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ASSESSMENT OF RADIATION RISK TO PERSONNEL AND PUBLIC FOR SHIPMENT OF SPENT FUEL OF EGP-6 REACTOR FACILITY FROM THE BILIBINO NPP TO MAYAK PA FOR REPROCESSING

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ABSTRACT

This paper presents the results of assessment of radiation risk to the personnel and public for scheduled shipment of the spent nuclear fuel (SNF) of EGP-6 Reactor Facility (RF) from Bilibino NPP to Mayak PA for reprocessing on completion of the Bilibino NPP operation in 2019.

The radiation risks under normal conditions and hypothetical accident conditions were assessed for the purpose of determining the possibility of safe shipment of the EGP-6 RF SNF in compliance with the Radiation Safety Standards (NRB-99/2009), preferable transport packagings and routes for shipment by road, rail, air or sea.

The assessment of individual and collective effective doses, individual and summarized radiation risks to the personnel and public and possible radiation contamination of the environment were analyzed to develop recommendations on the safest procedure for shipment of the EGP-6 RF SNF.

INTRODUCTION

At the time being, the planned shutdown of the Bilibino NPP power units raises a problem of further management of the EGP-6 RF SNF. The Bilibino NPP is situated in the permafrost zone, which seriously restrains the possible variants of the SNF removal. The authors of the present paper fulfill the task to assess the radiation risk to the personnel and public for different variants of the EGP-6 RF SNF shipment from the Bilibino NPP to Mayak PA.

METHODOLOGY

The method, applied by the Intertran 2 software, is used to assess radiation risks during the SNF shipment. The Intertran 2 software was developed within the framework of the IAEA Coordinated Research Program on “The Probabilistic Safety Techniques Related to the Safe Transport of Radioactive Material” by AMC Konsult AB Company under the contract with the Swedish Nuclear Power Inspectorate. The Intertran 2 software is based on the Radtran software [1].

The risk is defined in the Radtran methodology [2] as follows: "risk is the probability of the event, multiplied by its consequences". For the SNF transport under normal and accident conditions, consequences are understood as collective effective doses (person·Sv) of different personnel and public groups, which can become exposed to radiation from the packages with their contents.

In compliance with the Russian Radiation Safety Standards (NRB-99/2009) [3], radiation risk is the probability of harmful effects that can be caused to a person or his/her offspring as a result of exposure.
As recommended in ICRP Publication No.103 [4], the NRB-99/2009 Standards apply a linear no-threshold dependence between the risk of stochastic effects and the dose - proportion between the value of risk and effective dose through the risk factors - to assess radiation risks.

Table 1. Linear factors of radiation risks of cancer and hereditary defects

Exposed public group	Cancer risk factor, $\times 10^{-2}$ Sv^{-1}	Hereditary defect risk factor, $\times 10^{-2}$ Sv^{-1}	Total, $\times 10^{-2}$ Sv^{-1}
All public	5.5	0.2	5.7
Adults	4.1	0.1	4.2

An average risk factor equal to 0.05 Sv^{-1} is used to specify the dose limits for personnel and public.
In compliance with para. 2.3 of the NRB-99/2009 Standards [3] the limits of individual lifetime risk under normal operation make
– for personnel – $1.0 \cdot 10^{-3}$;
– for public – $5.0 \cdot 10^{-5}$.
Level of negligible risk equals 10^{-6}.
Limits of summarized risk of potential (accident) exposure (the probability of an event causing exposure, multiplied by the probability of death connected with the exposure):
– for personnel – $2.0 \cdot 10^{-4}$, $year^{-1}$;
– for public – $1.0 \cdot 10^{-5}$, $year^{-1}$.
Individual radiation risks were assessed to verify them for compliance with the established limits with the Regulations [5] taken into account.
Maximum individual effective doses for personnel and public can be calculated for normal operation during the EGP-6 RF SNF transport, whereas the corresponding maximum individual radiation risks can be determined by multiplying the individual effective doses by the average risk factor equal to 0.05 Sv^{-1}.
For potential (accident) exposure the total of maximum individual effective doses multiplied by the corresponding probabilities of unfavorable events (those which can cause exposure of people) and by the average risk factor equal to 0.05 Sv^{-1} shall be assessed. The field to apply such an approach is restricted to effective doses within the range of 0-500 mSv.

