P B M R

Pebble Bed Modular Reactor High Temperature Materials Graphite

I-16

Mark A Davies
October 2001

Purpose of Presentation

- Highlight the safety issues related to the use of graphite technology in High Temperature Reactors

- Identify options that lead to the successful resolution of these issues

Overview

- PBMR design
  - Functional Requirements
  - Assessment Criteria
- Graphite
  - Manufacture
  - Material Properties
  - Performance Assessment
  - Risk Mitigation
    - MTR Programme
    - Inner Reflector Replacement
- Conclusions

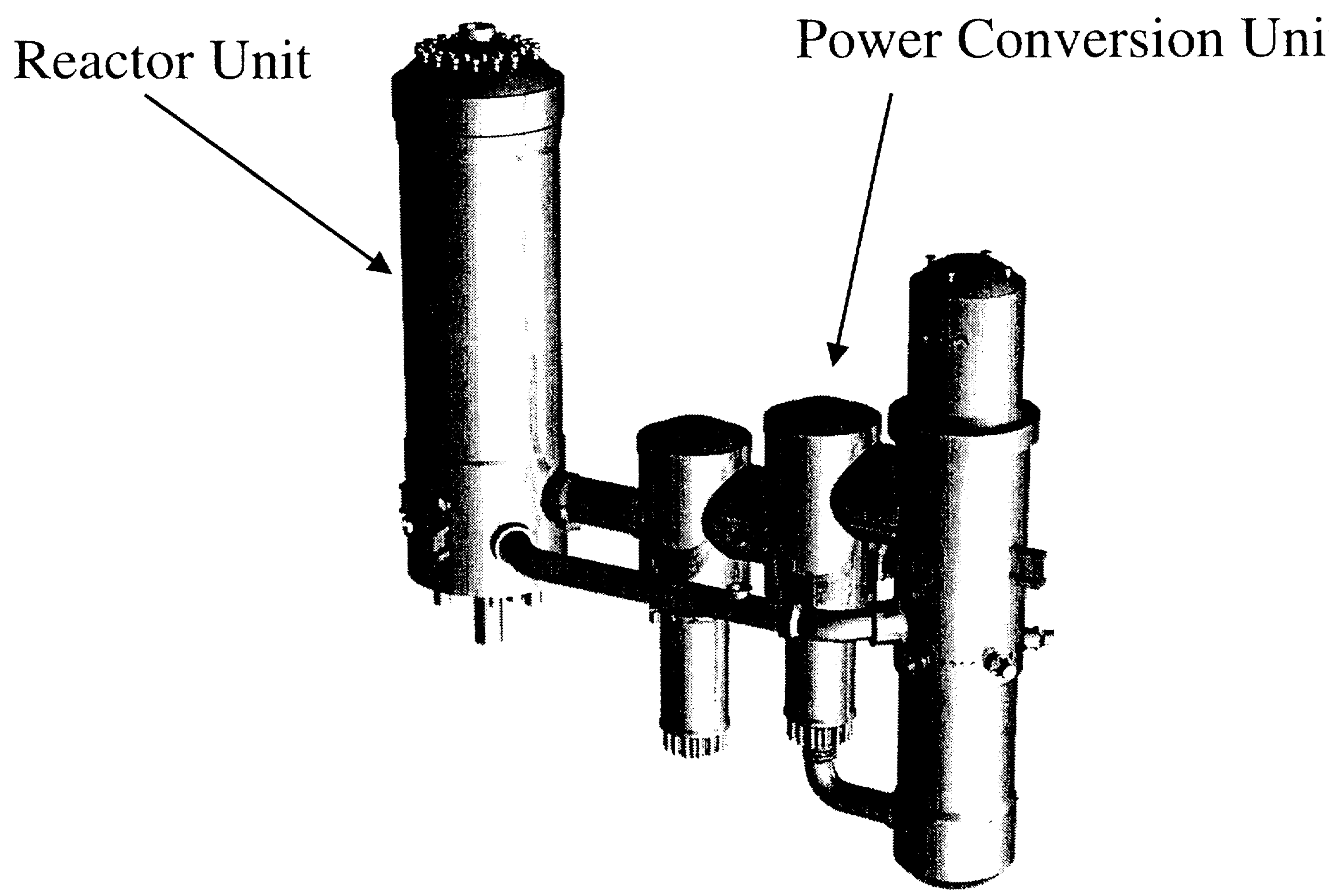
PBMR Design

- Core Structures Safety Functionality
  - Maintain Pebble Bed (PB) Geometry
  - Maintain Adequate Cooling of the PB under normal and abnormal conditions
  - Maintain Access for the Reactivity Control and Shutdown System (RCSS)
  - Maintain the De-fuelling Path

Performance Assessment Criteria

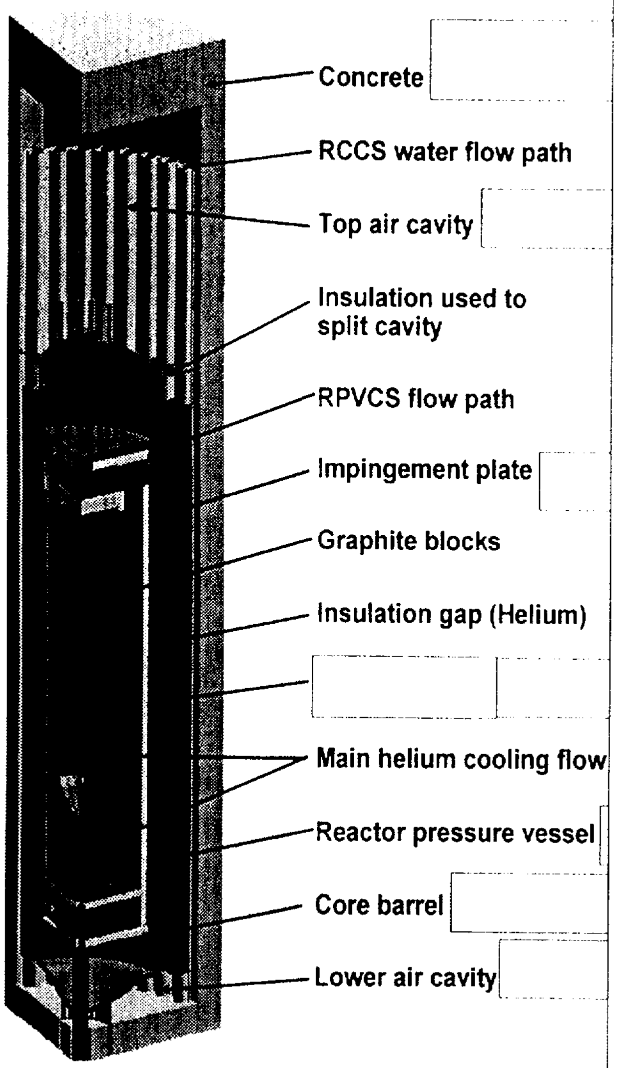
- Structural
  - Build up of stresses exceeding strength
- Deformation
  - Excessive distortion of reflector columns
- Material exhaustion
  - $f(\gamma, T_{irr})$

