3.7. Russian Federation

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3.7.1. Calculations of the principal neutronics characteristics of the VVER-1000 reactor loaded with PuO_2-ThO_2 fuel based on weapons-grade plutonium

3.7.1.1. Reactor design description

The simplest method to involve weapons-grade plutonium and thorium in fuel cycle was considered - full or partial replacement of uranium fuel of VVER-1000 reactor with plutonium and thorium dioxides mixture. Any lattice optimization was not examined.

The study concerns 1000 MW(e) reactor with three-batch core management and one year cycles duration. Two reactor options: full and partial (1/3 of core) loading of PuO_2-ThO_2 fuel in VVER-1000 reactor were investigated.

The option with full inventory has the homogenous core with only one type of fuel assembly thus avoiding fuel zoning in fuel assemblies (FAs). The partial thorium core consists of two types of FAs: uranium dioxide fuelled FA (zoned FA with average enrichment 4.23%) and zoned FA with plutonium-thorium fuel (average content of plutonium is 4.8%). Zoned UO_2 fuelled FA is the improved FA of a standard VVER-1000 reactor. These FAs differ from those of standard reactor by the replacement of steel in guide tubes and spacer grids with zirconium and slight changes in guide tubes, central tube and absorber pin dimensions as well. As in the case of standard UO_2 fuel reactor, the first year FAs use boron burnable poison rods that are removed in reloading. Reactivity change when burning is controlled by dissolved boron.
Tables 3.7.1 and 3.7.2 present the basic characteristics of the core and fuel assemblies [1]. Weapons-grade plutonium composition at the moment of reactor loading is taken as follows (in weight%) [2]:

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
0.02	93.94	5.81	0.18	0.03	0.02

The FA maps are presented in Figs 3.6.1 – 3.6.3. Figures 3.6.4 and 3.6.5 show the fuel assemblies arrangement and reloading patterns in reactor core (1/6 part). In reactor calculations, the operating group rods (FA № 4) are inserted at 71 cm core depth during the whole cycle.

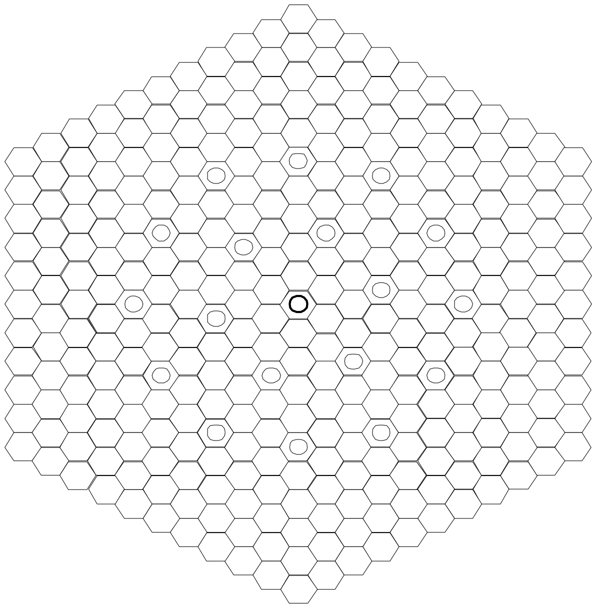
TABLE 3.7.1. CORE CHARACTERISTICS

Thermal power, MW(t)	3000
Core size (hot state):	
Height, m	3.55
Effective diameter, m	3.16
Number of Fuel Assemblies (Fas)	163
Coolant:	
Pressure, Mpa	15.7
Coolant mass flow, m^3/h	84500
Inlet temperature, °C	287
Average enthalpy rise, K	30.3

TABLE 3.7.2. FUEL ASSEMBLY FEATURES

Geometry	hexagonal
Assembly pitch, mm	236
Dimension across flats, mm	234
Fuel rod	
Number	312
Fuel rod pitch, mm	12.75
Outer diameter, mm	9.1
Cladding	
Thickness, mm	0.69
Material	zircalloy
Fuel pellet	
Diameter/central hole diameter, mm	7.53/2.3 *)
Guide tube for control rods and burnable poison rods	
Number	18
Outer diameter/wall thickness, mm	13.58/0.85
Material	zircalloy
Central tube	
Outer diameter/wall thickness, mm	11.2/0.8
Material	zircalloy
Control rod	
Number	18
Outer diameter/cladding thickness, mm	8.2/0.50
Absorber/cladding material	B_4C/stainless steel
Absorber diameter, mm	7.2
Boron carbide density, g/cm^3	1.8
Burnable poison rod (BPR)	
Number	18
Outer diameter/cladding thickness, mm	9.1/0.69
Absorber/cladding material	CrB_2 +Al_2O_3/zircalloy
Boron density, g/cm^3	0.036
Space grids	
Number within the core	14
Material/mass, kg	zircalloy/0.53

*) For fuel pins with UO_2 fuel, central hole in fuel pins with ThO_2-PuO_2 was absent

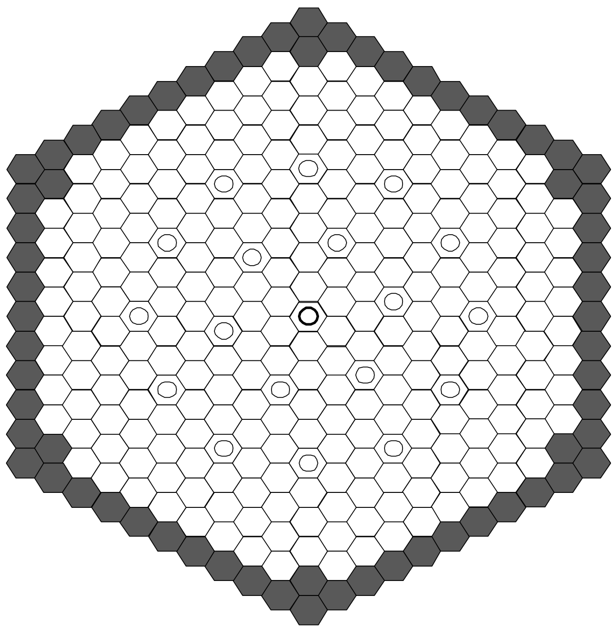


5.5 % ThO_2-PuO_2 fuel rod - 312

Guide tube +
BPRs in 1-st year FA or a water - 18

Central tube + water - 1

FIG. 3.7.1. Map of nonzoned ThO_2-PuO_2 assembly (full ThO_2-PuO_2 inventory).



