{FLUX DEPRESSION} = 1 - \frac{(\phi_p/\phi_e) \text{ UNPERTURBED}}{(\phi_p/\phi_e) \text{ PERTURBED}}$$



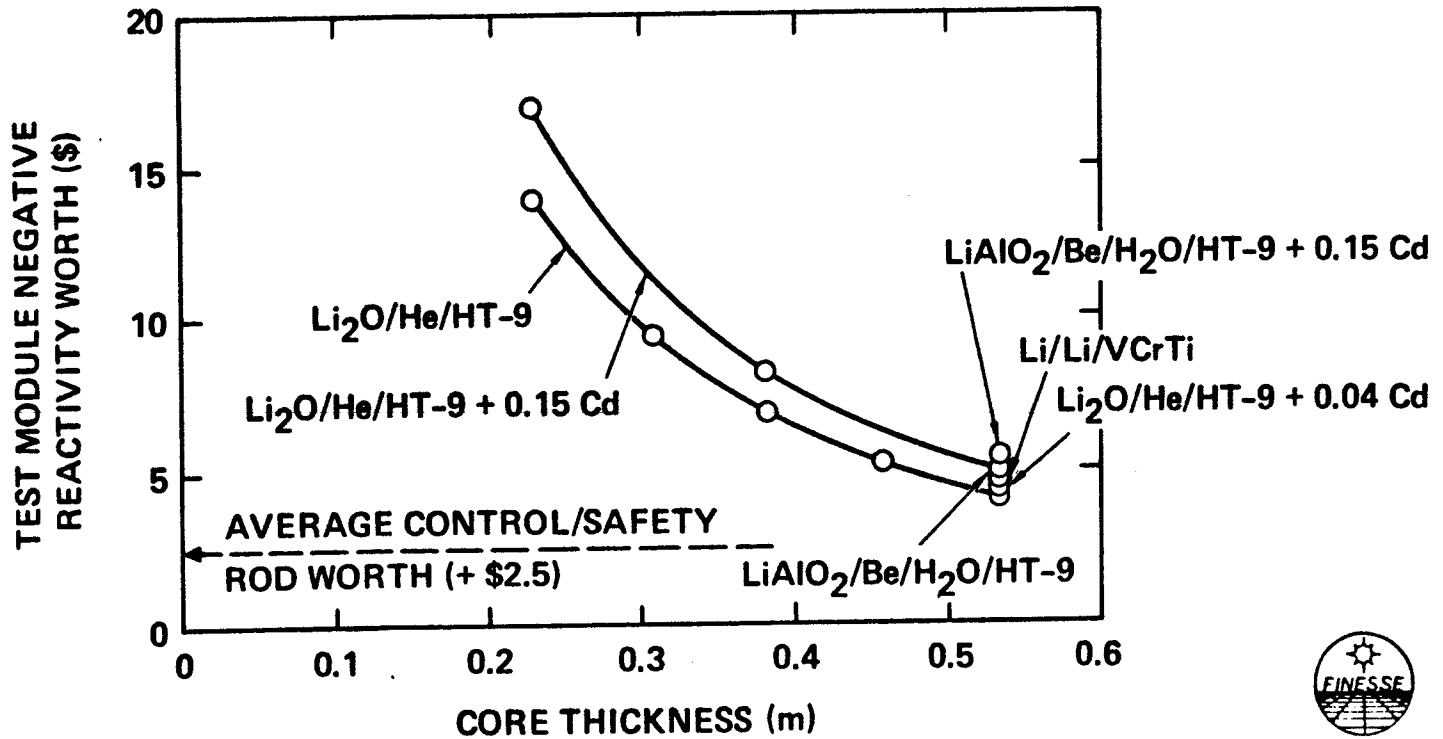
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FISSION REACTORS

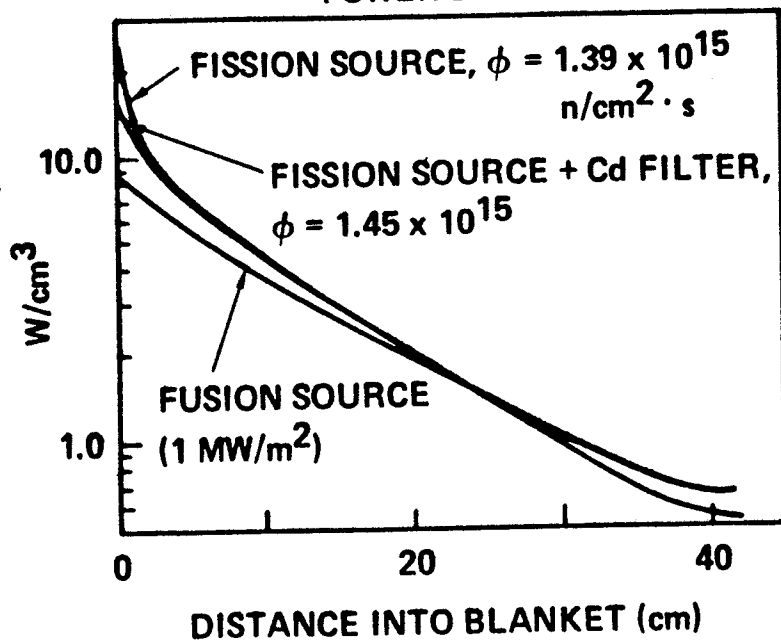
IMPACT OF SLAB TEST MODULE
PLACED AT THE SIDE OF FISSION REACTOR
ON CORE CRITICALLY



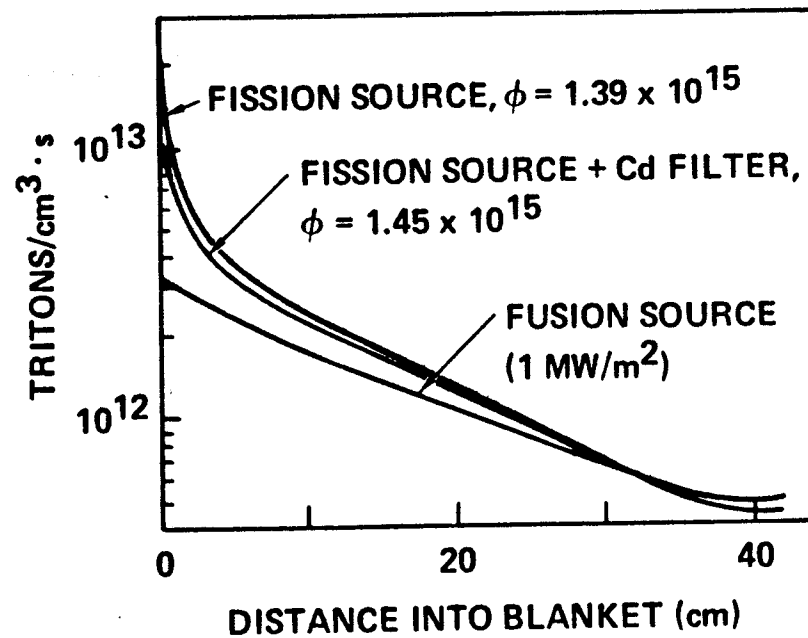
FISSION REACTORS: POWER DENSITY AND TRITIUM PRODUCTION PROFILES

- SIGNIFICANT SELF-SHIELDING EFFECTS IN FIRST SEVERAL CENTIMETERS, NOT GREATLY IMPROVED BY ADDITION OF Cd FILTER
- POWER DENSITY AND TRITIUM PRODUCTION RATES ARE LIMITED TO THAT EQUIVALENT TO $\sim 1 \text{ MW/m}^2$

POWER DENSITY



TRITIUM PRODUCTION



FUSION FACILITIES FOR
TESTING NUCLEAR COMPONENTS

ARE THEY NEEDED?

WE HAVE NOT YET FOUND AN ALTERNATIVE TO SATISFYING THE IDENTIFIED
CRITICAL TESTING NEEDS

WHY?

- VOLUME/SURFACE AREA OF TEST ELEMENT/MODULE
SOME TESTS REQUIRE: ~ 1 M X 1 M X 0.5 M
OBTAINABLE ONLY IN FUSION TEST DEVICE
- TOTAL VOLUME/SURFACE AREA OF TEST MATRIX
NEED: UNIFORM STEADY NEUTRON SOURCE WITH 2×10^{18} - 10^{19} n/s
OBTAINABLE ONLY IN FUSION REACTOR
- SIMULATION OF ALL ENVIRONMENT CONDITIONS
 - NEUTRONS
 - ELECTROMAGNETICS
 - PLASMA PARTICLES
 - TRITIUM
 - VACUUM
- NEUTRON SPECTRUM
 - 14 MEV SOURCE NEUTRONS
 - COMPLEX "SLOWING DOWN/BACKSCATTERING" SPECTRUM



FUSION NUCLEAR ENGINEERING TEST DEVICE
KEY TESTING/COST PARAMETERS

MAJOR PARAMETERS THAT ARE:

- CRITICAL TO SUCCESSFUL TESTING
- DRIVERS ON TESTING DEVICE COST

1. NEUTRON WALL LOAD (POWER DENSITY)
2. SURFACE HEAT LOAD
3. FLUENCE (FLUENCE ~ WALL LOAD X LIFETIME X AVAILABILITY)
4. MINIMUM CONTINUOUS (100% AVAILABILITY) OPERATING PERIOD
5. PLASMA BURN CYCLE (BURN/DWELL TIME)
6. MAGNETIC FIELD STRENGTH
7. SURFACE AREA FOR TESTING:
 - SURFACE AREA FOR TESTING ELEMENT
 - TEST MATRIX
8. VOLUME FOR TESTING:
 - DEPTH OF TEST ELEMENT
 - TEST MATRIX



ACT-ALIKE TEST MODULES ARE NECESSARY

BUT:

- THEY INVOLVE COMPLEX ENGINEERING ISSUES
- THEY ARE NEVER PERFECT

SIMPLE EXAMPLES

- AT LOWER q_s , P_{NW} : INCREASE STRUCTURE THICKNESS TO INCREASE (PRESERVE) THERMAL STRESSES
 - HOOP STRESS: LOWER AT LARGER THICKNESS
CAN PRESERVE TOTAL STRESS?
 - TEMPERATURE GRADIENT: CANNOT BE PRESERVED
IMPORTANT?
- AT LOWER q_s , P_{NW} : INCREASE SOLID BREEDER PLATE THICKNESS, PRESERVE TEMPERATURE WINDOW FOR TRITIUM RECOVERY
 - TRITIUM PRODUCTION RATE: LOWER
IMPORTANT FOR T RECOVERY?
EFFECT ON TBR
- LIMITED SIZE FOR LIQUID METAL BLANKET TEST: SHORTEN BLANKET TEST MODULE; BUT, TEMPERATURES AND FLUID FLOW ARE NOT ALWAYS FULLY DEVELOPED IN FUSION LIQUID METAL BLANKETS; MANY IMPORTANT PARAMETERS (E.G., HEAT TRANSFER COEFFICIENT, MHD PRESSURE DROP, ETC.) SENSITIVE TO GEOMETRY (ALSO TO B FIELD, NUCLEAR HEATING)
- CYCLING, BURN AND DWELL TIMES SUBSTANTIALLY ALTER MANY EFFECTS: TIME TO REACH EQUILIBRIUM, VALUES AT QUASI-EQUILIBRIUM, FAILURE MODES, ETC.



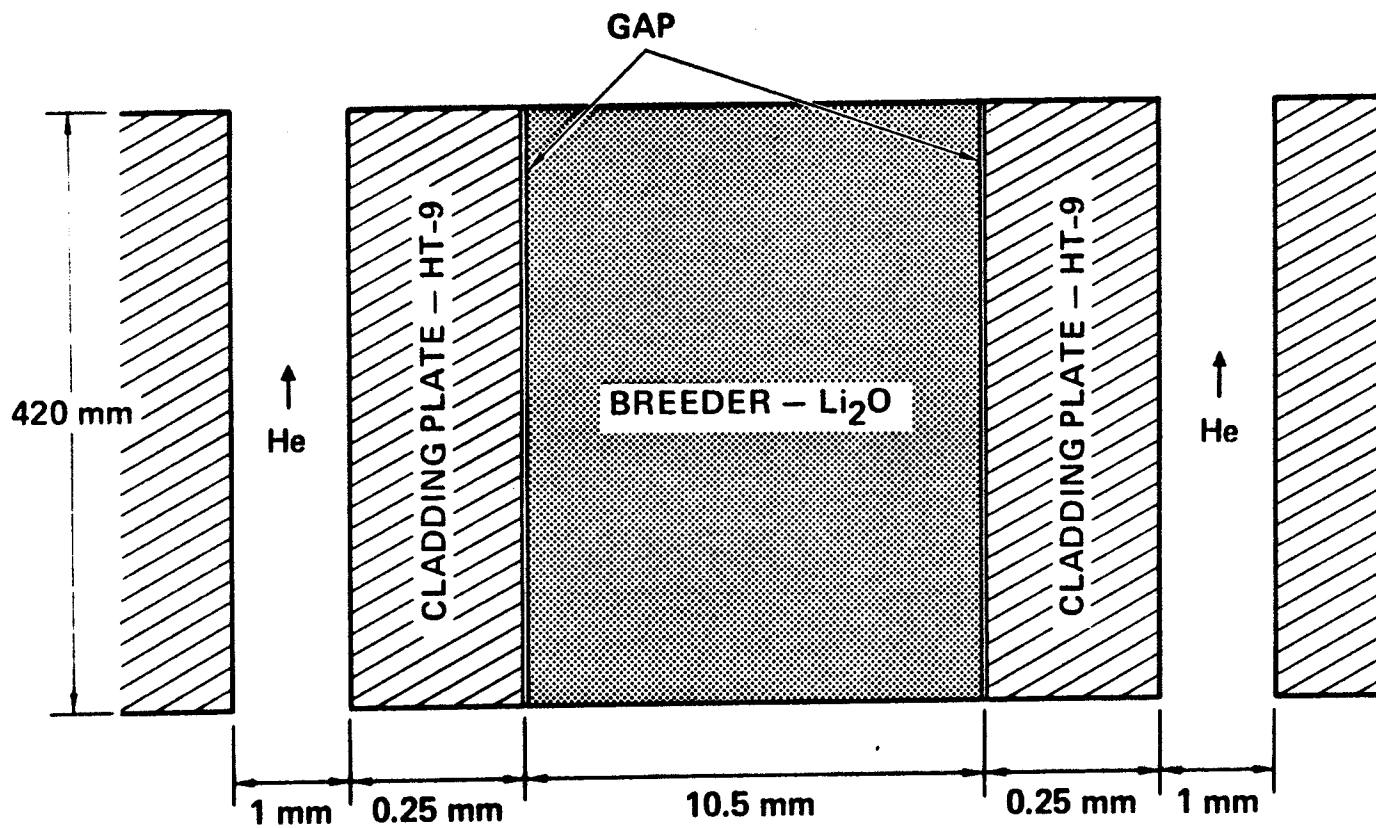
**LOOK-ALIKE TEST MODULES
DO NOT PROVIDE MEANINGFUL INFORMATION
UNDER SCALED-DOWN CONDITIONS**