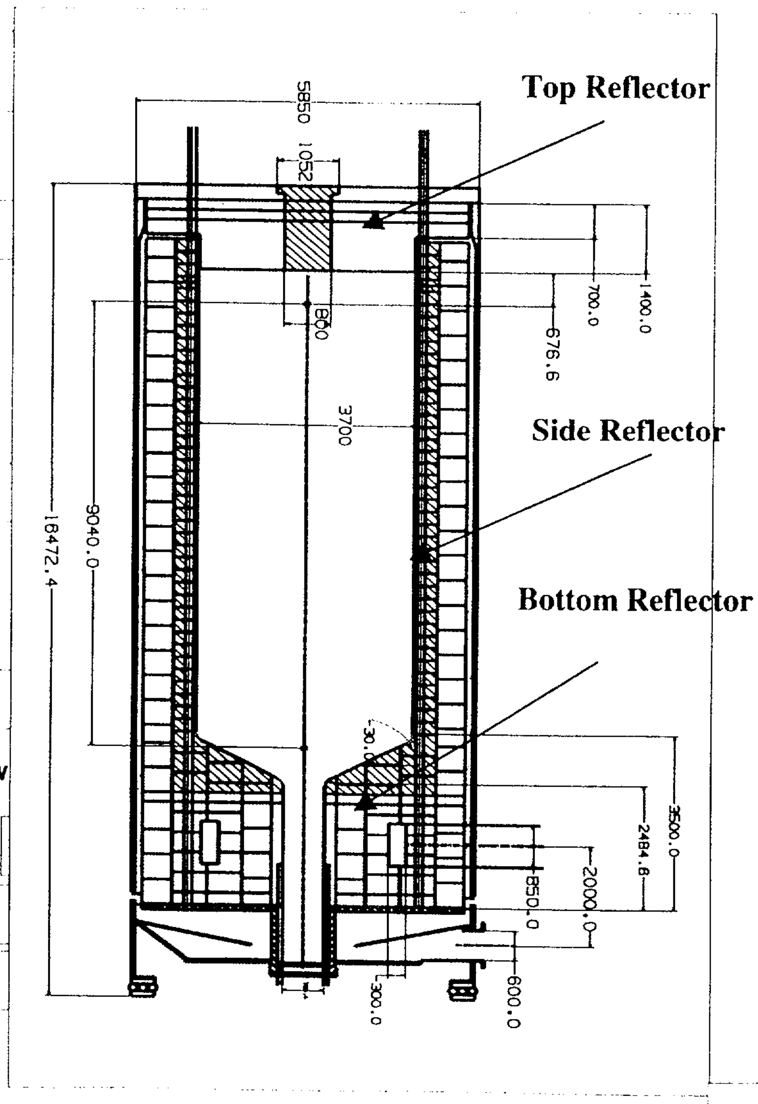
PBMR Design –
Main Power System

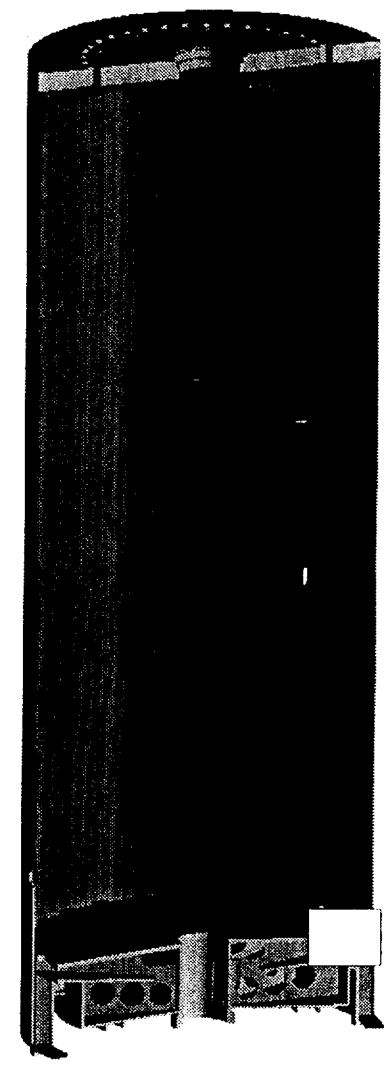


P B M R

PBMR Design –
Core Structures 1

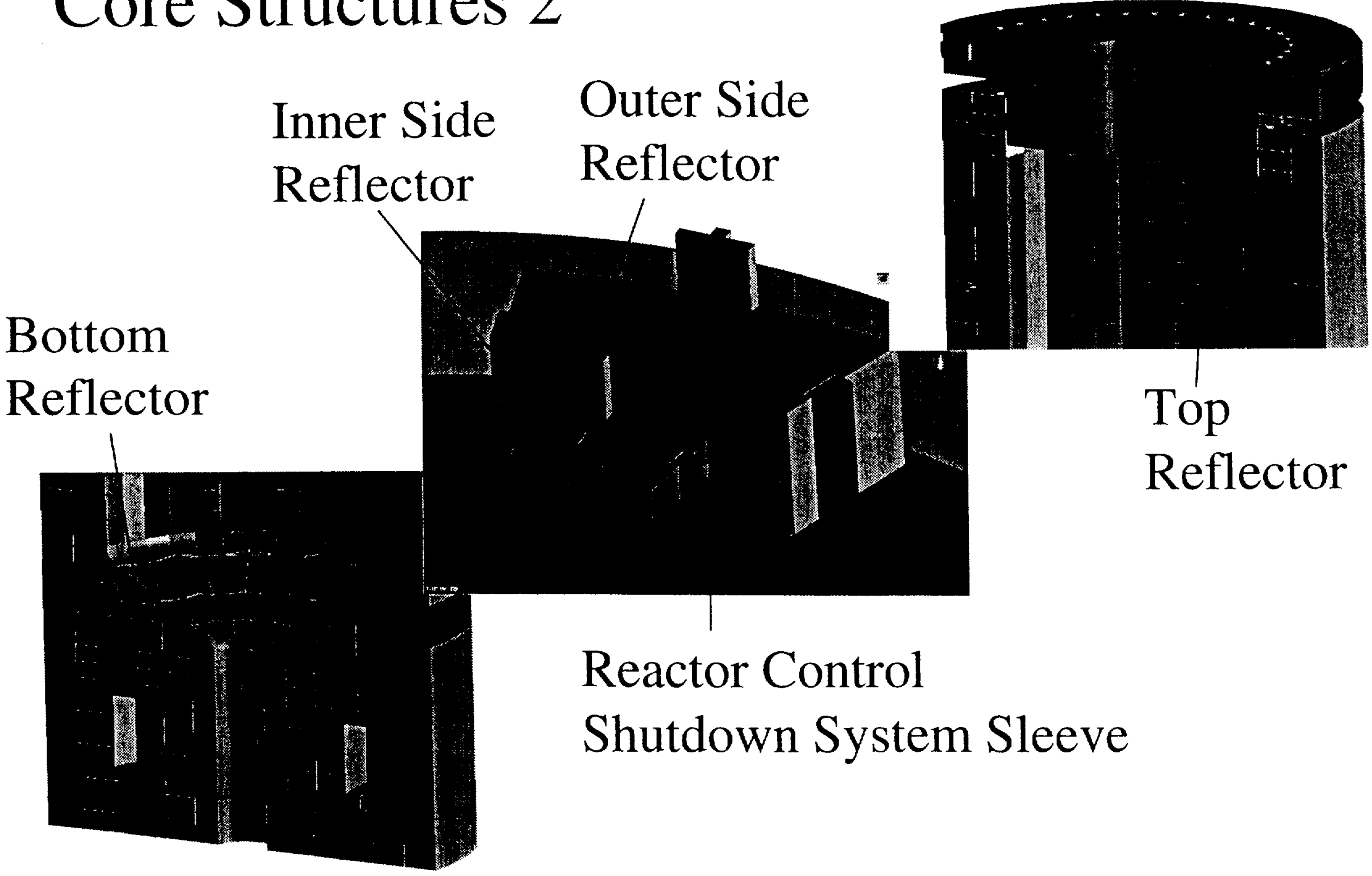




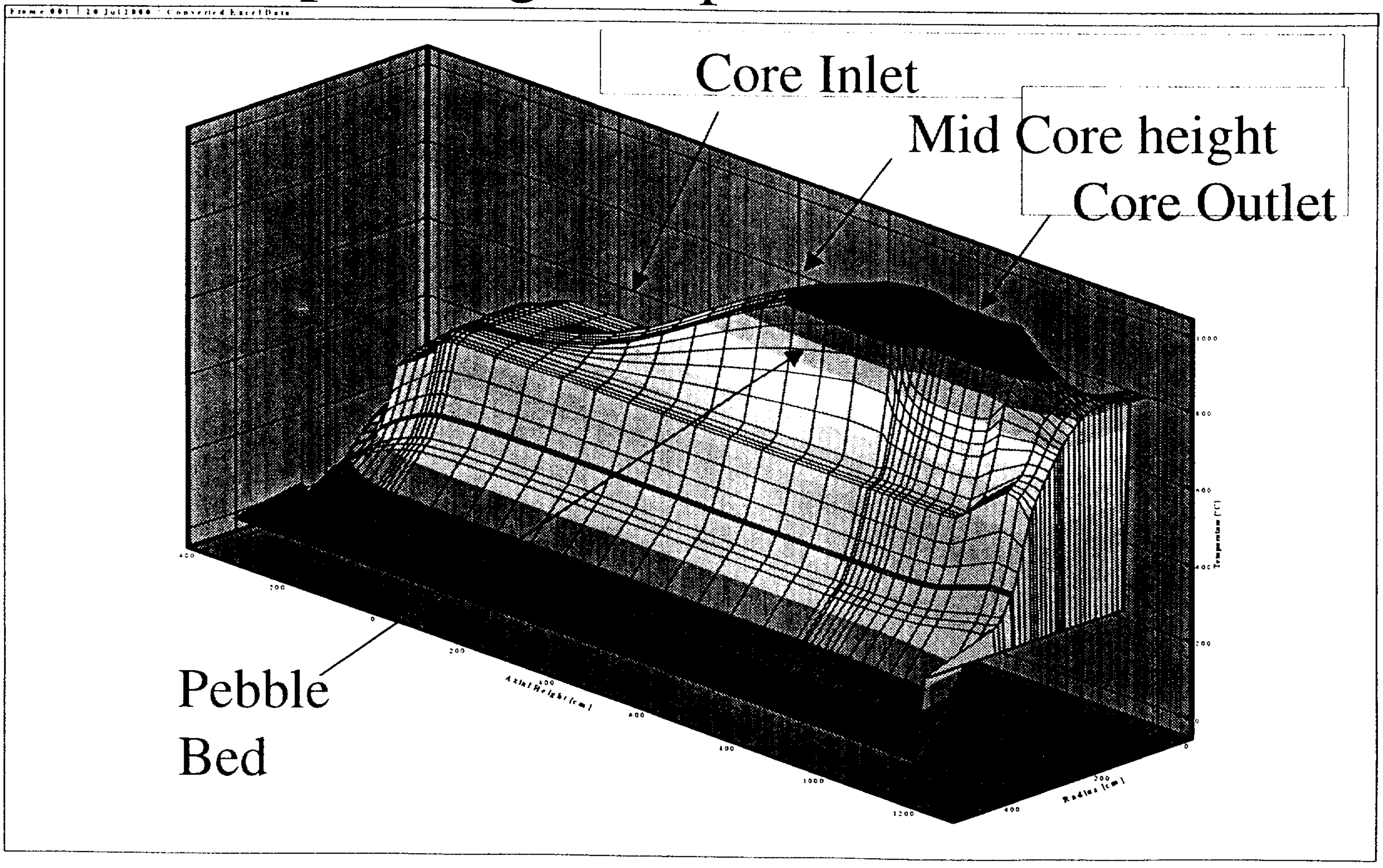


PBMR Design –

