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Reload startup physics tests for pressurized water reactors

Essais physiques au redémarrage pour les réacteurs à eau pressurisée

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Email: copyright@iso.org
Website: www.iso.org

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 6, *Reactor technology*.

This second edition cancels and replaces the first edition (ISO 18077:2018), which has been technically revised.

The main changes are as follows:

— discussion of the difference between review criteria and acceptance criteria was moved from the annex to the main part of the document with a clear statement that the document uses only review criteria;

— a new Subclause 5.3 was added to clarify that testing at the next power plateau should proceed only after acceptable results are obtained at the current power plateau;

— a footnote was added to Table A.1 to address cores designed to be asymmetric;

— several editing changes were made.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In conjunction with each refuelling shutdown or other significant reactor core alteration, nuclear design calculations are performed to ensure that the reactor physics characteristics of the new core will be consistent with the safety limits. Prior to return to normal operation, successful execution of a physics test program is required to determine if the operating characteristics of the core are accurately represented by the design predictions and to ensure that the core can be operated as designed.

This document specifies the content of the minimum acceptable startup physics test program for commercial pressurized water reactors (PWRs) and provides the bases for each of the tests. Previously used acceptable methods for performing the individual tests are provided in Annex A[1)]. Alternate methods may be used as long as they are shown to meet the requirements of Clause 6.

Successful completion of the physics test program is demonstrated when the test results agree with the predicted results within predetermined test criteria. Successful completion of the physics test program and successful completion of other tests that are performed after each refuelling or significant reactor core alteration provide assurance that the plant can be operated as designed.

This document assumes that the same previously accepted analytical methods are used for both the design of the reactor core and the startup test predictions. It also assumes that the expected operation of the core will fall within the historical database established for the plant and/or sister plants.

When major changes are made in the core design, the test program should be reviewed to determine if more extensive testing is needed. Typical changes that might fall in this category include the initial use of novel fuel cycle designs, significant changes in fuel enrichments, fuel assembly design changes, burnable absorber design changes, and cores resulting from unplanned short cycles. Changes such as these may lead to operation in regions outside of the industry's experience database and therefore may necessitate expanding the test program.

1) Annex A is the User's guidance, which provides acceptable methods, guidelines, precautions, suggestions and typical test criteria for each required test.

Reload startup physics tests for pressurized water reactors

1 Scope

This document applies to the reactor physics tests that are performed following a refuelling or other core alteration of a PWR for which nuclear design calculations are required. This document does not address the physics test program for the initial core of a commercial PWR.

This document specifies the minimum acceptable startup reactor physics test program to determine if the operating characteristics of the core are consistent with the design predictions, which provides assurance that the core can be operated as designed.

This document does not address surveillance of reactor physics parameters during operation or other required tests such as mechanical tests of system components (for example, the rod drop time test), visual verification requirements for fuel assembly loading, or the calibration of instrumentation or control systems (even though these tests are an integral part of an overall program to ensure that the core behaves as designed).

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
all rods out
ARO
all full-length control rods withdrawn

Note 1 to entry: Part-length rods may be inserted.

3.2
control rod
one or more reactivity control members mechanically attached to a single fixture

3.3
control rod group
one or more rods that are inserted or withdrawn simultaneously

Note 1 to entry: The term “all control rod groups” means all safety and regulating control rod groups. This term may also be shortened to simply “rod group.”

Note 2 to entry: Some utilities use the term "bank" instead of "group". A control rod bank is the same as a control rod group.

3.4
decades per minute
DPM
unit used to measure a rate of change in flux as measured by the ex-core detectors

3.5
hot full power
full power
rated thermal power
HFP
licensed core thermal power level

3.6
hot zero power
HZP
reactor operating state where the core is essentially critical but is not producing measurable heat from nuclear fission, the reactivity due to xenon is negligible, and the primary coolant system is at design temperature and pressure for zero power

Note 1 to entry: At HZP, the flux signal should be high enough so that the reactivity computer can account for contamination sources such as noise, gamma background, and leakage.

3.7
isothermal temperature coefficient
ITC
change in reactivity per unit change in the fuel and moderator temperature when the fuel and moderator are at the same temperature

3.8
part-length rod
control rod (3.2) whose primary absorber material does not extend the entire length of the *control rod* (3.2) (typically the lower half of the control rod's active length)

Note 1 to entry: It is used for axial shape control. For the purposes of this document, the term "part-length rod" can also represent a "part-strength" control rod.

3.9
percent milli-rho
pcm
unit of reactivity worth equivalent to 10^{-3} % $\Delta\rho$

Note 1 to entry: See definition of "reactivity worth" below.

Note 2 to entry: Throughout this document, pcm is the unit of reactivity to be used.

3.10
reactivity computer
analog or digital device that calculates the core reactivity by using an external signal that is proportional to the core neutron flux

3.11
reactivity worth
change in reactivity expressed in terms of percent

$$\%\Delta\rho = \frac{(k_2 - k_1)\cdot 100}{k_1 \cdot k_2}$$

where

k_1 is the effective multiplication constant for reactor state 1

k_2 is the effective multiplication constant for reactor state 2

3.12
regulating control rod group
group of *control rods* (3.2) that may be partially or fully inserted in the core during normal operation

3.13
safety rod group
control rod group (3.3) that remains withdrawn from the core during normal operation and is inserted during abnormal or accident conditions

3.14
test criterion
predetermined value for evaluating the result of each test

Note 1 to entry: There are two different levels of criteria, review and acceptance. A review criterion is based on differences between calculations and measurements that would suggest a problem with the as-built core, the measurement, or the prediction. Only review criteria are applicable to this document. An acceptance criterion is based on a safety analysis assumption or a Technical Specification limit and is outside of the scope of this document. See Annex A for a more complete discussion of the test criteria and applicability.

4 Relation to other standards

ANSI/ANS-3.2-2012(R2022)[2] provides requirements and recommendations for an administrative control and quality assurance program for the safe and efficient operation of nuclear power plants. Provisions for test and applicable test equipment control required by this document are also included in ANSI/ANS-3.2-2012(R2022). ANSI/ANS 3.1-2014(R2020)[3] provides for the selection, qualification, and training of personnel for nuclear power plants, including personnel responsible for startup testing.