UO_2 fuel rod 4.4% - 246

Guide tube +
BPRs in 1-st year FA or a water - 18

UO_2 fuel rod 3.6% - 66

Central tube + water -1

FIG. 3.7.2. Map of zoned UO_2FA (standard VVER-1000 FA).

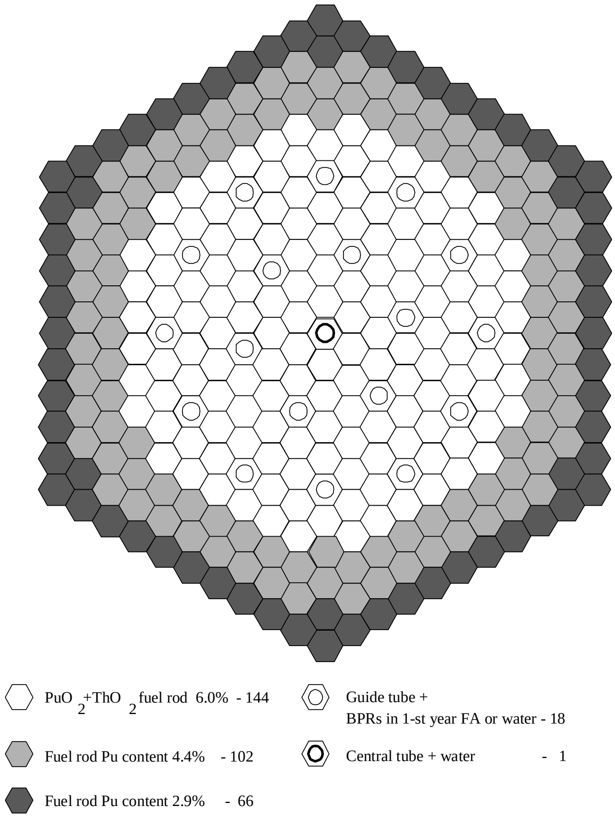


Fig. 3.7.3. Map of zoned fuel assembly with ThO_2-PuO_2 fuel.

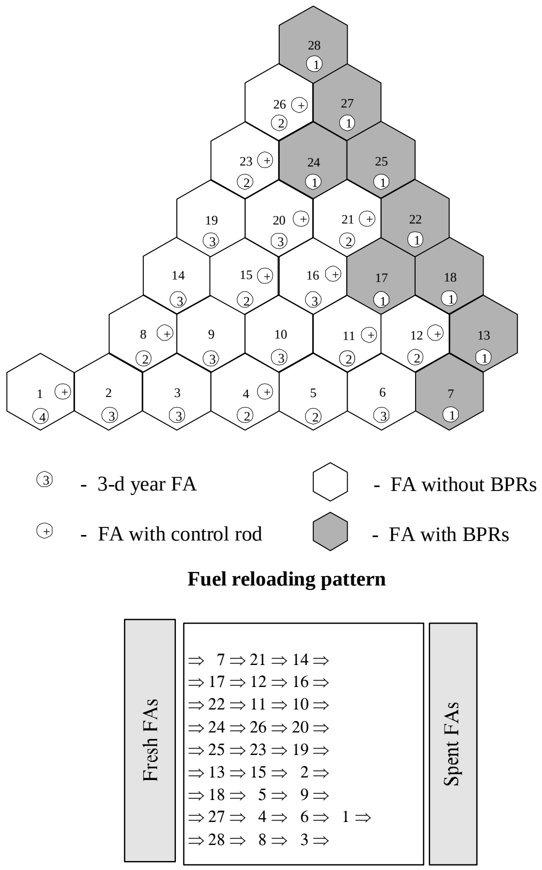


Fig. 3.7.4. FA arrangement in reactor with full load of PuO_2-ThO_2 fuel(1/6 part of core).

