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1. INTRODUCTION

In terms of the provisions of section 21 of the National Nuclear Regulator Act (NNRA), Act No.47 of 1999, the siting, construction, operation, decontamination or decommissioning of any nuclear installation as defined in section 1(xviii) of the NNRA should be authorised by way of a nuclear installation licence granted by the National Nuclear Regulator (NNR).

The Basic Licensing Requirements for the Pebble Bed Modular Reactor (PBMR) /3/ require that the facility should be designed, constructed, commissioned, operated, maintained and decommissioned according to good engineering practice.

This document presumes the identification of the required safety functions in a safety case compiled according to the requirements out of /3/. As such this Regulatory Guide (RG) focuses on the system engineering processes to be established for the demonstration of the reliability and capability of the required safety functions. These processes must consider the requirements on Quality and Safety Management as laid down by the NNR in /2/.

From a system engineering perspective the Testing, Qualification and Commissioning (TQC) process verifies that the design process has arrived at a physical architecture that satisfies the safety case requirements.

The Quality and Safety Management Requirements for Nuclear Installations, RD-0034 /2/ define inter alia, the following requirement (paragraph (77)) related to TQC:

> *A test programme must be implemented by the licensee or its suppliers to demonstrate the safe performance of new safety features. It must be ensured that the safety features will perform as predicted, to provide sufficient data to validate analytical codes, and that the effects of systems interactions are acceptable. The test program must include suitable qualification testing of a prototype simulating the most adverse design conditions. The test programme must be defined in writing and make provision for sign-offs as the test programme conditions are met.*

This document provides the guidance of the NNR for TQC of the Structures, Systems and Components (SSC) for the PBMR Demonstration Power Plant (DPP). The TQC programme should comprise the SSC life cycle phases of pre-qualification, qualification and commissioning (see appendix 1) commensurate to the safety importance and the specific 'First of a Kind' (FOAK) attributes of the individual SSC.

2. SCOPE

This RG is applicable to the PBMR DPP that is planned to be constructed under a nuclear installation application or licence as per the NNRA. It provides the NNR guidance for TQC of the SSC. This RG is not applicable to Fuel and Graphite Qualification, as separate requirements apply /6/, /7/. The requirements on Verification and Validation of Computer Codes and on Core Design are covered in relevant NNR documents /4/ and /5/.

3. GENERAL GUIDANCE

Note: This RG presumes the application of the corresponding overall requirements defined in /2/, /3/ and /4/. In addition, it considers that the TQC requirements from the selected codes and standards that apply to the individual SSC are implemented in the TQC Programmes and Plans (TQCPs) where applicable.

(1) The TQC organization and processes should be incorporated in the Safety and Quality Management Systems of the applicant/ licensee and the relevant suppliers. Organizational plans need to indicate independent oversight by the applicant/ licensee over all TQC activities. The requirements from reference document /2/ apply.

(2) As a basis for specification of the TQCP, the design requirements, including the safety requirements, of the SSC should be defined in SSC Design Specifications that are consistent with the Safety Case of the PBMR DPP. This should include the safety, environmental, seismic and quality class of the SSC. In case a SSC is FOAK design or used for FOAK applications, the FOAK attributes should be recorded in the Design Specification and considered for the TQCP.

(3) Development testing and design review and analysis should be performed for FOAK SSC as a basis for the subsequent TQC programme. Design development testing and design review / analysis of SSC are not part of the TQCP. Development testing of SSC should not be performed at PBMR DPP site.

(4) Overall TQCP should be defined for the SSC to allow for a balanced bottom up TQC process following the principle phases illustrated in appendix 1. As subsequent phases should consider the results of the previous phase, a holistic approach needs to be developed at the beginning of the TQC process. The individual qualification activities should be performed in the TQC process as early as reasonably possible to allow for early intervention on design improvements in cases where specified safety requirements are not verified by the specified qualification activities.

