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VERIFICATION OF USING SABINE-3.1 CODE FOR CALCULATIONS OF RADIOACTIVE INVENTORY IN REACTOR SHIELD

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ABSTRACT

This report presents the results of calculations of radioactive inventory and doses of activation radiation for the International Benchmark Calculations of Radioactive Inventory for Fission Reactor Decommissioning, IAEA, and measurements of activation doses in shield of VVER-440 (Armenian NPP), using one-dimension modified code SABINE-3.1.

For decommissioning of NPP it is very important to evaluate in correct manner radioactive inventory in reactor construction and shield materials. One-dimension code SABINE-3.1 [1,2] (removing-diffusion method for neutron calculation) was modified to perform calculation of radioactive inventory in reactor shield materials and dose from activation photons behind them. These calculations are carried out on the base of nuclear constant system ABBN-78 and new library of activation data for a number of long-lived isotopes, prepared by authors on the base of [9], which present at shield materials as microimpurities and manage radiation situation under the decay more than 1 year.

Calculations of radioactive inventory performs in accordance with formula :

$$A_i(r,\tau,T)=\frac{1}{\gamma}\times\sum_K(1-\exp(-\lambda_i\tau))\cdot\exp(-\lambda_i T)\cdot\rho_i^K\cdot\sum_j\sigma_K{}^j\Phi^j(r)$$

here :

$A_i(r,\tau,T)$ – activity of nuclide i (Bq/g) in mesh point r, under irradiation time τ, and decay time T;

ρ_i^k - nuclear concentration of parent nuclide i on release reaction channel K in mesh point r ;

λ_i - constant of half-life for nuclide i ;

σ_K^j - micro cross section of release reaction of nuclide i on channel K for neutron group j ;

$\Phi^j(r)$- neutron flux of group j in mash point r ;

K - release reaction channel for nuclide i;

γ - material density.

For calculations it were used 28 group constants for reactions $Co^{59}(n,\gamma)Co^{60}$, $Eu^{151}(n,\gamma)Eu^{152}$, $Eu^{153}(n,\gamma)Eu^{154}$, $Li^{6}(n,\alpha)H^{3}$, $Na^{23}(n,2n)Na^{22}$, $Ca^{40}(n,\gamma)Ca^{41}$, $Ca^{44}(n,\gamma)Ca^{45}$, $Fe^{54}(n,p)Mn^{54}$, $Fe^{54}(n,\gamma)$ Fe^{55}, $Ni^{58}(n,\gamma)Ni^{59}$, $Ni^{58}(n,np)Co^{57}$, $Ni^{58}(n,\alpha)Fe^{55}$, $Ni^{62}(n,\gamma)Ni^{63}$, $Ni^{64}(n,2n)Ni^{63}$, $Ni^{60}(n,p)Co^{60}$. Data on the release of activation photons are taken from ORIGEN-2.1code [7,8] libraries.

Code verification were performed on the results of experiments on measurements of radioactive inventory in rector vessel and concrete shield of JPDR reactor (Japan, IAEA benchmark [5,6]) and dose rate of activation photons in concrete shield of WWER-440 reactor of Armenian NPP [3,4].

1. Full-scale experiment on measurement of radioactive inventory and dose rate of activation photons in concrete shield of WWER-440 reactor of Armenian NPP

Reactor WWER-440 of the 1-st unit of Armenian NPP was put into operation in January of 1977 года, and was shutdowned in February 25 of 1989. Calculation model consists of core with height 244 см and radius 144 см, steel reactor vessel with thickness 14 см, facilities, which situated inside of reactor vessel (silow and internal shield), reactor shield made of serpentinite and conventional concrete. Last 43.6 см of serpentinite concrete contain boron carbide. Serpentinite concrete lined with metal liner, which thickness is 1.2 см. Thermal insulation set on the concrete liner. Distribution of fission density on height of the core, nuclear concentrations of main nuclides and impurities in reactor materials, as well as geometry dimensions it were taken from [3,4]. Operation and decay times, average thermal powers of reactor during work cycles were recalculated on the base of data on reactor operation published in [3], and present in Table 1.