ANSI/ANS-19.4-2017(R2022)[4] addresses reactor physics measurements that are intended to yield documented data of both the type and quality required for validating nuclear analysis methods. ANSI/ANS-19.11-2017(R2022)[5] describes how to calculate and measure the moderator temperature coefficient of reactivity. ANSI/ANS 19.6.1-2019[6] defines the minimum acceptable startup physics test program and acceptable test methods to determine if the reactor core operating characteristics are consistent with the design predictions and is the basis for this document.

5 Physics test program and selection criteria

5.1 Bases for startup physics test program

During the reload design process, the reactor safety is determined by analysis. Following the reload, specific core characteristics shall be confirmed by measurement to ensure that the reconstructed core is accurately represented by that analysis and is operating as designed. Thus, the testing results seek to confirm that the reactor can be operated within the bounds of the technical specifications, that there is sufficient operational flexibility, and that the plant can be expected to safely deliver the designed power output. The paramount objective of a physics test program is to demonstrate that the reconstructed core is accurately represented by the core design and safety analysis used to certify that the core is safe.

The important analysis characteristics that shall be confirmed by measurement are the following:

a) Reactivity balance: reactivity balance neutronically demonstrates that the total amount of fuel loaded in the core is consistent with design. The boron endpoint measurements confirm that the amount of various fissionable materials in the core, as well as the reactivity effects of various fixed poisons (e.g. burnable absorbers) and transient poisons (e.g. samarium), is consistent with the design calculations.

b) Reactivity control: reactivity control refers to the reactor core parameters that have an impact on the ability of the operators to control the plant. The primary parameter that confirms this is the isothermal temperature coefficient.

c) Power distribution: the power distribution is a measurement (check) that the core is loaded properly and will perform as designed. When the measured power distributions agree with predictions, there is high confidence that the as-built core and the designed core are the same. In addition, there is increased confidence that the conclusions of the safety analyses are correct. Finally, close agreement between measured and predicted power distributions increases the confidence that reactivity control parameters will perform as designed.

d) Capability to shutdown: capability to shutdown is demonstrated by showing that the measured control rod worths are consistent with the calculated values. The shutdown margin calculations are based upon design values, which have to be confirmed.

e) Requirements to shutdown: the requirements to shutdown are the reactivity elements that the safety and regulating control rods have to overcome in a reactor trip. The shutdown margin calculations are based upon design values, which have to be confirmed.

Any new testing process or program of tests that are not described in Annex A shall specify how the above parameters are to be confirmed.

A minimum test program is designed to ensure a complete certification, assuming no anomalies were identified during the test program. When results show deviations from predictions that are beyond the experience base, supplementary actions shall be identified and performed, as necessary. A complete design verification test program shall identify the minimum testing that will be performed and the supplementary actions that may be performed.

5.2 Required minimum test program

The characteristics required to be confirmed by this standard, example measured parameters used for confirmation, and power levels before which they shall be confirmed are provided by Table 1. The characteristics and power levels are requirements while there is some flexibility in how those requirements are met. For example, the power distribution shall be confirmed at lower powers before escalating to the next level even though the method for confirmation may be flexible. The parameters were selected by considering the following requirements:

a) The information obtained from the parameter cannot be inferred from other tests that are performed. This requirement means that redundant tests can be excluded. In the event that a particular parameter fails to pass the test criteria, however, other (redundant) tests should be performed to help resolve the discrepancy.

b) Each test shall be able to quantitatively confirm an important physics characteristic of the reactor core. This requirement means that the following types of measurements were excluded (although they may be performed for other reasons):

   1) Mechanical tests of system components (rod drop time, etc.),

   2) tests used solely for instrument calibration,

3) tests used to benchmark computer models.

c) Each measurement shall be accurate, and an accurate prediction shall be available. This requirement means that the expected difference between the measured result and the prediction shall be small so that if the measurement and the prediction agree, there is confidence that the core will behave as predicted. Conversely, if there actually is a design discrepancy in the core, the measurement will reveal it (the measurement and prediction will not agree).

d) The test program shall be designed to not violate the plant's shutdown margin requirements. This requirement means that the plant shutdown margin requirements shall not be violated while performing startup physics testing.

Table 1 — Required physics characteristics to be confirmed

Characteristic(s)	Example measured parameter to use for confirmation	Power level %
Reactivity balance	All-rods-out boron concentration	<5 [a]
Capability to shutdown, power distribution[b]	Control rod worths	<5
Reactivity control	Isothermal temperature coefficient	<5
Power distribution	Flux symmetry or direct power distribution measurement between 0 and 30 % of full power	0 to 30
Power distribution	If a direct low-power distribution measurement has yet to be confirmed, then it shall be confirmed (compared to predictions) prior to exceeding 50 % power[c]	30 to 50
Power distribution	Power distribution measurement results shall be assessed collectively to ensure that local and global core characteristic trends are acceptable prior to exceeding 80 % power	50 to 80
Power distribution	Direct power distribution measurement at full power	>90
Reactivity balance, requirement to shutdown	Hot-zero-power to hot-full-power reactivity measurement	>90

[a] Measurements made prior to power operation (<5 %) are special in that they confirm characteristics that cannot be adequately confirmed during operation at power.

[b] Although the power distribution may not be directly measured at <5 % power, an indirect measurement such as the control rod worth error distribution provides the first indication that the power distribution is consistent with predictions.

[c] See A.3.4.6 for a discussion of direct and indirect power distribution measurements.

5.3 Test program considerations

The startup test program shall be established to provide assurances that operation at the next plateau in the program will be acceptable. In other words, a safe and controlled approach to power ascension with a new core will be followed. This is accomplished by establishing the rules that dictate that favorable results of the tests at one power plateau meets the criteria to allow progression to the next power plateau. Therefore, this requires resolution of any observed differences (failure of a review or acceptance criterion) at any plateau prior to proceeding up in power.