(5) Procedures and record forms should be developed for execution and documentation of the individual TQC steps identified in the TQCP. Concerning technical review and quality assurance of the TQC documentation the Quality and Safety Management requirements given

in /2/ apply. The TQCPs and procedures of safety important SSC's should be made available to the NNR for review. The depth of NNR assessment depends on the safety importance of the SSC, the FOAK attributes and the qualification requirements for the SSC.

(6) The need for SSC qualification at special off site test facilities should be identified and specified within the design phase to allow for appropriate planning, specification and preparation of the test facilities. A description of the test facilities, the objectives of the tests and test plans together with the intended purpose, should be provided to the NNR for information. It is the responsibility of the applicant to ensure that the test facilities and the related test programmes meet the intended objectives.

(7) Where utilisation of test facilities is not reasonably possible and final (integrated) qualification tests are to be performed at PBMR DPP site, it should be demonstrated by modelling and simulation and through the staging of the TQC process, that nuclear safety is not compromised. The Verification and Validation requirements for modelling and simulation tools are detailed in /4/.

(8) Where credit is taken for previous SSC test and qualification, past experience or TQC results from other projects and/or applications, it should be demonstrated that those are applicable to the PBMR DPP and that the functional requirements of the DPP SSC are met.

(9) For safety important qualification activities, independent assessment and inspection should be considered commensurate with the safety classification of the SSC, as well as the applicable codes and standards. The involvement of Independent Inspectors should be documented in the TQCP.

(10) The NNR needs to be involved in the TQC process. The NNR will define Hold and Witness Points (HWP) along the TQCP for verification of safety important attributes taking into account SSC certification and the implementation of independent inspection. In case of deviations and events appropriate Non Conformance Reports (NCR) need to be submitted to the NNR.

4. COMPUTER CODE APPLICATION, VERIFICATION AND VALIDATION

(11) Where modelling and simulation forms part of the TQC process, the Verification and Validation (V&V) process of computer codes /4/ must be considered. It needs to be identified where test rigs are required for validation of the applied computer codes.

(12) The test instrumentation and monitoring devices at test rigs and SSC during commissioning should be appropriately qualified and allow for a sufficiently detailed validation of the computer code inputs and results.

(13) Where commissioning tests have an impact on nuclear safety, the test

procedures should be verified by computing and simulation methods in advance to the tests. This explicitly applies to commissioning tests after fuel loading. Computer simulations of commissioning tests should include appropriate conservatisms and explore the consequences of failures. Threshold values determined for the tests should consider the uncertainties of the respective analyses. An iterative approach comprising several tests may be necessary to reduce margins in the test threshold values.

(14) Specific input data for modelling should be provided to allow for independent analysis.

(15) A Quality Management (QM) process should be defined allowing for traceability of test and analysis data and verifying the validity of the collected data. The documentation should allow for evaluation of acceptance criteria and decision making and measures to be taken in the event that some test results fail to meet the acceptance criteria.

5. TQC PROCESS

5.1. Functional Analysis and Identification of Qualification Requirements

Note: The guidance given in this subsection is based on the Safety Case (see /3/) and the Design Process of the SSC.

(16) Functional analyses, Hazard and Operability Studies (HAZOP) and/or Failure Mode and Effect Analyses (FMEA) carried out as part of the design process are the basis for specification of the Functional Qualification Requirements (FQRs) for all SSC's (active as well as passive), see also IAEA guidance in /8/. The TQCP should consider FQR including potential failure modes that need to be excluded / verified. The FQR specified for the SSC should be demonstrated along the TQC process.

(17) The FQR should also consider the environmental conditions such as temperature, pressure, radiation, vibration and humidity and jet forces that may be as a result of potential external or internal events.

(18) The FQR should consider the required design life cycle of the SSC in terms of its durability e.g. to account for the effect of service conditions on the durability of SSC and reliability of the safety functions. Ageing and/or deterioration experienced during normal operations and potential degradation mechanism in case of events should be considered for specification of the TQCPs. Considering the lack of data for FOAK applications, conservative approaches need to be applied for definition of the FQR. Required provisions for investigation on long term effects like sampling for creep and embrittlement verification should be identified in the TQCPs.

