NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 4(4): 263–270
DOI 10.3897/nucet.4.31889

Research Article

A technique for detection of WWER fuel failures by activity of Xe radionuclides during reactor operation*

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Academic editor: *Yury Korovin* ♦ **Received** 10 September 2018 ♦ **Accepted** 22 November 2018 ♦ **Published** 13 December 2018

Citation: Kalinichev PM, Evdokimov IA, Likhanskii VV (2018) A technique for detection of WWER fuel failures by activity of Xe radionuclides during reactor operation. Nuclear Energy and Technology 4(4): 263–270. https://doi.org/10.3897/nucet.4.31889

Abstract

Fuel failures during operation of Nuclear Power Plants (NPPs) may lead to substantial economic losses. Negative effects of reactor operation with leaking fuel in the core may be reduced if fuel failures are detected in due time of the cycle.

At present time, the ratio of the normalized release rates of ^{131}I and ^{134}I is used to detect fuel failures in WWERs during steady state operation. However, based on the activity of iodine radionuclides, it is not always possible to detect the fuel failure. This situation may occur in case of a small defect in cladding of a leaking fuel rod or for high burnup fuel if the defect is overlapped by the surface of the fuel pellet. If it is so, fuel deposits may be the dominant contributor to iodine activity, and the fuel failure may not be noticeable.

In PWRs, fuel failures are detected by activity of radioactive noble gases. Noble gases are not adsorbed on cladding inner surface, as distinct from iodine radionuclides. Release of noble gases from the leaking fuel rod may be considerable even though defect in cladding is small.

In this paper, a technique is proposed for detection of fuel failures at WWER reactors by activity of radioactive noble gases in the primary coolant. It is shown that radioactive noble gases may be a more sensitive indicator of fuel failures than iodine radionuclides. Detection of fuel failures is based on monitoring of the ratio between ^{133}Xe and ^{135}Xe activity. Some examples of practical applications are given.

Keywords

WWER; fuel rod; fuel failure; fission products; technique; coolant activity; iodine radionuclides; radioactive noble gases

Introduction

Fuel failures may occur during operation of Nuclear Power Plants (NPPs). This may lead to substantial financial losses. Monitoring and analysis of primary coolant activity is used to ensure the radiation safety of power units and to mitigate the adverse effects of fuel failures (Shumkova et al. 2003, Burman 1991, Beyer 1991, Parrat

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2018, n. 2, pp. 101-113.

et al. 2003, El-Jaby et al. 2010, Likhanskiy et al. 2004, Oliver et al. 2017, Slavyagin et al. 2003). The prime task of coolant activity analysis is prompt identification of fuel failures.

According to the regulatory document (RD) (RD JeO 1.1.2.10.0521-2009 2016), if a spike event for activity of the reference radionuclides is absent, fuel failures should be detected by the ratio of the normalized release rates between ^{131}I and ^{134}I during steady-state reactor operation. However, fuel failures cannot be always clearly identified based on activity of iodine radionuclides. Practice shows that this is possible when the hydraulic resistance of the leaking fuel rod is high. High resistance occurs in case of a small defect in fuel cladding or when fuel burnup is high so that the defect is overlapped by the surface of the fuel pellet. In this case, the biggest contributor to the iodine activity may be fuel deposits (tramp uranium contamination), and the fuel failures may remain unnoticeable against the background activity level.

Activities of radioactive noble gases (NGs) are used for more reliable detection of fuel failures in PWR reactors. Noble gases do not interact with the fuel cladding (unlike surfactant iodine radionuclides). If much of the iodine is adsorbed on the inner surface of the fuel cladding, the release of the iodine radionuclides into the coolant, with all other things being equal, turns out to be smaller than the release of noble fission gases. The release of noble gases from a leaking fuel rod is detectable even when its hydraulic resistance is high.

In France, the fulfillment of one of the following conditions is taken as the criterion of the fuel failure during steady-state operation of PWR reactors: 1) the absolute value of the ^{133}Xe activity is higher than 10^6 Bq/kg, or 2) the ratio of the ^{133}Xe and ^{135}Xe activities is higher than 0.9 with the absolute activity of ^{133}Xe being in excess of 1.85×10^5 Bq/kg (The IAEA nuclear energy series 2018).

