

SAFETY STANDARDS
of the
Nuclear Safety Standards Commission (KTA)

KTA 3104
Determination of the Shutdown Reactivity
(October 1979)

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Comment:

In these English translations of KTA-Safety Standards the words shall, should and may are used with the following meanings:

- shall** indicates a mandatory requirement,
- should** indicates a requirement¹ to which exceptions are allowed. However, the exceptions shall be substantiated during the licensing procedure,
- may** indicates a permission and is, thus, neither a requirement (with or without exceptions) nor a recommendation: recommendations are worded as such, e.g., "it is recommended that".

The word combinations basically shall/shall basically are used in the case of mandatory requirements to which specific exceptions (and only those!) are permitted. These exceptions - other than in the case of should - are specified in the text of the safety standard.

¹ Please note that in the case of IAEA NUSS standards and ANSI standards, the word "should" indicates a mere recommendation.

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PLEASE NOTE:

Only the original German version of this safety standard represents the joint resolution of the 50-member Nuclear Safety standards Commission (Kerntechnischer Ausschuss, KTA). The German version was made public in Bundesanzeiger No. 44a on March 4, 1988. Copies may be ordered through the Carl Heymanns Verlag KG, Gereonstr. 18-32, D-5000 Köln 1.

Nuclear Safety Standards Commission (KTA)

Federal Republic of Germany

1 Scope

This Safety Standard applies to nuclear power plants with light water reactors. It applies to the determination of the shutdown reactivity of reactor cores for conditions following a shutdown during specified normal operation and for conditions during the course of incidents without loss of coolant. The specification of numerical values for the required shutdown reactivity is not dealt with in this safety standard.

2 Definitions

(1) Shutdown Reactivity

The shutdown reactivity is the reactivity of the reactor which was transferred to the subcritical condition with the equipment provided for this purpose.

Note:

The shutdown reactivity is a function of the reactor condition following shutdown.

(2) Reactivity Equivalent

The reactivity equivalent of a change of condition is the reactivity change caused by that change of condition.

(3) Reactivity Balance

The reactivity balance is the representation of a reactivity difference between two conditions as the sum of reactivity equivalents of simple or composite changes of condition.

(4) Reactivity Coefficient

The reactivity coefficient of a condition parameter is the partial derivative which represents the change in reactivity as a function of this condition parameter.

(5) Reactivity Measuring Method, Inversely Kinetic

The inversely kinetic reactivity measuring method is a method which determines the reactivity on the basis of the time history of a neutron flux signal.

(6) Effectiveness of Reactivity Control Elements, Differential

The differential effectiveness of reactivity control elements is the reactivity coefficient allocated to a control element.

(7) Effectiveness of Reactivity Control Elements, Integral

The integral effectiveness of reactivity control elements is the reactivity equivalent allocated to a control element.

3 Methods for the Determination of the Shutdown Reactivity

(1) The following methods are available for the determination of the shutdown reactivity:

- a) Using a calculation of the effective multiplication factor k_{eff} for the shutdown reactor in accordance with Section 4.
- b) Using a reactivity balance for the transition from a reference condition of known reactivity to the shutdown condition. The following can be used in this reactivity balance:
 - ba) reactivity equivalents calculated in accordance with Section 4, or
 - bb) reactivity equivalents measured in accordance with Section 6.1, or
 - bc) reactivity equivalents determined on the basis of equivalent changes of condition in accordance with Section 6.2, or
 - bd) calculated reactivity equivalents normalized by differential measurements in accordance with Section 6.3, or

be) a combination of calculated and measured reactivity equivalents.

c) As an equivalent change of condition in accordance with Section 7.

(2) The shutdown reactivity shall be determined at least for each operating period. The results of experimental demonstrations shall be extrapolated to cover the entire operating period, either by means of supplementary calculations or on the basis of generally valid physical laws.

Note:

Operating period is the time period during which the reactivity-determining configuration of the reactor core remains unchanged and the nuclear composition of the reactor core is changed only by progressive burnup. For example, an operating period is the time period between two refueling operations (burnup cycle) during which the burnup is, e.g. compensated for by a change in control rod positions or in the boron concentration. In as far as required by the relevant safety criteria to be applied, it shall be assumed that the shutdown equipment is not available in its entirety, e.g. because of a jamming of the most effective control rod.