(19) The TQCPs should consider seismic loads and other internally or

externally generated loads that are important to demonstrate the capability of the SSC to remain functional if required.

(20) The TQCPs should consider extreme service conditions for SSC capabilities that are claimed to exclude cliff edge effects, during and after accidents. If enveloping tests cannot reasonably be defined, evidence should be demonstrated by indirect verification e.g. by application of verified computer code modelling, testing of selected characteristics and research on specific phenomena.

(21) The TQCP for the SSC should cover the specified FQR. The TQCP should consider the verifiability and accessibility of the related SSC characteristics and attributes along the TQC process including potential interfaces with other SSC.

5.2. Manufacturing Inspection and Test Requirements

(22) Materials, codes and standards for SSC should be selected consistent with the specified FQR. If certain FQR are not completely covered by the applied codes and standards, additional specifications are required for manufacturing and inspection.

(23) The inspections and tests performed during manufacturing should demonstrate compliance with the specified SSC characteristics as per the requirements of the design specifications and provide the verified basis for the subsequent TQC steps.

(24) Manufacturing inspection and test records should be provided for demonstration of compliance with the design specifications and the Quality Control Plans (QCPs).

(25) Final Acceptance Tests (FATs) should preferably be conducted at the manufacturing site to verify that the manufactured SSC meet the specifications and the FQR where feasible at that stage before the SSC are shipped to the test facility or the PBMR DPP site.

(26) FOAK SSC development tests or prototype tests (see paragraph (3)) that may result in design or configuration changes should be performed in advance of the FATs.

5.3. Functional Assembly Testing and Test Rig Qualification Requirements

(27) Where the SSC qualification requires integration with other equipment, functional testing should be conducted with all required equipment assembled. Where off-site test facilities are not reasonably possible, functional assembly testing may be conducted at the PBMR DPP site with the equipment installed and integrated. Justification should be

provided on a case by case basis (paragraph (7) refers).

(28) If safety important SSC have innovative or non-proven design-features and/or require integration with interfacing or support systems to function, functional assembly testing should be conducted on test rigs which provides representative plant conditions. If full scale test facilities are not reasonably possible, part scale test rigs may be applied together with validated computer code applications.

5.4. Installation Inspection

(29) A process for incoming inspection of SSC and assessment of related documentation should be established at the PBMR DPP site. The inspection and assessment should be completed before construction / installation of the SSC.

(30) Installation inspections should be performed to verify the installation of SSC according to specifications and to verify the physical interfaces of the installed SSC assemblies.

(31) A staged approach should be implemented for construction and installation to allow for an inspection programme commensurate with the accessibility of the SSC.

(32) QCPs should be developed for construction and installation identifying the HWP on testing and acceptance (see paragraphs (9) and (10)).

(33) As-built assessments should be conducted and documented for identification of deviations. Deviations should be assessed for potential impact on the Safety Case and considered for update of computer code models, calculations and results. Safety significant deviations should be indicated to the NNR by NCR for acceptance together with the proposed measures for resolution before the TQCP can be commenced.

5.5. Requirements for the Commissioning Phase

The following requirements are based on IAEA guidance for commissioning of nuclear power plants /1/.

5.5.1. General

(34) The installation inspection for the SSC should be completed and accepted before commissioning of the SSC on PBMR DPP site is released.

(35) Commissioning tests should not be conducted, or operational plant states should not be established, if the specified off site pre-qualifications have not yet been completed and approved or the results of pre-

qualification have not yet been analysed, or if they fall outside of the range of analysis.

(36) Pressure tests that are required by codes and standards after installation should be carried out in advance of the commissioning programme. The plant conditions during pressure tests should allow for execution without any risk to the personnel and the public. This specifically applies to gas pressure tests.

(37) A detailed bottom up Commissioning Test Programme (CTP), as stipulated in /1/, should be prepared and submitted to the NNR for acceptance. The programme should allow for a stepwise process starting with a SSC specific commissioning and test phase prior to nuclear fuel loading and should comprise various power increase steps after fuel loading to allow for stepwise verification of predictions in advance of any potential unexpected plant excursions.

