



LICENCE DOCUMENT

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LD-1097	Qualification Requirements for the Core Structure Ceramics of the Pebble Bed Modular Reactor	0

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1 PURPOSE

This Licence Document (LD) details the requirements (indicated with numbers), and recommendations of the National Nuclear Regulator (hereafter referred to as the NNR) to be considered by ESKOM and PBMR (Pty) Ltd, for the introduction of a Material and Structure Qualification Programme for the Core Structure Ceramics (CSC) to be used in the Pebble Bed Modular Reactor (PBMR). The requirements contained in the document are mandatory and have to be adhered to. The CSC comprise all carbon and graphite components used for the reactor structures (reflectors) of the PBMR within the Reactor Pressure Vessel (RPV).

The objective of a Core Structure Ceramics Qualification Programme (CSC-QP) is to provide adequate confidence in the efforts expended for qualification and to ensure that scientifically sound standards and specifications will be applied. By means of a CSC-QP it must be ensured that the probability of failures of the CSC will be minimized and the consequences of such failures will be acceptable in terms of the licensing criteria defined in LG-1037: "Basic Licensing Requirements for the PBMR" /1/ for the workers, the public and the environment.

This objective is of particular importance since the irradiation behaviour of the CSC may depend significantly on the basic material properties and on the effect that operational impacts like fast neutron flux and temperature have on these properties over the design lifetime.

Since the CSC material properties are modified by fast neutron irradiation the following material properties are important for the design and safety of the PBMR /2/:

- Dimensional stability
- Thermal conductivity and thermal expansion
- Mechanical strength and Young's modulus
- Irradiation induced creep behaviour

Modifications of these properties and changes to the core structure as a whole during steady state operation over life and during transients require the consideration of, amongst others the following principal safety issues:

- Integrity of CSC components and of the core assembly
- Functioning of the core shutdown devices
- Passive core heat removal
- Helium bypass flows to the core / hot gas impact to metallic core internals
- Neutron and thermo-hydraulic characteristics
- Shielding of the surrounding steelwork

With respect to the licensing process, ESKOM and PBMR (Pty) Ltd are responsible for the design, construction, operation and decommissioning of the PBMR. This includes also full responsibility to introduce and implement the CSC-QP together with the demonstration of compliance with the requirements and consideration of the recommendations set out in this Licence Document. In exceptional cases alternatives to specific requirements of this Licence Document may be used when authorized by the NNR. A respective justification has to be submitted by Eskom/PBMR (Pty) Ltd before such an authorization can be granted.

2 SCOPE

This Licence Document (LD) stipulates the requirements and recommendations for the qualification of the CSC (graphite and carbon) materials and structures, and the quality control aspects related to the manufacturing processes of the graphite and carbon

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components, to be used for the various regions of the PBMR core. It also covers the requirements and recommendations for surveillance of the CSC from the construction stage up to the decommissioning of the plant.

This LD covers especially the following aspects:

- Selection of material and definition of required properties
- Manufacturing processes and quality assurance
- Qualification of material and irradiation testing
- Qualification of structures and assembly

It is based on the respective sections of the draft German standard KTA-3232 /4/.

The graphite matrix material of the fuel is not covered by this LD.

3 ABBREVIATIONS, TERMS AND DEFINITIONS

Term or Abbreviation	Definition
AC	Acceptance Criteria
Against-grain	The direction of the crystal lattice in a carbon or graphite body with preferred orientation that has the maximum c-axis alignment as measured in an x-ray diffraction test.
AGR	Advanced Gas cooled Reactor
AOA	Area of Application
Baking	Part of the production process of the CSC; the material is heated up to temperatures of about 1000°C to remove volatile material
Basic material	Graphite blocks at the end of the graphitisation process, these blocks will be finished mechanically to get the respective CSC dimensions
Compressive stress	The stress applied to materials resulting in their compaction (decrease of volume).
CSC	Core Structure Ceramics
CSC-DC	Core Structure Ceramics Design Criteria
CSC-IP	Core Structure Ceramics Irradiation Programme
CSC-QP	Core Structure Ceramics Qualification Programme
Dose (fluence)	A measure of the cumulative fast neutron irradiation received by the graphite
External loading (stresses)	The loading a component experiences by interaction with other components (by direct contact or via a keying system)
Forming	Part of the production process of the CSC; the raw material is formed into blocks of the required shape
FSF	Fundamental Safety Functions
GOR	General Operating Rules
Graphitisation	Part of the production process of the CSC; the material is heated up to temperatures of approximately 2800°C to increase the amount of hexagonal matrix of the crystal lattice inside the material
Heat (number)	Each single graphitisation run is generally referred to as a "heat" and is identified by a specific number
HTR	High Temperature Reactor
Impregnation	Part of the production process of the CSC; the baked material is impregnated with pitch to increase density

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Term or Abbreviation	Definition
Ingredients	Raw materials used for and during the manufacturing process of the basic material (coke, binder etc.)
Initial material	The first batch of material produced for the PBMR, which becomes the basis for further batches of the material after appropriate testing.
Internal loading (stresses)	The loading a component experiences due to internal variations in strain. The variations will arise due to fluence and temperature gradients. Stresses that arise due to differential irradiation induced shrinkage strains are referred to as shrinkage stresses and are always present. Those that arise due to variations in the coefficient of thermal expansion and temperature changes are referred to as thermal stresses and are transient.
ISI	In-Service Inspection
Manufacturing and Test Plan	Plan for manufacturing and/or testing of products listing the individual steps of the process and referring to the standards and specifications to be applied as well as defining the QA measures during manufacturing and/or testing including the hold and witness points of PBMR (Pty) Ltd and/or the NNR.
Must	"must" indicates mandatory requirement
MTR	Material Test Reactor
PIE	Postulated Initiating Event
Qualification and Test Programme	Overall programme on qualification and testing of materials or components. A Qualification and Test Programme covers several Test Plans.
QM	Quality Management
QSM(S)	Quality and Safety Management (System)
Reference material	The material tested in the past taken as a reference for the material to be produced for the PBMR
Should	"should" indicates a recommendation or an example of good practice
SSC	Systems, Structures and Components
Stress/strain analyses	Determine the stresses and strains in individual components caused by irradiation induced shrinkage, transient temperature changes, and external loading (static or dynamic)
V&V	Verification and Validation
With-grain	The direction of the crystal lattice in a carbon or graphite body with preferred orientation that has the maximum a-axis alignment as measured in an x-ray diffraction test.

Specific terms related to the CSC (graphite) materials and properties can be found in EPRI document "Graphite for HTRs" /2/.

