

UCLA Fusion Nuclear Technology

Briefing to

Dr. Paul Henri Rebut

By

Professor Mohamed Abdou

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Mechanical, Aerospace and
Nuclear Engineering

UCLA Program on
Fusion Nuclear Technology
(Professor Mohamed Abdou)

- * We believe ITER is critical
to the world program

- * We, at UCLA, are eager to and
capable of fully supporting the
ITER effort

- * Areas of Interest
(Technology R&D and Design)

- * Test Program
- * Blanket
- * Radiation Shield
- * Divertor
- * Tritium and Safety

UCLA Program on Fusion Nuclear Technology

(Professor Mohamed Abdou)

- * Large, most experienced group on FNT with outstanding record of achievements
- * Effort is focused on most critical issues
- * Effort is of fundamental importance to ITER, DEMO, and Power Reactors under any strategy
 - Modelling of the most important phenomena
 - Predictive capability
 - Experiments to verify basic concepts and most important phenomena
 - Design and Analysis

UCLA Fusion Nuclear Technology (FNT) Activities

Neutronics

- US/JAERI collaboration on integral experiments and analysis
UCLA leads the US effort
- Development of computational techniques; sensitivity/uncertainty analysis
- Experimental techniques for tritium production rate, nuclear heating and radioactivity

ITER-Specific Activities

FNT Modeling, Analysis & Experiments

Solid Breeder Blankets

- Tritium transport in lithium ceramics
- Innovative techniques for thermal control

Liquid Metal Components

- MHD models for thermal & fluid flow analysis of blankets
- Free surface film flows (divertor, HHFC)

Reactor Design Studies

- IFE
- DEMO

Test Program

- *UCLA leads US efforts*
- Definition of test program, international space allocation and device utilization
- Requirements on major device parameters

Nuclear R&D

- Thermal hydraulic studies: gap conductance, particle beds, purge flow characteristics
- Radioactivity & decay heat experiments
- Measurement techniques for nuclear heat deposition

Nuclear Design

- Blanket tritium & thermal design and analysis
- Shielding design for penetrations

UCLA FNT Program

Active Areas of Effort

- * Design and Analysis
 - ITER Blanket and Shield
 - DEMO Blanket and Shield
 - ICF REactor Study
(emphasis on Helium coolant, low activation, inherent safety)

- * Thermal Control and Thermomechanics Experiments and Analysis

- * Divertor
 - Heat Removal (innovative techniques using helium, helium with particulates, critical heat flux)
 - Advanced Divertors

- * Tritium Modelling (Blanket and PFC)

Active Areas of Effort continued

- * Neutronics, Shielding and Safety
(Integral experiments and analysis)

- Radiation transport
- Radioactivity, Decay heat
- Nuclear Heating
- Tritium Breeding

- * Test Program

- Engineering Scaling
(How to get the best information out of ITER)
- Test Module Design
- Requirements on ITER
- Test Program Details (Space, time sequence, boundary conditions, etc.)

Thermal Control Experiments and Modeling

Control of solid breeder blanket temperatures is important for effective tritium removal and to maintain all elements within acceptable temperature limits

Thermal control solves several problems:

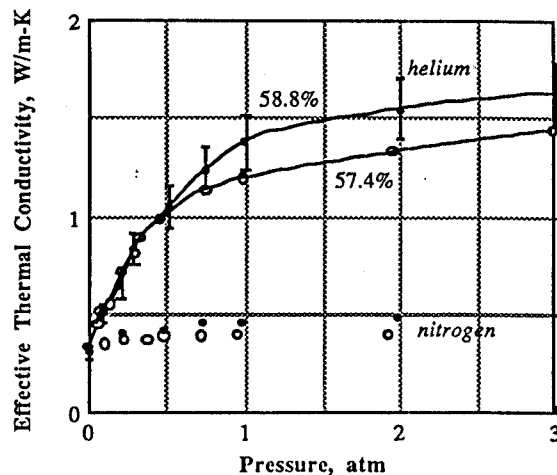
- Account for manufacturing tolerances & uncertainties in material behavior
- Operate over a range of power levels
- Accommodate changes due to operation
(high temperature, cycling, radiation effects)
- Used for engineering scaling and to control experimental conditions

Relevant to ITER base blanket, ITER test modules, DEMO and power reactor blankets

UCLA program:

- Metallic Particle Bed Experiments and Modeling
- Gap Conductance Between Solid Surfaces
- Thermomechanical Interactions (UNICEX)

Variation of Conductivity with Pressure in 0.1-mm Al Bed with Helium or Nitrogen



UCLA has developed and demonstrated techniques to improve the predictability and controllability of blanket temperatures through both passive and active means

Test Program Activities at UCLA

Goal is to maximize the usefulness of ITER (or any other device) as a nuclear test facility

Test Requirements

Analysis of component behavior under pulsed operation and at reduced power shows limits on the value of testing at reduced device parameters

Engineering Scaling

Techniques to maintain act-alike behavior in test articles and extrapolate to DEMO

Test Module Design

Real designs are needed to uncover problems in building and testing test modules

International Test Program

Showed that a coordinated international test program is possible to optimize utilization of the available test space and time

Nuclear Testing Requirements

Concept validation and DEMO qualification of nuclear components requires testing in an integrated fusion environment

First Wall – Divertor – Blanket – Shield – Tritium Cycle

Extensive analysis was performed and led to an international consensus on minimum and desirable test device features to meet the nuclear testing mission:

Device Parameter	Minimum	Highly Desirable	ITER CDA (Technology Phase)
Average neutron wall load at the test module, MW/m ²	≥1	2	1.34
Number of ports	5	7	5
		(+ segment or sector)	
Minimum port size	2–3 m ²	segment or sector	3.74
Total test area	10 m ²	20–30 m ²	18.7 m ²
		(+segment or sector)	
Plasma burn time	≥100 s	1–3 hours	2250 s**
		(to steady state)	
Dwell time	*	≤20 s	300-400 s
“Continuous” test duration	≥1 week	2 weeks	
Number of “continuous” tests per year	2–3	~5	
Average availability	10-15%	25–30%	18%
Annual neutron fluence (at the test module), MW-yr/m ²	0.1	0.4	0.14
Total neutron fluence (at the test module), MW-yr/m ²	≥1	2–4	1.53
Total neutron fluence (average at the first wall), MW-yr/m ²	1.5–2	4-6	1.7

* Minimum acceptable dwell time is highly dependent on the design concept, and is difficult to specify. Further analysis in this area is recommended.