(38) The CTP should take into account proper sequencing and hierarchy of tests. Commissioning of support systems such as electrical systems, control and instrumentation systems and service systems like fire protection systems and cooling water systems should have preference in order to ensure the availability of the necessary functions for the implementation of the commissioning programme without compromising nuclear or occupational safety.

(39) Process descriptions, commissioning instructions and general operation rules and procedures should be available to the plant personnel in advance of the commissioning tests. Staff should be suitably qualified and experienced for commissioning and training should allow for familiarisation with the expected SSC and plant behaviour. Simulator training should be considered where appropriate.

(40) The Control and Instrumentation (C&I) system of the DPP should comply with the needs of the commissioning tests. Besides operational controls and instrumentation, test instrumentation should be implemented to allow for monitoring and validation of predictions as well as analytical assessments. The commissioning and test instrumentation signals should be processed by computing methods for on-line visualisation and evaluation where necessary and should be electronically recorded.

(41) The specific commissioning procedures for the steps identified in the CTP should specify the principles, objectives, acceptance criteria and nature of tests. Where exceptions or adjustments of specified SSC operation conditions are needed, it should be clearly specified and the potential consequences should be assessed. The procedures should include the requirements on the specific test instrumentation as well as the criteria for evaluation of the results and the acceptance criteria.

(42) A review of test results and acceptance criteria should be undertaken

after each commissioning step before commencement of commissioning tests to ensure that the predictions are verified.

5.5.2. Non Nuclear Commissioning

(43) Commissioning tests conducted in advance of nuclear fuel loading should have preference to commissioning tests performed after fuel loading / nuclear power increase. These tests should simulate as far as practicable plant operating conditions, including Anticipated Operational Occurrences (AOOs) at typical temperatures, pressures and flow rates. This specifically applies to integrated plant tests of systems where limited information from integrated test rigs is given and to FOAK applications (paragraph 7 refers).

(44) The commissioning tests in advance of fuel loading should, to the extent reasonably possible, verify the mechanical and thermodynamic characteristics of the SSC. It should enable initial checking of flow rates, vibrations, clearances and other provisions made for accommodating the thermal expansion and dynamic loads of SSC. Examples are the effectiveness of heat transfer of the heat removal systems and the mechanistic behaviour of the Power Conversion Unit (PCU). The operation of instrumentation and other equipment should be verified and the relevant operation techniques should be confirmed.

(45) For safety functions of high safety importance validation should be performed before fuel is allowed to be loaded into the reactor. That explicitly applies to:

- Reactivity Control and Shutdown Systems
- Fuel Handling Systems
- Heat Removal Systems
- Radioactivity Confinement Systems

The commission phase without nuclear fuel should allow for appropriate process conditions, viz. temperature and pressure, for validation of the applied computer codes and verification of the performance of SSC. The system provisions for commissioning should allow for appropriate heating and pressurisation.

(46) Before nuclear fuel is loaded into the reactor the fuel handling system should be completely commissioned and the specified system functions verified. The provisions for fuel discharge from core and transport to the used fuel storage tanks should be tested and the performance verified.

(47) Before nuclear fuel is loaded into the reactor the Helium Purification Systems should be completely commissioned and the efficiency verified. The helium losses from the circuit at operational pressure level should be verified and confirmed to be within specifications.

(48) The circuit contamination monitoring systems, the radiation monitoring,

the radioactive release monitoring and helium leak detection systems should be verified in advance of nuclear fuel loading e.g. by using radioactive trace elements.