Core Structures 2

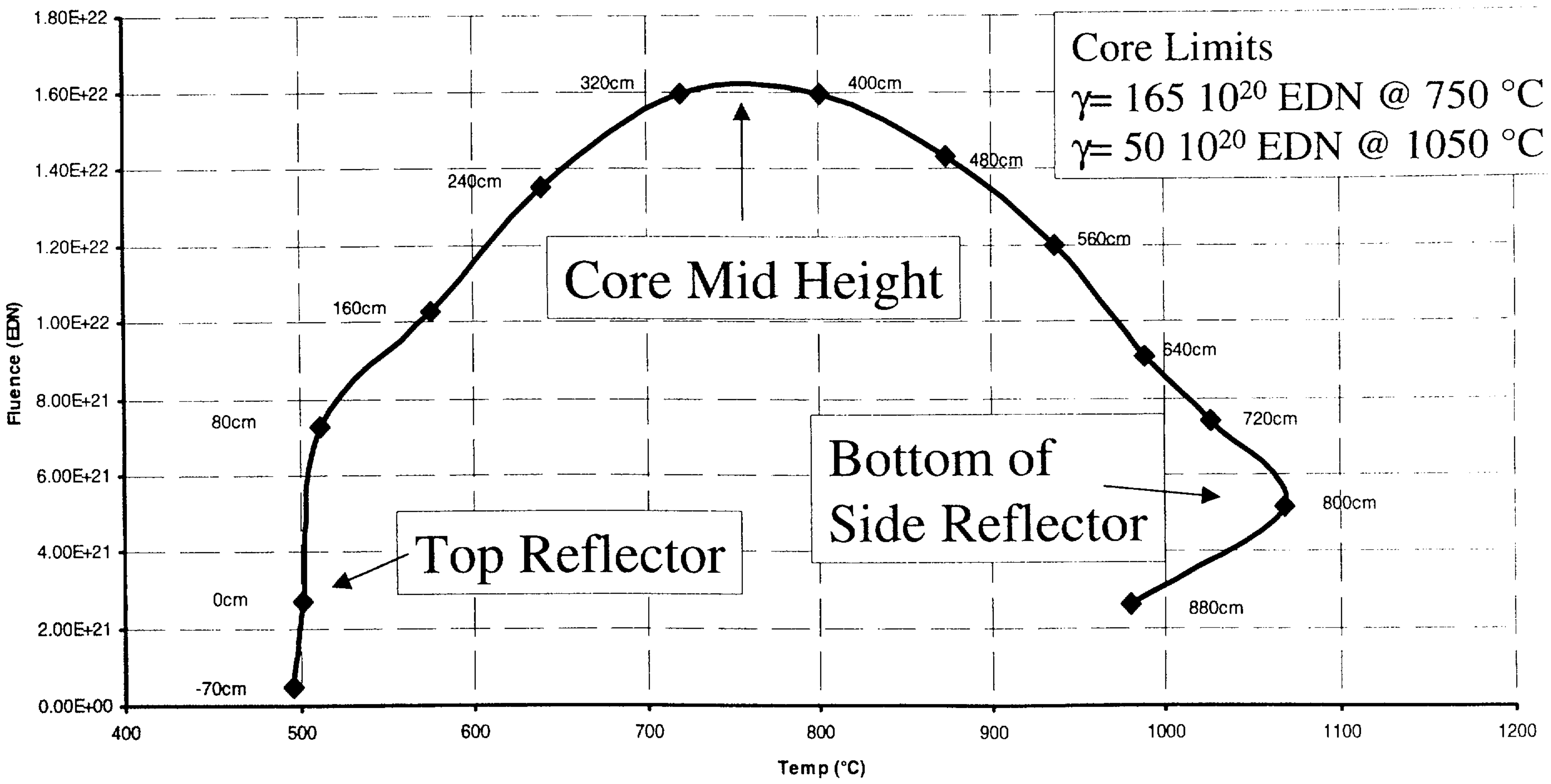


PBMR Reactor Data –
Normal Operating Temperature



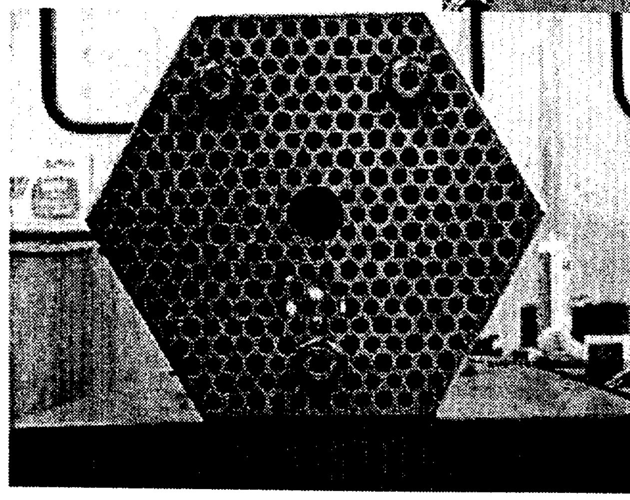
PBMR Reactor Data –

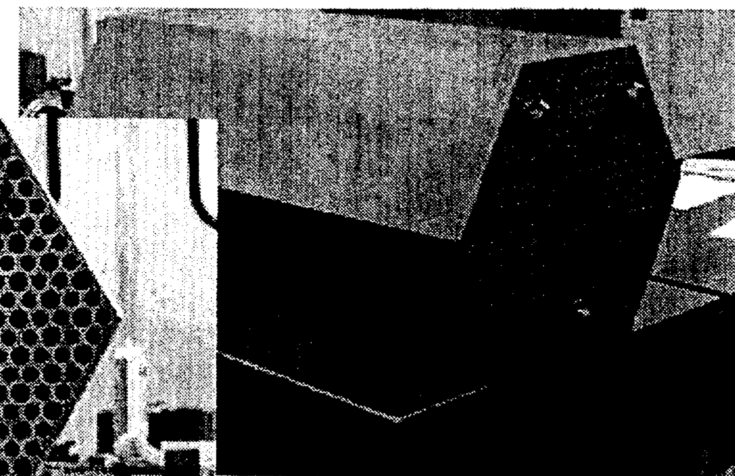
Fluence EDN (7.62 10^{20} n/cm^2 EDN $\equiv$ 1 dpa)