The criterion given in (The IAEA nuclear energy series 2018) cannot be used unchanged for WWER reactors for the following reasons. First, the absolute values and the ratios of the NG activities depend on the rate of the gas removal from the coolant (the rate of coolant degassing). The coolant degassing parameters are different in PWR and WWER reactors. Moreover, the rate of NG removal from the coolant may differ markedly among WWER units. Second, unlike PWR reactors, WWER power units do not currently use in practice coolant sampling at the reactor pressure. The gases are partially lost from the coolant samples with the existing sampling procedures, and the results of measuring the absolute NG activities may fail to be representative.

Below, a technique is proposed which makes it possible to detect fuel failures by NG activities during operation of WWER power units. The advantages of this technique are discussed against the criterion in (RD JeO 1.1.2.10.0521-2009 2016) based on the iodine activities. Some practical application examples are presented as well.

The procedure used to detect fuel failures based in iodine radionuclides

The criterion of fuel failure detection using iodine radionuclides under steady state operation conditions (see RD (RD JeO 1.1.2.10.0521-2009 2016)) is based on the concept of the normalized release rate A^*:

$$A^* = A(\lambda + \eta)/(\lambda Y), \quad (1)$$

where A is the measured activity; λ is the nuclide decay constant; η is the rate of the radionuclide removal from the coolant by the letdown filters; Y is the cumulative radionuclide yield per fission which is composed of the intrinsic yield y and the cumulative yield of the precursor nuclide Y_p.

According to RD (RD JeO 1.1.2.10.0521-2009 2016), a conclusion concerning the fuel failure can be made under the steady-state operation conditions in the event the ratio of the normalized release rates for ^{131}I and ^{134}I starts to exceed the threshold value. This value is equal to five for WWER-1000 reactors.

The key concepts which make it possible to obtain the criterion of type (RD JeO 1.1.2.10.0521-2009 2016) based on iodine activity are described below. After that, the behavior of the noble fission gases in the coolant is considered in the same approximations.

Behavior of iodine radionuclides in the primary circuit. Balance equations (Slavyagin et al. 2003a) are used to describe behavior of fission products (FPs) in the primary coolant, which can be written for the iodine radionuclides and their tellurium precursors as follows

$$\frac{dN_{\mathrm{I}}}{dt} = R_{\mathrm{I}} + \mathbf{R}_{\mathrm{I}} - (\lambda_{\mathrm{I}} + \eta_{\mathrm{I}})N_{\mathrm{I}} + \lambda_{\mathrm{Te}}N_{\mathrm{Te}}, \quad (2)$$

$$\frac{dN_{\mathrm{Te}}}{dt} = R_{\mathrm{Te}} + \mathbf{R}_{\mathrm{Te}} - \lambda_{\mathrm{Te}}N_{\mathrm{Te}}. \quad (3)$$

Here, R and $\mathbf{R}$ are the rate of the FP release into the coolant from fuel deposits and leaking fuel rod, respectively; N_{I} is the number of the iodine radionuclide atoms in the primary coolant, and N_{Te} is the number of tellurium atoms in the primary circuit. Tellurium is more superficially active than iodine, so it is assumed in equations (2), (3) that tellurium is adsorbed on the structural surfaces in the reactor core and is not removed from the primary circuit as the coolant flows through the letdown filters.

The presence of the tellurium precursor is important to take into account for ^{132}I and ^{134}I. It can be taken for ^{131}I, ^{133}I, and ^{135}I that the precursor decays practically instantaneously.

If the reactor operates in a steady-state mode, steady-state solution of equations (2) – (3) can be used. In these conditions, the normalized release rate (1) defines the intensity of the FP source in the coolant. For each iodine radionuclide, it is equal to the release rate into the

coolant divided by the probability of its formation (cumulative yield) per one fission of heavy nucleus.

Release of iodine radionuclides from fuel deposits. With no fuel failures in the reactor, the coolant activity is defined by the FP release from fuel deposits. Fuel deposits are uranium dust that builds up on the outer cladding surface during fabrication and/or is accumulated inside fuel assemblies when fuel is washed out from leaking fuel rods during operation at NPPs.