4 Calculation of the Shutdown Reactivity and of Reactivity Equivalents

(1) For the calculation of the shutdown reactivity and of reactivity equivalents, codes for stationary core calculation shall be used which have been verified for the respective scope of application.

(2) In the analytical methods the physics shall be represented by mathematical models which have been based on the physical laws governing them. For the purpose of describing individual partial physical aspects, it is also allowable, within the scope of an analytical method, to use correlations derived from experiments, provided these experiments are representative of the planned scope of application of the correlation concerned.

(3) An analytical method, including the associated data records, is considered to have been verified as soon as its applicability and accuracy have been demonstrated by means of reference cases. An analytical method is also considered to have been verified if its results show a known systematic deviation from the comparative values so that with a known correction they will be in agreement with the comparative values.

(4) The verification of an analytical method is only required to the extent its results are made part of the demonstration of the shutdown reactivity.

Note:

Example (a)

An analytical method which, with a certain set of input data, is to be used to demonstrate the effectiveness of control rods can be verified by a calculation of

- a) critical control rod configurations or
- b) integral effectiveness of control rods or
- c) differential effectiveness of control rods

which have either been measured or which have been calculated using a method that has already been verified.

Example (b)

If the same analytical method is to be used for the demonstration of temperature coefficients, with a suitably modified set of input data, it shall be verified for this particular application by a calculation of

- a) temperature coefficients or
- b) critical states at different temperatures

which have either been measured or which have been calculated using a method that has already been verified.

(5) As reference cases,

- a) measurements made on reactors or critical assemblies, or

- b) results of computer codes which have already been verified and are, as far as possible more accurate,

should be used. The reference cases shall be representative of the planned scope of application.

Note:

The following quantities are suitable for comparison:

- critical conditions,
- equivalent changes of condition,
- subcritical conditions of known reactivity,
- reactivity equivalents,
- reactivity coefficients.

When using two-dimensional analytical methods, the influence of changes of the condition parameters on the neutron flux distribution in the third dimension shall be taken into account.

5 Kinetic Methods of Reactivity Measurement

5.1 Physical Principles

5.1.1 Inverse Kinetics

- (1) The most reliable and direct method of the determination of reactivities is inverse point kinetics. This method shall be given preference.

Note:

Inverse point kinetics can be used in particular if the time-dependent distribution of the neutron flux density can be separated during the measuring process, with a sufficient degree of approximation, into a form function which depends only on position and energy and an amplitude function which depends only on time (as in the asymptotic condition).

- (2) The applicability of point kinetics can be assumed if the changes of condition considered are spatially homogeneous or quasi-homogeneous, for example changes of the temperature or concentration of a dissolved neutron absorber. However, if the change of condition involves an inhomogeneous distribution, e.g. in the case of control rod motions, it shall be checked whether point kinetics is applicable. A measurement criterion for the applicability of point kinetics is (for a physically stationary reactor condition) the constancy of the period or of the reactivity as calculated in accordance with point kinetics.

- (3) The following measures should be taken into account when using point kinetics:

- The measurement should be carried out such that the form function changes slowly (measurement with reactivity compensation; if possible, asymptotic time behavior should be awaited (period measurement)).
- The detector position should be chosen such that changes of the form function only have a small influence on the signal.

- (4) If the conditions for the applicability of point kinetics cannot be met, a kinetics model dependent on position can be used. The necessity for such an approach can especially result in the case of the rod drop method in accordance with Section 5.2.2.

5.1.2 Point Kinetic Parameters

- (1) Input parameters for the point kinetic equations are:

- Effective fraction of the delayed neutrons in group i following a fission of nuclide j ($\beta_{i,eff}^j$)
- Decay constants (λ_i^j) of the precursors of the delayed neutrons which belong to group i and originate from nuclide j .

Note:

In light water reactors without any noticeable (γ, n) neutron production, a subdivision into six groups is sufficient: $i = 1, 2, \dots, 6$. As the decay constants of nuclides j differ only slightly, they can be described by a uniform six group theorem λ_i , which is independent of j .

- c) Generation time A

Note:

In the majority of inverse point kinetics applications, the generation time need only be known approximately, as its value only has a minor influence on the result.

- (2) The computation rules for the effective fractions of the delayed neutrons and for the generation time should be derived from the correspondence between, on the one hand, the complete position and energy-dependent description of the reactor in accordance with the transport and diffusion theory and, on the other hand, the point kinetics formalism. Accordingly, $\beta_{i,eff}^j$ results from a weighted integral over the position and energy-dependent production of delayed neutrons by nuclide j , with the adjoint solution of the stationary eigenvalue problem as a weight function, divided by the weighted integral over the total production.