Table 1 Average thermal power of reactor on working cycles, operation and decay times for calculation of radioactive inventory in reactor shield and activation dose rate

№	Average thermal power, Fission·(c· см^3)$^{-1}$	Operation time, years	Decay time, years
1	$1.278 \cdot 10^{12}$	1.67	12.11
2	$2.348 \cdot 10^{12}$	0.75	11.28
3	$2.516 \cdot 10^{12}$	0.83	10.28
4	$2.502 \cdot 10^{12}$	2.25	7.94
5	$2.351 \cdot 10^{12}$	2.83	4.36
6	$2.274 \cdot 10^{12}$	0.67	3.28
7	$2.374 \cdot 10^{12}$	0.75	2.44
8	$2.624 \cdot 10^{12}$	0.583	1.61

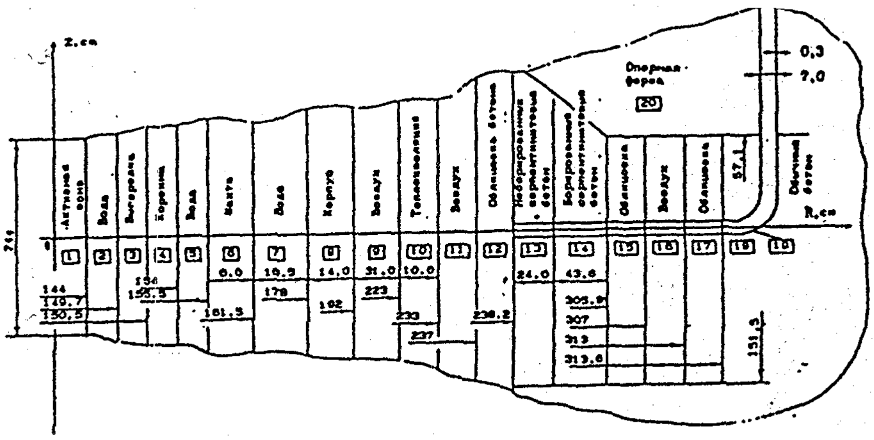

Fig. 1 Simulation scheme for WWER-440 reactor calculations (R,z)-geometry (in accordance with [3]).

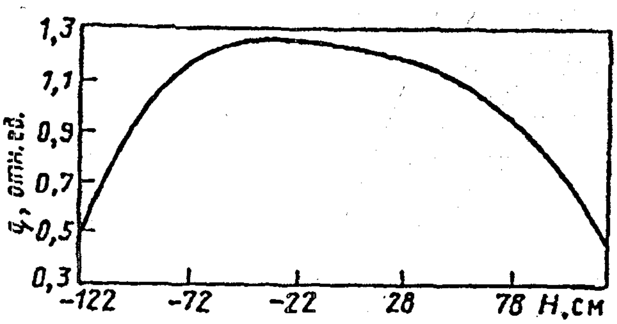

Fig. 2 Distribution of fission density on height of the core

All calculations were performed using cylindric geometry. Distribution of fission density on radius of the core is equal (in accordance with [3]).

Table 2 Nuclear concentrations of main nuclides and impurities for reactor materials, 10^{-24} см$^{-3}$

Nuclide	Number of physical zone					
	1	2,5	3,4,6	7	8,12,15, 17,19	9,11,16
H	$2.658\ 10^{-2}$	$5.08\ 10^{-2}$		$5.24\ 10^{-2}$		
^{10}B						
Li						
O	$2.55\ 10^{-2}$	$2.54\ 10^{-2}$		$2.62\ 10^{-2}$		$1.05\ 10^{-5}$
Al						
Si						
Ca						
Cr			$1.82\ 10^{-2}$			
Fe			$6.014\ 10^{-2}$		$8.48\ 10^{-2}$	
Co			$8.031\ 10^{-5}$		$2.008\ 10^{-5}$	
Ni			$8.547\ 10^{-2}$		$3.225\ 10^{-4}$	
Zr	$8.447\ 10^{-3}$					
Eu						
^{235}U	$1.11\ 10^{-4}$					
^{238}U	$5.996\ 10^{-3}$					