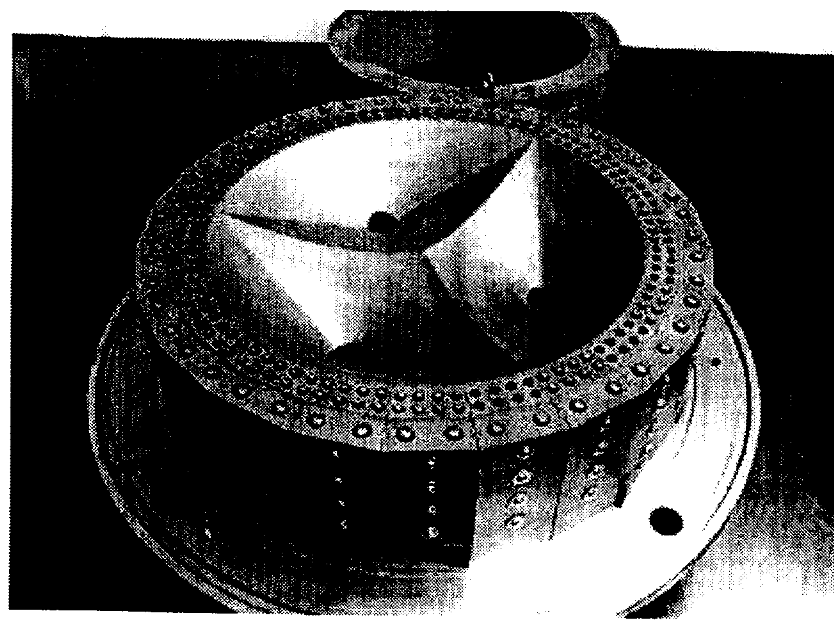
Nuclear Graphite Manufacture

UK AGR
Fuel Sleeve





US GA
Prismatic
Fuel Design

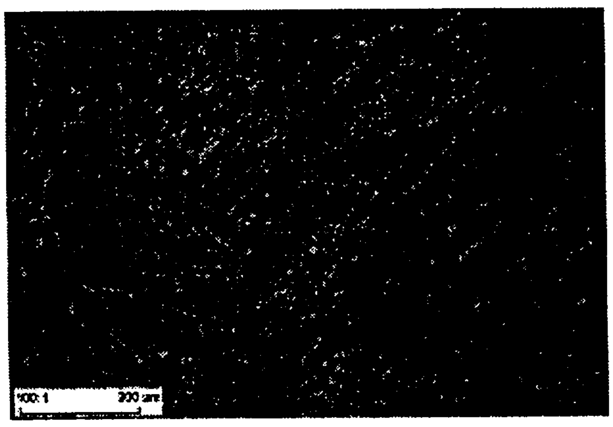


German
HTR 500
1/5 Scale

Nuclear Graphite Manufacture

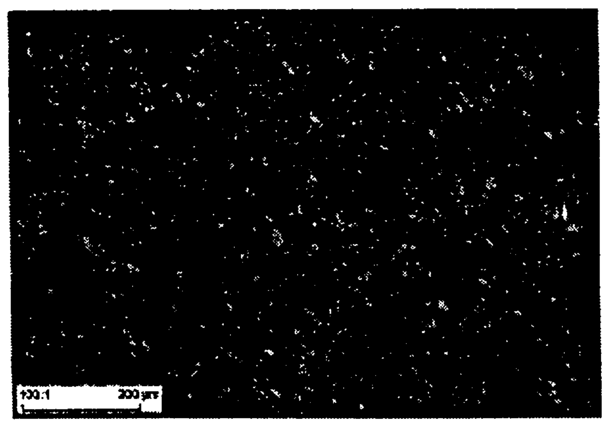
Particle size of different materials

Coarse grain



Electrodes

Medium grain

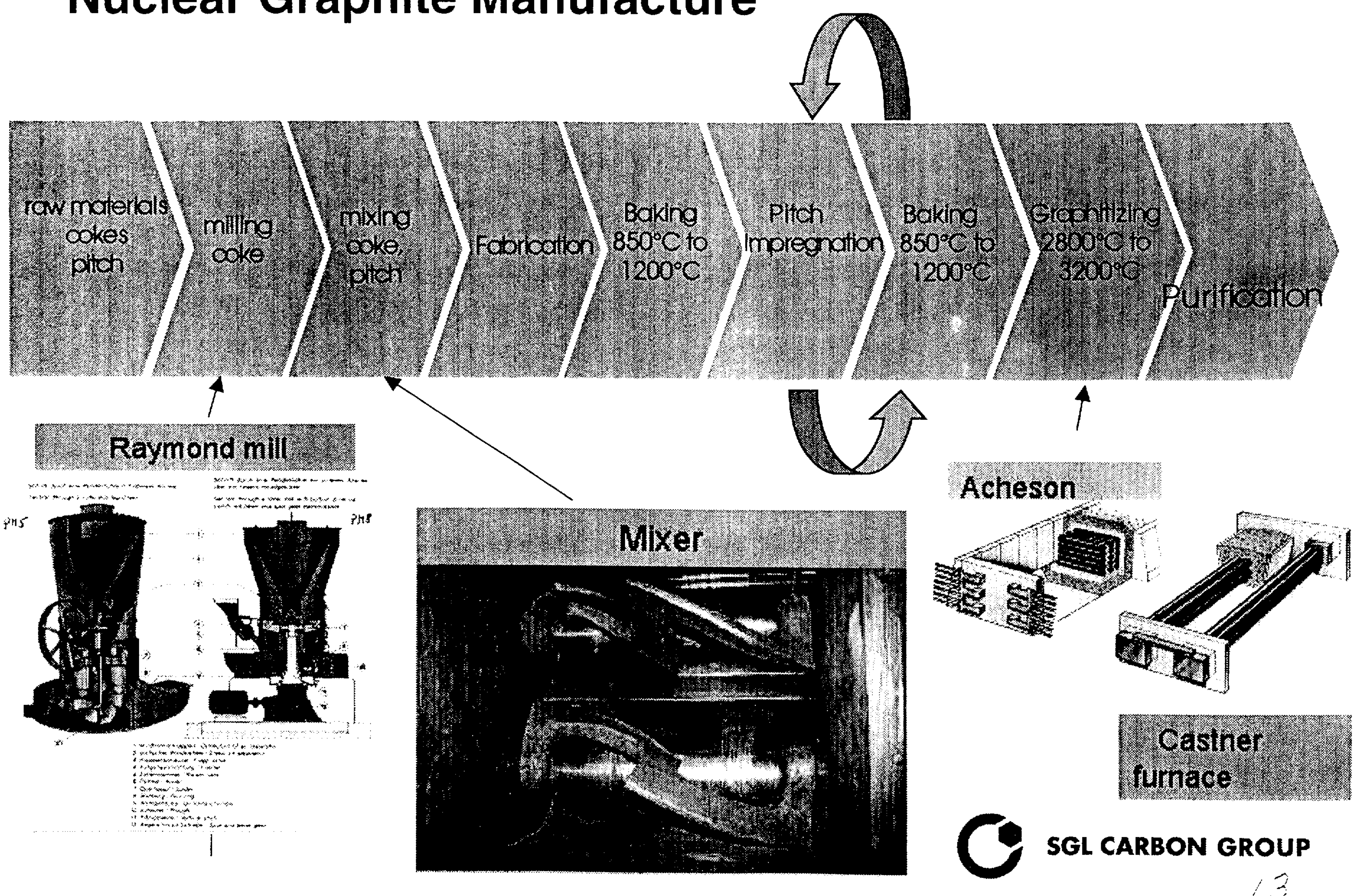


Most Nuclear Applications, e.g. MAGNOX, AGR, AVR, THTR

Fine grain

Recent Nuclear Applications, e.g. HTTR, HTR-10

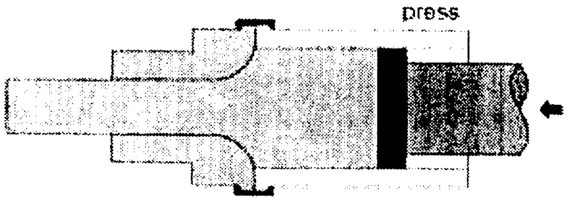
Nuclear Graphite Manufacture

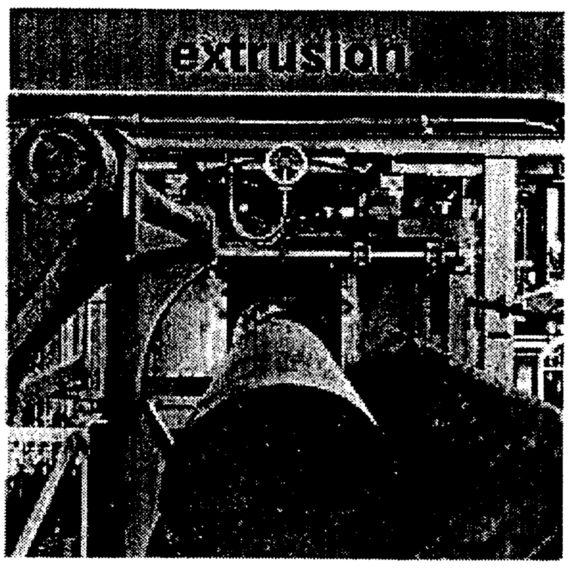


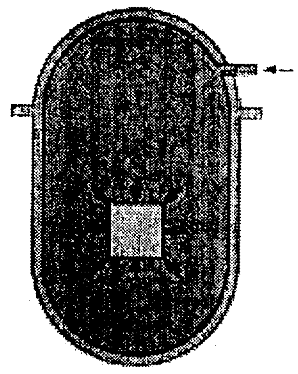
PBMR

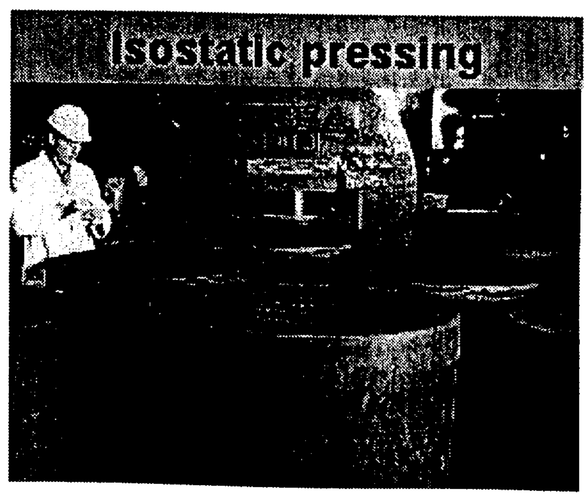
Nuclear Graphite Manufacture

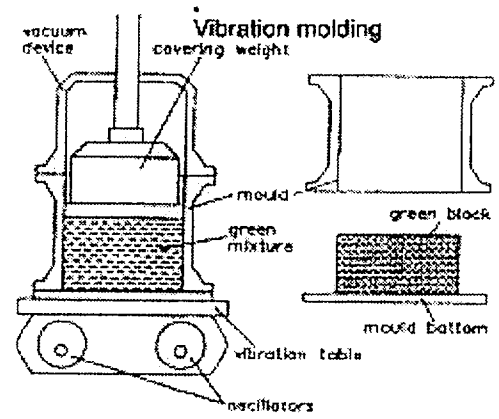
Fabrication techniques

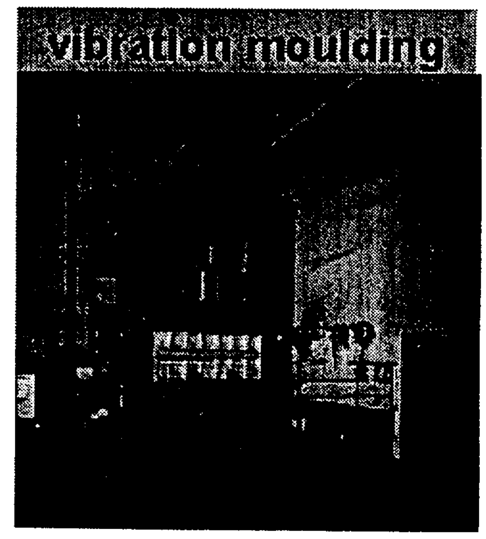












SGL CARBON GROUP

Manufacturing Summary

- The properties of Nuclear Grade Graphites can be determined by suitable choice of
  - Raw Materials
  - Grain size
  - Manufacturing Route
    - Fabrication
    - Impregnation
    - Purification

PBMR - SGL Unirradiated Material Properties

Property	Sleeve	Grade 1	Grade 2	Iso	Sasol
Density ($10^3 Kg/m^3$)	1.79	1.75	1.79	1.82	1.79
Thermal Conductivity @ Room Temperature (W/m.K)	Not known	130	130	133	130
CTE 20-200 °C (10^{-6} K)	4.35	4.2	4.4	4.1	4.7
Neutron Absorbancy (mBarns)	4.62	4.5	5.4	4.0	12
Compressive Strength (MPa)	72	55	65	100	70
Modulus of Elasticity (GPa)	8.9	9	10	10	10
Poisson's Ratio	0.21	0.21	0.21	0.21	0.21
Anisotropy Ratio (Par/Per)	1.1	1.1	1.1	1.1	1.1

P B M R

PBMR – SGL
Material Impurities ppb

	Element	Li	Be	B	Na	Mg	Al	K	Ca
Typical		2.1	380	250	310	45	680	79	2.6

	Element	Sc	Ti	V	Cr	Mn	Fe	Co	Ni
Typical		15	3.8	100	16	75	500	3.4	37

	Element	Cu	Zn	Ga	Ge	Se	Rb	Sr	Y
Typical		43	40	3.2	24	21	2.7	2.5	5.7

	Element	Zr	Nb	Mo	Ru	Rh	Ag	Cd	In
Typical		3.7	1.9	12	6	1.9	3.7	15	150

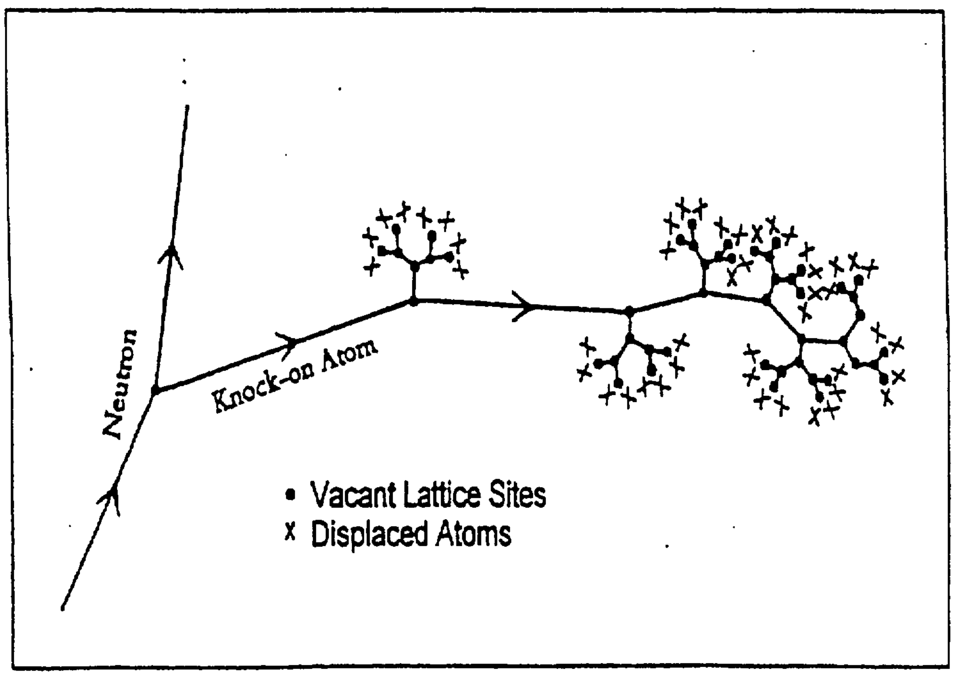
	Element	Sn	Sb	Te	Cs	Ba	La	Ce	Pr
Typical		6	3.4	27	1	2	1.9	3.8	7.6