- (3) Number and subdivision of the energy groups shall be consistent with the prevailing spectral regions of the prompt and delayed fission neutrons. A representation in at least three energy groups is required.

- (4) For the prompt and delayed fission yields and their energy-dependence the values contained in the evaluated Nuclear data file ENDF/B (1974) /1/ should be used. For the relative fractions of the delayed neutron groups and for the decay constants, the values specified in Keepin (1965) /2/ should be used.

- (5) The results of inversely kinetic reactivity measurements shall always be accompanied by a statement of the kinetic parameters which were used for the evaluation.

5.2 Applications

5.2.1 Period Measurement

The reactivity shall be maintained constant following a change of conditions made for measurement purposes, for example a change of control rod positions. After a transition time an asymptotic neutron distribution and a stable period are obtained. The reactivity shall be calculated on the basis of the measured stable period in accordance with the Inhour equation.

Note:

The period measurement is preferably used when measuring rod effectiveness of a boiling water reactor in accordance with Section 6.3. Its scope includes reactivities up to $\pm 0.3\%$.

5.2.2 Rod Drop Method

Starting from a stationary critical condition, control rods are dropped or injected. The detector signal shall be recorded as a function of time. The (negative) reactivity shall be determined on the basis of the course of the detector signal during and after the rod drop.

Note:

When interpreting point kinetically evaluated rod drop measurements, it shall be considered that these measurements are especially influenced detrimentally as a result of changes of the form function. The systematic failure will increase with increasing reactivity. This increase in failure sets the practical boundary for its scope of application.

5.2.3 General Application of Inverse Point Kinetics

The reactivity shall be determined as an inverse solution of the point kinetics equations from the time history of the neutron flux signal if the condition that the reactivity remains constant with the course of time, following a reactivity change carried out at the beginning, is not adhered to with the required degree of approximation.

Note:

This can be done using analog or digital computational methods. To carry out time-saving measurements on power reactors, in-process reactivity measuring instruments (so-called reactivity meters) which continuously calculate and display the reactivity on the basis of a detector signal have demonstrated successful service.

5.3 Measurement and Evaluation Methods

5.3.1 Requirements for the Measurement System

(1) The neutron measurement channel shall supply a signal with a sufficiently small component that is not proportional to the fission product energy release.

Note:

Measures in this direction are: γ -compensation, shielding of the detector, or alternating current method (Campbell method).

(2) The measurement channel shall have a firing-angle setting such that linearity errors are kept small over the entire amplitude range of the measurement signal. The detector should be placed such that changes of the form function during the measurement process will have only a minor influence. In the case of period measurements in accordance with Section 5.2.1, any detector position is adequate. The proper functioning of measurement channel and evaluation procedure should be checked with the aid of a simple test case, e.g. a stable period.

5.3.2 Variation Range of the Reactor Power

To ensure that the feedback and source-free zero power kinetics remains valid, the variation range of the reactor power shall remain limited during the measurement process. The upper limit is set by the initial temperature changes with their influence on reactivity. For this upper limit, the reference level is $\leq 1\%$ of nominal power. The lower limit is set by possible influences of neutron sources. The applicability of source-free and feedback-free zero power kinetics should be checked experimentally, for example by means of a period measurement covering the entire planned range of the detector signal.

6 Methods for the Measurement of Reactivity Coefficients and Reactivity Equivalents

6.1 Inversely Kinetic Methods

6.1.1 Performance of Tests for Measurements without Reactivity Compensation

The condition parameter p is changed by Δp . The resulting reactivity change $\Delta \rho$ is measured in accordance with one of the methods described in Section 5.2; it is equal to the reactivity equivalent $\Delta \rho_e$ of Δp (see Appendix B).

Note:

The application of the inversely kinetic measurement methods is the simplest type. Typical applications include the measurement of:

- reactivity coefficients $\Gamma_p = \Delta \rho_p / \Delta p$
- differential effectiveness of control rods,
- Integral effectiveness of control rods in accordance with the rod drop method.

With respect to the size of the measurable reactivity equivalents, the scope of application is limited by the fact that, with increasing reactivity ρ , the detector signal approaches the limits of its allowable range of variation at an ever increasing rate, so that the time available for carrying out the change of condition p and, possibly, for waiting for a stable asymptotic condition, is too short. For the limits of the range of application, reference levels from approx. -0.5% to $+0.3\%$ apply to continuous reactivity meters and period measurement.