** Alternate plasma scenario B2 provides for steady operation

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 Engineerin Scaling is Applied to Reproduce "Act-Alike" Behavior in Test Modules

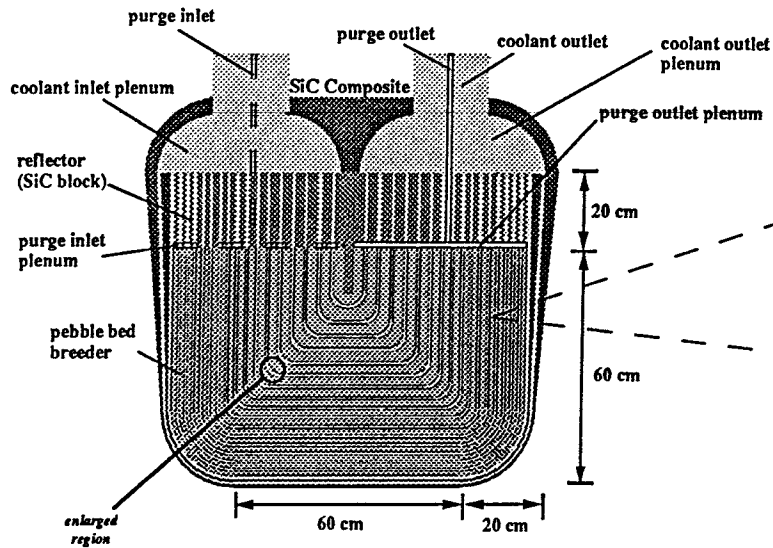
Reactor Conditions:

breeder heating rate	20 MW/m ³
breeder thickness	1 cm
breeder temperatures	500–750 C
multiplier heating rate	5 MW/m ³
multiplier thickness	1.2 cm

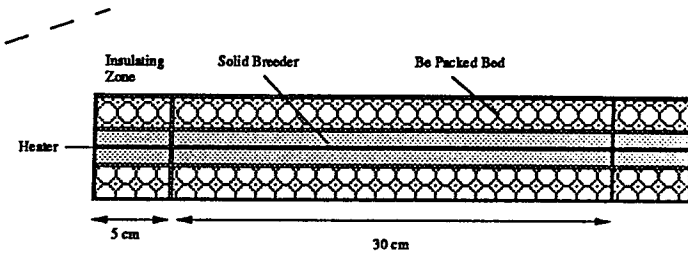
Experimental Conditions:

breeder heater	30 kW/m ²
breeder thickness	0.8 cm x 2
breeder temperatures	500–750 C
multiplier heater	25 kW/m ²
multiplier thickness	2.6 cm

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Reactor Blanket



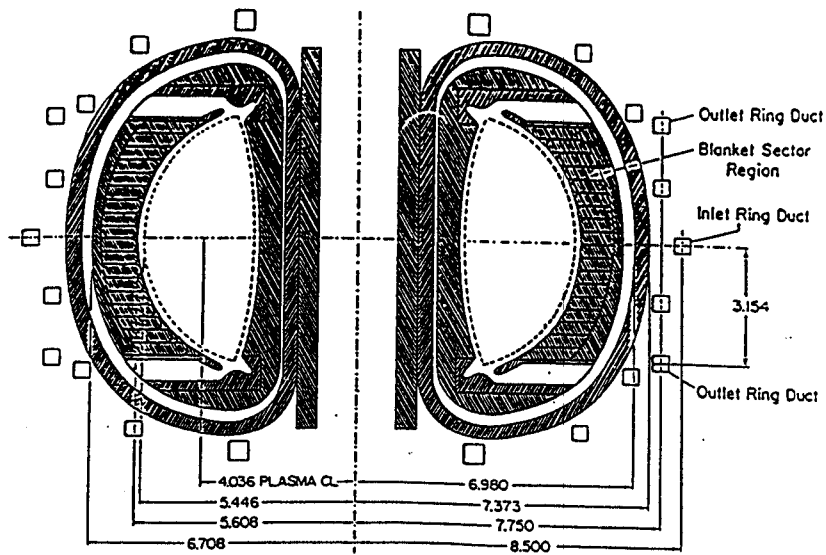
UNICEX (out-of-pile)
 Test Article

Blanket and Shield Design

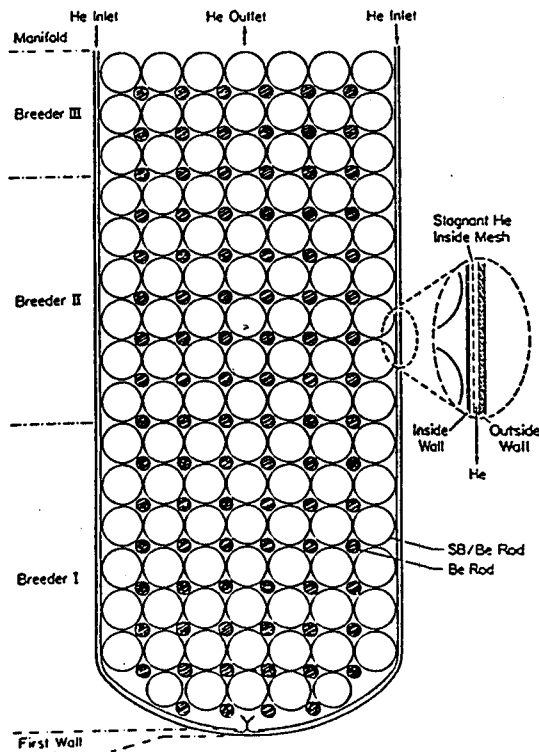
Substantial Capability and Experience in the Design of Blanket/Shield Systems

- Variety of applications
 - Magnetic Fusion and Inertial Fusion reactors
 - Power reactors, DEMO and ITER
- Helium-cooled designs for power reactors
- ITER base blanket
 - recommended reactor relevant blanket
 - developed helium-cooled design
 - proposed innovative active thermal control scheme to account for power variation
 - participated in design effort on water-cooled blanket
- Comparison of poloidal and toroidal cooling
- LOCA/LOFA analysis of blanket for ITER
- In parallel with our test module effort, interested in looking at helium-cooled shield/first wall and at possibility of replacement by hot blanket after Physics Phase

He-Cooled Solid Breeder Blanket Conceptual Design Originally Proposed by UCLA for ITER