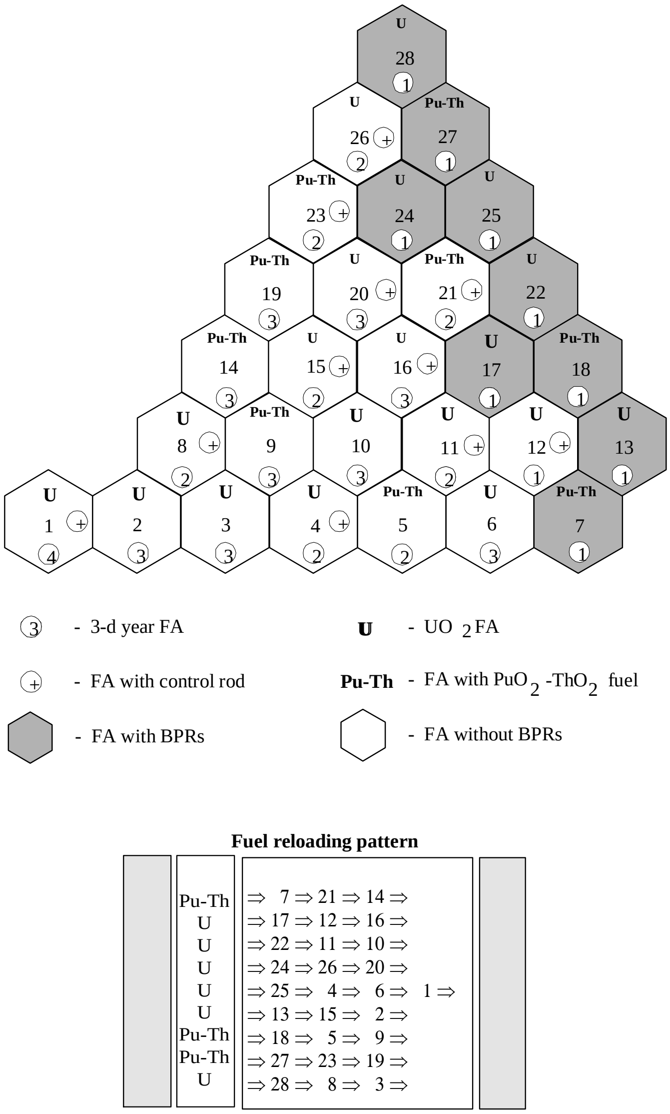


FIG. 3.7.5. FA arrangement in reactor with partial load of PuO_2-ThO_2 fuel(1/6 part of core).

3.7.1.2. Codes used in neutronics calculations

The calculation of neutronics characteristics was carried out using WIMS-ABBN, PARSEC, TRIANG-PWR and CREDE codes.

Code WIMS-ABBN [3] is a modernized WIMS-D4 [4]. The modernization was done to include minor actinide chains which were absent in an original version, and to take account the first resonance of ^{242}Pu with E_0 = 2.65 eV self-shielding. At the same time, the principle nuclide constants were updated in the code library. The intercomparisons made with calculated results using other codes including plutonium-thorium benchmarks coordinated by the IAEA, as well as with the experimental benchmarks give grounds to hope that the modifications aforementioned allow to use the WIMS-ABBN for calculating thermal reactors with fuels of any nuclide composition, in particular, with plutonium/thorium fuel.

The FAs burnup calculations were performed using the WIMS-ABBN code, and the macroscopic cross-sections of FAs were obtained at various combinations of core parameters that describe reactor state (water density, temperatures of water and fuel, concentrations of dissolved boron et al.). The results of calculations of macroscopic cross-sections were put in PARSEC code to determine the approximation coefficients. The calculation of the reactor was carried out by three-dimensional diffusion code TRIANG-PWR using the approximated macroscopic cross-sections.

CREDE code was used to calculate nuclide concentrations that were absent in WIMS calculations and leave the neutron balance unaffected, but were important from the point of view of radiotoxicity, for example ^{232}U. In addition this code corrects some flows of WIMS-calculations of nuclide concentration evolution, for example, WIMS code cannot treat branching in the capture process and the reaction (n,2n) cannot be considered if the reaction (n, γ) has been included. The list of nuclides involved in calculations is significantly enlarged (from stable isotopes of Pb and Bi up to ^{245}Cm). Besides, CREDE calculates nuclide composition and radiotoxicity of spent fuel over a long-term storage. The heavy nuclide chains, which are taken into account in CREDE code, are presented in Fig. 3.7.6.

3.7.1.3. Results of calculations

Table 3.7.3 shows FA criticality change when burning.

The k_{inf} calculations were made under the following conditions:

a) fissile material content in fuel rods was assumed to be equal to average value, i.e., zoning in FAs were not taken into account;

b) boric acid concentration was assumed to be constant and equal to average one over the cycle;

c) interreloading intervals were not taken into account, i.e. concentrations of ^{233}Pa and ^{233}U corresponded to equilibrium state;

d) boron burnable poison rods were not removed from FAs after first year. The influence of above-listed items was taken into account just in reactor calculations.