6.1.2 Performance of Tests for Measurements with Reactivity Compensation

(1) If the measurement is carried out with reactivity compensation, the limitation of the range of application of the inversely kinetic measurement without reactivity compensation does not apply.

(2) Starting out from a critical condition p_1, q_1 , two condition parameters p and q are changed alternatively by δp and δq . The steps δp and δq are selected such that they compensate each other approximately so that the reactor will not depart too far from the critical condition. In this context, the condition of the reactor moves at the (p, q) level in the environment of the critical path from the initial condition p_1, q_1 to the final condition p_2, q_2 .

(3) The reactivity changes $[\delta \rho]_i$ caused by the individual steps $[\delta p]_i, i = 1, 2, \dots$, are measured by the inversely kinetic method. The step intervals and the step sequence shall be selected such that the firing-angle setting of the measuring system will not be exceeded and form function changes will not be too fast.

(4) The result of the measurement is the sum of the reactivity changes $\sum_i [\delta \rho]_i$. In the borderline case of negligibly small step intervals, this sum changes over to the reactivity integral $(\Delta \rho)_p$, formed along the critical path from p_1, q_1 , to p_2, q_2 .

(5) Since the condition path of the reactor links two critical conditions, $\Delta \rho = 0$, and the following equation applies:

$$(\Delta \rho)_p = -(\Delta \rho)_q \quad (6.1)$$

or in other words, the measurement supplies the reactivity integral $(\Delta \rho)_p$ and, simultaneously, the reactivity integral $(\Delta \rho)_q$.

Note:

The following is a list of pairs of variables which can compensate each other in the case of such measurements:

- rod position - boron concentration,
- position of cluster A - position of cluster B,
- rod position - temperature,
- boron concentration - Xe concentration.

(6) For the pressurized water reactor, this method is the most frequently applied kinetic measurement method or the determination of reactivity equivalents of $> 0.3\%$, especially of rod effectiveness.

(7) For the transition from the measured reactivity integrals $(\Delta \rho)_p$ and $(\Delta \rho)_q$ to the corresponding reactivity equivalents $\Delta \rho_p$ and $\Delta \rho_q$ of the simple changes of condition

$$\Delta p = p_2 - p_1 \text{ and} \quad (6.2)$$

$$\Delta q = q_2 - q_1 \quad (6.3)$$

additional theoretical or experimental investigations are required.

Note:

The relationships will become especially simple if the variables p and q are decoupled within the range of variation being consid-

ered. In this case, the reactivity integrals are equal to the reactivity equivalents.

6.2 Substitution Method

(1) The substitution method supplies equivalent changes of condition. Starting out from a critical condition p_1, q_1 , a first parameter p is changed by a measurable amount Δp .

(2) The resulting reactivity change is compensated by the equivalent change Δq of a second parameter q such that the reactor remains in the critical condition or goes back to the critical condition. No condition parameters other than p and q may change.

(3) The reactivity equivalents $\Delta\rho_p$ and $\Delta\rho_q$ of the changes of condition Δp and Δq are equal with respect to their amounts. Thus an unknown reactivity equivalent $\Delta\rho_q$ can be determined from a known equivalent $\Delta\rho_p$.

Note:

A frequent application of this method is the so-called absorber substitution to determine greater reactivity equivalents for the pressurized water reactor. Here, the reactivity change caused by a change of condition is compensated by an opposing change in the concentration of the boric acid which is dissolved in the coolant. The change of boron concentration which is equivalent to the change of condition is the boron equivalent of the change of condition.

6.3 Normalization of Calculated Reactivity Equivalents by Measured Reactivity Coefficients

Reactivity equivalents can be determined as follows by a combination of calculation and measurement:

1. Calculation of the reactivity coefficient $\Gamma_p^{\text{theor}}(p)$, which is associated with the required reactivity equivalent, as a function of the condition parameter p , and subsequent integration in accordance with equation A 2.4.
2. Measurement of the reactivity coefficient Γ_p for a certain value p_0 of the condition parameter p (preferably in the vicinity of the critical condition).
3. Multiplication of the calculated reactivity equivalent by a normalization factor that is available as the relation between the measured reactivity coefficient $\Gamma_p^{\text{exp}}(p_0)$ and the theoretical reactivity coefficient $\Gamma_p^{\text{theor}}(p_0)$ calculated for $p = p_0$.