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4 QUALITY MANAGEMENT REQUIREMENTS

4.1 Requirements Regarding ESKOM and PBMR (Pty) Ltd

The following requirements (indicated in *Italics*) are strictly related to and already defined in /3/ as overall QM and SM requirements. Due to the high safety importance of the CSC for the PBMR these requirements are repeated here to indicate the need of specific adherence for the CSC qualification process.

- *ESKOM and PBMR (Pty) Ltd are responsible for the performance of the PBMR facility and must issue and submit documents that define the QM Process for the CSC for acceptance by the NNR. ESKOM and PBMR (Pty) Ltd must introduce such documents in the CSC design, manufacturing and qualification process.*
- *The QM System for the CSC must define the organisational structure and interfaces for the design, qualification and manufacturing process for the CSC, including all QA measures during these processes.*
- *If changes of accepted QSM documentation or an approved CSC-QP are required they must be indicated and submitted to NNR for review and acceptance.*

In addition the following requirements which are specific to CSC have to be fulfilled:

- (1) It must be ensured by the QSM System for the CSC that the CSC are designed using sound engineering/scientific principles and appropriate standards. Design work, including amendments, must incorporate applicable requirements and design bases. As part of the QSM Process the adequacy of the CSC design and corresponding characteristics must be verified and validated.
- (2) If previous experiences with nuclear grade graphite and CSC and records thereof are used for licensing purposes, this information must be submitted to a comprehensive V&V process.
- (3) The QSM documentation must include the specific design criteria of the CSC derived from the Safety Case Philosophy (and Safety Case) and the general design criteria defined in the PBMR design envelope.
- (4) The demonstration of compliance with the CSC design criteria must be the main objective of the CSC-QP (see 6.1).

Remark: Requirements regarding CSC design criteria are defined in Section 6.1.1.

4.2 Requirements Regarding the Manufacturers

The following requirements (indicated in *Italics*) are strictly related to and already defined in /3/ as overall QM and SM requirements. Due to the high safety importance of the CSC for the PBMR these requirements are repeated here to indicate the need of specific adherence for the CSC qualification process.

- *The manufacturers QSM system must comply with the requirements of the QSM system issued by ESKOM and agreed by the NNR (see /3/ paragraph 1). The manufacturers' QSM System must be audited according to /3/.*
- *If more than one manufacturer is involved, responsibilities and interfaces must be defined in the QSM documentation (see /3/ paragraph 5 & 6).*

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- *Based on the QM requirements for the PBMR project the manufacturers must create and apply their specifications and work instructions (see /3/ paragraph 71) based on the procurement specifications.*
- *Before manufacturing, the individual manufacturing steps and QA measures must be specified by the manufacturer in Quality Plans to be agreed by ESKOM / PBMR (Pty) Ltd (see /3/ paragraph 116).*

4.3 Definition of Safety Classes and Quality Classes

Safety Functions:

- (5) In order to reach the high quality levels necessary for the adequate performance of the CSC design and safety, specific safety functions of the CSC must be defined to accommodate the functions and characteristics of the CSC.

Remark: The specific safety functions of the CSC are related to the FSF. These are:

- *Heat removal*
- *Reactivity control (reactor shut down including assurance of long term non-criticality)*
- *Radioactivity confinement*

Specific safety functions to be provided by the basic material, the CSC parts / components and the whole assembly to support the FSF are, for example:

- Thermal conductivity of CSC materials and structures with consideration given to the effects of gaps and cracks in order to allow for sufficient heat removal.
- Sealing with respect to core bypass flow, hot gas impact on metallic materials and cooling of Reactor internals.
- Integrity with respect to the core assembly and the function of the shut down system.
- CSC graphite purity and oxidation / abrasion resistance with respect to activation, contamination and radioactivity transport.
- Neutron reflection with respect to the shielding of irreplaceable structures with limited allowable fluences.
- Prevention of pebble cluster formation and subsequent pebble flow blockage by appropriate design of reflector surfaces to the pebble bed.

Safety Classes and Quality Classes:

- (6) The CSC components must be safety classified according to the requirements of the classification system defined for the PBMR with respect to the related safety functions of the components and the consequences of failures.
- (7) According to the classification methodology for the PBMR the CSC components must also be allocated to quality classes with respect to the type / nature of the components concerning their failure probability.
- (8) For these quality classes adjusted measures for Quality Assurance (QA) must be specified in the specifications and other appropriate documents (Manufacturing and Test Plans).

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4.4 Requirements for Manufacturing and Accompanying Inspection

The following requirements (indicated in Italics) are strictly related and already defined in /3/ as overall QM and SM requirements. Due to the high safety importance of the CSC for the PBMR these requirements are repeated here to indicate the need of specific adherence for the CSC qualification process.

- *For the inspections throughout the manufacturing process adequate standardised measures must be installed for demonstration of compliance with the acceptance criteria. Thereby the requirements of /3/ must be considered.*
- *A comprehensive procurement specification must be produced (see /3/ paragraph 69) and must specify the QA requirements according to the safety classes and quality classes (see 4.3) and the control steps and hold and witness points to be considered during the manufacturing process (see /3/ paragraph 88).*
- *The documents defining the QA measures and hold and witness points for the manufacturing process must refer to the individual requirements and conditions based on the approved material specifications and the manufacturing and test equipment. Hold and witness points for inspections by the charged/independent inspecting institutions must be identified in these plans (see /3/ paragraph 116). All control and inspection steps of the CSC parts / components must be conducted based on approved specifications, manufacturing drawings and procedures.*

In addition the following requirements which are specific to CSC have to be fulfilled:

- (9) The specification of the materials and ingredients of the moulds and of the parts to be delivered must be included within the specification of the CSC.
- (10) Tests to be performed on specimens must also be included in the procurement specification.
- (11) The CSC manufacturing process and the respective Quality Assurance (QA) measures must adequately reflect the CSC design- and acceptance criteria.
- (12) The manufacturing conditions and allowable manufacturing tolerances must be defined.
- (13) The blocks and other components must be identifiable during the whole manufacturing process to allow full traceability through the forming, baking, impregnation, graphitising and machining stages (see /3/ paragraph 110).

Remark: Standard parts such as keys and dowels may be identified by lots with reference to the block they are made of.

- (14) Requirements for treatment of deficiencies:
 - It must be ensured that all predefined parameters will be checked by the manufacturer and by the inspection institution appointed in the Manufacturing and Test Plan before delivery of the parts / components.
 - All parts / components affected by deviations must be marked and separated by the manufacturer.
 - A separated component can be accepted only after a detailed judgement of concerned safety and technical aspects resulting in positive decisions. This judgement must be based on a documented post-processing procedure.