TABLE 3.7.3. FA CRITICALITY CHANGE WHEN BURNING

Reactor option with partial inventory of Pu-Th fuel				Reactor option with full inventory of Pu-Th fuel		
		UO_2 FA	PuO_2-ThO_2 FA	PuO_2-ThO_2 FA		
Average enrichment, %		4.23	4.8	Average enrichment, %		5.5
Eff. days	Burnup (MWdays/t)	k_{inf}	k_{inf}	Eff. days	Burnup (MWdays/t)	k_{inf}
0.0	0.000	1.181112	1.167882	0.0	0.000	1.186928
2.0	91.680	1.144760	1.142707	2.0	89.692	1.163192
29.5	1353.655	1.142027	1.120663	29.9	1340.895	1.142558
59.1	2707.311	1.141636	1.106274	59.8	2681.791	1.128906
88.6	4060.966	1.139362	1.095775	89.7	4022.686	1.118968
118.1	5414.621	1.135733	1.087125	119.6	5363.582	1.110794
147.7	6768.276	1.131117	1.079400	149.5	6704.477	1.103557
177.2	8121.932	1.125799	1.072306	179.4	8045.373	1.096861
206.7	9475.587	1.119835	1.065626	209.3	9386.268	1.090581
236.2	10829.242	1.113286	1.059217	239.2	10727.163	1.084526
265.8	12182.897	1.106215	1.053013	269.1	12068.059	1.078586
295.3	13536.553	1.098690	1.046907	299.0	13408.954	1.072781
324.8	14890.208	1.090783	1.040849	328.9	14749.850	1.067052
354.4	16243.863	1.082568	1.034783	358.8	16090.745	1.061366
383.9	17597.518	1.074124	1.028679	388.7	17431.641	1.055695
413.4	18951.172	1.065496	1.022501	418.6	18772.535	1.050003
443.0	20304.826	1.056753	1.016228	448.5	20113.430	1.044274
472.5	21658.480	1.047941	1.009851	478.4	21454.324	1.038488
502.0	23012.135	1.039105	1.003397	508.3	22795.219	1.032660
531.5	24365.789	1.030282	0.996814	538.2	24136.113	1.026789
561.1	25719.443	1.021493	0.990132	568.1	25477.008	1.020827
590.6	27073.098	1.012758	0.983352	598.0	26817.902	1.014749
620.1	28426.752	1.004093	0.976478	627.9	28158.797	1.008558
649.7	29780.406	0.995510	0.969518	657.8	29499.691	1.002262
679.2	31134.061	0.987019	0.962485	687.7	30840.586	0.995883
708.7	32487.715	0.978627	0.955387	717.6	32181.480	0.989432
738.3	33841.371	0.970340	0.948229	747.5	33522.375	0.982912
767.8	35195.027	0.962162	0.941038	777.4	34863.270	0.976330
797.3	36548.684	0.954094	0.933832	807.3	36204.164	0.969688
826.8	37902.340	0.946136	0.926641	837.2	37545.059	0.962985
856.4	39255.996	0.938291	0.919495	867.1	38885.953	0.956238
885.9	40609.652	0.930566	0.912422	897.0	40226.848	0.949451
915.4	41963.309	0.922965	0.905464	926.9	41567.742	0.942651
945.0	43316.965	0.915492	0.898629	956.8	42908.637	0.935859
974.5	44670.621	0.908150	0.891939	986.7	44249.531	0.929091
1004.0	46024.277	0.900942	0.885415	1016.6	45590.426	0.922362
1033.6	47377.934	0.893871	0.879083	1046.5	46931.320	0.915686
1063.1	48731.590	0.886938	0.872963	1076.4	48272.215	0.909086
1092.6	50085.246	0.880149	0.867071	1106.3	49613.109	0.902586
1122.1	51438.902	0.873503	0.861421	1136.2	50954.004	0.896218
1151.7	52792.559	0.867004	0.856024	1166.1	52294.898	0.889985
1181.2	54146.215	0.860652	0.850883	1196.0	53635.793	0.883895

TABLE 3.7.4. CRITICAL BORON CONCENTRATION VERSUS CORE CYCLE BURNING AT FULL POWER *(all the results presented below were obtained in equilibrium cycle)*

Reactor option with partial inventory of Pu-Th fuel		Reactor option with full inventory of Pu-Th fuel	
Days	C_B, ppm	Days	C_B, ppm
0	1319.6 *)	0	2200.8 *)
50	1033.2	50	1536.9
100	807.7	100	1157.2
150	590.2	150	825.3
200	380.3	200	524.4
250	177.4	250	250.9
295.3	0.0	299.2	0.0

*) ^{233}Pa decay during a 30-days reloading interval was taken into account.

Figures 3.7.7 and 3.7.8 present assembly power peaking factors for BOC and EOC for the reactor options under consideration.

a) begin of cycle *)

.675

1.079 .863

1.174 1.275 .913

.942 .920 1.135 .915

.894 1.155 .926 1.288 .866

1.148 .915 .928 1.234 1.086 .676

.682 .904 .942 1.047 1.155 1.018 .974

b) end of cycle

.758

1.045 .851

1.077 1.292 1.031

.895 .939 1.135 1.036

.882 1.100 .958 1.317 .860

1.134 .903 .929 1.158 1.063 .763

.815 .984 .969 .998 1.044 .978 .926

*FIG. 3.7.7. Assembly power peaking factors at BOC and EOC in reactor with partial inventory of ThO_2-PuO_2 fuel. *) ^{233}Pa decay during a 30-days reloading interval was taken into account.*

a) begin of cycle *)

.719

1.121 .941

1.203 1.334 1.009

.917 .977 1.241 1.009

.819 1.040 .977 1.335 .941

.928 .829 .918 1.203 1.121 .719

.585 .754 .824 .963 1.145 1.056 1.021

b) end of cycle

.654

1.037 .819

1.159 1.166 .860

1.007 .996 1.116 .860

.992 1.136 .996 1.166 .819

1.150 1.000 1.008 1.159 1.037 .654

.863 1.013 1.033 1.084 1.163 1.029 .929

*FIG. 3.7.8. Assembly power peaking factors at BOC and EOC in reactor with full inventory of ThO_2-PuO_2 fuel. *) ^{233}Pa decay during a 30-days reloading interval was taken into account.*

Tables 3.7.5 - 3.7.7 present fuel cycle characteristics.

TABLE 3.7.5. FUEL LOAD CHARACTERISTICS

Characteristics	Partial inventory (1/3)		Full inventory
Assembly type	UO_2	PuO_2-ThO_2	PuO_2-ThO_2
Fuel weight, t h. m.	43.8	22.1	66.9
Total	65.9		66.9
Average initial content in fuel, %			
^{235}U	4.23	-	-
Pu	-	4.8	5.5
Cycle duration, eff. Days	295.3		299
Annual load of			
Heavy metals, t	14.45	7.38	22.16
^{235}U, kg	611.5	-	-
Pu + ^{241}Am, kg	-	354	1220

TABLE 3.7.6. ESTIMATES OF RESOURCES REQUIREMENTS PER 1 GWe/YEAR

Fuel	Partial inventory (1/3)	Full inventory
Natural uranium, t	114.007	-
Thorium, t	7.02	20.94
Plutonium, t	0.354	1.22
SWU's	148 000	-
Fuel fabrication, t h.m.	21.83	22.16