One of the key mechanisms for the nuclide release from fuel deposits is the direct escape of fission fragments into the coolant. Another mechanism occurs if the fuel deposits include particles with a size larger than the fission fragment range in UO_2. In this case, fission fragments can stick in fuel and escape further into the coolant by the radiation transport mechanism. For the reference iodine radionuclides, this mechanism is reduced to "radiation-induced" diffusion (Wise 1988). The rate R of the FP release from deposits is composed of the direct fission fragment escape rate (recoil rate) R_r and the diffusive release rate R_D:

$$R = R_r + R_D. \quad (4)$$

Particles of fuel deposits may have a developed surface (this is possible, e.g., for pieces of high burnup fuel pellets that have entered the coolant) (White 2001, Olander 1976). We shall assume that the developed surface has been caused by the presence of open pores. Some fission fragments can enter open pores near surface. This results in an increased rate of the radionuclide release into the coolant. The expression for the recoil release rate was obtained in (Wise 1985). The model for the diffusive release of nuclides with a short-lived precursor is described in (Wise 1988). The values of the radiation-induced diffusion coefficients for radionuclides were determined in experiments (Turnbull and Friskney 1982, Rossiter and White 2002).

With regard for the results in (Wise 1988, Wise 1985), the FP release from fuel deposits for nuclides with a short-lived precursor, such as ^{131}I, ^{133}I, and ^{135}I, can be represented as follows

$$R = YJf(h), \quad (5)$$

$$J = \mathrm{e}r_f S_g F, \quad (6)$$

where r_f is the fission fragment range in fuel; F is the fission rate in fuel deposits in the core; e is the release efficiency; and S_g is the "geometrical" area of the fuel surface (with no regard for open pores). The value e is defined by the geometry and lies in a range of $0 < \mathrm{e} \leq 0.5$ (Wise 1985). The function f in expression (5) has the form

$$f(h) = 1 + k_1 S_t D_c/(S_g R_c) + k_2 S_t h/(\mathrm{e} S_g r_f). \quad (7)$$

The second term in the right-hand side of (7) describes the increase in the release rate due to the fission fragment "sticking" in open pores. Here, S_t is the total area of the exposed fuel surface; d_c is the mean pore diameter in fuel deposits; r_c is the fission fragment range in the pore-filling fluid; and k_1 is the coefficient allowing for the pore geometry. For a spherical pore with $k_1 = 2/3$, the value r_c depends on what is filling the pore. If the pore is filled with water with a pressure of 160 atm and a temperature of about 600 K, the fission fragment range is about $3 \cdot 10^{-5}$ m. If the pore is filled with gas, the fission fragment range will be larger.

The closing term in the right-hand side of (7) describes the diffusive release from fuel deposits. Here, k_2 is the coefficient of the order of unity taking into account the geometry of the fuel particles; $h = (D/\mathrm{l})^{1/2}$ is the diffusion length; and D is the diffusion coefficient. According to (Turnbull and Friskney 1982), the diffusion length h of the reference iodine radionuclides with a fuel temperature of below 600 K is less than 10^{-7} m. The range r_f of heavy fission fragments (in particular, iodine) in fuel is about $5 \cdot 10^{-6}$ m (Wise 1985), which is much larger than the diffusion length h. So the diffusion term in equation (7) becomes important only with the developed surface of the fuel particles in deposits ($S_t >> S_g$).

The normalized release rates of ^{131}I, ^{133}I, and ^{135}I can be represented as

$$A^* = R/Y = Jf(h). \quad (8)$$

In the case of "even" iodine radionuclides, the precursor lifetime cannot be ignored and the release of ^{132}Te and ^{134}Te needs to be considered separately from the iodine release. The release of tellurium is described by expression (5). For ^{132}I and ^{134}I, the intrinsic yield y is used instead of the cumulative yield Y to describe the direct escape, and the diffusion release rate has the form

$$R_D = k_2 S_t F h(y + Y_p h/(h + h_p)). \quad (9)$$

In this case, the function $g(h, h_p)$, similar to the function $f(h)$, may be introduced, and the rate of the radionuclide release into the coolant can be written as

$$R = yJg(h, h_p), \quad (10)$$

$$g(h, h_p) = f(h) + k_2 h S_t Y_p h/(\mathrm{e} r_f S_g y(h + h_p)). \quad (11)$$

The normalized iodine release rate, with regard for (2), (3), and (10), has the form

$$A^* = (R+R_p)/(y+Y_p) = Jf(h) + Y_p k_2 S_t h_p^2/(Y\mathrm{e} S_g r_f (h+h_p)). \quad (12)$$

In the event of a "short-lived" precursor ($h_p >> 0$), equation (12) goes over to (8). If the diffusion length h_p cannot be neglected, as compared with h, then, as can be seen from (12), the contribution of the precursor nuclide can increase the normalized release rate markedly.