Nuclide	Number of physical zone				
	10	13	14	18	20
H		$2.26\ 10^{-2}$	$2.26\ 10^{-2}$	$6.55\ 10^{-3}$	$5.55\ 10^{-3}$
^{10}B		$1.464\ 10^{-7}$	$5.93\ 10^{-4}$	$1.025\ 10^{-7}$	
Li		$5.02\ 10^{-6}$	$5.02\ 10^{-6}$	$4.01\ 10^{-6}$	
O		$3.84\ 10^{-2}$	$3.84\ 10^{-2}$	$4.58\ 10^{-2}$	$3.88\ 10^{-2}$
Al				$2.25\ 10^{-3}$	$1.91\ 10^{-3}$
Si		$2.39\ 10^{-2}$	$2.39\ 10^{-2}$	$1.53\ 10^{-2}$	$1.30\ 10^{-2}$
Ca		$4.48\ 10^{-3}$	$4.48\ 10^{-3}$	$2.83\ 10^{-3}$	$2.26\ 10^{-3}$
Cr	$2.91\ 10^{-3}$			$4.77\ 10^{-4}$	
Fe	$9.62\ 10^{-3}$	$8.64\ 10^{-4}$	$8.64\ 10^{-4}$	$1.39\ 10^{-3}$	$1.32\ 10^{-2}$
Co	$1.285\ 10^{-5}$	$1.86\ 10^{-6}$	$1.86\ 10^{-6}$	$7.60\ 10^{-7}$	
Ni	$1.31\ 10^{-3}$	$1.94\ 10^{-6}$	$1.94\ 10^{-6}$	$2.28\ 10^{-6}$	
Zr					
Eu		$2.65\ 10^{-9}$	$2.65\ 10^{-9}$	$3.61\ 10^{-9}$	

Table 3 Averaged on height activity of ^{60}Co in facilities and shield of WWER-440 reactor of the 1-st unit of Armenian NPP

Facility	Activity, $Bq \cdot см^{-3}$	
	SABINE	[4]
Выгородка	1.53e+09	-
Корзина	4.96e+08	-
Шахта	2.10e+08	2.0e+08*
Корпус	3.12e+06	2.6e+06**
Теплоизоляция	1.62e+04	6.0e+05***
Небор. серпентин. Бетон	3.05e+04	2.2e+04****
Бор. серпентин. Бетон	1.60e+01	-

Distance :
* - 157 см;
** - 185 см;
*** - 226 см;
**** - 262 см.

Data (result of SABINE calculations) are averaged for physical zone of shield (see Fig.1)