EXAMPLES

- THERMAL STRESSES ARE NOT MAINTAINED AT LOWER VALUES OF SURFACE HEAT FLUX (q_s) AND/OR NEUTRON WALL LOAD (P_{NW})
- TRITIUM TRANSPORT, INVENTORY ALTERED BECAUSE OF DIFFERENT q_s , P_{NW} , TEMPERATURE PROFILES
- CYCLING, BURN AND DWELL TIMES AFFECT TIME TO REACH QUASI-EQUILIBRIUM, TEMPERATURES, STRESSES, TRITIUM RECOVERY, ETC.
- CORROSION RATES AND FLUID FLOW CHARACTERISTICS CANNOT BE MAINTAINED AT LOWER q_s , P_{NW} , TEMPERATURE
- TOTAL AND RELATIVE CONTRIBUTIONS TO MHD PRESSURE DROP ARE SENSITIVE TO MAGNETIC FIELD AND VELOCITY AND TEMPERATURE PROFILES (DEPEND ON q_s AND P_{NW})



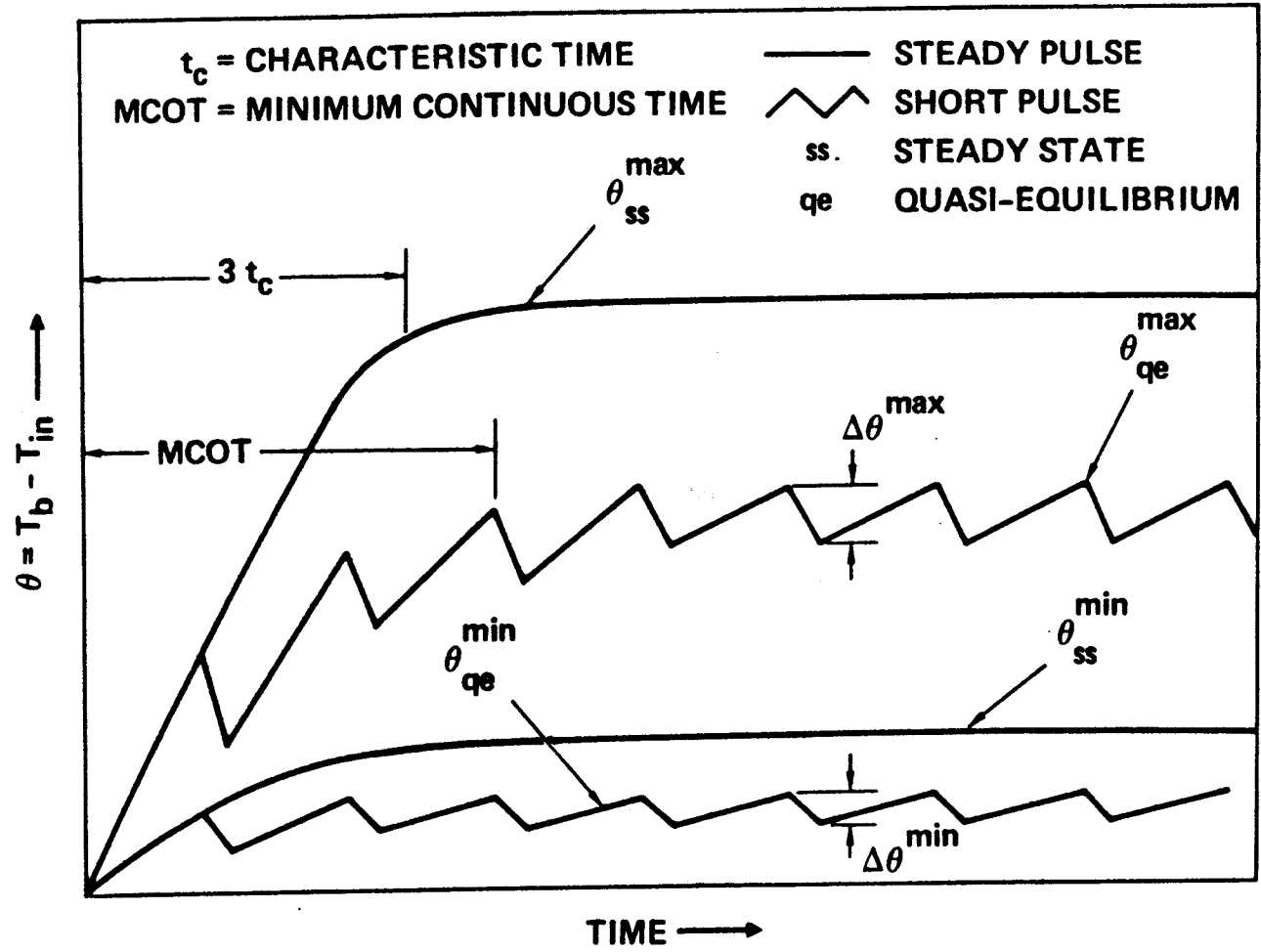
BLANKET MODEL



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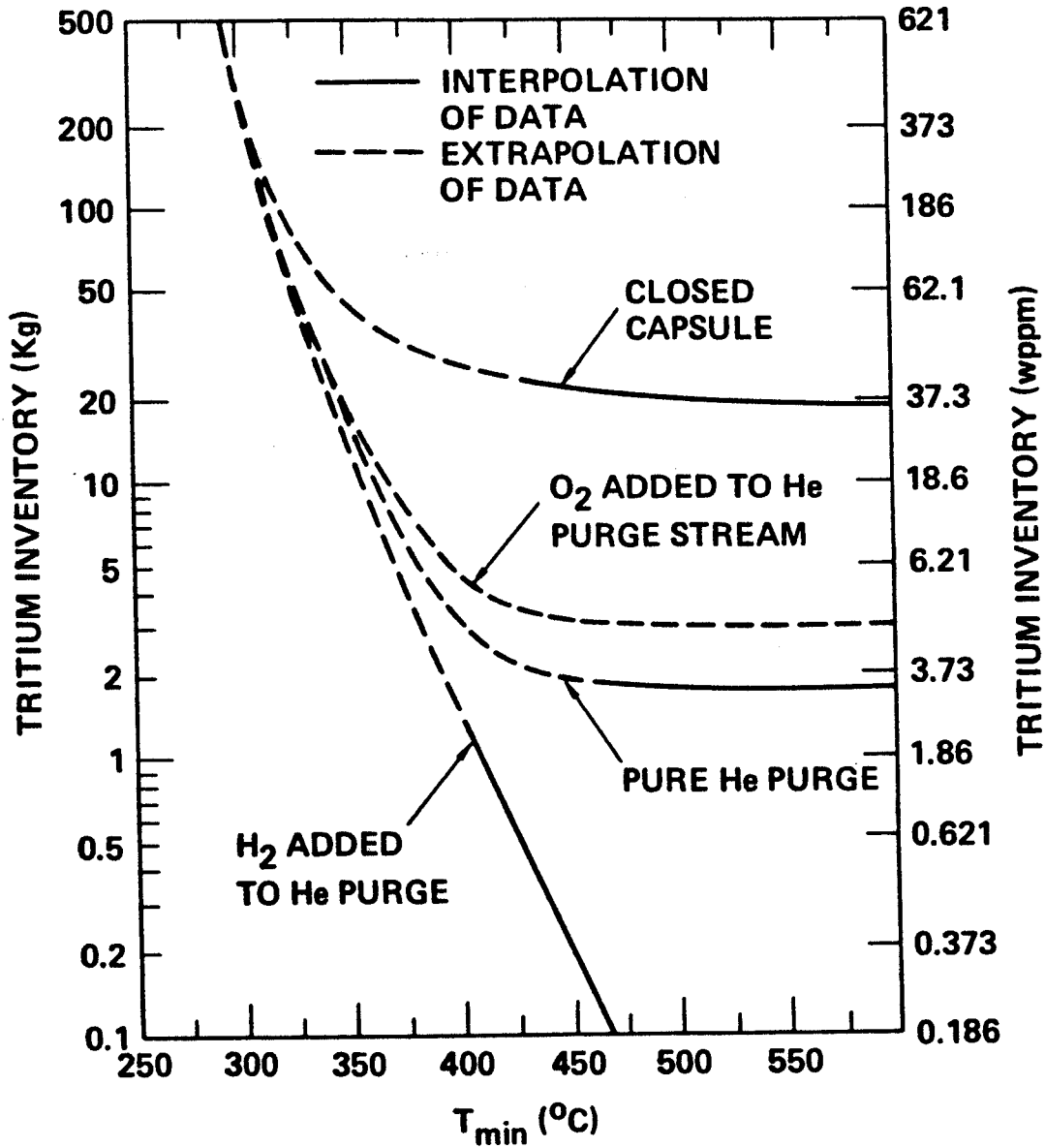


$$t_c = \frac{\rho_b C_{pb} \delta_b \left(\frac{2}{3} + \frac{2k_b}{h\delta_b} \right)}{h \frac{2k_b}{h\delta_b}}$$

$$\theta_{qe} = \theta_{ss} \frac{1 - e^{-t_b/t_c}}{1 - e^{-(t_b + t_d)/t_c}}$$

$$\Delta\theta = \theta_{qe} (1 - e^{-t_d/t_c})$$



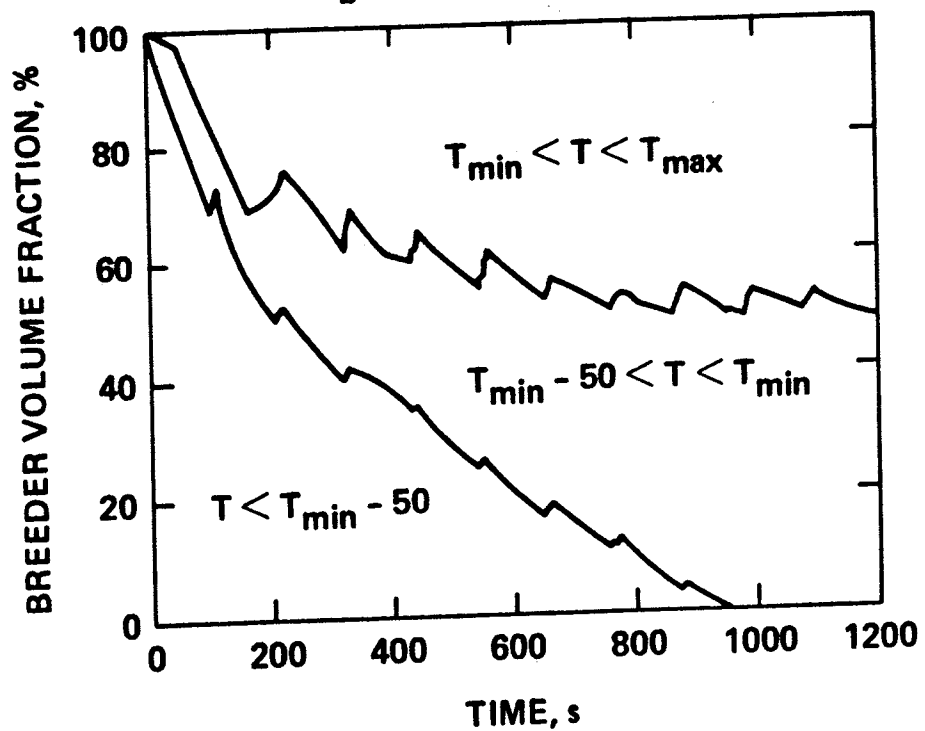


Model predictions for tritium inventory as a function of the minimum blanket temperature for the BCSS (LOBE-2B) $\text{LiAlO}_2/\text{H}_2\text{O}/\text{Be}/\text{HT-9}$ blanket. A maximum temperature of 950°C and a tritium generation rate of 866 g/day are assumed.