If fuel deposits consist of particles smaller than the fission fragment range, the radionuclide release can be considered in a "monolayer" approximation (RD JeO

1.1.2.10.0521-2009 2016). In equations (7) and (11), this corresponds to the formal transition $k_1 >> 0$ and $k_2 >> 0$ which gives $f = g = 1$. In this case, the calculated ratios of the normalized iodine release rates should be equal to unity (see the dashed line in Fig. 1). In practice, minor deviations from this value may be observed. This is explained by the fact that the value Y depends on the nuclide composition of the fuel in deposits which is, generally speaking, unknown. As a rule, the normalized release rates are calculated based on radiation measurement results by postulating a certain nuclide composition of deposits. For instance, it is accepted in (RD JeO 1.1.2.10.0521-2009 2016) that only ^{235}U is fissionable in deposits. The difference of the assumed from the actual nuclide composition leads to variation of the ratio between A^* for the iodine radionuclides in the limits of up to 30%.

If fuel deposits consist of large-size particles, the ratios of the normalized release rates (12) due to the diffusive release may deviate markedly from unity. RD (RD JeO 1.1.2.10.0521-2009 2016) presents an upper expert estimate for the respective ratios of normalized activities (see Fig. 1).

An analog of the dependence from RD (RD JeO 1.1.2.10.0521-2009 2016) for large-size particles in the deposits can be obtained from equations (1) – (12). Values of intrinsic and cumulative yields, as well as decay constants from the database in (Tasaka Kanj et al. 1990) were used throughout for the calculations. The highest values for the ratio of the normalized release rates of ^{131}I to ^{134}I are achieved in the event of the diffusive mechanism contributing predominantly to the iodine release from fuel deposits. Dependence (RD JeO 1.1.2.10.0521-2009 2016) can be obtained if it is assumed in equations (8) and (12) that $F = 4 \cdot 10^{19}$ m^{-3}s^{-1}, $S_f/S_g = 100$, and $S_f/S_g \times d_c << r_c$. Such parameters can be achieved if fuel deposits have compacted in the core to form a structure with a large number of small open pores. The result of the respective calculation is shown in Fig. 1.

Analysis of iodine normalized release rates and its constraints. If there is a fuel failure in the reactor, the source of each radionuclide R_c can be written as

$$R_c = R + \mathbf{R} = R + R_f \mu/(\lambda + \mu), \quad (13)$$

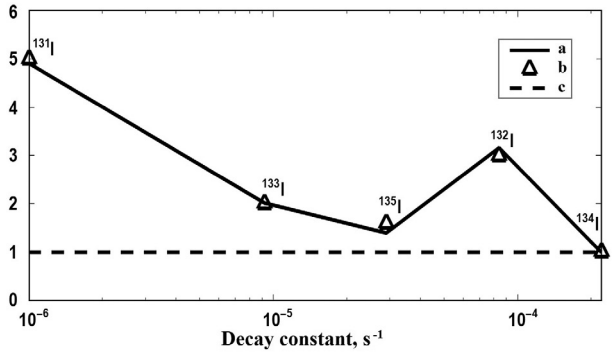

Figure 1. Ratio of the normalized release rates of iodine radionuclides to ^{134}I: a) a conservative calculation based on equations (4)–(12); b) threshold values from RD (RD JeO 1.1.2.10.0521-2009 2016); c) calculation for the "monolayer" case

where R_f is the FP release rate from fuel pellets to voids inside the fuel rod; and μ is the escape rate coefficient for the given radionuclide from fuel rod into the coolant. The escape rate coefficient relates the rate of the radionuclide release into the coolant to the total inventory of this radionuclide inside the fuel rod (Slavyagin et al. 2003a). The value μ depends on the characteristics of leaking fuel, the decay constant, and the radionuclide's chemical properties. For surfactant nuclides (iodine, in particular), μ can be much smaller than for the noble gases in the same leaking fuel rod.