(49) Before authorizing the loading of nuclear fuel and initial criticality, the NNR will complete as appropriate the review and assessment of the following:

- The as-built design of the plant;
- The outcome of pre-operational tests;
- The adequacy of the Operational Limits and Conditions (OLCs);
- The specific safety limits, limiting safety system settings and conditions for operation during the commission of the plant from first criticality to full power plant state;
- The adequacy of operating procedures and instructions, especially main administrative procedures, Normal Operating Procedures (NOPs) and Emergency Operating Procedures (EOPs);
- The QM system, staffing and management structure of the plant and arrangements for ensuring that qualification requirements are fulfilled and training is performed;
- The quality assurance programme for all commissioning, operation and maintenance activities;
- The records and reporting system for commissioning;
- The radiation protection programme;
- Emergency preparedness implementation;
- The arrangements for periodic testing, maintenance, In Service Inspection (ISI) and surveillance;
- The arrangements for configuration control, especially control of plant modifications;
- The measures for the accounting of fissile and radioactive materials;
- The adequacy of the arrangements for physical protection barriers important to nuclear safety;
- The adequacy of support for technical procurement, safety and other matters at the operating organization or at PBMR DPP site, if appropriate;
- The fulfilment of the applicable requirements in respect of PBMR DPP specific safeguards. This includes but is not limited to fuel transport infrastructure and proliferation, graphite dust monitoring in the primary circuit, site security, environmental monitoring and others.

A conformance checklist should be agreed with the NNR in advance to ensure completeness and fulfilment of the conditions.

5.5.3. Nuclear Commissioning and Normal Operation

(50) Before the Nuclear Commissioning Programme (as a part of the Commissioning Test Programme (CTP) stipulated in (37)) can be commenced, the licensee should prepare a report that addresses the

TQC results gained so far and the potential implications to the safety case and the design. Where necessary, change proposals should be submitted to the NNR for acceptance.

(51) The fuel loading process should allow for verification of the reactivity characteristics of the core and the worth assessment of the reactivity control systems. The loading process should follow a procedure validated by computer models and accepted by the NNR. The neutron flux instrumentation may need amendments for initial fuel loading. The requirements from /5/ apply.

(52) Nuclear commissioning should consist of a step by step approach to full power and full power tests. At each power stage a series of tests should be carried out for verification of analytical predictions and SSC performance. The commissioning tests at a certain power level should only be started if the shut down test of the reactor and the PCU has been verified by previous tests or specific tests performed at this power level. Additional transient testing like power shifts, load drops and reactivity increase should be conducted as early as possible along the nuclear commissioning process. In case of limited results at low power stages, repetition of tests should be considered at higher power levels.

(53) The applicant/licensee should specify hold points to be accepted by the NNR on nuclear power, neutron flux, hot gas temperature and on other relevant characteristics.

(54) For operation of the reactor at low power levels the set point values should be adjusted to ensure reactor power limitation and shut down in case of operational occurrences and events. Reactor power excursions should be limited by set points. The set points should consider the relevant measuring uncertainties as well as relevant response times. Analyses should demonstrate that the limitation and shut down functions are capable of excluding large power transients and the challenge of design acceptance criteria of SSC. For each power level the set point concept of the Operational Control System (OCS), the Equipment Protection System (EPS) and the Reactor Protection System (RPS) should individually be specified and accepted by the NNR. Procedures for adjustment of the set point values should be developed; the adjustment of the set points should be accepted by the NNR. The maximum values at the end of this phase should be in line with the licence conditions as laid down by the NNR.

(55) After fuel loading and initial criticality a series of performance tests should be carried out at low reactor power level. These tests should include checks on C&I, reactivity control systems, radiation monitoring, coolant flow rates, heat removal capacities, temperature and thermal stress profiles, active safety functions of the PCU and other important features of the primary circuit.

(56) In-core instrumentation for power distribution and core / fuel temperature profile measurements relying on indirect methods should adequately be verified by accepted engineering calibration or re-certification methods. Helium bypasses and pebble flow variations may lead to unpredicted core conditions. The computing methods for indirect measurements should be validated in advance and correlated with the stepwise power increase. Validation by experiments should be considered.

(57) The characteristics of the PCU in terms of thermodynamic mechanical behaviour may change significantly during power increase. The monitoring concept should allow for early indication of deviations and early operator intervention during this phase. In case early operator intervention is considered inadequate, additional thresholds for automatic actions may be implemented.

(58) The contamination level in the PCU may change significantly during power increase and subsequent operation. The monitoring concept should allow for early indication of deviations and operator intervention in advance of the specified contamination limits commensurate with the source term analysis. In case on-line operational measurements are considered inadequate, additional hold points for sampling should be implemented.