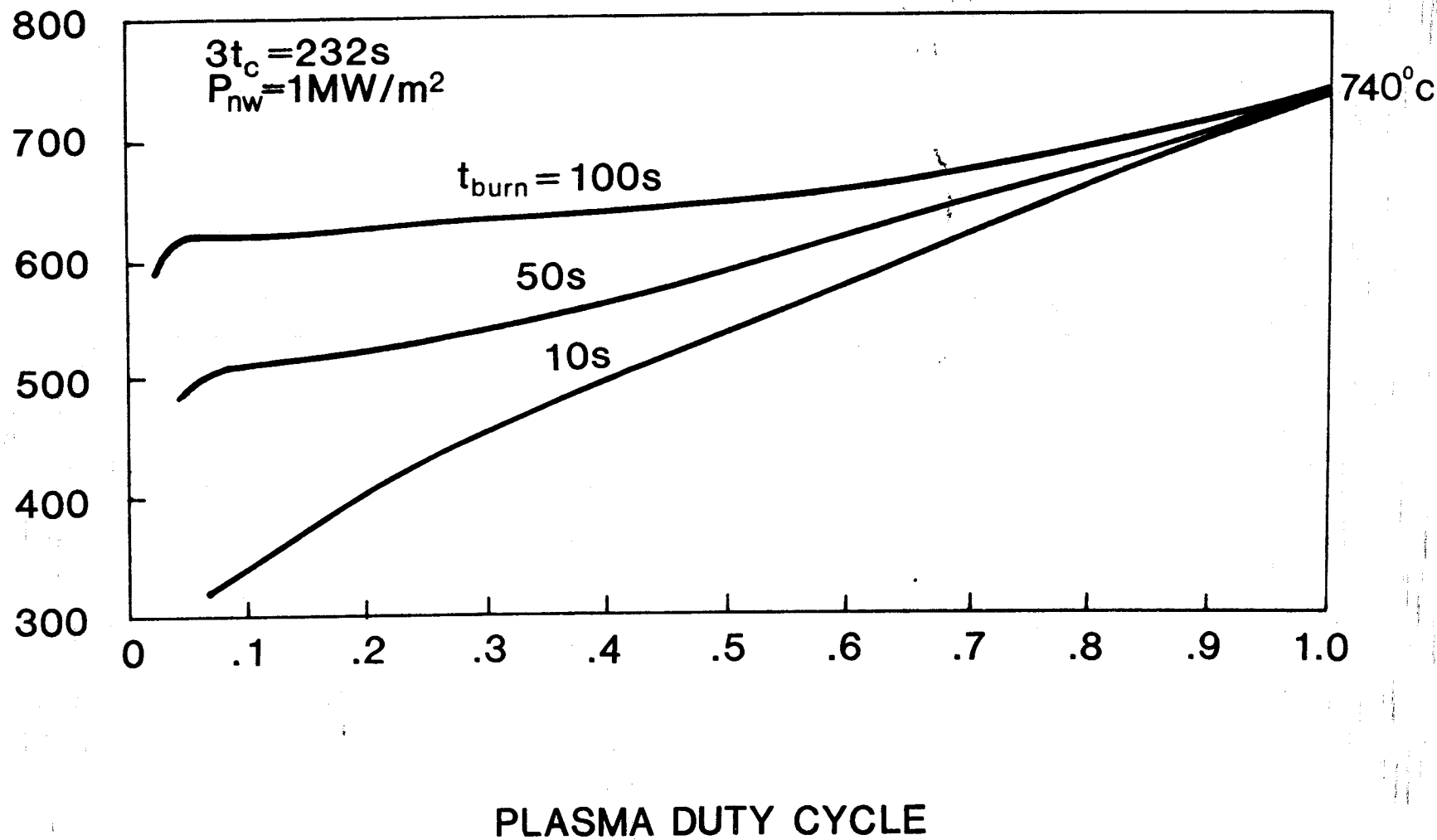


PULSING IMPACTS TESTING THE DEPENDENCE
OF TRITIUM RECOVERY ON TEMPERATURE

($t_b = 100$ s, $t_d = 10$ s)

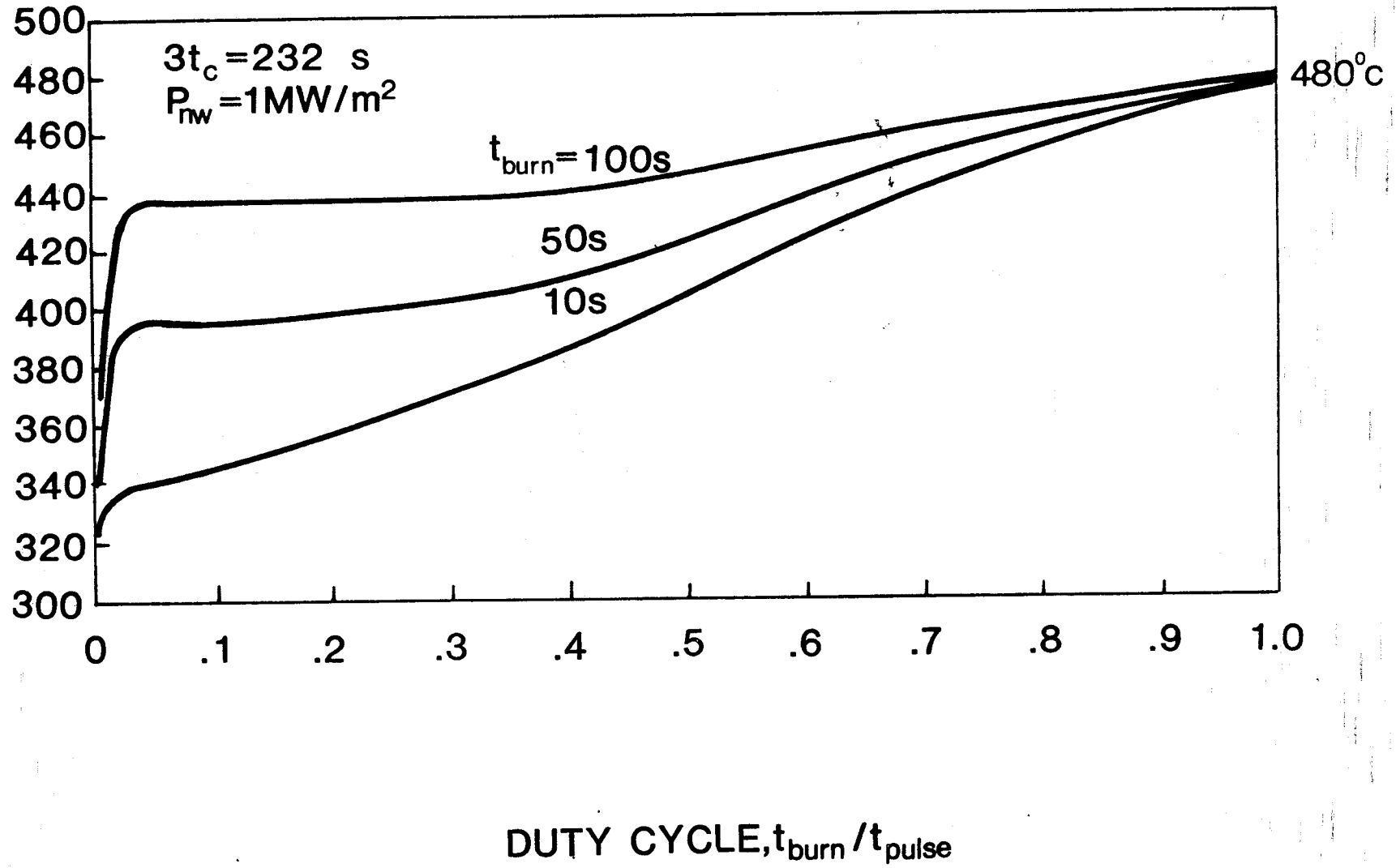


Dependence of Breeder Maximum Temperature on Plasma Duty Cycle and Burn Time



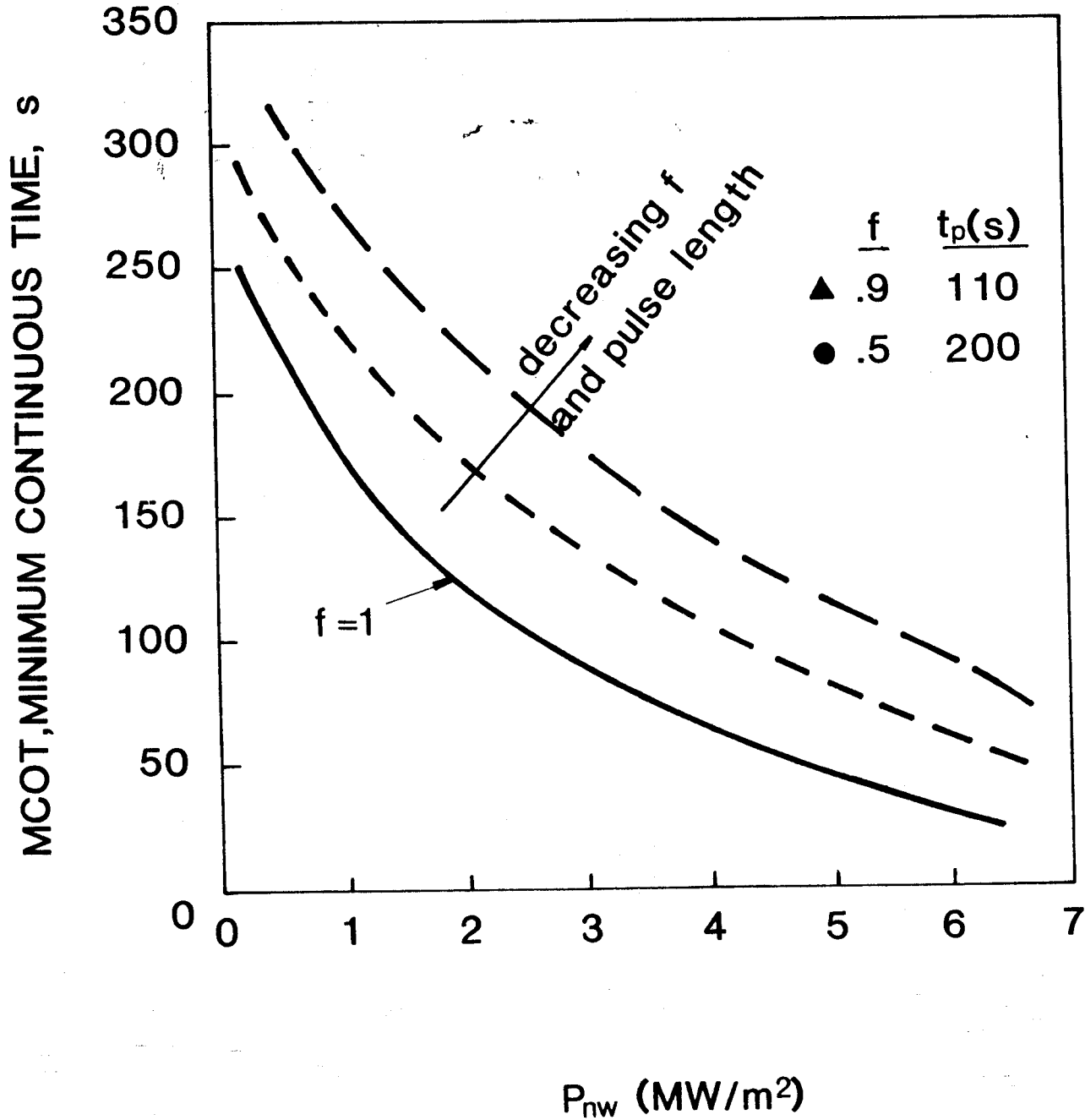
Dependence of Breeder Minimum Temperature On Plasma Duty Cycle and Burn Time

MINIMUM TEMPERATURE AT QUASI-EQUILIBRIUM, °C

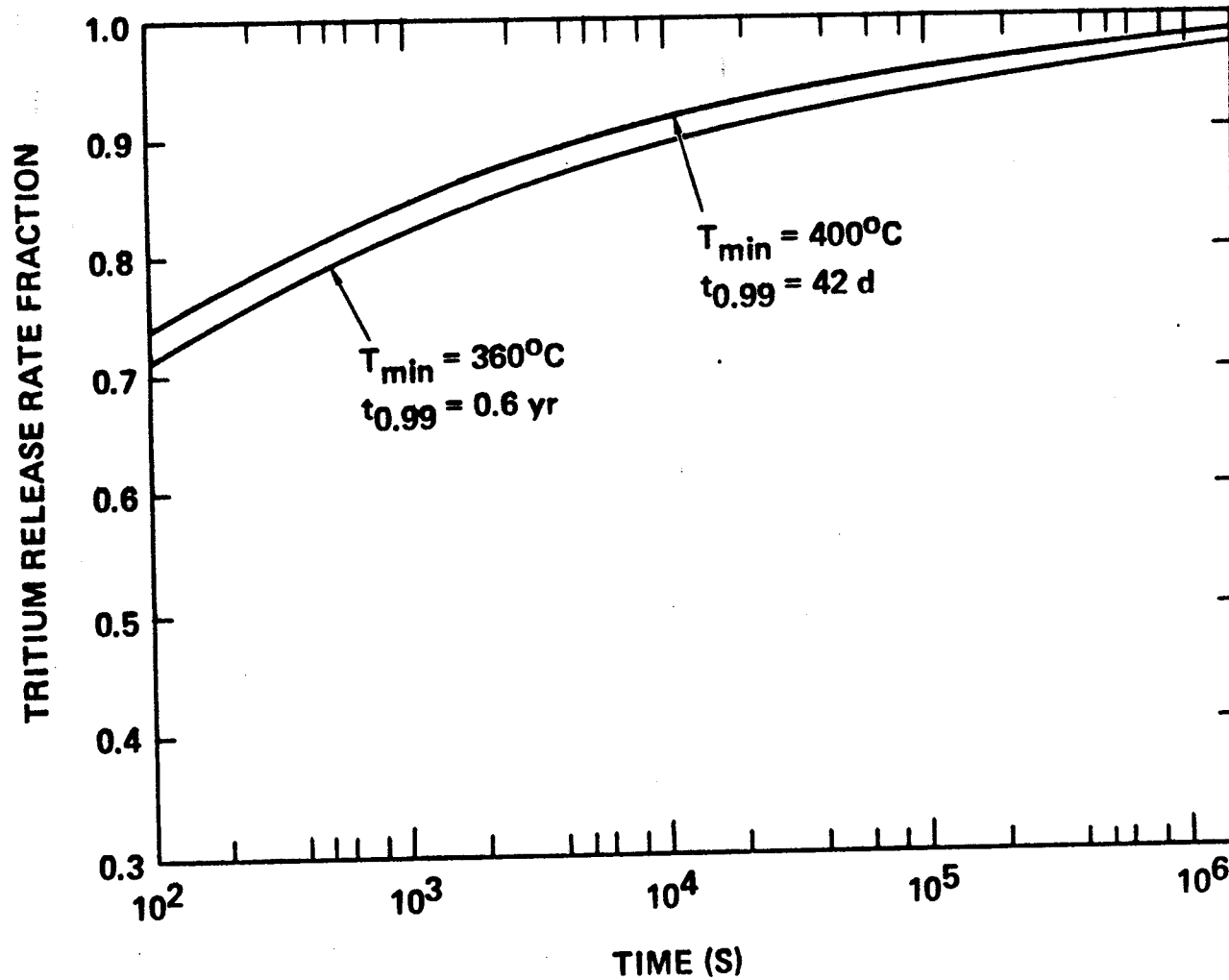


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Minimum Continuous Time To Reach Quasi-Equilibrium Increases With 1) lower wall load, 2) lower duty cycle, 3) shorter burn