Results of comparison for experimental and calculated data are present on Fig. 3

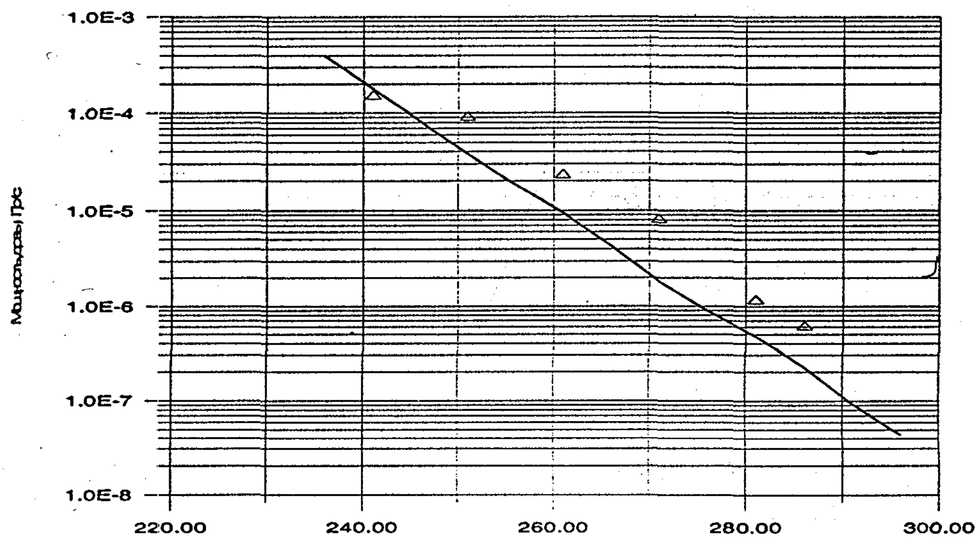

Fig. 3 Dose Rate of activation photons in serpentinite concrete shield :
Δ – experimental data [3]
-- calculated ones by SABINE-3.1

Calculation results basically are cohered with data of [3,4]. Causes of all differences result from :

- Non-correct simulation of 2-dimensional task with 1-dimentional code.
- High "broad" of photon energetic group in library of SABINE code.

2. Full-scale experiment on measurements of activity inventory in reactor vessel and concrete shield of JPDR reactor

Research reactor JPDR is a boiling, pool-type one, thermal power 90 MWt. It was put into operation in August of 1963 and shutdowned in March of 1976. Operation and decay times, averaged thermal powers on operation cycles were calculated on the base of [5] and present in Table 4. Data on distribution of fission density on height and radius of the core, nuclear concentrations of main nuclides and impurities in reactor materials, as well as geometry dimensions it were taken from [5,6] and present in Tables 5-7 and on Fig. 4-6. All calculations were performed for cylindric geometry of the core and shield. Height of the core of JPDR rector is 147 см, radius is 65.4 см.

Measurement results of activity inventory in reactor and shield materials after 15 years of decay were published in [6]. Comparison of calculated results (using SABINE-3.1 code) and measured ones are present on Fig. 7 and 8.

Table 4 Averaged thermal powers of JPDR reactor on operation cycles, operation and decay times for simulation of radioactive inventory in shield materials

№	Averaged thermal power, fission·(c· см^3)$^{-1}$	Operation time, years	Decay time, years
1	$1.403 \cdot 10^{11}$	0.441	26.997
2	$6.006 \cdot 10^{11}$	0.543	25.724
3	$7.073 \cdot 10^{11}$	0.623	24.874
4	$6.718 \cdot 10^{11}$	0.361	24.140
5	$8.290 \cdot 10^{11}$	0.222	23.748
6	$1.120 \cdot 10^{12}$	0.112	23.461
7	$9.493 \cdot 10^{11}$	0.099	22.866
8	$1.288 \cdot 10^{12}$	0.106	21.559
9	$2.277 \cdot 10^{11}$	0.315	18.595
10	$3.860 \cdot 10^{11}$	0.477	15.008