TABLE 3.7.7. ESTIMATES OF FUEL FLOW AT END OF CYCLE

Characteristics	Partial inventory (1/3)	Full inventory
Annually discharged fuel:		
Weight, t h.m.	21.83	22.16
Volume, m^3 of dioxides	2.78	2.78
Weight of Pu in discharged fuel, kg	266	462
Fissile isotopes in discharged Pu: ^{239}Pu, ^{241}Pu, total, %	44.6, 19.7, 64.3	36.3, 22.4, 58.7
Annual balance of Pu: unloading-loading, kg	-88	-758
^{233}U+^{233}Pa annual unloading, kg	100.1	293.7
^{232}U content in unloaded U, ppm	3862	3675
Minor actinides (^{231}Pa, Np, Am, Cm) annual unloading, kg	15.6	17.1
Average content in unloaded FAs, kg/t h.m.		
^{233}U+^{233}Pa	4.6	13.3
^{235}U	7.3	0.2
Pu	12.2	20.8
MA	0.71	0.77

TABLE 3.7.8. CHARACTERISTICS IMPORTANT FOR REACTOR SAFETY (BOC/EOC)

Reactor state characteristics	MPUM state		Rated power	
	Partial inventory	Full inventory	Partial inventory	Full inventory
$\Delta\rho_{BA}$, %	14.0/6.6	13.4/6.3	8.1/0	7.8/0
$\frac{\partial\rho}{\partial t_F}$, $\frac{10^{-5}}{^{\circ}C}$	-3.8/-3.9	-4.5/-4.5	-2.6/-2.7	-3.0/-3.1
$\frac{\partial\rho}{\partial t_{H_2O}}$, $\frac{10^{-5}}{^{\circ}C}$	-4.0/-25.3	-7.2/-23.5	-21.6/-52.4	-26.1/-50.9
β_{eff}, 10^{-2}	-	-	0.52/0.49	0.28/0.32
Total control rod reactivity value, %	-	-	6.63/6.85	5.48/6.12
^{233}Pa decay effect (total), % T = 20°C, P = 0	0.40/0.80	1.06/2.00	0.38/0.71	0.92/1.64

Table 3.7.8. shows some characteristics that are important for reactor safety. The calculations were performed at minimum power under monitoring (MPUM) (T = 279 °C, P = 0) and rated power. For the beginning of cycle the values are calculated considering decay of ^{233}Pa and accumulation of ^{233}U over a 30-days reloading interval.

3.7.2 Calculations of the principal neutronics characteristics of the VVER-1000 reactor loaded with PuO_2-ThO_2 fuel based on reactor-grade plutonium

The principle design parameters of reactor under consideration are the same as for burning weapons-grade plutonium, except:

1. In partial PuO_2-ThO_2 core average plutonium content in PuO_2-ThO_2 fuel assemblies (FA) is 7.0%.
2. In full PuO_2-ThO_2 core plutonium content is 8.1%.
3. Reactor-grade plutonium composition at the moment of core loading is taken as follows (in weight%) [2]:

^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{241}Am
0.9	61.0	22.0	10.09	4.1	1.1

TABLE 3.7.9. FA k_{inf} CHANGE VERSUS BURNUP

	Reactor option with partial inventory of Pu-Th fuel (1/3)		Reactor option with full inventory of Pu-Th fuel	
Average enrichment, %	7.0		8.1	
Eff. days	Burnup (MWdays/t)	k_{inf}	Burnup (MWdays/t)	k_{inf}
0.0	0.000	1.155527	0.000	1.166996
1.0	44.764	1.134449	44.705	1.147836
2.0	89.529	1.133264	89.410	1.146799
29.3	1311.600	1.117534	1 309.859	1.132341
58.6	2623.200	1.107673	2 619.719	1.122961
87.9	3934.800	1.100699	3 929.578	1.116332
117.2	5246.399	1.094911	5 239.438	1.110904
146.5	6557.999	1.089597	6 549.297	1.106015
175.8	7869.599	1.084547	7 859.156	1.101370
205.1	9181.198	1.079669	9 169.016	1.096886
234.4	10492.798	1.074896	10 478.875	1.092499
263.7	11804.397	1.070201	11 788.734	1.088156
293.0	13115.997	1.065566	13 098.594	1.083815
322.3	14427.597	1.060981	14 408.453	1.079531
351.6	15739.196	1.056438	15 718.312	1.075294
380.9	17050.797	1.051929	17 028.172	1.071094
410.2	18362.396	1.047451	18 338.031	1.066928
439.5	19673.996	1.043000	19 647.891	1.062795
468.8	20985.596	1.038566	20 957.750	1.058692
498.1	22297.195	1.034144	22 267.609	1.054618
527.4	23608.795	1.029746	23 577.469	1.050568
556.7	24920.395	1.025380	24 887.328	1.046540
586.0	26231.994	1.021035	26 197.188	1.042568
615.3	27543.594	1.016692	27 507.047	1.038630
644.6	28855.193	1.012373	28 816.906	1.034700
673.9	30166.793	1.008078	30 126.766	1.030786
703.2	31478.393	1.003806	31 436.625	1.026883
732.5	32789.992	0.999561	32 746.484	1.022962
761.8	34101.594	0.995341	34 056.344	1.019060
791.1	35413.195	0.991152	35 366.203	1.015159
820.4	36724.797	0.986986	36 676.062	1.011281
849.7	38036.398	0.982846	37 985.922	1.007424
879.0	39348.000	0.978735	39 295.781	1.003585
908.3	40659.602	0.974663	40 605.641	0.999769

