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Reload startup physics tests for pressurized water reactors

Essais physiques au redémarrage pour les réacteurs à eau préssurisée

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Contents

Page

Foreword

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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).

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

For an explanation on 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 the following URL: www.iso.org/iso/foreword.html.

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

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 consistent with 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 test. Acceptable methods for performing the individual tests are provided in Annex A. Alternate methods can 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 refueling or significant reactor core alteration provide assurance that the plant can be operated as designed.

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[1)].

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).

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 plant's experience database and therefore may necessitate expanding the test program.

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 http://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

1) The good practices discussed in this document should be considered for use in the physics test program for the initial core of a commercial PWR. One test that provides useful information (without additional test time) is the hot-zero-power to hot-full-power reactivity measurement.

3.3
control rod group
one or more rods that are inserted or withdrawn simultaneously (also known as “control rod bank”)

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.”

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
HFP
full power
rated thermal power
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 whose primary absorber material does not extend the entire length of the control rod (typically the lower half of the control rod’s active length)

Note 1 to entry: 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 as follows:

$$\%\Delta\rho = (k_2 - k_1) \times 100 / k_1 k_2$$

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 that may be partially or fully inserted in the core during normal operation

3.13
safety control rod group
shutdown rod group
shutdown bank
control rod group that remains withdrawn from the core during normal operation

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

Note 1 to entry: The value is based on differences between calculations and measurements that would suggest a problem with the as-built core, the measurement, or the prediction. The value is not based on safety analysis assumptions. See the Annex for a more complete discussion of test (review) criteria used in this document.

4 Relation to other standards

American National Standard ANSI/ANS-3.2-2012 (R2017)[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 (R2017). American National Standard ANSI/ANS-3.1-2014[3], provides for the selection, qualification, and training of personnel for nuclear power plants, including personnel responsible for startup testing.

American National Standard ANSI/ANS-19.4-1976 (R2000) (W2010)[4], and American National Standard ANSI/ANS-19.5-1995 (W2005)[5], address reactor physics measurements that are intended to yield documented data of both the type and quality required for validating nuclear analysis methods. American National Standard ANSI/ANS-19.11-2017[6], describes how to calculate and measure the moderator temperature coefficient of reactivity. American National Standard ANSI/ANS-19.6.1-2011 (R2016)[7], 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(7). ANSI/ANS-19.6.1-2011 (R2016) was used as the basis for this standard (ISO 18077).

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 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 end point 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*: 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 shall be confirmed.

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

The reload startup testing program is constructed such that as the power ascension proceeds, the level of confidence in confirmed reactor characteristics continues to improve. Similarly, the results of testing at a given power level shall provide reasonable assurance that the next proposed power level can be achieved without risk of violating the design or licensing bases of the plant.

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 should 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 document, example measured parameters used for confirmation, and power levels before which they shall be confirmed are provided by Table 1. The parameters were selected by considering the following requirements:

a) *The information obtained from the parameter cannot be inferred from other tests that will be 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 measure 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.

b) *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).

c) *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
Capability to shutdown, power distribution[a]	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[b].	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] Although the power distribution may not be directly measured at <5 % power, an indirect measurement such as control rod worths provides the first indication that the power distribution is consistent with predictions. Such an indirect measurement is not required to be performed prior to exceeding 5 % power but may be used to support an increase in power from 30 % to 50 % by which the first direct power distribution needs to be measured. This indirect power distribution measurement may have tighter test criteria than that for control rod worths.

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

6 Test method requirements

Established test methods for the confirmation of each characteristic required by this document are described in the Appendix. 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.

6.1 General test considerations

6.1.1 Test objective

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

6.1.2 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.

6.1.3 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. So, 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.

6.1.4 Test methods

For each test, Annex A provides abstracts of acceptable methods for performing the test. Alternate methods can be used as long as they are shown to be acceptable by meeting the requirements of this clause. 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.

6.1.5 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.

6.2 Test criteria

If the difference between the measured and predicted values for a physics parameter exceeds the predetermined criterion, the measurements shall be reviewed, and if necessary, a thorough review of the predictions shall be performed. If a measurement is repeated, either the same measurement technique or an approved alternate technique shall be used. If these actions do not resolve the discrepancy, the impact on plant safety shall be evaluated, and if necessary, appropriate operating restrictions shall be established.

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