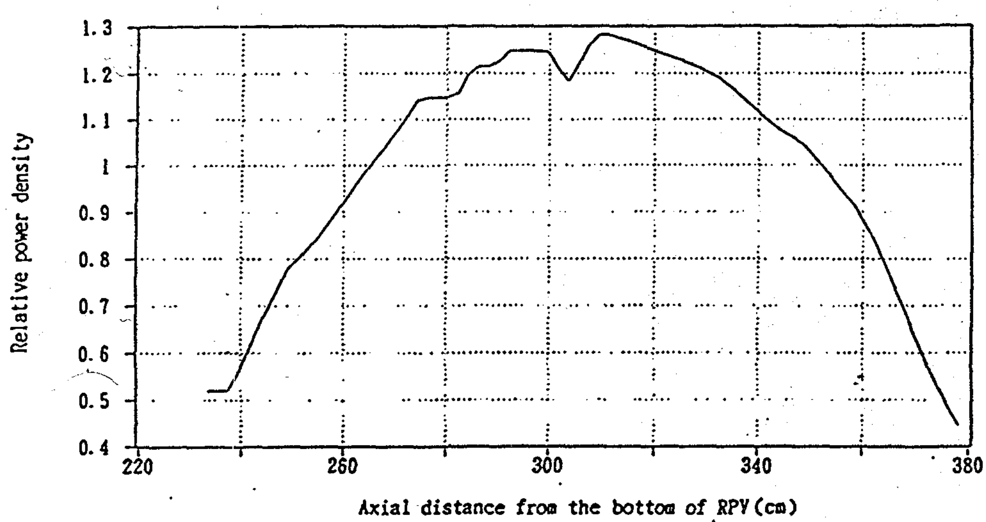

Fig. 4 Distribution of fission density on height of core of JPDR reactor

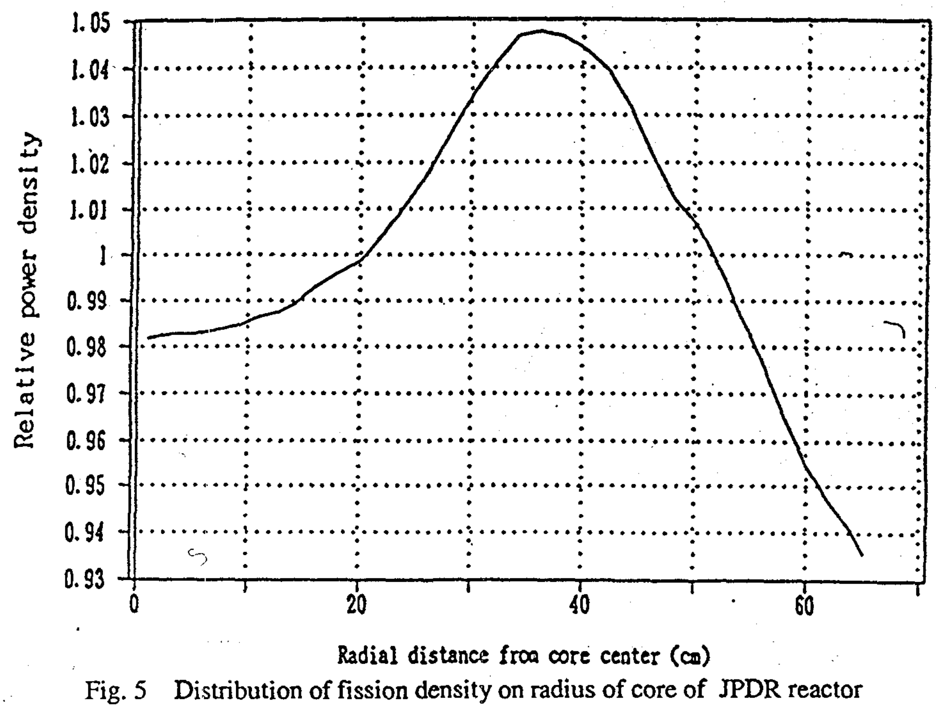

Fig. 5 Distribution of fission density on radius of core of JPDR reactor

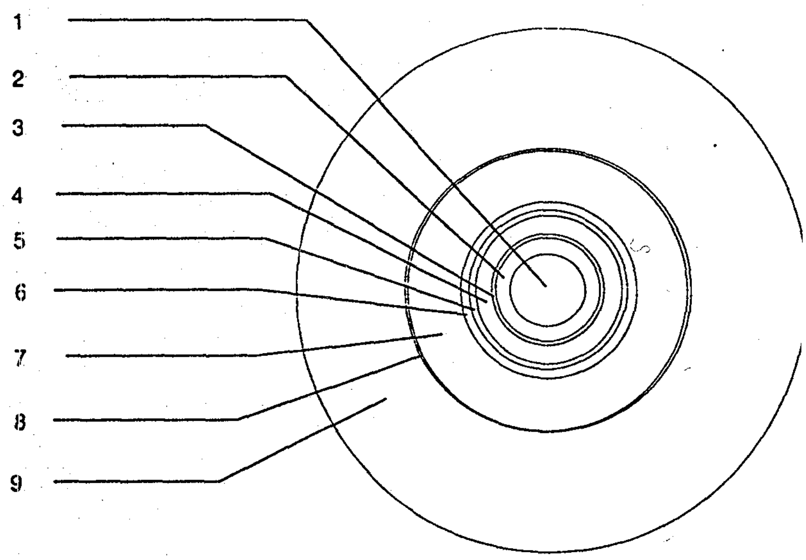

Fig. 6 Simulation scheme for JPDR calculations

Table 5 Simulation scheme for JPDR calculations

Zone	Name	Size, cм
1	Core	64.5
2	Water shield	13
3	Reactor vault	1.3
4	Water shield	22.79
5	Reactor vessel liner	1.4
6	Reactor vessel	6.7
7	Air gap	23.3
8	Concrete linear (steel)	1.3
9	Concrete	198.7

Таблица 6 Ядерные концентрации для материалов и примесей разных зон, 10^{-24} $см^{-3}$

Element	Zone*					
	1	2,4	3,5 SUS-27	6 ASTM - A302B	8	9 Concrete
H	$2.78\ 10^{-2}$	$5.055\ 10^{-2}$				$1.059\ 10^{-2}$
Na						$8.403\ 10^{-4}$
C			$3.173\ 10^{-4}$	$9.829\ 10^{-4}$	$8.266\ 10^{-4}$	
O	$2.489\ 10^{-2}$	$2.527\ 10^{-2}$				$4.513\ 10^{-2}$