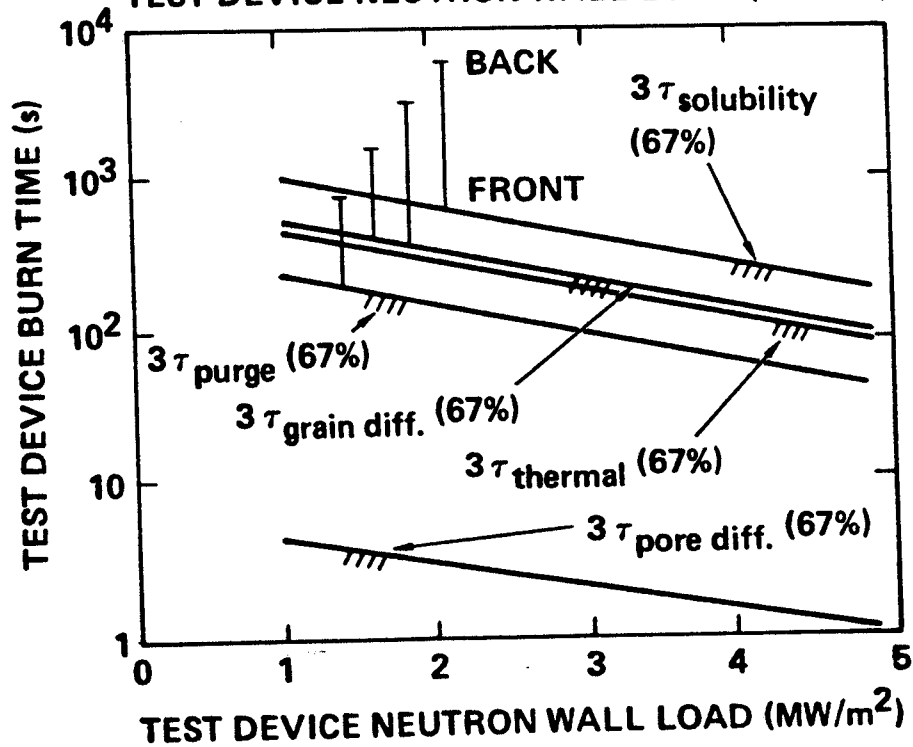
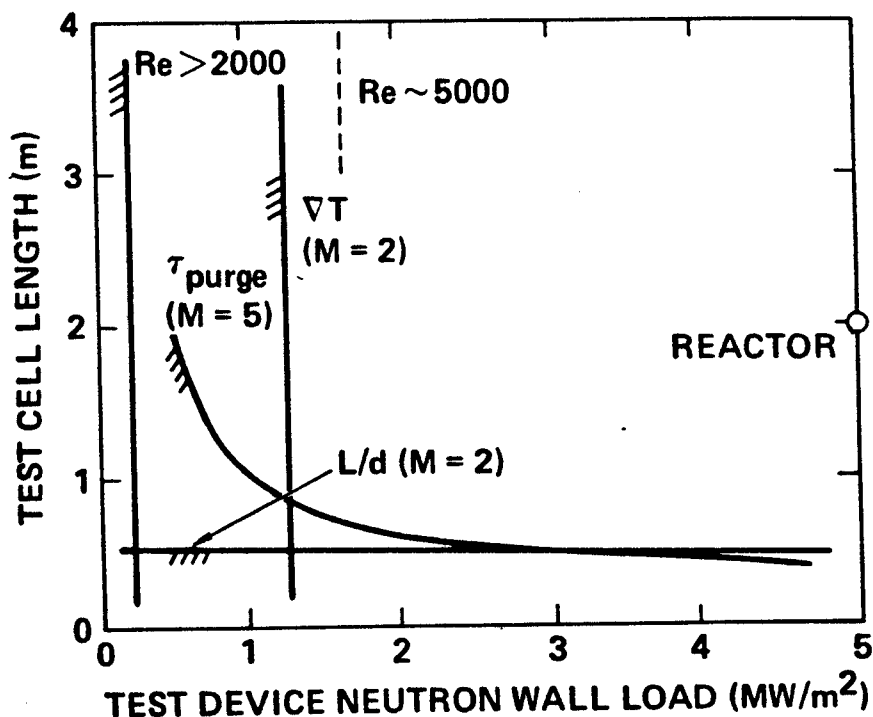
TIME TO EQUILIBRIUM IN
LiAlO₂/Be/H₂O/HT-9 BLANKET



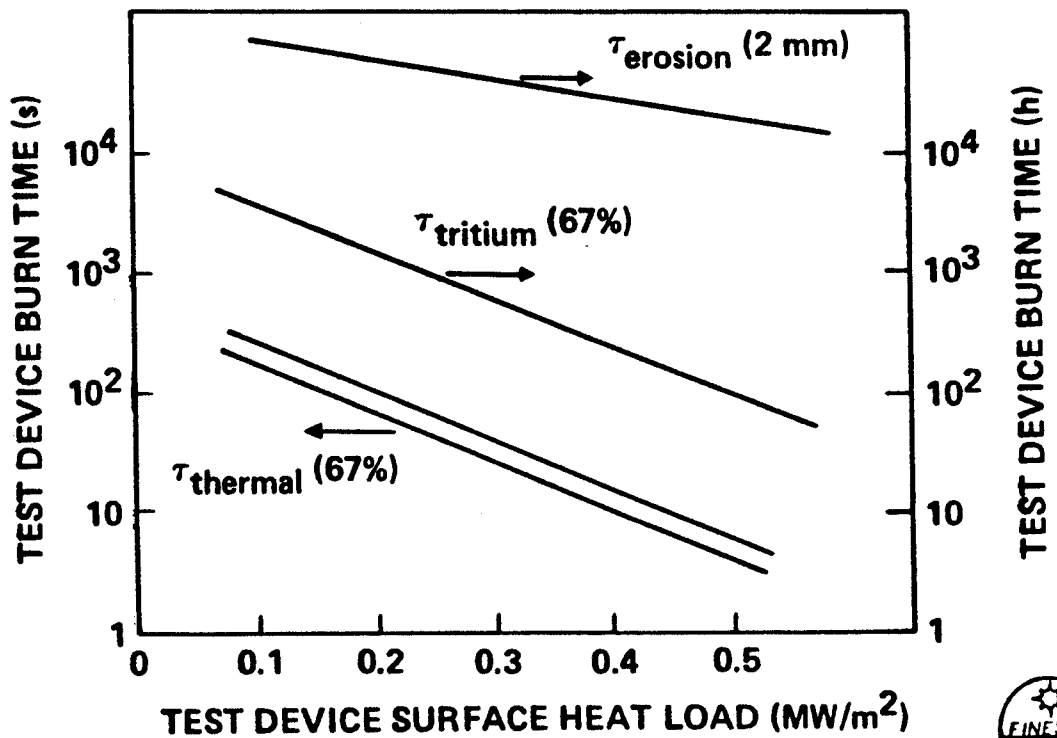
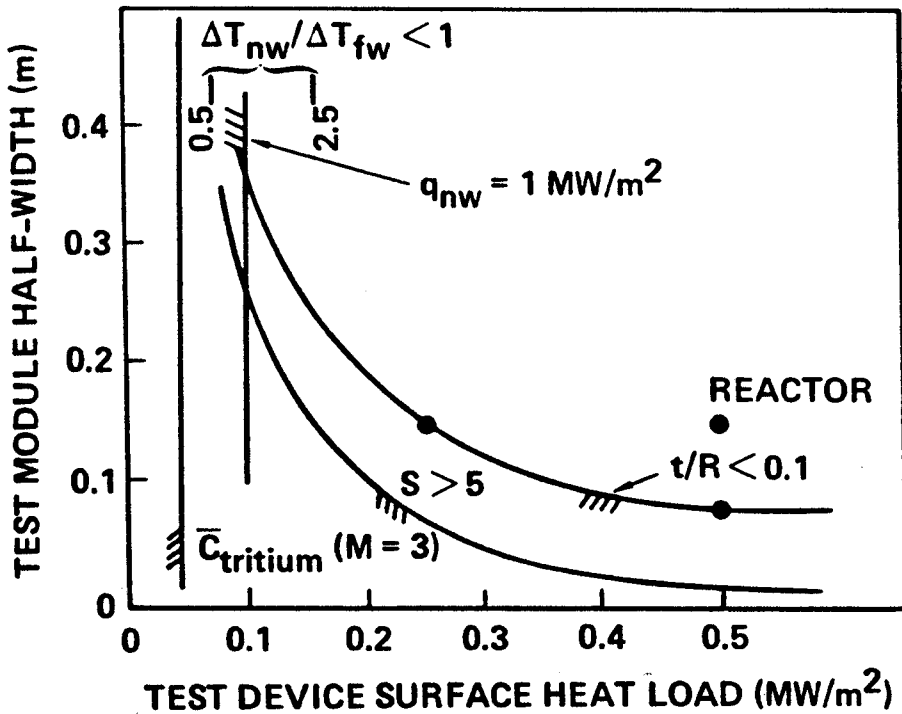
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Li₂O/He/HT-9 BREEDER REGION SCALING (BOL)

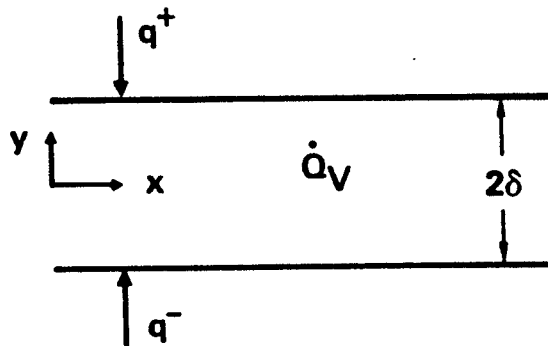


Li₂O/He/HT-9 FIRST WALL SCALING



NUSSELT NUMBER DEPENDS ON VOLUMETRIC HEATING

Consider laminar channel flow with heat generation and surface heat flux:



Velocity profile

$$U = \frac{2n+1}{2n} [1 - (y/\delta)^{2n}] U_b = f(y/\delta) U_b$$

The Nusselt numbers are calculated as:

$$\frac{1}{Nu^\pm} = \frac{1}{4} - I_1/8 - (I_1/16)(q^\mp/q^\pm - 1) + (I_2/4)(\dot{Q}_V \delta/q^\pm)$$

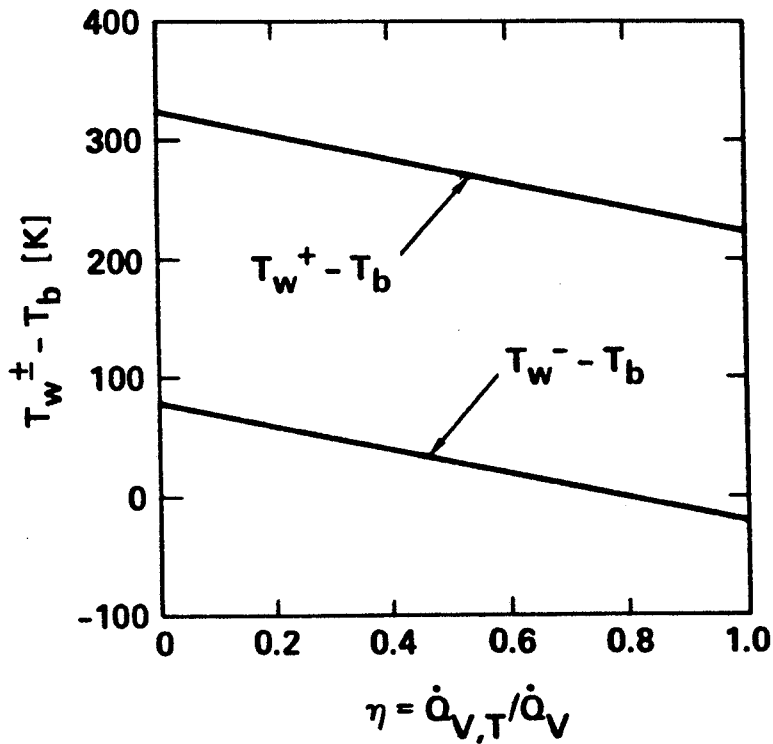
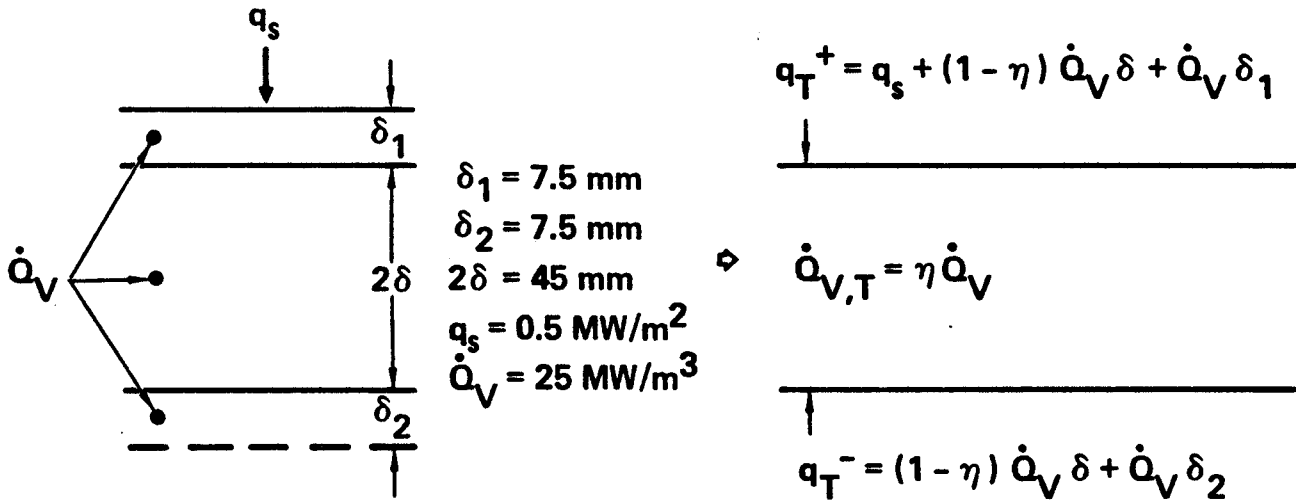
where

$$I_1 = \int_{-1}^1 d\eta f(\eta) \int_{-1}^{\eta} d\eta \int_{-1}^{\eta} d\eta f(\eta)$$