When plugging expression (13) into equations (2), (3), and (1), one can see that a fuel failure may cause the ratio of the normalized ^{131}I and ^{134}I activities to increase markedly. This circumstance is used to detect the fuel failure in the reactor.

According to RD (RD JeO 1.1.2.10.0521-2009 2016), the region above the solid curve in Fig. 1 corresponds to the presence of leaking fuel in the reactor. If the data lie in the region between the solid and the dashed curves in Fig. 1, the iodine activity can be defined by FP release both from leaking fuel and from fuel deposits. For this region, no firm conclusion can be made as to the presence or absence of leaking fuel in the core proceeding only from the iodine activities (RD JeO 1.1.2.10.0521-2009 2016).

Noble gas activities as a means for fuel failure detection

Differences in xenon and iodine behavior. It follows from equation (13) that the contribution of the leaking fuel to the cumulative FP source in the coolant is defined by the ratio between the decay constant λ and the escape rate coefficient μ. The ^{133}Xe and ^{131}I decay constants are close (Tasaka Kanj et al. 1990). If chemical properties of xenon and iodine were similar, a marked deviation of the ^{133}Xe and ^{131}I activity from the background during fuel failure would be observed simultaneously. However, due to iodine adsorption on the cladding inner surface, in a certain range of the failed fuel characteristics it is possible that ^{131}I activity is still defined by its release from fuel deposits but ^{133}Xe activity already exceeds the background level significantly. The width of this range is the larger the more intensively iodine is adsorbed inside the leaking fuel rod (the temperature near the defect is assumed to be higher than the water saturation temperature; if the defect is in the fuel's "cold" zone and is covered with water, iodine can dissolve in it and be carried out of the failed fuel rather intensively). Thanks to such peculiarities, the NG activities can be a more sensitive failure indicator than the iodine activity.

For efficient detection of fuel failures based on the ratio of the NG activities, it is desired to use a pair of gaseous FPs with the following properties.

- The lifetime of the selected FPs should differ greatly. In this case, much of the short-lived gas will de-

cay having no time to leave the leaking fuel rod, as the activity of the long-lived gas will grow markedly after the failure.

- The radiation yields of the selected gases should depend weakly on the fuel's nuclide composition. As the burn-up of fuel deposits is normally unknown, the use of radionuclides with the release depending strongly on the fuel's nuclide composition may lead to major uncertainties. In particular, this is the reason for ^{85m}Kr and ^{88}Kr being not suitable for analysis.
- The nuclides used should be isotopes of one chemical element. A part of the gases dissolved in the coolant changes to a gas phase and is lost in the sampling process. Since gases have different solubility, the gas losses during sampling vary for isotopes of different chemical elements.

The pair of ^{133}Xe and ^{135}Xe satisfies to these conditions among the NGs whose activities are monitored at NPPs.

Release of xenon radionuclides from fuel deposits. To describe the activities of ^{133}Xe and ^{135}Xe in the primary circuit, it is required to take into account the behavior of the precursor iodines, ^{133}I and ^{135}I respectively. The balance equation for the xenon radionuclides in the primary circuit has the following form

$$\frac{dN_{\mathrm{Xe}}}{dt} = R_{\mathrm{Xe}} + \mathbf{R}_{\mathrm{Xe}} - (\lambda_{\mathrm{Xe}} + \eta_{\mathrm{Xe}})N_{\mathrm{Xe}} + (\lambda_{\mathrm{I}} + B\eta_{\mathrm{I}})N_{\mathrm{I}}. \quad (14)$$

Designations as in equation (2) are used here; the coefficient B allows for xenon which enters the core due to decay of precursor iodine in the letdown filters. It is assumed that the ion-exchange filters and the degasser are connected in series in the letdown system, and the coolant flow rate through these is identical. The cleaning rate η_{Xe} can be written in the form

$$\eta_{\mathrm{Xe}} = Q\alpha/M, \quad (15)$$

where Q is the mass flow rate of water to the ion-exchange filters and the degasser; M is the mass of the water circulating in the primary circuit; and α is the degassing efficiency assuming the values of zero to unity. The coefficient B relates to the degassing efficiency a as $B = 1 - \alpha$.