Having established processes for resolution of a specific criterion failure would be very helpful in executing a physics test program efficiently. Utilizing the information in Table A.2 and A.3 will provide guidance on how to establish such a resolution process.

6 Test method requirements

6.1 General

Established test methods for the confirmation of each characteristic required by this document are described in Annex A. Whether one of these methods or a different method is used, the user shall verify that the following requirements are met:

a) The intent, content, purpose, and other requirements of the overall startup program as outlined in this document are met;

b) The method unambiguously confirms one or more of the five physics characteristics described in 5.1;

c) The method has been validated by successful benchmarking;

d) The method has withstood independent peer review.

6.2 General test considerations

6.2.1 Test objective

The general objective of each test is to measure a reactor physics parameter.

6.2.2 Test purpose

The general purpose of each test is to determine if the measured reactor physics parameter is consistent with the predicted value. Data from the test results may also be used to establish appropriate operating limits or to determine compliance with appropriate Technical Specifications.

6.2.3 Initial conditions

In general, initial conditions are specified for each test such that an accurate measurement can be performed at the same or nearly the same conditions assumed in the prediction. The test results or predictions shall be adjusted to account for any difference between the specified conditions and those that were present at the time of measurement. Except for unusual circumstances, each adjustment due to different conditions shall have a negligible effect on the uncertainty in the measured-versus-predicted comparison. All adjustments shall be documented.

6.2.4 Test methods

For each test, Annex A provides abstracts of proven methods for performing the test. Alternate methods can be used as long as they are shown to be acceptable by meeting the requirements of 6.2. In general, the stated initial core conditions shall be achieved as closely as practical, and the reactor physics parameter shall be measured accurately (i.e. consistent with the assumptions used to establish the test criteria). To ensure that the measurement uncertainty is minimized, precautions are provided in Annex A. During each test, the appropriate core conditions shall be recorded, and those conditions shall be maintained within the specified range for the test.

6.2.5 Evaluation

In general, each test is considered to be successful if the difference between the prediction and the measurement (or, for some tests, the physics parameter inferred from the measurement) is less than a predetermined criterion. This difference shall be evaluated after appropriate adjustments have been made to account for any differences between the specified core conditions and those that were present at the time of measurement.

The predetermined criteria shall be developed with adequate allowance for uncertainties in both the measurement and prediction. Typical criteria based on current technology and best practices are provided in Annex A.

6.3 Test criteria

If the difference between the measured and predicted values for a physics parameter exceeds the predetermined criterion, these actions should be taken:

a) Validate that there are no measurement process failures and that the test conditions are consistent with the conditions modelled in the predictions.

b) Confirm the result by reanalysis, a repeat measurement, or an alternative measurement method.

c) Inform the core design organization to ensure that there are no unintended consequences to this failure and that no safety concerns are evident.

The test criteria are flexible since it is unknown what problems or deficiencies might be encountered during testing and to what extent test conditions may vary from those assumed in developing the test predictions and criteria. The test criteria shall, therefore, be applied along with common sense and historical perspective (previous cycles, sister plants, etc.) to establish whether or not the reactor core has satisfactorily passed the test program. The simple meeting or failing a test criterion does not definitively establish whether or not a core is deficient in a given area. The results should be reviewed not only as individual tests but also as related sets and in light of results from previous cycles and results from similar cores. Most problems will cause deviations from expected results in more than one parameter. By reviewing the results in a global sense, considerably more assurance can be given that the reactor core is functioning as expected.

The physics test program results should be evaluated along with the results of other tests performed during startup. The failure of one or more of the physics test results to meet the test criteria shall be evaluated relative to the implications on plant safety. The results of this evaluation shall be employed as a guide for continued plant operation.

7 Requirements of this document

Conformity with this document shall be demonstrated by meeting the following requirements:

a) Test program: have ability to accurately confirm the required physics characteristics listed in Table 1;

b) Test methods: perform each test using a verified and validated procedure (examples are given in Annex A);

c) Test acceptance: compare the results of each test to predetermined test criteria;

d) Test documentation: document the results of the test program including, as a minimum, the following items:

   1) the test methods employed;

   2) the measured parameters;

   3) the predicted parameters and any corrections made to account for different core conditions;

   4) the predetermined test criteria for test acceptance;

   5) an evaluation of the test results based on a comparison between the measured and predicted parameters, taking into account the uncertainties in both the measurements and predictions.

Annex A
(informative)

User guidance

A.1 General

The purpose of this annex is to provide the users of this document a set of acceptable methods, general guidelines, precautions, and suggestions for each test. Also included in this annex are values of test criteria based on industry experience at the time of its writing. Users should develop their own test criteria based on expected differences between measurements and predictions. This annex should help the user formulate a startup physics test program that will meet the requirements of this document. This annex is not a set of requirements nor should it be used as a detailed procedure for performing each test.

A.2 Acronyms

Following are definitions of acronyms used in this annex.

ARO: all rods out

CBC: critical boron concentration

DBW: differential boron worth

DPM: decades per minute

DRWM: dynamic rod worth measurement

FP: full power

HFP: hot full power

HZP: hot zero power

ITC: isothermal temperature coefficient

M/D: movable detector

pcm: percent milli-rho

ppm: parts per million by weight

PWR: pressurized water reactor

RCS: reactor coolant system

rms: root-mean-square (square root of the average squared difference) = $\sqrt{\sum_{i=1}^{N} \frac{(\Delta \text{RPD})_i^2}{N}}$.

RPD: relative power density

VCT: volume control tank (also known as letdown storage tank)

A.3 Typical criteria and bases

A.3.1 Overview

The use of criteria for evaluation of test results is a long-standing practice in industry. This method allows for on-the-spot evaluation of the test results against the nuclear design predictions. The ideal criterion to be used is tight enough such that no design anomaly would go unnoticed but loose enough such that typical differences would not violate the criterion. Some of the factors that enter into the determination of the criteria are the design model limitations, the measurement limitations, and the compatibility between the design and measurement methods. The criteria are established by differences between calculations and measurements that would suggest a problem with the as-built core, the measurement, or the prediction. The criteria are not established by rigorous analysis of the test methods or design models.