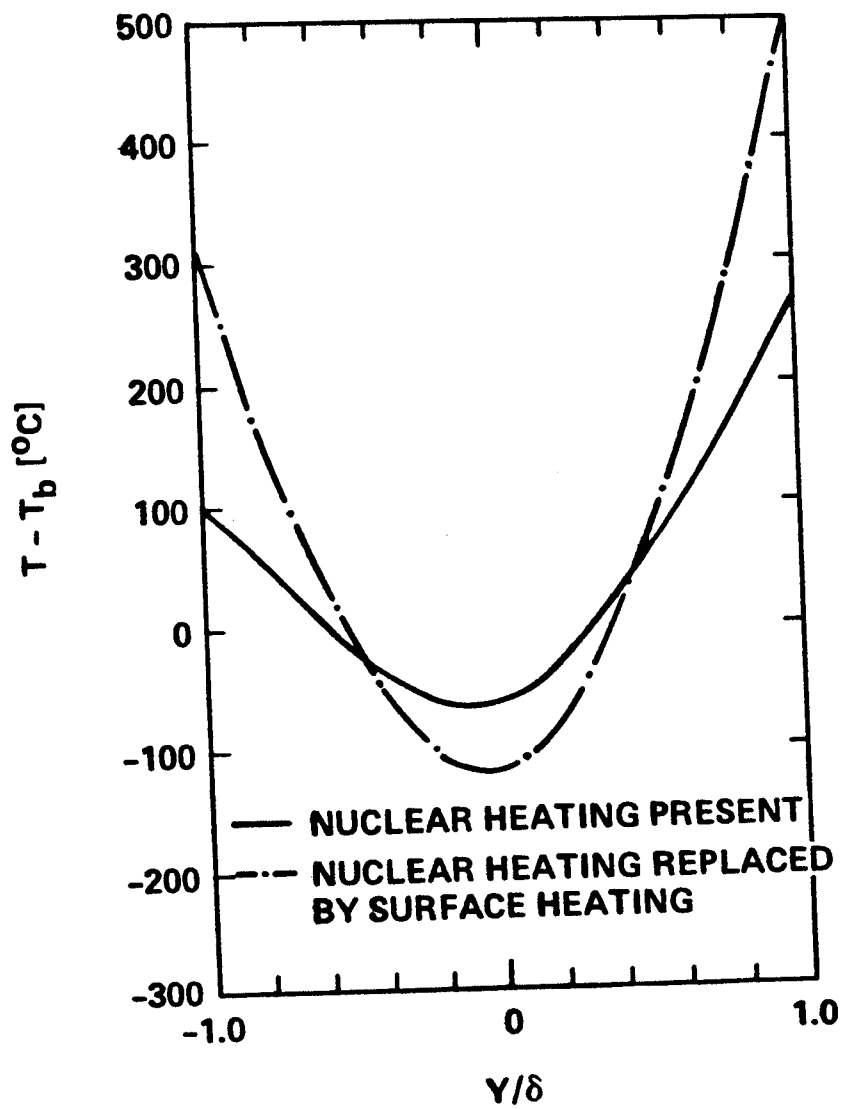
$$I_2 = \frac{1}{2} \int_{-1}^1 d\eta f(\eta) \int_{-1}^{\eta} d\eta \int_{-1}^{\eta} d\eta [f(\eta) - 1]$$



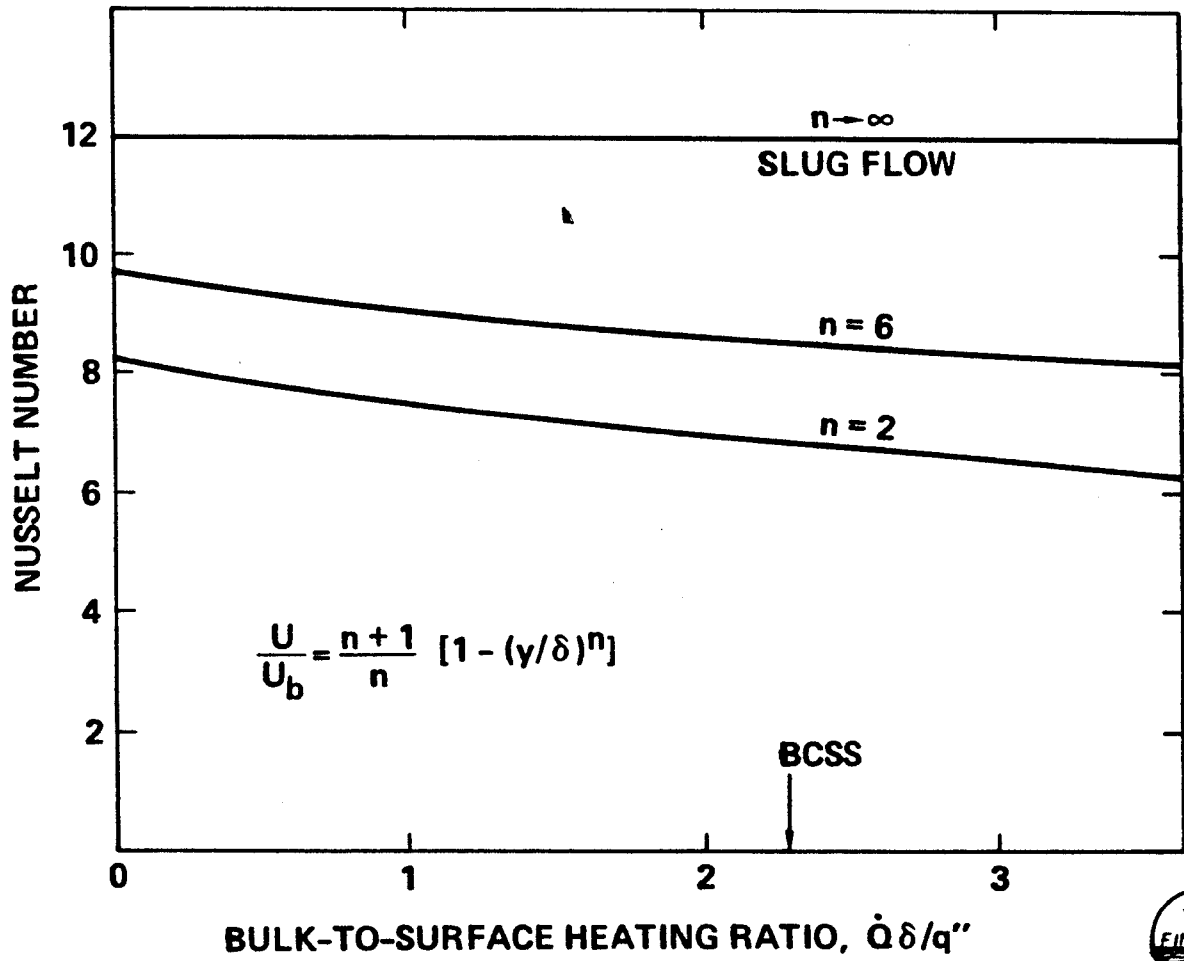
WALL TEMPERATURE AS A FUNCTION OF VOLUMETRIC HEATING IN TEST MODULE WITH TOTAL ENERGY INPUT PRESERVED



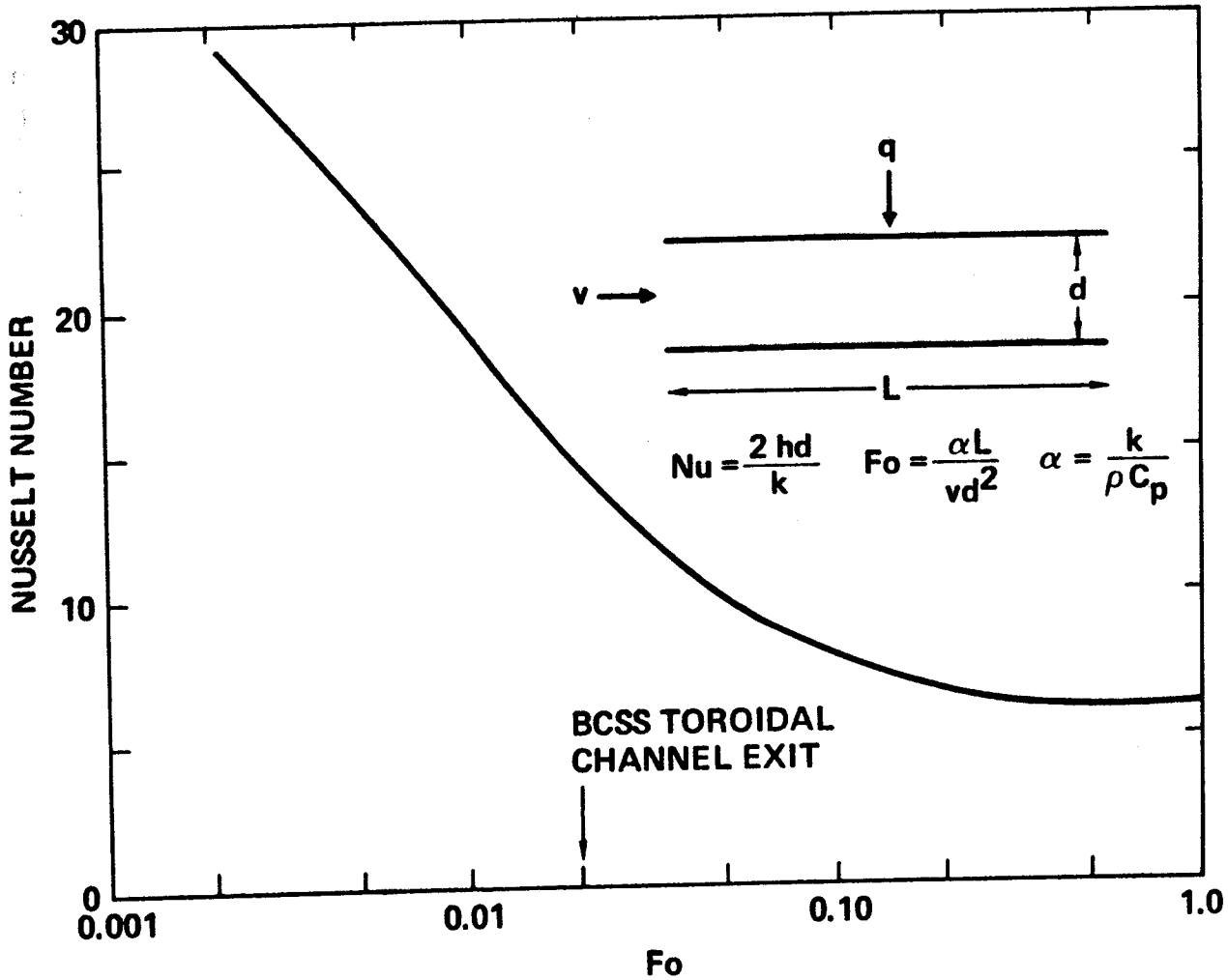
TEMPERATURE PROFILE DEPENDS ON VOLUMETRIC HEATING



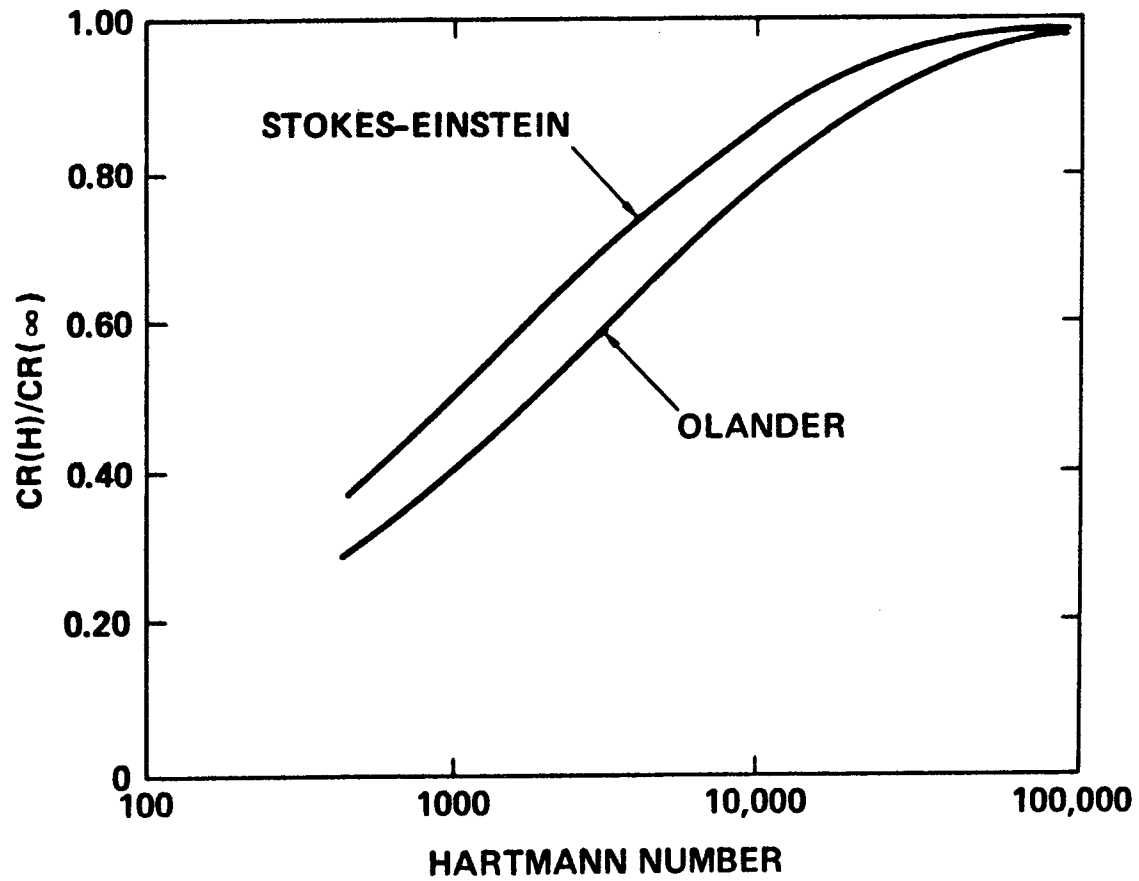
EFFECT OF BULK HEATING ON TEMPERATURE PROFILES