INPUT DATA FOR TRANSPORTATION RISK ASSESSMENT THROUGH THE DIFFERENT ROUTES

The feasibility studies revealed that two variants of the SNF removal from the Bilibino NPP for reprocessing were most reasonable. The first variant involves, apart from automobile and railroad, air conveyance, while the second - sea conveyance. Further in the text they are referred to as air and sea routes. The EGP-6 RF SNF is regarded to be transported by sea in Type B(U) package and by air in Type B(U) and C packages. Table 2 summarizes the input data for both routes. The characteristics of packages, including their capacity, were chosen basing on the economical evaluations.

Table 2. Data on the transport routes

Route section	Sea	Air	
Type of package used	**B(U) "sea"**	**B(U) "air"**	**C**
Number of shipments a year (route length, km):			
- by road	64 (270)	73 (80)	30 (80)
- by rail	4 (3634)	37 (2300)	37 (2300)
- by sea	4 (5000)	–	–
- by air	–	73 (4700)	60 (4700)

For calculations with the Intertran 2 software, the routes were divided into sections in accordance with conveyances, which are supposed to transport the SNF, and the density of the population at each of the sections (Table 3).

Table 3. Number of sections, each route was divided into

Route section	Number of sections with different population density
Sea	
Road	3
Sea	1
Railroad	41
Air	
Road 1	3
Air	3
Road 2	3
Railroad	29

INPUT DATA FOR TRANSPORTATION RISK ASSESSMENT FOR INCIDENT-FREE ANALYSIS

Table 4 presents surface dose rates at the distance of 1 m, 2 m depending on the type of the package for SNF transport.

Table 4. Dose rate from the packages, mSv/h

Route	Sea	Air	
Type of package used	**B(U) "sea"**	**B(U) "air"**	**C**
EDR, mSv/h:			
- at the surface of the package	0.22	0.27	0.38
- at 2 m from the package surface	0.08	0.09	0.1
- at 1 m from the package surface	0.13	0.15	0.17

INPUT DATA FOR TRANSPORTATION RISK ASSESSMENT FOR ACCIDENT ANALYSIS

Input data to assess the risk of transportation by different conveyances and in different package types under accident conditions are presented in Table 5.

Table 5. Input data for transportation risk assessment for accident analysis

Route	Sea	Air	
Type of package used	**B(U) "sea"**	**B(U) "air"**	**C**
Probability of transport-involved accident, km^{-1}:			
- by road [6]	10^{-5}		
- by rail [6]	$1.8 \cdot 10^{-8}$		
- by sea [6]	$1 \cdot 10^{-6}$		
- by air [7]	$2.1 \cdot 10^{-10}$		
Probability of accident per categories, relative units			
- by road			
- category I	0.91	0.91	0.996
- category II	0.09	0.09	0.004
- by air			
- category I	-	0.894	0.894
- category II	-	0.0431	0.1011
- category III	-	0.0629	0.0049
- by rail			
- category I	0.8	0.8	0.998
- category II	0.2	0.2	0.002
- by sea			
- category I	0.9768	-	-
- category II	0.0197352	-	-
- category III	0.00028	-	-

In compliance with the Russian normative document NP-053-04 [8], specifying the requirements for the transport of radioactive materials, the loss of the radioactive contents from type B(U) and type C package shall not exceed $10^{-6} \cdot A_2$ per hour under normal conditions of transportation, and $10 \cdot A_2$ per one week for Kr-85 and A_2 - for all the rest radionuclides under accident conditions, defined in [8].

In accordance with the NP-053-04 [8], the release makes 1.4% of the allowable radioactive content release [9] for accidents of categories I and II (taking into account that the SNF is transported in leak-tight canisters).

The data regarding the release fractions of radionuclides for type B(U) package (both for sea and air shipments) and type C package, depending on the category of the accident, are given in Tables 6-7.

Table 6. Release fraction of a radionuclide in relation to its contents in the package, depending on the accident category, for type C and B(U) ("sea") packages

Accident category/Radionuclide	Category I	Category II	Category III
	Release fraction, relative units	**Release fraction, relative units**	**Release fraction, relative units**
^{3}H	$2.68 \cdot 10^{-7}$	$6.69 \cdot 10^{-3}$	1
^{60}Co	$5.93 \cdot 10^{-11}$	$5.93 \cdot 10^{-5}$	1
^{85}Kr	$3.16 \cdot 10^{-9}$	$3.16 \cdot 10^{-2}$	1
^{90}Sr	$7.51 \cdot 10^{-12}$	$7.51 \cdot 10^{-6}$	1
^{137}Cs	$1.23 \cdot 10^{-11}$	$1.23 \cdot 10^{-5}$	1