Al						$2.657\ 10^{-3}$
Si			$1.810\ 10^{-3}$	$3.870\ 10^{-4}$	$1.147\ 10^{-4}$	$1.607\ 10^{-2}$
Ca						$2.651\ 10^{-3}$
Cr	$1.900\ 10^{-4}$		$1.741\ 10^{-2}$			
Mn			$1.734\ 10^{-3}$	$1.140\ 10^{-3}$	$9.810\ 10^{-4}$	
Fe	$7.324\ 10^{-4}$		$5.787\ 10^{-2}$	$8.220\ 10^{-2}$	$8.430\ 10^{-2}$	$4.857\ 10^{-4}$
Ni	$8.287\ 10^{-5}$		$8.112\ 10^{-3}$	$4.430\ 10^{-4}$		
Zr	$5.066\ 10^{-3}$					
^{235}U	$1.446\ 10^{-4}$					
^{238}U	$5.349\ 10^{-3}$					

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* Air gap (зона 7) has following characteristics:
N (nitrogen) = $3.91\ 10^{-5}$, O (oxigen) = $1.045\ 10^{-5}$ (10^{-24} $см^{-3}$)

Table 7 Impurity concentrations (in reactor vessel and concrete shield)

Isotope	Material		
	SUS-27	ASTM-A302B	Concrete
^{60}Co	$9.2936\ 10^{-5}$	$1.5117\ 10^{-5}$	$1.2550\ 10^{-7}$
^{152}Eu	-	-	$9.7375\ 10^{-9}$
^{154}Eu	-	-	$1.0625\ 10^{-8}$