(59) A review should be carried out at the end of each power stage to confirm that the operational limits and conditions are adequate and practicable, and to identify any constraints on the further power increase. Appropriate hold points should be defined and agreed by the NNR.

(60) Experiences gained during commissioning and data collected should be used to inform the following processes, if so required:
- Design Change and Modification process
- Maintenance life cycle
- General Operating Rules (GORs) Development
- Safety Case Update
- Safety Analysis
- Control and Instrumentation Optimisation
- Fuel handling
- Emergency Preparedness
- Radiation Monitoring

A report needs to be compiled concluding on the TQC results gained so far together with a review of potential implications to the safety case and the design. Where necessary change proposals should be submitted to the NNR for acceptance before operation can be commenced.

(61) For the PBMR DPP the commissioning data gathered through monitoring instrumentation should be safely kept after completion of the commissioning period. This data is an essential benchmarking tool when history profiling and trending of equipment characteristics is required. In addition to the commissioning data, long term operational data are

required to be collected for evaluation of long term trends of contamination, core temperature, thermodynamic and mechanical behaviour as well as degradation mechanisms.

(62) Routine reports on plant performance should be submitted to the NNR containing the relevant performance data, including radioactivity releases and operational occurrences and events.

(63) Regular assessment of data during normal operation should allow for early indication of deviations that are relevant to the licensing criteria (e.g. increase of contamination levels).

(64) The shut down and maintenance phases should allow for early indication of deviations that can not be monitored by on-line instrumentation. The ISI and sampling concept should be defined in advance of nuclear commissioning.

(65) The application to increase power to the next level should be supported by an updated set of data and analyses and submitted for NNR acceptance.

6. REFERENCES

/1/ Commissioning for Nuclear Power Plant, IAEA Safety Standards Series, Safety Guide, No.NS-G-2.9

/2/ RD-0034, Quality and Safety Management Requirements for Nuclear Installations

/3/ RD-0018, Basic Licensing Requirements for the Pebble Bed Modular Reactor

/4/ RD-0016, Requirements For Licensing Submissions Involving Computer Software and Evaluation Models For Safety Calculations

/5/ RD-0019, Requirements for the Core Design of the Pebble Bed Modular Reactor

/6/ LD-1096, Fuel Qualification Requirements For The Pebble Bed Modular Reactor

/7/ LD-1097, Qualification Requirements for the Core Structure Ceramics of the Pebble Bed Modular Reactor

/8/ Safety Assessment and Verification for Nuclear Power Plants, IAEA Safety Standards Series, Safety Guide, No.NS-G-1.2

7. ABBREVIATIONS

Abbreviation	Definition
AOO	Anticipated Operational Occurrence
C&I	Control and Instrumentation
CTP	Commissioning Test Programme
DPP	Demonstration Power Plant
EOP	Emergency Operating Procedure
EPS	Equipment Protection System
FAT	Final Acceptance Tests
FEM	Finite Element Method
FMEA	Failure Mode and Effect Analysis
FOAK	First of a Kind (SSC or Applications)
FQR	Functional Qualification Requirements (for SSC)
GOR	General Operating Rule
HAZOP	Hazard and Operability Study
HWP	Hold and Witness Point
ISI	In Service Inspection
NCR	Non Conformance Report
NNR	National Nuclear Regulator
NNRA	National Nuclear Regulator Act
NOP	Normal Operating Procedure
OCS	Operational Control System
OLC	Operational Limit and Condition
PBMR	Pebble Bed Modular Reactor
PCU	Power Conversion Unit
QCP	Quality Control Plan
QM	Quality Management
RCSS	Reactivity Control and Shut down System
RG	Regulatory Guide
RPS	Reactor Protection System
SSC	Structures, Systems and Components
TQC	Testing, Qualification and Commissioning
TQCP	TQC Programmes and Plans
V&V	Verification and Validation

APPENDIX 1: SSC TQC PROCESS AND LIFE CYCLE