Another long-standing practice in the industry is the establishment of two level criteria for the evaluation of the test results. These two criteria are often referred to as "Test (review) criteria" and "acceptance criteria". The differences in these two criteria are better defined in the following descriptions.

A.3.2 Test (review) criteria

Test (review) criteria are based on differences between calculations and measurements as discussed above and are not based on the safety analysis. Therefore, these criteria typically have two-sided tolerances. These criteria are used to identify measurement or design errors. Failure of any one test criterion does not necessarily warrant stopping the testing process or power ascension. The user should address these test criteria as part of a continuing evaluation of the design and measurement processes.

A.3.3 Acceptance criteria

Acceptance criteria are those criteria that have a direct link to the safety analysis or are defined by Technical Specifications. These criteria are typically one sided and are constructed from Safety Analysis or related assumptions. Failure of these criteria should not prevent further testing at the current power plateau for supporting information. Failure of these criteria, however, should prevent power ascension until the issue is resolved. Resolution of a failure is often performed under established procedures (e.g. Technical Specification action statements). The established procedures will typically stipulate the power ascension requirements.

For the purposes of this annex, all criteria referenced herein are test (review) criteria. It is outside the scope of this annex to define or require acceptance criteria because the safety analysis basis is plant specific. Typical test criteria for each test are shown in Table A.1. These values are guidelines only and represent about twice the expected differences between measurements and predictions being seen by the industry as of the writing of this annex.

Table A.1 — Typical test criteria

Test parameters	Test criteria
HZP critical boron	±50 ppm or ±500 pcm equivalent
Control rod worth Individual group or user-specified group Sum of groups or total integral of measured worths	±15 %[a] or ±100 pcm, whichever is greater (For rod swap, the reference group should be within 10 %.) ±10 %[a] (For DRWM, the total worth should be within 8 %.)
ITC	±4 pcm/°C
Flux symmetry[b] Deviation between the highest and lowest values in the symmetric locations	±10 % [c] (*Meas* versus *Meas*)
Power distribution	±0,10 RPD[d] for each measured assembly power and rms[e] (radial) < 0,05
HZP to HFP reactivity measurement	±50 ppm or ±500 pcm equivalent or ±10 %[a]

[a] For calculating percent differences use (*Meas* - *Pred*) × 100/Pred, where *Meas* indicates the measured value and *Pred* indicates the predicted value. Having percent difference defined with *Pred* (i.e., predicted) in the denominator is consistent with comparisons of measured-versus-predicted data for safety-related purposes (e.g. total control rod worth and peaking). This definition of percent difference simply recognizes that PWR reload cores are licensed with calculated (predicted) data.

[b] If a core is designed with a known asymmetry, the review criteria for this test is changed to comparison of measured flux in symmetric locations to predicted flux in the same location to within ±10 %.

[c] Percent difference is (Highest - Lowest) × 100/*Avg*, where Highest is the largest measured value in a particular symmetric location, Lowest is the smallest measured value, and *Avg* is the average of all the measured values in the same symmetric location (which could be 2, 4, or 8 values).

[d] RPD (Relative Power Density; also assembly power density/core average power density) Average RPD = 1,00)

[e] rms (Root Mean Square of the relative power difference)

A.3.4 Bases

A.3.4.1 Bases for test criteria

The test criteria shown in this annex are indicative of industry experience at the time of this writing. As industry experience changes, the criteria should change with it. Also, new technology, more advanced fuel cycles, etc., may necessitate different criteria until industry experience is gained.

The test criteria are based on differences between calculations and measurements. The intent of each test criterion is to provide a value that, if exceeded, suggests that something may be wrong. When a test result falls outside of the test criteria, it means that there may be a problem with the as-built core, the measurement itself, the test equipment, or the design calculations or that the conditions during the measurement were significantly different from the conditions assumed for the prediction.

The test criteria are established assuming that known biases are accounted for in the predictions before comparisons are made.

A.3.4.2 Bases for critical boron concentration measurement

The objective of this test is to confirm the reactivity balance. This test measures the overall reactivity of the reactor and validates the accuracy of the predicted criticality calculations. This test is performed at a nearly all rods out (ARO) configuration to minimize error from the use of control rod worth to correct for any control rod insertion that may exist. This test provides a verification of the design models used to perform reactivity balance calculations and to provide operators with estimated critical conditions. This verification ensures that predicted shutdown boron concentrations provide the necessary margin to criticality to meet operability requirements.

This test provides verification that soluble boron sources provide adequate negative reactivity as modelled in the accident analyses.

A.3.4.3 Bases for control rod measurement

The objective of the control rod worth measurement is to confirm the capability to shut down and control reactivity. It demonstrates that the reactivity worth of the safety and regulating control rods is consistent with predictions. This test provides a level of assurance that the fuel and core components are configured consistent with design assumptions. The total safety and regulating control rod worth verifies adequate shutdown margin capability. Control rod group worths and shapes provide initial indication of an acceptable power distribution. Also, the rod group shapes provide an indication of the reactivity control characteristics of the core.

Since control rod worth cannot be inferred from other operating parameters, this test represents the only opportunity to verify that the rod worths are consistent with those assumed in the shutdown margin calculations and in the safety analyses for the core. This test is performed prior to power ascension to maximize available design margin in case some problem with the rod worths exists. Also this test helps ensure the integrity of the rods and that the rods are latched. Several different methods are available for the measurement of control rod worths. Each method has its own inherent measurement process control issues that are to be addressed to obtain reliable results.

A.3.4.4 Bases for Isothermal temperature coefficient measurement

The objective of the isothermal temperature coefficient (ITC) measurement is to confirm the reactivity control characteristic. The test demonstrates that the reactivity response to temperature changes in the reactor core is consistent with design predictions. This measurement is performed at a nearly ARO condition, thus maximizing the boron concentration for the test and resulting in the most positive ITC. This measurement is performed at hot zero power (HZP) to ensure that the ITC is consistent with design and operational expectations before power ascension.