Cross-Section of ITER Canister Layout



Canister Configuration

Tritium Analysis

Development Over Last Seven Years of Sophisticated Tritium Modeling Capabilities

- MISTRAL, a state-of-the-art comprehensive model with transient capability for tritium transport in ceramic breeder
- Interaction with other groups, e.g. ANL, Saclay for analysis of experiments
- Reasonably good agreement between model predictions and experimental data in many cases
- Application to several blanket design studies, including ITER base blanket and test modules
- Model is under development for steady-state and transient tritium behavior in Be
- Proposed adaptation of MISTRAL and Be model to plasma facing situation by including tritium implantation flux; applicable to Be coating and to porous carbon composite
- Fuel Cycle Model based on tritium residence time in different components

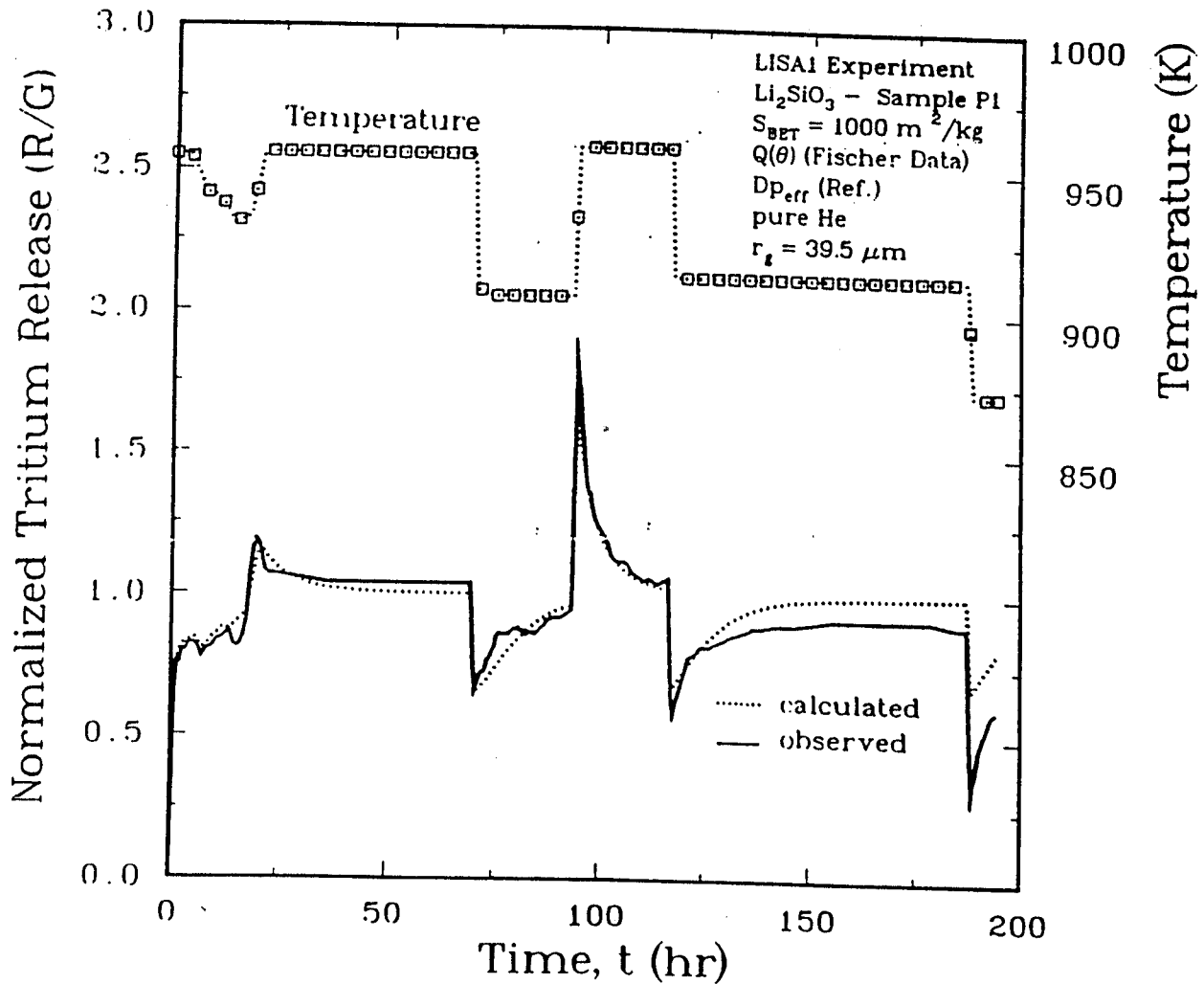
EVALUATION AND COMPARISON OF RESULTS

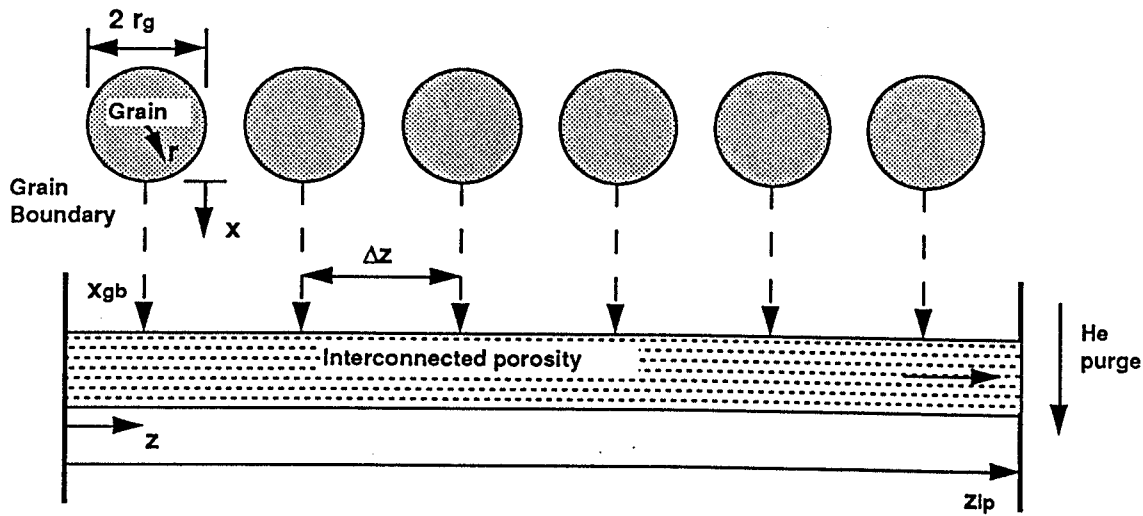
Tritium Behavior After A Change In Temperature