Note:

This method is applied for the determination of the net shutdown reactivity of boiling water reactors. In this case, p is the position, and Γ_p the differential effectiveness of the individual control rod, and $\Gamma_p(p)$ is the differential characteristic of the control rod.

6.4 Sources of Error

Possible sources of error in the experimental determination of reactivity coefficients and reactivity equivalents are the following:

- a) the uncertainties of the kinetic parameters,

- b) systematic changes of the form function during the measurement,
- c) the measurement errors of the varied condition parameters,
- d) fluctuations of condition parameters which shall be maintained constant,
- e) consequential effects of the preceding power operation of the reactor, for example an instationary xenon poisoning.

7 Determination of the Shutdown Reactivity as an Equivalent Change of Condition

For the monitoring of operation, an equivalent change of condition can also be determined as a measure for the shutdown reactivity. The change of condition that is equivalent to the shutdown reactivity is that change of a condition parameter which would just transfer the stationary sub-critical reactor to the critical condition. The frequency of such measurements can be seen in Section 3.

Note:

The determination of the shutdown reactivity as an equivalent change of condition is of importance for the experimental demonstration of a sufficient subcriticality.

It is applied in the following cases:

- a) Boiling water reactor: The fact that the shutdown reactor will become critical when the most effective rod is withdrawn completely and an adjacent rod is withdrawn partly, results in the individual quantity "greater than or equal to a complete and a partial length of rod insertion" with respect to the shutdown reactivity.
- b) Pressurized water reactor: The demonstration that a reduction in the boron concentration by ΔC will take the reactor to the just critical condition, results in the boron equivalent ΔC as an individual quantity with respect to the shutdown reactivity.
- c) Loading: The monitoring of subcriticality during a classical "loading experiment" by extrapolation of a measured $1/Z$ curve ($Z =$ counting rate) to 0 also supplies an equivalent change of condition as the distance to the critical condition, for example the "minimum amount of fuel still to be loaded before criticality is reached".

8 Documentation

(1) For the demonstration of the shutdown reactivity, the licensee shall prepare documentation and reports. With respect to calculations input data, results of the calculations and a description of the method or code shall be submitted. For the measurements, both the results and the methods used shall be stated.

(2) The verification of the shutdown reactivity within the scope of the licensing and regulatory procedure is carried out by authorized experts as prescribed by the licensing authority (in accordance with Sec. 20 of the Atomic Energy Act). The results and the documents referred to above shall be kept at least for four years, or for a minimum of four operating periods, as described in Section 3, Note.

Appendix A

References

- /1/ Kerndatensammlung ENDF1B (1974) Evaluated Nuclear Data File, 8 format, Version IV, released 1974 by National Neutron Cross Section Center, BNL Available for OECD member states from: CCDN NEA Neutron Data Compilation Centre B.P. 9, 91190 GSF SUR YVETTE, France
- /2/ Keepin (1965) G.R. Keepin, Physics of Nuclear Kinetics, Addison Wesley 1965

Appendix B

Explanations with Respect to the Terms Reactor Condition, Change of Condition, Reactivity Coefficient, Reactivity Equivalent, Reactivity Integral and Reactivity Balance

Reactor Condition and Change of Condition

The physical condition of the reactor is described by condition parameters p, q, r, \dots

Condition parameters include, e.g.:

- mean density, mean temperature, mean void content, and pressure of moderator or coolant
- mean fuel temperature,
- position of the control rods,
- concentration of a neutron absorber dissolved in the moderator or coolant,
- burnup state of solid neutron absorbers,
- mean concentration of fission and decay products,
- mean concentration of fissile nuclides (fuel burnup).

Reactivity ρ is a function of the physical condition of the reactor as described by the condition parameters:

$$\rho = \rho(p, q, r, \dots) \quad (\text{A 2.1})$$

The condition parameters form a condition volume, the dimension of which depends on the number of condition parameters to be included in each individual case. Each change of condition can be described as a path of the condition point through the condition volume. An excellent path is the critical path for which the following equation applies:

$$\rho(p, q, r, \dots) = 0 \quad (\text{A 2.2})$$

Changes of condition which influence only one condition parameter are termed simple changes of condition. They are parallel to the coordinate axes of the condition volume.

