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Technical approaches to calculating different components of the annual effective dose due to release of actinides into air during long-term operation of a BN-type reactor

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Abstract. The aspect of ensuring NPP safety has always attracted scrupulous attention. Experience in operating power plants with different reactor types shows that radiation situation in the NPP area, environmental contamination depend very much on the integrity of the fuel cladding – one of the most important protective barriers.

In practice, some fuel pins in the core can have certain cladding defects occurring during the normal plant operation, with a BN-type reactor used. Np, Pu, Am, Cm transuranic elements may take special part in contaminating the primary circuit with actinides. Presence of actinides in the process media of the reactor facility may have radiation effect not only on the NPP staff but also on the population living outside the buffer area.

There is little information on the problem in scientific publications. Computer codes are mainly oriented to the calculation of the effective doses the population take as a result of release of radionuclides into the air during the first year of NPP operation. Increasing the duration of NPP operation results in significantly complicated calculations. This paper presents a simplified method of calculating the main components of the annual effective dose the population receive due to release of actinides into the air over «n» partial refuelings after reactor startup.

1. Introduction

The aspect of ensuring NPP safety has always attracted a scrupulous attention. As early as at the stage of designing first power producing fast reactors, much attention was paid to the safety aspect, both during their normal operation and in emergency situations. Search directions for corresponding design solutions were dictated by the requirement to eliminate intolerable impact on the environment and population by means of reactor inherent safety, effective systems of accident management mitigating the aftermath.

Experience in operating power plants with different reactor types shows that radiation situation in the NPP area, environmental contamination depend very much on the integrity of the fuel cladding – one of the most important protective barriers.

In practice, some fuel pins in the core can have certain cladding defects occurring during the normal plant operation, with a BN-type reactor used. These are microcracks that cause fission gas release or macrocracks that can lead to direct interaction of sodium with the fuel, with the result that a certain amount of nonvolatile fission products or even fuel may appear in the sodium. In the latter case, Np, Pu, Am, Cm transuranics may play special part in contaminating the primary circuit with actinides.

Presence of actinides in the process media of the reactor facility (in the primary-circuit sodium, on the inner surfaces of the primary-circuit equipment that cannot be removed, on the surfaces of the SFA discharged from the reactor facility, etc.) may have radiation effect not only on the NPP staff but also on the population living outside the control area.

There is little information on the problem in scientific publications. The known computer codes RELEASE-3.1 (Certification ID 395 of July 14, 2016), EXPRESS [1]) are mainly oriented to the calculation of the effective doses the population take as a result of release of radionuclides into the air during the first year of NPP operation. Increasing the duration of NPP operation results in significantly complicated calculations. This is most typical of long-lived actinides and is the focus of research for the authors [2, 3].

The paper presents a simplified method of calculating the main components of the annual effective dose the population receive due to release of actinides (for the specific *i* – th radionuclide) into the air over «n» partial refuelings after reactor startup:

- The annual effective dose of external exposure due to actinide cloud – $D_{cloud}(n)$.
- The annual effective dose of external exposure due to surface contamination of soil with actinides – $D_{surface}(n)$.
- The annual effective dose due to actinide inhalation – $D_{inhalation}(n)$.
- The annual effective dose due to food chains (via air) - $D_{food}^{air}(n)$.
- The annual effective dose due to food chains (via roots) - $D_{food}^{root}(n)$.

Total effective dose is a sum:

$$D_{total}^{i}(n) = D_{cloud}^{i}(n) + D_{surface}^{i}(n) + D_{inhalation}^{i}(n) + D_{i,food}^{air}(n) + D_{i,food}^{root}(n)$$

The evaluated components of the effective dose are the result of added contributions of all the actinide isotopes involved in the calculations. Presented below are algorithms for calculating specific components of the effective dose. The reactor facility is supposed to operate in a steady state mode.