LISA1 Experiment

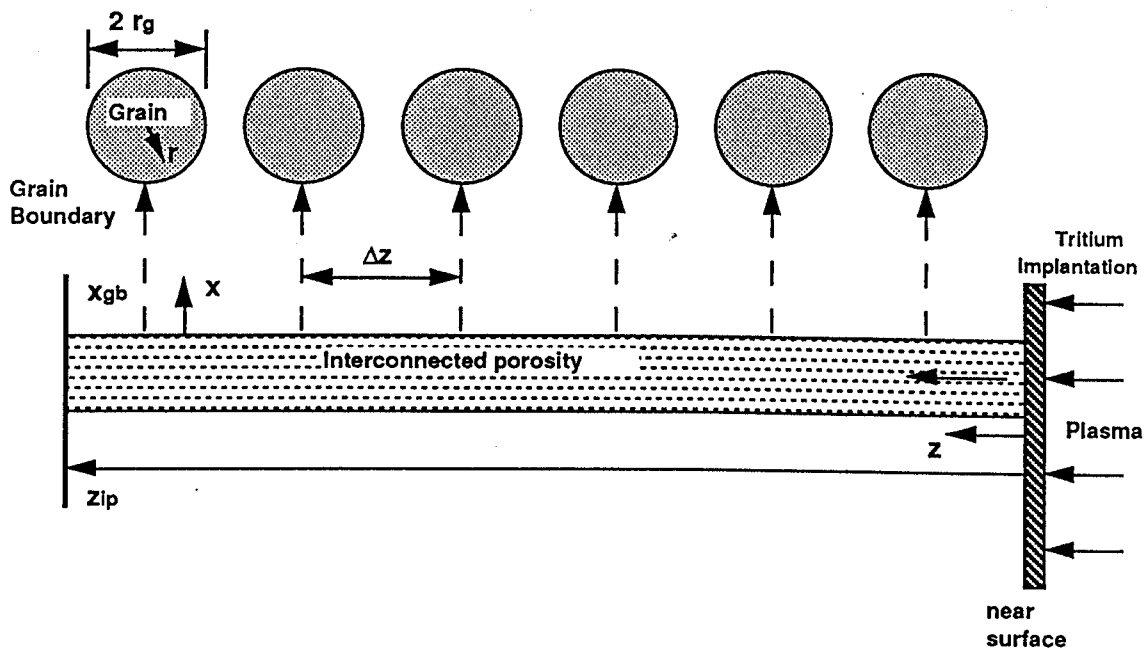
Sample P1 - Li_2SiO_3

Pure Helium Purge





Schematic of MISTRAL unit cell for tritium transport in ceramic breeders



Schematic of model for tritium transport in porous PFC material

Divertor Cooling System

Interested in Drawing on our Capabilities and Experience (Fusion Engineering Group and UCLA Department) to Address Key Heat Removal Issue

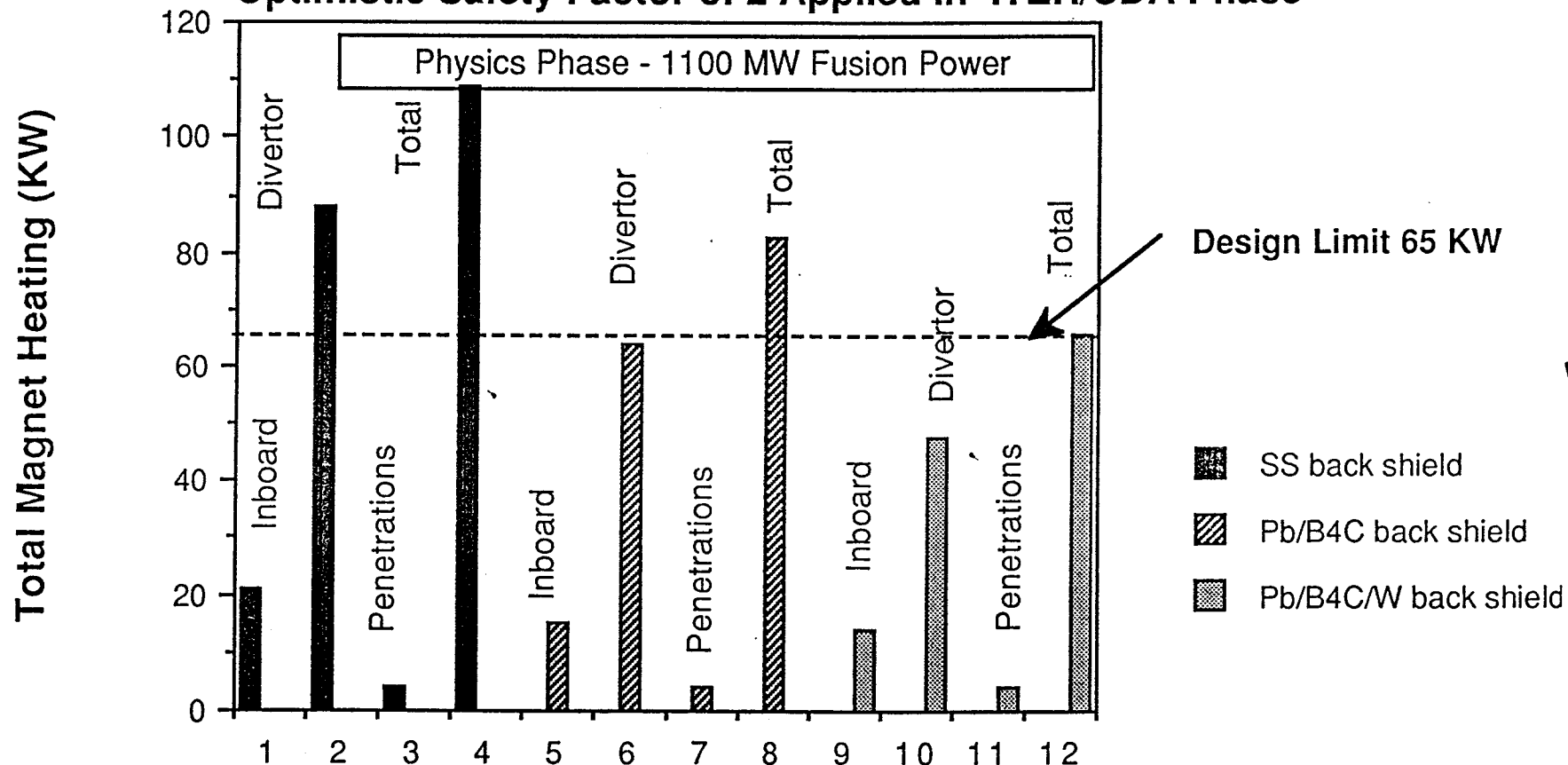
- Water Coolant
 - Heat transfer enhancement techniques (e.g. twisted tapes)