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5 MATERIAL QUALIFICATION OF THE CORE STRUCTURE CERAMICS

5.1 Past Experience

Remark: Substantial knowledge has already been gained regarding the properties of many different graphite and carbon materials and the way in which the properties of the different graphite materials are modified by fast neutron irradiation at different temperatures. However, the specific graphite materials previously used for the HTRs are potentially not available for the PBMR.

Owing to the conditions to be expected in the PBMR (neutron flux, temperatures and specific loads) and design differences, the experience on carbon and graphite materials from previous graphite reactors is not completely transferable to the PBMR. Thus the selected materials have to be appropriately qualified using test programs and other measures to determine the irradiation behaviour and other important properties.

- (15) When past experience is to be used, the differences between the reference materials from the past and the PBMR basic materials are to be considered and addressed. As a minimum, the following requirements must be fulfilled:
- A clear identification of the reference materials (graphite and carbon) must be ensured to avoid a mixture of results and properties of different grades, types, manufacturing methods, impurities etc.
 - The scope of previous CSC design criteria that are important to the safety case must be identified.
 - The qualification of the reference materials must cover the PBMR design envelope.
 - The state of the art concerning CSC design, manufacturing and quality as well as test and measuring devices in comparison to the reference material must be considered.
- (16) If PBMR parameters concerning material performance and design criteria are lying outside of previous experience, justification must be given that the deviation is acceptable. Otherwise the CSC-QP must consider these issues respectively. A detailed comparison of the specifications of the PBMR-CSC with those of the reference material is required as a basis.

5.2 Specification of Basic Material

- (17) The basic materials of the CSC must be able to fulfil all defined requirements with respect to the life cycle of the CSC. Detailed specifications for the basic materials of the CSC must be compiled. The specifications must provide all the information necessary to achieve compliance of the basic materials with the standards to be applied and with the properties required for the life cycle of the CSC.

Remark: Requirements to the basic materials apply to all material properties that are needed to demonstrate compliance with the regulatory requirements set in /1/ for Category A, Category B and Beyond Category B events. These comprise strength and thermal property values for structural and thermal analysis as well as other properties which could influence the source term analyses. Examples are given in Appendix 2.

- (18) The specifications must contain details of material testing and V&V as well as the respective acceptance criteria.

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- (19) Independent from the quality assurance departments of the manufacturing company the approval of the basic materials with respect to their specification must be conducted by ESKOM CO and PBMR (Pty) Ltd. The scope of approvals required according to the quality classes of the CSC (see subsection 4.3) must be identified in appropriate documents.

Remark: The NNR reserves the right to delegate their expertises for specific purposes to third parties.

- (20) To demonstrate compliance of the materials with the specifications, documentation must be provided regarding as a minimum the following aspects:

- QA-measures
- Composition of materials (impurities)
- Type, scope of material test procedures and results.
- Physical, mechanical, thermal and chemical properties

Material Data Sheets

- (21) Material data sheets must be available for the CSC materials used in the reactor. These material data sheets must contain all relevant un-irradiated material properties with their uncertainties, and their prospective variation during irradiation with their uncertainties. These must cover the full neutron fluence and temperature range as specified by the design envelope for the PBMR.

Remark: The properties of un-irradiated material will form part of the material specification to be met by the manufacturer

- (22) All materials must be allocated to areas of applications (AOA) to be defined by ESKOM CO and PBMR (Pty) Ltd.

Remark: Examples for areas of application (AOA) are:

- *Inner reflector*
- *Outer reflector, core bearing structure, channels for hot gases*
- *Central column*
- *Core bottom*

5.3 Preconditions for Manufacturing

- (23) It must be ensured that the manufacturers of the CSC basic materials are capable of meeting the following quality requirements as a minimum:

- The manufacture of materials must utilise processes that will ensure that the specified material properties of the reference materials are met.
- Current calibration certificates must be available for the test equipment.
- Approved documentation containing manufacturing, inspections and test requirements (e.g. Manufacturing and Test Plans) in keeping with the applicable rules and standards and with respect to proof tests and inspections must be produced and made available.
- Specifications for sample preparation and subsequent material testing must be applied.
- Test specifications for destructive and non-destructive testing must be produced and applied.

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5.4 Basic Material Testing

5.4.1 General Requirements for Basic Material Testing

- (24) To ensure that the CSC materials fulfil all requirements during the life cycle, a Test Programme consisting of physical and mechanical testing and, if necessary, a CSC Irradiation Programme (CSC-IP) must be carried out that must address the CSC design criteria.

Remark: Requirements regarding CSC design criteria are defined in Section 6.1.1.

- (25) If credit shall be taken from previous material qualification programmes the following aspects must be considered and analysed in a detailed and comprehensive manner and respective documentation must be submitted to the NNR as a minimum:

- Compatibility of the previous test results with the present programme (especially CSC-IP),
- Comparability of the manufacturing process,
- Comparability of previous CSC material and test specifications with the design requirements for the PBMR,
- Scientific reliability of the data and comprehensive documentation basis,
- Applicability of experience concerning behaviour of the previous materials during reactor operation,
- Further development and investigation after finalisation of past Qualification Programs and consequences of their results to the CSC-QP

- (26) The equipment and instrumentation for the PBMR-specific tests and CSC-IP must be adequate for investigation and establishment of the specified parameters and tolerances.

5.4.2 Requirements on Statistics

- (27) For tests involving the basic material the number of test specimens utilised must be substantiated by statistical calculation, allowed variances and past experience balanced according to the required level of conservatism.

- (28) A sufficient number of samples must be tested at representative irradiation temperatures and over the full expected neutron fluence range to verify the required material properties.

- (29) Since most CSC materials are anisotropic in specific properties, equal numbers of samples must be measured in the two major directions, namely with-grain and against-grain.

- (30) Based on the statistical considerations data must be derived from the tests and applied for design analysis respectively for verification of data used in the CSC design.

Remark: Conservative data or best estimate data may be used for design analysis dependent on the approach which the designer has chosen. Requirements to justify this approach are defined in Section 6.2.3.

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5.4.3 Requirements for Tests on un-irradiated Material

- (31) Tests must be performed on the un-irradiated material, as specified in the material test programme, to demonstrate that the un-irradiated material complies with the material specifications.
- (32) If credit shall be taken from previous qualification programs, the tests must also demonstrate compliance with the properties and characteristics found in the past.
- (33) After completion of the manufacturing process, samples from each production lot must be sectioned up to provide the required number of test specimens of the required type. When required, additional quality control checks are to be developed and conducted to ensure the quality and 'equivalence' of the material with the reference material. The scope of tests and checks to be performed in later stages of CSC material development may be limited compared to the number carried out in the initial qualification programme. The selected quality checks must be such that the comparability of future material and initial material can be established in all aspects.
- (34) Depending on the AOA of the CSC, test data must be obtained on the effect of thermal oxidation on the material properties (as a minimum on strength, Young's modulus, thermal conductivity, fracture toughness) as a function of the oxidation. The determination of oxidation rates of CSC as a function of weight loss and temperature caused by a large air ingress must also be tested.