2. Methods and results

2.1. Annual effective dose of external exposure due to actinide cloud

The annual effective dose of external exposure due to actinide cloud is estimated as

$$D_{cloud}^{i}(\mathrm{n}) = D_i^I \cdot K_i^{circuit}(\mathrm{n})$$

where

D_i^I is the dose of external exposure due to actinide cloud. It is the average individual dose the population receive (from the cloud) for a particular *i* – th radionuclide at the early stage of BN reactor operation (dose over the first year of reactor operation). The RELEASE-3.1 code is used for this purpose at SSC RF-IPPE;

$K_i^{circuit}(n)$ is the coefficient to include the change in the content of i-th radionuclide in the primary circuit. For each nuclide, it is necessary to find the dependence of the $K_i^{circuit}(n)$ value on the time of BN reactor operation (it marks the increased effective dose the population receive over time).

$$K_i^{circuit}(n) = \frac{[1-(1-\omega)^n \cdot e^{-(\Delta\tau+\tau)\cdot\lambda_i \cdot n}]}{[1-(1-\omega)\cdot e^{-(\Delta\tau+\tau)\cdot\lambda_i}]}$$

where

ω=0,05 is the annual fraction of fuel that escapes from the primary circuit when a spent FA is reloaded (from fuel present in sodium and on the inner surfaces of primary-circuit equipment);

τ – is the duration of the partial refueling, eff. days;

$\Delta\tau$ – is the duration of the refuelling shutdown;

($\Delta\tau+\tau$)=(35 days+330 eff. days);

λ_i – is the decay constant of the i – th radionuclide;

N – is the number of fulfilled partial reloadings.

2.2. *Annual effective dose of external exposure due to surface contamination of soil with actinides*

The annual effective dose of external exposure due to surface contamination of soil with actinides is estimated from

$$D_{surface}(n) = (1-0{,}004)\cdot D_i^{II}\cdot K_i^{circuit}(n)\cdot K_i^{S}(n);$$

Based on experience and conducted research, the following correction is introduced into the formula: 0,004 = 0,4% is the average amount of drain per year (share of the i-th radionuclide that penetrated into soil surface).

The authors will calculate the D_i^{II} value by using the RELEASE-3.1 code. The value is the average individual dose the population receive (from the contaminated surface) at the early stage of BN reactor operation (dose over the first year). The $K_i^{circuit}(n)$coefficient to include the change in the amount of actinides in the primary circuit («n» dependence) has already been used in Section 1.

$$K_i^{circuit}(n) = \frac{[1-(1-\omega)^n\cdot e^{-(\Delta\tau+\tau)\cdot\lambda_i\cdot n}]}{[1-(1-\omega)\cdot e^{-(\Delta\tau+\tau)\cdot\lambda_i}]}$$

$K_i^S(n)$ is the coefficient which allows a more accurate estimation of the dynamics of change in the content of i – th radionuclide in the contaminated soil layer 5 cm thick during long-term BN reactor operation (5 cm is the surface root soil layer [4]).

$$K_i^S(n) = \frac{(1-e^{-(\lambda^i_{discharge}+\lambda^i_{migration}+\lambda^i_{decay})\cdot(\tau+\Delta\tau)\cdot n})}{(1-e^{-(\lambda^i_{discharge}+\lambda^i_{migration}+\lambda^i_{decay})\cdot(\tau+\Delta\tau)})}$$

where

$\lambda^i_{discharge}$ is the constant of washing the i – th radionuclide out of the contaminated soil layer 5 cm thick;

$\lambda^i_{migration}$ is the constant of i – th radionuclide release from the contaminated soil layer 5 cm thick due to migratory processes.

The indicated constants ($\lambda^i_{discharge}$, $\lambda^i_{migration}$) are presented in paper [4] and amount to $\lambda^i_{discharge}$ = 0,006 /year^{-1}; $\lambda^i_{migration}$ = 0,122 /year^{-1}.