- Innovative cooling systems
 - multi-phase with particulates
 - helium with particulates

- Liquid Metal
 - Advanced concept
 - Ongoing experiment and analysis
 - Substantial contribution to liquid metal modeling and analysis

Total Heating Rate in ITER TF Coil (Physics Phase)

Optimistic Safety Factor of 2 Applied in ITER/CDA Phase

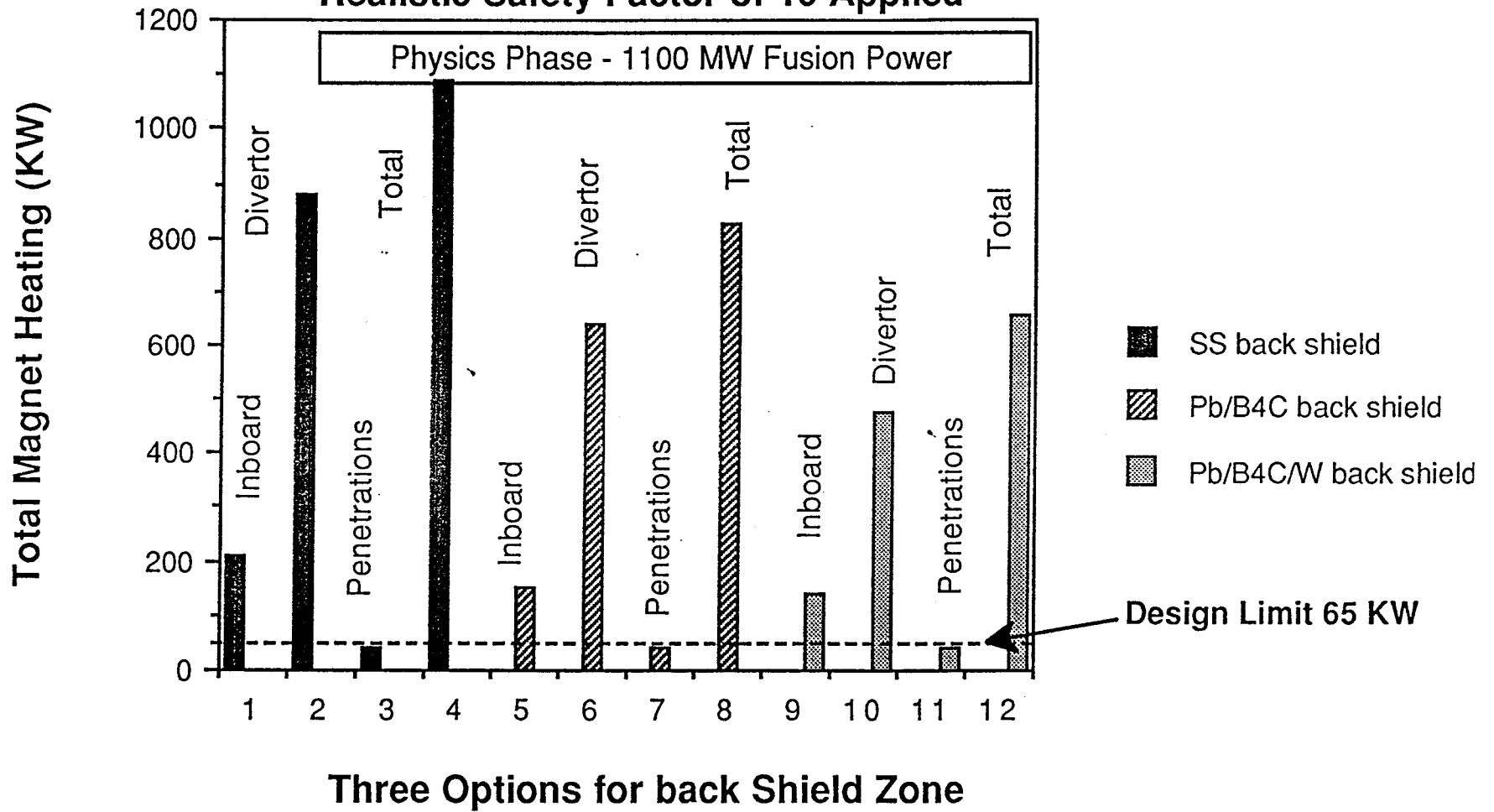


Three Options for back Shield Zone

Design Limit 65 KW

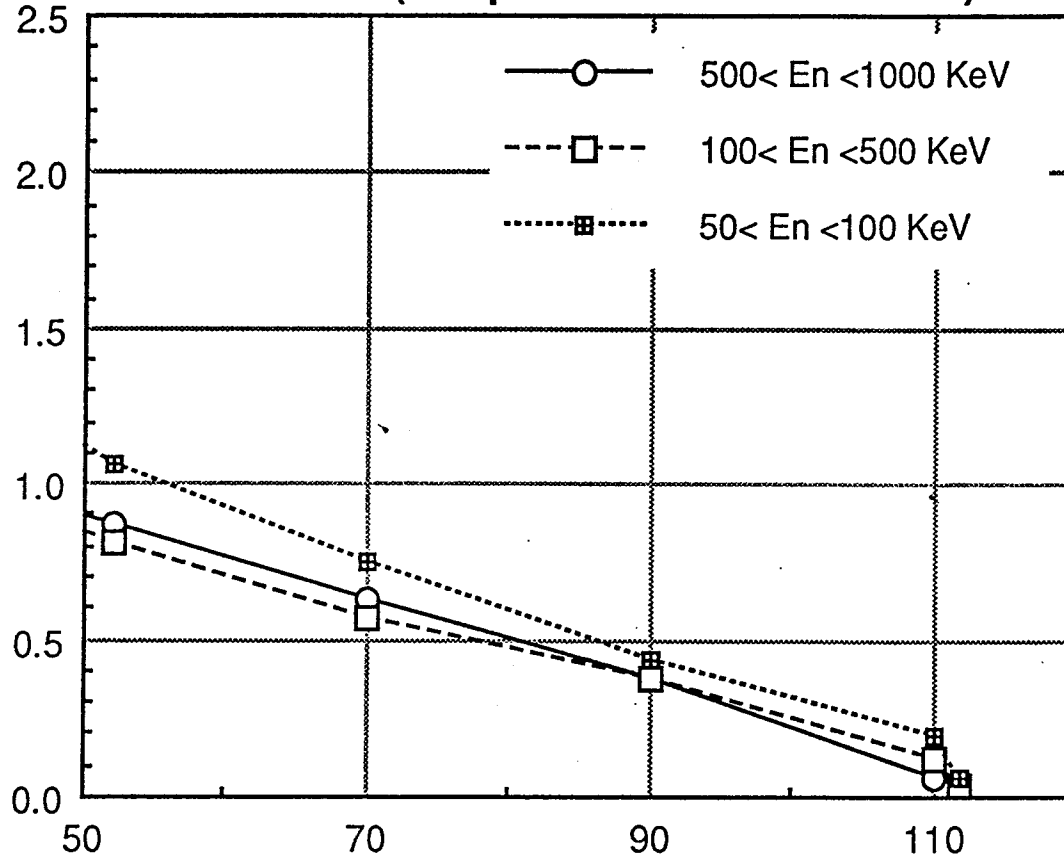
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**Total Heating Rate in ITER TF Coil
(Physics Phase)
Realistic Safety Factor of 10 Applied**