(cont'd)

TABLE 3.7.9. FA K_{inf} CHANGE VERSUS BURNUP

937.6	41971.203	0.970639	41 915.500	0.995979
966.9	43282.805	0.966668	43 225.359	0.992219
996.2	44594.406	0.962756	44 535.219	0.988488
1025.5	45906.008	0.958907	45 845.078	0.984786
1054.8	47217.609	0.955129	47 154.938	0.981117
1084.1	48529.211	0.951428	48 464.797	0.977473
1113.4	49840.812	0.947811	49 774.656	0.973869
1142.7	51152.414	0.944284	51 084.516	0.970309
1172.0	52464.016	0.940854	52 394.375	0.966796
1201.3	53775.617	0.937525	53 704.234	0.963336
1230.6	55087.219	0.934302	55 014.094	0.959932
1259.9	56398.820	0.931190	56 323.953	0.956588
1289.2	57710.422	0.928192	57 633.812	0.953309
1318.5	59022.023	0.925315	58 943.672	0.950099
1347.8	60333.625	0.922573	60 253.531	0.946961
1377.1	61645.227	0.919960	61 563.391	0.943900
1406.4	62956.828	0.917467	62 873.250	0.940919
1435.7	64268.430	0.915110	64 183.109	0.938023
1465.0	65580.031	0.912888	65 492.969	0.935212

TABLE 3.7.10. CRITICAL BORON CONCENTRATION VERSUS CORE CYCLE BURNING AT FULL POWER

Reactor optionwith partial inventory of Pu-Th fuel		Reactor optionwith full inventory of Pu-Th fuel	
Days	C_B, ppm	Days	C_B, ppm
0	1223.7	0	1678.3
50	976.1	50	1195.5
100	770.7	100	916.2
150	570.8	150	659.7
200	374.8	200	427.1
250	184.0	250	205.6
299.5	0.0	300	0.0

Tables 3.7.11 - 3.7.13 present fuel cycle characteristics.

TABLE 3.7.11. FUEL FLOW CHARACTERISTICS

Characteristics	Partial inventory (1/3)		Full inventory
Assembly type	UO_2	PuO_2-ThO_2	PuO_2-ThO_2
Fuel weight, t h. m.	43.8	22.2	
Total	66.0		67.1
Average initial content in fuel, %			
^{235}U	4.23	-	-
Pu	-	7.0	8.1
Cycle duration, eff. days	299.5		300
Annual load of			
Heavy metals, t	14.45	7.4	22.2
^{235}U, kg	611.5	-	-
Pu + ^{241}Am, kg	-	518.7	1803
Average burnup, Mwdays/kg HM	41.4	40.2	
	41.0		

TABLE 3.7.12. ESTIMATES OF RESOURCES REQUIREMENTS PER 1 GW(el)/YEAR

Fuel	Partial inventory (1/3)	Full inventory
Natural uranium, t	114 007	-
Thorium, t	6.9	20.3
Plutonium, t	0.519	1.803
SWU's	148 000	-
Fuel fabrication, t h.m.	21.85	22.2

TABLE 3.7.13. ESTIMATES OF FUEL FLOW AT END OF CYCLE

Characteristics	Partial inventory (1/3)	Full inventory
Annually discharged fuel:		
Weight, t h.m.	21.85	22.2
Volume, m^3 of dioxides	2.78	2.78
Weight of Pu in discharged fuel, kg	401	953
Fraction of ^{239} Pu in discharged Pu, %	36.6	29.5
Annual balance of Pu: unloading-loading, kg	-117	-850
^{233}U+^{233}Pa annual unloading, kg	99.6	291
^{232}U content in discharged U, ppm	3550	3322
Minor actinides (^{231}Pa, Np, Am, Cm): annual unloading, kg	32.4	67.0
Average content in unloaded FAs, kg/t h.m.		
^{233}U+^{233}Pa	4.5	13.1
^{235}U	7.2	0.2
Pu	18.3	42.9
MA	1.5	3.0

Radioactivity of annually discharged fuel (without any reprocessing) is shown in Table 3.7.6 (per 1 GW(el)/year) for EOC, 10 years after discharge, 100, 1000, 10000, 100000, and 1 million years.

TABLE 3.7.14. RADIOACTIVITY AND RADIOTOXICITY OF SPENT FUEL

Cooling time (years)	Partial (1/3) inventory			Full inventory		
	Bq	Sv for water	Sv for air	Bq	Sv for water	Sv for air
0	0.21E+20	0.24E+11	0.22E+13	0.17E+20	0.33E+11	0.61E+13
10	0.22E+18	0.46E+10	0.98E+12	0.57E+18	0.12E+11	0.26E+13
100	0.18E+17	0.31E+10	0.61E+12	0.48E+17	0.81E+10	0.16E+13
1 000	0.38E+16	0.87E+09	0.16E+12	0.99E+16	0.22E+10	0.42E+12
10 000	0.91E+15	0.22E+09	0.37E+11	0.23E+16	0.52E+09	0.89E+11
100 000	0.27E+15	0.27E+08	0.45E+10	0.74E+15	0.70E+08	0.12E+11
1 000 000	0.27E+14	0.25E+07	0.37E+09	0.62E+14	0.57E+07	0.87E+09

Table 3.7.15 shows some reactor safety characteristics. The calculations were performed at minimum power under monitoring (MPUM) (T = 279 °C, P = 0) and rated power. For the beginning of cycle the decay of ^{233}Pa and accumulation of ^{233}U in course of 30-days reloading interval were taken into account.