Accident category/Radionuclide	Category I	Category II	Category III
	Release fraction, relative units	Release fraction, relative units	Release fraction, relative units
^{154}Eu	$1.04 \cdot 10^{-9}$	$1.04 \cdot 10^{-3}$	1
^{238}Pu	$3.34 \cdot 10^{-12}$	$3.34 \cdot 10^{-6}$	1
^{239}Pu	$4.57 \cdot 10^{-12}$	$4.57 \cdot 10^{-6}$	1
^{240}Pu	$4.11 \cdot 10^{-12}$	$4.11 \cdot 10^{-6}$	1
^{241}Am	$1.98 \cdot 10^{-12}$	$1.98 \cdot 10^{-6}$	1
^{241}Pu	$2.14 \cdot 10^{-12}$	$2.14 \cdot 10^{-6}$	1

Table 7. Release fraction of a radionuclide in relation to its contents in the package, depending on the accident category, for type B(U) ("air") package

Accident category/Radionuclide	Category I	Category II	Category III
	Release fraction, relative units	Release fraction, relative units	Release fraction, relative units
^{3}H	$1.61 \cdot 10^{-6}$	$4.02 \cdot 10^{-2}$	1
^{60}Co	$3.56 \cdot 10^{-10}$	$3.56 \cdot 10^{-4}$	1
^{85}Kr	$1.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-1}$	1
^{90}Sr	$4.51 \cdot 10^{-11}$	$4.51 \cdot 10^{-5}$	1
^{137}Cs	$7.4 \cdot 10^{-11}$	$7.4 \cdot 10^{-5}$	1
^{154}Eu	$6.24 \cdot 10^{-9}$	$6.24 \cdot 10^{-3}$	1
^{238}Pu	$2.01 \cdot 10^{-11}$	$2.01 \cdot 10^{-5}$	1
^{239}Pu	$2.74 \cdot 10^{-11}$	$2.74 \cdot 10^{-5}$	1
^{240}Pu	$2.47 \cdot 10^{-11}$	$2.47 \cdot 10^{-5}$	1
^{241}Am	$1.19 \cdot 10^{-11}$	$1.19 \cdot 10^{-5}$	1
^{241}Pu	$1.28 \cdot 10^{-11}$	$1.28 \cdot 10^{-5}$	1

TRANSPORTATION RISK ASSESSMENT OF SPENT FUEL OF EGP-6 DURING NORMAL OPERATION

Air shipment of SNF in type B(U) package

The results of assessment of radiation risk to the personnel and public are presented in Tables 8 and 9. The radiation risk limits, specified in the NRB-99/2009, for A-group personnel ($1 \cdot 10^{-3}$), B-group personnel ($2.5 \cdot 10^{-4}$) and public ($5 \cdot 10^{-5}$) during accident-free air shipment of the EGP-6 RF SNF will not be exceeded. The summarized collective effective dose to public and personnel will make $1.9 \cdot 10^{-1}$ person·Sv ($1.77 \cdot 10^{-1}$ person·Sv – for personnel exposure and $1.33 \cdot 10^{-2}$ person·Sv – for public exposure).

Table 8. Maximum annual individual effective doses and individual radiation risks to personnel and public during the transport of the EGP-6 RF SNF in course of a year

Category	Maximum individual effective dose, Sv	Maximum individual radiation risk, relative units	Note
Public	$2.72 \cdot 10^{-6}$	$1.36 \cdot 10^{-7}$	At railroad section
Personnel	$9.21 \cdot 10^{-3}$	$4.61 \cdot 10^{-4}$	At air section

Table 9. Radiation risks (collective effective doses) to personnel and public during the transport of the EGP-6 RF SNF in course of a year

Category	Collective effective dose, person·Sv
Public	$1.33 \cdot 10^{-2}$
Personnel	$1.77 \cdot 10^{-1}$
Subtotal	$1.9 \cdot 10^{-1}$

Sea shipment of the EGP-6 RF SNF in type B(U) package

The results of assessment of radiation risk to the personnel and public are presented in Tables 10 and 11. The radiation risk limits, specified in the NRB-99/2009, for A-group personnel ($1 \cdot 10^{-3}$), B-group personnel ($2.5 \cdot 10^{-4}$) and public ($5 \cdot 10^{-5}$) during accident-free shipment will not be exceeded. The summarized collective effective dose to public and personnel will make $1.134 \cdot 10^{-1}$ person·Sv ($1.13 \cdot 10^{-1}$ person·Sv – for personnel exposure and $3.94 \cdot 10^{-4}$ person·Sv – for public exposure).