Calculations under-predict Integrated Neutron Flux Beyond Shield Thickness of 50 cm (Deep Penetration Problem)

Calculated/Experimental Value (C/E)



Distance Inside Shield, cm

NECESSITY OF AN AGGRESSIVE PROGRAM FOR ITER SHIELDING R&D

* There is an unacceptable risk in proceeding with ITER/EDA Phase without laying out a well-planned experimental program to validate ITER shielding performance during both physics and technology phases prior to construction.

* Issues to be examined to verify the prediction capabilities (transport codes and nuclear data) are:

- Adequate protection of the SCM during operation
- Total heating rate in the coil case and winding packs do not exceed design limit.
- Accumulated dose in the insulator is below design limit
(bulk shield performance)
- Hot spots with excessive local values (e.g. heating) due to existence of gaps, slots, coolant channels with less attenuation characteristics
- Neutrons and gamma rays streaming through large penetrations
- Verification of the required waiting time before permitting personnel access after shut down
- activation level of components during operation and after shut down
- biological dose outside biological boundaries
- afterheat level in critical components (e.g inboard shield, divertor shield)

* **Design safety factors** have been routinely used in ITER shield design, both during Physics and Technology Phases of ITER /CDA phase. These Safety factors **have never been verified experimentally** in prototypic configuration to ITER design.

Safety factors used in ITER /CDA Shield Design

Response	<u>1-D Analysis</u>		<u>3-D Analysis</u>	
	Local	Integral	Local	Integral
Correction factor for:				
- Assembly gaps	1.7	1.2	-*	-*
- Modeling	1.3	1.3	1.1	1.1
- Uncertainties in cross-section data	1.4	1.3	1.4	1.3
<u>Safety factors</u>	3	2	1.5	1.4

* These safety factors are applied to the calculated response under consideration and shield design is determined such that design limits are not exceeded.

* Increasing the shield thickness to cover modeling, design and data uncertainties could be prohibitively costly. (Typically ~5 M\$ for each 1cm increase in a S.S-type shield)

- Example:

In TIBER-II reactor (major radius ~3.0 m, minor radius ~0.8 m, average wall load ~1.0 MW/m²) it was estimated that an incremental machine cost (direct and indirect cost) of 10-14 M\$ is needed to increase the thickness of the PCA shield (58 cm-thick) by 1.5-1.8 cm to cover the uncertainties in magnet damage parameters (e.g. total heating rate in the SCM) of 20-26% due to nuclear data uncertainties.

The situation could be worsen in ITER by a factor of ~6 higher in this compensating cost.

(bigger machine, larger shield thickness ,73 cm including vacuum vessel)

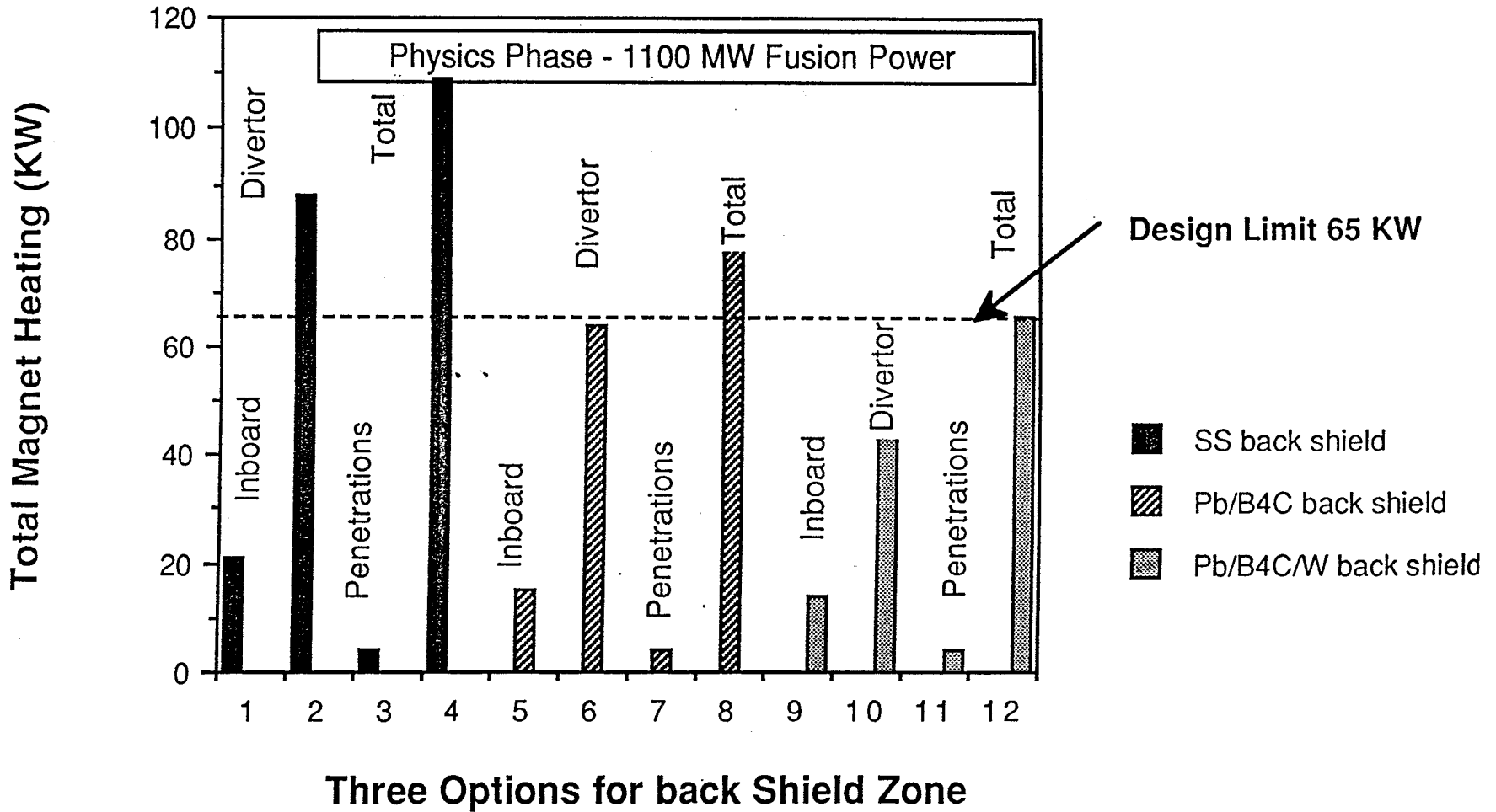
* Even in the physics phase of ITER operation (Fusion power ~1100 MW), the total heating rate in the TF coil could exceed the design limit of 65 KW for some shielding materials unless tungsten is used at some locations (particularly behind divertors) with applying a safety factor of only 2.