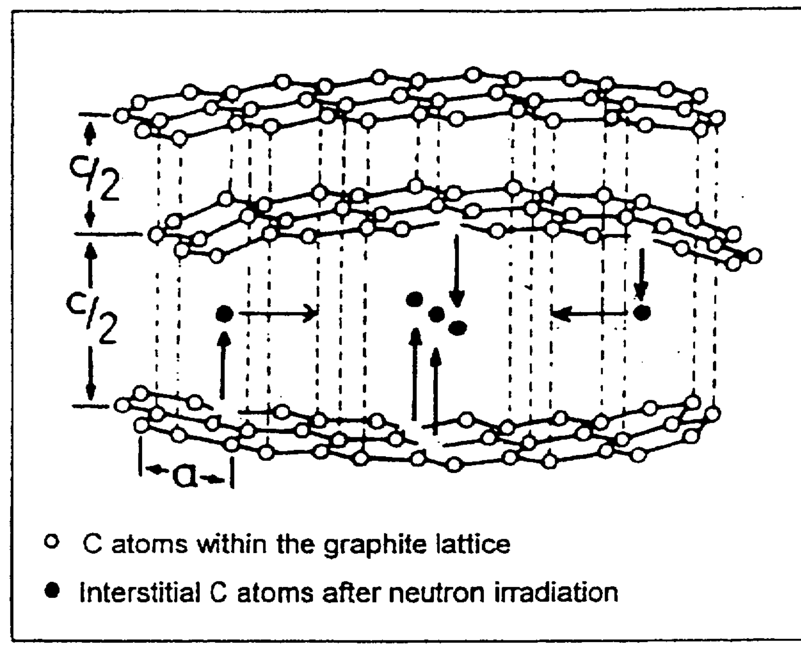
	Element	Nd	Sm	Eu	Gd	Hf	Ta	W	Re
Typical		11	13	4	12	7.1	4.1	7.3	5.2

	Element	Au	Hg	Tl	Pb	Bi	Th	U	
Typical		1.3	4.2	1.8	3.1	1	1	2.4	

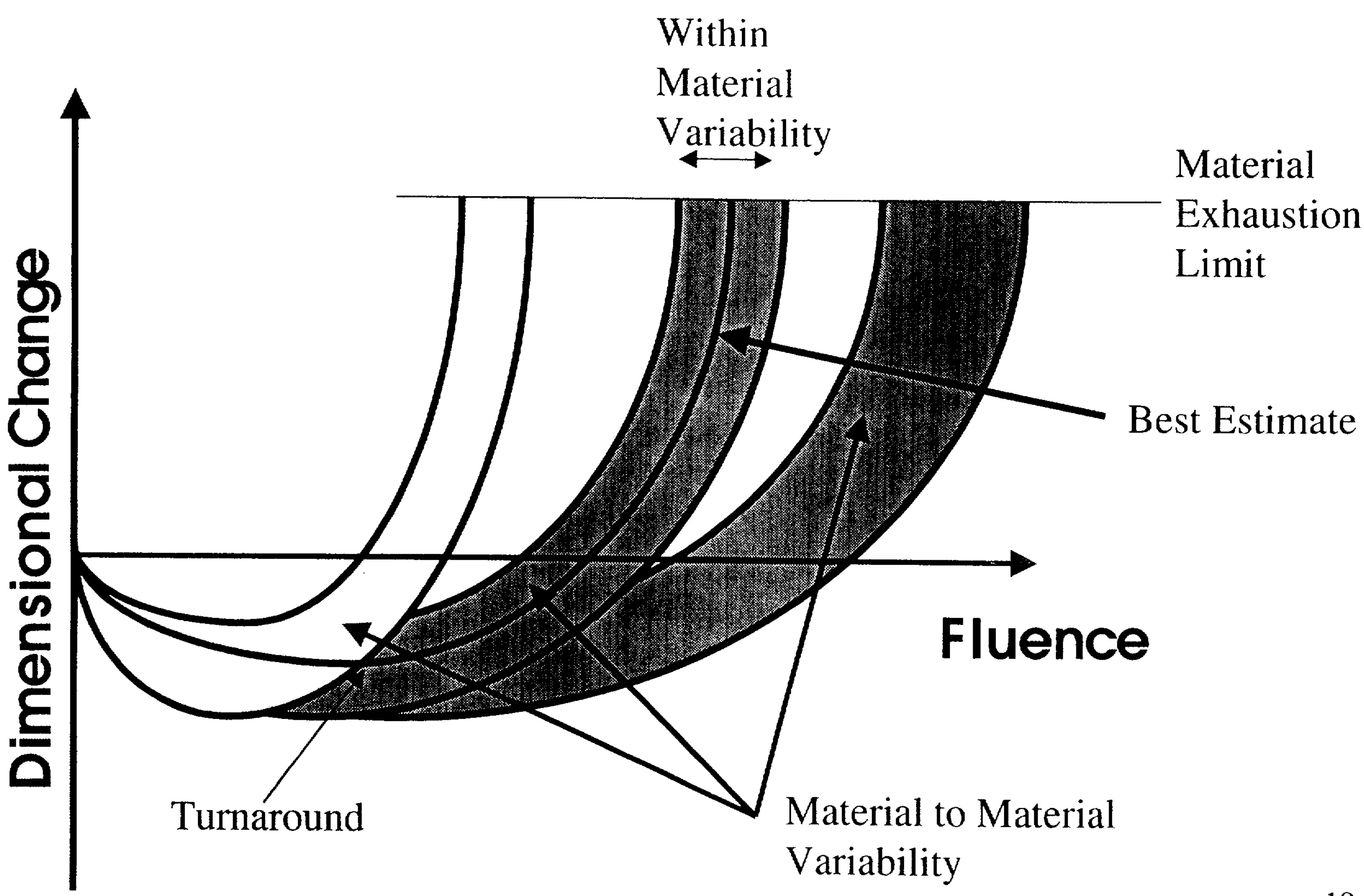
P B M R

Graphite Irradiated Behaviour





Material Property Variation



Dimensional Change

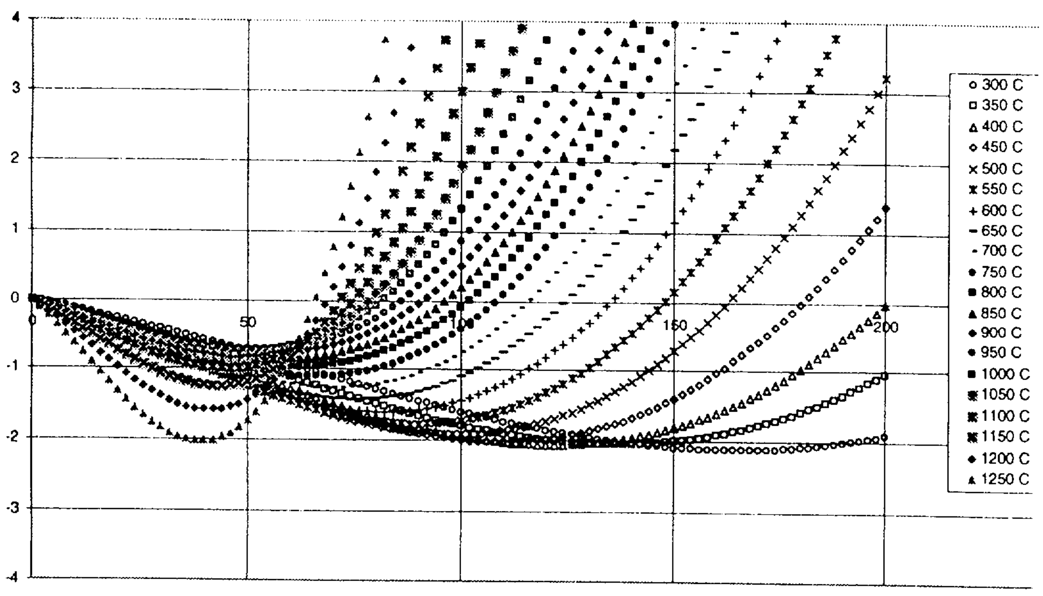


Figure 18. Perpendicular dimensional changes for generated PBMR graphite, for different values of EDT