Table 10. Maximum annual individual effective dose and individual radiation risk to personnel and public during the transport of the EGP-6 RF SNF in course of a year

Category	Maximum individual effective dose, Sv	Maximum individual radiation risk, relative units	Note
Public	$4.71 \cdot 10^{-7}$	$2.36 \cdot 10^{-8}$	At road section
A-group personnel	$1.31 \cdot 10^{-2}$	$6.55 \cdot 10^{-4}$	At road section
B-group personnel	$2.9 \cdot 10^{-4}$	$1.45 \cdot 10^{-5}$	

Table 11. Radiation risks (collective effective doses) to personnel and public during the transport of the EGP-6 RF SNF in course of a year

Category	Collective effective dose, person·Sv
Public	$3.94 \cdot 10^{-4}$
Personnel	$1.13 \cdot 10^{-1}$
Subtotal	$1.134 \cdot 10^{-1}$

Air shipment of the EGP-6 RF SNF in type C package

Like in course of the EGP-6 RF SNF transport in type B(U) package, in course of type C package application the limits of radiation risks to personnel and public, set in the NRB-99/2009 for normal operation, will not be exceeded (Tables 12, 13). The summarized collective effective dose to public and personnel will make $7.48 \cdot 10^{-2}$ person·Sv ($6.94 \cdot 10^{-2}$ person·Sv – for personnel exposure and $5.36 \cdot 10^{-3}$ person·Sv – for public exposure).

Table 12. Maximum annual individual effective dose and individual radiation risk to personnel and public during the transport of the EGP-6 RF SNF in course of a year

Category	Maximum individual effective dose, Sv	Maximum individual radiation risk, relative units	Note
Public	$1.82 \cdot 10^{-7}$	$9.1 \cdot 10^{-9}$	On road section
A-group personnel	$3.79 \cdot 10^{-3}$	$1.9 \cdot 10^{-4}$	On air section
B-group personnel	$2.81 \cdot 10^{-4}$	$1.41 \cdot 10^{-5}$	On railroad section

Table 13. Collective effective doses to personnel and public during the transport of the package with the EGP-6 RF SNF in course of a year

Category	Collective effective dose, person·Sv
Public	$5.36 \cdot 10^{-3}$
Personnel	$6.94 \cdot 10^{-2}$
Subtotal	$7.48 \cdot 10^{-2}$

TRANSPORTATION RISK ASSESSMENT OF SPENT FUEL OF EGP-6 IN ACCIDENT CASE

Air shipment

Summarized radiation risk during the transport of the EGP-6 RF SNF by air for type B(U) and C package is presented in Table 14.

The values of collective radiation risks during the transport of the EGP-6 RF SNF by air for type B(U) and C package are presented in Table 15. The values obtained from calculations with Intertran-2 software (using the dose coefficients of the program developers) as well as the calculation results using the dose coefficients complying with the NRB-99/2009 [3] are given (60 ICRP Publications 10]).

Table 14. Calculated annual summarized radiation risks during the transport of the EGP-6 RF SNF by air

Package	By road	By air	By road	By rail	Total
B(U)	$9.25 \cdot 10^{-8}$	$4.53 \cdot 10^{-6}$	$1.54 \cdot 10^{-7}$	$3.05 \cdot 10^{-8}$	$4.82 \cdot 10^{-6}$
C	$4.05 \cdot 10^{-9}$	$2.9 \cdot 10^{-7}$	$6.75 \cdot 10^{-9}$	$5.01 \cdot 10^{-11}$	$3.01 \cdot 10^{-7}$

Table 15. Collective radiation risks during the transport of the EGP-6 RF SNF by air, person – Sv

Package	By road	By air	By road	By rail	Total
Intertran-2					
B(U)	$8.12 \cdot 10^{-5}$	$4.54 \cdot 10^{-5}$	$3.42 \cdot 10^{-2}$	$3.69 \cdot 10^{-6}$	$3.43 \cdot 10^{-2}$
NRB-99/2009					
B(U)	$1.05 \cdot 10^{-4}$	$1.56 \cdot 10^{-5}$	$4.46 \cdot 10^{-2}$	$4.84 \cdot 10^{-6}$	$4.47 \cdot 10^{-2}$
Intertran-2					
C	$7.31 \cdot 10^{-7}$	$3.38 \cdot 10^{-6}$	$2.80 \cdot 10^{-4}$	$6.07 \cdot 10^{-7}$	$2.85 \cdot 10^{-4}$

Package	By road	By air	By road	By rail	Total
NRB-99/2009					
C	$9.55 \cdot 10^{-7}$	$9.97 \cdot 10^{-7}$	$3.69 \cdot 10^{-4}$	$7.97 \cdot 10^{-7}$	$3.72 \cdot 10^{-4}$

Sea shipment

Summarized radiation risk during the transport of the SNF by sea for type B(U) package is given in Table 16.