A.3.4.5 Bases for flux symmetry measurement

The objective of this measurement is to confirm that the power distribution in the core is consistent with design predictions at low power prior to escalating to higher power. The flux symmetry measurement is applicable only to plants that choose to not perform a complete power distribution measurement at low power (such as those with a fixed in-core detector system). While fixed in-core detector systems can provide continuous power distribution indication during power ascension, the accuracy may not be sufficient to perform a complete power distribution measurement below 30 % power. The flux symmetry measurement may reveal core anomalies (e.g. dropped rods, detached rod fingers, fuel misloadings, flow anomalies, etc.) prior to complete power distribution tests at higher power levels.

A.3.4.6 Bases for power distribution measurements

The objective of the power distribution measurements is to confirm that the power distribution is consistent with design predictions at low, intermediate, and high power levels. The measurements verify that the power distribution is within its design and licensing bases, and they may identify any power distribution anomalies. These measurements provide comprehensive assurance that the fuel and core components are configured consistent with design assumptions.

The power distribution is confirmed by measurement at various power conditions during power ascension. Confirmation may be direct (e.g. in-core detectors) or indirect (e.g. all bank worths). The level of confidence in the power distribution results is minimal with the bank worth results, good with the flux symmetry results, and best with a direct power distribution measurement using in-core detectors. A direct power distribution measurement is necessary before exceeding 50 % of full power (FP) to provide a high level of confidence that unforeseen power distribution anomalies will not result in violations of design assumptions. All of the power distribution measurement results are to be assessed collectively to ensure that local and global core characteristic trends are evaluated during power ascension.

Startup power distribution measurements using in-core detectors should be taken using as many detector locations that cover as much of the core as practical. Thus, any core configuration anomaly (e.g. misloaded fuel assembly or dropped rod) will have a higher chance of being detected.

A.3.4.7 Bases for HZP to HFP reactivity measurement

The objective of the HZP to hot full power (HFP) reactivity measurement is to confirm the requirement to shutdown. The test demonstrates that the reactivity deficit resulting from the increase in reactor power from zero to near FP (> 90 %) is consistent with design predictions. While this test incorporates a number of reactivity effects (xenon, moderator temperature, fuel temperature, soluble boron worth), it is the only measurement that provides verification of the calculated total power defect. This measurement is performed to ensure the power deficit is consistent with design predictions and operability requirements for shutdown margin.

Measurement of the power deficit verifies the reactivity requirements of the safety and regulating control rod system to ensure adequate shutdown margin is maintained.

A.4 Acceptable test methods

The following sections provide, for each test, acceptable methods for performing the test. Alternate methods may be used as long as they are shown to meet the requirements of Clause 6. In addition, there is a set of guidelines, precautions, and suggestions that will help the user perform the test and evaluate the results. Typical values for rates of change and stability requirements are also included.

A.4.1 Critical boron concentration

A.4.1.1 Test objective

To measure the HZP critical boron concentration (CBC) with all rods fully withdrawn (part-length rods may be inserted).

A.4.1.2 Purpose

To determine if the measured and predicted total core reactivities are consistent.

A.4.1.3 Initial conditions

The reactor core is at HZP with all full-length rods withdrawn except that the lead regulating rod group may be inserted (but not more than 200 pcm or 20 % of the worth of the lead group). Specific guidelines are as follows:

a) Power: HZP;

b) Reactor coolant system (RCS) temperature: within 1 °C of the reference temperature;

c) RCS pressure: within 350 000 Pa of the reference pressure;

d) Rod groups: ARO except the lead regulating rod group may be inserted in the core but not more than 200 pcm or 20 % of the total worth.

A.4.1.4 Test method

Measure the CBC and record the appropriate reactor conditions. Adjust the measured value for differences between the specified conditions and those that were present at the time of measurement. Specific guidelines are as follows:

a) Take boron samples from the RCS, the pressurizer, or the volume control tank (VCT) (if available) every ~20 min. Continue sampling until each of three consecutive samples of the RCS boron concentration differs by <10 ppm from the average of the three samples and there is no significant trend. Boron samples taken concurrently from the pressurizer and VCT should differ by <50 ppm from the comparable RCS sample. Maintain core reactivity close to zero by adjusting the position of the inserted control rods. Record RCS temperature and control rod position;

b) Take an RCS boron sample and save for an independent analysis;

c) Measure or predict the worth of the inserted control rods to the reference position.

A.4.1.5 Hints/precautions

a) While establishing equilibrium boron concentration, maintain core reactivity near zero or hold the power constant, by adjusting the position of the inserted control rods. Be sure the flux signal for the reactivity computer is above electrical and background noise when performing reactivity measurements;

b) Allow the boron concentration in the RCS, the pressurizer, and the VCT to come to equilibrium;

c) Minimize the magnitude of the corrections made to the measured boron concentration by maintaining reactor conditions as near as possible to the reference conditions;

d) Keep the amount of control rod movement small to minimize the corrections to the boron values and to prevent the measurement from causing reactor control or reactivity indication problems;

e) Any time control rods are moved, record their new position.

A.4.1.6 Evaluation

Determine the difference between the adjusted measured and predicted boron concentration. Compare the difference to the test criterion. Specific guidelines are as follows:

a) Determine the *CBC* to compare to the predicted value as follows in Formula (A.1).

$$CBC = C_{\mathrm{M}} + \frac{\left(\Delta\rho_{\mathrm{Rods}} + \Delta\rho_{\mathrm{Temp}} + \Delta\rho_{\mathrm{Burnup}}\right)}{DBW} \quad \text{(A.1)}$$

where

C_{M} is the measured RCS boron concentration. The last two measured values can be averaged, or the last measured value can be used;

$\Delta\rho_{\mathrm{Rods}}$ is the measured or predicted reactivity between the control rod position at which C_{M} was determined and the reference position;

$\Delta\rho_{\mathrm{Temp}}$ is the equivalent reactivity worth of the difference between the RCS temperature during the test and the reference temperature. If this correction is required, either the measured or predicted temperature coefficient can be used;

$\Delta\rho_{\mathrm{Burnup}}$ is the equivalent reactivity worth attributable to the difference in core average burnup between the measurement and the prediction. This adjustment should normally be zero because any needed burnup correction should be made in the prediction;

DBW is the differential boron worth (pcm/ppm) used to convert reactivity worths to equivalent boron concentration. The predicted value can be used to make this correction.

b) Compare the adjusted measured *CBC* with the predicted value, and determine if the difference is within the test criterion.