LIQUID METAL HEAT TRANSFER COEFFICIENT FOR
NON-FULLY DEVELOPED FLOW DEPENDS ON
TEST MODULE GEOMETRY AND FLOW CHARACTERISTICS



CORROSION RATE DEPENDENCE ON MAGNETIC FIELD STRENGTH

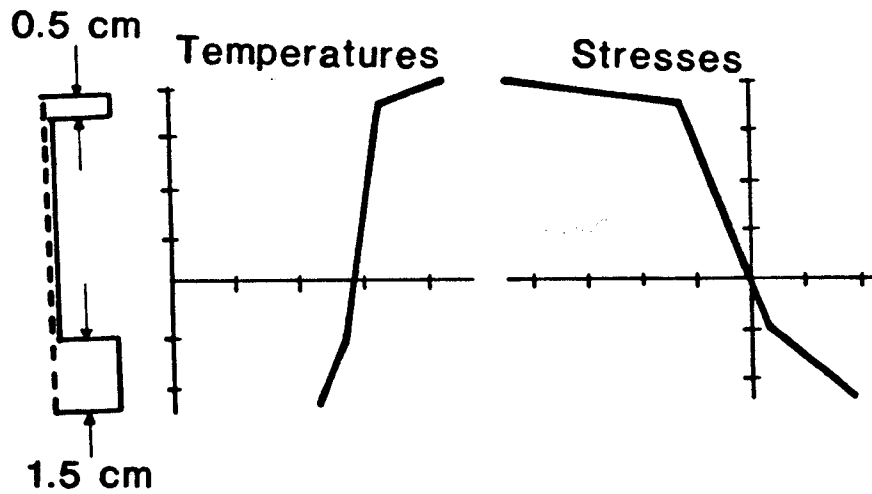


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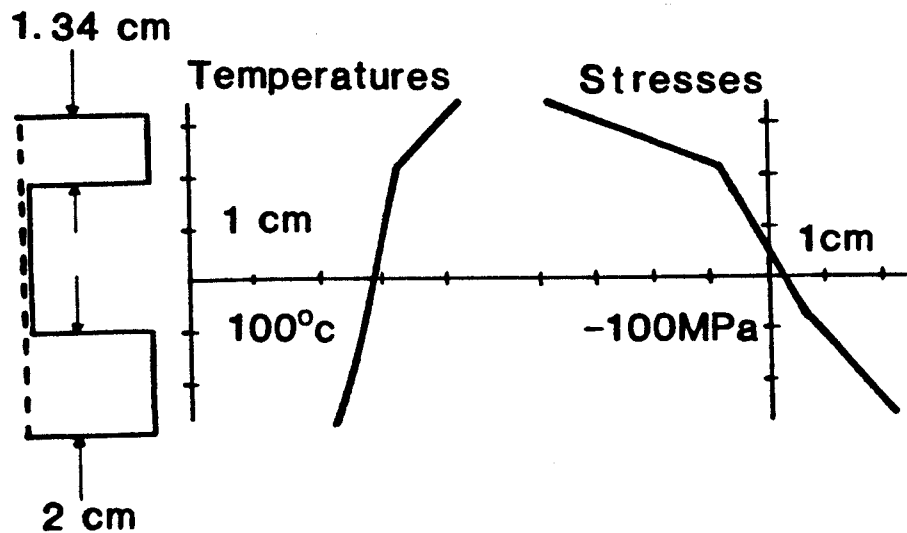
Composite Wall Stresses

BCSS THERMAL STRESSES

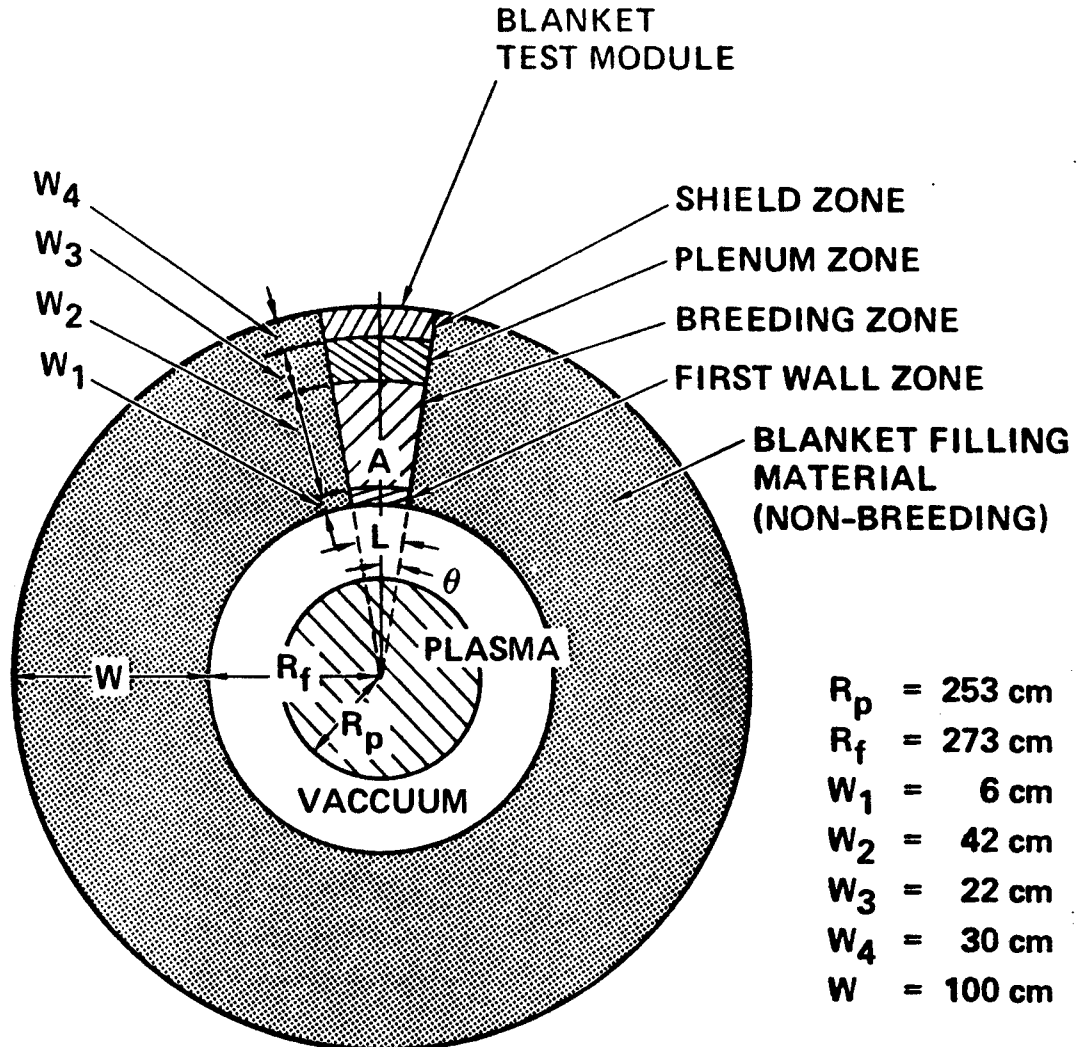


Composite Wall Stresses

TEST MODULE THERMAL STRESSES



BLANKET TEST MODULE TRITIUM PRODUCTION



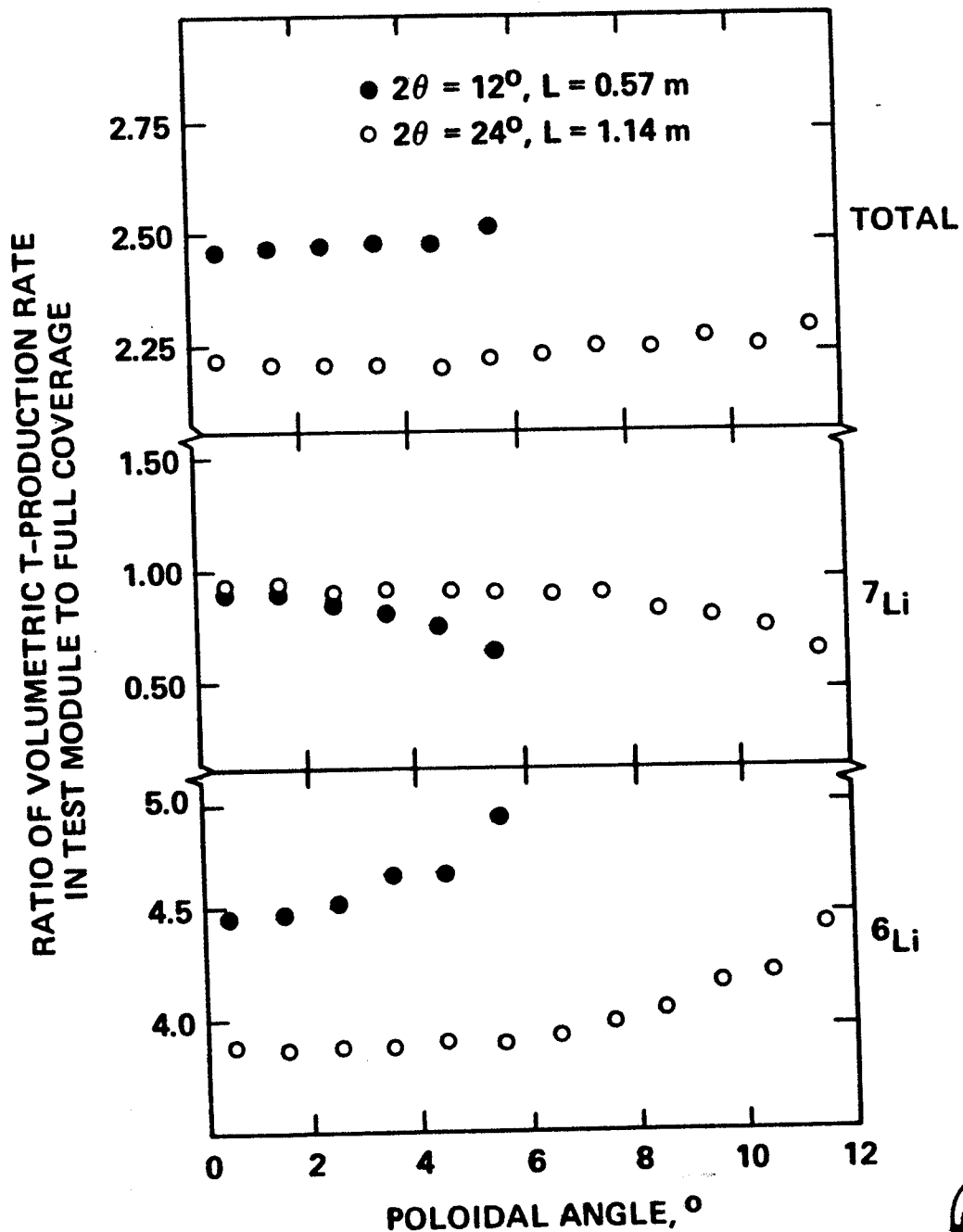
- $R_p = 253 \text{ cm}$
- $R_f = 273 \text{ cm}$
- $W_1 = 6 \text{ cm}$
- $W_2 = 42 \text{ cm}$
- $W_3 = 22 \text{ cm}$
- $W_4 = 30 \text{ cm}$
- $W = 100 \text{ cm}$

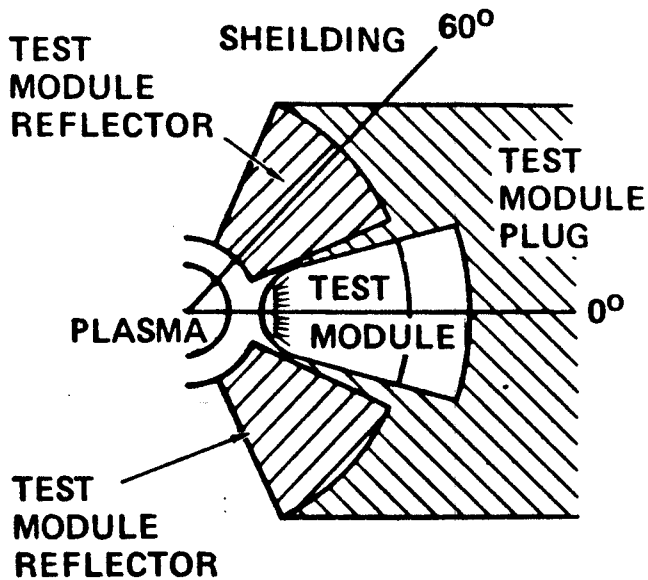
$$L = \frac{2\pi R \cdot 2\theta}{360}$$

- FIRST WALL ZONE:** PCA, 6.6% DENSE, BALANCE HELIUM
- BREEDING ZONE:** 6% PCA, 85% Li_2O (DENSITY FACTOR 0.8) BALANCE HELIUM
- PLENUM ZONE:** PCA, 10% DENSE, BALANCE HELIUM
- SHIELD ZONE:** 100% STAINLESS STEEL