TABLE 3.7.15. SOME REACTOR SAFETY CHARACTERISTICS (BOC/EOC)

Reactor state characteristic	MPUM		Rated power	
	Partial inventory	Full inventory	Partial inventory	Full inventory
$\Delta\rho_{BA}$,%	13.3/6.5	10.5/6.0	7.4/0	4.8/0
$\frac{\partial\rho}{\partial T_F}, \frac{10^{-5}}{^\circ C}$	-4.7/-4.7	-5.5/-5.5	-2.6/-2.7	-2.9/-2.9
$\frac{\partial\rho}{\partial T_{H_2O}}, \frac{10^{-5}}{^\circ C}$	-4.6/-25.0	-7.4/-21.5	-26.4/-57.3	-36.5/-56.2
$\beta_{eff}, 10^{-2}$	-	-	0.54/0.49	0.33/0.35
Total control rod reactivity worth, %	-	-	6.4/6.6	5.2/5.5

Table 3.7.16 shows the protactinium effect at rated power. The figures correspond to total effect and to 30-days loading interval effect as well.

TABLE 3.7.16. ^{233}Pa EFFECT VALUES, %

Reactor state	Partial inventory		Full inventory	
	30-days effect	Total effect	30-days effect	Total effect
BOC	0.16	0.29	0.39	0.73
EOC	0.26	0.49	0.64	1.19

3.7.3. Assessment of the effect of plutonium burning on the waste toxicity

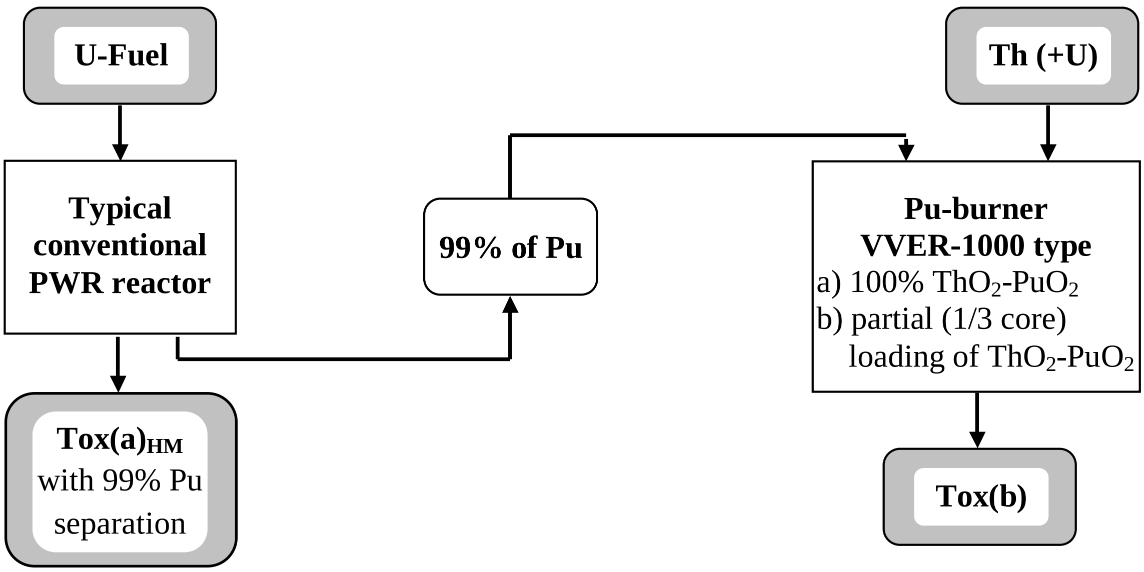
In the benchmark should be compared heavy metal radiotoxicity per 1 GWa(el) (where 1 year = 300 FPD) of spent fuel from:

1) typical conventional PWR reactor loaded with UO_2 fuel (case 1), and
2) in alternative plutonium burning in fuel cycle (case 2).

The calculation of radiotoxicity of a typical PWR (1000 MW(el), 300 FPD) case 1 was the subject of investigation at stage 3 of IAEA Benchmark, and the results were presented in Section 2.

The radiotoxicity of spent fuel in the fuel cycle shown in Fig. 3.7.9 – case 2 has to be determined as a sum of:

— heavy metal radiotoxicity of a typical conventional uranium PWR reactor after extracting 99% of plutonium isotopes from its spent fuel (Tox(a)); and



— radiotoxicity of spent fuel of reactor (Tox(b)) in which plutonium recycle is made (reactor-burner).

FIG. 3.7.9. Fuel cycle scheme, case 2.

Radiotoxicity has to be normalized per 1 $GW_{el}a$ produced in the cycle. As this take place, a relationship between capacities of a typical uranium PWR and reactor-burners was defined based on plutonium mass balance, and total radiotoxicity of fuel cycle per 1 $GW_{el}a$ (case 2) can be determined as:

$$R = \frac{R_1 + xR_2}{1 + x},$$

$$x = \frac{G_{Pu}^{D(1)}}{G_{Pu}^{C(2)}},$$

where

R_1 - radiotoxicity of discharged fuel of a typical PWR without of 99% of plutonium-Tox(a);

R_2 - radiotoxicity of discharged recycled fuel from reactor-burner - Tox(b);

$G_{Pu}^{D(1)}$ - annual plutonium discharge from a typical PWR (245 kg Pu/1 GW_{el}a as follows from Benchmark task for stage 3 (part 1));

$G_{Pu}^{C(2)}$ - annual plutonium charge for reactor-burners.

$G_{Pu}^{C(2)}$ - corresponds to individually chosen reactor-burners - for Russian Federation they are VVER-1000 type reactors with full or partial inventories of PuO_2-ThO_2 fuel: $G_{Pu}^{C(2)}$ - = 1803 kg for full inventory and $G_{Pu}^{C(2)}$ = 519 kg of plutonium for partial inventory.