The behavior of the precursor iodine in (14) is described by equation (2). If the reactor operates in a steady-state mode, a steady-state solution can be used for equation (14).

For the xenon radionuclides, as well as for iodines, the rate of release from fuel deposits can be described using the functions f and g (see above). It follows from equation (14) that the ratio between the ^{133}Xe and ^{135}Xe activities in the reactor, when there is no fuel failure, has the form

$$\frac{A_{\mathrm{Xe\text{-}133}}}{A_{\mathrm{Xe\text{-}135}}} = \frac{y_{\mathrm{Xe\text{-}133}} g(h_{\mathrm{Xe\text{-}133}}, h_{\mathrm{I\text{-}133}}) + \dfrac{\lambda_{\mathrm{I\text{-}133}} + B\eta_{\mathrm{I}}}{\lambda_{\mathrm{I\text{-}133}} + \eta_{\mathrm{I}}} Y_{\mathrm{I\text{-}133}} f(h_{\mathrm{I\text{-}133}})}{y_{\mathrm{Xe\text{-}135}} g(h_{\mathrm{Xe\text{-}135}}, h_{\mathrm{I\text{-}135}}) + \dfrac{\lambda_{\mathrm{I\text{-}135}} + B\eta_{\mathrm{I}}}{\lambda_{\mathrm{I\text{-}135}} + \eta_{\mathrm{I}}} Y_{\mathrm{I\text{-}135}} f(h_{\mathrm{I\text{-}135}})} \times \left(1 + \frac{\eta_{\mathrm{Xe}}}{\lambda_{\mathrm{Xe\text{-}135}}}\right)\left(1 + \frac{\eta_{\mathrm{Xe}}}{\lambda_{\mathrm{Xe\text{-}133}}}\right)^{-1}. \quad (16)$$

The right-hand side of equation (16) may be dealt with as a family of curves $G(\eta_{\mathrm{Xe}})$ depending only on the xenon removal rate. The largest value of the function G, with the fixed value η_{Xe}, is reached if the "diffusion" terms in the functions f and g are the predominant contributors. The parameters, with which this condition is fulfilled, are described above. The solid line in Fig. 2 shows the upper envelope for the considered family of curves $G(\eta_{\mathrm{Xe}})$. The following parameters were varied to plot this with each value of the xenon removal rate: water flow rate to the filters, iodine removal efficiency, and nuclide composition of fuel deposits.

The solid line in Fig. 2 can be looked upon as the upper limit for the value of the potential ratio of the ^{133}Xe and ^{135}Xe activities if the only FP source in the primary circuit is fuel deposits.

Determination of the NG removal rate. The absolute values and the ratios of the gaseous FP activities depend on the degassing rate.

No measurement of degassing parameters is stipulated by the actual WWER regulations. The degassing parameters can be determined by measuring the NG activities downstream and upstream of the degasser. In this case, the degassing efficiency a in (15) is calculated from the formula

$$\alpha = A^2_{\mathrm{Xe}}/A^1_{\mathrm{Xe}}, \quad (17)$$

where A^1_{Xe}, A^2_{Xe} are the activities of xenon downstream and upstream of the degasser respectively.

The NG activities downstream and upstream of the degasser are measured, e.g. at the Temelin NPP (twice a month).

A technique to detect fuel failures based on the xenon radionuclide activity. Fig. 2 shows the "threshold" dependences of the ratios between the ^{133}Xe and ^{135}Xe activities on the degassing rate. The dashed line represents the "monolayer" approximation, and the solid line represents fuel deposits comprising large fuel particles with a developed surface. If the ratio of the measured xenon activities turns out to be above the solid line, it can be stated that there is a fuel failure in the reactor. If the activity measurement results fall within the region below the solid line, then, proceeding only from the Xe radionu-