2.3. *Annual effective dose due to actinide inhalation*

The annual effective dose due to actinide inhalation is calculated from

$$D^i_{inhalation}(n) = D_i^{III}\cdot K_i^{circuit}(n)\cdot K_i^{DECAY,I}(n),$$

where

D_i^{III} is the average individual dose the population receive due to actinide inhalation at the early stage of BN reactor operation for a year, calculated by using the RELEASE-3.1 code;

The $K_i^{circuit}(n)$ coefficient has already been used in Sections 1 and 2. Unchanged, the coefficient will be used and considered in Section 3.

Another coefficient - $K_i^{DECAY,I}$ - is to be introduced to include biological decay of the inhaled radionuclides.

$$K_i^{DECAY,I} = \frac{(1-r^n)}{(1-r)},$$

where

$$r = e^{-(\lambda_{decay}^i + \lambda_{biol.dec.inh.}^i)\cdot(\tau+\Delta\tau)};$$

$$r^n = e^{-(\lambda_{decay}^i + \lambda_{biol.dec.inh.}^i)\cdot(\tau+\Delta\tau)\cdot n};$$

$\lambda_{biol.dec.inh.}^i$ is the constant of biological decay of the i-th inhaled radionuclide due to biological processes.

The indicated constant is presented in paper [5] and amounts to 0,693/25 years=0,02772 year^{-1}.

2.4. Annual effective dose due to food chains (via air)

The annual effective dose due to food chains (via air) is calculated as following

$$D_{i,\,food}^{air}(n) = D_i^{IV} \cdot K_i^{circuit}(n) \cdot K_i^{DECAY,I}(n),$$

where

D_i^{IV} is the annual effective dose the population take due to food chains (via air) after the first year of BN reactor operation, calculated by using the RELEASE-3.1 code;

The $K_i^{circuit}(n)$ coefficient has been used in Sections 1, 2 and 3 (it is proposed to be used unchanged in Section 4);

The $K_i^{DECAY,I}(n)$ coefficient has been used in Section 3 (it is proposed to be used unchanged in Section 4).

2.5. The annual effective dose due to food chains (via roots)

The annual effective dose due to food chains (via roots) is calculated as

$$D_{i,\,food}^{root}(n) = D_i^{V} \cdot K_i^{circuit}(n) \cdot K_i^{DECAY,II}(n),$$

where

D_i^{V} is the annual effective dose the population take due to food chains (via roots) after the first year of BN reactor operation, calculated by using the RELEASE-3.1 code;

$K_i^{circuit}(n)$ has been used in Sections 1, 2, 3 and 4 (it is proposed to be used unchanged in Section 5);

In case of the «root» variant, a new $K_i^{DECAY,II}(n)$ coefficient is introduced.

$$K_i^{DECAY,II}(n) = \frac{(1-r^n)}{(1-r)},$$

where

$$r = e^{-(\lambda^i_{discharge}+\lambda^i_{migration}+\lambda^i_{decay}+\lambda^i_{\substack{biol.dec.\\(via\\roots)}})\cdot(\tau+\Delta\tau)},$$

$$r^n = e^{-(\lambda^i_{discharge}+\lambda^i_{migration}+\lambda^i_{decay}+\lambda^i_{\substack{biol.dec.\\(via\\roots)}})\cdot(\tau+\Delta\tau)\cdot n}$$

The indicated constant of ($\lambda^i_{\substack{biol.dec.\\(via\\roots)}}$) is presented in papers [4, 5].

3. Conclusions

This paper presents a simplified method of calculating the main components of the annual effective dose the population receive due to release of actinides (for the specific *i* – th radionuclide) into the air over «n» partial refueling after the startup of a reactor with defective fuel claddings in the core.

Further calculations are planned to find the radiation effect of actinides on the population under long-term operation of an NPP with a BN-type reactor. These data are crucial for designing BN reactor facilities where fuel with a high content of transuranic Pu, Np, Am, Cm elements will be used

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