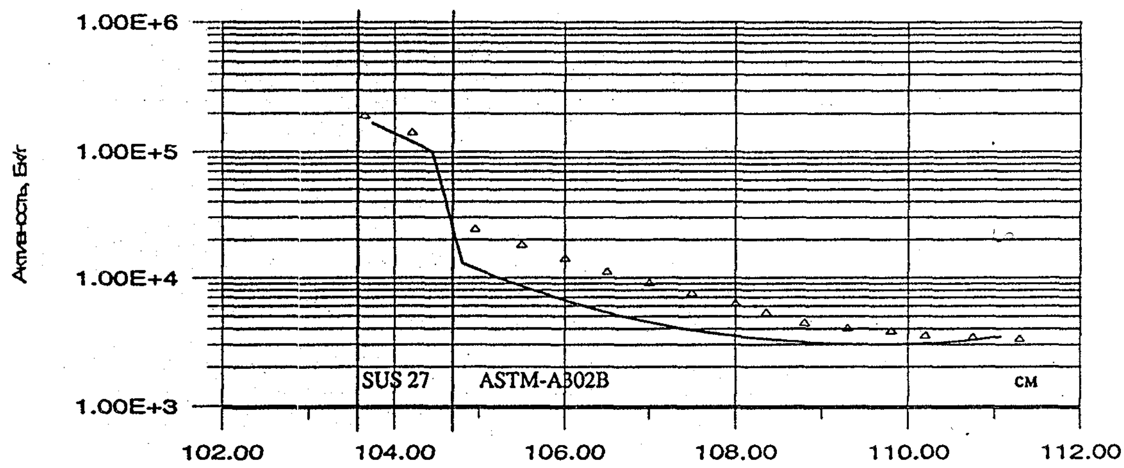

Fig. 7 Distribution of activity inventory for ^{60}Co on the thickness of reactor vessel of JPDR (height 360 см)

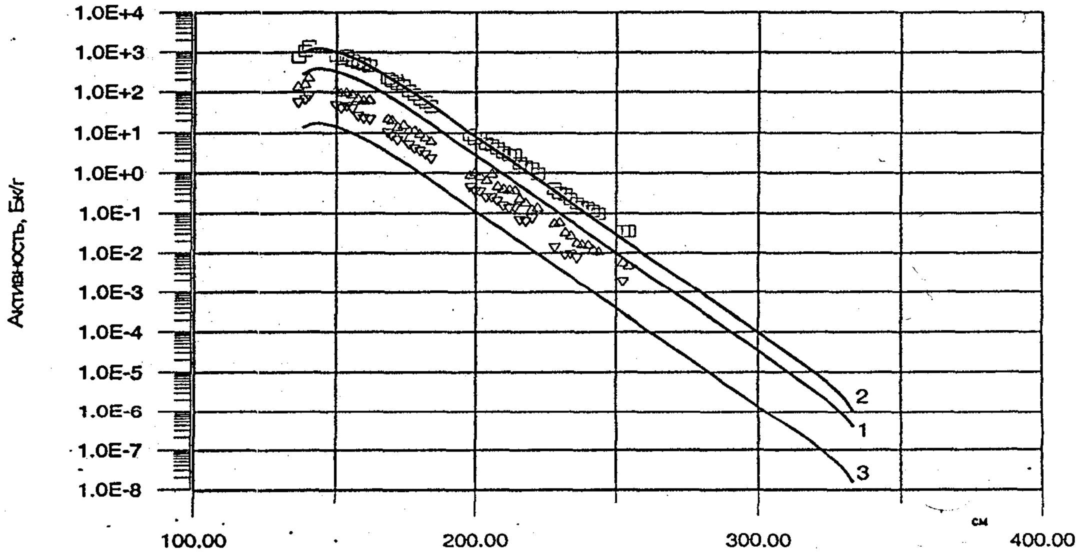

Fig. 8 Distribution of activity inventory on the thickness of concrete shield for JPDR reactor (height 340 см)

Δ – measured data for ^{60}Co

1 – calculated data for ^{60}Co

€– measured data for ^{152}Eu

2 – calculated data for ^{152}Eu

∇– measured data for ^{154}Eu

3 – calculated data for ^{154}Eu

Discrepancy for calculated activity of ^{154}Eu and measured one results from simple formula for calculating of activity, which doesn't take into account channels of reaction on target isotopes and use only $^{153}Eu\ (n,\gamma)\ ^{154}Eu$. These kind of reaction present in constant system ABBN-90 and JENDL-2. Nonetheless, generally there is a good coherence of results.

As result it should be noted, that SABINE-3.1 code may be used for conceptual analysis of activation inventory in reactor shield for decommissioning purposes and dose rates of activation photons during dismantling processes.

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