Collective radiation risk during the transport of the SNF by sea for type B(U) package is given in Table 17.

Table 16. Calculated annual summarized radiation risks during the transport of the EGP-6 RF SNF by sea

Package	By road	By sea	By rail	Total
B(U)	$1.46 \cdot 10^{-7}$	$3.59 \cdot 10^{-7}$	$4.97 \cdot 10^{-9}$	$5.1 \cdot 10^{-7}$

Table 17. Collective radiation risk during the transport of the EGP-6 RF SNF by sea, person – Sv

Package	By road	By sea	By rail	Total
Intertran-2				
B(U)	$3.09 \cdot 10^{-5}$	$7.04 \cdot 10^{-9}$	$1.26 \cdot 10^{-4}$	$1.59 \cdot 10^{-4}$
NRB-99/2009				
B(U)	$4.04 \cdot 10^{-5}$	$9.13 \cdot 10^{-9}$	$1.62 \cdot 10^{-4}$	$2.02 \cdot 10^{-4}$

COMPARED RISKS OF AIR AND SEA SHIPMENTS OF EGP-6 RF SNF FROM BILIBINO NPP TO MAYAK PA

Summarized radiation risk during the transport of the EGP-6 RF SNF by different routes is given in Table 18. Collective risks of the SNF transport are given in Table 19.

Table 18. Calculated annual summarized radiation risks during the transport of the EGP-6 RF SNF from Bilibino NPP to Mayak PA

Rout	Total value
Air (type B(U) package)	$4.82 \cdot 10^{-6}$
Air (type C package)	$3.01 \cdot 10^{-7}$
Sea	$5.1 \cdot 10^{-7}$

Table 19. Collective radiation risk during the transport of the EGP-6 RF SNF, person – Sv

Rout	Total value	
	Intertran-2	NRB-99/2009
Air (type B(U) package)	$3.43 \cdot 10^{-2}$	$4.47 \cdot 10^{-2}$
Air (type C package)	$2.85 \cdot 10^{-4}$	$3.72 \cdot 10^{-4}$
Sea	$1.59 \cdot 10^{-4}$	$2.02 \cdot 10^{-4}$

CONCLUSIONS

The obtained results show, that the radiation risks to personnel and public under normal operation do not exceed NRB-99/2009 annual limits ($1 \cdot 10^{-3}$ for A-group personnel, $2.5 \cdot 10^{-4}$ for B-group personnel and $5 \cdot 10^{-5}$ for public) for all considered routes, transport and package types.

The obtained data on the potential consequences allows concluding that safe sea transport of the EGP-6 RF SNF loaded in type B(U) packages is possible and complies with the NRB-99/2009 and NP-053-04. Annual summarized exposure risk to public (personnel) makes up $5.1 \cdot 10^{-7}$, while the limit value for public is $1 \cdot 10^{-5}$ and for A-group personnel is $2 \cdot 10^{-4}$ [3].

The possibility to ensure safe (for personnel and public) air transport of EGP-6 RF SNF loaded in type C packages (18 SFAs in each package) in compliance with the current standards and rules is also undisputed. Summarized exposure risk to public (personnel) can reach a value of $3.01 \cdot 10^{-7}$ in this case, which is significantly lower than the radiation risk limits, specified in the NRB-99/2009.

In case of an accident, maximum exposure risk to personnel and public will be during the air transport of EGP-6 RF SNF loaded in type B (U) (three SFAs in each package). In this case the calculated summarized radiation risk is $4.82 \cdot 10^{-6}$ which does not exceed the limit for the public $1 \cdot 10^{-5}$, but moreover has a safety margin (about 2).

Taking into account ambiguous input data of the calculations and severe consequences of the accident (including radioactive contamination of the environment), the air shipment of EGP-6 RF SNF is the safest provided the use of type C package.

If fabrication of the type C package with the required specifications is not available, sea shipment of EGP-6 RF SNF shall be preferable.

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