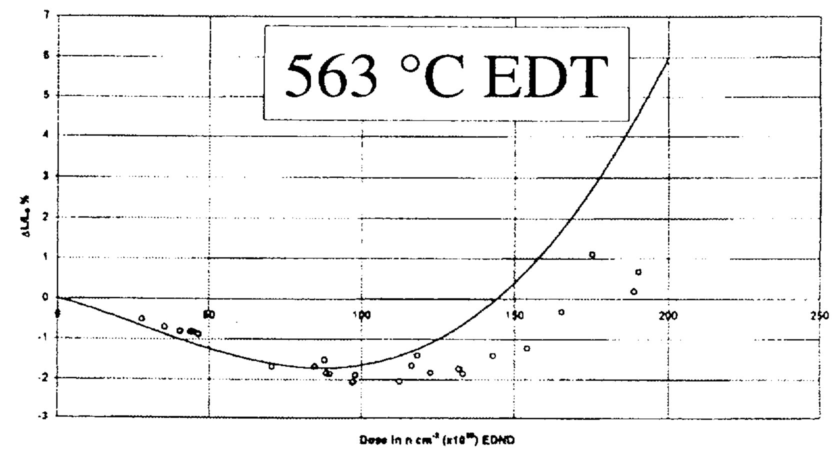


Figure 14. Comparison of predicted dimensional change curves with experimental data (perpendicular direction)

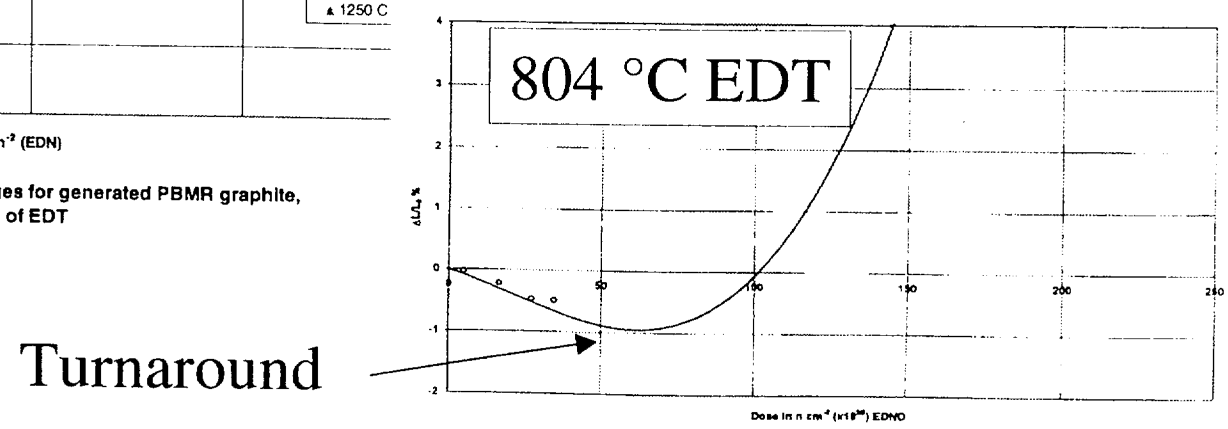


Figure 15. Comparison of predicted dimensional change curves with experimental data (perpendicular direction)

Thermal Resistivity

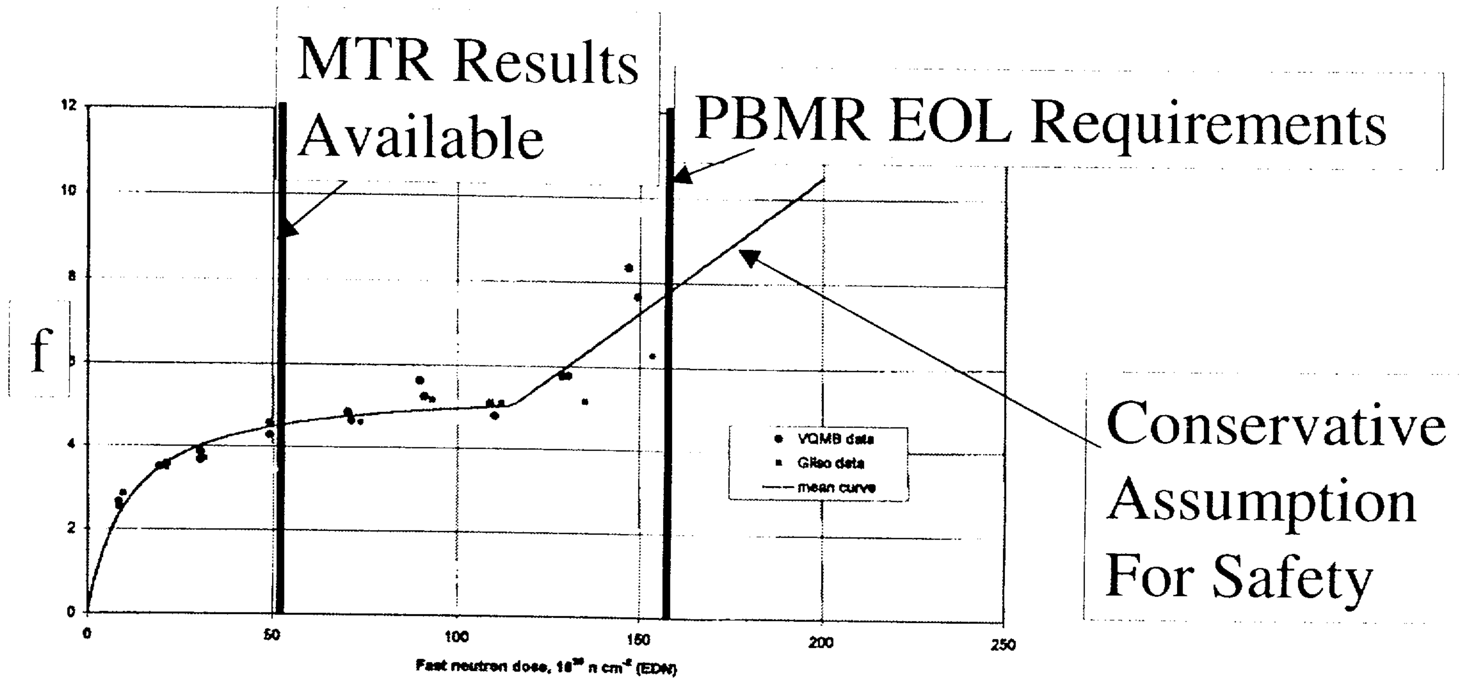


Figure 57. Thermal Resistivity changes of VQMB graphite (Temperature = 535 °C EDT)

$$\frac{1}{K_y(\gamma,T)} = S_k(\gamma)\left[\frac{1}{K_y(0,T)} + \delta(T)\frac{f}{K(0,30)}\right] \cdot \left[\frac{K_o}{K}\right]_{ox}$$

Young's Modulus

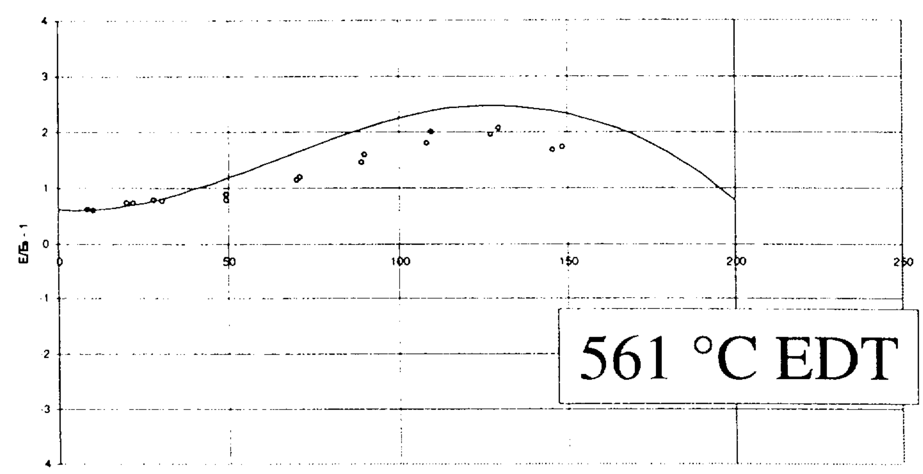


Figure 45. Young's Modulus changes, comparison of generated curves with experimental data

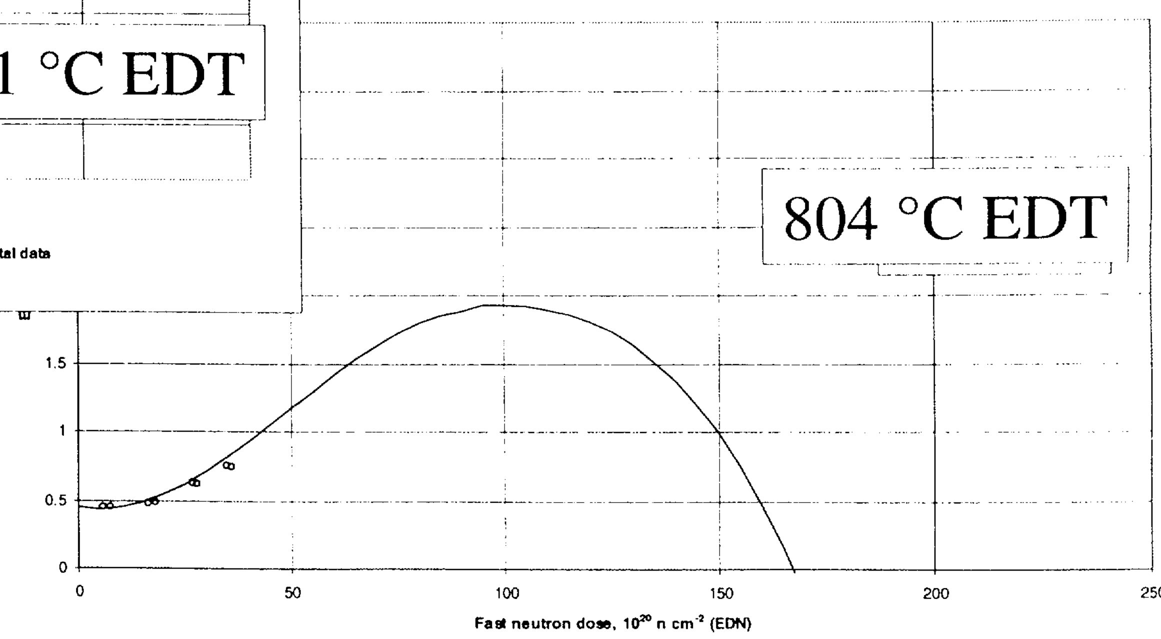


Figure 46. Young's Modulus changes, comparison of generated curves with experimental data