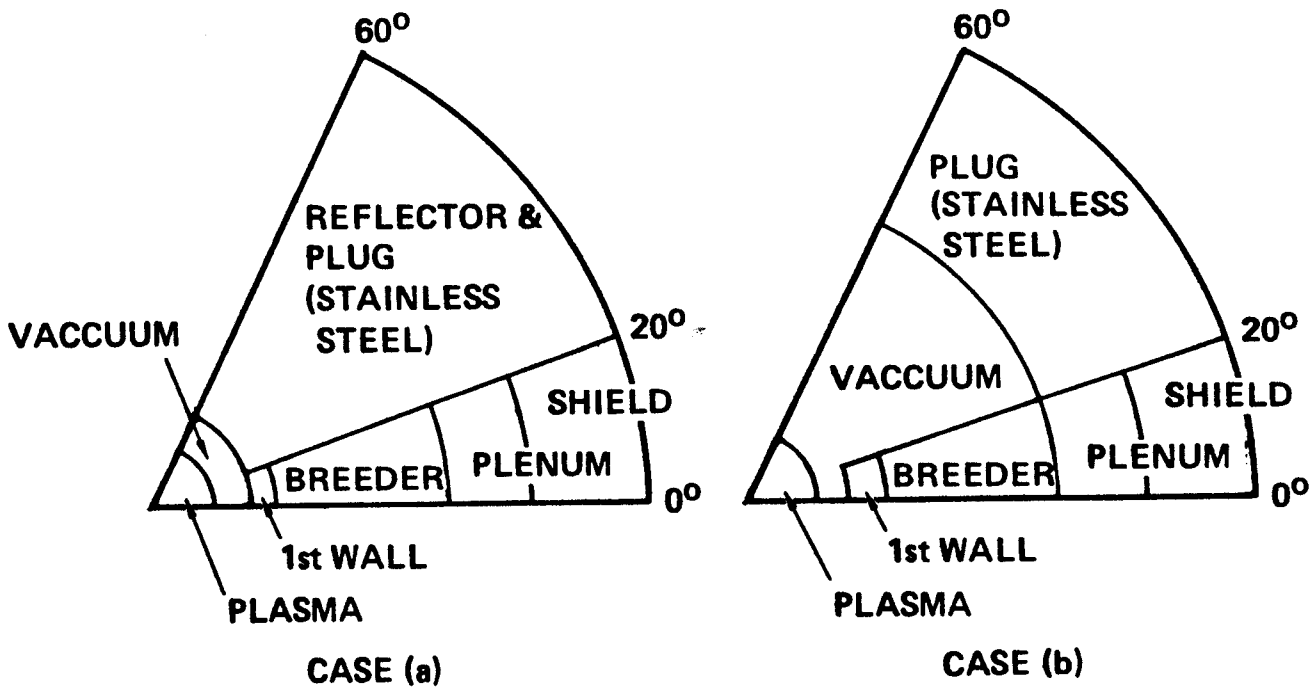


LIMITING BLANKET TEST MODULE SIZE SUBSTANTIALLY CHANGES TRITIUM PRODUCTION PROFILES



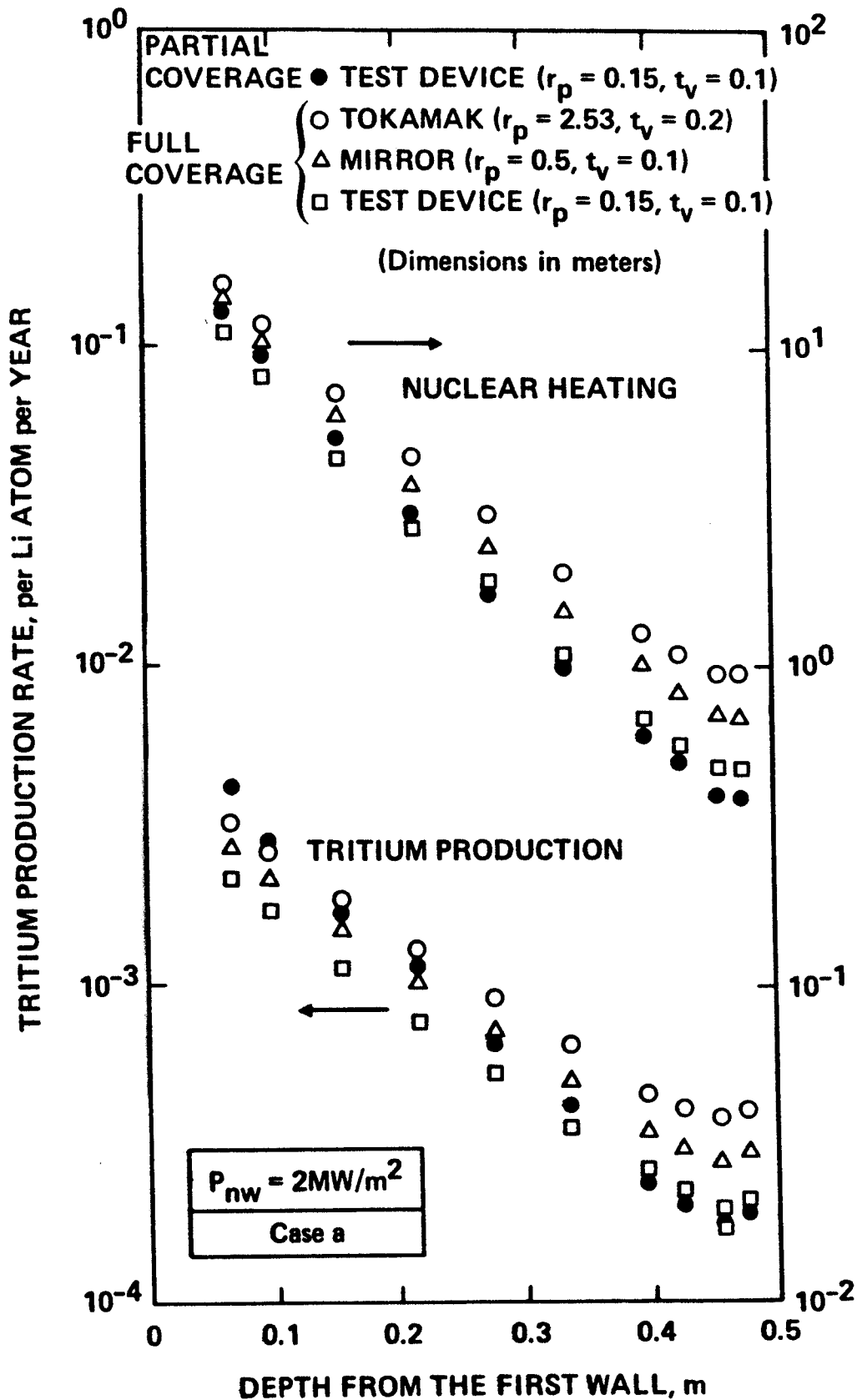


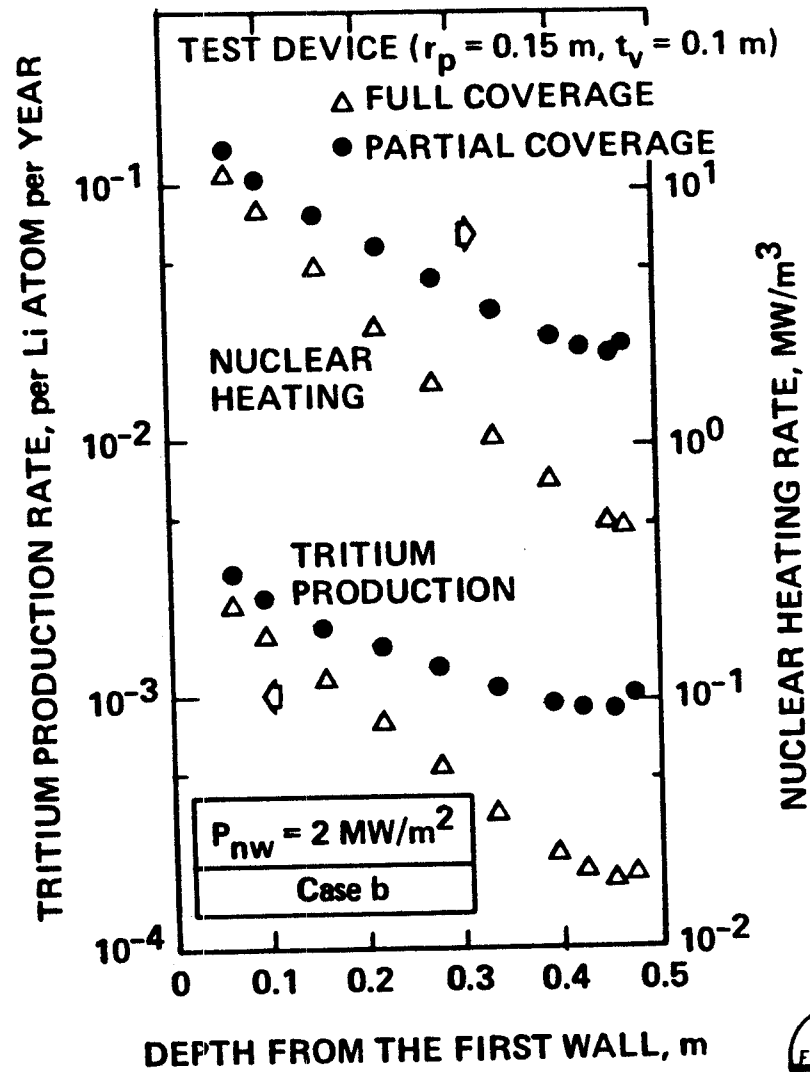
MOCKUP OF MODULE TEST DEVICE



TWO DIMENSIONAL CALCULATION MODEL







EXAMPLES OF IRRADIATION EFFECTS
AS A FUNCTION OF EXPOSURE

EXPOSURE MW-YR/M ²	PHENOMENA/EFFECTS
0-0-2	<p>THERMOPHYSICAL PROPERTY CHANGES SOLID BREEDER CRACKING LIQUID METAL EMBRITTLEMENT OF STRUCTURE LI₂O SWELLING MULTIPLIER SWELLING FIRST WALL EROSION WELD/JOINT INTEGRITY INITIAL OPERATIONAL STRESS EFFECTS SURFACE DAMAGE EFFECTS ON TRITIUM DESORPTION PURGE GAS COMPOSITION EFFECTS ON TRITIUM RECOVERY TRITIUM PERMEATION THROUGH FIRST WALL AND CLAD</p>
0-2-1	<p>THERMOPHYSICAL PROPERTY CHANGES LI₂O SWELLING DOMINATES BREEDER/CLAD MECHANICAL INTERACTION CLADDING CREEP DUCTILITY DROPS SHARPLY (HT-9, 316) FATIGUE AND CREEP/FATIGUE INITIATED IRRADIATION EFFECTS ON WELDS/JOINTS FIRST WALL EROSION + SURFACE CRACKING RELAXATION OF THERMAL STRESSES RADIATION-INDUCED TRAPPING</p>
1-3	<p>BREEDER/CLAD PERMEATION-BARRIER BREAKDOWN CLADDING CREEP EMBRITTLEMENT SATURATES (HT-9, 316) FRACTURE TOUGHNESS REDUCTION INITIATED (STRUCTURE) STRESS RELAXATION COMPLETE POROSITY IN BREEDER MAY CLOSE OFF RADIATION-INDUCED SINTERING GRAIN GROWTH BURNUP EFFECTS ON CHEMISTRY HOT TRANSPORT BREEDER/CLAD CORROSION</p>

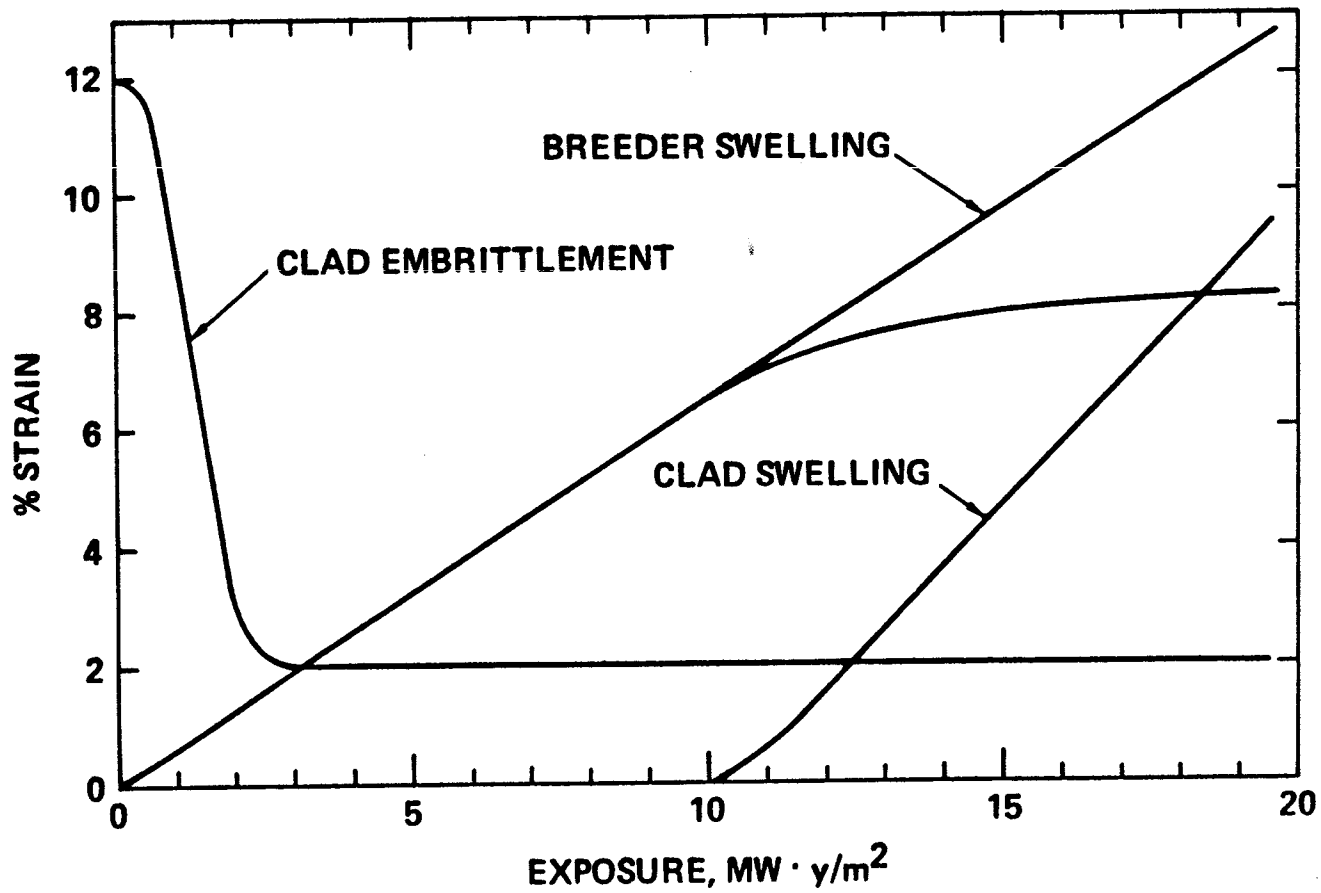


EXAMPLES OF IRRADIATION EFFECTS
AS A FUNCTION OF EXPOSURE
(CONTINUED)