5.4.3.1 Requirement concerning Material Data Correlation

Remark: Examples of properties to be measured on the un-irradiated material are listed in Appendix 2.

- (35) ESKOM and PBMR (Pty) Ltd must ensure that the results of these tests will be documented in a certificate, produced by the manufacturer, that contains all the required details of the charge e.g. the heat number, type of material, number of blocks, a list of all the block numbers in the heat, and the measured properties. Full traceability must be ensured.

5.4.3.2 Requirements concerning Material Utilisation

Remark: The material property requirements for CSC materials are dependent on both the in-reactor location of the CSC and the function of the CSC components.

- (36) In order to ascertain the need for material property evaluation and as a consequence to define the type and number of measurements required, a detailed plan of the location of the CSC within the reactor must be compiled.
- (37) In order to ascertain the need for tests of material in the irradiated condition the enveloping fast neutron fluences of the components must be determined for the locations in the reactor. By this means the range of neutron fluence will be determined for all operating conditions.

5.4.4 Requirements for Irradiation and Subsequent Tests

- (38) The CSC-IP must cover the full range of calculated temperatures and fast neutron fluences up to the maximum fluence defined for lifetime of the components at their respective location. The temperatures at which the tests are carried out and the interval between them must be justified. All material properties that are subject to change as a result of irradiation must be determined (Examples are given in Appendix 2).

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- (39) The irradiation creep behaviour of the CSC materials must be determined in order to permit the analyses of the stress levels to which the component is subject during its lifetime. In the case that irradiation creep data will not be measured in the CSC-IP, justification must be given for the data to be used in the analysis based on results of past experience.
- (40) For irradiation tests, the number of test specimens required to adequately define the variation in a property must be respectively substantiated. Representative conditions covering the range of irradiation fluences and temperatures of the PBMR design must be defined. The temperatures at which the tests are carried out and the interval between them must be justified. With respect to the test facilities and laboratories used to perform the CSC-IP it must be demonstrated that the specified conditions for testing and examination can be met. The capacity of the equipment and instrumentation must be such that the test and examination targets are realised.
- (41) In the event that the CSC-IP cannot be finalized in time and as the result does not cover the irradiation level expected during PBMR operation, justification must be given, that this aspect is recognised and additional acceptable irradiation results must be provided in an adequate period before the material in the reactor will exceed the limits ensured by the CSC-IP. Otherwise operational restrictions must be defined to avoid any negative impact to safety.

5.4.5 Requirements for In-Situ-Tests and Surveillance During Operation

Remark: Although a CSC-IP can ascertain important material parameters, it cannot be entirely representative for the in-core conditions with respect to the various overlapping loadings to which CSC are exposed during operation and transients. Therefore reactor operation has to be accompanied by periodical inspections. Respective requirements are defined in Section 6.5.4.

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6 STRUCTURAL QUALIFICATION

6.1 Design Requirements

6.1.1 General

(42) For the determination of the requirements to be fulfilled by the CSC design a core design envelope must be defined that is based on the overall PBMR design envelope. The core design envelope must include as a minimum:

- Reactor power output and partial load factors
- Design lifetime (full power years)
- Core temperature range
- Thermal and fast neutron fluence range
- Coolant gas flow paths and flow rate estimates
- Plant operating conditions

(43) Based on these requirements and the results of the safety analysis specific CSC design- and acceptance criteria (DC / AC) must be determined.

Remark: Examples for results of the safety analyses which may have an impact on CSC design- and acceptance criteria are:

- *Differential pressures*
- *Seismic loads and other induced shock waves and vibrations*
- *Thermal expansion loads (e.g. during start up, shut down and passive heat removal events)*

(44) Each CSC component must fulfil general structural requirements, independent of the core region the component will be placed, and independent of its Quality Class (see chapter 4.3). ESKOM and PBMR (Pty) Ltd must define these general structural requirements considering the following issues as a minimum:

- The core structures must be designed in a way that compressive stress is the main type of stress occurring.
- A failing of one single component/part must not endanger the structural integrity of other CSC and the core assembly.
- The sum of the single components' tolerances must be chosen in a way that additional compressive stresses are excluded.
- To avoid stress peaks, edges of drillings and dowel holes and other cut-outs shall be rounded. Outer edges shall be chamfered if necessary.
Remark: Holes and cut-outs should be avoided as far as possible in components exposed to high neutron flux and temperatures.
- It must be ensured that the influence of any Wigner energy generation is negligible over the design lifetime.

(45) In order to ensure that the reactor is operating within the design assumptions and operating limits, sufficient instrumentation for the on-line monitoring of graphite and steelwork temperatures and gas pressures must be included. Information on the extent and locations of such instrumentation must be made available.

Remark: Details of the instrumentation regarding also replaceability of individual thermocouples are expected in the Surveillance and Instrumentation Plan to be submitted by ESKOM/PBMR (Pty) Ltd. This plan will be subject to NNR acceptance.

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6.1.2 Positioning and Sealing

(46) ESKOM and PBMR (Pty) Ltd must define requirements to be considered for the positioning and sealing of the CSC respecting the various boundary conditions at different locations in the reactor core. The following aspects must be considered as a minimum:

- The mechanical loads occurring in a single component must be transferred safely to the next neighbouring components that fulfil bearing tasks.
- Mutual displacement of neighbouring components caused by thermal or irradiation induced deformations must not result in a blockage of expansion gaps of other components.
- Irradiation induced dimensional changes must not impact the stability of the whole assembly, cause disengagement of components, or take up available clearances.
- The combination of occurring differential expansions must not result in impermissible loads within the assembly or in neighbouring structural components.
- The CSC must be designed in a way that the occurring thermal and irradiation induced dimensional changes do not impact the structural stability of the core assembly in an impermissible way.
- The control rod and coolant channels arranged in the CSCs, and the alignment of brick-to-brick interfaces must not reduce the shielding functions of the components.
- The displacement of single components and the addition of expansion gaps must not exceed allowable limits.
- The CSCs must be sealed in a way that core bypasses and other flows do not exceed the conditions considered in the thermal hydraulic analyses.
Remark: The sealing should be designed in a way that maintenance aspects (e.g. replacement) are considered.