Radiotoxicity computations were made on the basis of Dose Coefficients of Intake recommended by ICRP (ICRP publications, 1991, 1994). Only heavy atoms were taken into account.

The results are shown in Table 3.7.17 and Figs 3.7.10 and 3.7.11. From this figures it is obvious that reactor-grade plutonium recycling does not tend to essential change in radiotoxicity: at initial stage of storage (tens of years) radiotoxicities are closely allied, then radiotoxicity when recycling appears to be slightly below radiotoxicity of open fuel cycle, between 10^5 and 10^6 years recycling causes increase in radiotoxicity in case of using plutonium-thorium burners, and at the end of given period they prove to be close again. By and large it can be noted that the use of thorium for decreasing in radiotoxicity does not give clear merits.

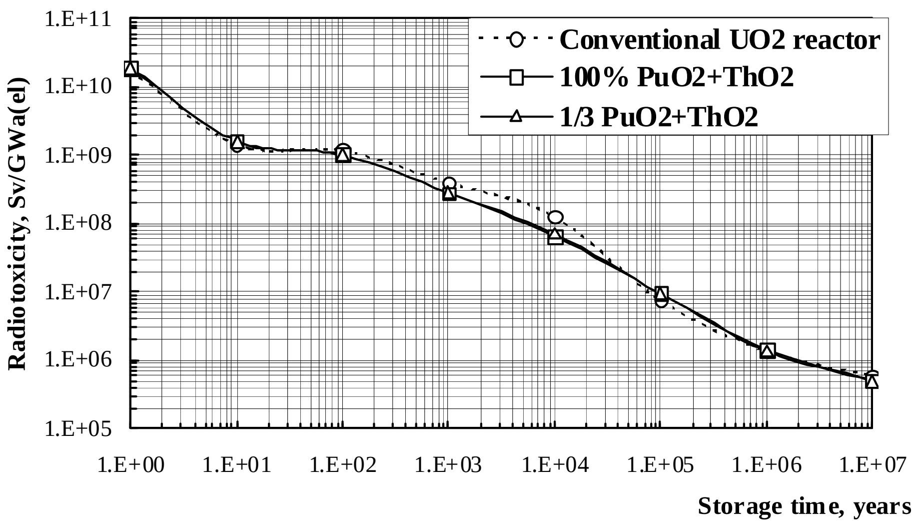


FIG. 3.7.10. Ingestion hazard of heavy metals. Conventional UO_2 reactor and one-through cycle of plutonium discharged from a typical PWR in PuO_2-ThO_2 reactors.

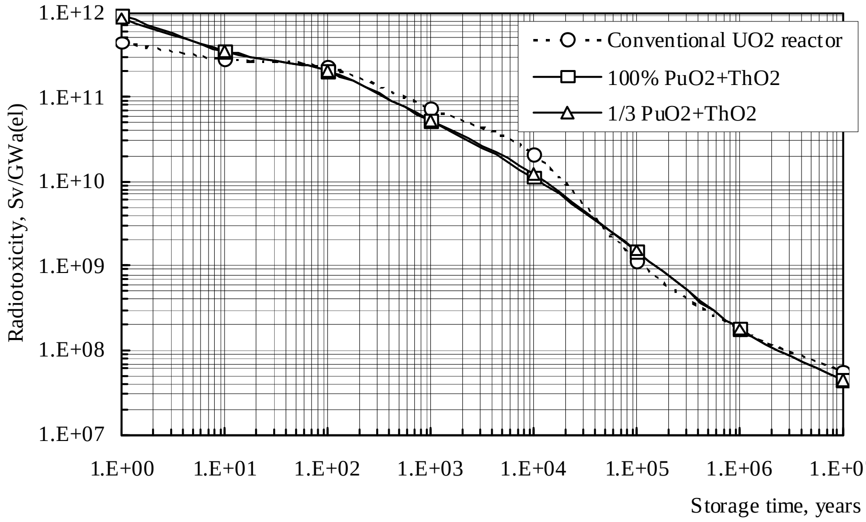


FIG. 3.7.11. Inhalation haggard of heavy metals. Conventional UO_2 reactor and one-through cycle of plutonium discharged from a typical PWR in PuO_2-ThO_2 reactors.

TABLE 3.7.17. RADIOTOXICITY OF HEAVY METAL FROM SPENT FUEL, $Sv/GW_{el}a$

Storage time (years)	Conventional UO_2 loaded reactor No Pu separation	Recycling 100% PuO_2-ThO_2 loaded burner	Pu in 1/3 PuO_2-ThO_2 loaded burner
Ingestion			
0	1.79E+10	1.87E+10	1.90E+10
10^1	1.43E+09	1.63E+09	1.60E+09
10^2	1.16E+09	1.02E+09	1.03E+09
10^3	3.99E+08	2.79E+08	2.88E+08
10^4	1.28E+08	6.56E+07	7.14E+07
10^5	7.63E+06	9.44E+06	9.51E+06
10^6	1.36E+06	1.42E+06	1.38E+06
10^7	5.88E+05	5.08E+05	4.89E+05
Inhalation			
0	4.41E+11	9.25E+11	8.59E+11
10^1	2.79E+11	3.52E+11	3.44E+11
10^2	2.24E+11	2.01E+11	2.03E+11
10^3	7.22E+10	5.18E+10	5.35E+10
10^4	2.13E+10	1.12E+10	1.22E+10
10^5	1.14E+09	1.50E+09	1.52E+09
10^6	1.74E+08	1.78E+08	1.76E+08
10^7	5.58E+07	4.47E+07	4.42E+07

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