EXPOSURE MW-YR/M ²	PHENOMENA/EFFECTS
3-5	IRRADIATION HARDENING (<450°C)/SOFTENING (>450°C) SATURATES FRACTURE TOUGHNESS, ΔDBTT SATURATES FATIGUE CRACK PROPAGATION IRRADIATION CREEP/SWELLING OF AUSTENITIC ALLOY ONSET CLAD, SWELLING (316) DOMINATES BREEDER/SWELLING INTERACTION
5-10	IRRADIATION CREEP/SWELLING OF HT-9 ONSET CLADDING SWELLING (HT-9) CREEP DOMINATES BREEDER/CLADDING INTERACTION FATIGUE FAILURE
10-20	END-OF-LIFE PHENOMENA <ul style="list-style-type: none">• OPERATIONAL STRESS EFFECTS<ul style="list-style-type: none">- REDUCED TOUGHNESS- FIRST WALL THINNING - UNSTABLE DEFORMATION- FATIGUE, CREEP FATIGUE - UNSTABLE CRACKING



CLAD/BREEDER MECHANICAL INTERACTION
(ESTIMATES FOR Li₂O/HT-9/He)



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BLANKET TESTING AND DEVELOPMENT ISSUES
MUST BE A MAJOR CONSIDERATION IN:

- **SELECTING OVERALL FUSION DEVELOPMENT SCENARIO, E-G-:**
 - **COMBINED: PHYSICS AND TECHNOLOGY TESTING IN A SINGLE DEVICE (INTOR-TYPE)**
 - **PARALLEL: PHYSICS AND NUCLEAR TECHNOLOGY FACILITIES**
 - **SEQUENTIAL: PHYSICS DEVICE FOLLOWED BY TECHNOLOGY FACILITY.**

- **SELECTING THE TYPE AND CHARACTERISTICS OF A DEDICATED FUSION NUCLEAR TECHNOLOGY FACILITY (NTF).**



**COMBINING PHYSICS AND NUCLEAR TESTING
IN A TOKAMAK MANDATES A
TRITIUM-PRODUCING BLANKET IN THE TEST DEVICE**

NEUTRON/TRITIUM REQUIREMENTS

A. PHYSICS ONLY (TOKAMAK)

~ 380 m², 1.3 MW/m²

DT BURN: 2 x 10⁵ s

NUMBER OF NEUTRONS = 4.4 x 10²⁵

TRITIUM CONSUMPTION = 0.22 KG

B. NUCLEAR TESTING ONLY (ASSUME A DEVICE NOT PHYSICS LIMITED)

~ 10 m², 1.3 MW/m²

DT BURN: 5 CONTINUOUS YEARS

NUMBER OF NEUTRONS = 9 x 10²⁶

TRITIUM CONSUMPTION = 4.5 KG

C. COMBINED PHYSICS AND NUCLEAR TESTING IN SINGLE TOKAMAK

~ 380 m², 1.3 MW/m²

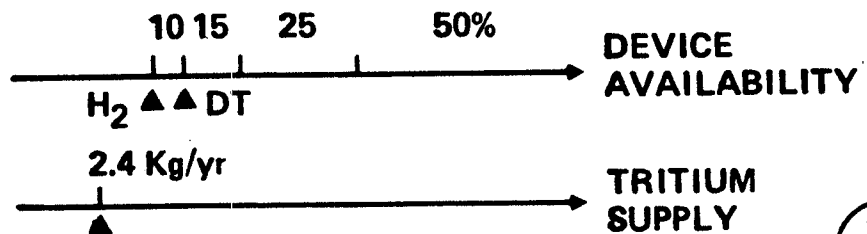
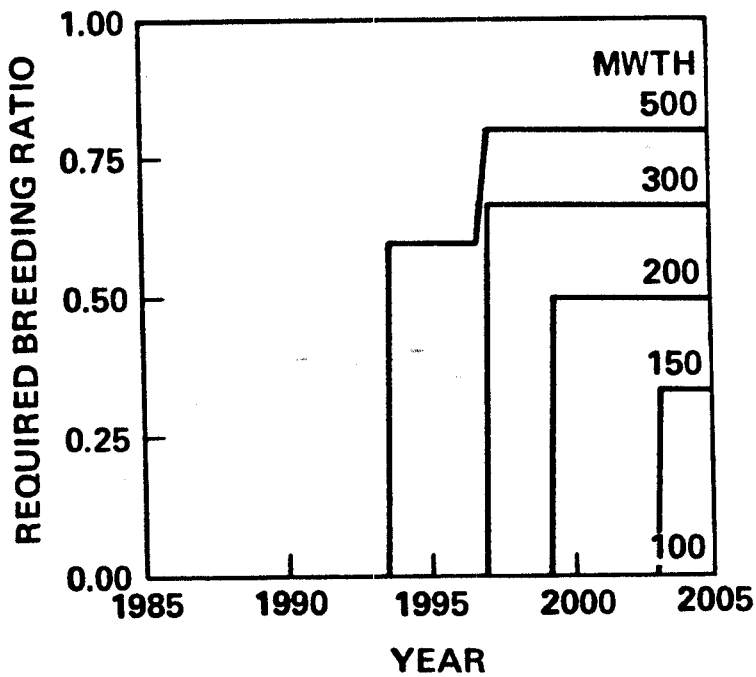
DT BURN: 5 CONTINUOUS YEARS

NUMBER OF NEUTRONS: 3.4 x 10²⁸

TRITIUM CONSUMPTION: 171 KG



**THE NEED FOR A TRITIUM-PRODUCING BLANKET
IN A FUSION TEST REACTOR STRONGLY DEPENDS
ON FUSION POWER AND FLUENCE GOALS**



**PUZZLE OF OBTAINING TRITIUM FOR
COMBINED PHYSICS AND TECHNOLOGY
TOKAMAK TEST FACILITY**

- **CONVENTIONAL (IGNITED) TOKAMAK USED FOR NUCLEAR TESTING
REQUIRES LARGE AMOUNT OF TRITIUM. OPTIONS:**
 - **BUY TRITIUM**
 - * **NOT AVAILABLE**
 - * **COST UNACCEPTABLY HIGH (~ \$2 B)**
 - **PRODUCE OWN TRITIUM (BLANKET IN TEST DEVICE)**
 - * **THERE IS NO LOW TECHNOLOGY OPTION**
 - * **BREEDING BLANKET WILL BE BUILT WITHOUT PRIOR FUSION
TESTING**

- **BREEDING BLANKET WITHOUT PRIOR FUSION TESTING WILL INCREASE
COST AND RISK**
 - **UNNECESSARY COST (COMES ONLY FROM COMBINING PHYSICS AND
TECHNOLOGY)**
 - **HIGH RISK**
 - * **INITIAL AVAILABILITY PER MODULE LOW**
 - * **MANY MODULES + OVERALL BLANKET AVAILABILITY LOW**
 - * **FAILURE IN BLANKET MODULE GENERALLY REQUIRES DEVICE
SHUTDOWN + OVERALL DEVICE AVAILABILITY LOW**
 - + **RISK IN ACCOMPLISHING DEVICE MISSION**



MAJOR DIFFERENCES BETWEEN:
A) BLANKET PRODUCTION MODULES
B) BLANKET TEST MODULES

NUMBER OF MODULES

PRODUCTION MODULES: LARGE (>60)
TEST MODULES: SEVERAL PLUS TEST ELEMENTS

CONTAINMENT

PRODUCTION MODULES: INSIDE VACUUM BOUNDARY
TEST MODULES: MOSTLY OUTSIDE VACUUM BOUNDARY

FAILURES LEADING TO UNSCHEDULED DEVICE SHUTDOWN

PRODUCTION MODULES: MOST LIKELY (INSIDE VACUUM BOUNDARY,
NEED CONTINUED OPERATION FOR TRITIUM)
TEST MODULES: NOT NECESSARY

IMPACT ON DEVICE AVAILABILITY

PRODUCTION MODULES: SEVERE (PROBABLY UNACCEPTABLE)
TEST MODULES: SIGNIFICANT, ACCEPTABLE

BENEFITS/COST OF LEARNING

PRODUCTION MODULES: LOW
TEST MODULES HIGH

CORRECTING FOR FATAL FLAWS IN DESIGN/OPERATION OR
INCORPORATING IMPROVEMENTS BASED ON TEST RESULTS ARE VERY
COSTLY AND TIME CONSUMING FOR THE LARGE NUMBER OF PRODUCTION
MODULES.



CONCLUSIONS

- MANY OF FUSION'S REMAINING KEY UNRESOLVED ISSUES ARE IN NUCLEAR TECHNOLOGY.
- WE MUST SEEK SUCCESSFUL AND TIMELY RESOLUTION OF THE NUCLEAR ISSUES.
- RESOLVING THESE ISSUES WILL BE RELATIVELY COSTLY AND REQUIRES LONG LEAD TIME.
- NON-FUSION FACILITIES (TEST STANDS, POINT NEUTRON SOURCES, FISSION REACTORS) ARE VERY USEFUL, AND WE MUST EFFECTIVELY USE THEM.
- HOWEVER, NON-FUSION FACILITIES ARE NOT ADEQUATE FOR CRITICAL INTERACTIVE AND INTEGRATED TESTS. SERIOUS LIMITATIONS RELATE TO SIZE AND MULTIPLE ENVIRONMENTAL CONDITIONS.
- SUBSTANTIAL TESTING OF KEY NUCLEAR COMPONENTS IN FUSION TEST FACILITIES IS REQUIRED PRIOR TO INCORPORATION AS OPERATING COMPONENTS IN AN INTEGRATED SYSTEM.
- THE DESIGN AND OPERATION OF A FUSION TEST FACILITY MUST SATISFY CERTAIN CRITICAL REQUIREMENTS IN ORDER TO OBTAIN MEANINGFUL INFORMATION FROM NUCLEAR TESTS.



CONCLUSIONS

(CONTINUED)

- NUCLEAR TEST REQUIREMENTS ARE BEING QUANTIFIED IN FINESSE. BENEFIT/COST/RISK ANALYSIS IS PLANNED.

EXAMPLES OF PRELIMINARY REQUIREMENTS

- WALL LOAD

- MINIMUM: $> 1 \text{ MW/m}^2$
- SUBSTANTIAL BENEFITS: $2-3 \text{ MW/m}^2$

- SURFACE HEAT LOAD

- CRITICAL FOR TESTS OF FIRST WALL, SOLID BREEDER BLANKETS, LIQUID METAL BLANKETS
- TOKAMAK COMMERCIAL REACTORS WILL HAVE $> 80\%$ OF α POWER ON THE WALL
- NEEDED IN TEST FACILITY: $> 15\%$ OF P_{MW}
- NON-STANDARD MEANS REQUIRED TO ENHANCE SURFACE HEAT FLUX IN FUSION TEST FACILITIES, PARTICULARLY MIRRORS

- PLASMA BURN CYCLE

- PULSING SHARPLY REDUCES THE VALUE OF MANY TESTS.
- PREFER STEADY STATE.
- BURN TIME: $> 1000 \text{ s}$ - DWELL TIME $< 40 \text{ s}$

- MINIMUM CONTINUOUS TIME

- MANY PERIODS WITH 100% AVAILABILITY.
- DURATION OF EACH PERIOD: SEVERAL WEEKS



CONCLUSIONS

(CONTINUED)

- FLUENCE

- SHOULD BE DRIVEN BY THE VALUE OF WHAT WE LEARN FROM COMPONENT TESTS (NOT BY STRUCTURAL MATERIAL SPECIMEN TESTS).

- HIGHER FLUENCES ARE DESIRABLE BUT COSTLY.

- MODEST FLUENCES ARE STILL EXTREMELY VALUABLE.

CRITICAL: 1-2 MW·Y/M²

VERY IMPORTANT: 2-4 MW·Y/M²

IMPORTANT: 4-6 MW·Y/M²

- LARGEST SIZE OF TEST ELEMENT

- INTERACTIVE TESTS (SUBMODULE): ~ 0.2 m x 0.2 m x 0.1 m

- INTEGRATED TESTS (MODULE): 1 m x 1 m x 0.5 m

- TEST SURFACE AREA

- CRITICAL: > 5 m²

- VERY IMPORTANT: > 10 m²

- IMPORTANT: > 15 m²



CONCLUSIONS

(CONTINUED)

- THE SELECTION OF A SCENARIO FOR FUSION DEVELOPMENT INVOLVES COMPLEX ISSUES THAT REQUIRE FURTHER EXAMINATION:
 - PHYSICS TESTING REQUIRES LARGE DEVICE POWER, LOW FLUENCE (TOKAMAK)
 - NUCLEAR TESTING REQUIRES LOW DEVICE POWER, HIGH FLUENCE
 - COMBINING LARGE DEVICE POWER AND HIGH FLUENCE IN A SINGLE DEVICE INTRODUCES SERIOUS DEMAND FOR LARGE TRITIUM SUPPLY
 - SUPPLYING TRITIUM REQUIRES LARGE-COVERAGE BREEDING BLANKET

- INSTALLING A LARGE-COVERAGE BREEDING BLANKET WITHOUT PRIOR FUSION TESTING RAISES MANY DIFFICULT ISSUES:
 - LOW DEVICE AVAILABILITY LIKELY
LONGER TIME TO ACHIEVE FLUENCE GOALS
 - HIGHER RISK IN ACHIEVING MISSION?
 - HIGHER COST

- THERE ARE CONSIDERABLE INCENTIVES TO EXAMINE THE SCENARIO OF TWO PARALLEL DEVICES, ONE FOR PHYSICS AND THE OTHER FOR NUCLEAR TECHNOLOGY
 - CAN WE DESIGN A LOW POWER (< 50 MW), HIGH WALL LOAD DEVICE?
 - TMR?
 - SMALL TOKAMAK (WITH COPPER COILS, DRIVEN PLASMA)?