6.2 **Structural Analysis**

6.2.1 Definition of Loads

- (47) Concerning the life cycle of the CSC all loads must be specified and for each group of components enveloping loads must be considered for design.
- (48) ESKOM and PBMR (Pty) Ltd must define how the enveloping loads will be determined respecting the loads and combinations of loads resulting from operation and from the Postulated Initiating Events (PIE) defined for the CSC.
- (49) Additionally the following loads resulting from physical properties and boundary conditions must be considered:
- Loads induced by mass and preload forces, friction forces etc.
 - Loads induced by temperature and/or neutron fluence gradients,
 - Loads during events
 - Loads due to fuel pebbles

6.2.2 Definition of the Load Cases and the Stress Categories

(50) Concerning the loads and load combinations identified for the CSC, Load Cases must be defined, which are enveloping and representative for design and analysis of the CSC (components and parts).

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- (51) Stress categories must be defined for the load cases taking into account the probability of the load/load combination and the consequences of failures in terms of safety and post-event condition of the component.
- (52) Allowable stresses/probabilities of failure for the different stress categories must be defined considering the differing requirements to the integrity of the CSC, which are defined above.
- (53) For load cases comprising Category A events (according to /1/) the allowable stresses/probabilities of failure in the respective stress categories must be defined such that the post-event integrity and functionality of the CSC can be guaranteed for the remaining CSC lifetime.
- (54) For load cases for Category B events the allowable stresses/probabilities of failure must be defined such that the required safety functions are ensured during and after the event.
- (55) During Beyond Category B events the required safety functions of the CSC may be impaired. Therefore an assessment of the event consequences must be performed which must demonstrate compliance with the risk criteria defined in /1/ for Category C events.
- (56) Operation of the reactor after Category B or Beyond Category B events is only allowed if it is proven by analysis or inspection that the CSC components and core assembly as a whole have not been affected unduly. Also consequences such as operational restrictions, shortened inspection and maintenance intervals and replacement of CSC must be considered in such cases.

6.2.3 Structural Analysis

- (57) By the use of structural analyses it must be demonstrated that each CSC or part of the CSC withstands the specified load cases in the different stress categories. The calculations to be performed must use appropriate calculation methods and specified initial and boundary conditions.
- (58) Either conservative analyses or best estimate analyses with accompanying uncertainty analyses must be performed. In any case the selected approach must be justified and sufficient conservatism of the results must be demonstrated.
- (59) It must be taken into account that the accuracy of the calculated results depends on several aspects, like geometrical idealisation of the component, accuracy of assumptions concerning loads, material properties and boundary conditions and accuracy of calculational routines. The uncertainty of the calculated results must be assessed as a part of the analysis.
- (60) Alternatively, or additionally, experimental methods can be used. Calculational and experimental methods must be sufficiently verified and validated (V&V). If both methods shall be applied, they must be subject to an adequate V&V process.

6.2.3.1 Stress analysis of un-irradiated CSC

- (61) Within the description of the calculational models and the respective boundary conditions it must be defined which kind of material behaviour is assumed.

Remark: Material behaviour is understood e.g. as linear elastic or elastic / plastic behaviour.

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(62) In the calculations thermal stresses must be considered. The material properties used in the calculations must be adequately validated for the covered range of temperatures.

6.2.3.2 Stress Analysis of irradiated CSC

(63) For components close to the reactor core, which are affected by high fluences of fast neutrons, the impact of the neutron irradiation on the material properties over the range of operating temperatures must be considered.

(64) It must be described how the CSC parts and components are allocated to staged irradiation zones.

(65) Internal loading - The effects of temperature and irradiation on dimensional change and material property changes must be considered when performing stress/strain analysis of such components. As the analysis will require the use of a sophisticated method involving Finite Elements, the method must be verified and validated.

(66) External loading - The stresses arising in components due to external loading (which are additive to those due to internal loading) must be determined using appropriate models and loading conditions.

6.2.3.3 Fatigue Analysis and Lifetime Assessment

(67) Time-dependent calculations must be performed considering the specified reactor operation period. To avoid unallowable failures of parts / components due to structural fatigue caused by load and temperature cycles, fatigue analyses must be carried out.

(68) For lifetime assessment the impact of expected oxidation rates must be adequately accounted for.

(69) The methods applied must be verified based on tests including irradiation tests and operational experiences. Uncertainties must be considered for lifetime restriction. The limiting aspect for lifetime restriction must be identified clearly (fatigue, neutron fluence or corrosion) for the CSC component groups.

6.2.3.4 Requirement for experimental methods for structural analysis

(70) The following aspects must be considered as a minimum when using experimental methods for the structural analysis:

- Influence of the model scale
- Different dimensional tolerances of component models compared to real components
- Differences between model and real components concerning strength and other material properties
- Different boundary conditions of the experiments and of the real application

Furthermore the documentation of the experiments must include a detailed discussion of the aspects mentioned above.

Remark: The consideration of these and other aspects is to ensure that the experimental results are conservative and reflect the structural parameters of the component in an appropriate way.

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6.2.3.5 Preparation and Approval of Design Reports

(71) The results of the structural analysis of the CSC must be provided in the appropriate form which contains the following items as a minimum:

- Declaration of the problem and description of the solution process,
- Definition of boundary conditions of the analysis,
- Declaration of applied design codes and standards,
- Used computer codes and definition of the calculational process,
- Description of the structural model and provision of the geometrical data,
- Input data (loads and material properties),
- Interpretation of results and uncertainties and comparison to allowable values,
- Consequences resulting from interpretation of results and uncertainties,
- V&V measures and considered experiments,
- References.

(72) In the cases where experiments are used for strength verification (see Section 6.2.3), the following information must be given in these documents as a minimum:

- Description of the experiment,
- Amount and kind of instrumentation,
- Definition of the test parameters,
- Results of the experiments in the form of tables and diagrams,
- Evaluation of the results,
- Discussion of differences between experimental specimen and real component to be verified,
- Consequences from evaluation of the results.

6.3 QA Requirements during Manufacturing

Remark: Principal QA requirements to be considered during the manufacturing are contained in Sections 4.2 to 4.4 of this LD. The following specific requirements have to be considered additionally:

Geometrical Control:

(73) The geometry of the CSC parts / components must be checked based on approved manufacturing drawings. Allowable tolerances must be indicated in the drawings.

Surface inspections:

(74) Surface standards must be defined. Beside others special regard must be given to the following surface characteristics:

- Cracks
- Cavities and pores
- Chamfers and scratches
- Damage on edges, grooves and surfaces
- Un-finished areas of the surface

Specification must be provided for allowable deviations, and procedures must be provided for the control methods to be applied.