Reactivity Coefficient

The reactivity coefficient Γ_p of the condition parameter p is defined by:

$$\Gamma_p(p, q, r, \dots) = \frac{\delta \rho(p, q, r, \dots)}{\delta p} \quad (\text{A 2.3})$$

$$q, r, \dots = \text{constant}$$

Reactivity Equivalent, Reactivity Integral

The reactivity equivalent $\Delta \rho_p$ of a simple change of condition $p_1 \rightarrow p_2$, with the remaining condition parameters q, r, \dots being kept constant, is defined by

$$\Delta \rho_p = \int_{p_1}^{p_2} \Gamma_p(p, q_1, r_1, \dots) dp \quad (\text{A 2.4})$$

$$q = q_1 = \text{constant}$$

$$r = r_1 = \text{constant}$$

..

..

Any given composite change of condition from $p_1; q_1, r_1, \dots$ to $p_2; q_2, r_2, \dots$ leads to a reactivity change

$$\begin{aligned} \Delta \rho = \int_1^2 dp = & \int_{p_1, q_1, r_1, \dots}^{p_2, q_2, r_2, \dots} \Gamma_p(p, q, r, \dots) dp + \\ & + \int_{p_1, q_1, r_1, \dots}^{p_2, q_2, r_2, \dots} \Gamma_q(p, q, r, \dots) dq + \\ & + \dots \end{aligned} \quad (\text{A 2.5})$$

$$= (\Delta \rho)_p + (\Delta \rho)_q + \dots \quad (\text{A 2.6})$$

$\Delta \rho$ is the reactivity equivalent of the change of condition considered; it depends only on the initial and final conditions and not on the course of the condition path between these two

points in the condition volume. Along a critical path, by definition, $\Delta\rho = 0$. The quantities $(\Delta\rho)_p$, $(\Delta\rho)_q$, ... are the reactivity integrals of the condition parameters p , q , ... corresponding to this change of condition. In general, they depend on the course of the condition path.

The reactivity integrals $(\Delta\rho)_p$, $(\Delta\rho)_q$, ... in accordance with equation (A 2.5) will become identical with the reactivity equivalents $\Delta\rho_p$, $\Delta\rho_q$, ... in accordance with equation (A 2.4) if the variables p , q , ... are decoupled, i.e. if the reactivity can be described as

$$\rho(p, q, \dots) = \rho_p(p) + \rho_q(q) + \dots \quad (\text{A 2.7})$$

Reactivity Balance

Equation (A 2.5) is the general definition of a reactivity balance. As the result $\Delta\rho$ of the balance is not a function of the course of the condition path, any path may be chosen for the theoretical calculation of the balance.

The description becomes particularly clear if the condition path is made up of simple changes of condition. In this case, the following equations apply:

$$\begin{aligned} \Delta\rho &= \int_1^2 d\rho = \int_{p_1}^{p_2} \Gamma_p(p, q_1, r_1, s_1, \dots) dp + \\ &+ \int_{q_1}^{q_2} \Gamma_q(p_2, q, r_1, s_1, \dots) dq + \\ &+ \int_{r_1}^{r_2} \Gamma_r(p_2, q_2, r, s_1, \dots) dr + \\ &+ \dots \\ &= \Delta\rho_p + \Delta\rho_q + \Delta\rho_r + \dots \end{aligned} \quad (\text{A 2.8})$$

$$= \Delta\rho_p + \Delta\rho_q + \Delta\rho_r + \dots \quad (\text{A 2.9})$$

This is the usual form of the reactivity balance. The terms of this balance are the reactivity equivalents of the simple changes of condition $p_1 \rightarrow p_2$, $q_1 \rightarrow q_2$, ... in accordance with equation (A 2.4). It shall be ensured that these reactivity equivalents can, in each individual case, be formed for a certain combination of the other condition parameters which have been kept constant.

Appendix C

Example of the Reactivity Balance for a Pressurized Water Reactor

Determination of the Shutdown Reactivity following a "Main Steam Pipe Break" Incident

When calculating the reactivity balance, stationary operation is considered as the initial condition. To characterize the most reactive condition for which the reactivity balance should be calculated, the course of the incident is briefly described:

The rapid decrease of the main steam pressure which follows the break of the main steam pipe causes a scram and the isolation of the steam generator affected. Within a few seconds, the reactor power decreases to the decay power while the fuel temperature decreases from its initial level to almost the level of the coolant temperature. The steam escaping from the affected steam generator withdraws heat from the primary circuit, so that transition to the zero power state is superimposed by a cooldown process. In the course of the flashing of the steam generator, the coolant temperature reaches a minimum. This minimum characterizes the most reactive condition which occurs as a result of the incident.