A.4.2 Control rod worth

A.4.2.1 Test objective

To measure the worth of selected safety and regulating control rod groups (part-length rods are excluded). If boron dilution or boron exchange is used, regulating rod groups having a cumulative predicted worth of at least 3 000 pcm or all of the regulating rod groups should be measured. For other test methods, all control rod groups should be measured.

A.4.2.2 Purpose

To determine if the worth of selected control rod groups is consistent with predictions.

A.4.2.3 Initial conditions

a) Power: HZP;

b) RCS temperature: within 1 °C of the reference temperature;

c) RCS pressure: within 350 000 Pa of the reference pressure;

d) Rod groups: ARO except the lead regulating rod group may be inserted in the core but not more than 200 pcm or 20 % of its predicted worth;

e) RCS boron: Each of three consecutive RCS samples should differ by <10 ppm from the average of the three samples taken ~20 min apart, and there is no significant trend.

A.4.2.4 Boron exchange method

Begin changing the primary coolant boron concentration in a continuous manner. Move one of the control rod groups to be tested over the entire range of its travel in response to the change in reactivity caused by the changing boron concentration. The worth of control rod groups may be measured in the normal operational configuration (for example, overlapped) with worth comparisons made at locations for which predictions are available. Measure the reactivity resulting from each incremental rod group movement using a reactivity computer.

Sum the incremental changes in reactivity over the total travel of the rod group. Correct for any changes in reactor conditions that occurred during the test. Repeat this sequence for each control rod group to be tested.

This method exchanges the reactivity of a test control rod group with the reactivity of the boron concentration in the RCS:

a) As control rods are inserted into the core, inject unborated water into the RCS so that the boron concentration of the RCS is diluted. During this process, keep the core nominally critical;

b) Limit the control rod group motion so that the reactivity value associated with each movement is within the reliability range of the reactivity computer (allow at least 4 min between movements to obtain a stable rate of change of core reactivity from the reactivity computer). Establish the dilution/boration rate so that the reactivity exchange rate is compatible with the operational requirements of the reactivity computer. The rate is fast enough to allow reasonable step changes in rod position and slow enough to allow the reactivity to stabilize from the spatial effects;

c) Use the reactivity computer to monitor core reactivity and directly measure the reactivity worth of the control rod groups.

A.4.2.5 Hints/precautions

a) Ensure that the boron in the system is well mixed (RCS, pressurizer, VCT).

b) Measure the control rod groups in order of their normal sequencing.

c) Terminate the boron exchange prior to reaching the full insertion/withdrawal of the test control rod group to minimize any overshoot or undershoot of the rod group position at the end of the test.

d) In the data analysis, account for the reactivity spatial effects (overshoot or undershoot) that may be present on the reactivity traces.

e) Keep the reactivity changes such that the average over time is approximately zero, the indications are within the normal operating range and display of the reactivity computer, and sufficient time is allowed between rod group motions that the reactivity spatial effects are resolved.

f) Estimate the total amount of either water or boric acid that will be used prior to performing the test.

g) Perform a spot check of the differential rod worths during the data collection and compare to predicted values.

A.4.2.6 Rod swap method

Measure the worth of a predetermined reference rod group using boron exchange (described above) and obtain the integral rod group worth curve over the full length of its travel. With the reference rod group near full insertion, record the reference rod group position. Withdraw the reference rod group while inserting a test rod group. Establish a critical condition with the test rod group fully inserted, and record the position of the reference rod group. Determine the worth of the test rod group. Account for the difference between the actual and predicted position of the reference rod group. Correct for any changes in reactor conditions that occurred during the test. Repeat this sequence for each rod group to be tested.

This method exchanges the reactivity of a test rod group with the reactivity of a reference rod group. All rod groups are measured when using this technique except that part-length rod groups are excluded.

a) Insert the most reactive rod group (hereafter referred to as the reference group) into the core while diluting the boron concentration, and measure its reactivity worth using the boron exchange method.

b) At the completion of the reference group reactivity worth measurement, stabilize the RCS temperature and boron concentration so that the reactor is critical with the reference group at or near full insertion.

c) Determine a boron statepoint by moving the reference group to its fully inserted position (if necessary), and record the core reactivity and moderator temperature.

d) Perform a rod swap maneuver by inserting the test rod group while withdrawing the reference group or a previously inserted test group.

e) Keep the core nominally critical throughout this rod swap until the test group is fully inserted and the reference group is at a position in which the core is just critical.

f) Record statepoint data (rod position, core reactivity, and RCS temperature) with the reference group at the measured critical position.

g) Repeat the rod swap process [steps (d), (e), and (f)] for each remaining rod group.

A.4.2.7 Hints/precautions

a) Ensure that the boron in the system is well mixed (RCS, pressurizer, VCT).

b) Control RCS temperature closely to within 0,5 °C of the reference temperature to minimize temperature effects on the critical positions.

c) If a test group has the potential for being worth more than the reference group, measure it last. If the test group is indeed worth more than the reference group, measure the remainder of the test group worth using the boron exchange method.

d) If applicable, do not change the group selector switch, and move rods if the subgroups are not at the same position. This will cause problems with the rod control system sequencing logic.

e) Ensure that the VCT is at a high level at the start of the exchange with the reference group. Minimize makeup to the VCT during this test.