*** The safety factors applied (1.5-3) could be very optimistic and larger factors should be used for two reasons:**

- recent measurements at FNS (JAERI) indicated that the transmitted neutrons (and consequently gamma rays) at the back of a 112 stainless steel shield are larger than calculated values by a factor as large as 15. For thinner shield, this factor is smaller (typically ~8-10).

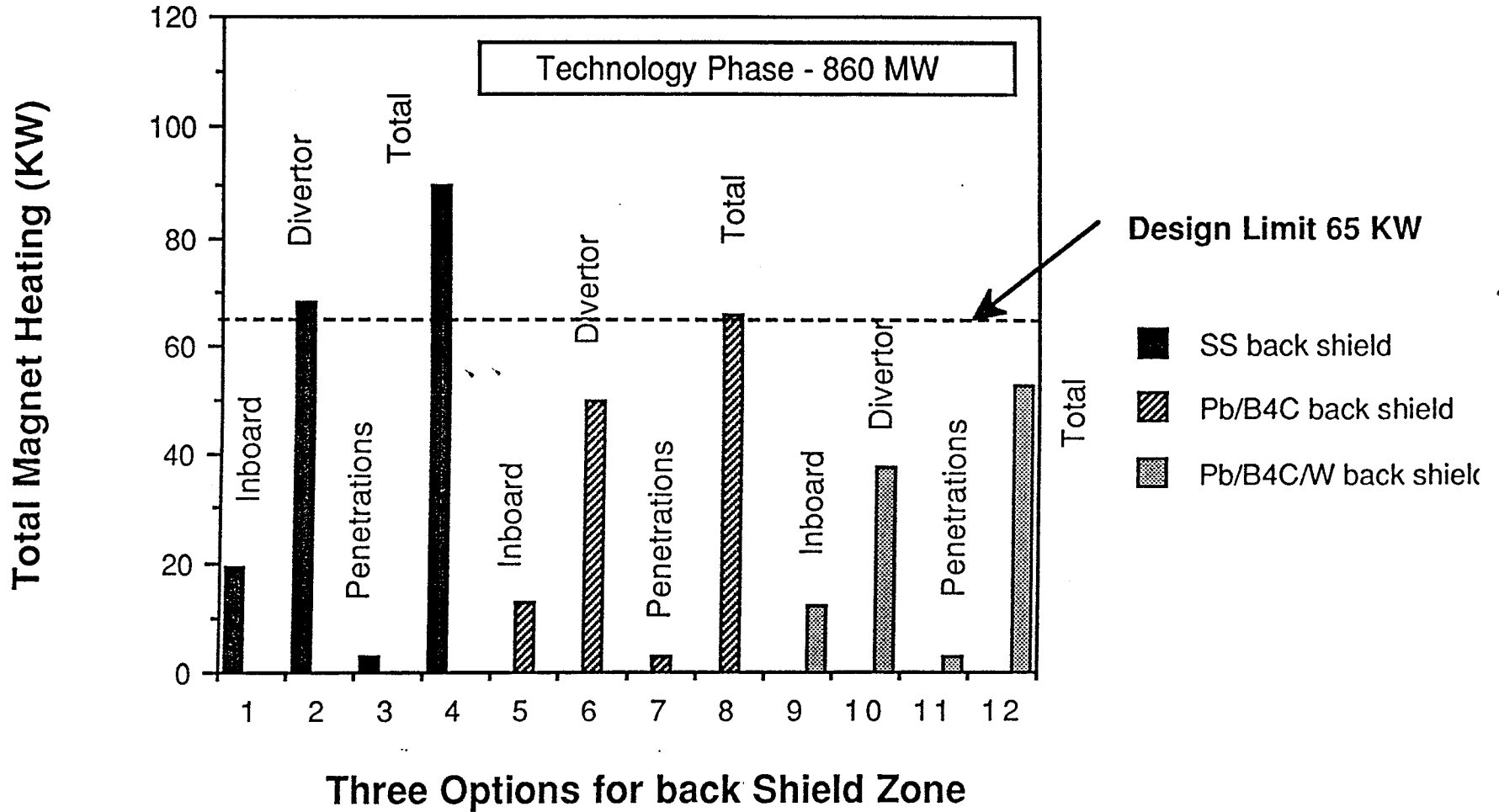
- the kerma factors used to derive the heating rate in TF coil materials have been shown to be erroneous, thereby amplifying the applicable safety factors.

Total Heating Rate in ITER TF Coil (Physics Phase)