The shutdown reactivity in this most reactive condition is determined assuming that the most effective rod does not take part in the shutdown.

When calculating the reactivity balance the following condition parameters shall be considered:

a) Variable parameters:

- mean fuel temperature T_u ,
- mean coolant temperature T_k ,
- rod position s ,

coolant pressure p (can be neglected as long as the coolant is subcooled, i.e. as long as no steam voids occur in the reactor core).

Another variable parameter is reactor power P . Indirectly, it determines the fuel temperature and the thermohydraulic condition of the coolant (mean value and distribution of coolant temperature, coolant pressure). However, as reactivity does not explicitly depend on reactor power, it is not included here as an independent condition parameter.

b) Constant parameters:

- boron concentration (mass concentration) C ,
- Xe concentration X ,
- burnup A .

Initial Condition

The initial condition is a stationary operating condition with reactor power $P = P_0$; at the same time, it is the reference condition of known reactivity:

$$\begin{aligned} T_u &= T_{u0} \\ T_k &= T_{k0} \\ s &= s_0 \\ C &= C_0 \\ X &= X_0 \\ A &= A_0 \\ \rho_{\text{ref}} &= 0 \end{aligned}$$

For the reactivity balance, the composite change of condition is reduced to a sequence of simple changes of condition. This reduction is random. One of the possibilities is described below:

Step 1: Transition to Zero Power

Reactor power P: $P_0 \rightarrow 0$

Fuel temperature T_u : $T_{u0} \rightarrow T_{k0}$

Remain constant: $T_k = T_{k0}$, $s = s_0$

The reactivity equivalent of this change of condition is:

$$\Delta\rho_D = \int_{T_{u0}}^{T_{k0}} \Gamma_u(T_u, T_{k0}, s_0) dT_u \quad (\text{A 3. 1})$$

with

$$\Gamma_u = \frac{\partial\rho}{\partial T_u} \quad (\text{A 3. 2})$$

Reactivity coefficient of the fuel temperature in the condition T_{k0} , s_0 , C_0 , X_0 , A_0 .

Here, the fuel temperature coefficient Γ_u describes

- the direct influence of the fuel temperature T_u on the reactivity, in particular the so-called Doppler effect;
- the influence of the distribution of the coolant temperature which is bound to be variable due to T_u (with fixed mean value T_{k0})

In accordance with these two influences, the transition to zero power is occasionally subdivided into two partial steps 1.1 and 1.2:

- $T_{u0} \rightarrow T_{k0}$ with a fixed distribution of the coolant temperature; the corresponding reactivity equivalent is referred to as "Doppler reactivity".
- Initial distribution of the coolant temperature \rightarrow zero power distribution of the coolant temperature with a fixed mean value T_{k0} . The redistribution of the coolant temperature is particularly pronounced in the axial direction (disappearance of the enthalpy rise). The reactivity equivalent corresponding to this transition is referred to as "reactivity of redistribution".

Step 2: Cooldown to T_{kmin}

Coolant temperature T_k : $T_{k0} \rightarrow T_{kmin}$

Fuel temperature T_u : $T_{u0} \rightarrow T_{kmin}$

Remain constant: $P = 0$, $s = s_0$

The reactivity equivalent of this change of condition is:

$$\Delta\rho_T = \int_{T_{k0}}^{T_{kmin}} \Gamma_T(T, s_0) dT_u \quad (\text{A 3. 3})$$

with

$$\Gamma_T = \frac{\partial\rho}{\partial T} = \Gamma_k + \Gamma_u \quad (\text{A 3. 4})$$

Reactivity coefficient of the temperature in the zero power condition, s_0 , C_0 , X_0 , A_0

$$\Gamma_k = \frac{\partial\rho}{\partial T_k} \quad (\text{A 3. 5})$$

Reactivity coefficient of the coolant temperature

$$\Gamma_u = \frac{\partial\rho}{\partial T_u} \quad (\text{A 3. 6})$$

Reactivity coefficient of the fuel temperature

$$T = T_k = T_u \quad (\text{A 3. 7})$$

Temperature of the (isothermal) reactor at zero power.