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Clean Conditions during handling and manufacturing:

Remark: Internal procedures that stipulate how clean conditions during the manufacturing process will be reached should be developed by the manufacturer. Arrangements should be introduced to avoid the intrusion of foreign matters that may affect the purity of component surfaces and materials. Overall rules given in internationally accepted standards (e.g. /4/) should be considered.

Marking of the components:

Remark: For a clear identification of the components the requirements of Section 4.4 apply.

Treatment of deficiencies:

Remark: Requirement (14) applies. (see Section 4.4)

6.4 Requirements for CSC and Core Assembly

6.4.1 CSC parts and components

(75) The identification system of the CSC parts/components must ensure their localisation within the core and traceability in terms of the accompanying documents.

(76) The following documentation must be available as a minimum for the CSC parts/components before starting the assembly:

- Approved documentation about manufacturing, inspections and tests
- Certificate of incoming components inspection*.

* After transport and un-packaging of CSC it must be checked if damage of the CSC parts and components has occurred during transportation.

6.4.2 Core Assembly

Assembly Plans and Documentation

(77) Before assembly, approved drawings, Test Plans and procedures must be available. It must be ensured that all components in each layer are at their correct locations according to the requirements of the respective documentation. Deviations from the approved drawings must be documented in detail to allow an assessment of consequences or revision of the structural analyses under respect of the requirements of non-conformance procedures. QA measures and hold and witness points must be part of the assembly plans to be applied.

Trial-build Assembly and Tests

Remark: Before final assembly of the CSC in the reactor a Test Plan should be determined, defining trial-build assemblies outside the reactor and the structural tests to be performed.

Commissioning Programme

(78) The Commissioning Programme and the Test Plans must be available before assembly in the reactor vessel. The content must be adequate to allow the confirmation of design assumptions.

Remark: Besides measures for preparation such as calibration and drying (see Section 6.5.1) the determination of the sealing factors and thermal expansion behaviour should be part of the programme including a measuring of flow rates. In the case that there are

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significant differences to what has been assumed, a reassessment of the design will be necessary.

ISI Programme:

(79) Since the core assembly must be periodically checked e.g. for damage, aging and abrasion, to ensure that the safety functions can still be fulfilled, ISI Plans must be made available prior to assembly of the core which define how and how often inspections will be conducted depending on the different core regions, the quality classes and the results of lifetime assessment. The radiation exposure of the inspectors must be considered in the concept.

Replacement and Decommissioning Concept:

(80) Concepts for replacement and decommissioning including the description of the respective activities must be submitted before assembly.

(81) The radiation exposure of the workers performing the replacement or decommissioning activities must be evaluated and considered for planning. Containment of radioactivity must be ensured by additional measures adjusted to the required activities. For estimation of radioactive doses conservative methods must be applied.

(82) For interim or final storage and transport of radioactive items a concept must be provided including a calculation of the radioactive inventory and a plan for confirmation of calculational assumption by respective measures, e.g. general surveys and selective sampling. The concept must also show how the environment will be protected against the release of radioactive inventory. Detailed replacement or decommissioning plans must be submitted and agreed by the NNR before application.

Documentation:

(83) The following documentation must be available as a minimum before starting the CSC assembling in the reactor:

- Approved assembly documentation
- Test Plans for trial assembly and structural testing, if applicable
- Commissioning programme and Manufacturing and Test Plans
- Inspection and maintenance programme
- Concept for replacement and decommissioning
- Estimated radioactive inventory, distribution and potential dose uptake to personnel during the lifetime

6.5 Requirements for Commissioning, Operation and Surveillance

6.5.1 Requirements concerning Impurity and Corrosion

Remark: Oxidation and corrosion of the CSC parts / components are caused by impurities in the cooling gas (He) like hydrogen, oxygen and carbon-dioxide.

(84) The following main reasons for ingress of impurities must be considered:

- Moisture content of the CSC
- Leakages in the heat exchangers during outage and maintenance
- Air ingress and adsorption of oxygen at the CSC components during outage and maintenance

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- Remaining air in the reactor pressure vessel after maintenance
- Air ingress after a DLOFC event

Drying of the core assembly:

- (85) During commissioning and after outages it must be ensured that the moisture level of the core assembly is below the specified limits specified for the core temperature stages to minimize CSC corrosion.
- (86) It must be ensured that the respective procedures consider all operational constraints/limits and that the procedures and results are documented adequately.

Remark: Examples for relevant operational constraints/limits are drying temperature and duration and moisture measuring.

Monitoring:

- (87) The corrosion of the CSC components must be monitored during lifetime and the consequences for lifetime of the CSC must be evaluated.
- (88) The corrosion rate must be observed during the lifetime of the reactor. A description of the measurement method including specification of the oxidation level of the CSC during operation must be part of the GOR.
- (89) The material specific radiolytic and thermal corrosion rates must be determined depending on the operating conditions for the CSC.
- (90) To determine the CSCs loss of strength the corrosion profiles must be considered in the structural analysis.
- (91) The operating temperature of the side reflector, central column and side restraint system, and the pressure of the coolant gas must be measured at an adequate number of locations to ensure that they are according to the design assumptions/calculations. These must be monitored in accordance with the Instrumentation and Measurement Plan to ensure that design limits are not exceeded.

6.5.2 Requirement concerning Sealing and Thermal Behaviour

- (92) During commissioning the coolant flows and thermal behaviour must be investigated based on instrumentation and respective measuring results. The sealing factors must be examined at the relevant operational power and temperature levels.

6.5.3 Requirement concerning Transients

Remark: During operation of the reactor the CSC are exposed to temperature and pressure transients. As a result additional primary stresses and thermal stresses may be induced.

- (93) Based on the results of structural analysis (see Section 6.2.3) the transients must be limited in terms of gradient and number. Appropriate operational procedures must be determined to meet these limits specified for the CSC.

6.5.4 Requirements for Surveillance Programme

- (94) It is required to accompany operation with periodical inspections. Also indicators must be identified for early recognition of deviations of material characteristics.

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(95) A surveillance and inspection plan must be developed for the CSC and adjusted to the results of the qualification programme and lifetime assessment. The following items must be considered in the programme:

- Description and objectives of measurements
- Time period and number of inspections
- Appropriate allocation of CSC to QAC and AOA
- Number, location and ranking of neutron fluences of the specimen in the reactor
- Description of the handling of the irradiated items and evaluation of their properties
- Inspection of replaced CSC and statistics on performance

(96) By application of a surveillance programme it must be ensured that the impacts of oxidation, neutron irradiation and fatigue do not exceed the limits determined in the design of the CSC. If these limits are exceeded or if it is predictable that they would be exceeded within the lifetime of the CSC, a re-assessment of the design must be performed and corrective measures and/or operational restrictions must be introduced.