A.4.2.8 Dynamic rod worth method

The core is critical with the lead regulating control rod group having ~65 pcm reactivity inserted (this value may depend on the loaded core). The lead control rod group is fully withdrawn, placing the core on a 0,2 to 0,4 decades per min (DPM) (rate of change in reactivity in units of DPM) positive startup rate. Once the flux level increases to a preset value, the rod group being measured will be inserted in a continuous motion from the ARO position to near fully inserted. The group will then be withdrawn to the ARO position, stopping withdrawal when the startup rate indicates ~1 DPM due to subcritical multiplication, to allow the flux to increase to the initial condition. The measured data are analyzed by the reactivity computer while the group is being withdrawn. The group insertion-withdrawal-analysis sequence is repeated for each group. After the last group is measured, the flux is controlled in the zero-power testing range by lead control rod group insertion.

A.4.2.9 Hints/precautions

a) The rod group is inserted in one continuous motion. Failure to adhere to this requirement will require a repeat measurement of the group.

b) To avoid overshoot during insertion, the operator will stop rod motion before the group is fully inserted.

c) During group withdrawal, there could be a temporary indicated excessive positive startup rate while subcritical on the intermediate range; however, this is due to the subcritical multiplication associated with the rod motion and is not a sustained startup rate. The true startup rate will reach a maximum value when the group is fully withdrawn and cannot exceed the value associated with a 75 pcm positive reactor period (~0,4 DPM).

d) During the test, groups may be inserted that are ≈1 % in reactivity (1 000 pcm).

A.4.2.10 Boron endpoint method

Record the appropriate reactor conditions, including the boron concentration, with one of the selected control rod groups near one end of its travel. Move this control rod group to the other end of its travel. Maintain criticality by changing the boron concentration to compensate for the control rod group movement, or reestablish criticality after the control rod group movement. Record appropriate reactor conditions with the control rod group at its final position. Repeat this sequence for each control rod group to be tested.

For each control rod group, calculate the difference between the initial and final measured boron concentrations. Correct for the difference between the actual and predicted rod group travel. Correct for any changes in reactor conditions that occurred during the test.

This method exchanges the reactivity of a test control rod group with the reactivity of the boron concentration in the RCS.

a) As control rods are inserted into the core, inject unborated water into the RCS so that the boron concentration of the RCS is diluted;

b) When the final condition is reached, record the CBC with the test control rod group fully inserted.

A.4.2.11 Hints/precautions

a) Ensure that the boron in the system is well mixed (RCS, pressurizer, VCT).

b) Measure the control rod groups in order of their normal sequencing.

c) Terminate the boron exchange prior to reaching the full insertion/withdrawal of the test control rod group to minimize any overshoot or undershoot of the rod group position at the end of the test.

d) Estimate the total amount of either water or boric acid that will be used prior to performing the test.

A.4.2.12 Evaluation

Determine if the difference between the measured and the predicted worth of each selected control rod group is within the test criterion. Determine if the difference between the sum of the measured worths and the predicted value is within the test criterion.

A.4.3 Isothermal temperature coefficient

A.4.3.1 Test objective

To measure the ITC of the reactor.

A.4.3.2 Purpose

To determine if the measured ITC is consistent with the predicted value.

A.4.3.3 Initial conditions

a) Power: HZP.

b) RCS temperature: within 1 °C of the reference temperature and changing <0,5 °C/h.

c) RCS pressure: within 350 000 Pa of the reference pressure.

d) Rod groups: ARO except the lead regulating control rod group may be inserted in the core but not more than 200 pcm or 20 % of the predicted worth.

e) RCS boron: critical boron well mixed (each of three consecutive samples differs by <10 ppm from the average of the three samples, and there is no significant trend). The boron concentration between the RCS, VCT, and pressurizer should be within 50 ppm.

A.4.3.4 Test method

a) Record plant conditions (RCS temperature, boron concentration, core reactivity, and control rod positions).

b) Begin continuous recording of reactivity and temperature.

c) Adjust the steam dump or bypass flow to increase (decrease) the RCS temperature by 5 °C/h to 10 °C/h.

d) Increase (decrease) the RCS temperature by 0,5 °C to 5 °C; then stabilize (within 0,2 °C for at least 5 min), and record plant conditions.

e) Repeat steps c) and d) with the temperature change in the opposite direction.

f) Take a minimum of two temperature ramps.

A.4.3.5 Hints/precautions

a) Equalize the boron concentration between the RCS, pressurizer, and VCTs before performing the test.

b) To mix the system well, maximize the flow through the charging, letdown, and pressurizer spray lines over an extended period of time.

c) Isolate temperature-sensitive systems from the RCS such as the ion exchangers (mixed bed demineralizers), etc.

d) Maintain stable system operating parameters as constant as possible.

e) Position the flux level of the detector used for the reactivity computer at either the high or low end of the recorder scale, depending on whether the reactivity is expected to decrease or increase as a result of the temperature change.

f) Avoid moving control rods during the test. If rods are moved, however, move them in one steady motion, and record the rod position both before and after the movement.

g) Temperature from only one loop is sufficient (it is important that an auctioneer method not be used where the source of the measurement can change).

h) Maintain a high water level in the VCT to prevent automatic makeup flow.

i) If temperature is decreasing, maintain a nondecreasing level in the pressurizer.

j) Stabilize the system before taking data.

A.4.3.6 Analysis

A.4.3.6.1 Slope method

a) In this method, the results consist of traces of reactivity as a function of RCS temperature.

b) Determine the “best fit” straight line through the linear portion of the traces.

c) Any nonlinearity not caused by rod motion is usually due to RCS-pressurizer-VCT boron concentration differences. Ignore nonlinear data.

d) Average the slopes of the lines to obtain the ITC. The individual slopes should be consistent (within 2 pcm/°C).

e) Adjust the ITC to correct for changes in rod position that occurred during the test.

A.4.3.6.2 End-point method

a) Divide the total reactivity change by the corresponding RCS temperature change.

b) The value for both heatup and cooldown ramps should be consistent (within 2 pcm/°C).

c) Adjust the ITC to correct for changes in boron concentration and rod position that occurred during the test.

d) Average the heatup and cooldown values to obtain the ITC.