Irradiation Induced Creep
(Beneficial)

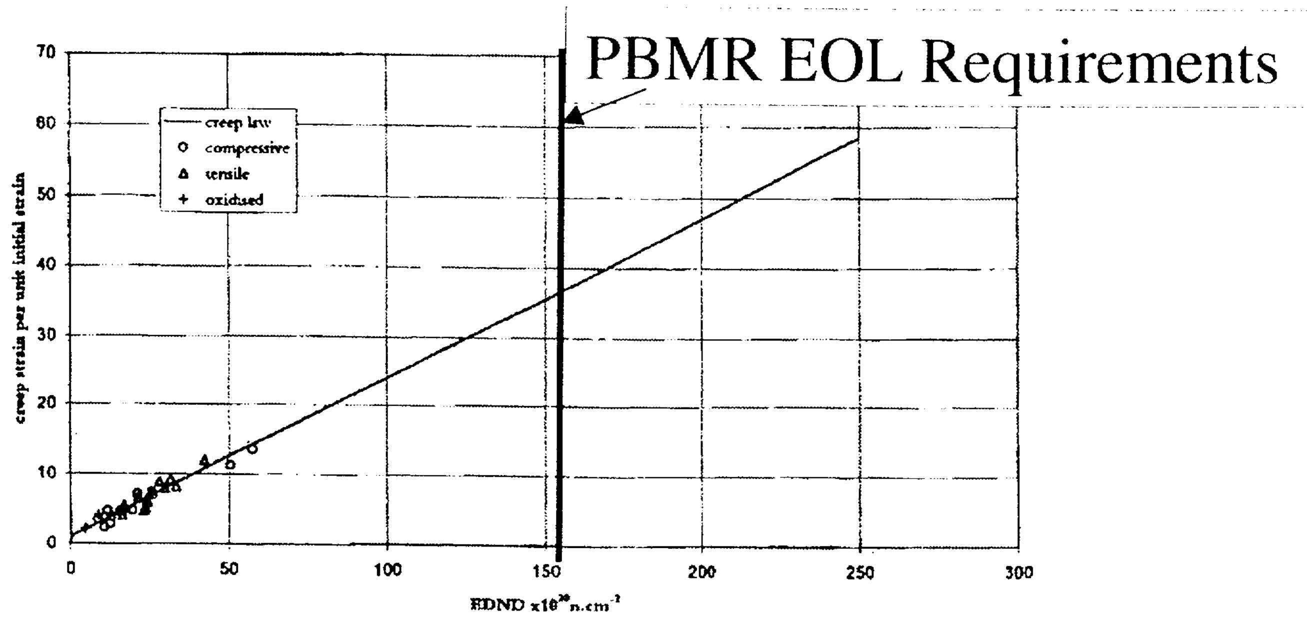


Figure 52 Constant Stress Irradiation Creep Data (Isotropic Graphite)

$$\varepsilon_c = \alpha(T_i)\frac{\sigma}{E_c}\left[1 - e^{-\frac{\gamma}{\gamma_o}}\right] + \frac{K}{E_c}\beta(T_i)\sigma\gamma$$

P B M R

Strength

- Weibull 'weakest link' theory
  - Typical Nuclear graphite Weibull Modulus = 10
- German Performance Assessment Model
  - Probability of Failure = 10^{-4}
  - Safety Factor = 2.4
- Irradiation behaviour is correlated with Young's Modulus
  - Pre turnaround (Y.M irradiation induced change)$^{1/2}$
  - Post turnaround (Y.M irradiation induced change)^{1}

Material Summary

- There is considerable graphite data, empirical relationships and operational experience available to PBMR from previous gas-cooled, graphite moderated reactor programmes, e.g. MAGNOX, AGR, AVR & THTR.
- Pre-Turnaround Graphite Behaviour

  There is a high degree of confidence that the existing graphite database is sufficient to describe the behaviour of graphites currently available to PBMR up to the point of turnaround – approximately 15 years of PBMR operation at the peak flux position (inner surface of inner side reflector at mid-core height).

Summary (Continued)

- Post-Turnaround Graphite Behaviour

  Beyond the point of turnaround there is uncertainty in the PBMR graphite database for performance assessment due to the following:

  - lack of knowledge of behaviour of graphite at high fluence (beyond return to initial volume)
  - lack of actual data for PBMR graphite
  - Validation of reactor parameters

Performance Assessment

- There are numerous different approaches to assessment of structural performance of graphite moderated cores
  - UK
  - US
  - Germany
  - Japan

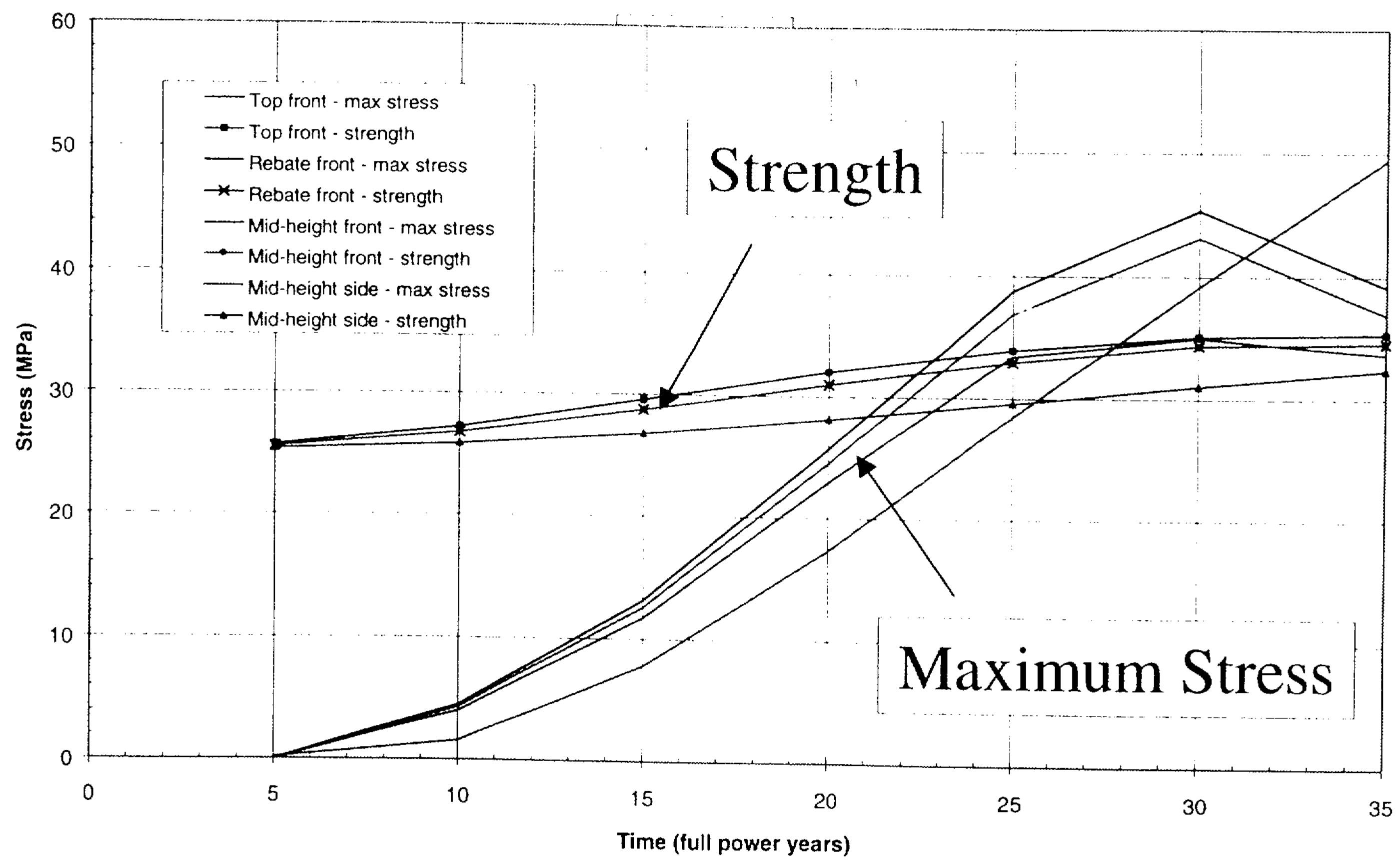
(PBMR adopted)

Structural performance

- Primary or External
    - The reflector is subject to several external loads pebble bed hydrostatic pressure, coolant differential pressure, deadweight and pebble bed 'breathing' pressure.
- Secondary or Internal
    - Under irradiation graphite exhibits significant dimensional change and material property change. These property changes can set up significant shrinkage and thermal stresses. Additionally when graphite is subjected to load it exhibits creep.

Stress Time History

Deterministic Best Estimate



Deformation

- Local deformation is caused within the block due to shrinkage strain, thermal strain and creep strain.
- Large global deformation could occur towards end of life due to the accumulation of local deformation, i.e. within a column. This may lead to
  - control rod articulation limits being exceeded
  - unacceptably high leakage/bypass flows and unacceptable peak fuel temperatures

P B M R

Material Exhaustion

- As discussed earlier at high fluence, graphite exhibits significant swelling and associated reduction in Modulus and Strength. This is a material limit and is determined by the irradiation fluence and temperature
- The limit for PBMR graphite has been nominally set to 5% swelling and some parts of the side reflector exceed this value for the assumed material data.

PBMR

Performance Summary

- PBMR has adopted a combination of German and UK approaches to graphite component performance assessment
- Up to turnaround, assuming the current graphite database, the performance assessment criteria, structural, deformation and material exhaustion, are met for the current design of the PBMR.
- At EOL, assuming the current graphite database, the performance assessment criteria, structural, deformation and material exhaustion, are not met for the current design of the PBMR.