Step 3: Regular Shutdown (all rods dropped)

Rod position s (bank): $s_0 \rightarrow s_{max}$

Remain constant: $P = 0$, $T_u = T_k = T = T_{kmin}$

The reactivity equivalent of this change of condition is the effectiveness of all rods, calculated from position s_0 , for the zero power condition, T_{kmin} , C_0 , X_0 , A_0 :

$$\Delta\rho_s = \int_{s_0}^{s_{max}} \Gamma_s(s, T_{kmin}) ds \quad (\text{A 3. 8})$$

with

$$\Gamma_s = \frac{\partial\rho}{\partial s} \quad (\text{A 3. 9})$$

Differential rod effectiveness

Step 4: Withdrawal of the most effective rod (stuck rod)

Rod position s (stuck rod): $s_{max} \rightarrow s_0$

All the other variables remain constant.

The reactivity equivalent of this change of condition is the stuck rod value $\Delta\rho_{StR}$ calculated between s_{max} and s_0 for the zero power condition, T_{kmin} , C_0 , X_0 , A_0 .

Final Condition

$$\begin{aligned} P &= 0 \\ T_u &= T_{kmin} \\ T_k &= T_{kmin} \\ C &= C_0 \\ X &= X_0 \\ A &= A_0 \\ s \text{ (bank)} &= s_{max} \\ s \text{ (stuck rod)} &= s_0 \end{aligned}$$

Reactivity Balance

The net shutdown reactivity ρ_N in the final condition is:

$$\rho_N = \rho_{ref} + \Delta\rho_D + \Delta\rho_T + \Delta\rho_s + \Delta\rho_{StR} \quad (\text{A 3.10})$$

Appendix D

Example of the Reactivity Balance for a Boiling Water Reactor

Determination of the Minimum Shutdown Reactivity

The condition of minimum shutdown reactivity for a boiling water reactor is the cold, xenon-free shutdown condition at a certain burnup of the reactor core (most reactive state). For reactor cores without burnable neutron absorbers, the most reactive condition is at the beginning of the cycle; for reactor cores with burnable absorbers, it may also occur in the course of the cycle following a burnup increase ΔA_r of the reactor core, depending on the burnup characteristic of the absorber. Thus, the demonstration of a sufficient shutdown reactivity shall be submitted for the regularly shutdown reactor; in this context, it is assumed that the most effective control rod did not participate in the shutdown process (net shutdown reactivity).

Reference Condition

As it is usual for the demonstration to be submitted at the beginning of the cycle, the following reference condition of known reactivity is available:

- cold, xenon-free, only most effective rod withdrawn;
- burnup-free, rod adjacent to the most effective rod withdrawn in addition as far as the criticality position s_{krit} .
- Reactivity $\rho_{ref} = 0$.

Starting out from the reference condition a reactivity balance is calculated for the most reactive condition. For this, the condition parameters as specified in a) above remain unchanged, whereas those specified in b) are variable and are changed in two consecutive steps.

Step 1: Production of the stuck rod configuration, i.e. complete insertion of the adjacent rod

Rod position s (adjacent rod):

$$s_{krit} \rightarrow s_{ins}$$

All the other condition parameters: as in the reference condition.

The reactivity equivalent of this simple change of condition is the effectiveness of the adjacent rod $\Delta\rho_{NS}$ between s_{krit} and s_{ins} , with the most effective rod withdrawn and with a cold, xenon-free burnup-free reactor. Up to an order of magnitude of -0.3%, this reactivity equivalent can be measured directly by determining a negative period. For the determination of greater rod effectiveness, measured differential rod effectiveness is frequently combined with calculated sequences of effectiveness.

Step 2: Increase in core burnup by AA_r

$$\text{Burnup A: } A_0 \rightarrow A_0 + \Delta A_r$$

All the other condition parameters: as in Step 1.

The reactivity equivalent of this simple change of condition is the maximum reactivity gain $\Delta\rho_A$ under stuck rod conditions by a leading burnup of the burnable absorber. This is determined analytically.

Final Condition of the Reactor

- cold, xenon-free, only the most effective rod withdrawn;
- cycle burnup - ΔA_r , all the other control rods inserted.

Thus, the most reactive condition of the reactor is set.

Reactivity Balance

The net shutdown reactivity ρ_N of the reactor for this most reactive condition results from the reactivity balance:

$$\rho_N = \rho_{ref} + \Delta\rho_{NS} + \Delta\rho_A \quad (\text{A 4. 1})$$