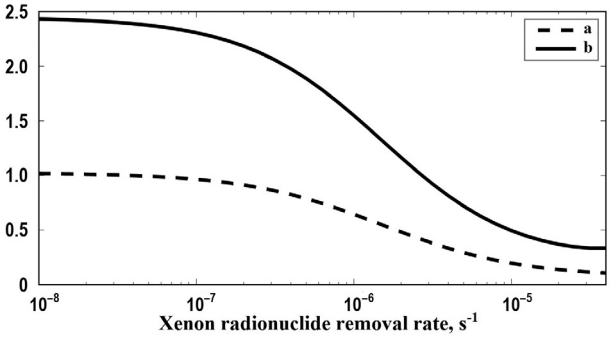

Figure 2. Threshold ratio between the ^{133}Xe and ^{135}Xe background activities for WWER-1000 reactors: a) for "monolayer" deposits; b) for deposits in the form of large fuel particles

clide activities, no clear answer can be given. In this case, it is required to analyze other factors: ratios of the normalized release rates for iodine radionuclides, presence of a spiking event, and presence of activity escalations during steady-state reactor operation.

The fuel failure detection procedures can be formulated as follows.

1. The rate of the xenon removal from the coolant h_{Xe} is determined (see above). If the removal rate has not been measured, a conservative estimate is used: $h_{Xe} = 0$.
2. Using the diagram in Fig. 2 (the solid line), the threshold value is determined for the ratio between the ^{133}Xe and ^{135}Xe activities corresponding to the h_{Xe} value.
3. The obtained value is compared with the ratio between the measured ^{133}Xe and ^{135}Xe activities. If the ratio between the measured ^{133}Xe and ^{135}Xe activities turns out to be higher than the threshold, this indicates that there is a fuel failure in the core.

Constraints. The ratio between the ^{133}Xe and ^{135}Xe activities after the fuel failure depends non-monotonically on the escape rate coefficient m for the leaking fuel rod. After the fuel failure, this ratio starts to grow if m increases. The growth continues for as long as the relatively long-lived ^{133}Xe releases predominantly from the fuel, and the ^{135}Xe activity is still defined by the background. As the extent of damage to fuel cladding progresses, the time of the radionuclide "delay" inside the leaking rod prior to the release into the coolant starts to decrease. When ^{135}Xe starts to go out of the leaking fuel in a noticeable quantity, the ratio between the ^{133}Xe and ^{135}Xe activities starts to diminish.

In the event of a severe failure (e.g., when secondary defects are formed in the failed fuel cladding), the time of "delay" may become smaller than the lifetime of ^{135}Xe. In the limiting case of severe cladding degradation, the ^{133}Xe and ^{135}Xe release from the leaking fuel rod will be such as if there is no cladding at all and there is a direct contact of fuel pellets with the coolant. If it is so, there will be no difference between the FP release from the leaking fuel with a low power and the FP release from a large mass of fuel deposits. For high power leaking fuel, when diffusion is a major contributor to the FP release from fuel pellets, the ratio between the ^{133}Xe and ^{135}Xe activities in the coolant may also fall within the "uncertainty zone" shown in Fig. 2 (between the solid and the dashed lines). Then, using only the ratio between the ^{133}Xe and ^{135}Xe activities in some measurements, it is not possible to detect the fuel failure in the reactor, so other fuel failure symptoms need to be used.

Table 1. Average ratios of the ^{133}Xe and ^{135}Xe activities in different WWER-1000 power units for cycles with no fuel failures

Unit No. – Cycle No.	A-1	B-1	C-1	D-1
A_{133Xe}/A_{135Xe}	0.08	0.1	0.11	0.07

Table 2. Maximum weekly average ratios of the ^{133}Xe and ^{135}Xe activities in different WWER-1000 power units during steady-state reactor operation in cycles with fuel failures

Unit No. – Cycle No.	C-2	E-1	F-1	G-1
A_{133Xe}/A_{135Xe}	8	10	3.7	6.5

Application examples

Table 1 presents average values for the ratios between the steady-state ^{133}Xe and ^{135}Xe background activities for several cycles with no fuel failures in different WWER-1000 power units. It can be seen that all of the values are below the solid line in Fig. 2. This is as it should be when there is no fuel failure.