PBMR

Risk Mitigation

- MTR Programme to determine irradiation behaviour beyond turnaround
  - To achieve PBMR fluence will require
    - 8-10 year programme at a low flux facility
    - 14 months at a high flux facility
- Inner Reflector Replacement
  - via the central Plug

Inner Reflector Replacement

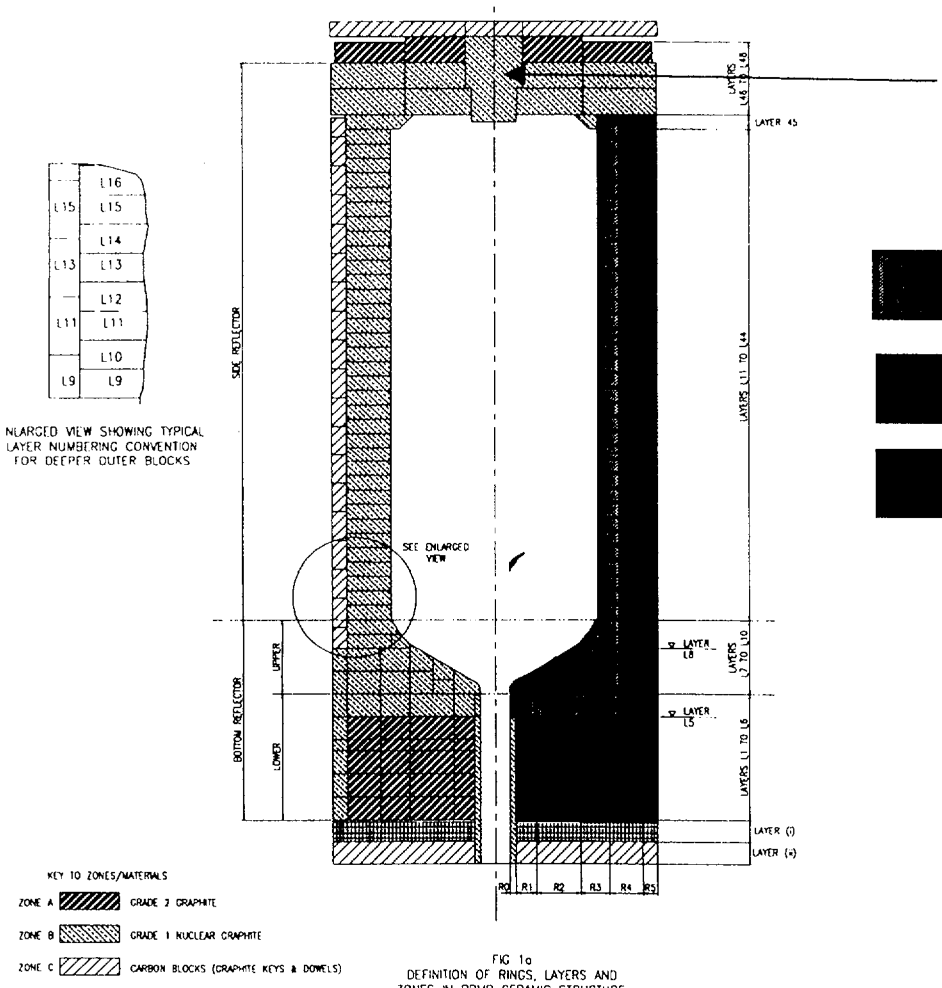


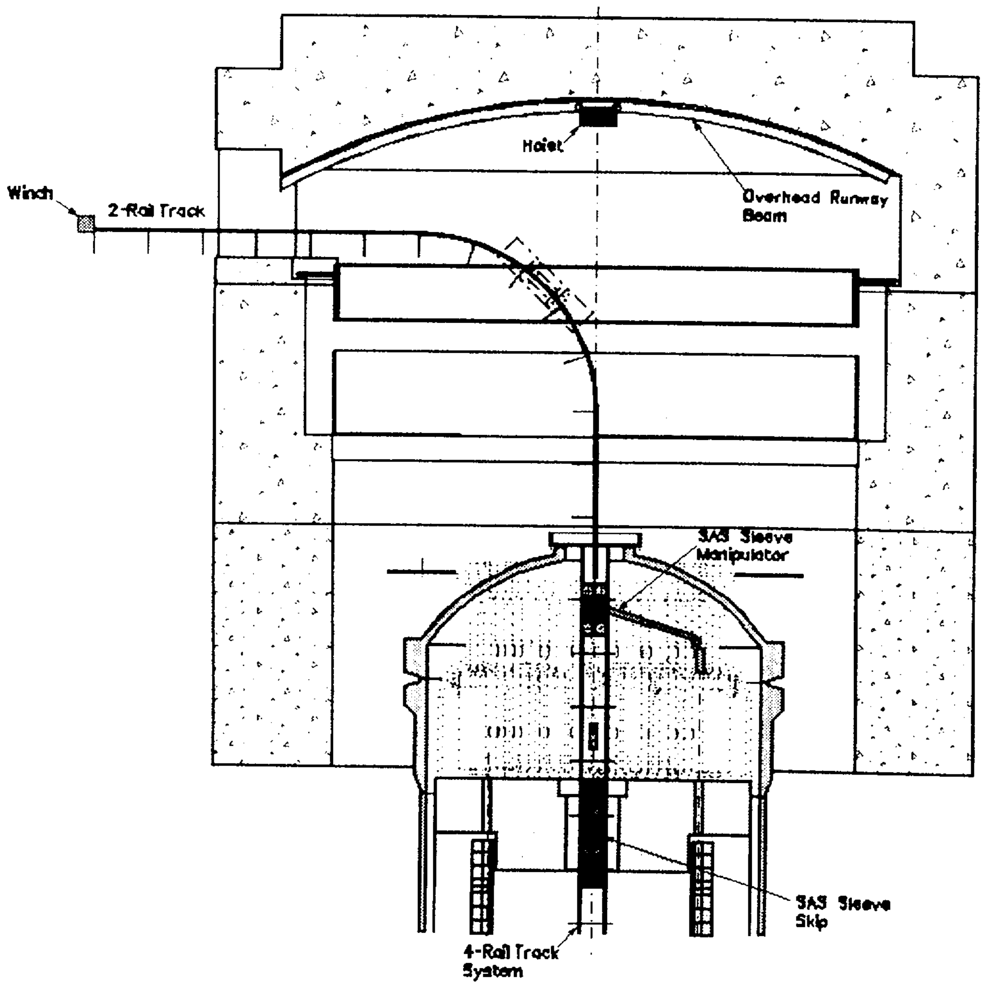
FIG 1a DEFINITION OF RINGS, LAYERS AND ZONES IN PBMR CERAMIC STRUCTURE

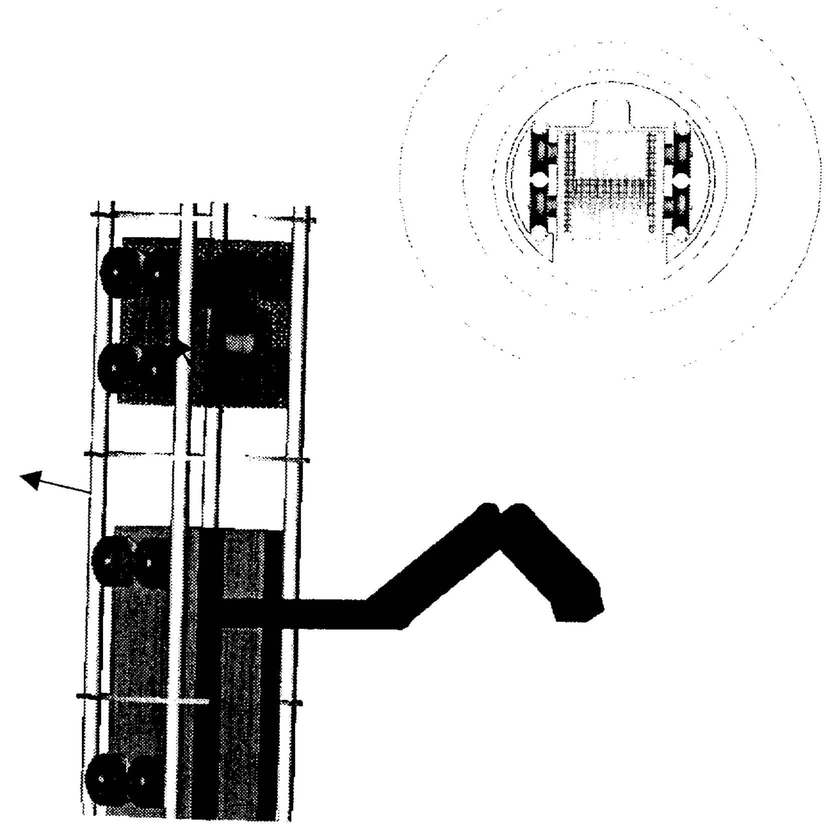
Replaceable Reflector

Permanent Side Reflector

Permanent Bottom Reflector

Inner Reflector Replacement System





Inner Reflector Replacement

- Replacement of the Inner Reflector will:
  - Mitigate risk from lifetime issues
    - Structural performance
    - Distortion
    - Material Exhaustion
  - Increase margin to peak fuel temperature limit (lower thermal resistivity @ EOL)
  - Allow continued operation w/o replacement subject to satisfactory MTR programme results

Conclusions 1

- There is substantial experience in operating gas-cooled, graphite moderated reactors around the world, e.g. UK.
- Suitable Nuclear Grade Graphites can be determined by appropriate choice of manufacturing process parameters

Conclusions 2

- Sufficient information is available to justify PBMR operation up to the point of turnaround, approximately 15 full power years at the peak flux position.
- Graphite Technology is still mainly empirical, especially at high fluence and temperature and uncertainty exists in the material database assumed for PBMR beyond turnaround

Conclusions 3

- A MTR programme is required to characterise PBMR graphite and to remove uncertainty associated with performance assessment of PBMR graphite components beyond turnaround
- The risks associated with performance of graphite components in PBMR can be mitigated by replacement of the inner reflector