6.6 Requirement for Decommissioning and Final Storage

(97) Before interim and final storage of the CSC, an adequate verification programme must be developed and performed to verify the assumptions underlying the design of the CSC with regard to these purposes. The following issues must be considered in the programme as a minimum:

- Impact of handling and storage on the CSC
- Release rates of contaminated dust or activation products
- Investigation of CSC decontamination in terms of waste minimisation
- Investigation of long term storage behaviour
- Development of conditions for final storage
- Radiation protection measures during decommissioning activities

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7 CONDITIONS FOR LICENSING STAGES

Stage 1: Acceptance of Concept Safety Case

- (98) The CSC Design Envelope must be defined. It must be based on the planned PBMR-design parameters and characteristics. Justification must be given for the CSC design that it is generally appropriate concerning the PBMR design requirements and the state of the art.

Stage 2: Construction and Installation

- (99) Before a construction licence can be granted, it must be demonstrated that the requirements set out in this LD will be met by the CSC.
- (100) The CSC-QP must adequately reflect the CSC design- and acceptance criteria, that are derived from the evaluation of the PBMR Design Envelope against past experience, manufacturing impacts and the state of the art.
- (101) Except for the tests that are agreed to be performed at later stages, the CSC-QP must be finalised before construction and installation.
- (102) Except for the tests that are agreed to be performed at later stages, all tests must be finalised with acceptable results. The test results must verify the parameters used as input data in the respective structural, thermal hydraulic and safety analyses.
- (103) The following additional documents must be submitted for stage 2 / construction license as a minimum:
- Documents defining the CSC Design Envelope for operation and the PIE categories according to /1/. If analyses of transients and parameters are not finalised at this stage, conservative margins must be applied for CSC design and qualification, which however must be covered by parameters verified for design of the CSC in the past. (Otherwise a “full scope” CSC qualification for the PBMR is required.)
 - Documents justifying the CSC design- and acceptance criteria.
 - Documents evaluating conditions and results of material tests performed in the past. The documents must justify the applicability of these test results for the PBMR-CSC.
 - Documents defining the manufacturing conditions for PBMR-CSC to be qualified and inserted in the PBMR, including an evaluation of deficiencies of manufacturing conditions for CSC tested in the past, if credit from these tests shall be taken.
 - Inspection instructions, which specify how CSC characteristics will be measured during qualification and manufacturing.
 - The number of test samples must be statistically justified.
 - Documents describing a concept for in-situ tests and for surveillance during operation.
 - Identification of specific tests to be performed in the reactor during commissioning and operation and conceptual description of these tests including consideration of possible impacts on safety.
 - Test instructions defining the targets and conditions for the tests specified in the CSC-QP.
 - Documents describing the oxidation behaviour of the CSC-material respecting all normal operation and PIE conditions.

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- Documents providing a conceptual description of the interim storage system for replaced CSC.
- Documents describing the replacement and decommissioning concept.
- Results of the CSC-QP demonstrating compliance with the CSC-DC and AC to be used to validate the input data for the transient analyses.

Stage 3: Fuel on Site, Fuel Loading, Testing and Commissioning

(104) The following documents must be submitted for stage 3 / fuel at site / commissioning license as a minimum:

- Final results of the CSC-QP demonstrating compliance with the CSC-DC and AC and the input data used in the analyses.
- Assembly records showing the adequacy of the core build, which list any concessions and their appropriate assessments in accordance to specified requirements.
- Analysis and evaluation of the impacts on the safety of specific tests to be performed in the reactor during commissioning and operation.

Stage 4: Plant Operation

(105) The following documents must be submitted for stage 4 / operation license as a minimum:

- Documents defining the operating conditions for the CSC (GOR).
- Documents defining the measuring / surveillance of CSC characteristics during normal operation and after events.
- Documents providing the final description of the interim storage system for displaced CSC.
- Documents defining the final replacement procedure.
- Documents identifying possible deviations from normal operation and the impacts of these deviations on safety margins of the CSC.

Stage 5: Decommissioning

(106) Before a licence for decommissioning can be granted, the final storage conditions for removed CSC must be defined in detail. It must be proven that the characteristics of the displaced CSC comply with estimated and/or predicted values.

(107) Preparation and realisation of removal, transport, interim and final storage of CSC as well as radiation protection during and after these activities must be described and specified with respect to the technical requirements and quality aspects. Documents like concept and process descriptions, design reports, specifications, long term performance studies etc. are required.

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8 REFERENCES

- /1/ LG 1037 "Basic Licensing Requirements for the PBMR"
- /2/ EPRI Technical Report 1003013, August 2001 "Graphite for HTR"
- /3/ LD-1094 Quality and Safety Management Requirements for Pebble Bed Modular Reactor
- /4/ KTA 3232: HTR Ceramic Pressure Vessel Internals
Draft Safety Standard Proposal (Dec. 1992, amended 15.06.1993)
KTA-Doc.- No. 3232/92/3 (in German)