Caution — This method does not show the effects of boron changes due to inadequate mixing or system makeup during the measurement. Therefore, it should be used with care.

A.4.3.7 Evaluation

Determine if the difference between the measured and predicted ITC is within the test criterion. If the measured ITC does not agree with the predicted value within the test criterion, the following are suggested:

a) review the data and data reduction;

b) verify that the conditions during the measurement were consistent with the conditions assumed in the prediction.

A.4.4 Flux symmetry

A.4.4.1 Test objective

To measure the degree of radial symmetry of the neutron flux at ≤ 30 % of rated thermal power.

A.4.4.2 Purpose

To determine if the measured radial flux symmetry is consistent with the expected symmetry.

A.4.4.3 Initial conditions

a) Power: ≤30 % of full power. The test should be performed at as low a power as practical. The power level should not change by more than 1 % during data acquisition and should not change more than 2 % during the entire test.

b) RCS temperature: within 1 °C of the reference temperature.

c) RCS pressure: within 350 000 Pa of the reference pressure.

d) Rod groups: above the insertion limits. Control rod motion should be limited to 8 cm during the test.

A.4.4.4 Test method

a) Record the responses of the in-core flux detectors at selected radial and axial locations that are well distributed throughout the core.

b) At least 50 % of the detectors in a given detector string should be operable in order to assign valid data to that core location.

c) Convert the detector responses to relative power density (RPD) for each instrumented assembly in the core. The constants that are used to convert the responses of the detectors to RPD should adequately reflect the condition of the core during the test.

A.4.4.5 Hints/precautions

a) As an additional verification, compare axial flux traces to expected shapes. No specific test criteria are suggested. However, this information can provide additional insight into core behaviour prior to ascending to higher power levels.

b) Wait 5 min for the self-powered neutron detectors to reach a constant signal at a specific power.

c) At low powers, the background signal (induced noise) in the detectors can be a significant fraction of the total signal. Make corrections to the signals if this component is significant.

A.4.4.6 Evaluation

Compare the measured assembly RPD for symmetric core locations. Each difference should meet the test criterion.

A.4.5 Power distribution measurements

A.4.5.1 Test objective

To measure the RPD of the core.

A.4.5.2 Purpose

To determine if the measured power distribution is consistent with design predictions.

A.4.5.3 Power distribution test with a fixed detector system

A.4.5.3.1 Initial conditions

a) Power: within 10 % of the desired value and not changing by >1 % FP/h.

b) RCS temperature: within 1 °C of the reference temperature.

c) RCS pressure: within 350 000 Pa of the reference pressure.

d) Rod groups: Positions are close to the reference position.

e) Xenon concentration: within 10 % of the equilibrium value or the actual xenon conditions are accounted for in the predictions.

A.4.5.3.2 Test method

a) Record the responses of the in-core flux detectors at selected radial and axial locations that are well distributed throughout the core.

b) Convert the detector responses to RPD for each instrumented assembly in the core. The constants that are used to convert the responses of the detectors to RPD should adequately reflect the condition of the core during the test.

A.4.5.3.3 Hints/precautions

a) The number of core locations that are monitored should be consistent with the number assumed in the development of the measurement uncertainty factors that are associated with the test results. At least 50 % of the detectors in a given fixed detector string should be operable in order to assign valid data to that core location.

b) Before recording the data, wait 5 min for the self-powered neutron detectors to reach a constant signal at a specific power.

c) The quality of the power distribution measurement is generally better if the reactor power and plant conditions are stabilized for ~1 h prior to the data collection.

A.4.5.3.4 Test evaluation

Compare each measured RPD to the predicted value. The difference should meet the test criterion. The root-mean-square (rms) of all the differences between the measured and predicted values should meet the test criterion. Also, compare the measured core average axial power shape to the design prediction.

A.4.5.4 Power distribution test with a movable detector system

A.4.5.4.1 Initial conditions

a) Power: within 10 % of the desired value and not changing by >1 % FP/h.

b) RCS temperature: within 1 °C of the reference temperature.

c) RCS pressure: within 350 000 Pa of the reference pressure.

d) Rod groups:

   1) intermediate power: at a position to control the axial power shape but not changing by >8 cm throughout the measurement unless specifically accounted for in the measurement;

   2) full power: lead rod group slightly inserted and not changing by >8 cm throughout the measurement unless specifically accounted for in the measurement;

e) Xenon concentration: within 5 % of the equilibrium value or the actual xenon conditions are accounted for in the predictions.

A.4.5.4.2 Test method

a) Record the movable detector (M/D) response as it is withdrawn from the core.

b) Calibrate the detectors by driving each detector through a common core location at least twice during the measurement process.

c) Obtain data from all accessible core locations.

d) Record control rod position, ex-core detector response, and RCS temperature for each traverse through the core.

e) Record plant calorimetric power information at the start, middle, and end of the measurement.

A.4.5.4.3 Hints/precautions

a) Determine detector operating voltage plateau prior to the measurement.

b) Minimize control rod motion during the measurement. Power level/temperature control can be accomplished by small dilutions instead of rod motion. If rod motion is required, however, do not move them while data are being acquired by the M/Ds.

c) Ensure that the detectors are correctly positioned in the core for data recording. Ideally, the detector should be at the top of the active fuel (bottom-mounted instrumentation) when the data recording is initiated. The detectors can be positioned by using the flux depressions from the fuel grid spacers and extrapolating from there to the top of the fuel. Detector coasting after the scan should also be considered.

d) Some M/Ds exhibit changes in their response characteristic as a function of time or operating temperature. Account for changing detector responses during the measurement by using the calibration traces (this detector should later be replaced). If the detector shows sensitivity to its operating temperature, then wait at least 1 min with the detector inserted prior to the data recording.

e) Review the detector calibration factors from measurement to measurement to determine if any detector's response characteristics are changing. If a significant trend is exhibited, then consider replacing the affected detector(s).