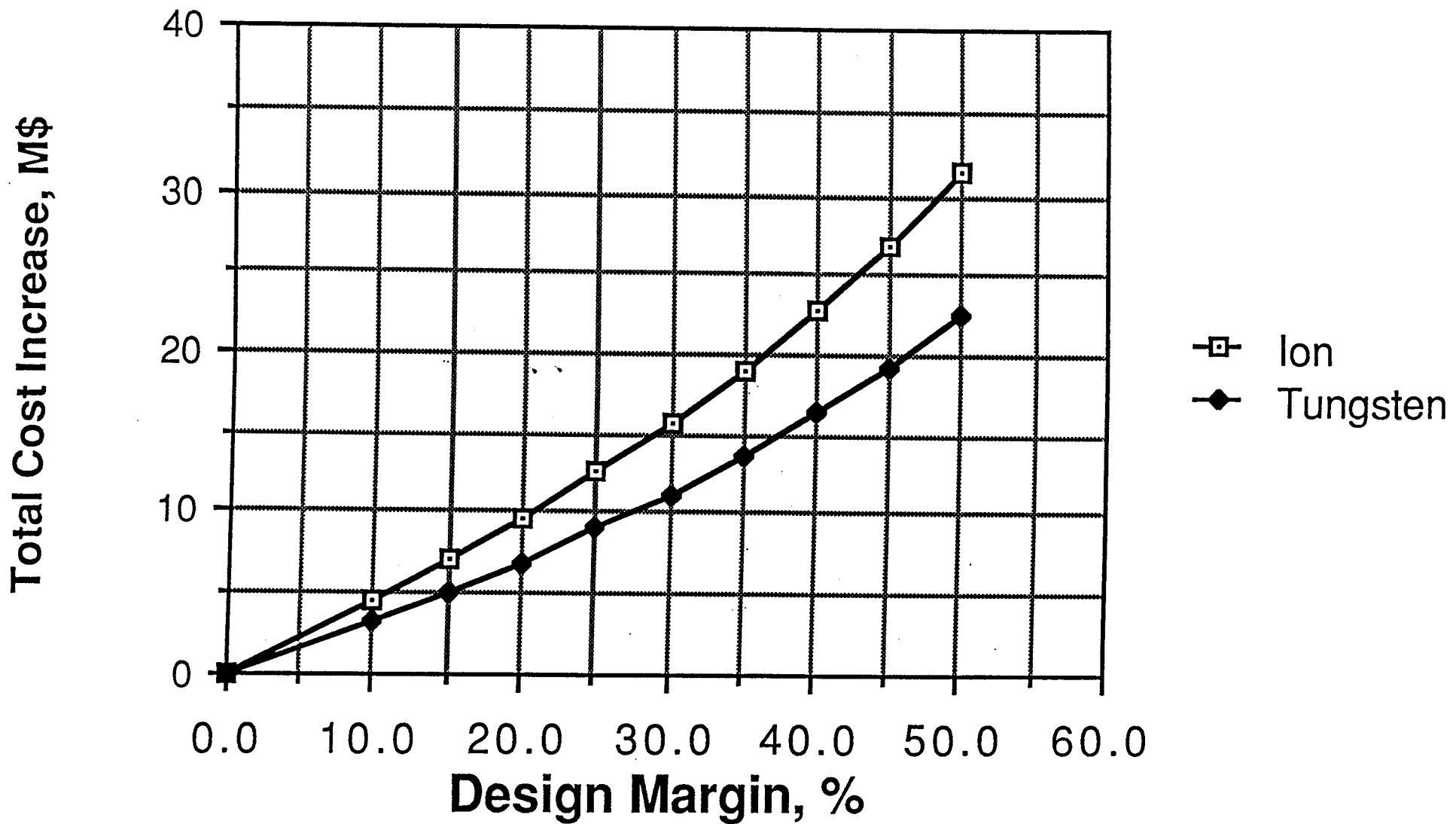
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Total Heating Rate in ITER TF Coil (Technology Phase)



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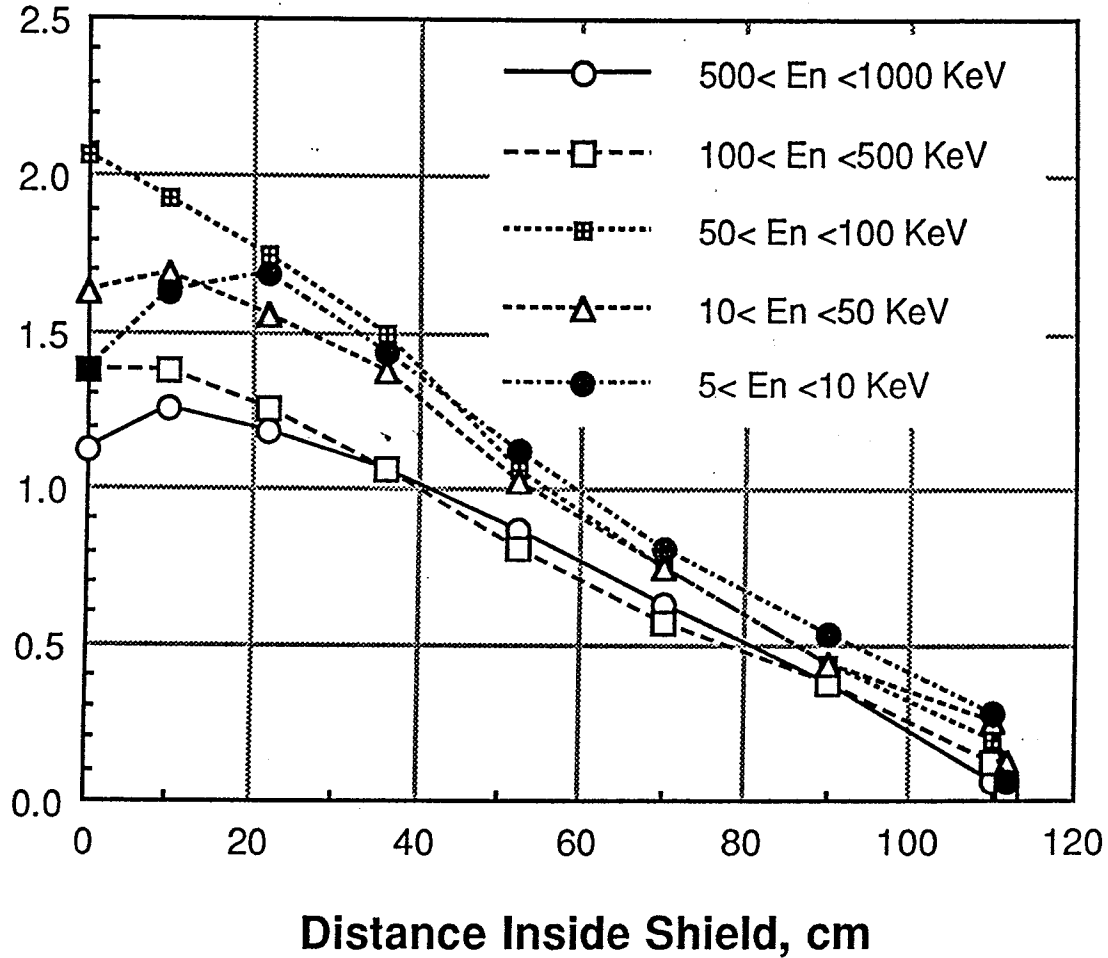
INCREMENTAL INCREASE IN TOTAL COST



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Calculations under-predict Integrated
Neutron Flux Beyond Shield Thickness
of 50 cm (Deep Penetration Problem)

Calculated/Experimental Value (C/E)



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