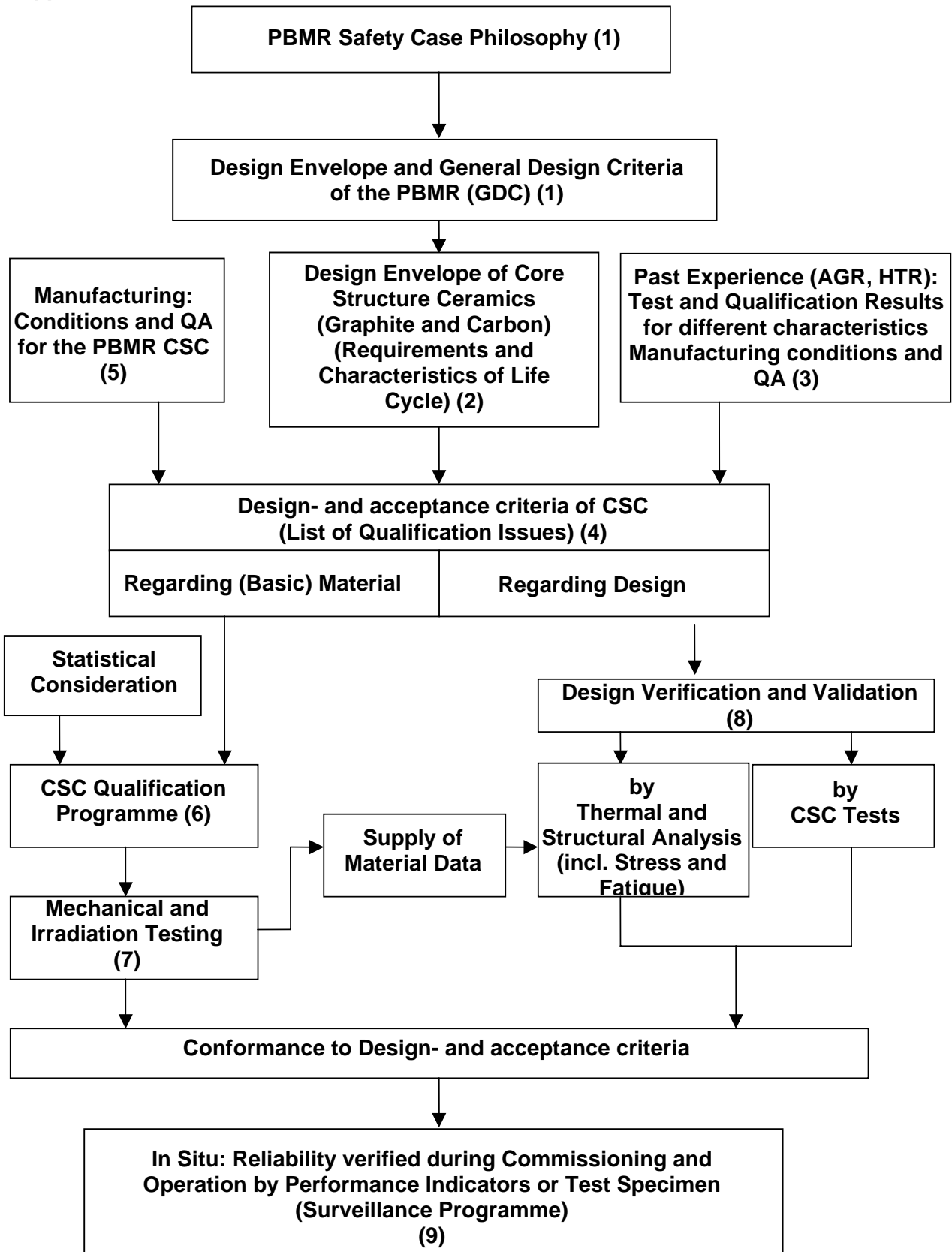
9 APPENDICES

Appendix 1: CSC Qualification Flowchart

Appendix 2: Material Properties to be measured

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Appendix 1: CSC Qualification Flowchart



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Legend on CSC Qualification Flowchart:

Remark: The purpose of this legend is to ease understanding of the flowchart only. It does not define any requirements in addition to those defined already in the text of the LD.

- (1) The Safety Case Philosophy of the Plant and the PBMR Design Envelope as well as the general design criteria (GDC) is the basis for the specification of the CSC.
- (2) The CSC Design Envelope is based on (1) and specify specific CSC design criteria for CSC. Since the CSC design envelope is the basis for the stipulation of the CSC Design- and acceptance criteria, this envelope has to be a detailed specification covering loads and required characteristics. (E.g. geometrical parameters, structure and materials, chemical specification and purity)
- (3) Several Test and Qualification (T&Q) results are given based on past experience (AGR, HTR). The versions and manufacturing samples are different as well as the test targets and boundary conditions of the tests. The T&Q results of the past has to be evaluated against the PBMR CSC Design Envelope. Only T&Q results, which are in line with PBMR design criteria, shall be judged to be applicable. Also the test and evaluation procedure of the past has to be evaluated concerning current V&V-requirements. This includes also general aspects such as number of samples and quality of documentation. Data to be used for this qualification based on past experience has to be auditable.
- (4) The applicable T&Q results of the past are to be allocated to the list of PBMR CSC design criteria. This comparison has to be provided in sufficient detail. Based on the CSC Design Envelope the covering CSC design- and acceptance criteria has to be determined. That means that the criteria, which are significant for CSC design and behaviour has to be identified. Those, which cannot be justified by accepted information or checked by measures easily to apply, has to be defined as Qualification Issues (criteria / characteristics to be qualified and validated). Conservative margins are to be applied to ensure that the design requirements can be met even if analysis results and manufacturing impacts are not known completely at this stage. The resulting list of design- and acceptance criteria of PBMR CSC has to be evaluated in terms of applicable T&Q results and the impact of manufacturing conditions and has to be used for definition of the CSC Qualification Programme (CSC-QP).
- (5) The CSC design- and acceptance criteria (4) have to be evaluated concerning the impact of the CSC manufacturing process and the respective Quality Assurance (QA). The manufacturing conditions and allowable manufacturing tolerances are to be defined. It is required that the samples used for T&Q are representative for the CSC basic material to be inserted in the PBMR.
- (6) The CSC-QP has to be defined concerning the steps described above. The focus must be set on the CSC acceptance criteria in terms of the safety case.
- (7) Part of the CSC-QP is the mechanical and irradiation testing for resolution of CSC acceptance criteria. The results of these tests shall supply data to support the CSC thermal and structural analysis (8).
- (8) The CSC design has to be verified and validated to ensure its conformance to the CSC design- and acceptance criteria. The verification can be done by calculational methods (thermal and structural analysis) and the validation by proof tests and commissioning tests.
- (9) The part of the CSC-QP, which shall be performed in the reactor (during commissioning and operation), has to be justified concerning the safety case. Also respective Performance Indicators are to be defined to demonstrate that possible deviations of the CSC can be measured and evaluated before limits relevant to safety can be reached.

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Appendix 2: Examples of CSC Material Properties to be measured (except fuel)

Material Property (Examples)	Before Irradiation	After Irradiation
Density of complete bricks and small samples	X	X
Tensile strength	X	X
Four point bend strength longitudinal to axis and transverse to brick	X	X
Compression strength	X	X
Dynamic Young's modulus	X	X
Linear Coefficient of thermal expansion (CTE) longitudinal to axis and transverse to brick	X	X
Thermal conductivity at room temperature	X	X
Specimen Dimension	X	X
Fracture Toughness	X	X
Irradiation Behaviour in Case of Alternating Irradiation Temperatures	X	X
Creep Coefficient		X
Ash value	X	
Anisotropy factor	X	
Oxidation rate during the specified corrosion test	X	
Neutron capture cross section	X	
Sulphur content	X	
Chemical analysis (ash)	X	
Effective Open Pore Volume	X	
Open Pore Volume (to be used as a control on effective OPV)	X	
Permeability (CSC bricks only)	X	
Diffusivity	X	
Electrical Resistivity (complete bricks)	X	
Specific Heat Coefficient	X	
Coefficient of Friction (Fuel / CSC and CSC / CSC)	X	X
Thermal shock resistance (CSC bricks only)	X	