Table 2 presents the maximum weekly average ratios of the ^{133}Xe and ^{135}Xe activities during steady-state reactor operation in fuel cycles with fuel failures clearly identified based on other symptoms. It can be seen that all of the values are above the solid curve. On the whole, the analysis of the WWER-1000 NPP fuel cycles for the past 10 years shows that, in most cases when fuel failures were confirmed by the ratio of the normalized release rates foe ^{131}I and ^{134}I, the ratio of the ^{133}Xe and ^{135}Xe activities also turned out to be higher than the threshold dependence in Fig. 2.

One of the examples to illustrate higher sensitivity of the proposed procedure is cycle N-1. Fig. 3 shows the ratio between the normalized release rates of ^{131}I and ^{134}I calculated based on the data on iodine activity in the nominal mode of the reactor operation. This figure also shows how the ratio of the ^{133}Xe and ^{135}Xe activities varied during the cycle. As xenon removal rate from the coolant was not monitored in this unit, the analysis used the conservative thershold value for the ratio of the ^{133}Xe and ^{135}Xe activities, which corresponds to the zero h_{Xe} value.

It can be seen from Fig. 3 that the ratio of the normalized release rates for ^{131}I and ^{134}I did not exceed five. Accordingly, as shown in RD (Tasaka Kanj et al. 1990), no firm conclusion could be made based on the ^{131}I and ^{134}I activities up to the end of cycle as to the presence of a fuel failure in the reactor core. However, the ratio of the ^{133}Xe and ^{135}Xe activities started to grow approximately on the 250th day and was markedly in excess of the threshold value. This clearly indicates that there was leaking fuel in the core.

One leaking FA was found after cycle N-1 was over. Therefore, the analysis of the NG activities made it possible to detect the fuel failure promptly.

Conclusion

The paper proposes the technique to detect fuel failures in WWER units based on the activity of radioactive noble gases in the reactor primary circuit. It has been shown

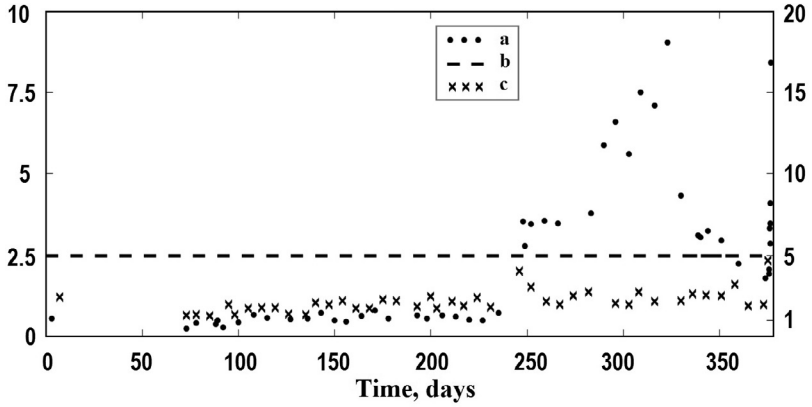

Figure 3. a). Ratio of the ^{133}Xe and ^{135}Xe activities (the vertical axis on the left) during steady-state reactor operation in the course of cycle N-1. b). Threshold value corresponding to the fuel failure criterion for NGs in the zero degassing rate approximation (the vertical axis on the left) and for the iodine radionuclides (the vertical axis on the right). c). Ratio of the normalized release rates for ^{131}I and ^{134}I

that the activity of noble gases can be a more reliable indicator of a fuel failure than the activities of iodine radionuclides. The proposed fuel failure detection criterion is based on analysis of the ratio between the ^{133}Xe and ^{135}Xe activities.

The procedure has a low sensitivity to the primary coolant sampling technique and to the extent of the water degassing during sampling, as well as to the actual nuclide composition of fuel deposits.

Examples of several fuel cycles show that, when there is no fuel failure in a WWER-1000 NPP, the ratio of the ^{133}Xe and ^{135}Xe activities is below the boundary as it follows from the obtained criterion. If there is a fuel failure, the ratio of the ^{133}Xe and ^{135}Xe activities turns out to be above the criterion boundary in most cases.

It has been also demonstrated that the proposed criterion is capable to detect fuel failures during steady-state reactor operation even if the ^{131}I and ^{134}I activities do not make it possible to make a firm conclusion on the presence or absence of leaking fuel in the core.

The authors express their gratitude to Oleg Vladimirovich Khoruzhy for the valuable discussion of the findings.

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